WORKING GROUP REPORT

Lidar Technologies

June 2006

NASA Earth Science Technology Office
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EXECUTIVE SUMMARY

The NASA Earth Science Technology Office (ESTO) recently formed a technology working group in the area of laser and lidar technologies in order to identify detailed technology requirements for implementing the NASA Earth Science research objectives. The key objective for this initiative is to develop a strategy for targeted technology development and risk mitigation efforts at NASA by leveraging technological advancement made by other government agencies, industry and academia and move NASA into the next logical era of laser remote sensing by enabling such critical measurements as tropospheric winds, CO2 profile, 3D vegetation structure, high resolution ice surface topography, clouds and aerosols, trace atmospheric species, Ozone, and phytoplankton physiology from space. Lidar uniquely provides for high vertical resolution measurements of these parameters, both in the Earth and planetary science arenas.

Lidar enables several key measurements that can not be obtained by any other technique:

- Global tropospheric winds are acknowledged as the greatest unmet observational need for improving global weather forecasts. Doppler lidar is recognized as the only means for acquiring such data with the required precision (1 m/s, 100-km horizontal resolution).
- Differential absorption lidar (DIAL) is the only method for high precision profiling of tropospheric CO2 (0.3% mixing ratio, 2-km vertical scale), essential to understanding the global carbon cycle, greenhouse warming and the sustainability of life on Earth
- Lidar is the only method for measuring particle profiles in the oceans' mixed layer, necessary to understand how oceanic carbon storage and fluxes contribute to the global carbon cycle
- DIAL is the only technique for global tropospheric ozone profiling with high resolution (1-2 km vertical, 100 km horizontal), essential for the modeling and assessment of chemical, radiative, convective, dynamical, and transport processes in the troposphere
- DIAL is the only technique for global moisture profiles at high resolution (0.5 km vertical by 50 km horizontal) in the boundary layer, essentially needed for the understanding of convective processes and severe storm development
- Backscatter lidar is the only method for high vertical resolution (50 m) measurements of optical properties of clouds and aerosols including planetary boundary height, cloud base, cloud top, cloud depolarization, and aerosol scattering profiles needed in climate modeling and research
- Laser altimetry is the only technique for profiling a surface level changes of less than 1 cm/year, essential for studying landcover vegetation, land surface tropography, volcano monitoring, global sea level, and polar ice sheet level changes caused by climatic changes

The results of this roadmapping activity have been captured in this report.

The working group consisted of three technology subgroups focused on the topics of laser transmitters, detection and optics, and data acquisition and utilization. The requirement definition process began with a set of quantitative science requirements defined by NASA/HQ program scientists and their communities. The science requirements encompassed the six science focus areas of atmospheric composition, carbon cycle and ecosystems, climate variability and change, Earth surface and interior, water and energy cycle, and weather. For each science requirement, one or more measurement scenarios were developed and technology challenges corresponding to each scenario were identified. Measurement scenarios included various lidar techniques such as ranging and altimetry, Doppler lidar, backscatter lidar, differential absorption lidar (DIAL), and laser interferometry (for applications such as Earth gravity measurement). The technology challenges for each scenario were studied in detail and a capability breakdown structure was developed for each of the technology challenges.

The following prioritization criteria were used to prioritize the needed technology capabilities in the order of importance: scientific impact of the measurement, societal benefit of the measurement, measurement scenario uniqueness, technology development criticality, technology utility (i.e. degree of cross-cutting value), measurement timeline; value of technology in reducing mission failure/risk.

Based on the above criteria, it was determined that the requirements for certain measurements will be best met by lidar technique and that to satisfy the related science requirements, specific technology development is required. These measurements are: tropospheric wind vertical profile, ice mass balance, CO2 vertical profile, 3D vegetation structure, and phytoplankton physiology.

The technology requirements for each measurement in the area of laser transmitters, detection and optics, and data acquisition and utilization are tightly coupled. The working group strongly recommends that the highest priority measurement(s) be identified at the agency level. Technology development to satisfy the priority measurement(s) in the three technology categories must then be targeted and coordinated in order to get maximum return on investment.

In the area of laser transmitters, investments must be made carefully according to the priority measurement in mind. Low energy, high pulse rate 1-micron laser development is most suitable for ice topography and 3D biomass measurements. The technology development in this type of laser can be leveraged off by both types of measurements. High energy, low pulse rate 1-micron lasers are recommended for direct Doppler wind measurements and certain atmospheric chemistry measurements using DIAL or the backscatter lidar. 1.5 micron fiber laser now extensively developed in the telecom industry is most suitable for low tropospheric CO2 measurements but are also under consideration for other application areas such as high resolution topography and vegetation structure. Technology development in this area can be leveraged off from industry. However, these types of lasers have not been qualified in space and have limited statistics available regarding their performance. Alternatively, the high energy low pulse rate, 2 micron laser can also serve as a candidate for the CO2 measurement concept and is the laser of choice for coherent Doppler wind measurement. There are certain technologies that are needed along with laser development. The highest priority technologies are those of Vis-UV wavelength conversion and beam director technologies. These technologies are laser transmitter specific and investment in them should be made in accordance with the high priority laser transmitter investment.

In the area of detection (receiver) and optics, alignment maintenance technology is critically needed for enabling a variety of measurement. The requirement is 5μrad for coherent Doppler wind detection and 50 μrad for Direct Doppler wind detection. The Technology Readiness Level (TRL) ranges from 4 (for the coherent technique) to 7 (for the direct technique). This technology is also critical for enabling the CO2 and 3D biomass measurements. Scanning system technology has also been a tall pole for the Doppler wind measurement. Conical or step-stare, full azimuth at 30-50o is required and the TRL is between 3 and 5.

In terms of optics, the tallest pole is the 3m diameter mirror required by the CO2 measurement. When the diameter is this large, a mirror with areal density of less than 25 kg/m2 is required. In addition, development of high efficiency detectors in the 1.5 and 2 micron wavelengths reduce the power needed for the laser transmitter.

The end-to-end technology requirement definition was completed by folding data acquisition and data utilization requirements in the picture. The data subgroup of the lidar working group worked closely with the instrument technology teams and defined data acquisition and utilization technologies relevant to the priority laser remote sensing measurements. The highest relevant technologies that have the most immediate impact are: airborne/ground validation systems for rapid calibration and validation of lidar data; intelligent sensor health and safety technologies for applications such as laser life optimization; science model-driven adaptive targeting for opportunistic science and the 3 hour stringent requirement for weather forecast: and on-board sensor control technologies for measurement autonomy.

Detailed technology requirements are discussed in Chapter 5. Prioritization analysis and integrated technology roadmap is presented in Chapter 6. In summary, technology investments in the three different technology areas (transmitter, receiver, and data) should be made carefully and in a manner such that technologies complement each other toward enabling priority measurements.

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Introduction

The NASA Science Mission Directorate (SMD) has recently developed a set of Earth science roadmaps in six specific focus areas. The roadmaps are in the areas of Atmospheric Composition, Carbon and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather. The roadmaps (as of November 2005) appear in Appendix 1A. These roadmaps characterize the NASA Earth science objectives to be achieved in the next decade. The letter "T" in each roadmap identifies technology areas that require future investments in order to accomplish the Earth science objectives.

In order to identify detailed technology requirements for implementing the Earth science research objectives, the Earth Science Technology Office (ESTO) has assembled a technology working group specifically focused in the area of lidar technology. The working group membership has been by invitation only and was comprised of members from NASA centers, academia, FFRDCs, and industry. Dr. Azita Valinia (NASA/GSFC) served as the working group chair. A list of working group members appears in Appendix 1B.

Focusing on lidar technologies only, the working group's charter was to develop a decadal technology implementation plan and technology roadmaps for enabling the SMD Earth science roadmaps. The roadmaps are intended to guide ESTO's investment strategy for future technology developments.

This working group report is the second in a series of technology implementation plans and roadmaps developed to address needed technologies for enabling the SMD Earth science objectives. A previous volume focused on active and passive microwave technologies. Other volumes to follow will focus on passive optical, IR, and UV techniques.

Technology Requirement Definition Process

In order to give the community the opportunity to provide direct input in this technology roadmapping activity, the working group members invited the community to an open forum on January 10, 2006, held in Washington, DC. Input from the community was accepted for both science and technology requirements. Inputs were accepted via an electronic input submission website which was open for approximately four weeks. The community was also invited to give oral presentations at the forum. A list of forum participants appears in appendix 1C.

ESTO had also sponsored a comprehensive technology planning workshop in March of 2003. During that workshop, technology requirements were derived and validated by the community in all technology thrust areas (sensors and platforms). These requirements are available in searchable format on the Earth Science Technology Integrated Planning System (ESTIPS) database. The final report of the workshop is also available on the database at http://esto.nasa.gov/estips.

In this planning activity, focusing lidar technologies, the working group started from the ESTIPS data, SMD Earth System Science roadmap missions, and submissions to the National Research Council Earth Science Decadal Survey Request for Information. The working group then incorporated the community's input and did extensive research to add many layers of detail to the top level requirements available in ESTIPS.

The working group consisted of three technology subgroups focused on the topics of laser transmitters; detection, processing and optics (receivers); and data acquisition and utilization. Technology subgroup membership appears in appendix 1D. There were also three science subgroups focused on atmospheric composition, atmospheric dynamics, and oceans and topography (Figure 1-2). Appendix 1E shows the science subgroup membership. The working group members met four times in the Washington, DC area. The kickoff meeting occurred on November 8, 2005. The subsequent meetings took place on December 14, 2005; and January 11 and February 7, 2006. Group members worked independently in between the meetings and used the scheduled meetings to give progress reports and define the next set of milestones to be delivered at the subsequent meetings.

An overview of the requirement definition process appears in Figure 1-1.

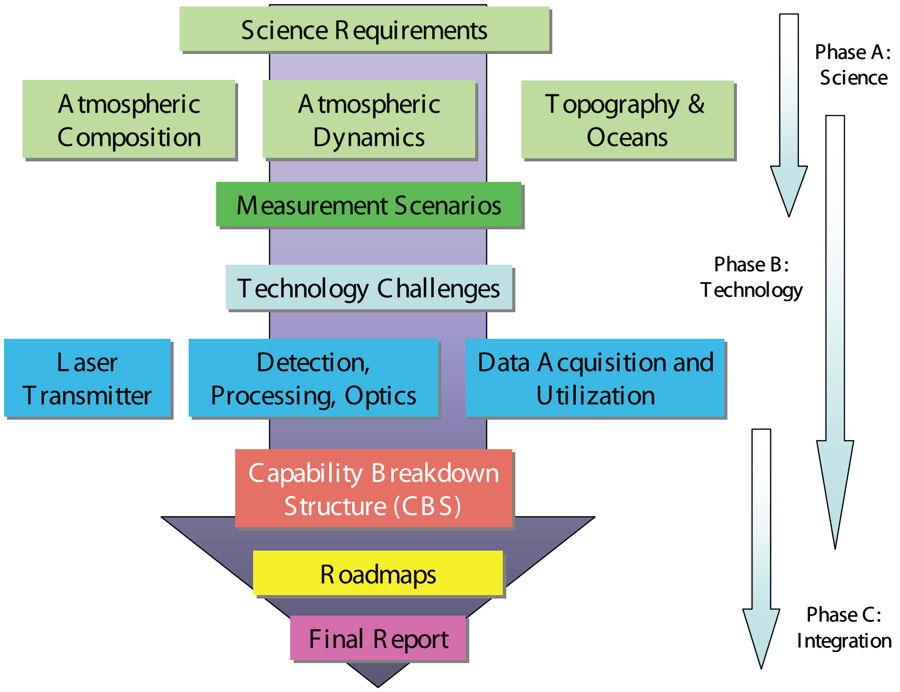


Figure 1-1: Overview of the Technology Requirements Definition Process

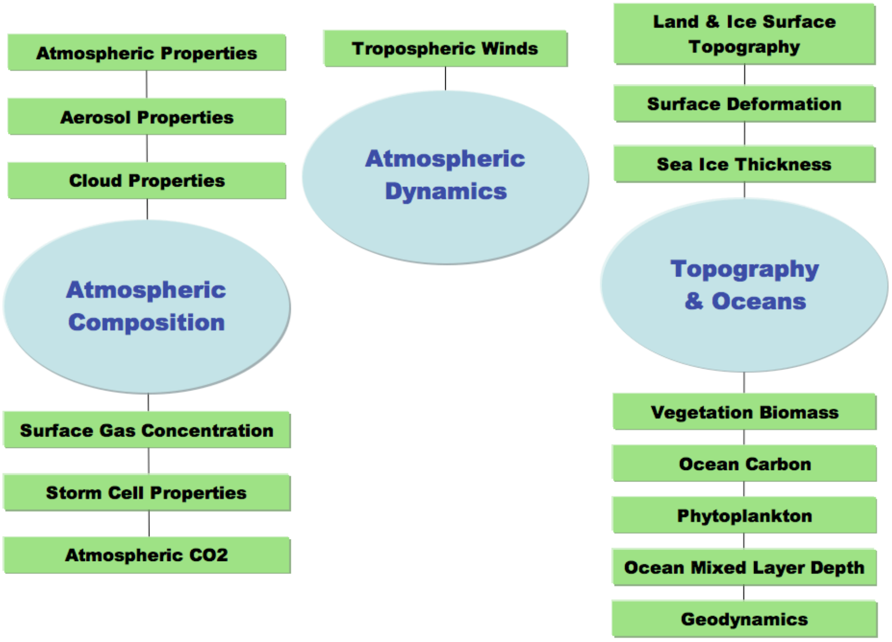


Figure 1-2: Scope of Science Subgroups

Chapter 2 of this document describes the quantitative science requirements and their relevance to lidar measurement techniques. Chapter 3 reviews all lidar measurement scenarios considered by the working group. Chapter 4 describes the data acquisition and utilization scenarios which relate lidar measurements to information system requirements. Chapter 5 discusses the technology challenges for the scenarios discussed in chapter 3 and gives the capability breakdown structure for each of the required technologies. Technology roadmaps corresponding to the ESE science focus areas are presented in chapter 6, along with an analysis and summary of the prioritized technology requirements.

2. The Scientific Basis for the Technology Development Program

The frontier of Earth system science is to: (1) explore interactions among the major components of the Earth System - continents, oceans, atmosphere, ice, and life, (2) distinguish natural from human-induced causes of change, and (3) understand and predict the consequences of change. To examine these complex processes, the NASA Science Mission Directorate has defined the following six focus areas:

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

The NASA developed roadmaps to articulate the activities needed to achieve the long-term goals for each of the focus areas are summarized in Appendix 1A.

Lidar remote sensing is a powerful tool for enhancing our knowledge and understanding of a wide variety of environmental phenomena related to the atmosphere, oceans, land surface, and ice cover, and ultimately to life. The scientific basis for the Lidar remote sensing technologies proposed for development by NASA's Earth Science Technology Office is presented in this chapter. The goals of each science focus area, and the roles that Lidar remote sensing can play in achieving those goals, as well as the benefits to society of making the proposed measurements, are all discussed below.

The technologies identified in this report have a common goal of supporting the development and deployment of a Lidar remote sensing capability by NASA in support of these science focus areas. Many of these technologies that are proposed in this report support not only satellite-based remote sensing concepts but airborne and ground based approaches as well. There are a number of reasons why environmental phenomena are often best observed from satellites, rather than from UAVs (Unmanned Airborne Vehicles), manned aircraft, or *in situ* networks of sensors. Satellites afford large-area synoptic coverage. Satellites in a polar orbit can provide global access (which is especially important in remote areas such as the South Pacific). A constellation of satellites flying Lidar sensors may be configured to give relatively good temporal refresh (12 hours or less) depending on the availability to achieve the appropriate swath coverage from each satellite in the constellation. However, ground based and airborne systems provide a very important complement to satellite remote sensing. For example, ground based and airborne systems provide complementary observations during the Calibration and Validation (Cal/Val) phase of spaceborne missions. The availability of such routine monitoring is important for parameters that are highly variable in space and time. Satellites can provide data with fixed spatial resolution from a circular orbit, which simplifies data analysis compared to that from an airborne platform.

The stability and repeatability of satellite orbits compared to aircraft trajectories is important, for example in Lidar observations of surface topography and the performing change detection for land cover applications. Satellites do not have the human restrictions imposed by manned aircraft. Finally, by international agreement, satellites have no over-flight restrictions. Satellite observations do have limitations such as relatively fixed orbits that generally fix their spatial and temporal sampling characteristics, and the achievable horizontal spatial resolution is constrained by the orbital altitude and aperture size (for passive systems). Instrument repair is current not possible at the typical orbital altitudes used for remote sensing. Spaceborne instruments must be space qualified, which typically involves long and costly development programs. But the benefits of spaceborne platforms for the monitoring of global phenomena distinctly outweigh their limitations in the majority of cases.

Lidar observations provide specific atmospheric, oceanographic, terrestrial and cryospheric (ice) parameters that are directly relevant and critical to meeting the goals of the six focus areas. The potential for Lidar remote sensing to contribute to the measurement of environmental phenomena related to the six science focus areas is summarized in Table 2-1.

Lidar Report Section 2 Table 2-1

Table 2-1A. Lidar Remote Sensing Contribution to Science Focus Areas (P = Lidar Primary; C = Lidar Complementary).

	Atmospheric Composition	Carbon and Ecosystems	Climate Variability and Change	Earth Surface and Interior Structure	Water And Energy Cycle	Weather
Atmosphere & Radiation						
Atmospheric Temperature			C		C	C
Atmospheric Water Vapor			C		C	C
Cloud System Structure	C					C
Cloud Particle Properties and Distribution	C					
Tropospheric Winds		C	C		C	P
Storm Cell Properties						C
Total Aerosol Amount	P					
Volcanic Gas & Ash	P					
Stratospheric Aerosol Dist						
Aerosol Properties	P		C			C
Total Column Ozone	P					
Ozone Vertical Profile	P					
Tropospheric Ozone & Precursors	P					
Trace Gas Sources (total col.)	P					
Surface Trace Gas Concentration						
CO2 and Methane (profiles)	P	P				
Atmospheric Properties in the Tropopause						
Lightning Rate						
Global Precipitation					C	C
Total Solar Irradiance						
Solar UV Irradiance						
Earth Radiation Budget						

Table 2-1B. Lidar Remote Sensing Contribution to Science Focus Areas (P = Lidar Primary; C = Lidar Complementary).

	Atmospheric Composition	Carbon and Ecosystems	Climate Variability and Change	Earth Surface and Interior Structure	Water And Energy Cycle	Weather
Land						
Soil Moisture						
Terrestrial Primary Productivity		P			P	P
Land Cover and Land Use		C	C	C	C	C
Vegetation Biomass		P	P			
Fire Occurrences and Extent	C	C				
Fuel Quantity and Quality	P	P				
Land Surface Temperature						
Snow Cover Accumulation and Snow Water Equivalent						
Growing Season Length (Freeze-Thaw Transition)						
River Stage Height						
River Discharge Rate					P	
Surface Deformation and Stress				P		
Land Surface Topography				P	P	
Earth Surface Composition/Chem.						
Earth Gravity Field				P		
Earth's Magnetic Field				P		
Terrestrial Reference Frame				P		
Motions of Earth's Interior						

Table 2-1C. Lidar Remote Sensing Contribution to Science Focus Areas (P = Lidar Primary; C = Lidar Complementary).

	Atmospheric Composition	Carbon and Ecosystems	Climate Variability and Change	Earth Surface and Interior Structure	Water And Energy Cycle	Weather
Oceans						
Ocean Surface Winds						C
Sea Surface Temperature						
Ocean Surface Topography			C	P		
Sea Surface Salinity						
Ocean Surface Currents						
Deep Ocean Circulation						
Phytoplankton physiology and functional groups		P	P			
Mixed Layer Depth and Illumination		P	P			
Global Ocean Carbon/Particle Abundance	P	P	P			
Coastal Carbon	C	C	C			

Table 2-1D. Lidar Remote Sensing Contribution to Science Focus Areas (P = Lidar Primary; C = Lidar Complementary).

	Atmospheric Composition	Carbon and Ecosystems	Climate Variability and Change	Earth Surface and Interior Structure	Water And Energy Cycle	Weather
Cryosphere						
Sea Ice Extent (incl. Melt Extent & Seasons, Shore-fast Ice)				C		
Sea Ice Thickness				C		
Snow Depth on Sea Ice						
Sea Ice Motion (small & lrg scale)				C		
Sea Ice Surface Temperature						
Sea Ice Meltpond Fraction						
Sea Ice Velocity				C		
Polar Ice Sheet Velocity				C		
Ice Surface Topography				C		
Polar Ice Sheet Bed Topography						
Snow Accumulation on Polar Ice Sheet						
Polar Ice Melt Extent & Seasons				C		

Table 2-1 lists the measurement parameters by their domain, atmosphere, land, oceans and cryosphere. For each case where Lidar observation of a particular measurement parameter makes a contribution to a particular science focus area there is an entry in Table 2-1. The entry "P" indicates where Lidar remote sensing is the primary contributor (compared to other remote sensing technologies). A "C" indicates that Lidar remote sensing complements other remote sensing technologies, but is secondary.

The complete set of validated science requirements for the six focus areas are given in a set of tables provided in Appendix 2A – 2F. In addition to a description of each environmental measurement requirement and the source of its validation, the required horizontal resolution, vertical resolution, revisit rate, and measurement accuracy are given. In these four columns, in all cases where there are two numbers separated only by a semicolon, the first number is the threshold requirement, which represents the minimum required performance, and the second number is the goal or objective, which represents the maximum desired performance. The measurement accuracy is the one-sigma rms random noise (where the bias is assumed to be indistinguishable from zero).

2.1 Unique Contributions of Lidar Systems

Lidar remote sensing techniques offer several unique capabilities when compared to active or passive microwave or passive Electro-Optical approaches. These are the result of the inherent use of a laser for the source of illumination, and advanced detection subsystem technologies. First, the Lidar measurement approach in many cases is a direct retrieval of the geophysical quantity (e.g., species concentration) and does not require complex inversion schemes that depend on detailed models of the remote sensing environment. . This "direct" inversion provides potentially higher sensitivity and lower measurement uncertainty when compared to the other techniques. This has an important impact on all atmospheric composition measurements that involve measurement of the species concentration.

Secondly, given that Lidar systems carry their own source of illumination they are able to operate independently of day/night conditions. This benefits all science focus areas as lidar systems are thus able to provide continuous global observations at all times, independent of solar illumination. Also, since the sensitivity to the detection of very low species concentration scales with the transmit power Lidar systems are able to detect very low concentrations of important trace gas species.

Thirdly, Lidar systems offer very high range resolution for the determination of geophysical parameter profiles (for example, profiles of species concentration or temperature), compared to either passive EO or microwave techniques. This same high range resolution is the key to contributions to the Carbon and Ecosystems profiling of the vegetation canopy and accurate measurements of the Earth's surface, both land and ice.

Fourthly, due to the narrow spectral line width of the laser signals lidar systems maybe designed to minimize interference for other molecular species and aerosols (not intended to be sampled by the lidar), and due to the narrow beam widths the impact of clouds may also be reduced or eliminated.

These key advantages of lidar remote sensing uniquely contribute to the science measurements. For example the measurement of atmospheric composition benefits from the direct observation of species concentration to provide measurements at very low concentration levels. This also benefits climate related measurements as it contributes to highly accurate atmospheric vertical moisture and temperature profiles. For weather, tropospheric wind measurements employ the Doppler lidar technique. The short laser wavelength, e.g., 0.355 or 2 microns, permit the signal to be obtained by light backscattering off air molecules or aerosol particles, respectively. These observations will have a significant improvement in forecast model predictions.

And finally, with some of the technology advances proposed in this report it should be possible to develop Lidar systems with not only high horizontal spatial resolution but wide area coverage cross-track (wide swaths). This will provide improved area coverage on a global scale for all Lidar observables.

2.2 Atmospheric Composition

Atmospheric Composition science focus area addresses the gaseous and particulate species in the atmosphere including O3, H2O, CO2, CH4, CO, N2O, NO, NO2, SO2, aerosols and clouds. Although these species are of primary importance in atmospheric composition, they also play a key role in all six of the science focus areas of NASA's Science Mission Directorate's (SMD) Earth-Sun Division. Air quality is determined by atmospheric composition and atmospheric composition influences weather, climate, carbon cycle and biogeochemical processes. The needs for profiling of O3, H2O, CO2, aerosols, and clouds have been identified in ESE Science Roadmaps (see http://science.hq.nasa.gov/strategy/roadmaps). NASA SMD's research within the atmospheric composition focus area is geared toward answering the following science questions:

- How is atmospheric composition changing?
- What trends in atmospheric constituents and solar radiation are driving global climate?
- How do atmospheric trace constituents respond to and affect global environmental change?
- What are the effects of global atmospheric chemical and climate changes on regional air quality?
- How will future changes in atmospheric composition affect ozone, climate, and global air quality?

As noted in the introduction to Section 2, Lidar systems provide unique measurement capabilities that are needed to improve our understanding of many of the chemical, radiative, transport, and thermodynamical processes in the atmosphere and to develop data assimilation and predictive capabilities in the areas of climate and environment. Lidar systems have been well demonstrated to profile key atmospheric constituents including O3, H2O, CO2, CH4, CO, SO2, aerosols, and clouds (Measures, 1984; and Kovalev and Eichinger, 2004). In particular lidar is ideally suited for tropospheric profiling of O3, H2O, CO2 and other gas species (Browell et al., 1998). Lidar systems have the capability to penetrate into the troposphere relatively well, in comparison with passive optical and IR sensors. Passive limb sounding instruments do a pretty good job of retrieving profiles in the stratosphere, although with coarse horizontal resolution.

However they are very handicapped for tropospheric profiling due to the presence of aerosols and clouds along the long integrated atmospheric path length. The data from passive nadir or near-nadir sounders and imagers are usually cloud-contaminated and, in general, have coarse vertical resolution. The algorithms for cloud-clearing used by the passive sensors are complex and often not very reliable.

The science requirements for measurements of O3 (and its precursors), H2O, CO2, CO, CH4, SO2, aerosol and cloud properties are given in Appendix 2, Tables 2A-2F. The requirements for atmospheric composition are expected to be achievable, using Lidar sensor technology, within the next 10 to 15 years. Development of these measurement capabilities will significantly advance our knowledge of atmospheric science.

Tropospheric chemistry is considered to be the *next frontier* of atmospheric chemistry, and understanding and predicting the global influence of natural and human-induced effects on tropospheric chemistry will be the next challenge for atmospheric research over the foreseeable future. In the troposphere, trace-gas species of interest include ozone, OH, NOx (NO and NO2), CO, and some hydrocarbons; H2O, and aerosols and clouds. In particular, atmospheric ozone is one of the key tropospheric chemical species because of its influence in many atmospheric processes. Active remote instruments that can provide vertical profile measurements of ozone will lead to better understanding of atmospheric phenomena such as: the production, distribution, and loss of ozone; anthropogenic pollution; biomass burning; atmospheric transport and dynamics; photo-chemical processes in the atmosphere; stratospheric-tropospheric exchange; atmospheric climate and radiation; and influences of atmospheric lightning. Knowledge of these phenomena is needed to evaluate the effects of chemical changes on the global hydrological cycle, the cycling of nutrient compounds through the earth environment, the accumulation of greenhouse gases, the acidity of rain and snow, and the formation of ozone in the troposphere. These are global scale problems that are particularly well suited to the use of space-based lidar observations. Atmospheric SO2 is an urban pollutant produced from the burning of fossil fuels and an indicator of economic activity. Atmospheric sulfate aerosols are produced by jet aircraft fuel consumption and are linked with the net loss of atmospheric ozone with the associated implication for increase in UV and cancer. Volcanic eruptions are a major source of large-scale injection of stratospheric SO2 (Zereda-Gostynska G, 1997) and their subsequent droplet /aerosol formation, their evolution, and subsidence into the troposphere and decay. Space-based lidar SO2 profiling capability in conjunction with global O3 profiling capability would enable the study of the evolution and influences of volcanic eruptions. Carbon monoxide (CO) is produced in fossil fuel and biomass burning and is an indicator of pollution, it is an excellent long-term tracer of atmospheric dynamics and transport.

Water vapor (H2O) is a key constituent and state variable of the atmosphere. The transport and distribution of water vapor in the atmosphere is one of the most important drivers of the Earth’s climate, meteorology, and atmospheric dynamical processes. Measurements of water vapor are important for a number of atmospheric applications including climate, meteorology, transport, chemistry, and atmospheric transmission. Water vapor is the most active infrared molecule in the atmosphere and so will play a major role in any global warming scenario associated with increased carbon dioxide (Cess, 1990).

Since most climate models have found significant increases in water vapor in response to global warming, the strong positive feedback associated with this increased water vapor has led models to show a 70% higher surface temperature response due to this feedback in addition to the direct effects of increased CO2 (Arkin, 1990). Recent modeling has shown the importance of the relatively small amounts of water vapor in the upper troposphere. This further underscores the need for accurate measurements of the vertical distribution of water vapor. Climate model simulations have shown that relative, rather than absolute, changes in the vertical distribution of water vapor content are important in assessing any global warming scenario. Understanding and parameterization of the processes that control the atmospheric radiative balance require an accurate measurement of water vapor because uncertainties in the water vapor distribution dominate the spectral effects in the atmospheric window region (800-1200 cm-1 or 8.3-12.5 µm) (DOE, 1990). Therefore, improved measurements of water vapor, and in particular upper tropospheric water vapor, are required

Accurate water vapor measurements are also required for quantitative prediction of precipitation. Models that predict the initiation of convection are highly dependent on very accurate estimates of water vapor within, and just above, the boundary layer (Crook, 1996). Recent measurements in hurricane regions have shown the impact of high-resolution water vapor on the prediction of hurricane track and intensity (Kamineni et al., 2006). In addition to hurricane research, improved water vapor measurements are needed for input to high-resolution mesoscale models, which are increasingly being used by the atmospheric community. But as pointed out in the December Community Workshop of the US Weather Research Program (USWRP) "the full benefit of enhanced forecast model resolution has not been and will not be realized without commensurate improvements in high resolution meteorological observations …" (Dabberdt, et al., 2005). Only space-based lidar systems offer the capability to provide accurate high vertical resolution (0.5 km) H2O profiling capability to delineate and understand processes from the boundary layer to upper troposphere.

Atmospheric CO2 concentrations are higher now than they have been in the past 25 million years. They may double or triple in the future as fossil fuels are burned and land use practices result in biomass burning and depletion of forest stocks. Currently about half of the anthropogenic emissions do not stay in the atmosphere but are sequestered in oceans and land surfaces. However considerable uncertainty exists as to the mechanisms responsible for these sinks. A change in the current behavior of these sinks will have important consequences for the future atmospheric composition and its associated climate forcing.

Much of what we know today about how the atmosphere is changing comes from an in-situ network of surface atmospheric sampling stations. These observations are sparse (surface only, large land and ocean areas un-sampled) thus limiting advances in understanding and predicting processes responsible for variability in atmospheric composition. Global measurements of CO2 profiles in the atmosphere are only feasible from satellite platforms. High-resolution measurements of CO2 are required to determine the sources and sinks of CO2 with sufficient accuracy to help balance the carbon budget and determine changes in sources and sinks related to natural and human-induced factors.

An advanced capability for satellite remote sensing of atmospheric CO2, capable of resolving the CO2 response to carbon management activities, has been identified as a high priority for development at the NASA, US national, and international levels. The 2003 NASA Earth Science Enterprise Strategy (ESE, 2003) identifies the CO2 laser sounder explicitly as a future required observational capability. On the US national level, justification for a an active CO2 monitoring mission is given in the Strategic Plan for the 2003 US Climate Change Science Program chapter on the carbon cycle (CCSO, 2003), and new satellite CO2 capabilities beyond 4 years from present are recognized as a required milestone for the program. Advancing space-based CO2 Profiling capability is one of the main goals of the US Climate Change Technology Program to develop, demonstrate, and deploy technologies to measure and monitor the distribution and fluxes of greenhouse gases in the Earth's atmosphere. The need for development of an active CO2 sensor is also recognized by the Integrated Global Observing Strategy (IGOS), which is partnered with the Global Observing Systems, Committee on Earth Observation Satellites and International Global Change Science and Research Program. Their 2004 Carbon Theme Report (IGOS, 2004) specifically seeks to initiate technology development in the area of lidar for operational satellites, which may provide a complete profile of atmospheric CO2 and other carbon molecules.

Methane is the second most important anthropogenically produced greenhouse gas, after Carbon Dioxide. Though its atmospheric abundance is much less than CO2 (~0.5%) per molecule it has 20X greater greenhouse heating potential (see Figure 2-2). Methane also contributes to pollution in the lower atmosphere through chemical reactions leading to ozone production. Atmospheric methane concentrations are highly variable and have been increasing as a result of increased fossil fuel production, rice farming, livestock and land fills. Natural sources of methane include wetlands, wild fires, termites and perhaps other unknown but significant sources (e.g. Keppler et al., 2006). Vast amounts of methane are contained in the continental shelf in the form of methane hydrates and mass extinction events in the past have been attributed to climate altering releases from these stores. Important sinks for methane include non-saturated soils and oxidation by hydroxyl radicals in the atmosphere. Trends in methane increases in the atmosphere have been highly variable over the last two decades for as yet poorly understood reasons. Better knowledge of the methane distribution and emissions is indispensable for a correct assessment of its impact on global change (Houghton, et al., 2001).

Simultaneous measurements of methane with other trace gases such as CO2 can provide valuable information about the processes controlling surface fluxes of these gases. Variability in CO2 and methane mixing ratios are often correlated especially when fluxes are due to wildfires. On the other hand, other processes such as wetland emissions of CO2 and methane are not necessarily correlated. Active measurements simultaneously of CO2, O2 and CH4 from the same platform would provide this unique and powerful capability to distinguish processes controlling greenhouse gas emissions.

Aerosols and clouds play a critical role in climate, weather, and atmospheric chemistry. Aerosols are a major source of uncertainty in our knowledge of global climate forcing that is capable of inducing long-term global temperature changes. Aerosols are a source of climate forcing by directly absorbing and scattering of solar radiation or by modification of cloud radiative properties (indirect forcing). Clouds influence climate by amplifying or damping climate forcing, and this is referred to as climate feedback. The process of climate feedback has major implications for climate change. Because of the key role of aerosols and clouds in climate, their role in climate is further discussed in the section on Climate Variability and Change.

Knowledge of microphysical properties of clouds is central to study of weather and sever storms. Global satellite-based Lidar measurement of the distribution of clouds, including their altitude, occurrence frequency, and cloud optical depth would revolutionize our knowledge of cloud classification; deficiencies in the understanding of the physical processes; and deficiencies in numerical model parameterizations and data assimilation inputs. Polar stratospheric clouds and atmospheric aerosols are known sources of ozone depletion in the stratosphere that leads to increase in the solar UV on the surface of the Earth that has a major environmental impact. Space-based lidar measurements will provide unique capability to provide high-resolution information about the 3-D distribution of aerosol and clouds, and the retrieval of many of the key optical properties that are not available from other techniques.

2.3 Carbon Cycle and Ecosystems

One critical science focus for NASA in the coming decades is the development of technology that facilitates the observation and modeling of processes important for carbon cycling and ecosystem health. This initiative is called out in the NASA Strategic Roadmap for Carbon Cycle and Ecosystems, summarized as follows (NASA-Carbon, 2004):

NASA research in Carbon Cycle and Ecosystems will employ NASA's unique perspective to reduce uncertainties and provide quantitative information concerning atmospheric concentrations of greenhouse gases, changes in terrestrial ecosystem and oceanic carbon sinks, trends in primary productivity, species extinction and invasion, land cover and land use change, and the health and sustainability of global ecosystems.

The Carbon Cycle and Ecosystems Focus Area poses the following questions:

- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change?
- What are the consequences of land cover and land use change for human societies and the sustainability of eco systems?
- What are the consequences of climate change and increased human activities for coastal regions?
- How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?

2.3.1 Terrestrial Ecosystems

The effects of natural and anthropogenic forest structural changes and dynamics on carbon cycling are of critical interest. One of the major sources of error in estimates of land surface carbon and other biogeochemical fluxes arises from uncertainty in prescribing initial forest carbon stocks. Forests are typically a heterogeneous mixture of stands of different successional age and both ecosystem structure and carbon fluxes vary strongly with successional status. Attempts to ascertain the sign of carbon fluxes for particular areas, i.e. source or sink, are further limited by the difficulty in assessing the change in forest structure, such as accumulation in biomass via regrowth, over time and across the landscape. As such, getting at these first order changes in land cover have been identified as a priority of the North American Carbon Program, the Land Use Change in Amazonia Program, and for the Carbon cycle and Ecosystems science focus area in general.

Likewise, biological diversity and the related topics of habitat characterization and ecosystem health and function, are topics of increasing importance and international interest. Suggestions of rapid losses of unique and potentially valuable species are relevant for a host of reasons. There is urgent need to develop and quantify forest metrics related to species richness, ecosystem function and health, ranging from canopy cover to primary productivity, over large areas to target conservation efforts, mitigate losses in rapidly changing areas, and focus limited resources on so-called “hot spots.” In addition, our ability to sustainably manage natural resources, whether for habitat, food or fiber, is predicated on a quantitative characterization of ecosystem structure and status. A major limitation in these areas has been the difficulty in obtaining information on forest structure, especially vertical structure, over large enough areas and at sufficient resolution to enable meaningful comparison with field data and model outputs across environmental gradients. Without such data, it has been difficult to test existing hypotheses and to develop new hypotheses based on observational evidence.

Another important area is that of fire as has been demonstrated in recent years by the severe fire seasons that affect not only carbon cycling, but also have enormous impact ecologically and economically. According to the National Interagency Fire Center (NIFC) in 2002, 88,458 fires burned 6,937,584 acres and fire suppression costs for Federal agencies totaled over $1.6 billion. It is now widely accepted that altered fuel loads due to past management practices combined with extended drought conditions have increased fire risk.

Accurate measurement of canopy fuel loads and their spatial distribution over large areas is critical to predicting fire hazard potential and prioritizing management options. Models can be used to predict the behavior of ongoing wildfires and also to study the effects of potential mitigation strategies. However, for the models to be used appropriately existing fuel complex must be quantified. This requires information about the amount and location (both horizontal and vertical) of available fuels in the canopy. Characterizing forest vertical structure is a central component to these efforts.

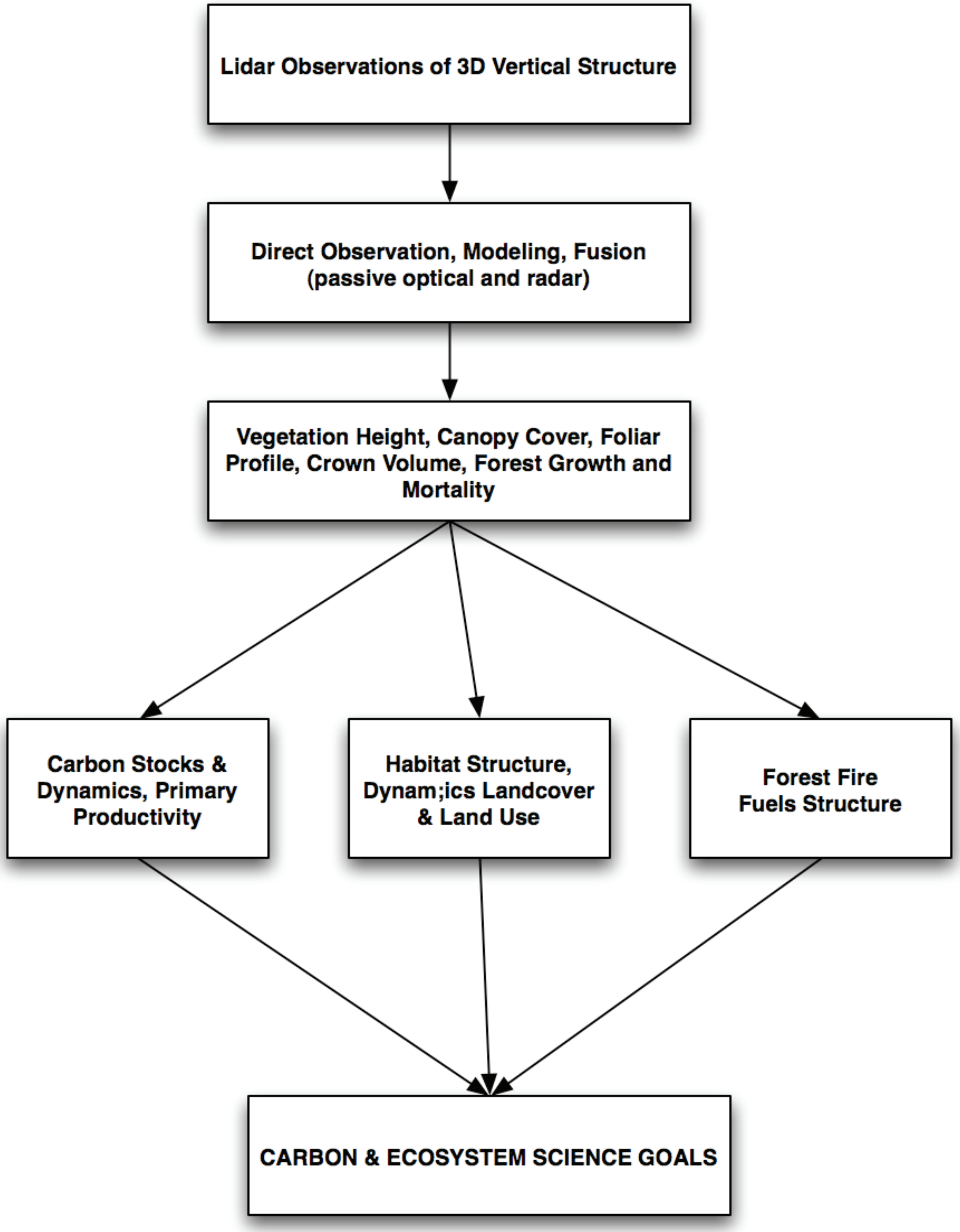
As stated in the Carbon Cycle & Ecosystems Roadmap, our ability to contend with changes in ecosystem function and dynamics, resulting from changes in land use, land cover and forest structure, requires observations and modeling that further our understanding of the responses of ecosystem processes and dynamics to environmental change and to disturbance by human activities and natural events. This is because these changes will have broad societal implications for carbon management, food production, the conservation of biodiversity, and sustainable resource management, among others. For example, how much should a forest be thinned so that it decreases fire hazard, but does not adversely affect habitat suitability and carbon balance?

Central to the Carbon Cycle and Ecosystems initiative is the development of remote sensing technologies that provide improved *land surface characterization* as the foundation for describing ecosystem function and dynamics. Although NASA efforts in this area have led to major advances in our ability to monitor and model the land surface, current remote sensing missions provide few of the quantitative measurements that are required to meet the science objectives of the Carbon Cycle and Ecosystems Roadmap. For example, structure parameters such as canopy cover, tree height and volume, vertical foliar profile, stem density, and biomass are difficult to observe or model using passive optical and radar remote sensing, because these are all related to the vertical structure of the land surface. Consequently, the Carbon Cycle and Ecosystems Roadmap specifically calls for technology development for quantifying vegetation 3D structure, biomass and disturbance leading to characterization of terrestrial carbon stocks and species habitat.

Lidar remote sensing directly measures the needed vertical structure, and is thus, along with radar, a key technology for advancement in this area. Lidar data obtained using existing airborne systems have already been shown to estimate many of the needed structural variables with high accuracy. These have included canopy height, canopy cover, crown volume, aboveground biomass, vertical leaf (foliar) and branch profiles, tree density, light profiles, crown fire fuel amount, and canopy base height (for fire), among others. Scenarios have been proposed to estimate these with lidar from space using novel approaches requiring technological development guided by ESTO. Figure 2-1 illustrates the impact of direct Lidar observations of the 3D canopy structure on the Carbon Cycle and Ecosystems science focus area goals. Therefore advances in Lidar technology necessary to enable these observations, along with advances in modeling and remote sensing fusion, will have a direct impact our achieving these NASA science goals.

It is anticipated that the maturation of some of these lidar technologies, combined with advances in modeling and remote sensing fusion, will be exceptionally responsive to goals set forth in the Carbon Cycle and Ecosystems science focus area, as shown below.

Figure 2-1: Dependence of Terrestrial Carbon and Ecosystems Science Goals on Lidar Observations of 3D Vegetation Structure.



2.3.2 Ocean Biology and Biogeochemistry

The oceans have a key role in the Earth System, particularly climate and global environmental change. The oceans represent 71% of Earth's surface and 90% of the Earth's biosphere attributable to their depth and extension. The coastal ocean, adjacent to where the majority of humans reside, is an extremely productive and valuable socio-economic resource that is subject to anthropogenic impacts, particularly resulting from changes in land use (e.g., urbanization) that significantly affect ecosystem health. The health and state of the ocean in turn has a direct connection with human health. The primary objectives of NASA's ocean research programs are to describe, understand, and predict the time-varying three-dimensional circulation of the ocean and the biological regimes of the upper ocean as determined from space, aircraft, and other suborbital platforms. Oceanography programs encompass core research within the sub-disciplines of Physical Oceanography and Ocean Biology and Biogeochemistry, the latter falling within the Carbon Cycle and Ecosystem Focus Area.

Biological and biogeochemical regimes in the upper ocean can respond to and therein be indicators of changes in Earth's climate and local environmental processes. Ocean biology and biogeochemistry research has a clear and critical link to physical oceanographic, land and atmospheric observations, and must be studied if NASA is to understand the Earth System. Emerging science questions in NASA's Ocean Biology and Biogeochemistry Program include:

- How are ocean ecosystems and the biodiversity they support influenced by climate or environmental variability and change, and how will these changes occur over time?

- How do carbon and other elements transition between ocean pools and pass through the Earth System, and how do biogeochemical fluxes impact the ocean and Earth's climate over time?

- How (and why) is the diversity and geographical distribution of coastal marine habitats changing, and what are the implications for the well-being of human society?

- How do hazards and pollutants impact the hydrography and biology of the coastal zone? How do they affect us, and can we mitigate their effects?

Cross-cutting these questions are multiple observational needs, requiring improved information on open and coastal ocean absorbing aerosols, particles and other optical constituents, fluorescence, mixed-layer depth and habitat health/structure, among others. Development of new technologies and observational capabilities to address these needs is crucial. Lidar in particular is expected to play an extremely important role, providing both primary/novel measurements as well as working in concert with other types of observations (e.g., visible spectral radiance – ocean color).

Vertical changes in light scattering properties measured through the atmosphere and into the ocean from a space-based lidar can provide important new information for solving major ocean carbon and biogeochemistry science questions. A primary need exists to address atmospheric correction issues associated with absorbing aerosols, as well as improve the separation of optically active in-water constituents. Regarding the former, all future missions (polar or geo- orbiting) targeting retrieval of geophysical parameters related to ocean elemental cycles through measurements of water-leaving radiances (~ocean color) are critically dependent on accurate atmospheric corrections. Accounting for the contribution of absorbing aerosols to top-of-atmosphere radiances is particularly important and requires information on their vertical distributions as well as total optical thickness. Lidar measurements have been shown to provide information on vertical aerosol structure at a resolution well beyond that necessary for ocean applications (<0.5 km). Lidar aerosol profiling measurements simultaneous with passive radiometric data would enable unsurpassed atmospheric corrections and consequently enable retrieval of vastly improved ocean geophysical parameters.

While unparalleled water leaving radiance accuracies are fundamental to future remote sensing observations, they are not enough. Classic 'ocean color' bands were not optimized for spectral matching algorithms and are not adequate for fully resolving the multitude of unique optical properties associated with specific in-water constituents. Enhanced measurement capabilities are necessary, and active approaches such as lidar can provide independent measures of critical elemental stocks. For example, lidar sub-surface light scattering profiles can yield important information on particle biomass abundance. Further, spectral analysis of laser-stimulated backscatter signal allows quantitative characterization of water constituents, including fluorescence assessments of chlorophyll-a concentration and chromophoric dissolved organic matter (CDOM) (Hoge et al., 2001, Lyon et al., 2004, Chekalyuk et al., 1995).

Lidar and supporting advanced measurement techniques and analytical protocols can also provide additional crucial information in support of the above ocean biology and biogeochemistry questions. This includes assessments of phytoplankton photo-physiological status (via measurements of variable fluorescence (Chekalyuk et al., 2000a, b), accessory pigments (chlorophylls, phycobiliproteins (Hoge et al., 1998) and carotenoids), and identification of algal functional groups. In particular, globally defining and monitoring seasonal to interannual variations in physiological provinces through variable fluorescence measurements from a space-based lidar would be an exciting and important development. In other domains, active fluorescence methods have particular advantage over passive retrievals in optically complex coastal waters due to availability of constituent-specific fluorescence bands that can be retrieved from the laser-stimulated backscatter emission. Selective multi-wavelength laser excitation, broadband hyperspectral signal detection and spectral deconvolution were identified as the key solutions to address the optical complexity of coastal environments. Fluorescence normalization to laser-stimulated water Raman backscatter signal (e.g., Chekalyuk et al., 1995) allows accounting for spatial and temporal variability in atmospheric and oceanic optical properties for accurate quantitative assessment of aquatic characteristics.

Most of the above lidar methods and techniques in question have been extensively tested from shipboard and airborne platforms; some of the new measurement protocols have been proven to be feasible. For example, variable fluorescence has been measured in the field for > 20 years and recently, through NASA support, has been successfully demonstrated from aircraft. For space-based applications, the 'pump and probe' technique employed for these airborne tests will need to be modified to reduce lidar energy demands and to meet eye safety requirements. Space-borne implementation may open up conceptually new possibilities for oceanographic remote sensing, including coastal applications and other ecological assessments.

Another important measurement for ocean biology and biogeochemistry (as well as physical oceanography) is mixed layer depth. For almost all of the open sea, the upper layer of the ocean is well mixed due to air-sea exchanges of buoyancy and momentum. Within this well mixed zone, the vertical distribution of all physical, chemical and biological variables are homogenized. Oceanographers refer to this zone as the mixed layer and its depth is called the mixed layer depth (MLD). Knowledge of the MLD is essential for many branches of oceanography as it controls the depth range over which air-sea exchanges of heat and momentum are averaged over and it controls the depth range over which organisms and chemical constituents are mixed. Values of MLD can range from practically nothing to more than 500 m and it varies on time scales from hours to seasons. Of particular importance are the large changes in MLD associated with the seasonal cycle of heating and cooling at mid latitudes. From mid-latitudes to high latitudes, mixed layer depths can vary from several to many 100's or meters over the seasonal cycle. This alters the depth range over which biological and biogeochemical constituents are found in the upper ocean– and are sampled using satellite remote sensed technologies. Hence, knowledge of mixed layer depth and its temporal changes over all relevant space and time-scales is critical for NASA's Ocean Biology & Biogeochemistry Program. However, this is a difficult measurement to obtain synoptically (and remotely). Several challenging approaches could use active remote sensing (lidar) measures to assess MLD remotely (sub-orbital and/or space-based platforms). For example, one possible path is to use the time-dependent return of a 532 nm laser pulse from scattering layers to assess the depth of the mixed layer. Another potential path would be to use laser emission/excitation spectroscopy to determine upper ocean concentrations of rapidly evolving photochemical species. By knowing the light driven kinetics of this chemical species and examining differences in its concentrations at different times of day, estimates of MLD may be derived.

Per the above science drivers and observational needs, several measurement scenarios (#'s 17, 27, and 42) are briefly discussed in Chapter 3, as well as described in greater detail in the ESTIPS database.

2.4 Climate Variability and Change

The Climate Variability and Change Focus Area addresses the following major questions:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- How can predictions of climate variability and change be improved?

2.4.1 Climate and Atmospheric Composition

Knowledge of global climate forcing and feedbacks are the essential ingredients needed for climate models for the prediction of future climate trends. Atmospheric aerosols, clouds, and CO2 have been identified as elements of the NASA Earth Science Climate Variability and Change Roadmap. Lidar systems are uniquely suited to provide the high vertical resolution and fine structural information concerning the distribution of aerosols and clouds and their optical and physical characteristics needed to evaluate radiative forcing and climate feedback estimates. The considerable variability in global distributions of aerosols and clouds and their climatology require measurements from space-based platforms. Detailed science requirements for the space-based lidar measurement of aerosol and cloud properties for climate studies are provided in Appendix 2, Tables 2A-2F.

An example of the role of the aerosols in climate forcing is illustrated in Figure 2-2 (IPCC, 2001). This figure shows the contributions of various atmospheric species in climate forcing, and in particular the significant role aerosols play. It shows that 1) the magnitude and even the sign of the forcing depends upon the aerosol type 2) the large uncertainties in the knowledge of the forcing, and in fact the combined root-mean-square uncertainty is larger than that due to the combined uncertainty from all the trace gases including CO2, and 3) the very large uncertainty due to the aerosol cloud effect that is the influence the aerosols have in could forcing (aerosol indirect effect). These aerosol forcings are poorly understood and are the largest source of uncertainty in predicting future climate change. Thus, there is a very low level of confidence in the knowledge of the contribution of aerosols to radiative forcing estimates in current climate studies. Measurements of the physical characteristics of the aerosols and retrieval of their optical properties would greatly improve the knowledge of the contribution of aerosols to radiative forcing.

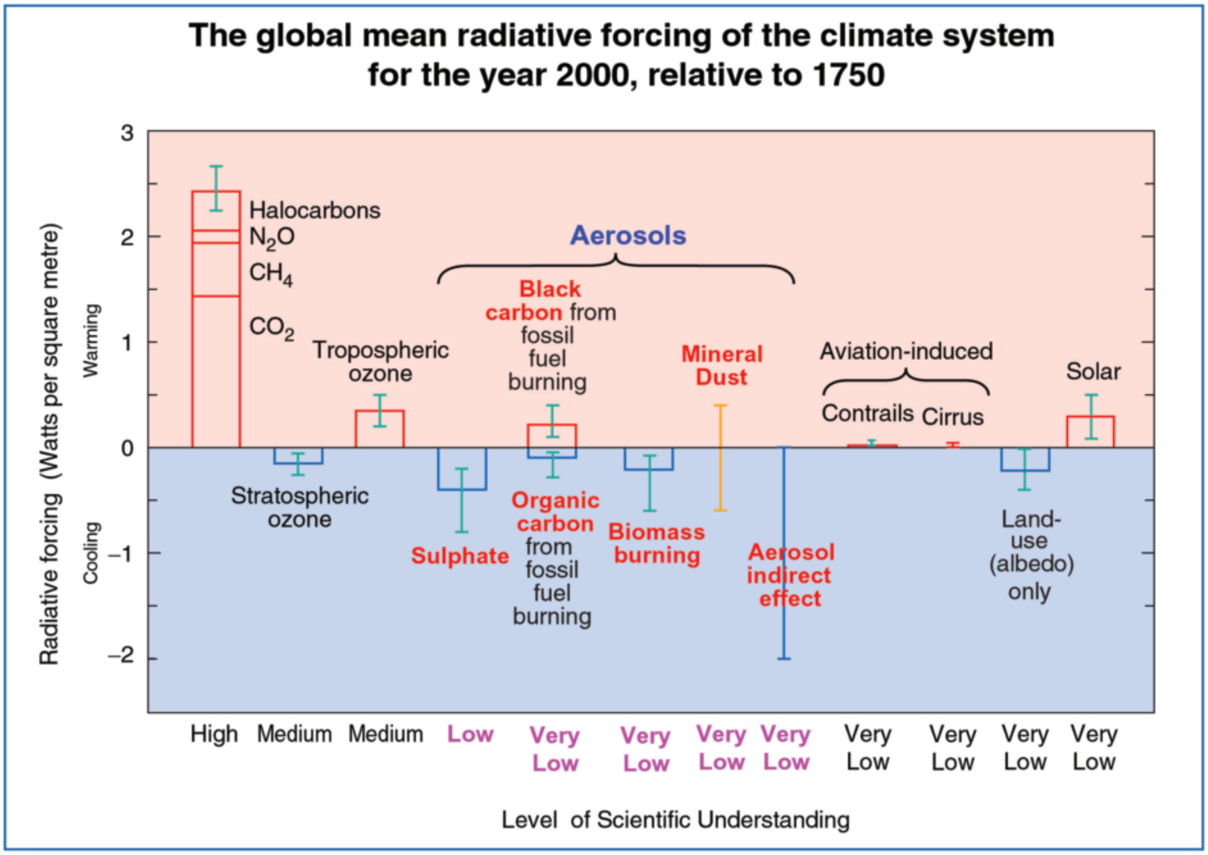


Figure 2-2: Contribution of atmospheric species to radiative forcing (IPCC, 2001).

Cloud feedbacks have been identified as a major source of uncertainty in predictions of climate change (Cess et al., 1990; Houghton et al, 2001). Space-based cloud lidar can provide two of the three critically needed cloud parameters, cloud height and cloud fraction, to evaluate cloud feedback. Cloud optical depth is the third critically needed parameter that is difficult to achieve for dense optical clouds and may need to be derived from passive sensors. To constrain cloud-induced uncertainties in climate, cloud properties need to be measured to reduce the cloud feedback uncertainties to 0.3 W/m2/decade. Capabilities of the future generation cloud lidars can aid in attaining this target. Because cloud autocorrelation lengths are ~200 km, cross-track scanning/sampling is needed to obtain the best sampling of cloud height and fraction amounts. Cloud ice/water phase is also a critically needed parameter that can be derived from depolarization measurements. In fact current uncertainties in ice/water partitioning in models give uncertainties in radiative forcing much larger than the forcing from a doubling in atmospheric CO2.

The science measurement requirements for the next generation (with capability beyond that of LITE, GLAS and CALIPSO) aerosol and cloud lidar systems are given in Tables 2-3 and 2-4.

Table 2-3: Aerosol Lidar Measurement Requirements.
1. Aerosol Optical Depth accuracy 10% (or 0.1 whichever is greater)
2. Other aerosol measurement requirements

Aerosol Properties	**Along-Track Resolution**	**Accuracy**	**Cross-Track Coverage**
Detection of aerosol layers (including optically thin cirrus)	5 km Δx, 100 m Δz (tropospheric); 10-50 km Δx, 500 m Δz (stratospheric)	10-20% above molecular	± 700 km
Extinction and backscatter profiles	5 km-Δx, 100 m Δz (tropospheric); 10-50 km Δx, 500 m Δz (stratospheric)	10%	± 700 km
Aerosol depolarization	Layer	2–5%	
Refractive index (Complex)	Layer	Real: ± 0.03 – 0.05 Imaginary: Order of magnitude if < 0.01 50% if > 0.01	
Single scattering albedo	Layer	0.03 – 0.05	
Size distribution (radius and width, assuming single mode)	Layer	20%	

Notes:
Cross-track coverage for aerosols: ±700 km gives quasi 2-day global coverage, ultimate requirement is this coverage for all parameters, a more limited requirement would be for an instrument intended to provide profile data for passive retrievals. In this case ± 700 km is required only for aerosol detection and extinction/backscatter profiles.
*$\triangle x$ refers to horizontal resolution and $\triangle z$ to vertical resolution.

Table 2-4. Cloud Lidar Measurement Requirements.

Measurement	**Accuracy**	**Along-track Resolution**	**Cross-track Coverage**
Cloud detection (base/ top)	Sensitivity (532):		
Boundary layer	0.1 /km/sr	100 m Δx, 10 m Δz	+/- 500 km
Free troposphere	4E-4 /km/sr	10 km Δx, 30 m Δz	+/- 500 km
Cloud depolarization ratio			
Ice cloud	2%	10 km Δx, 30 m Δz	
Water cloud	2%	1 km Δx, 10 m Δz	
Cloud optical depth			
Boundary layer	10%	100 m Δx, layer	
Free troposphere	10%	10 km Δx, layer	
Cloud backscatter/Ext. profiles			
Boundary layer	20%	100 m Δx, 5 m Δz	
Free troposphere	20%	10 km Δx, 100 m Δz	

2.4.2 Cryosphere

Observations of the Earth's Cryosphere play a critical role in address many climate related questions and developing adequate models. The NASA Earth Science questions that will be addressed from a cryospheric perspective are:

- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- What are the consequences of climate change and increased human activities for coastal regions?
- How can predictions of climate variability and change be improved?

We further address these issues in the context of ice surface topography, ice sheet velocity and sea ice edge and thickness observations by Lidar systems.

NASA's ICESat (Ice Cloud and Land Elevation Satellite) is currently revealing new information on the behavior of the Earth's ice cover. Its range and pointing accuracy have enabled important cryospheric measurements in regions that have been severely limited by other approaches.

2.4.2.1 Ice Surface Topography and Velocity

Ice sheets are complex and dynamic elements of our climate system. Their evolution has strongly influenced sea level in the past and currently influences the global sea level rise that threatens our coasts. Ice streams that speed up, slow down, and change course illustrate their dynamic nature. Atmospheric factors cause snowfall to vary in space and time across their surfaces. In Antarctica, small ice shelves continue to retreat along the Antarctic Peninsula, and large icebergs are released from the largest ice shelves. In Greenland, the ice sheet margins are thinning and the inland parts of the ice sheet appear to be thickening. Surface meltwater seeps into the ice sheets and accelerates their flow. Some of the factors controlling the mass balance of the ice sheets, and their present and future influences on sea level, are just beginning to be understood.

Mechanisms that control an ice sheet's behavior and how they may change express themselves in the ice sheets shape. Therefore, precise observation of elevation characteristics is an essential component of understanding key ice sheet processes. More significantly, however, changes in an ice sheet's volume are directly related to its contributions to sea level rise. Today, we do not know the extent to which ice sheets will grow or shrink in a changing climate, but we do know that they are changing dramatically in many places, and there is a pressing need to observe and understand these changes.

Continuous high-accuracy measurements of ice sheet topography and its changes over time will enable us to assess ice sheet contributions to sea level change and understand the interactions between ice and climate. Accuracies on the order of 10 cm per shot with contiguous or nearly contiguous along-track sampling are needed to capture the small variations over interior regions of the ice sheets. Pointing knowledge to better than an arc second is needed to quantify changes on the steeply sloping margins, where changes are most dramatic. Measurements must be continuous and sustained for a period on the order of 7 to 10 years to adequately quantify ice sheet growth/shrinkage, and determine how these ice sheets respond and influence a changing climate.

The dynamics of outlet glaciers that drain the ice sheets has been changing recently, with signs of acceleration in many areas. In some cases, this acceleration is quite rapid, suggesting potential instabilities in certain regions of the ice sheets. Visible imagery and interferometric Synthetic Aperture Radar (InSAR) have provided important information on the flow rates of these glaciers and how they are changing. However, visible imagery requires cloud-free solar illumination and InSAR is limited in area coverage and repeat pass configuration. Active laser techniques could provide an alternative approach to full three-dimensional observations of these changes so the stresses and strains that control these flow processes can be fully understood, and ultimately predicted. Achieving this capability requires a lidar swath width on the order of several kilometers, and a pixel size on the order of 20 meters.

2.4.2.2 Sea Ice Edge and Thickness

Sea ice plays an important role in the Earth system by modulating the exchange of energy and moisture between the ocean and the atmosphere. As such, it exhibits a strong influence on atmospheric and ocean circulation. In addition, it helps keep the planet cool by reflecting incoming sunlight. When sea ice cover diminishes, exposing the darker ocean surface underneath, the polar regions absorb much more solar energy, which promotes further warming. Thus the effects of sea ice retreat are self-compounding. The ice edges or the marginal ice zones are areas of rich biological and chemical activity. For these and other reasons it important to understand the movement and changes in the ice margins.

Detection of ice margins is currently done with visible, and passive and active microwave satellite imagery. Visible imagery is only available during sunlit conditions, passive microwave and scatterometry data are very coarse in resolution and have ambiguities associated with ice and ocean surface conditions, and Synthetic Aperture Radar data, though of very high resolution, is limited in coverage. Because ice floats, ice of any thickness greater than about 20 cm will protrude above the ocean surface by an amount that should be detectable against the "noise" of the ocean signal.

A system designed for measuring sea ice thickness, and/or ice sheet topography, should be capable of measuring ice edges as well. This would require along-track measurement spaced no more than about 100 meters (requirements for sea ice thickness would be for more dense sampling), and footprints smaller than about 70 meters.

Currently ICESat is capable of making such ice-edge measurements, but its limited sampling (3 sets of 33-day measurements each year) limits this utility to a demonstration. Continuous operation of a similar instrument would provide the data needed to draw meaningful conclusions from the ice edge information.

Because sea ice is among the most sensitive parameters to climate change, it exhibits such a strong influence on global climate, understanding its thickness characteristics and how it is changing is crucial to understanding present and future climates.

Until the launch of ICESat, observations of ice thickness had only been achieved in a rudimentary sense through the use of satellite radar altimetry which measures the height of ice above the ocean surface (freeboard). This freeboard height represents about 10% of the ice thickness, so small errors in measurement translate to large errors in thickness estimates. High precision (approximately 2 cm) contiguous along-track measurements with footprints smaller than 50 meters are needed for such measurements. Ideally, smaller footprints, (10 meters) and a swath capability would be desired, but planning of limited laser lifetime should be prioritized to maximize measurement duration. Once this is sufficiently achieved (7-10 year laser lifetime), swath capabilities should be pursued.

ICESat has demonstrated a remarkable ability of high-accuracy laser altimetry to estimate thickness from freeboard elevation, but its limited sampling (3 sets of 33-day measurements each year) limits this utility of this information. Continuous operation of a similar instrument would provide the data needed to draw meaningful conclusions from the ice edge information.

2.4.2.3 Physical Oceanography

The importance of oceans within the Earth system was briefly articulated in Section 2.3.2 on Ocean Biology and Biogeochemistry. In particular, the oceans are a major part of the climate system, as reflected in the following NASA Earth science questions:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?

In this context, a unique NASA contribution to climate science is the near-global coverage of observations from space of a number of physical ocean properties every 2 to 10 days, providing assessments of the physical state of the ocean and its variability in space and time. Lidar has the ability to complement existing and planned ocean observing capabilities, as well as provide primary, novel measurement capabilities. Regarding the former, satellite radar altimetry is the principal current (e.g., Jason) and future (e.g., OSTM) means for measuring Ocean Surface Topography (OST). Accurate measurements of OST are important for studying the ocean's tides, circulation and heat budget. The observations are used to help predict short-term changes in weather and longer-term climate patterns. A recent study (Urban and Schutz, 2005) has demonstrated that laser altimetry (ICESat) could be used to provide information on sea surface anomaly and mesoscale variability. Synoptic coverage represents a significant limitation, however. As such future laser altimeters developed for other applications (e.g., see ice thickness) could be expected to provide complementary measurements to the primary OST observations acquired from space-based radar altimeters. In terms of a primary application of lidar for physical oceanography, ocean mixed layer depth (MLD) represents an important measurement from both an ocean physics and ocean biology & biogeochemistry perspective. As discussed in section 2.3.2 above (as well as in Scenario 42 in Chapter 3), lidar provides a potential approach by which MLD can be characterized remotely, through sub-orbital and possibly space-based platforms. Substantial technology challenges need to be addressed, but significant scientific benefits will be returned.

2.5 Earth Surface and Interior Structure

This science focus area addresses the following questions:

- How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How can our knowledge of earth surface change be used to predict and mitigate natural hazards?

2.5.1 Land Surface Topography

Land surface topography measurements can be used to address science focus areas involving the Earth's solid surface and its change over time, and promote a better understanding of the planet and understand the consequences of change. For example, measurements of land surface topography can be used to assess, mitigate and forecast natural hazards such as earthquakes, volcanic eruptions, landslides, coastal and interior erosion, land subsidence (due to the extraction of fluids such as oil, natural gas, and water), mountain building and floods. Such observations are a vital input to solid earth, geologic, climate and other models describing the dynamic internal and external forces shaping the earth's surface. Ultimately, this combination of observation and modeling may provide accurate forecasting of natural hazards.

For example, clues to understanding the dynamics of the earthquake process are provided by knowledge of how the Earth deforms both during and after an earthquake. Faults respond to local stresses as well as those from hundreds of kilometers away. Thus in order to capture the dynamics of the full earthquake cycle, surface and surface change observations must be made at both local and regional scales, and repeated over timescales of minutes to decades or longer. Space-based observations of surface change have revolutionized this field in the past decade, enabling the integration of geodetic and seismic models for a better understanding of seismic zone dynamics.

Moderate success in near-term volcanic eruption prediction has also been achieved. Short-term deformation before and after eruptive activity has been studied, but our knowledge of the long-term interactions of magma movement within volcanoes and plate tectonic motion is incomplete. Continued and future deformation observations at both long and short time scales will enable accurate assessments of volcano hazards and eruption prediction.

Lidar remote sensing provides accurate and precise, high-resolution images of the earth's surface topography. Most importantly, the technique possesses the ability to consistently penetrate through vegetation layers to directly measure the sub-canopy topography at otherwise unobtainable resolution and accuracy. Furthermore, the unambiguous surface topography and change measurements provided by lidar generate an excellent data set for calibration and validation of other remote sensing systems such as interferometric SAR, as well as an important background data set for such systems.

It is envisioned that future lidar laser altimeter systems will be able to achieve spatial resolutions on the order of 1m, and vertical precisions of approximately 1cm.

2.5.2 Earth Gravity Field

High accuracy and high spatial-temporal resolution measurements of the Earth's static geopotential and its time variation provide important insight into the composition of the solid Earth and its change. More importantly, these gravity measurements provide unique observations of the planet's surface mass flux interchange between land, water, ice, oceans and atmosphere. These observations provide important understanding and constraints on geophysical fluid models of the atmosphere, hydrosphere and cyrosphere.

Continuous, high-accuracy and high spatial-temporal resolution measurements of the Earth's changing gravity field will give us new understanding in several core areas including Earth's mantle/lithosphere, ocean currents and energy transport, ocean tides, ice mass trends, continental hydrology, and sea level rise.

Currently the GRACE mission inter-satellite K-band ranging measurements are providing unprecedented observations of the Earth's changing gravity field at ~400km and 30-day resolution with an accuracy of approximately 2-3 cm equivalent surface water height. Laser technology will significantly improve upon these observations with the evolution of a future spaceborne gravity mission employing laser interferometer sensor technology. It is envisioned that a future laser interferometer based spaceborne gravity mission will be able to achieve observations of the Earth's gravity field at < 100 km and 10-day resolution with an accuracy of less than 1 cm equivalent surface water height. While, gradiometers for gravity field measurement have so far been based on electrostatically suspended accelerometers (e.g. the GOCE mission), future gravity gradiometers will use slow moving (cold) atoms to sense the gravity field and lasers will be used to control and interrogate these atoms. The lasers in these systems will be continuous wave lasers precisely tuned to provide cooling and florescence. Lasers will be used in optical traps, as beam splitters for atomic beams, and to detect atoms after interacting with the gravitational field.

2.5.3 Terrestrial Reference Frame

A terrestrial reference frame (TRF) provides the basis from which all geodetic observations are tied and compared over space and time. The TRF establishes the highly accurate datum that all geodetic point positions can be measured. The state-of-the-art realization of the TRF is the International TRF (ITRF) developed from four space geodetic techniques: (1) Satellite Laser Ranging (SLR), (2) Very Long Base Interferometry (VLBI), (3) Global Positioning System (GPS) and (4) Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS). Essential to the realization of the ITRF is the definition of its origin relative to the center of mass of the Earth system and its scale defined by the speed of light. The SLR techniques most important contribution is to define these crucial components. The accurate definition of these components and their stability over time is an absolute necessity for many high profile geodetic measurement applications including: crustal deformation, ice sheet change and sea level change. Improvements in the SLR network are critical to future crustal, ice sheet and sea level change investigations.

2.6 Water and Energy Cycle

The Water and Energy Cycle focus area addresses the exchange of water and energy between the oceans, atmosphere, terrestrial waters and terrestrial ice stores. The specific science questions answered through this focus area are:

- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?

Lidar remote sensing can be used to measure several of the relevant environmental measurement parameters that are of interest to NASA, such as water vapor and cloud cover, as previously discussed in this section. The importance of measuring these parameters is clear. Improved measurement techniques would lead to improved models, resulting in improved forecasts of precipitation, snowmelt, soil moisture and runoff, and floods and droughts. Better knowledge of the water budget at sub-continental and seasonal scales would help lead to higher-resolution weather and climate models. Improved measurements would improve our understanding of the effects of cloud feedback on climate change.

Water dominates human society through its importance to the very existence of terrestrial life, through its impact on the world's food supply, and also as a natural or human-induced hazard through river flooding. Better understanding of the water and energy cycle will greatly improve human preparedness for disaster management of river flooding, and more importantly improve the water resources management of food supply. It will also provide better understanding of the link between human activity and climate change. As a resource, amounts of water can be managed to maximize benefits to society. As an example, the untimely presence of snow and its rapid melt can cause significant damage to life and property. Better management through a better understanding of the water and energy cycle will help to reduce damage and costs from water-related hazards and will enable the better global management of water resources for global communities.

2.7 Weather

Weather refers to the state of the atmosphere and its variability on time scales of minutes to months. A complete characterization includes not only the state of the atmosphere, but also the temperature and moisture characteristics of the atmosphere-Earth surface interface, since these parameters are drivers of the weather. The specific science questions answered through this focus area are:

- How are variations in local weather, precipitation and water resources related to global climate change?
- Is the global water cycle through the atmosphere accelerating?
- How well can weather forecasting be improved by new global observations and advances in data assimilation?

Atmospheric state parameters of temperature, pressure, wind and moisture play a dominating role in weather and these are also key meteorological parameters and part of any weather prediction model. Evaporation, condensation and precipitation are thermodynamical processes controlled by the state parameters. Deep convection and formation of clouds are associated with the development of severe storms and hurricanes. Thus improved characterization the atmospheric state parameters (temperature, pressure, winds, and moisture) and clouds using lidar systems are likely to improve weather and severe storm prediction. The key measurement parameter observable with Lidar is global winds. This is a very important parameter that will have significant impact on short term weather forecast model performance.

2.7.1 Global Wind Observations

2.7.1.1 Introduction

The 2006 NASA Strategic Plan lists 6 Strategic Goals, and Sub-goal 3A states that NASA's Earth Science program should "improve prediction of climate, weather, and natural hazards" by "working to advance radar, laser, and light detection and ranging technologies to enable monitoring of such key Earth system parameters as land surface, oceans, ice sheet topography, and *global tropospheric winds* that could lead to advances in weather and severe storm prediction" (NASA, 2006).

The science and operational communities of the United States and other countries greatly desire global vertical profiles of horizontal vector winds for many applications:

- Improved weather prediction;
- Greater understanding of climate processes;
- Mitigation of weather-related hazard, deaths, injuries, and economic costs.

These three primary applications were ranked first, second, and fourth in a list of nine key societal benefits emphasized in a recent report by the cabinet-level National Science and Technology Council (NSTC) (NSTC, 2005). The report lists "wind profiles at all levels" as the highest priority observations for improved weather forecasting. The value of wind measurements to improved weather prediction is highlighted by the fact that it is ranked as the highest priority unmet measurement by the National Polar-orbiting Operational Environmental Satellite System/ Integrated Program Office (NPOESS/IPO), which is a joint office representing Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), and NASA (NPOESS,1996). A very strong case for the benefits of tropospheric wind profiling from space has been made in the scientific literature (Atlas, 1985, 1998, 2003; Rohaly, 1993; Baker, 1995; Riishojgaard, 2003; Emmitt, 2005). Wind measurements have been shown to promise a large positive economic benefit to the country (Cordes, 1995, 1998), as has improved weather prediction in general (Canavan, 1999).

Realization of the benefits of the wind measurements, for the three stated primary NASA applications, result from assimilation of the wind measurements into computer models used for weather forecasting and climate studies. The model outputs provide the improved weather forecasting, and climate studies are assisted since weather forecast results allow refinement of climate computer models. This assimilation of the wind data into models is to be considered in addition to other benefits achieved by direct use of the wind measurements themselves. The DOD, for example, desires wind measurements for applications that both use and do not use model assimilation (NASA, 1985; Piotrowski, 1999). This bifurcation in the way that the wind data are used does not necessarily double the required technology development since the same lidar technology and techniques that would be advanced by NASA's three primary applications can be envisioned to also enable the "direct use" applications.

2.7.1.2 Relevance to NASA's Science Focus Areas

Of NASA's 18 science focus areas (NASA IIP-2004 NRA), the technology recommended herein for tropospheric wind measurements will make a primary contribution to 4 areas, and a secondary contribution to 11 other areas, for a total of 15 areas receiving a contribution. This relevance is shown in Table 2-5 and summarized in Table 2-1 as well. Note that CO2 measurements can be made with the same lidar system at the same time as winds, aerosols, and clouds.

Table 2-5: Connection of proposed effort to NASA's science focus areas.

Science Focus Area	Measurement Enabled By This Effort	Contribution
Weather	Tropospheric Winds, Clouds, Aerosols	Primary
Disaster Management	Weather Forecasts (Hurricane Tracks, see Fig. 1)	Primary
Air Quality Management	Weather Forecasts, Aerosols, Winds	Primary
Aviation	Weather Forecasts, Winds	Primary
Climate, Variability and Change	Clouds, Aerosols, CO_2	Secondary
Atmospheric Composition	Aerosols	Secondary
Carbon Cycle, Ecosystems and Biogeochemistry	CO_2	Secondary
Water and Energy Cycles	Clouds, River Discharge	Secondary
Carbon Management	CO_2	Secondary
Coastal Management	Weather Forecasts, Winds	Secondary
Energy Management	Clouds, Aerosols, Weather Forecasts	Secondary
Homeland Security	Winds, Circulation Models	Secondary
Invasive Species	CO_2	Secondary
Public Health	Weather Forecasts	Secondary
Water Management	Weather Forecasts	Secondary

Of NASA's six Earth System Science focus areas (Earth Science Applications Plan, 6/1/2004), the technology for tropospheric wind measurements will primarily contribute to "Climate Variability and Change" and "Weather", and will also contribute to "Carbon Cycle and Ecosystems" and "Global Water and Energy Cycle".

NASA SMD's research within the weather focus area is geared toward answering the following science questions that are relevant to wind measurements:

- How can weather forecast duration and reliability be improved?
- How can predictions of climate variability and change be improved?
- How can predictions of time, location, path, and intensity of weather disasters (hurricanes, floods, tornadoes, snowstorms, icing) be improved to save lives and money?

2.7.1.3 Requirements for Vertical Profiles of Horizontal Vector Winds

The measurement requirements for global vertical profiles of horizontal vector wind have been steadily evolving since the potential use of Doppler lidar systems was first discussed in the 1970's. In 2000, NASA formed the Global Tropospheric Winds Sounder (GTWS) mission formulation team to address a Congressional directive that NASA obtain global wind measurements through a commercial data buy approach (GTWS, 2001). One of the many activities undertaken by the GTWS team was to form a Science Definition Team (SDT) to determine the measurement requirements (GTWS-SDT, 2001). The GTWS SDT concentrated on measurement requirements for the "model assimilation" use of the data. NASA lidar technologists participated in the process to ensure that all of the requirements necessary to unambiguously define a Doppler wind lidar space mission were included (Kavaya, 2001a, 2001b; Gentry, 2001; Emmitt, 2001). Previous statements of wind measurement requirements lacked sufficient details to permit definition of the size of the Doppler wind lidar instrument, since ambiguities of several tens of dB were possible. The SDT developed both "Threshold" and "Objective" requirements. The threshold requirements were defined as "minimum requirements for wind data that would be useful for NOAA forecasting models and NASA science investigations" or "noticeable improvement". The objective requirements were defined as "optimum data specification" or "significant improvement".

The Threshold and Objective requirements were released for comment on 16 October 2001 jointly by the NASA Earth Science Enterprise (ESE) and the NOAA National Environmental Satellite Data and Information Service (NESDIS) (see http://space.hsv.usra.edu/LWG/Index.html). The 21-page document was called the "Draft Global Tropospheric Winds Sounder (GTWS) Science and Operational Data Specification". In addition to the requirements, the document contained definitions, explanations, and design atmospheres. The design atmospheres comprise 9 tables covering 3 laser wavelengths for 3 aerosol conditions. The 3 laser wavelengths are 355, 1060, and 2051.8 nm.

Tables 2-6 and 2-7 list the wind measurement requirements. Note that these tables include traditional measurement requirements, such as resolution and accuracy, and also contain specifications of the "design" atmosphere to assist sensor performance prediction calculations, and requirements in recognition of the nature of the Doppler lidar measurement technique, such as angular separation between the two line-of-sight (LOS) perspectives of a "horizontal" wind measurement. Appendix 2G contains supplementary explanations and definitions, and Appendix 2H contains the design atmospheres with corresponding definitions. Corrections to the original requirements developed in October 2001 are shown in red in the Tables 2-6 and 2-7 and Appendix 2. The information in the Appendices, including the design atmospheres, must accompany Tables 2-6 and 2-7 to represent a completely defined set of requirements for mission designs. In this way, various mission concepts with different technologies and/or techniques may be compared to each other with "equal requirements" and "equal atmospheres".

In the years since the GTWS requirements were generated, it has become attractive to consider a demonstration wind mission in earth orbit that would demonstrate the lidar technology, the measurement technique, and the ability to scan the lidar beam as required to measure two collocated LOS wind profiles (bi-perspective) at 4 (threshold) or 12 (objective) cross track distances (see Table 2-6) with a horizontally projected angle between the two perspectives of 30-150 degrees (see Table 2-7). The cost and risk of this demonstration mission could be kept down by relaxing the measurement requirements while preserving the primary validation objectives. As part of this Laser/Lidar Working Group, we developed a new set of "Demo" requirements in consultation with the members of the GTWS SDT, and with the members of the Working Group on Space-Based Lidar Winds (WGSBLW) (WGSBLW). These "Demo" requirements are also shown in Tables 2-6 and 2-7. Note that the requirements for vertical resolution and number of cross-track positions (wind tracks) have been eased, among others.

Table 2-6: Primary Wind Measurement Requirements (Part I).

	Demo	**Threshold**	**Objective**	Units
Vertical depth of regard (DOR)	0-20	0-20	0-30	km
Vertical resolution:				
Tropopause to top of DOR	Not Req.	Not Req.	2	km
Top of BL to tropopause (~12 km)	2	1	0.5	km
urface to top of BL (~2 km)	1	0.5	0.25	km
Number of collocated LOS wind measurements for horiz wind[A] calculation	2 = pair	2 = pair	2 = pair	-
Horizontal resolution	350	350	100	km
Number of horizontal wind[A] tracks[B]	2	4	12	-
Velocity error[C] Above BL	3	3	2	m/s
In BL	2	2	1	m/s
Minimum wind measurement success rate	50	50	50	%
Temporal resolution (N/A for single S/C)	N/A	12	6	hours
Data product latency	N/A	2.75	2.75	hours

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an "effective" horizontal wind measurement. The two LOS winds are reported to the user.

[B] The cross-track measurements do not have to occur at the same along-track coordinate; staggering is permitted.

[C] Error = 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 175/100/25 km square box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction as reported with the data.

BL = Boundary Layer

(red text = errata to original requirements from October 2001)

Table 2-7: Secondary Wind Measurement Requirements (Part II).

	Demo	**Threshold**	**Objective**	Units
Vertical location accuracy of LOS wind measurements	1	0.1	0.1	km
Horizontal location accuracy of LOS wind measurements	5	0.5	0.5	km
Allowed angular separation of LOS wind pair, projected to a horizontal plane	30-150	30-150	30-150	degree
Maximum allowed horizontal separation of LOS wind pair	50	35	35	km
Maximum horizontal extent of each horizontal wind[A] measurement	175	100	25	km
Minimum horizontal cross-track width of regard of wind measurements	N/A	±400	±625	km
Maximum cross-track spacing of adjacent cross-track locations	N/A	350	100	km
Maximum design horizontal wind speed: Above BL Within BL	 50 50	 75 50	 100 50	 m/s m/s
Design 1σ wind turbulence level: Above BL Within BL	1 1	1.2 1	1.4 1	m/s
Max. LOS wind unknown bias error, projected to a horizontal plane	1	0.1	0.05	m/s
Minimum design a priori velocity knowledge window, projected to a horizontal plane (using nearby wind measurements and contextual information)	26.6	26.6	26.6	m/s
Design cloud field: Layer from 9-10 km, extinction coefficient Layer from 2-3 km, 50% of lidar shots untouched, 50% blocked	 0.14 50, random	 0.14 50, random	 0.14 50, random	 km^{-1} %
Aerosol backscatter coefficients: 2 vertical profiles provided	 Provided	 Provided	 Provided	 $m^{-1}sr^{-1}$
Aerosol backscatter: Probability density function (PDF) PDF width	Lognormal Provided	Lognormal Provided	Lognormal Provided	m sr $m^{-1}sr^{-1}$
Atmospheric extinction coefficient: 2 vertical profiles provided	 Provided	 Provided	 Provided	 km^{-1}
Orbit latitude coverage	N/A	80N to 80S	80N to 80S	Degree
Downlinked data	All	All	TBD	-

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an "effective" horizontal wind measurement. The two LOS winds are reported to the user.

(red text = errata to original requirements from October 2001)

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3. Measurement Scenarios (Instrument Concepts)

This chapter addresses the lidar measurement scenarios that have been formulated to meet the science requirements described in chapter 2. A measurement scenario is an instrument and mission concept, i.e., a sensor on a platform in a particular location or orbit.

The scenarios have been organized according to lidar technique: ranging and altimetry, Doppler, backscatter, differential absorption, and other. These categories roughly correspond to a related set of science measurement goals. (Figure 3-1.) Ranging and altimetry scenarios are used for ocean and topography measurements. The Doppler technique is used to make wind measurements. Backscatter lidar addresses both ocean and topography and atmospheric composition (chemical constituents and particulate microphysical parameters) while the differential absorption technique is used to measure atmospheric chemical constituents only. The one scenario in the “other” category is a quantum gravity gradiometer that uses a laser in matter-wave interferometry.

The defining strength of lidar techniques, and not coincidentally the root of many of its unique application scenarios, is the ability to recover fine-scale target structure, be it of the Earth’s surface or distributed, so-called “soft” targets such as the atmosphere.

Many lidar applications make use of range gating, which involves sampling the received signal at specific times after the laser pulse has been generated. Range gating allows the lidar instrument to recover information from targets at different ranges. This is useful for filtering out unwanted returns and also for specifying the altitude at which atmospheric parameters are measured.

At the end of this chapter is a summary of how the measurement scenarios relate to the six science focus areas.

Each measurement scenario has been assessed with regard to its potential to meet the measurement goals and thresholds (where defined) associated with the various science requirements, as presented in Appendices 2A-F. This assessment is indicated by a letter in parentheses at the end of each paragraph describing a given scenario. That letter may be interpreted as shown in Table 3-1.

Note that scenarios that have only numerical designations (e.g., Scenario 188) were taken from the current ESTIPS online database. Scenarios that have an “NRC” prefix (e.g., NRC-01) were taken from responses to a 2005 Request for Information from the National Research Council Committee on Earth Science and Applications from Space. Scenarios with a “2300” prefix (e.g., 2300-09) were taken from the ESTO presentation charts entitled, “Earth System Science: Potential Roadmap and Measurement Development Activities, May 19, 2005.” The material in these presentation charts is the latest version for taking the six Earth science roadmaps and interpreting to science objectives and measurement scenarios. Scenarios that have the prefix “LWG” (e.g., LWG-AD-SP1) were developed by the Lidar Working Group.

For more information on the scenarios mentioned in this chapter, see the following sources:

ESTIPS online database: http://estips.gsfc.nasa.gov/

NRC Decadal Survey website: http://qp.nas.edu/QuickPlace/decadalsurvey/Main.nsf/h_Toc/4df38292d748069d0525670800167212/?OpenDocument

ESTO website: http://esto.gsfc.nasa.gov/

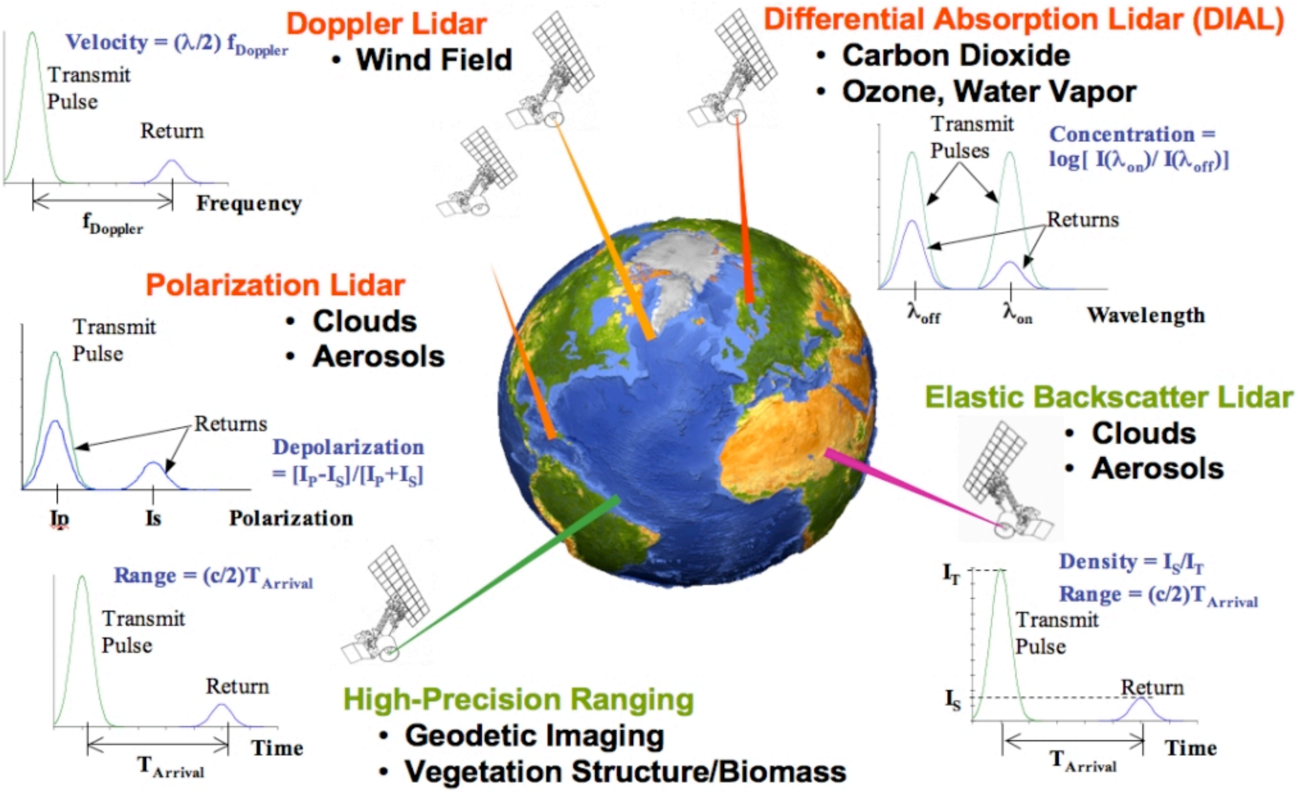

Figure 3-1: Laser Remote Sensing Techniques

G	scenario meets all threshold requirements (where defined) and meets one or more of the science measurement goals defined in Appendix 2 (horiz res, vertical res, revisit, and accuracy)
E	scenario meets all threshold requirements (where defined) and exceeds one or more (horiz res, vertical res, revisit, and accuracy)
T	scenario meets but does not exceed all the threshold science requirements (horiz res, vertical res, revisit, and accuracy)
D	scenario meets requirements for a demo mission
P	scenario fails to meet one or more of the stated thresholds and fails to meet requirements for a demo mission

Table 3-1: Measurement Scenario Assessment Designation

3.1 Ranging and Altimetry Lidar

Ranging and altimetry lidar functions similar to radar except that lidar uses light instead of radio waves. The lidar emits a light pulse and determines range to the target by measuring the round trip time from pulse generation to the moment the reflected signal is received by the instrument. This is termed "time-of-flight" measurement. Since lidar uses much shorter electromagnetic wavelengths than radar, it can be used to detect and image much smaller scattering features. Thus, lidars can generate extremely accurate digital elevation maps of land surfaces beneath the vegetation cover, detect fault lines, determine displacement due to earthquakes, detect small changes in glaciers and rivers, and measure the three-dimensional size and distribution of forest canopies. By measuring the distance between two spacecraft with great accuracy, ranging lidars can also be used to measure the Earth's gravitational field. Ranging and altimetry lidars have been flown in space (ex. MOLA, SLA, Clementine, NEAR, GLAS).

Measurement scenario NRC-14 is for an advanced ICESat follow-on mission to measure ice surface topography and sea ice thickness, as well as land surface topography and several other parameters. The required laser has an extended transmitter lifetime of 7-10 years for polar ice sheet and sea ice science and operates at a single wavelength of 1064 nm. The instrument has 70 meter diameter laser footprints with ~70 meter separation and 100 Hz PRF. Scanning is not required. Requirements include 2 cm range precision, 3 cm radial orbit accuracy, well-calibrated surface reflectivity, minimal telescope FOV with respect to laser pulse size, active alignment of beam within the FOV, and 2 arcsecond pointing knowledge. The instrument also has an off-nadir targeting capability, with cross-track targeting accuracy of < 30 meters (1 sigma) to allow for more targeting sites than ICESat-1. Hybrid analog/photon counting detectors eliminate the need for a green laser channel, simplifying the laser design. This scenario meets the ice surface topography measurement goals and exceeds threshold for some others. (G)

Scenario 48 is an ice and land surface topography scenario similar to NRC-14. This sensor option measures high-precision land surface and ice height from time-of-flight of a back scattered laser beam. The instrument consists of a telescope (1 m aperture), a diode-pumped Nd:YAG laser transmitter (Q-switched), an altimeter receiver electronics package, and a waveform digitizer coupled to the altimeter receiver for capturing the backscattered echoes from the interaction of short duration laser pulses with the Earth's surface. The instrument is a tool for geodetic topographic sampling and for direct measurement of local scale surface vertical structure. Dual wavelength (1064 nm and 532 nm) laser is required for accurate polar ice measurements. 1064 nm is required because it does not penetrate the ice. 532 nm is required to accommodate optical path length changes due to clouds, aerosols and blowing snow. Higher PRF is required for higher spatial sampling due to typical size of melting glaciers. This scenario meets the ice surface topography measurement goals and exceeds threshold for some others. (G)

Since scenarios 149 and 150 are so similar to scenario 48, it is recommended that all three scenarios be combined into a single record.

Scenario 186 is another topography scenario. It uses a photon-counting imaging lidar to map surface elevations, including ground topography, river and lake stage, ice surface elevation, and sea ice freeboard. Laser transmitter is solid-state, CW pumped, passively Q-switched, frequency-doubled Nd:YAG, yielding 4 mJ transmit energy at 532 nm wavelength at 1 kHz laser fire rate. Receiver consists of a 1 m diameter telescope and a pixelated, 10 x 10 detector array with 5 m ground FOV per pixel and a low-deadtime, multi-GHz, multi-stop, photon counting, digital timing channel for each of the 100 array elements. Maintaining alignment between the transmit pulse and receiver and cross-track scanning to generate a swath are accomplished by two transmissive, counter-rotating, optical wedges. A stellar reference system provides pointing knowledge of the transmit/receive path for each laser pulse to 1 arc sec or better. Frequency doubling yields a green pulse that will experience penetration into water and ice; the range to the water or ice upper surface, transmission properties, and depth to bottom for shallow water can be derived from the point-cloud of single photon range measurements.

Range correlation techniques are used to distinguish surface single photon returns from solar background returns. The photon-counting technique has not yet been validated for this application. Simulations might justify its ability to contribute to ice surface topography measurements, but there is concern in the community that it may have systematic biases that would limit it eventual accuracy. This approach needs to be demonstrated to validate its ability to make science measurements. (D)

Scenario 188 uses a wide swath imaging laser altimeter to map topography and vegetation on the Earth's surface. This sensor option will provide landscape-scale (10 km swath), high-resolution (10 m pixels), 3-dimensional mapping of the Earth's surface (vegetation and surface topography, ice sheet topography, etc.) using the proven high signal-to-noise (SNR), full return-waveform measurement technique. The full Earth surface can be mapped within 6-12 months. Topography measurements will be made at decimeter absolute vertical accuracy. The instrument will measure vegetation canopy height, vertical structure and land cover change, along with topographic change detection at sub- centimeter relative vertical accuracy (including subtle topographic change beneath vegetation). This is a wide-swath, imaging laser altimeter (i.e. 3-D imager). Efficient fiber-based, lasers and imaging techniques are required. This instrument is capable of illuminating and mapping landscape-scale swaths of data in a single pass. The instrument concept involves scanning a low power, high repetition rate laser to achieve full mapping. Based on a proven measurement technique employed in the Laser Vegetation Imaging Sensor (LVIS) this instrument is uniquely capable of penetrating dense canopies to achieve accurate sub-canopy measurements. This scenario meets vegetation biomass goals and exceeds thresholds for most others. (G)

The NRC-11 scenario is a multi-beam lidar operating at 1064 nm that measures forest structure and biomass. (The lidar could be co-located with polarimetric, interferometric UHF radar for complementary observations.) The lidar is a multi-beam laser altimeter that samples the landscape to provide canopy top and bottom elevation and the vertical distribution of intercepted surfaces. The instrument has three beams with 25 meter spatial resolution and better than 1 meter vertical accuracy in vegetated regions. Decimeter-level accuracy is possible over bare ground. The instrument has a mission lifetime of three years. This scenario meets vegetation biomass goals and exceeds thresholds for most others. (G)

The Lidar Working Group considered Scenario NRC-08 ("Structure and Inventory of Vegetated Ecosystems (STRIVE)") and believes that it is not necessary to add it to ESTIPS as a separate record because it is adequately represented by Scenario NRC-11, which is very similar.

Scenario 187 is a waveform-recording, multi-beam lidar that samples surface elevation along multiple ground tracks based on the round-trip travel time of back-scattered laser pulses. The scenario is optimized to estimate above ground biomass and rates of biomass change based on measurements of vegetation height and vertical structure. Measurements are also obtained of ground topography, river and lake stage, fuel quantity and land cover. In order to obtain sufficient sampling (10% to 20% of land area) over the 3 to 5 year mission lifetime to achieve improved characterization of global and regional carbon pools, sinks, and sources (10-25 km scales and 5-10 Mg/ha accuracy), six solid-state, 5 W Nd:YAG laser transmitters are used spaced across a 12 km wide FOV (four active and two spares). Each laser operates at 100 pulses/sec and yields continuous, 75 m diameter footprints. The receiver consists of a 1.5 m diameter Be telescope and a 3 x 3 Si:APD detector array for each laser with a 20 x 20 m ground FOV for each array element. Digitizers operating at 1 GHz convert the analog output of each array element into a waveform, yielding a 3 x 3 waveform array for each laser footprint. The waveform array provides information on along- and across-track ground topography and vegetation structure. A stellar reference system provides pointing knowledge of the transmit/receive path for the laser pulses to 1 arc sec or better. The instrument is an evolutionary advance building upon the ICESat/GLAS and VCL/MBLA designs. This scenario meets vegetation biomass goals and exceeds thresholds for most others. (G)

Scenario LWG-OT-1 is a narrow swath orbital imager. This laser altimetry approach measures the surface height and scattering properties of ice, water and land surfaces in ~10 m footprints configured in a contiguous mapping swath (100-300 m wide). The basic measurement is the time-of-flight of the individual laser pulses in the laser beam and could be augmented to include further characterization of the return signal energy, pulse shape, and depolarization.

The instrument consists of a set of short-pulse laser transmitters which illuminate the Earth surface in a push-broom or scanned swath. The swath is composed of a parallel set of individual laser profiling lines, each of which is composed of a series of laser spots. The laser backscatter from the surface is collected with a ~1 m diameter telescope and illuminates a set of sensitive photon counting or analog detectors. The detector outputs go to a set of timing electronics, which measure the time of flight in the case of photon-counting or the return signal shape characteristics in the case of higher-SNR, pulsed altimetry.

Statistics related to the vertical structure and surface topography are generated along each profile track in the swath. The laser beam may be polarized, and using a polarization sensitive detector system permits resolving optical polarization properties (i.e. diffuse vs. specular) of the surface. The swath mapping altimeter measures the range distribution within contiguous ~10 m diameter pixels in each profile track of the swath. The choice of individual spot size and swath width is dependent on trades between the mission science drivers, measurement goals, the laser technology availability, the measurement wavelength choice, and the spacecraft power. The measurement approach has not yet been validated for this application. Simulations might justify its ability to contribute to ice surface topography measurements, but there is concern in the community that it may have systematic biases that would limit it eventual accuracy. This approach needs to be demonstrated to validate its ability to make science measurements. (D)

Scenario LWG-OT-2 is a high resolution imager mounted on a UAV platform. This laser altimetry approach measures the surface height and scattering properties of ice, water and land surfaces in ~1 m footprints configured into a contiguous mapping swath 100-1,000 m wide. The basic measurement is the time-of-flight of the individual laser pulses in the laser beam and could be augmented to include further characterization of the return signal energy, pulse shape, and depolarization.

The instrument consists of one or more short-pulse laser transmitters which illuminate the Earth surface by being scanned across a swath. For each illuminated footprint, the laser backscatter from the surface is collected with a telescope and illuminates one or more detectors. The detector output is sent into a set of timing electronics, which measure the time of flight for up to five returns for each laser pulse. These multiple returns are used to calculate statistics along each laser spot in the swath. The laser beam may be polarized, and using a polarization sensitive detector system permits resolving optical polarization properties (i.e. diffuse vs. specular) of the surface. The laser light might also consist of multiple wavelengths from which one could extract additional information on the sampled surface. These spot measurements form a swath, and allow a long contiguous strip image of surface height and scattering properties to be measured.

This system would operate in a low or high-altitude aircraft such as a UAV. Total system laser rep-rate required is 10,000 Hz - 100,000 Hz to produce a 100 m to 1,000 m wide swath, respectively. The laser operates at a wavelength of ~1 micron, with pulsewidth on the order of 2-5 nsec and a divergence appropriate to produce a 1 m spot from the aircraft operational altitude. For example, if the aircraft is operating at 10,000 m, then a divergence of 0.1 milliradians would be required. The receiver and timing circuitry requires ~5 cm vertical resolution and analog Si: APD detectors. A compact, rugged, lightweight, low-power, and autonomous implementation of this measurement concept would be compatible with numerous aircraft, including lightweight UAVs and could be deployed to remote areas of the Earth for vegetation or ice sheet monitoring. Even though it can really only achieve regional (or maybe national) mapping, this scenario would make a contribution that meets the threshold for vegetation biomass. (T)

Scenario 56 is an advanced follow-on to the GRACE mission, which maps the Earth's gravitational field. This sensor option is a laser interferometer to measure changes in the distance (or range) between two spacecraft in low-Earth orbits separated by 50-200 kilometers to detect perturbations caused by the Earth's gravity field, along with a force reduction system on each spacecraft to reduce non-gravitational forces. The instrument is distributed, with each spacecraft containing identical transmit/receive optical systems, frequency-stabilized lasers, measurement electronics, and force reduction system. Each spacecraft transmits a continuous laser signal to the other spacecraft, and each spacecraft measures the frequency shift of the laser signal it transmits relative to the signal received from the other spacecraft. The frequency measurements, when combined in post-processing, allows determination of changes in distance between the two spacecraft with sub-nanometer accuracy. The force reduction system is achieved by using a Gravitational Reference Sensor which provides a shielded test mass to which the position of the spacecraft is compared and controlled using Micro-Thruster system capable of adjusting the position of the spacecraft with an accuracy of a few nanometers.) (G)

Scenario 52 consists of a terrestrial network of ground stations that determine the range to orbiting satellites using lasers. Improved satellite laser ranging network will provide a factor of 5-10 improvement in reference frame and satellite POD. Satellite Laser Ranging (SLR) provides center of mass and scale; dual color for atmospheric correction is optimal. Ranging to orbiting satellites: at least to 22,000km altitude to link to GPS satellite constellation. Horizontal spacing is about 5000 km (2000 km optimal). The scenario has global coverage and daily to weekly observations with continuous observations as optimal goal. Precision is 205 mm (1mm optimal). (E)

NRC-07 is a scenario with a scanning laser altimeter that is co-located with an L-band synthetic aperture radar (SAR), a Ku-band interferometric SAR, and a nuclear reactor for both electric propulsion and power. The laser altimeter, which uses cross-track scanning, measures both land surface topography and vegetation canopy thickness. The nuclear-powered spacecraft provides a platform to operate higher-power lasers than have previously been possible. The laser operates at 1064 nm, requires 45 W of power, and has a mass of 50 kg. The instrument has a 25 meter spot size with 1.5 km spacing and 0.5 meter vertical resolution. The data rate is less than 10 kbps and the average duty cycle is 30%. PRF is 100 pulses per second. The instrument uses a 1 meter nadir oriented telescope. The instrument operates in both Earth and Lunar orbit. (G)

3.2 Doppler Lidar

Doppler lidar instruments determine wind velocity by emitting a laser pulse and measuring the Doppler shifted frequency of the returned signal. Since this type of lidar is sensitive to frequency, Doppler lidars require a frequency stable, narrow linewidth pulsed laser beam. The pulsed laser is transmitted to the atmosphere at an angle typically between 30 an 45 degrees. A fraction of the laser energy is scattered back towards the lidar by aerosols and molecules in the atmosphere and collected by a telescope. The collected signal is recorded as a function of range then processed by the detection system which measures the Doppler shift in the laser frequency produced by the motion of the atmosphere. The measured Doppler shift is directly related to the component of the wind along the line of sight of the laser. A scanning system is used with the Doppler lidar to obtain line-of-sight wind measurements from multiple perspectives (e.g. forward and backward views) of each sample volume. The horizontal components of the wind field can be obtained by combining line-of-sight velocities from the multiple views. Doppler lidar instruments have been tested on the ground and on airborne platforms, but have not yet been deployed in space.

There are currently two kinds of wind lidar instruments being considered for future NASA Earth science missions: coherent lidar and direct detection lidar. A heterodyne or coherent detection Doppler lidar measures the Doppler shift by coherently combining the atmospheric return signal backscattered with a local oscillator on an appropriate photodetector. In the absence of any wind velocity, the frequency of the atmospheric return signal will differ from the local oscillator frequency due to any purposeful offset frequency generated by the lidar system hardware, due to the Doppler shift from the relative velocity of the spacecraft and the earth, and due to the Doppler shift from the velocity of the atmosphere due to earth rotation.

By subtracting these three contributions from the total measured frequency offset, the Doppler shift due to wind velocity along the laser beam line of sight may be found. The beat frequency is typically in the RF domain and standard radar electronics and signal processing techniques can be adapted to determine the frequency shift. The key technologies are a high energy, pulsed laser transmitter with a narrow spectral linewidth, a precise tunable laser local oscillator, a diffraction limited telescope and scanning system and an efficient heterodyne detector. Coherent Doppler wind lidar uses returns from aerosols or clouds to detect wind velocity. This technique works well in regions where aerosol density is high, such as in the planetary boundary layer, the 0 to 3 km altitude region. In the free troposphere, the aerosol density tends to drop and the coherent technique would have decreasing success rates, but would still occasionally get useful data from clouds, areas of high aerosol backscatter, and high-SNR speckle surges which occur regularly on a statistical basis. Coherent Doppler wind lidars have been under development for about twenty-five years.

A direct detection Doppler lidar measures the Doppler shifted frequency by observing the frequency of the backscattered signal through a high resolution spectral analyzer e.g. interferometer or etalon. The direct detection lidar can process the signal return from either aerosols or molecules. The molecular return is thermally broadened by the random motion of the molecules which spreads out width the molecular spectrum to about 600 m/sec in equivalent Doppler velocity units. The spectral spreading of the molecular signal makes a precise measurement of the wind more difficult but this disadvantage is offset by the fact that the molecular signal is always present while the aerosol return is highly variable in altitude as well as globally. The backscattered signal can be greatly increased by operating at shorter wavelengths in the ultraviolet because of the λ-4 dependence of the backscatter coefficient. The key technologies for the direct detection Doppler lidar are the high energy pulsed laser transmitter, the high spectral resolution spectral analyzer and sensitive detectors, single element and arrays, capable of single photon detection. Lightweight, large aperture telescopes and scanning systems are also required although these systems do not require diffraction limited performance as the telescope performs more like a “light bucket” in the direct detection lidar. Direct detection lidars tend to work best in the clear air regions of the upper troposphere from 3 to 20 km altitude. Several direct detection Doppler lidar systems have been demonstrated from the ground in the past 15 years. The European Space Agency is developing a direct detection Doppler lidar operating at 355 nm for the Atmospheric Dynamics Mission.

Numerous space based wind lidar implementation studies have been performed in the last 25 years, including the Laser Atmospheric Wind Sounder (LAWS) instrument originally selected as a facility instrument on the Earth Observing System (EOS). Typically these studies have employed a single Doppler lidar approach, coherent or direct detection, scaled to meet the full measurement requirements. The resulting single lidar instruments have all been extremely large in size and power required and technologically challenging. Recent studies have shown that the instrument size is largely driven by the need to scale the single instrument technology to measure winds where it is least efficient. For a coherent aerosol lidar this would be the clear air regions of the free troposphere where aerosols are sparse. For a direct detection molecular Doppler lidar the measurement requirements for high accuracy and vertical resolution in the lowest 3 km of the atmosphere drive the instrument size and power. The current consensus of the wind lidar community is that a hybrid (or combined coherent and direct detection) Doppler lidar instrument is the most efficient way to measure tropospheric winds through the entire 0 – 20 km altitude range with the necessary accuracy, spatial and temporal resolution. The hybrid approach takes advantage of the complementary measurement capabilities of the coherent and direct detection lidars. The coherent and direct detection channels of the hybrid system are significantly smaller than systems with comparable capability developed with one technology alone. The technology requirements for the hybrid lidar components are achievable with today's technology.

Scenario LWG-AD-AIR1 is an airborne scanning Doppler wind lidar for hurricane monitoring. The instrument package includes both a 2 micron sensor for coherent wind measurements in the lower troposphere and a 0.355 micron sensor for direct detection measurements in the upper troposphere. The two sensors usually provide overlapped measurements, which allows for calibration and validation. The 0.355 micron sensor will reduce the search space for the 2 micron sensor, thereby increasing the vertical coverage of the 2 micron sensor into lower aerosol backscatter regions. The 2 micron sensor will also provide sensor pointing knowledge using the ground return "velocities"; this pointing knowledge can be transferred to the 0.355 micron sensor through mechanical or optical linkage. The duty cycle is close to 100% for both sensors, although they will only operate for a few hours during each mission sortie. The instrument package will use space-like geometry and scanning. (D)

Scenario LWG-AD-SP1 is a Doppler wind lidar mission in a 400 km altitude orbit with 100% duty cycle targeting the 'demonstration' measurement requirements. This scenario uses a combination of 2 micron and 0.355 micron sensors, as in the airborne scenario. The intent of this scenario is to provide an initial demonstration of the Doppler wind lidar technique from space. The wind measurements will be scientifically useful with some impact on operational weather prediction. The instruments will be scalable to a fully operational mission with some additional technology development. (D)

Scenario LWG-AD-SP2 is a Doppler wind lidar demo mission in an 833 km polar orbit. This instrument is an attached payload on an NPOESS satellite and uses adaptive targeting to reduce the duty cycle of the direct detection sensor. The instrument uses 2 micron and 0.355 micron sensors, as do the other Doppler wind lidar scenarios. The intent of this scenario is to provide an initial demonstration of the Doppler wind lidar technique from space. The wind measurements will be scientifically useful with some impact on operational weather prediction. The instruments will be scalable to a fully operational mission with some additional technology development. (D)

Scenario LWG-AD-SP3 is a Doppler wind lidar in a 400 km altitude orbit. This scenario is a "threshold" mission: it satisfies the threshold science and operational requirements for tropospheric wind measurements over a three-year lifetime. This instrument uses 2 micron and 0.355 micron sensors with adaptive targeting to reduce the duty cycle of the direct detection sensor. (T)

The Lidar Working Group considered Scenarios 78, 79, 80, and 82 and recommends that they be deleted from the ESTIPS database because they have been superseded by the new Doppler wind lidar scenarios described above. Also, the Lidar Working Group considered Scenarios NRC-05 ("Improved Weather Prediction, Climate Understanding, and Weather Hazard Mitigation through Global Profiling of Horizontal Winds with a Pulsed Doppler Lidar System"), NRC-10 ("Space-based Doppler Wind LIDAR: A Vital National Need"), and NRC-13 ("Providing Global Wind Profiles- The Missing Link in Today's Observing System"). The Group believes that it is not necessary to add these scenarios to ESTIPS as separate records because the new scenarios documented above adequately reflect the current thinking of the Doppler wind lidar community.

3.3 Backscatter Lidar

Technically, most lidars are backscatter lidars in that they measure light that is reflected back in the direction of the laser source. In practice, "backscatter lidar" refers to instruments that measure the signal strength returned from the target. Backscatter lidars are used to measure atmospheric composition as well as ocean and ecosystem parameters. Types of backscatter mechanisms used in lidar measurements include Rayleigh scattering, Mie scattering, fluorescence, and Raman scattering.

The backscatter lidar is the simplest and most widely used atmospheric lidar. It involves a laser transmitter, an atmospheric medium that backscatters the laser radiation, and a light collection and detection system. Backscatter lidar systems have been used since 1960's and they have proven to excellent tools for the detection of clouds and aerosol layers, and for obtaining atmospheric structural information via backscatter profiling. Lidar systems have been operated from ground, airborne, and space-based platforms. Space-based atmospheric backscatter lidars have used Nd:YAG laser transmitters and already provided global scale aerosol and cloud profiles from LITE and GLAS systems, and NASA is in the process of launching CALIPSO that will carry a backscatter lidar.

Standard backscatter lidars are commonly used to derive aerosol backscatter and extinction profiles. However, a standard backscatter lidar actually measures *attenuated backscatter*: i.e., the product of the backscatter and the two-way transmission of the atmospheric volume between the lidar and the backscatter volume in question. In standard backscatter lidar systems, the retrieval of both aerosol extinction and backscatter relies on an assumption of their ratio, *S*. Error in the assumed or derived value of *S* leads to errors in both the backscatter and extinction profiles.

3.3.1 Cloud and Aerosol Scenarios

Scenario NRC-03 describes an advanced backscatter lidar system called the High Spectral Resolution Lidar (HSRL) that takes advantage of the spectral distribution of the lidar return signal to discriminate aerosol returns from molecular returns and thereby measure aerosol extinction and backscatter independently. Not only is there no reliance on an assumed value of S (called the lidar ratio, the ratio of extinction to backscatter), the techniques offer a measurement of S itself – a valuable measurement in its own right. HSRL systems will be needed to derive many of the aerosol properties needed in estimating aerosol radiative forcing for climate studies.

The HSRL transmitter is an injection-seeded Nd:YAG laser that is frequency doubled to transmit at the principal wavelength of 1064 nm and doubled 532 nm. Spectrally resolved signals are derived from the 532 nm channel. The bandwidth of the 532 nm pulses is less than 100 MHz. The spectral properties of the lidar backscatter depend upon the type of scatterer. Lidar backscatter from air molecules is Doppler (Rayleigh) broadened by a few GHz due to the high-velocity random thermal motion of the molecules. The Doppler broadening of backscatter from aerosols is only of the order of a few tens of MHz, however, due to the fact that aerosol particles are much heavier and the velocities of their random thermal motions are significantly lower. Discrimination between aerosol and molecular returns in the receiver is accomplished by splitting the returned signal into two optical channels: one with an extremely narrow-band iodine vapor (I2) absorption filter to eliminate the aerosol returns (the molecular channel) yet passing the wings of the molecular spectrum, and another that passes all frequencies of the returned signal (the total scatter channel). Note that the iodine filter does not require any new technology development. After calibration, the signals are used to derive profiles of extinction, backscatter, and extinction-to-backscatter ratio. Measurements in the UV, visible, and IR wavelengths are needed to derive a host of aerosol properties, including the aerosol bulk properties: optical depth, extinction profile, backscatter profile, and aerosol depolarization (using a polarization sensitive channel); and aerosol microphysical properties: single scattering albedo, refractive index, aerosol size distribution (mode size). The retrieval of aerosol microphysical properties requires complex retrieval algorithms. (T)

The Lidar Working Group considered Scenario 2300-09 (“High Spectral Resolution Lidar”) and believes that it is not necessary to add it to ESTIPS as a separate record because it is adequately represented by Scenario NRC-03, which is very similar but much more comprehensive and detailed.

Scenario LWG-AC-1 measures cloud and aerosol properties using a backscatter lidar with multiple wavelengths and depolarization, having multiple fields of view for cross-track coverage, from low Earth orbit. Multiple transmit and/or receive beams are used to provide cross-track measurements +- 100 to 500 km of nadir track. The instrument has 5 to 10 CALIPSO-like fixed beams which require a corresponding increase in power and/or efficiency requirements. The telescope for this instrument is challenging. It requires a 1 to 2 meter aperture with +/- 30 degree field of view. The individual potential beams will have a much smaller instantaneous field of view. The instrument has a minimum of two wavelength bands in the UV (350 nm) to near-IR (1064 nm) range, with depolarization capability on at least one of the wavelengths. This sensor will be able to detect aerosol layers with enhancements of aerosol scattering >20% above the molecular level, measure total aerosol optical depth to better than 10% (or 0.1 whichever is greater), cloud top height, and aerosol/cloud depolarization of 2-5%. The along track resolution for these measurements will be 5 km with a vertical resolution of 100 m. Measurements at the two wavelengths will be used to obtain a coarse assessment of particle size distribution. The sensor will provide global coverage with a revisit time of 1 week. (E)

Scenario LWG-AC-2 measures cloud and aerosol properties using a backscatter lidar with multiple wavelengths and depolarization from low Earth orbit. The instrument has a minimum of two wavelength bands in the UV (350 nm) to near-IR (1064 nm) range, with depolarization capability on at least one of the wavelengths. This sensor will be able to detect aerosol layers with enhancements of aerosol scattering >20% above the molecular level, measure total aerosol optical depth to better than 10% (or 0.1 whichever is greater), cloud top height, and aerosol/cloud depolarization of 2-5%. The along track resolution for these measurements will be 5 km with a vertical resolution of 100 m. Measurements at the two wavelengths will be used to obtain a coarse assessment of particle size distribution. The sensor will provide global coverage with a revisit time of 1 week. (E)

Scenario 180 is an airborne multi-wavelength backscatter lidar for cloud/aerosol studies.
This sensor option uses at least two wavelengths: UV (350 nm) to near-IR (1064 nm), with depolarization capability. This sensor system will provide fine scale structure of tropospheric clouds. It measures cloud top heights (and bottoms for optically thin clouds) with a vertical resolution of 30 m and horizontal resolution of 200 m. Depolarization will be measured with an accuracy of 5%. The two wavelength lidar can be used to distinguish between fine (<1 micron) and coarse particle distributions in aerosol layers. (E)

The Lidar Working Group considered Scenario NRC-06 ("Climate-quality Observations from Satellite Lidar") and believes that it is not necessary to add it to ESTIPS as a separate record because it is adequately represented by Scenario 180, which is very similar.

Scenario 116 is a 2-wavelength (532 nm and 1064 nm) polarization-sensitive lidar that provides high resolution vertical profiles of aerosols and clouds. The transmitter is a laser which is doubled to provide simultaneous output pulses at the two wavelengths. Instrument has radiometric and polarimetric capability. The instrument is capable of measuring tropospheric and stratospheric aerosol scattering ratio and wavelength dependence; planetary boundary layer height, structure, and optical depth; stratospheric density and temperature; and cloud vertical distribution, multilayer structure, fractional cover and optical depth. Parameters: Lidar type Nd:YAG, diode-pumped, Q-switched, frequency-doubled Repetition rate 20 Hz Telescope aperture 1.0 m Horizontal/vertical resolution 333 m/30 m. (G)

The Lidar Working Group recommends that Scenario 114 be deleted from the ESTIPS database because of its similarity with Scenario 116.

Scenario 182 characterizes cloud formation and evolution by performing airborne profiling of water vapor, aerosol extinction, extinction to backscatter ratio, aerosol depolarization, and cloud optical depth. This sensor option is a compact, autonomous, airborne UV Raman lidar with multi-channel detection system for discrimination of aerosol/cloud depolarization signatures and water vapor Raman signals. Wavebands include 355 nm Rayleigh Mie and depolarization, 387 nm Raman nitrogen, 403 nm Raman liquid water, and 407 nm Raman water vapor. This system will provide profiles of water vapor in the troposphere with an accuracy of 10% and resolution of 0.2-0.5 km in the vertical and 30 km in the horizontal. It will provide simultaneous profiles of aerosol distributions to detect layers of aerosols and clouds (including cirrus) with scattering above 10% of the molecular level with a high resolution of 50 m (vertical) and 1 km (horizontal). Aerosol depolarization will be measured with an accuracy of 5% and aerosol optical depth to an accuracy of 0.1. Maximum cloud liquid water content to 1 gm-3 and particle radius in the range 3-40 microns can be derived. The sensor will provide day/night coverage. The UAV will be able to fly in the altitude range of 10-20 km and monitor the development of storm (or hurricane) over a 1-2 day period continuously (enhancing platform requirement). (E)

The Lidar Working Group recommends that Scenarios 178 and 183 be deleted from the ESTIPS database because of their similarity with Scenario 182.

3.3.2 Ocean and Ice Scenarios

Scenario 99 directly measures sea ice thickness using a lidar profiler in low Earth orbit. Laser radiation penetrates the bulk ice to profile its depth by detection of the water/ice interface. This sensor option probes sea-ice at a wavelength in the optimum transmission region (530-550 nm). Time- and spatially-resolved measurement of the volumetric subsurface backscatter aureole locates the water/ice interface and provides a direct measurement of ice thickness. Implementation of this measurement scenario will have to overcome difficulties associated with interference and losses caused by atmospheric aerosols and snow covering the sea ice. Successful observations should yield information on aerosol and snow amounts and properties, in addition to sea ice thickness. Observations could be combined with microwave or other sea ice thickness observations for enhanced accuracy. (P)

Scenario 17 uses green (520-532 nm) pulsed laser to stimulate the broadband (520-800 nm) backscatter emission integrated over the upper ocean layer measured with a hyperspectral sensor. Spectral deconvolution of the overlapped constituent fluorescence bands and water Raman scattering allows accurate assessment of chlorophyll and phycobiliprotein pigment biomass and CDOM content. Spectral analysis of pigment fluorescence provides for basic characterization of phytoplankton functional types. The pump-and-probe dual pulse laser operation is used for measurements of variable fluorescence to assess phytoplankton photo-physiological status. The hyperspectral sensor also provides retrievals of natural (solar-induced) fluorescence band (650-750 nm) via spectral deconvolution of "ocean color" passively measured between the laser shots. An optional wide-looking imaging camera provides large-scale mapping of natural fluorescence. (G)

Scenario 27 uses a lidar in low Earth orbit to estimate particulate carbon and particle abundance vertically in the ocean (actually measuring particulate backscatter via particulate scattering coefficient) to get at phytoplankton carbon, POC, PIC, suspended sediments, including in near-shore waters. The lidar should be coupled with a passive radiometer to measure particle species. The lidar resolves absorbing aerosol heights to 0.5 km from surface to stratosphere. Height resolution from stratosphere to top-of-atmosphere must be greater than 1 km. Particle lidar requires vertical resolution of 1 – 3 m and retrieved signal from multiple depth bins below the surface (min = 3) for blue water conditions (chl = 0.02-10 ug/L) ; penetration to no less than 5m (coastal) to 15 m (open ocean). (G)

The Lidar Working Group considered Scenario NRC-09 ("The Ocean Carbon, Ecosystem and Near-Shore (OCEANS) Mission Concept") and believes that it is not necessary to add it to ESTIPS as a separate record because it is adequately represented by Scenario 27, which is very similar.

Scenario 42 measures ocean mixed layer depth using a lidar in Earth orbit. This sensor option images lidar backscatter in order to resolve the spatial dynamics imposed on an incident laser beam profile by the turbulent processes that characterize the ocean mixing layer. Time gating of the return should be employed to achieve 5-m depth resolution or better. Concept is still under development and theoretical modeling is still being undertaken. Eye safety and SNR issues will likely preclude this instrument from satellite operation in a 5-10 year time frame. Aircraft deployment is more feasible in this time frame. (G)

3.3.3Temperature Scenarios

Scenario 69 is a direct detection lidar which uses Rayleigh scattering from the atmosphere in UV to measure temperature profile. The spectral width of the Rayleigh scattering from the air molecules is directly proportional to atmospheric temperature. Temperature profiles are derived from spectrally resolved line shape of the molecular backscatter using high resolution optical filters. This scenario uses a UV laser in order to achieve maximal Rayleigh response; retrievals complicated in the presence of aerosols, especially in boundary layer. Lidar temperature measurement would need to have accuracy and spatial resolution better than existing passive techniques (e.g., AIRS). (G)

3.4 Differential Absorption Lidar (DIAL)

The differential absorption technique is used to determine the concentration of a chemical compound in the atmosphere. When light hits a target, some of the energy is absorbed and some of the energy is reflected or scattered. The amount of energy absorbed by a molecule varies by wavelength. So, by transmitting two frequency stable narrow linewidth beams and measuring the difference in intensity of the returned signals, it is possible to determine the atmospheric concentration of a particular chemical.

3.4.1 Atmospheric Water Vapor, Temperature, Cloud and Aerosol Scenarios

Scenario NRC-01 is a DIAL in a 450 km altitude Earth orbit that makes high vertical resolution measurements of atmospheric water vapor, aerosols and clouds along the satellite ground track. The DIAL is intended to be co-located with a passive Fourier transform spectrometer for three-dimensional water vapor and temperature coverage. The instrument uses a 500 mJ laser at 5 Hz double-pulsed PRF. A 3 m aperture is required in the receiver telescope. Optical transmission is 50% and quantum efficiency is 40%. The filter has a 0.2 Angstrom bandwidth at night and 0.1 Angstrom bandwidth during day. The receiver has a 1.3E-4 radian FOV. (E)

The Lidar Working Group recommends that Scenario 71 be deleted from the ESTIPS database because of its similarity with Scenario NRC-01.

Scenario 72 measures atmospheric water vapor and temperature using an IR-UV backscatter lidar in low Earth orbit. This sensor option is a differential absorption lidar (DIAL) which uses laser backscatter in the H2O absorption line (940 nm) to measure atmospheric water vapor and the oxygen A band (760 nm) to measure temperature profile. This instrument uses nonlinear conversion techniques (harmonic generation, mixing, optical parametric oscillation) to generate widely tunable coherent radiation from discrete pump sources. This system will provide tropospheric profiles of atmospheric temperature with an accuracy of <1K and resolution of 50 km (horizontal) and 0.5 km (vertical) in the troposphere. It will provide profiles of water vapor in the troposphere with an accuracy of 10% and resolution of 0.5-1 km in the vertical and 50 km in the horizontal. The sensor will provide global day/night coverage and a nominal revisit time 1-2 weeks. The sensor will be configured to achieve targeted sampling (by changing pointing direction) to focus on events of interest like hurricanes or severe storms. (E)

The Lidar Working Group recommends that Scenario 118 be deleted from the ESTIPS database because of its similarity with Scenario 72.

The Lidar Working Group considered Scenario NRC-12 ("MATH: Monitoring Atmospheric Turbulence and Humidity") and believes that it is not necessary to add it to ESTIPS as a separate record because the specific technologies defined in this scenario are already covered by Scenarios NRC-01 and 72.

Scenario 70 measures atmospheric temperature and stratospheric aerosol profiles using an IR backscatter lidar in low Earth orbit. This sensor option is a differential absorption lidar (DIAL) which uses laser backscatter in the oxygen A-band (760 nm) to measure temperature and stratospheric aerosol profiles. The oxygen A-band transition is sensitive to both temperature and pressure and provides a surrogate for these thermodynamical properties throughout the atmospheric column. Differential attenuation of the lidar signal is dependent on the pressure modulated linewidth of the A-band transition. The instrument transmits in one IR band. This system will provide tropospheric profiles of atmospheric temperature with an accuracy of <1K and resolution of 50 km (horizontal) and 0.5 km (vertical) in the troposphere. It will provide information about the distribution aerosol layers in the stratosphere including the polar stratospheric clouds with a vertical resolution of 200 m, along the track resolution of 10 km, and a sensitivity of aerosol scattering of 0.2 above the molecular background level. It will also measure total aerosol optical depth to better than 10% (or 0.1 whichever is greater). Multiple sensors will be deployed to provide global coverage and a revisit time of 3 hrs to 1 day. (E)

Scenario 81 measures aerosols and water content in and around storm cells using an airborne lidar. Payload is mounted on a UAV. This sensor option is a differential absorption lidar (DIAL) which measures aerosols, H2O, and clouds in and around storm cells by laser backscatter from the atmosphere. Instrument is tunable across H2O line. This instrument is not capable of measuring wind because the H2O line is between the two frequencies used for wind measurement. A separate instrument or hybrid concept must be used to satisfy the wind structure part of the science requirement for storm cell properties. The instrument operates in one IR band. This system will provide profiles of water vapor in the troposphere with an accuracy of 10% and resolution of 0.2-0.5 km in the vertical and 10 km in the horizontal. It will provide simultaneous profiles of aerosol distributions to detect layers of aerosols and clouds (including cirrus) with scattering above 10% of the molecular level with a high resolution of 50 m (vertical) and 1 km (horizontal). The sensor will provide day/night coverage. The UAV will be able to fly in the altitude range of 10-20 km and monitor the development of storm (or hurricane) over a 1-2 day period continuously (enhancing platform requirement). (E)

The Lidar Working Group considered Scenario 2300-54 ("Active Atmospheric Lidar Sounder") and believes that it should not be added to ESTIPS because the scenario lacks detail and the technology does not seem to be applicable to atmospheric composition.

3.4.2 Tropospheric Ozone Scenarios

Scenario 181 makes range resolved measurements of tropospheric ozone using a UV DIAL system from a high altitude drone. This sensor option measures tropospheric pollution, ozone and trace gases and their impact on global climate change. This system makes range resolved measurements of tropospheric ozone along the aircraft's flight track. Capabilities include wavelengths adjustable from 290-330 nm, repetition rate to 1000 Hz, vertical resolution better than 150 meters. Horizontal resolution depends on aircraft but is on the order of a km. Instrument uses four wavelengths: 2 UV, 1 visible and 1 NIR. (T)

Scenario 185 makes height resolved measurements of tropospheric ozone using an IR occultation technique from low Earth orbit. The IR differential absorption lidar is located on the International Space Station. The instrument uses small, inexpensive retro-reflectors in polar orbit. This is essentially an "active limb sounding" implementation which would benefit from the use of as many retro-reflectors as can be deployed. Sensor will measure tropospheric ozone and pollution and their impact on global climate change. Capabilities include O3 vertical resolution to 250 meters, horizontal resolution ~200 km, direct detection, 100 Hz. Laser operates at 9.5 microns. (T)

Scenario 113 makes height-resolved measurements of tropospheric ozone using a UV DIAL in a highly inclined low altitude orbit. High inclination orbit is needed to provide coverage of the mid-latitudes. Low altitude orbit is needed to accommodate range-squared signal loss of UV-DIAL system and UV signal attenuation through the stratospheric O3 layer. This sensor option measures tropospheric pollution, ozone, and trace gases and their impact on global climate change. The UV Dial system will make height-resolved measurements of tropospheric ozone along a thin line associated with the ground track of the satellite. Instrument parameters: 308/320 nm @ 10Hz; O3 vertical resolution 2.0-2.5 km in troposphere; horizontal resolution 100 km; IFOV < 100 m; aerosols @ a visible/NIR wavelength (TBR by laser approach), 4 bands UV. (T)

The Lidar Working Group recommends that Scenario 117 be deleted from the ESTIPS database because of its similarity with Scenario 113.

3.4.3 CO2 Scenarios

Scenario NRC-02 combines a continuous wave laser instrument operating in the 1.57 micron region for column measurements of CO2 down to the surface or cloud tops and a pulsed aerosol and cloud lidar to determine surface elevation and aerosol and cloud distributions along line-of-sight of the CO2 laser instrument. The CW laser uses fiber laser technology from the communications industry to produce several simultaneous laser wavelengths across a CO2 absorption line to provide total column absorption of CO2 at line center and a weighted column absorption in the lower troposphere on the side of the line. Due to the small laser footprint and concentrated laser intensity, CO2 measurements can be made to the surface between clouds and to cloud tops in the day or night. The proposed pulsed aerosol and cloud lidar would be similar to the European Space Agency's Atmospheric Lidar. (G)

NRC-04 is a space-based direct detection lidar/altimeter similar to the ICESat GLAS instrument. The lidar measures the global distribution of CO2 mixing ratio in the lower troposphere, day and night. The laser sounder is nadir pointing in a polar orbit. Laser transmitters for CO2 and O2 are rapidly turned on an off the gas absorption lines near 1570 nm and 768 nm respectively. The sounder uses a third wavelength (1060 or 1550 nm) to simultaneously profile the aerosol backscatter in the same measurement path. The laser sounder technique uses tunable very narrow (MHz) linewidth lasers, sensitive photon counting detectors, and has much higher spectral resolutions and precisions than are possible with passive spectrometers. The instrument operates in a 500 km polar sun-synchronous dawn-dusk orbit. Individual measurements are made at KHz rates, averaged to 1 and 10 seconds. The instrument is estimated to be 1.5x1.5x1.5 m in size, have a mass of 300 kg, and use about 700 W of power. (G)

The Lidar Working Group recommends that Scenario 184 be deleted from the ESTIPS database because of its similarity with Scenario NRC-04.

Scenario 24 provides lower tropospheric CO2 mixing ratio profiling using standard range-gated direct detection DIAL approach, possibly using double-pulse 2-micron laser transmitter currently under development. Laser operates in one wavelength in the IR. High PRF transmitter will be necessary in order to approach the precision/grid scale requirement. Telescope aperture is 300 cm. This sensor system will provide tropospheric profiles of atmospheric CO2 with an accuracy of <0.5% and resolution of 100-300 km (horizontal) and 1-3 km (vertical) in the troposphere. This pulsed laser system will provide distinct CO2 layering information with a clear delineation of the boundary layer. It will be relatively free from aerosol and cloud influences provide a straight forward inversion of CO2 profiles. Simultaneous aerosol distribution information will be available with a vertical resolution of 100 m and horizontal resolution of 10 km. No additional surface range measurements are required. The sensor will provide global day/night coverage with a revisit time of 2 weeks. (E)

Scenario 179 is for determining CO2 fluxes in lower 5 km with precision of 1 ppm in 10 minutes. This scenario can utilize either fiber lasers or OPO pumped by Nd:YAG. Boundary layer aerosols provide signal returns. High average power and high SNR required. Target accuracy for system is 1 ppm with 300 m vertical resolution and temporal resolution of 1 hour. Minimally functional system would provide adequate data under conditions of relatively high aerosol loading. Enhanced system could detect Rayleigh as well aerosol backscatter, enabling operation under a wider range of atmospheric conditions. Laser operates in 2 bands, on line and off line, IR, near 1.6 microns. (G)

Scenario 23 conducts high-precision boundary layer CO2 mixing ratio profilometry via integrated path differential absorption (IPDA) by using a laser absorption spectrometer in low Earth orbit. This sensor option is for determining distribution of CO2 abundance in the lowermost 5 km of the troposphere with measurement precision of 1-2 ppm CO2 on a grid no coarser than 100x100km. The IPDA approach utilizes a laser transmitter frequency offset from the line-center of a CO2 absorption feature, along with a separate transmitter frequency in the "window region" between lines, to measure differential absorptance. Surface backscatter provides the return signal and off-line-center tuning is used to "weight" the response of the instrument to various altitudes, permitting mixing ratio profile determination with a vertical resolution of 1-2 km. High CW powers (2-5 W) and high SNR are required in order to approach the precision/grid scale requirement. Telescope aperture is 75 cm and is near-nadir pointing. The transmitter operates in two IR bands. (G)

3.5 Other Lidars

Gravity field mapping is one of the key measurements required in order to understand the solid earth, ice and oceans, and dynamic processes in a comprehensive model of our planet. Such a model is critical not only in our ability to study climate and forecast weather but also in our ability to monitor global resources and to understand the solid earth structure. There have been a number of gravity measurement missions such as CHAMP and GRACE. These missions use satellites themselves as test masses and measure the gravity through the precise monitoring of the motion of the satellites. Other gravity missions using mechanical gravity gradiometers such as GOCE have also been planned or are under study. The recent advent of laser cooling and laser manipulation of atoms has led to an entirely new class of gravity sensors: quantum gravity gradiometer (QGG) based on atom-wave interferometry. Unlike any previously described gravity sensors, the quantum gravity gradiometer uses atoms themselves as drag-free test masses. At the same time, the quantum wave-like nature of atoms is utilized to carry out interferometric measurement of the effect of gravity on atoms. The exquisite sensitivity potentially achievable with atom-wave interferometry holds a great promise for new gravity mapping and monitoring capabilities — higher measurement sensitivity, finer spatial resolution, and the capability for temporal monitoring.

A gravity gradiometer is a fundamental device for characterizing gravitational fields by measuring the acceleration difference between proof masses at a fixed distance. It can independently determine the global gravitational field on a moving platform such as a spacecraft. The successful development of this new technology will enable unprecedented Earth observation measurement capabilities and will bring a breakthrough, ultra-sensitive gravity gradiometer to usher in a new era beyond the current GRACE capability, for precision gravity mapping at global as well as regional scales. The new capability will allow detailed study of lithographic thickness and composition, lateral mantle density heterogeneity, and translational oscillation between core and mantle. The study of sub-surface dynamics with the sensitivity of this instrument will particularly impact volcanology and seismology, allowing, for the first time, a detailed mapping of temporal changes over the time intervals of scientific interest (e.g. from hours to years). Study of the dynamics of ice mass variations, ground water storage, and ocean tidal variations will also be revolutionized with the unprecedented sensitivity of this technique.

The instrument will make new and fundamental contributions to our understanding by continued monitoring at a high spatial and temporal resolution measurements of the time-dependent changes in the geoid that have important implications for oceanography, hydrology, and glaciology. Finally, this approach makes it possible to examine the validity of current models of the solid and fluid Earth at an unprecedented level, and help create new and effective models with accurate predictive capability.

The Quantum Gravity Gradiometer (Scenario 57) will consist of two interferometers separated by a distance in a range similar to the case of GRACE. The two interferometers measure the accelerations at this separation distance, resulting in a value for the gravity gradient. Such a configuration has been recently used in the laboratory to measure the gradient at the 1% level with only a 1 m separation between the interferometers. The two acceleration measurements are performed simultaneously and by using the same laser systems, so that the common-mode noise and uncertainties are effectively cancelled out. This laboratory measurement, impressive at this sensitivity level, was limited by the signal to noise ratio due to the number of atoms, and can be improved further. Since the sensitivity scales with the square of the time between successive pulses, and the low gravity environment of space allows interrogation times of 10 s or longer, it is easy to see how an improvement can be obtained in space even at the loss of the number of atoms due to the finite thermal expansion of the atom cloud. Assuming one employs the free-space Raman cooling with 106 detectable atoms after 20 second, one can estimate the expected differential acceleration measurement sensitivity in a flight experiment with 20 s interrogation time to be <4x10-13g/□Hz, which results in a gravity gradient sensitivity < 4x10-4 E/□Hz (gravity gradient unit 1 E =10-9 s-2.) with the baseline separation of 10 m. This number scales linearly with the baseline, yielding an impressive sensitivity at sub-micro E level, if the two spacecraft carrying each interferometer are separated by 100 km. (G)

3.6 Relationship of the Measurement Scenarios to the Science Focus Areas

A summary of which measurement scenarios support which science focus areas is presented in Table 3-2. It is clear from this table that advanced lidar remote sensing techniques can make significant and wide-ranging contributions to the Earth science goals of NASA. The technologies required to develop implement these measurement scenarios are discussed in detail in the next chapter.

Table 3-2: Mapping from Measurement Scenarios to Science Focus Areas

Scenario Description	ID	Atmospheric Composition	Carbon & Ecosystems	Climate	Earth Surface & Interior	Water & Energy	Weather
Ranging and Altimetry							
Advanced Ice Cloud and Land Elevation Lidar	NRC-14	X	X	X	X	X	X
Biomass Monitoring Lidar	NRC-11	X	X	X	X	X	X
Earth-Moon Laser Altimeter	NRC-07		X		X		
Ice and Land Topography Lidar	48, 149, 150	X	X	X	X	X	X
Inter-spacecraft Gravity Gradiometer	56				X		
Laser Ranging Network	52				X		
Narrow Swath Orbital Imager	LWG-OT-1			X	X	X	
Photon-counting, Imaging Lidar	186			X	X	X	
UAV High Resolution Imager	LWG-OT-2		X	X		X	
Waveform Recording, Multi-beam Lidar	187	X	X	X	X	X	X
Wide Swath Imaging Laser Altimeter	188	X	X	X	X	X	X
Doppler							
Doppler, 400 km, Demo Mission, 100% duty cycle	LWG-AD-SP1						X
Doppler, 400 km, Threshold 3-yr Mission, w/adaptive targeting	LWG-AD-SP3						X
Doppler, 833 km, Demo Mission, w/adaptive targeting	LWG-AD-SP2						X
Doppler, Airborne, Scanning	LWG-AD-AIR1						X
Backscatter							
Backscatter Lidar	180	X					X
Cloud and Aerosol Lidar	116	X					X
Cross-track Backscatter Lidar	LWG-AC-1	X					X
Direct Sea Ice Thickness Lidar	99			X			
Fluorescence Lidar Active-Passive Suite (FLAPS)	17		X	X			
Aerosol Global Interactions Lidar	NRC-03	X					
Ocean Particle and Aerosol Lidar (OPAL)	27	X	X	X			
Ocean Mixed Layer Depth Lidar	42		X	X			
Raman Lidar	182	X				X	X
Spaceborne Backscatter Lidar	LWG-AC-2	X					X
UV Temperature	69						X
DIAL							
Active Mission for Global CO2 Lidar	NRC-02	X	X				X
CAPES DIAL	NRC-01	X				X	X

CO2 Dial	24	X	X				
Differential Absorption Lidar	179	X	X				
Differential absorption lidar	181	X					
IR Differential	185	X					
Absorption Lidar IR-DIAL Temperature	70	X					X
IR-DIAL Temperature and Water Vapor	72					X	X
Laser Absorption Spectrometer (LAS)	23	X	X				
Orbital Laser Sounder for Global CO2	NRC-04	X	X				X
Storm Cell DIAL	81						X
UV DIAL	113	X					
Other							
Quantum Gravity Gradiometer	57				X		

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4. Data ATA Acquisition and Utilization Concepts

4.1 Introduction

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. For a more complete assessment of information technology drivers, the working group considered how the lidar measurement, i.e. data, would be managed and used, as well as how it would be acquired. During the laser measurement science goal assessment, participants addressed requirements and constraints for 1) acquiring measurements (e.g. onboard processing), 2) producing data (e.g. algorithms, analysis, model input) and 3) supporting user applications (e.g., weather forecasting, climate modeling, earthquake warning, etc.).

Data acquisition includes those mission elements that contribute to the data collection and delivery to the science data processing system. This includes space segment elements such as the spacecraft, sensor(s), communication and control sub-systems, onboard data management (e.g. buffering, storage, processing), and data downlink. Also included are the ground segment components for mission planning and operations, orbit determination, and communications.

Data utilization elements start with the collected raw sensor data (bits), transform these into useful data products (e.g. analysis and model results), distribute these products to users and archive the data. Mission data processing may involve both the generation of traditional NASA science data products and the more recent techniques of data assimilation into models. Data distribution includes access to both new and archived data.

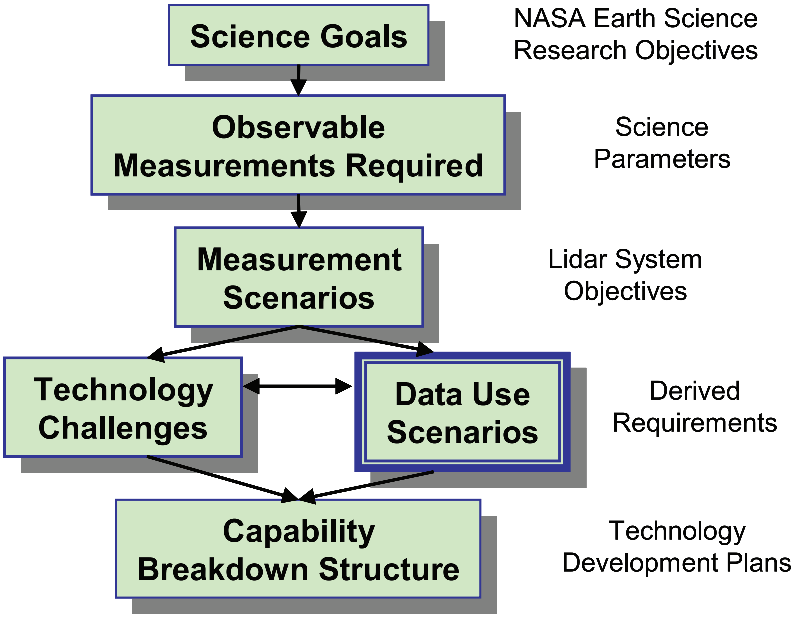

Figure 4-1: Data Use Scenario Context

Combining the technology challenges with data use scenarios, as seen in Figure 4-1, helps make requirements, assumptions, and constraints explicit as well as identifying needed system functionality. Representative data use scenarios have been developed to describe how a future lidar mission would operate and describe the role of supporting data and operations. Each scenario describes the flow of data capture, identifies interfaces with instruments and associated technology, and specifies the resulting data and products. Hence information technology challenges were derived from representative lidar measurement scenarios, which in turn contributed to the data utilization concepts depicted in the use scenarios. The data use scenarios help quantify technology requirements for typical uses of the lidar measurements, narrowing the system trade space for selected mission concepts. 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.

The team excluded some technologies 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.

An assessment of the lidar measurement scenarios resulted in a set of potential information technology drivers listed below:

- Real-time data products (e.g., weather application)
- Conservation of resources (e.g., limited laser life-time)
- Automated health & safety (e.g., sense laser thermal, material or tuning degradation and respond before failure)
- Precise spacecraft location e.g.,
  - For ocean surface height or
  - For laser ranging (spacecraft crosslinks)
- Coordinated instrument operations “adaptive targeting” e.g.,
  - Detection of event activates coincident precision laser measurement or
  - Event acts as a trigger that identifies desired target for precision laser observation
- Cal/Val error bar management (e.g., how to accurately validate high precision winds measurement)
- Model ingest strategy (e.g., map high precision measurements to grid)
- Data quality strategy (e.g., for decision support systems)
- Data volumes / data rates / data storage (e.g., imagers)

The team also evaluated data processing lessons learned from recent experience with laser instruments, IceSat’s GLAS and CALIPSO, and from the Wind Lidar OSSE (Observing System Simulation Experiments). IceSat GLAS laser altimeter was launched in December 2002; 2 of 3 flight laser transmitters have failed but limited data sets are available. The CALIPSO lidar was recently launched in April 2006. Findings relate to steps taken in preparing for science operations and data processing. Several Wind Lidar OSSE’s have been run to specify the sensor requirements. By simulating the collection and rapid handling of the new wind profile measurements from spacecraft to weather forecast system, detailed sensor specifications are now well understood. Most of the findings are related to system engineering. However, the focus here is to consider the technology that can enhance the mission data collection and processing. The findings are summarized in the following list:

- Laser orbit and pointing requirements are very challenging
- Plan for near real time products in future (e.g. atmosphere / sea ice boundaries)
- Plan for reconfigurable on-board processing (anticipate changes in instrument performance, e.g. degradation of optics, laser efficiency)
- On-board processing (e.g., for cloud detection) would have significantly improved the value of real time quick look data
- On-board storage capacity to include look-up tables, and digital elevation maps would enable classification capabilities to improve ancillary data
- Science software framework (i.e. open systems, reuse) would enable intelligent reprocessing, automation, and development of user supplied processing tools

Another consideration is ancillary data needed for processing. Use of lidar data products often is dependent upon or coupled with collecting other measurements. This may require ancillary instruments to be flown on the same or other instrument platforms. If flown on the same platform, the data processing on-board as well as the downlink capacity required is affected. In both cases, the data must be coordinated for modeling and assimilation. Table 4-1 provides a description of these ancillary data needs.

A key driver for on-board processing is data latency. The goal is to downlink data within 3 hours of capture as well as to process the data within 3 hours of reception for use in weather forecasting. The data processing would need to support a variety of algorithms, such as averaging, arranging data on regular grids, rejection or inclusion of clouds in the data, pattern recognition, layer height determination and type determination for aerosols, and orbit propagator for geolocation.

Table 4-1: Ancillary Data Needs

Measurement scenario	Lidar type	Other data needed	Ancillary instrument	Combined data product	Data rate	Lidar-ancillary instrument requirements
Atmospheric water vapor	IR DIAL	temperature	FTS radar	Numerical Weather Prediction, accurate hurricane track	low	similar data capture timeliness & location & accuracy
Winds	DWL	pointing knowledge	star trackers, GPS	vertical profiles of tropospheric horizontal vector winds		optical connection of DWL and star trackers; DWL nadir viewing, star trackers zenith viewing
Topography	scanning laser altimeter	location	GPS	surface topography and biomass		same or other platform?
Carbon dioxide	IPDA	temperature profile altimetry	FTIR	tropospheric CO2	low low	ground based validation & calibration

About forty lidar measurement scenarios were analyzed for categorization into representative mission concepts across the earth science domains:

- Atmospheric Dynamics/Modeling & Assimilation - Winds Lidar
- Carbon Dioxide IR-IPDA
- Aerosols / Water Vapor / Clouds - Water Vapor DIAL
- Vegetation Canopy / Surface Topography - Wide Swath Land Imager
- Ocean Topography / Mixed Layer Depth
- Gravity Fields (only 2)

The representative set was needed to address both data acquisition and data utilization aspects. By focusing on a mission concept within the data use scenario, the team could narrow the trade space for information technology (i.e. the trade off between competing approaches to achieving the mission objectives exemplified by the traditional trade off between data volume and data communications capacity). The data use cases were selected to highlight anticipated drivers. The resulting technology capability breakdown structure is applicable to multiple measurement scenarios.

The data use scenarios provided here are representative of lidar missions that may be possible in the next 15 years. Developing data use scenarios 1) identifies stakeholders in the mission (e.g. the atmospheric scientists, technologists, forecasters), 2) provides traceability from science goals through technologies used to acquire data, and on to final data products and dissemination, 3) makes explicit the assumptions about expected technology improvements as well as required and desired capabilities, and 4) helps identify requirements that drive technology improvements and mission approaches.

A data use scenario is presented for each of the science subgroups:

- Atmospheric dynamics: winds
- Atmospheric composition: water vapor
- Oceans and topography: wide swath land imaging

In addition, a data use scenario that presents a challenge to on-board processing capabilities has also been developed:
- Atmospheric components: carbon dioxide

In the next section summaries of the data use scenarios are given. For detailed descriptions of the data use scenarios, please refer to Appendix 4.

4.2 Data Use Scenarios

In this section, each of the four use cases is summarized and key considerations and technology drivers are highlighted.

Winds Lidar (incorporating modeling and assimilation)

Atmospheric wind field data, acquired by a global tropospheric wind lidar, would provide the needed coverage, accuracy and resolution of wind velocity, a critical input for significant improvements in numerical weather prediction. Two scenarios are anticipated for future observing system, a survey mode and either autonomous or on-demand targeting modes.

In the survey example, a lidar operates independently on a regular schedule to collect observations, store on board and downlink to the ground, where it is processed to level 2 and distributed to NOAA forecasters. The operational data assimilation cycle would execute at the standard synoptic times: 0:00, 6:00, 12:00, and 18:00 Greenwich Mean Time (GMT). Rapid product turnaround is critical for operations, the data assimilation would have to execute within 3-4 hours of each synoptic time. Hence the 0:00 GMT analysis would require all data collected at that observation time to be processed, quality-controlled, and made available to the data assimilation system by 3:00 GMT. The subsequent forecast would then be launched such that the public products would be made available.

It is highly desirable for next-generation operational forecast systems to possess two-way interaction between the model/data assimilation system and the observing system, and to also provide the ability for a scientist or domain expert to manually task the observing system assets to maximize sampling of a particular feature of interest. In the adaptive targeting mode, the data assimilation system would identify an optimal observation suite and autonomously task the observing system to collect data at specific locations in space and time. The goal of autonomous targeting is to check the error growth in the model such that its predictive skill may be improved. Typically errors occur in “sensitive regions” of the atmosphere that are devoid of data, where there are sharp gradients in the air flow, in baroclinic boundary regions, or other areas that are now topics of research. Investigations have shown that the model error in such areas grows non-linearly over time and propagates with the air flow. Targeting the observing system to collect data in these locations may help to diminish the error. Autonomous targeting would also be useful to track specific features of interest, such as hurricanes, or to provide better measurements over areas in which there are large departures between observations and the model’s first guess.

Technology Highlights:

- Data downlinks <3 hrs for input to weather forecast models
- Quality control detects errors w/out manual intervention
- Model-driven (on demand) adaptive targeting
- Intelligent scheduling/goal-oriented commanding
- Generate L2 wind vector products (within minutes)
- Operational data assimilation executes <3 hrs

Water Vapor DIAL

Weather forecasters use their knowledge of atmospheric water vapor fields to predict the ground tracks of hurricanes and other tropical disturbances. They rely on this knowledge to issue timely and accurate hurricane warnings and evacuation notices. The quality of their numerical weather prediction tools is significantly improved by the assimilation of high resolution water vapor measurements into the forecast models.

In this use case, the necessary measurements are acquired by a differential absorption lidar (DIAL) system flying aboard a satellite launched into low Earth orbit. During any orbit, adaptive targeting technology installed as part of the satellite sensor systems will allow the DIAL instrument to be automatically and precisely pointed at the area of greatest meteorological interest. The backscattered laser pulses are digitized at high spatial resolution and stored in an on-board computer. Real-time data processing modules in the instrument's digital data handling unit analyze the signal to identify cloud and aerosol layers, and derive profiles of water vapor from the raw backscatter measurements. These derived data products are downlinked at the earliest possible opportunity, so that the water vapor profiles are available for use in forecast models within three hours (or less) of the initial measurement. On-board data storage use is monitored, and the raw data is downlinked as necessary for subsequent use in long-term climate analyses.

Technology Highlights:
- RT data quality checks made on-board
- On-board processing of averaged signal data, derived water vapor profiles & layer boundaries (<1 hr) & transmit to ground
- Level 2 production of gridded climate quality estimates (<3 hr total) for input to weather forecast models

Wide Swath Land Imager

Global mapping of surface topography and vegetation height and structure, with targeted re-imaging for change detection are measurements needed for estimating global biomass and monitoring changes in biomass (including natural hazards). This use case concept involves an imaging laser altimeter operating ~ 6 months in the 30% duty cycle mode over all land/ice surfaces. Afterwards, operations transition to a targeted imaging mode to fill in gaps and to re-image and monitor specific targets over multiple years.

Technology Highlights:
- Targeted imaging, real-time GPS drives autonomous control (on/off)
- Precision pointing to target (off nadir)
- On-board data processing & storage
- Autonomous fault detection/handling
- Super-waveform processing algorithm (to improve SNR)

The Carbon Dioxide IR-IPDA

This Infra-Red Integrated Path Differential Absorption instrument concept measures total column CO2, methane and trace gas sources from low earth orbit with high accuracy pointing stability required and power management for thermal control of the online and offline lasers. The on-board system continuously monitors housekeeping data along with a subset of backscatter returns to detect faults. Fault handling algorithms recognize when laser power is not steady and when the optical throughput and detector signal processor subsystems identify faults. For on-board processing of the science data, satellite cross-link capability with neighboring satellites that provide ancillary data would be needed.

Technology Highlights:
- Coincident temperature profile and altimetry
- Precision pointing (off nadir) accuracy & stability
- On-board synchronized control (monitoring reference laser, online/offline lasers)
- Data calibration / quality control
- On-board data processing & storage
- Satellite cross-links to access ancillary data (on-board processing to reduce data downlink volume)
- Automated fault handling

4.3 Conclusions

Table 4-2 provides a comparison of the four data use scenarios that have been developed. The comparison starts by specifying the goals and the scientific measurement scenarios of each data use scenario. Next driving requirement are identified, followed by a description of the lidar, other ancillary instruments whose data is needed for processing, and spacecraft characteristics. Next are the required vertical and horizontal resolution values. The data utilization row describes the data products to be derived from the measurements. Based on the data use scenarios, information technology challenges were identified and are presented in the final portion of the table.

Table 4-2: Comparisons of Data Use Scenarios

Data use scenario	**CO2**	**Winds**	**Water vapor**	**Land imaging**
Goals	improve climate change understanding	improve weather forecasts and warnings	improve hurricane track accuracy	estimation of global biomass and monitoring changes in biomass
Measurement scenario	IR-IPDA Carbon Dioxide; Temperature Profile and Altimetry from systems on board or (most likely) from assets on other platforms flying in tandem	Tropospheric winds	IR-DIAL Water Vapor; FTS-Temperature & DIAL Water Vapor	Imaging Laser Altimeter for Earth Surface Mapping
Driving requirements	level 0 data accessible and distributed in 3 hours	downlink of data in < 3 hours; on-demand targeting; data assimilation < 3 hours	3-hr time latency from satellite overpass to issuing warnings	targeted precision pointing to target
Lidar				
type	IPDA	Doppler Wind Lidar	DIAL	Scanning Laser Altimeter
laser mode	CW	PRF=10 and 100 Hz	PRF=20 Hz	PRF=750 Hz
channels	5 (2 high rate=100MHz & 3 low rate=10MHz)	coherent and direct detection	6 (1000 data points per channel); 10 Hz	1(1024 data points)
digitizer	14 bits	respectively	14 bits	6 bits
data capture rate	3.22 Gbps		840 kbps	461 Mbps
Other instruments & measurements needed	temperature profile and altimetry		FTS temperature profile	GPS
Spacecraft				
orbit	LEO 400 km	LEO 400 km	LEO 400 km	LEO 400 km
pointing	0.25 deg off-nadir (0.4 mr accuracy)		0.1 mr accuracy	1 mr (control), 0.045 mr (knowledge 3 sigma)
scan type	Fixed nadir		whisk broom	linear
Resolution				
vertical	NA	1km mid/upper trop, 250m in PBL	0.5- 1.0 km	0.05-0.5 m
horizontal	100 km	100 km	20-50 km	10 m
Data utilization				
	carbon dioxide profiles with error estimate	vertical profiles of horizontal "vector" winds by measuring two perspectives	cloud and water vapor profiles and aerosol properties derived	maps of veg canopy Height (m) or Biomass kg C/ ha
				Ocean Height - data also used to derive Ocean Surface Temperature
				Height of Ice surface

Table 4-2: Comparisons of Data Use Scenarios (continued)

Data use scenario	CO2	Winds	Water vapor	Land imaging
Info technology challenges	–Coincident temperature profile and altimetry	–Data downlinks <3 hrs for input to weather forecast models	–RT data quality checks made on-board	–Targeted imaging, RT GPS drives autonomous control (on/off)
	–Precision pointing (near nadir) accuracy & stability	–Quality control detects errors without manual intervention	–On-board processing of averaged signal data, derived water vapor profiles & layer boundaries (<1 hr) & transmit to ground	–Precision pointing to target (off nadir)
	–On-board synchronized control (monitoring reference laser, online/offline lasers)	–Model-driven (on demand) adaptive targeting	–Level 2 production of gridded climate quality estimates (<3 hr total) for input to weather forecast models	–On-board data processing & storage
	–Data calibration / quality control	–Intelligent scheduling/goal-oriented commanding		–Autonomous fault detection/handling
	–On-board data processing & storage	–Generate L2 wind vector products (within minutes)		–Super-waveform processing algorithm (to improve SNR)
	–Satellite cross-links to access ancillary data (OB processing to reduce data downlink volume) –Automated fault handling	–Operational data assimilation executes <3 hrs		

5. TECHNOLOGY REQUIREMENTS

Introduction

The ultimate goal of this report is to provide some insight into the considerations that come into play when deciding how best to invest limited funds in technology for active optical sensing.

This chapter defines and discusses the lidar technology requirements for Earth science and is divided into three major sections, representing three primary classes of technology which together comprise the lidar system as a whole: Transmitter Technologies, Detector, Processing and Optical Technologies, and Data Acquisition/Utilization Technologies. In each section the required technical capabilities and technical challenges are discussed and summarized as a guide to the decision maker. However, before delving into detail there are a few general observations that should be kept in mind with respect to investments in laser remote sensing technologies.

First of all, as alluded to above, a complete lidar system includes the laser source, a receiver subsystem, and data handling subsystem. To first order the performance of the system is a product of the performance of each subsystem—this is to say that if for instance one can double the efficiency of the receiver then one can halve the output of the laser source and achieve equivalent performance. However, this is not true in every case. Many laser remote sensing applications must perform in the presence of a background, usually arising from scattered solar flux. In these instances an improvement in the detector increases not only the laser signal but also the background that the laser signal must be observed against. In these cases improvements in the detector do not improve the quality of a measurement as much as an improvement in the laser itself. There are some systems, however, in which improvements in band-pass filter design may reduce this background while improving throughput to the detector. It is also the case in some instances that the detector performance is already limited in the upward direction. For example, many photomultiplier tubes (PMTs) have a quantum efficiency of ~30% in the UV. Since the efficiency cannot exceed 100% no amount of effort expended on PMT development can improve the system performance by more than a factor of 3.3.

A second observation we might usefully make is that the commonly used rating system for technology development status—the Technology Readiness Level (TRL)—can be misleading if the context is improperly understood. For instance, one might need a laser with an output of 100 millijoules per pulse and observe that such a system has flown in space—TRL 9. But perhaps in addition the laser for this measurement requires a narrower linewidth, or shorter pulse duration, or a slightly different wavelength, or better beam divergence or beam quality, etc. The point is that the specific requirements on the laser source performance for a particular application may be unique and as such render previous versions of lasers in space irrelevant to the requirements of their particular intended mission.

It has been a goal of this Working Group to provide a degree of prioritization for laser technologies, which is treacherous ground from the technologist's point of view. The priority of a technology is closely linked to the priority of the observation for which it is needed. One often cited viewpoint is that it might be wise to select for development lidar techniques and approaches that have broad applicability for many potential missions. This was the philosophy that underpinned the NASA Laser Risk Reduction Program (Peri et al., 2003) which has been conducted at NASA's GSFC and LaRC for the last five years. However, this approach might neglect the technology required for a singular mission whose importance arises later and outshines that of all other potential missions.

Finally, it should be noted that laser remote sensing systems as represented by the present state-of-the-art have a relatively low data rate, implying that they are not strong technological drivers in the areas of onboard data handling and communications. However, as will be argued below, the unique observations offered by lidar systems and the potential importance of the observations they permit in areas such as severe weather forecasting may drive the urgency of the need to process and disseminate their results quickly. It is in these areas that lidar may impact the abilities of the information technology community as it applies to satellite data.

The process of identifying and quantifying technology challenges for recommended future investment began with a comprehensive review of the measurement scenarios (Chapter 3). For each scenario the putative technology challenges were mapped in qualitative fashion across the complete set of technology categories enumerated in this Chapter. For the purposes of this report three basic classes of technology challenge were recognized:

- **E**: Enabling (technology regarded as essential for accomplishing the target measurement)
- **CR**: Cost Reducing (technology which, while not strictly essential to conducting a given mission, could nevertheless lead to substantial mission cost savings)
- **PE**: Performance Enhancing (technology which could reduce performance demands on one or more instrument subsystems, leading to reduced risk)

The resulting master Technology Challenge Matrix (TCM) can be found in Appendix 3 of this report. The absence of a specified challenge against a given technology category can mean that the technology in question is not applicable to the scenario under consideration or that the technology is applicable, but that the requirement may be met by the current state-of the-art and does not therefore need further development investment.

Next, for each technology identified in the challenge matrix the specific levels of performance required from the technology to achieve the desired measurements were evaluated. These quantitative requirements are captured in the Capability Breakdown Structures (CBS) for each technology area, which are reproduced in Appendices 5A, 5B, and 5C. Note that for both the TCM and the CBS considerable effort has been expended to consolidate individual technology performance benchmarks across multiple measurement scenarios and instrument types whenever possible.

5.1 Transmitter Technologies

Development of high-performance laser transmitters with long in-space lifetime is the primary technical challenge to the efficient and reliable operation of laser remote sensing systems in space. Although several different space lidar missions have flown successfully, experience gained during the development of these systems has shown that the laser transmitter presents the greatest development challenges and poses the greatest risk. This was true for the lasers on both the ICESat (Ice, Cloud, and land Elevation Satellite; Schutz et al., 2005) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations; Winker et al., 2003) missions.

There are numerous needed Earth science measurements and they require many different types of lasers. However there are common characteristics needed for space lasers, which differentiate them from lasers developed for commercial use, including:

- Rugged designs able to operate after being subjected to launch shock and vibration levels
- Space vacuum compatible (at the box level and some internally)
- Tolerance to temperature variations (operating and non-operating ranges)
- Tolerance to the space radiation environment
- Conductively cooled (thermal transfer) from the laser box level
- Good electrical efficiencies (ideally >5 %)
- Operation can be tested in the normal space instrument development cycle (i.e., in thermal vacuum chambers)
- Long in-space operating lifetimes with high confidence. This implies needs for the following components and characteristics:
    - Reliable pump laser diode assemblies
    - Long lifetime laser optics
    - Optical contamination threats (internal and external) which are well understood and mitigated
    - Failure modes that are well understood, contained, and do not cascade
    - Use of architectures (for a single laser and/or for a group of lasers) which minimize the impact of single point and/or single device failures

Additionally, some applications require internal laser wavelength converters, such as frequency doublers and triplers and optical parametric conversion crystals. These optical elements also need to be compatible with many of the characteristics above. They may also have additional requirements (for example, long optic lifetimes in the UV).

The transmitter technologies subdivision is intended to include all elements of the system up to and including the beam launch optics. A total of eight generic yet distinct technology classes were recognized during the deliberations in preparation for this report:

- Low energy, high pulse rate sources in the 1-micron wavelength region
- High energy, low pulse rate single frequency sources in the 1-micron region
- Multi-watt narrow-linewidth CW and quasi-CW sources in the 1.6-micron region
- High energy, low pulse rate single frequency sources in the 2-micron region
- Wavelength converters for the vis-UV
- Wavelength converters for the IR
- Other sources
- Beam directors

Although the first two laser types listed above address notionally identical wavelength requirements, the difference in performance asked of each connote fundamentally divergent system architecture aspects which the Group felt were worth distinguishing. The 1-micron wavelength specifier is intended to include both established and emerging neodymium (Nd) and ytterbium (Yb) doped laser media across the 940-1070 nm spectral region, while recognizing that within the 10-year scope of this report the practical alternatives for space-based application will in all probability be limited to the Nd:YAG family of materials, since these have a decades long development history and have significant demonstrable space heritage. However, this does not preclude the use of less well developed lasing media for the airborne and surface-based measurement scenarios also considered by the Working Group.

All space-capable solid-state laser systems will in addition incorporate laser diode arrays (LDAs) to pump the transmitter laser medium. This particular component class continues to pose a significant mission risk due to performance and lifetime issues experienced with their use in past space missions (NASA, 2004). Hence, for all the laser transmitter systems described below it should be taken as implicit that the associated technology development program includes a substantive effort on the packaging and qualification of the required LDAs.

The list of transmitter technologies recognizes the ongoing rapid emergence of fiber-based laser architectures, principally in the 1.5-1.7 micron telecom bands but with increasing interest in Yb systems operating around 1.05 microns. The former are attractive because of the high level of development they have received courtesy of the optical telecom industry. Qualification of systems and components to current Telcordia standards represents a significant step towards space qualification. (Telcordia is lacking primarily in the areas of ionizing radiation tolerance and thermal-vacuum environmental testing.) Fiber-based systems should be regarded as complementary in capability—as opposed to competitive with—their bulk-material cousins. The latter are capable of so-called “giant pulse” high-energy operation, whereas fibers exhibit far lower energy storage capacity with concomitantly smaller output pulse energy capability. However, fiber lasers are already available with ~30% wall-plug efficiency (WPE) and the roadmap to >75% WPE is already being addressed. Such WPE performance will likely never be possible from bulk-material systems (for which the current demonstrated WPE record is ~8%) so that the fiber option lends itself especially to the resource constrained environment of the typical space platform. Comparison trials between both system types across this performance envelope are currently in process and should better elucidate the trade space, but in the 1-40 mJ/pulse realm with pulsewidths down to 1 ns, the 7.5-40 kHz PRF range is addressable by both technologies. Finally, fiber systems can also be frequency controlled by means of lithographically embedded gratings, which represents a considerable advantage over the more complex and less mechanically robust frequency control schemes that are available to bulk-material lasers.

5.1.1 1-100 W, 0.1-50 mJ 1-micron laser

This class of transmitter lasers is characterized by low pulse energy and moderate-to-high PRF. These systems are oriented toward applications that call for a large number of pulse integrations (low measurement SNR) or that are required to make single-pulse measurements on a high-density grid (high SNR), e.g., geodetic imaging, 3-D vegetation structure. In general, such systems would be pumped by CW or quasi-CW LDAs. Although this mode of LDA operation is not devoid of risk, it is generally regarded as less stressing (and therefore more conducive to component longevity) than pulse mode operation.

5.1.2 100 W, 100 Hz 1-micron laser

This class of transmitter lasers is characterized by high pulse energy and low PRF with some scenarios calling for single frequency operation. These systems are geared toward applications that call for minimal pulse accumulation in a low-SNR measurement scenario or are required in order to pump non-linear wavelength conversion units, e.g., systems for ozone profiling or direct detection Doppler winds. The wavelength conversion efficiency in these cases is considerably increased by high spatial beam quality ($M2 \leq 1.5$) and spectral purity (single axial mode emission). In general, such systems would be pumped by repetitively pulsed or burst-mode LDAs, which have been implicated in several mission limiting incidents and remain a source of concern for space-based systems.

5.1.3 1-100 W 1.5-micron fiber laser

Tunable frequency-stable multi-watt CW and high-PRF fiber-based oscillator and amplifier systems operating in the telecom wavebands around 1.6 microns are desired primarily for lower tropospheric carbon dioxide measurement, but are also under consideration for other application areas such as high resolution topography and vegetation structure. A limited number of systems have been space qualified, but available in-space performance statistics are minimal.

5.1.4 20 W, 1 J 2-micron pulsed laser

NASA ESTO has invested significantly in the development and packaging of frequency-stable pulsed 2-micron laser systems for coherent Doppler wind measurement and also for DIAL lower tropospheric carbon dioxide profiling. Current joule-class performance needs to be extended to PRFs commensurate with operational needs and the associated space qualification protocols developed. Rugged long-life laser diode arrays at the 792-nm pump wavelength are also flagged for further development.

5.1.5 Wavelength converters for the vis-UV

Frequency doublers/triplers and parametric conversion devices are required to generate visible and/or UV light through upconversion of the fundamental wavelengths of systems covered under sections 5.1.1 and 5.1.2. The efficient operation of these components is contingent on a high degree of alignment stability. They must therefore be mechanically robust, as well as resistant to optical damage under high fluence irradiation conditions throughout the specified mission lifetimes. Application scenarios include systems for ozone profiling and direct detection Doppler wind measurement.

5.1.6 Wavelength converters for the IR

Means for generating tunable mid-IR radiation from the fundamental wavelengths of systems covered under sections 5.1.1, 5.1.2, and 5.1.3 are required. Optical parametric converters are the favored mechanism for achieving this goal and the efficient operation of such systems is contingent on a high degree of alignment stability. They must therefore be mechanically robust, as well as resistant to optical damage under high fluence irradiation conditions throughout the specified mission lifetimes. The target application is primarily the measurement of atmospheric trace gases, notably tropospheric carbon dioxide.

5.1.7 Other laser

This technology class addresses several laser types that fall outside the above classification divisions. In particular, this includes tunable multi-watt frequency-stable CW 2-micron lasers (including long-life 792-nm pump LDAs) which are required for lower tropospheric carbon dioxide measurement.

5.1.8 Beam director

Reliable, repeatable beam scanning approaches are required for a number of proposed geodetic imaging scenarios. These applications require a high degree of beam pointing accuracy. Novel techniques for accomplishing beam scanning without the need for moving parts (e.g., optical phased arrays) are highly desirable for this purpose, but are in their infancy. For the Doppler wind lidar scenarios the conically-scanned transmit aperture is common with the receive aperture. These systems are covered under section 5.2.3, below.

5.2 Detector, Processing and Optical Technologies

This group of technologies encompasses all elements from the collection optics to the signal handling and processing electronics that follow the detection stage, but prior to the data acquisition subsystem:

- Alignment maintenance
- Scanning system
- Doppler offset compensation technologies
- Large effective area, lightweight telescopes
- Mechanical metering structures
- Specialty optics
- Narrowband optical filters
- Detectors and amplifiers
- Optical high resolution spectral analyzers
- Detection electronics

Included in this list are direct (non-coherent), heterodyne (coherent), and photon-counting detection options, employing single-pixel detectors and focal plane arrays. There are also provisions for lidar operating wavelengths from the ultraviolet to the mid-infrared, and receiver spectral bandwidths, fixed or tunable, ranging from <1 pm to several nanometers. .

5.2.1 Alignment maintenance

Proper optical alignment is critical to the operation of lidar systems and is important in both the transmitter and receiver subsystems. In the transmitter, misalignment of the optical cavity can result in steering of the output beam causing a loss of returned signal in the receiver. Optical misalignment can also result in degradation of the beam divergence and/or the transverse profile resulting in poor performance or could possibly lead to catastrophic optical damage. In the receiver, maintaining alignment of the internal optical elements is critical to maximizing optical throughput and efficiency. Changes in the receiver alignment can affect the field of view, filter throughput and detector performance. An additional important area is maintaining alignment of the transmitted laser with the telescope field of view. Lidar system designs can rely on passive mechanical metering structures (see 5.2.5) to establish the boresight alignment for the transmitter and receiver. However in some applications active techniques based on mechanical, electro-mechanical or electro-optical technologies are needed to maintain or control the on-orbit alignment of the telescope aft optics and receiver optical train. For the purposes of this report, alignment maintenance does not include metering structures. This technology is enabling for measurements such as tropospheric wind and CO2 that use heterodyne instruments requiring precise beam overlap on the detector plane. Alignment maintenance is also enabling for certain altimetry measurements as well as laser-induced fluorescence measurements of phytoplankton physiology and functional types.

5.2.2 Scanning Systems

Techniques or technologies are needed to extend the field of regard of the receiver beyond a single beam fixed pointing system. Includes, for example, cross track 1-D and 2-D raster scans in combination with focal plane detector or fiber arrays for imaging topographic lidar or conical scanning techniques for Doppler wind lidar. Scanning systems can be enabling technologies for various missions (e.g., tropospheric wind lidar) and also may extend the capabilities of other missions by improving coverage or measurement repeat cycle times (e.g., swath imaging topographic lidar). This technology is also enabling for IR DIAL measurements of atmospheric temperature and water vapor.

5.2.3 Doppler Offset Compensation Technologies

Off-nadir viewing lidars will have a Doppler frequency shift proportional to the component of the spacecraft velocity projected onto the transmitted laser frequency. For spectrally narrow band lasers and matched receivers, methods of compensating for the spacecraft Doppler frequency shift must be developed. Examples include tunable filters and frequency-agile local oscillators required for wind lidar. Also includes the means to process real time spacecraft velocity, attitude and pointing information in order to assess the required Doppler correction. Offset compensation is important to these types of measurement, but has not been classified as an enabling technology for any measurement.

5.2.4 Large Effective Area, Lightweight Telescopes (Including stray light control)

The telescope is a critical component of the lidar optical system. The telescope aperture defines the signal collecting power of the system and the general trend is toward increasing the effective aperture of space qualified lidar telescopes to enable a variety of new lidar measurements from space. Telescope apertures exceeding 1 meter diameter are considered enabling for many of the atmospheric and oceanographic measurement scenarios. At this size the telescope becomes a defining component for the lidar instrument mass and volume requirements so, in addition to aperture, reduced areal density materials (e.g., SiC, beryllium, and carbon composites) and the use of novel techniques such as segmented primaries and deployable telescopes must be considered. Technology development for >2.5 meter deployable telescopes is in its very early stages. Work has been funded to understand the micro-dynamics of deploy and latch mechanisms of such a telescope and the current TRL is 2. In some lidar measurement scenarios aperture is not the defining metric of the lidar telescope and other characteristics including optical quality, instantaneous field of view, addressable field of view, rugged and durable coatings, are considered. Finally, it would seem that lidar telescopes might leverage technology investments in very large space telescopes (e.g., James Webb Space Telescope, Terrestrial Planet Finder); however the telescope requirements for lidar and astronomical applications are sufficiently different that it is unclear to what extent these technology developments might be directly applicable. This technology area is enabling for laser altimetry measurements; differential absorption measurements for atmospheric temperature, water vapor, ozone, and CO2; independent measurements of aerosol extinction and backscatter; spaceborne Doppler wind measurements; and laser-induced fluorescence measurements of phytoplankton physiology.

5.2.5 Mechanical Metering Structures

This addresses the requirements on the mechanical alignment quality for the lidar receiver system elements and maintaining that alignment post-launch over the mission lifetime of the instrument. One clear example would be the metering technologies of the on-orbit deploy and latch mechanisms needed for a large aperture deployable telescope. Other examples include requirements for thermally stable, lightweight optical bench or truss structures to passively maintain alignment of the transmit/receive optical train under extreme conditions. Mechanical metering structures are an enabling technology for differential absorption measurements of atmospheric temperature, water vapor, ozone, aerosols, clouds, and CO2; fluorescence measurements of phytoplankton physiology; and ocean particle measurements.

5.2.6 Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront

Various lidar measurement scenarios require low-loss optical receiver technologies including radiation hardened, environmentally stable bulk substrate materials and optical fibers. High transmission and wavefront quality optics are required for polarization analysis and control or wavefront compensation and control, e.g., lag angle compensation optics for coherent Doppler wind lidar and coherent DIAL systems. Specialty optics are an enabling technology for measurements of phytoplankton physiology, ocean mixed layer depth, and sea ice thickness. These technologies also enable independent measurements of aerosol extinction and backscatter.

5.2.7 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. For maximum benefit, the filters must have narrow spectral bandpass with high transmission while providing high out-of-band rejection. The transmission must also be linear across the aperture. For some applications the filters must not introduce wavefront aberrations. Improvements in the filter transmission result in a decrease in laser energy required to obtain the same lidar performance. Narrowband optical filters are an enabling technology for differential absorption measurements of atmospheric CO2, temperature, aerosol, and ozone; sea ice thickness measurement; and independent measurements of aerosol extinction and backscatter. This technology is also cost-reducing for many different types of measurements.

5.2.8 Detectors (Including Arrays) and Amplifiers

This category encompasses all technologies and approaches employed to detect the lidar return photons (coherent, direct detection, photon counting, single-/multi-pixel). The category specifically includes photo-conductive, photovoltaic detectors and arrays, photomultiplier tubes, avalanche photodiode detectors and arrays, CCDs and amplifier technologies. Wavelengths of operation extend from the ultraviolet to the mid-infrared. Detector technologies enable differential absorption measurements of ozone and CO2; direct detection of CO2; altimetry measurements; ocean mixed layer depth measurements; and sea ice thickness measurements. Detectors are also cost-reducing for a number of measurements.

5.2.9 Optical High Resolution Spectral Analyzers

Spectral frequency analyzers (e.g., interferometers or grating spectrometers) are required for analysis of multi-wavelength lidar returns or fluorescence. Potential technologies include gratings, Michelson or Mach-Zender interferometers, Fabry-Pérot etalons, and atomic vapor filters. This technology enables measurement of phytoplankton physiology and independent measurements of aerosol extinction and backscatter.

5.2.10 Detection Electronics, e.g., high-speed ADC, multi-channel scaler, boxcar averager

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.

5.3 Data Acquisition and Utilization Technologies

Traditionally, information technology has not been tightly coupled with instrument or spacecraft system design. Thus, it has not been able to make a significant impact in innovative technology trades and to enable missions without a significant cost growth. In order to infuse information technology at an early instrument conception stage, the policy adopted in forming the Working Group was to include experts not just from instrument technology areas, but also from the information technology community. Hence this section delineates areas where information technology (IT) could enable new missions or extend mission life.

During the requirements gathering process as discussed in Chapter 4, we focused on two areas: lessons learned from past lidar missions and use cases for science focus areas where lidar could make a significant impact. The lessons learned assessment consists of ICESat/GLAS data processing, CALIPSO retrospective, and Wind Lidar OSSE (Observing System Simulation Experiments). From the use case analyses, IT needs were also identified. Various lidar techniques that support measurement scenarios are summarized in the following four use cases:

- Wind Lidar / Modeling & Assimilation
- Carbon Dioxide IR-IPDA
- Water Vapor DIAL
- Wide Swath Land Imager

Through interactions with the lidar community, we identified key technologies based on mission enablement, cross-cutting technology, mission life, and IT-unique capability. The following IT capabilities merit particular attention:

- Airborne/ground lidar validation systems (to enable rapid cal/val)
- Intelligent sensor for automated health & safety monitoring and fault handling
- On-board sensor control for autonomous data acquisition (planning, execution, precision pointing)
- Science data processing (pattern recognition, event detection, on-board calibration)
- Science model-driven adaptive targeting
- Space qualified terabyte solid state storage
- Space qualified high performance computing, FPGAs and programming tools

There are six additional technologies identified by reference to the measurement scenarios under consideration for each of the high-priority science objectives stipulated in the Earth Science Research Plan. The following summarizes the findings of the working group for data acquisition and utilization.

5.3.1 Airborne/ground lidar validation systems

It is critical to rapidly validate and calibrate data to improve weather forecast models, to allow an inter-comparison of data from different instruments produced over time, and to quantify the instrument performance degradation over time. A combination of technology and system engineering approach is desired to enable rapid validation and calibration of lidar data by integrating data from in situ sensors such as radiosonde or ground based radiometer, H&S sensor parameters, platform ancillary data, etc. A simulation based testing and validation capability to optimize science return and to meet stringent timing requirements for wind drives the technology requirements. OSSE (Observing System Simulation Experiment) technology is an important component for enabling this capability. It will enable missions for measuring tropospheric wind, ice mass, biomass, and phytoplankton.

5.3.2 Intelligent sensor health & safety

The needs for this technology are mainly derived from lidars that require high power (>20 W), high PRF, or high degree of alignment stability. This technology provides the knowledge-based approach to increase lidar life. The current lasers flown in space have a 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 instrument life. It requires technologies to enable autonomous monitoring of lidar health and status, and a decision tree of actions to take if anomalous conditions are observed. It also complements the instrumentation suite for monitoring H&S. Major controlling aspects include lidar temperature drift/gradients, lidar frequency stability, lidar degradation modes including radiation effects, and optical particulate contamination.

By monitoring and diagnosis software with a particular lidar, a trend database is built for lasing system diagnostics such as pump beam misalignment vs. energy input, beam profile monitoring with Quad CCD detector, OPO control loop, etc. Parameters are flagged to demonstrate diagnosis and prognosis software (ground or onboard) that meets the laser performance metrics. It will enable missions for 3-D biomass monitoring, tropospheric wind, and high resolution atmospheric CO2 measurements.

5.3.3 On-board sensor control

These technologies make possible autonomous data acquisition based on a set of defined conditions (e.g., acquire only if cloud free) and catastrophic failure avoidance (based on instrument health and monitoring data (5.3.2)). It also allows graceful degradation of the laser by controlling the lasing environment or reducing the number of laser duty cycles. The location specification of detected events must be within the pointing accuracy to enable the target to be acquired on a later pass. Detection, diagnostics, and response for errors in the control system require sufficient speed to maintain pointing accuracy. The precision pointing requirements (e.g., 0.25 degree or 4 mrad accuracy) and the thermal control system for cooling the lasers and diode pumps (e.g., 3-4 kW avg.) require design of a flight control architecture to provide engineering data and attitude information that meet operation goals. Although algorithms to detect these events are not covered by this report, algorithms to process data on board go hand in hand with the development of the control architecture and processing hardware. These are often compute-intensive. This task may include hardware implementations or onboard science co-processors to meet speed and accuracy requirements as described in 5.3.7. It will enable missions for measuring tropospheric wind, aerosols, high resolution atmospheric CO2, and phytoplankton physiology and functional types.

5.3.4 On-board near RT data production

A general consensus was that most of the science data production requirements would be achieved by ground data processing. However, on-board data production becomes apparent in order to support strict real time requirements and event tracking indicated for tropospheric wind, aerosol, high resolution atmospheric CO2, and phytoplankton physiology and functional types measurements. Any data processing algorithms require constant reprocessing and formalized data processing policy. Thus, technologies to allow reconfigurable processing of Level 1 or Level 2 data from calibrated lidar data are also identified. For example, an integrated, parallel-processing algorithm suite implementing all-numerical methods required for DIAL retrieval might consist of background subtraction, horizontal and vertical averaging, and numerical differentiation. Due to the large volume of data traffic on-board, real-time on-board database technology is highly desirable.

5.3.5 Science model-driven adaptive targeting

This technology is targeted to the support of weather forecast applications with RT requirements such as tropospheric wind, aerosols, and high resolution atmospheric CO2 measurements. It requires technologies to allow for rapid data acquisition based on conditions determined by model predictions (e.g., estimated location of storm front). It may also require inputs from other sensors (e.g., cloud detection) for data validation and calibration. Based on model outputs, it should generate scripts for autonomous event scheduling, command sequence, and quality control of targeting. Scientific targeting schemes (i.e., adjoin methods) need to identify “critical regions” of the atmosphere. An overarching targeting control system to link all elements together, and simulation of an end-to-end adaptive targeting environment are necessary. The assumption is that existing technologies for the elements and sub-elements of a model-driven targeting capability already exist, but considerable effort is needed to integrate and orchestrate an end-to-end system. Extensive testing is needed to identify and control feedback loops in the sensor/model system that could adversely impact overall performance.

5.3.6 Space-qualified terabyte storage hardware

As identified by other sections of this report, technology supporting non-volatile solid state storage is required for storing raw sensor data, related telemetry, and on-board look-up tables to support imaging or high resolution lidar such as for ice mass balance, 3-D biomass monitoring, and phytoplankton measurements. Also it supports near RT data production. The key challenge is to scale up storage volume while keeping size and power low. NASA should do a periodic (biennial) study to determine the current state-of-the-art in both ground based and spaceborne non-volatile solid state flash memory. The study should determine the technology lag between ground and space and develop recommendations for NASA on how to shorten that gap and how to achieve TB scale non-volatile solid state flash memore in space by 2010. Current space qualified hardware lags in storage volume and uses too much power to reasonably scale to TB sized storage.

5.3.7 Space-qualified HPC hardware and programming tools

On-board high-performance computing processor requirements (CPUs, DSP boards, FPGAs) are critical capabilities needed to support intelligent sensor monitoring and control and near RT data production. The needs are for multi-core CPUs and high performance FPGAs, and associated programming environments to reduce programming complexity and cost. This also involves the development of the processor and memory chips required for on-board data processing for 3-year mission lifetime. Current radiation hardened technology at 0.35 and 0.25 microns, is usually 2 or 3 generations behind commercial technology. Large government investment is needed to satisfy future flight HPC needs. As devices get ever denser and more tightly integrated (e.g., system on a chip), innovative advanced radiation hardened technology will be in high demand. It is also possible to leapfrog the currently acceptable technology in the commercial world, and try to propose something entirely new and daring! It will enable missions for measuring tropospheric wind, ice mass, aerosol, high resolution atmospheric CO2, and phytoplankton.

5.3.8 Spacecraft area network

As needs for sharing engineering and science data on board arise, technologies are needed to interconnect sensors within single or across multiple spacecraft or in situ platforms. This technology is required to support rapid sharing of status and control data (e.g., communication protocols) for formation flying, sensor web scenarios, or instrument monitor and control. With packetizing standards (e.g., CCSDS, CFDP) and bus protocols (e.g., MIL-STD-1553B, LVDS, RS-422, etc.), new architecture design is needed to allow interaction between instruments. Demonstration of feasibility by prototyping in an Instrument Development Lab or testbed environment is desired.

5.3.9 Formation flying

Formation flying, which enables gravity and water mass measurements, requires technologies to provide accurate knowledge of spacecraft/sensor position and to sense and control satellite attitude. However, capabilities to support these requirements can be achieved with existing hardware for laser frequency stabilization optics, accurate test mass control, and position sensors. The challenge lies in data simulation software to solve for gravity field to degree and order of 300 times better than the current capability. Inversion of 200,000 x 200,000 matrix for gravity field estimation is needed to optimize a formation mission design.

The second type of formation flying involves a cluster of satellites that share information to acquire data for a specific target such as cloud detection or storm tracking. Most of these requirements will be addressed by technologies described in 5.3.3 and 5.3.8.

5.3.10 Model lidar data resampling techniques

Resampling is a method of assimilation and compression that can support intelligent data assimilation to an Earth science model. The key factor for resampling is defining the sampling interval. Resampling intervals based on data content assume an uneven density of information in the data stream. Samples should be taken with consideration to how the measurements change over time and/or space. Resampling can be based on co-varying or dependent data fields such as land cover, a digital elevation model or optically derived biomass maps. These approaches assume that the co-varying field determines the sampling rate. For example, dense green areas under MODIS EVI or LAI/FPAR would be most likely to benefit from lidar canopy height to assist modelers in discriminating dense LAI regions under re-growth from those in mature forests.

Techniques to address lidar data ingest and assimilation issues include algorithms to enable rapid resampling of data to various model grid specifications, reformatting heterogeneous data sources, and re-projecting data into a desired grid. It will enable missions for measuring tropospheric wind, aerosols, high resolution atmospheric CO2, and biomass.

5.3.11 Knowledge Discovery

This refers to machine assisted approaches to rapidly discover robust reusable models from lidar signatures, weather related features, and forest stand characteristics and document the errors and performance of the models. Ideal models will correspond to the physically meaningful and measurable phenomena in the data collection system including the instrument, sources of error in the collection system and forest structure. Computational resources may limit the degree to which data can be processed with high fidelity models. Short cuts can be taken to reduce the computation load such as lookup tables and reduced form models. Machine learning will enable reproduction of complex high fidelity models as well as data driven models of incompletely understood processes and interactions.

Two approaches are considered. 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.

5.3.12 Data compression

High resolution imaging lidar and atmospheric chemistry lidar could potentially generate over 1 TB/orbit. The goal is to increase the number of measurements with reduced accuracy due to lossy compression but adequate for model inputs (e.g., wind in upper troposphere). By conducting cost/performance experiments between lossy and lossless, prototypes for reconfigurable compression rates for on-the-fly compression should be evaluated. Also, compression techniques are needed to support region of interest identification, lossy event detection, data summarization, and alternative data reduction (e.g., buffer prioritization). Science programs must supply researchers with example data from suborbital instruments used in real science investigations for meaningful experimentation to meet requirements.

However, since the use of lidar data in modeling is relatively immature when compared to optical data, there is reasonable expectation that scientists will require reprocessing and reanalysis of lidar data from level 1 and level 0 sources when better models are formulated. Data compression should initially be lossless or managed in such a way that representative samples of lossless data are available to reanalyze the data. These situations include field campaigns where intensive ground studies are taken for calibration and validation involving long term ecological research areas and tower sites where a concerted effort is made to measure and model ecosystem structure and function.

5.3.13 Data Management/Service Oriented Architecture

For ground based application, real time requirements and large volumes of heterogeneous data call for techniques to provide data management of lidar data, including rich metadata descriptions and ontology to enable efficient search, retrieval and processing. High speed network protocols (>1 TB/sec) and service oriented architecture enable the lidar software community to share algorithms and techniques, leverage web services, and address real-time requirements for transmission quality of service and fault tolerance. Community-based standards for archival/delivery, accepted dataset formats, and metadata standards will enable wide distribution and integration of services (e.g., OGC). Seamless access to various product levels is desired. Higher-level products should be managed under measurement themes as opposed to being categorized by instrument.

5.4 Summary

The process of identifying and quantifying lidar technology challenges adopted here has assumed a holistic philosophy. By this we mean that the entire end-to-end process from the instrument/platform combo to the measurement target (atmosphere, land or ocean), and on to the data acquisition, processing, dissemination and exploitation phases (through the use case scenarios), has been critically examined in order to flush out the complete set of technology tall poles relevant to the laser remote sensing science arena.

This approach has identified a large number of instrument technologies, many in areas already recognized as requiring further investment. It also has indicated cases where advanced or high-performance computing and information handling provisions are a prerequisite for effective utilization of the instrument data by the user constituency.

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6. TECHNOLOGY PRIORITIZATION AND ANALYSIS

In this Chapter, we perform an analysis to determine investment priorities for the technology requirements discussed in the previous chapter.

The prioritization criteria developed by the working group are as follows (in the order of importance):

1. *Scientific Impact*: The degree to which the proposed measurement via lidar technique will impact our scientific understanding of the Earth System and will 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.) used to improve the accuracy of natural disaster forecasts).
3. *Measurement Scenario Utility*: Whether lidar technique is the primary or unique technique for making the proposed measurement. Another factor is whether the scenario meets or exceed threshold or goal science requirement, 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 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.

We now discuss each criterion in more detail.

6.1 Scientific Impact

The key here is the *scientific impact achieved because of the uniqueness of lidar measurement technique*. Chapter 2 covers the scientific basis for the technology development program. Lidar technique makes significant and unique contribution to our scientific understanding specifically for the following measurements:

1. *Tropospheric Winds*, where timely measurement on a global scale is impossible using any other currently known technique. This is true in the case of tropospheric wind measurement where vertical profiling of the wind field from space has remained a tall pole. Knowledge of tropospheric wind measurement is vital for understanding the weather system and for accurate prediction of severe weather events such as hurricanes.

2. *Tropospheric CO2 Profile*, where the desired spatial resolution or vertical profiling is not feasible with any other technique than lidar. This is true for example in the case of CO2 profile measurement. Determining the CO2 profile in the atmosphere has tremendous impact on our understanding of changes in this primary green house gas and its impact on the Earth system. In order to properly characterize the magnitude and location of CO2 sources and sinks, it is essential to acquire high resolution measurements within the lowermost layers of the atmosphere, i.e., boundary layer and free troposphere.

3. *High Resolution ice sheet topography and velocity*, where the high spatial resolution and 3D imaging is best achieved by laser altimetry. Complemented by Interferometric SAR to measure the flow of the ice sheet, together these measurements have tremendous impact on our understanding of the Earth's long-term climate and implications for the Earth's changing sea-levels, which can threaten coastal areas

4. *Vegetation 3D Structure*, Biomass and Disturbance, where lidar systems offer very high range resolution compared to either passive EO or microwave techniques. This high range resolution is the key to accurate profiling of the vegetation canopy and change in forest structure.

5. *Phytoplankton Physiology*, where lidar is expected to play an important role, providing both primary/novel measurements as well as working in concert with other types of observations applicable to solving major ocean carbon cycle and biogeochemistry questions.

6.2 Societal Benefit

NASA's Earth Science Division has great interest in investing in areas of Earth Science application for the benefit of mankind. Science research to improve life on Earth has been a high priority of the agency and is explicitly stated in its charter.

Recent natural disaster events in the US and the world have made it clear that the ability to predict severe weather events is not only of great value for improving life on Earth but also is of great importance for national security. For example, last year hurricane Katrina killed thousands of people, displaced many thousands more, and threatened the oil refineries in the Gulf of Mexico region, thereby causing adverse economical consequences and exposed vulnerability of our homeland security system. Had we been equipped with accurate and advanced hurricane path and intensity forecasts, some of these extreme adverse consequences could have been avoided, or at least mitigated, through the issuance of timely warnings.

Accurate knowledge of the 3D global tropospheric wind field is a must for accurate numerical weather forecast and severe weather prediction capability. For this reason, obtaining the tropospheric wind profiling capability has the most immediate societal benefit.

A series of Observing System Simulation Experiments (OSSEs) carried out at Goddard Space Flight Center, the National Centers for Environmental Prediction, and the Forecast Systems Laboratory have shown that accurately measuring the global wind field will have a major impact on numerical weather forecast skill at both regional and synoptic scales. Measurement of global wind profiles has been recognized as the greatest unmet observational requirement for improving weather forecasts by the World Meteorological Organization, the large collection of nations planning the Global Earth Observation System of Systems, the NOAA/Integrated Program Office, and NASA in its Weather Research Roadmap. In addition, better wind measurements will directly support the missions of DOD, FAA, EPA, FEMA, DOT, DOE, USDA, and DHS.

In addition to the benefit for weather forecasting, accurate measurement of the three-dimensional, global wind field will allow major advances in our understanding of a host of key climate change issues such as: 1) improved knowledge of the vertical and horizontal transport of water vapor to verify the performance and integrity of climate models and to better understand the impact of deforestation on rainfall, 2) more accurate partitioning of the heat transport by oceanic and atmospheric components of the earth system, 3) improved understanding of the sources and sinks of the carbon cycle which is currently based on the a *priori* specification of the wind field, and 4) improved understanding of long-range transport of aerosols and trace gases to assess the impact they may have on the regional and global climate.

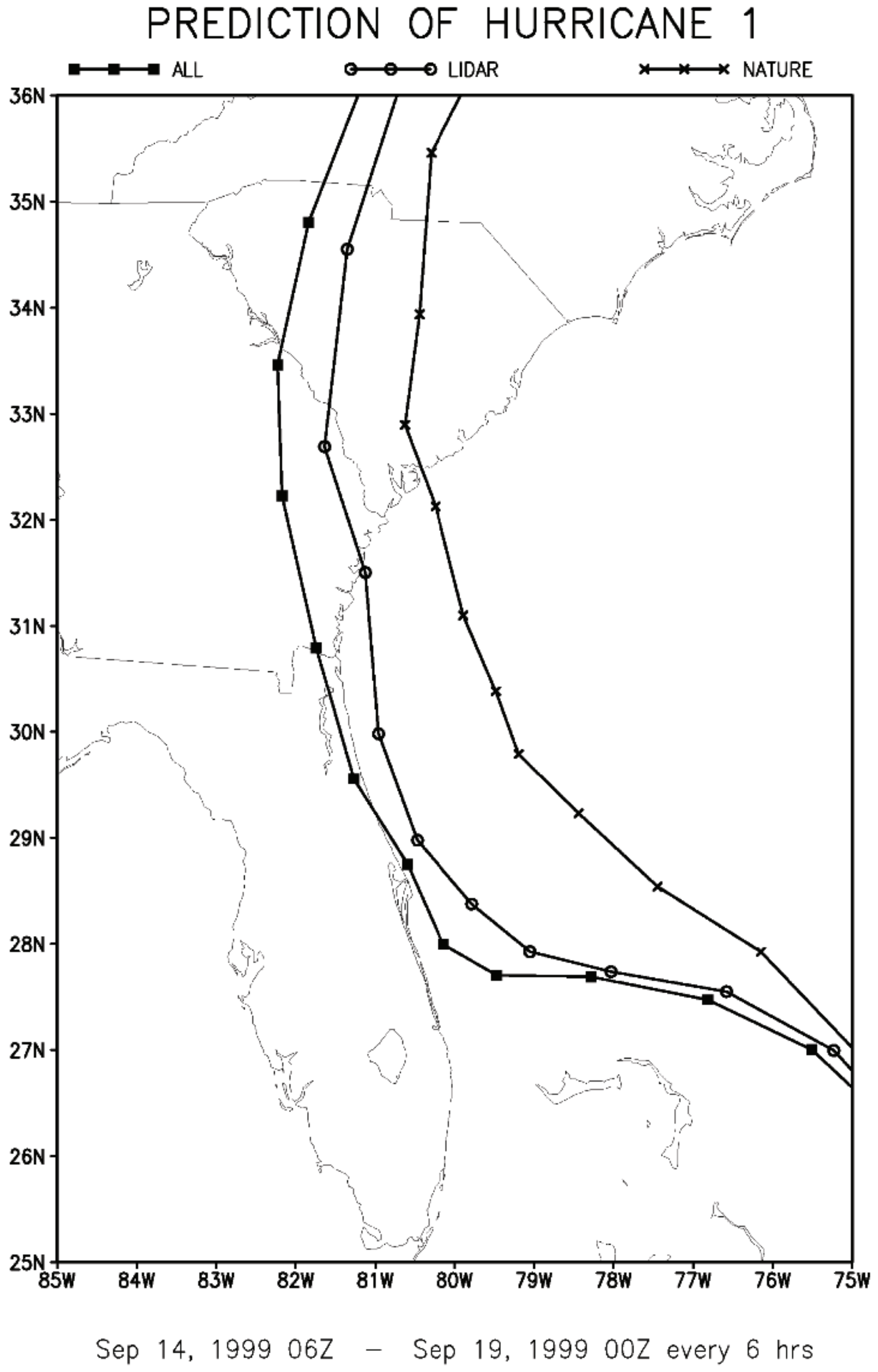


Figure 6-1: Lidar impact on hurricane track prediction. X's mark the nature run track (verification). Squares mark the control run track. Circles mark the improved track using lidar winds. (Ardizzone and Terry, 2006)

To assess changes in the Earth's long-term climate, accurate measurements of CO2 column, changes in the ice sheet mass balance, and 3D changes in the forest structure are also of high priority. In particular, advancing space-based CO2 profiling capability is one of the main goals of the US Climate Change Technology Program. See Chapter 2 for detailed discussion of the importance of these measurement parameters for understanding changes in the Earth's climate. *The long-term societal benefits of understanding climate change cannot be overemphasized.*

6.3 Measurement Scenario Utility

The technology capability challenge matrix (TCM) in Appendix 3C shows that the following measurements (with the desired requirements) can primarily be achieved via the lidar/laser technique (as indicated in the column with heading "Lidar Utility"):

- Tropospheric Winds
- CO2 Vertical Profile
- Vegetation Biomass
- High Resolution Ice Surface Topography
- Phytoplankton physiology and functional groups
- Ocean carbon/particle abundance
- Earth gravity field
- Terrestrial Reference Frame

The value of lidar for several of these applications has already been discussed in Section 6.1 above. For the rest of these applications, an explanation for lidar utility is given below.

Lidar is required for ocean carbon/particle abundance because hyperspectral imaging alone does not provide accurate retrievals of particle scattering coefficients when there is a significant absorbing aerosol load - a particular problem in coastal/continental shelf regions. The improved range measurements provided by laser interferometry are necessary to improve Earth gravity field observations to less than 100 km and 10-day resolution with an accuracy of less than 1 cm equivalent surface water height. (Current GRACE Ka-band observations are ~400km and 30-day resolution with an accuracy of approximately 2-3 cm equivalent surface water height.) An improved satellite laser ranging network will provide a factor of 5-10 improvement in reference frame and satellite precision orbit determination over current measurements.

For additional information on the value of lidar measurements, see Section 2.

6.4 Technology Development Criticality

The criticality of the technology development has been labeled in the master TCM (Appendix 3C) as E (= enabling technology regarded as essential for accomplishing the target measurements), CR (= cost reducing technology, which, while not strictly essential to conducting a given mission, could nevertheless lead to substantial mission cost savings), and PE (= performance enhancing technology which could reduce performance demands on one or more instrument subsystems, leading to reduced risk.

6.5 Technology Utility

Referencing the Technology Challenge Matrix (TCM) in Appendix 3C, we develop histograms of the utility of technology challenges being called out by certain scenarios. We caution the reader that the histograms should serve as a relative guide regarding the utility of a certain technology as opposed to being interpreted strictly in a quantitative way. This is because in some cases several scenarios calling for the same technology are variation of each other addressing the same intrinsic measurement. Furthermore, measurement scenarios themselves have different levels of development and maturity.

The following figures summarize the utility of technologies in the laser, receiver, information system, and spacecraft technology areas, respectively. The reader is referred to Chapter 5 regarding detailed requirements.

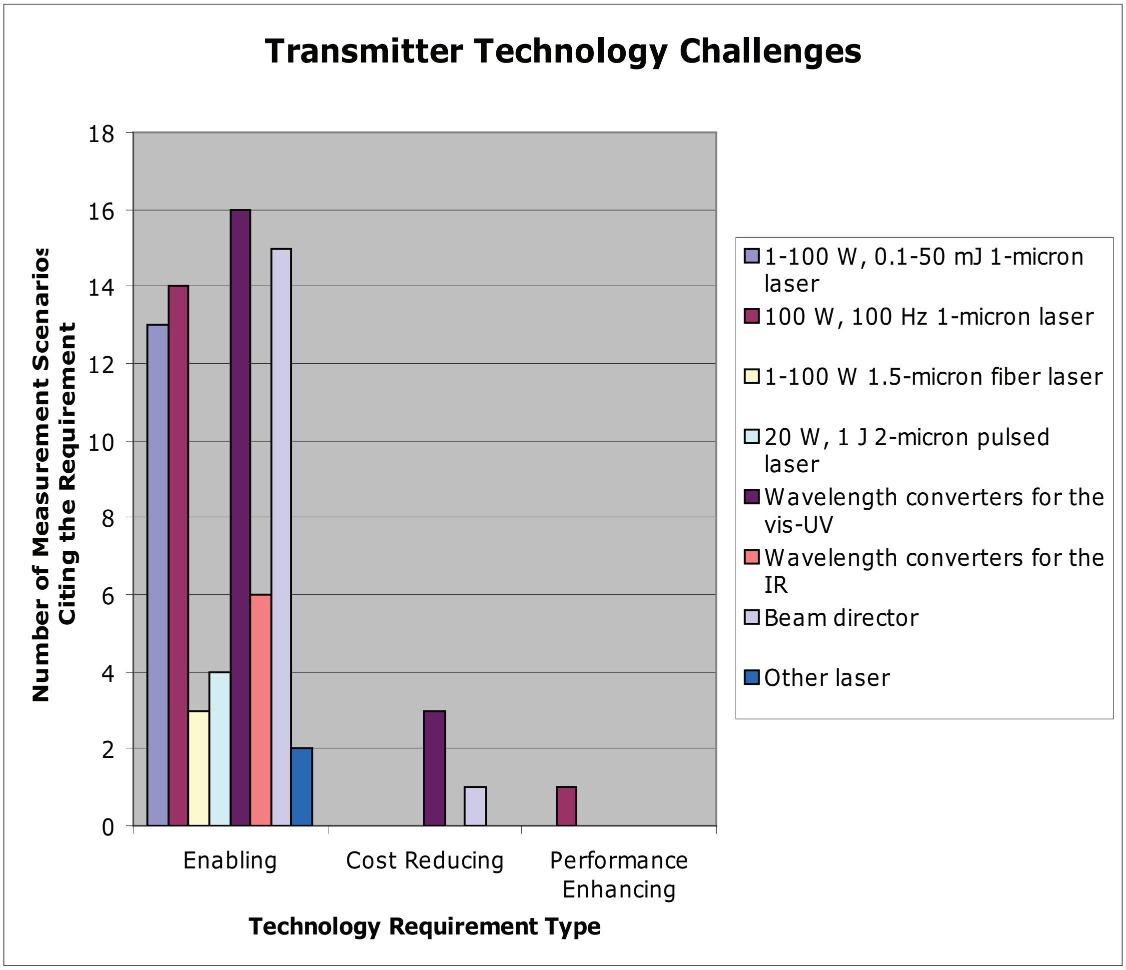


Figure 6-2: Transmitter Technology Challenges

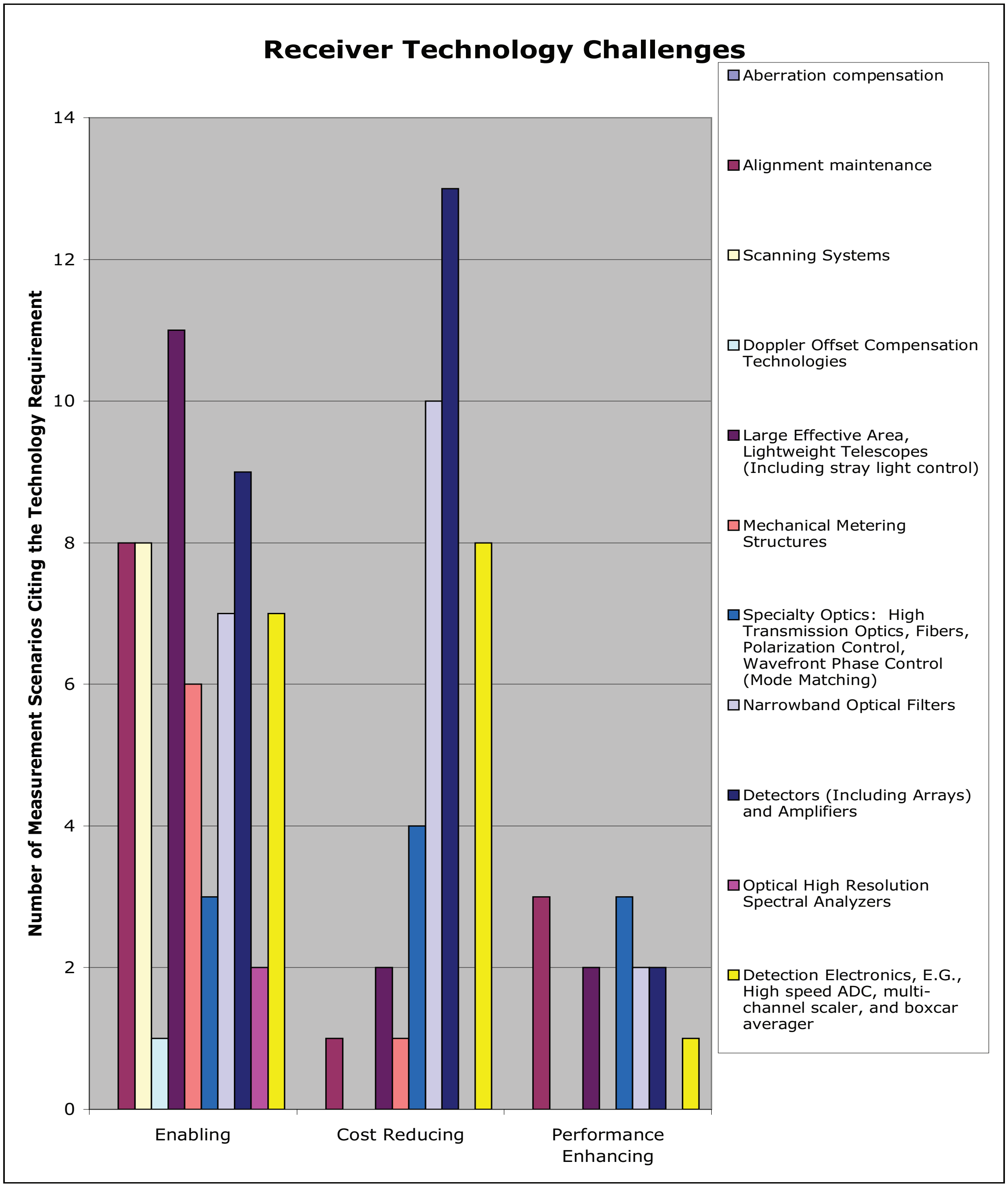


Figure 6-3: Receiver Technology Challenges

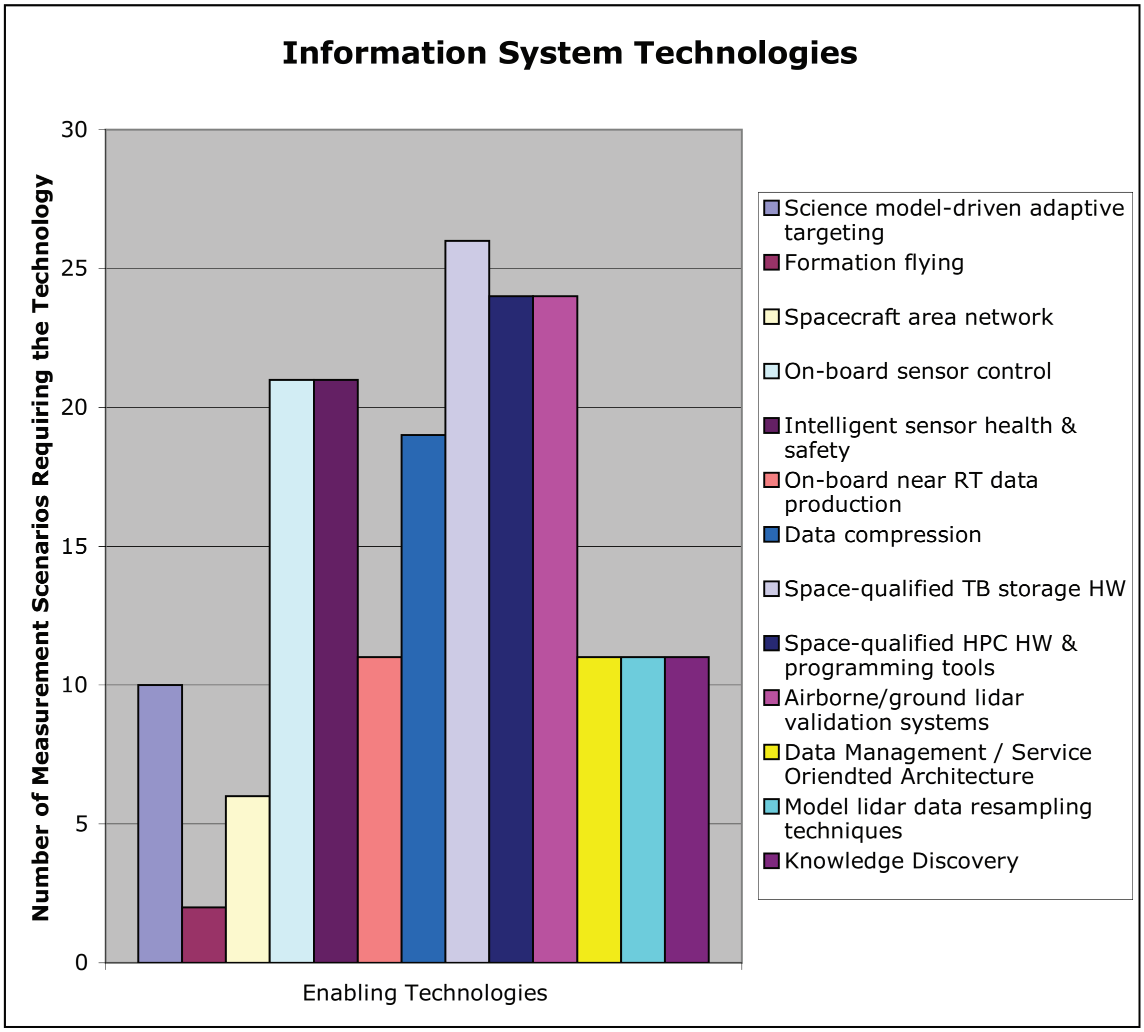


Figure 6-4: Information System Technology Challenges

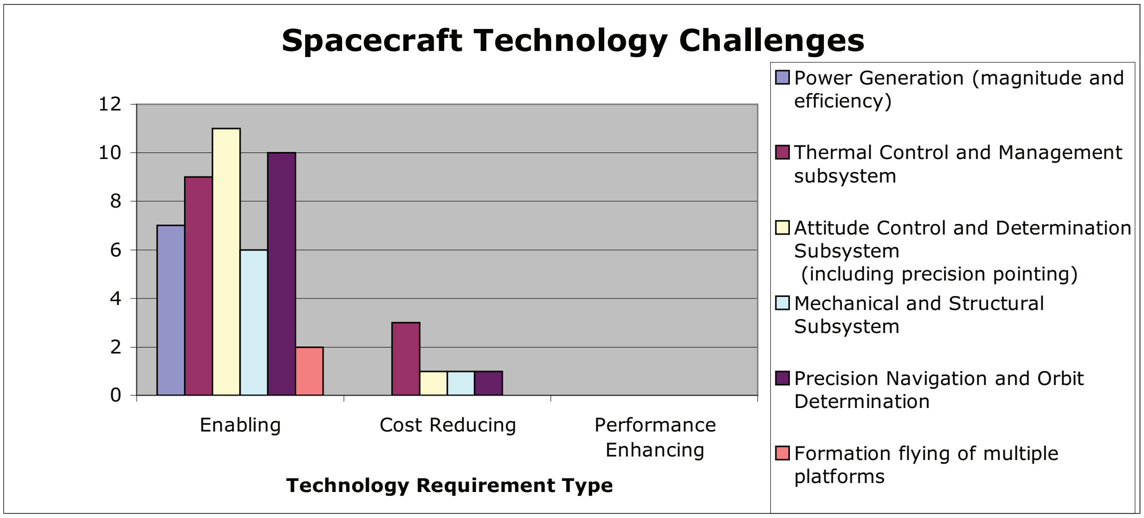


Figure 6-5: Spacecraft Technology Challenges

6.6 Measurement Timeline

The desired timeline for the measurements is reflected in the NASA Earth science roadmaps. Further discussion of the timeline is limited to the societal benefit of the particular measurements, as discussed previously. As such, tropospheric wind measurement has the most immediate societal benefit followed by parameters discussed above that contribute toward understanding of Earth's climate change.

6.7 Risk Reduction

Although several lidar missions have flown successfully, experience has shown that the laser transmitter presents the greatest development challenge and poses the greatest risk. Therefore, risk reduction laser transmitter technologies are of highest priority. In addition, alignment maintenance and scanning systems technologies also contribute significantly toward mission success.

6.8 Laser Transmitter Technology Priorities

Based on the prioritization criteria discussed in sections 6.1-6.7, high priority laser transmitter technologies are summarized in Appendix 6A (laser transmitter priorities spreadsheet) and Figure 6-6. An overview of these priorities is also given in Figure 6-9. Additionally, in this figure, each technology is traced to the measurement application, outlining different choices of laser technologies for some applications. In summary, the highest priority technologies in this area are classified as follows:

1. *1-100W, 0.1-50 mJ, 1-micron laser:* These low pulse energy, moderate-to-high PRF systems are oriented toward applications for ice surface topography and 3-D vegetation structure.
2. *100 W, 100 Hz, 1-micron laser:* These high pulse energy, low PRF systems are essential for tropospheric wind measurement (direct detection Doppler retrieval), ice mass, and phytoplankton and physiology functional group measurements.
3. *1-100 W, 1.5 micron fiber laser:* These systems have heritage in the telecom industry and are primarily desired for lower tropospheric carbon dioxide measurements. However, a limited number of these systems have been space qualified and their in-space performance statistics are minimal.
4. *5-20 W, 2-micron laser:* These systems are essential for tropospheric wind measurement (coherent Doppler retrieval). Note that this category combines pulsed and continuous-wave transmitters listed in Appendix 6A
5. *Wavelength Converters:* These systems are essential for direct detection Doppler wind, ice mass, CO2, and phytoplankton physiology measurements. Note that this category combines both UV-Vis and IR wavelength converters in Appendix 6A.
6. *Beam Director:* Reliable, repeatable beam scanning technologies are essential for 3-D biomass vegetation structure.

The current state of the art for all priority technologies listed above (items 1-6) is TRL of approximately 4.

6.9 Detector, Processing and Optical (DPO) Technology Priorities

Based on the prioritization criteria discussed in sections 6.1-6.7, high priority DPO technologies are summarized in Appendix 6B (DPO priorities spreadsheet) and Figure 6-7. An overview of these priorities is also given in Figure 6-9. Additionally, in this figure, each technology is traced to the measurement application, outlining different choices of DPO technologies for some applications. In summary, the highest priority technologies in this area are classified as follows:

1. *Alignment Maintenance:* This technology is essential for tropospheric winds. The requirement varies for different measurements and varies from approximately 5-50 μrad. Current state of the art is in the TRL range4-7.
2. *Scanning Systems:* Technologies are needed to extend the field of regard of the receiver beyond a single beam fixed pointing system. This is an essential technology for tropospheric wind and 3D biomass measurements. The current state of the art is at a TRL of 2-5.
3. *Large, Lightweight Telescopes (< 25 kg/m2):* Telescope apertures in the range 1-2 m in diameter are required for certain altimetry measurements. Aperture as high as 3m is required in the case of carbon dioxide and phytoplankton physiology measurements. Current TRL is about 2.
4. *Detectors (Including Arrays), Amplifiers and Electronics:* 1.5 and 2-micron detectors with high quantum efficiencies are needed for CO2 measurements. These technologies will also permit relaxation of laser and optics requirements and will improve alignment maintenance options. Analog-to-digital converters are needed for altimetry measurements. Current TRL ranges from 4-5. Note that this category combines detectors and detector electronics in Appendix 6B.

5. Optical Filters and Specialty Optics: These technologies enable carbon dioxide and phytoplankton measurements. Current state of the art is TRL 4.

Note that high resolution spectral analyzers (Appendix 6B) were not included in this list because they are relevant only to phytoplankton measurements. The other categories listed above apply to multiple measurements.

6.10 Data Acquisition and Utilization (DAU) Technologies

Based on the prioritization criteria discussed in sections 6.1-6.7, high priority DAU technologies are summarized in Appendix 6C and Figure 6-8. In Figure 6-8, the priority technologies are mapped with representative science scenarios and illustrated with requirements for data processing time and data volume. Each color box in the three DAU technology tables represents a specific priority technology. Then, they are mapped to specific science scenarios which require the technology. Finally, the graph indicates ranges of requirements for data processing time and data volume for each technology area. Additionally, in this figure, each technology is traced to the measurement application, outlining different choices of DAU technologies for some applications. In summary, the highest priority technologies in this area are classified as follows:

1. *Airborne/Ground Validation Systems:* Rapid calibration and validation of data is needed for a variety of purposes such as improving weather forecast models, and quantifying the instrument performance degradation over time. OSSE (Observing System Simulation Experiment) technology is an important component of this enabling technology. This technology benefits ice mass, 3D biomass, and phytoplankton physiology measurements.
2. *Intelligent Sensor Health and Safety*: Lidars with high power and high PRF or high degree of alignment stability greatly benefit from this technology intended to increase lidar life. Biomass and CO2 measurements greatly benefit from this technology due to the nature of lidar used.
3. *Science model-driven adaptive targeting:* In order to meet stringent time requirements, especially for weather forecasting, autonomous methods to identify targets and command the spacecraft are necessary to fill data gaps for a decision support system. Without model-driven data gap identification, weather related mission goals are not achievable. This technology also applies to carbon dioxide measurements.
4. *On-board Sensor Control:* This type of technology is needed for autonomous data acquisition based on a set of defined conditions (e.g. cloud-free) and for instrument catastrophic failure avoidance. This technology is relevant to ice mass and CO2 measurements.

Although there are 7 priorities identified, we have only addressed 4 areas in the road map since storage, processors, and on-board computing technologies are already either funded by existing programs or advanced by industries. There are 3 different timing requirements for information processing needs identified in the roadmap:

1. Real time requirement— based on an on-board processing architecture to achieve instrument pointing control and a real-time sensor web for on-the-fly data calibration/validation
2. 1 hour requirement— based on a spacecraft and instrument command and sequence ground operation system. Requirement addresses timely delivery of ancillary data to validate and calibrate weather related data and provide to a weather forecasting system in 3 hours.
3. 3 hour requirement— based on cooperating science ground data systems to support a decision support system. Requirement addresses data production and management, data assimilation, and interfaces to mission operations and model forecasting systems.

6. 11 Integrated Technology Roadmap

Figure 6-9 shows integrated high priority technology investment needs in the three technology areas (lasers, receivers, data systems) linked to the specific measurements they enable. This highly condensed technology roadmap is for illustrative purposes and is based only on the following representative scenarios:

- Tropospheric Winds: scenario LWG-AD-SP3
- Ice Mass: scenarios 48, NRC-14
- CO2: scenarios 179, NRC-02, NRC-04, 23, 24
- Biomass: scenarios 188, NRC-11
- Phytoplankton: scenario 17

In summary, technology investments in the three technology areas must be made wisely and in coordination such that as a result, priority measurements can be enabled.

6.12 References

Ardizzone, J., and J. Terry, Observing System Simulation Experiments for Wind LIDAR Instruments, Version 1.1, January 19, 2006. Prepared for NASA Goddard Space Flight Center.

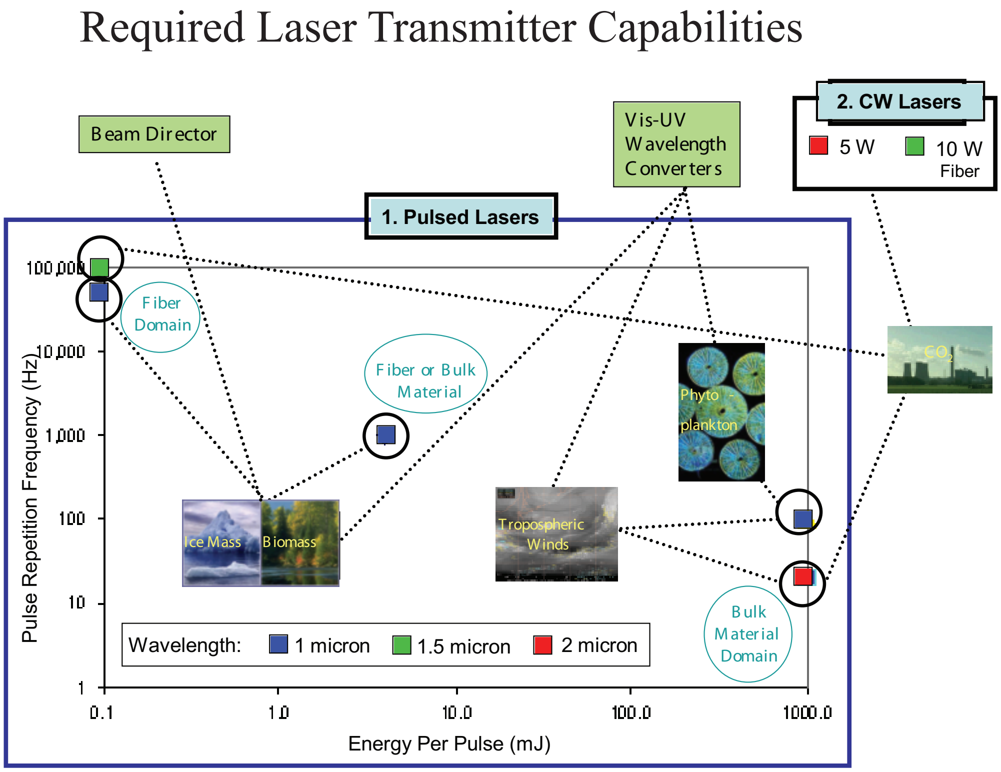


Figure 6-6: Laser Transmitter Applications

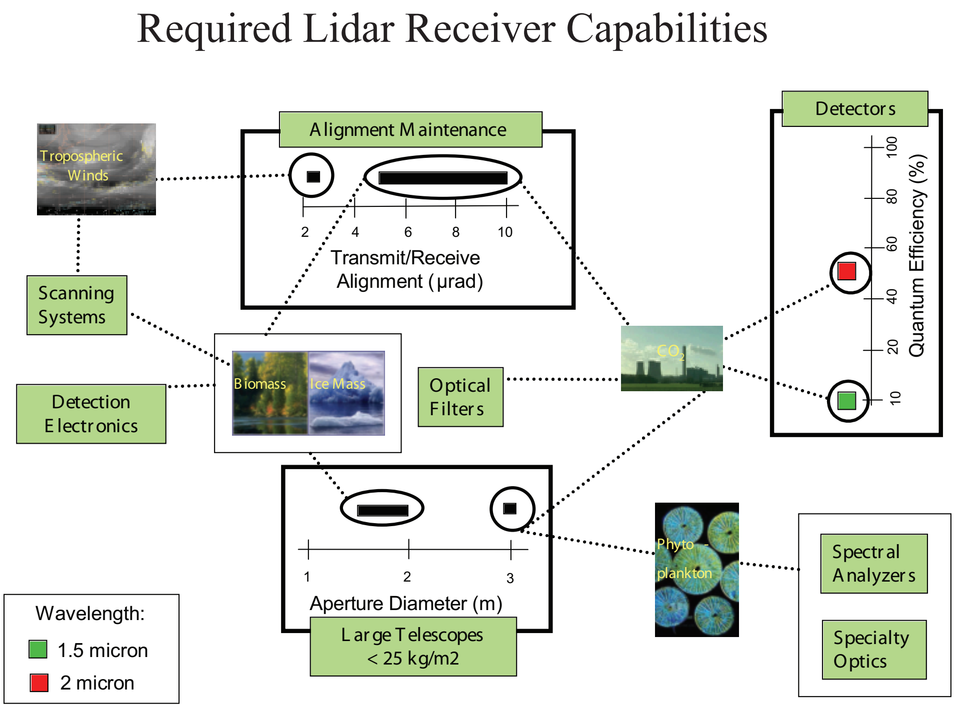


Figure 6-7: Lidar Receiver Applications

Data Acquisition and Utilization Applications

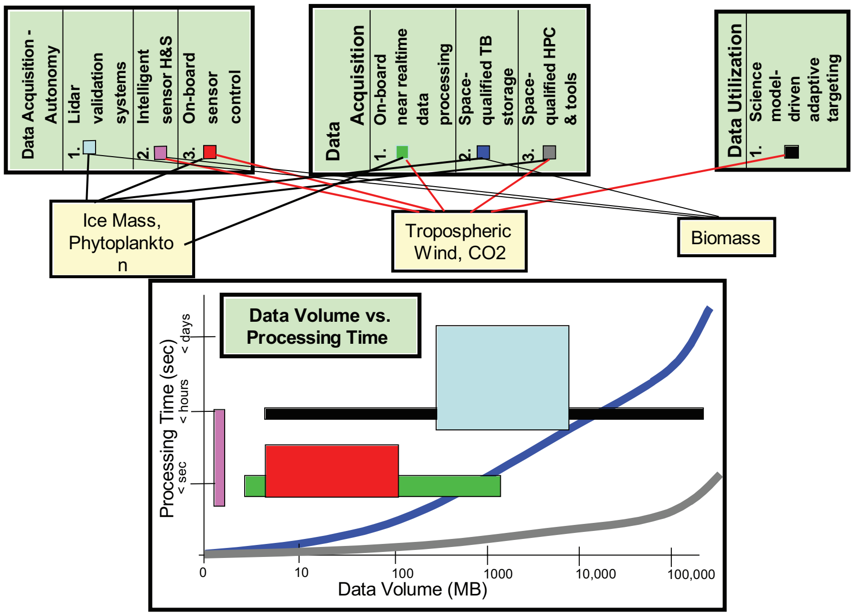
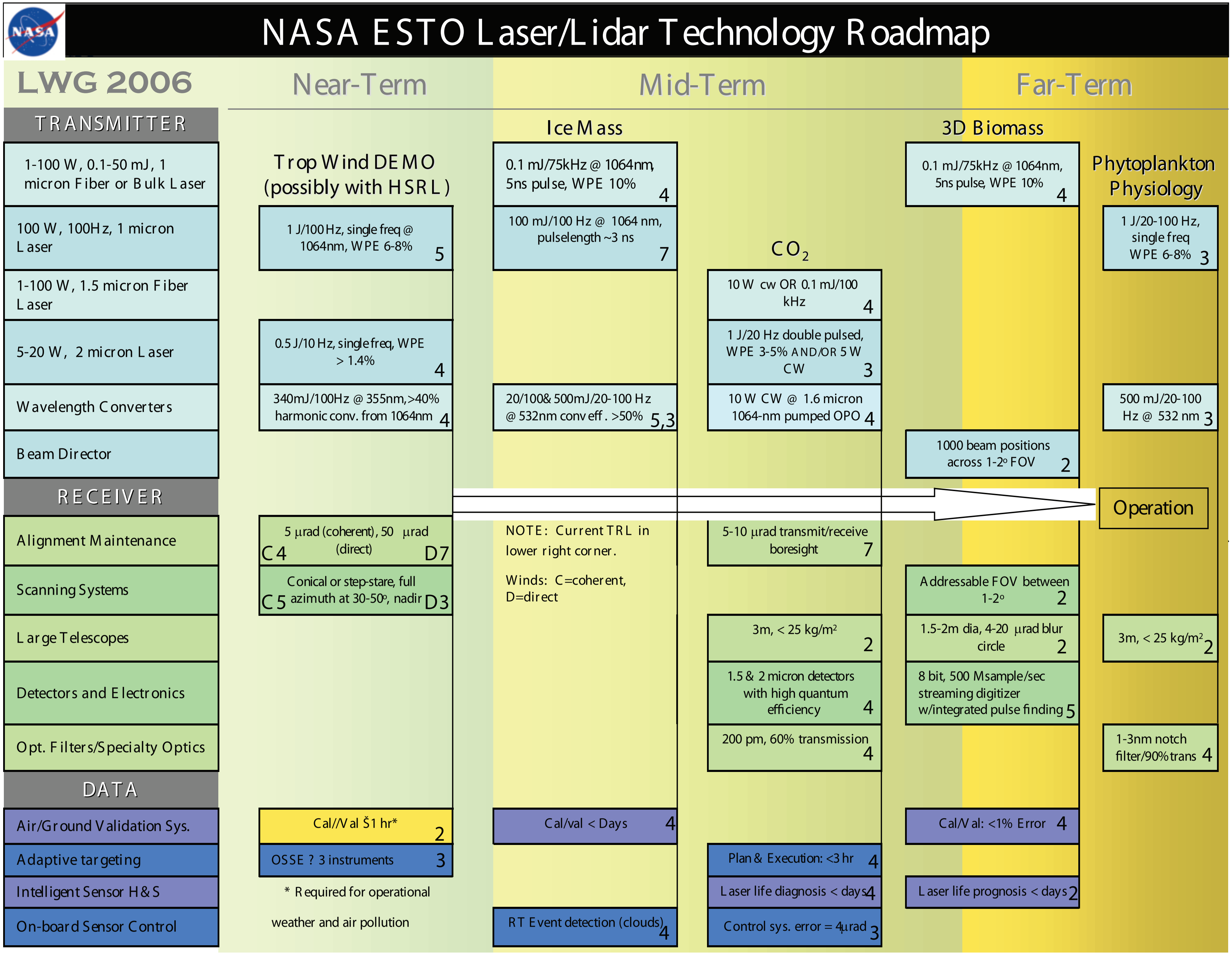


Figure 6-8: Data Acquisition and Utilization Applications



NASA ESTO Laser/Lidar Technology Roadmap

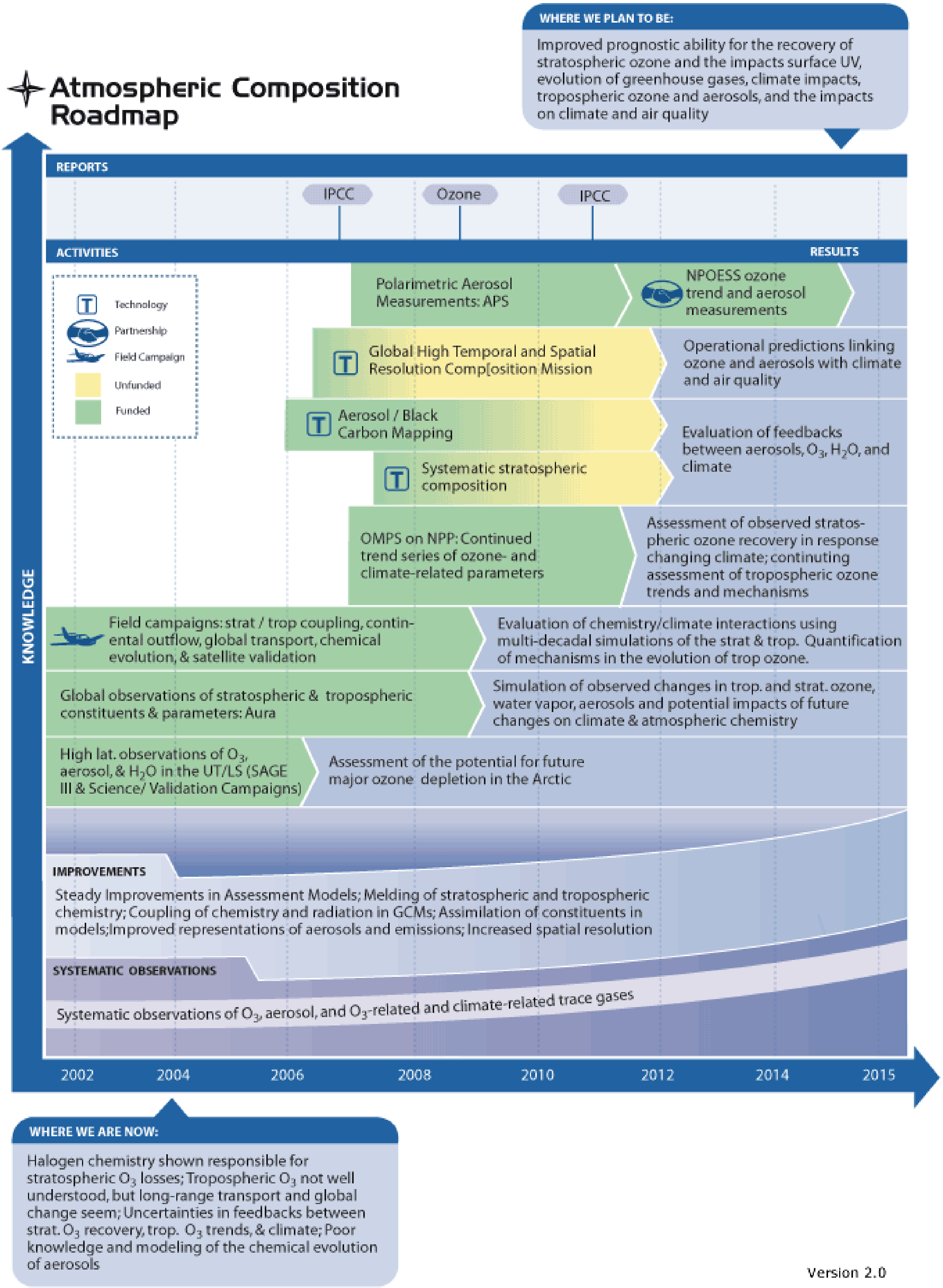
LWG 2006	Near-Term	Mid-Term		Far-Term	
	Trop Wind DEMO (possibly with HSRL)	Ice Mass	CO$_2$	3D Biomass	Phytoplankton Physiology
TRANSMITTER					
1-100 W, 0.1-50 mJ, 1 micron Fiber or Bulk Laser		0.1 mJ/75kHz @ 1064nm, 5ns pulse, WPE 10% 4		0.1 mJ/75kHz @ 1064nm, 5ns pulse, WPE 10% 4	
100 W, 100Hz, 1 micron Laser	1 J/100Hz, single freq @ 1064nm, WPE 6-8% 5	100 mJ/100 Hz @ 1064 nm, pulselength ~3 ns 7			1 J/20-100 Hz, single freq WPE 6-8% 3
1-100 W, 1.5 micron Fiber Laser			10 W cw OR 0.1 mJ/100 kHz 4		
5-20 W, 2 micron Laser	0.5 J/10 Hz, single freq, WPE > 1.4% 4		1 J/20 Hz double pulsed, WPE 3-5% AND/OR 5 W CW 3		
Wavelength Converters	340mJ/100Hz @ 355nm,>40% harmonic conv. from 1064nm 4	20/100& 500mJ/20-100 Hz @ 532nm conv eff. >50% 5,3	10 W CW @ 1.6 micron 1064-nm pumped OPO 4		500 mJ/20-100 Hz @ 532 nm 3
Beam Director				1000 beam positions across 1-2° FOV 2	
RECEIVER					Operation
Alignment Maintenance	5 µrad (coherent), 50 µrad (direct) C4 D7	NOTE: Current TRL in lower right corner. Winds: C=coherent, D=direct	5-10 µrad transmit/receive boresight 7		
Scanning Systems	Conical or step-stare, full azimuth at 30-50°, nadir C5 D3			Addressable FOV between 1-2° 2	
Large Telescopes			3m, < 25 kg/m² 2	1.5-2m dia, 4-20 µrad blur circle 2	3m, < 25 kg/m² 2
Detectors and Electronics			1.5 & 2 micron detectors with high quantum efficiency 4	8 bit, 500 Msample/sec streaming digitizer w/integrated pulse finding 5	
Opt. Filters/Specialty Optics			200 pm, 60% transmission 4		1-3nm notch filter/90% trans 4
DATA					
Air/Ground Validation Sys.	Cal//Val Š1 hr* 2	Cal/val < Days 4		Cal/Val: <1% Error 4	
Adaptive targeting	OSSE ? 3 instruments 3		Plan & Execution: <3 hr 4		
Intelligent Sensor H&S			Laser life diagnosis < days 4	Laser life prognosis < days 2	
On-board Sensor Control		RT Event detection (clouds) 4	Control sys. error = 4µrad 3		

* Required for operational weather and air pollution

Figure 6-9: Laser/Lidar Technology Roadmap

APPENDIX

Sections 1A - 6D



Atmospheric Composition Roadmap

WHERE WE PLAN TO BE:

Improved prognostic ability for the recovery of stratospheric ozone and the impacts surface UV, evolution of greenhouse gases, climate impacts, tropospheric ozone and aerosols, and the impacts on climate and air quality

REPORTS

IPCC

Ozone

IPCC

ACTIVITIES

RESULTS

T Technology
Partnership
Field Campaign
🟨 Unfunded
🟩 Funded

Polarimetric Aerosol Measurements: APS

NPOESS ozone trend and aerosol measurements

T Global High Temporal and Spatial Resolution Comp[osition Mission

Operational predictions linking ozone and aerosols with climate and air quality

T Aerosol / Black Carbon Mapping

T Systematic stratospheric composition

Evaluation of feedbacks between aerosols, O_3, H_2O, and climate

OMPS on NPP: Continued trend series of ozone- and climate-related parameters

Assessment of observed stratospheric ozone recovery in response changing climate; continuing assessment of tropospheric ozone trends and mechanisms

Field campaigns: strat / trop coupling, continental outflow, global transport, chemical evolution, & satellite validation

Evaluation of chemistry/climate interactions using multi-decadal simulations of the strat & trop. Quantification of mechanisms in the evolution of trop ozone.

Global observations of stratospheric & tropospheric constituents & parameters: Aura

Simulation of observed changes in trop. and strat. ozone, water vapor, aerosols and potential impacts of future changes on climate & atmospheric chemistry

High lat. observations of O_3, aerosol, & H_2O in the UT/LS (SAGE III & Science/ Validation Campaigns)

Assessment of the potential for future major ozone depletion in the Arctic

IMPROVEMENTS

Steady Improvements in Assessment Models; Melding of stratospheric and tropospheric chemistry; Coupling of chemistry and radiation in GCMs; Assimilation of constituents in models; Improved representations of aerosols and emissions; Increased spatial resolution

SYSTEMATIC OBSERVATIONS

Systematic observations of O_3, aerosol, and O_3-related and climate-related trace gases

WHERE WE ARE NOW:

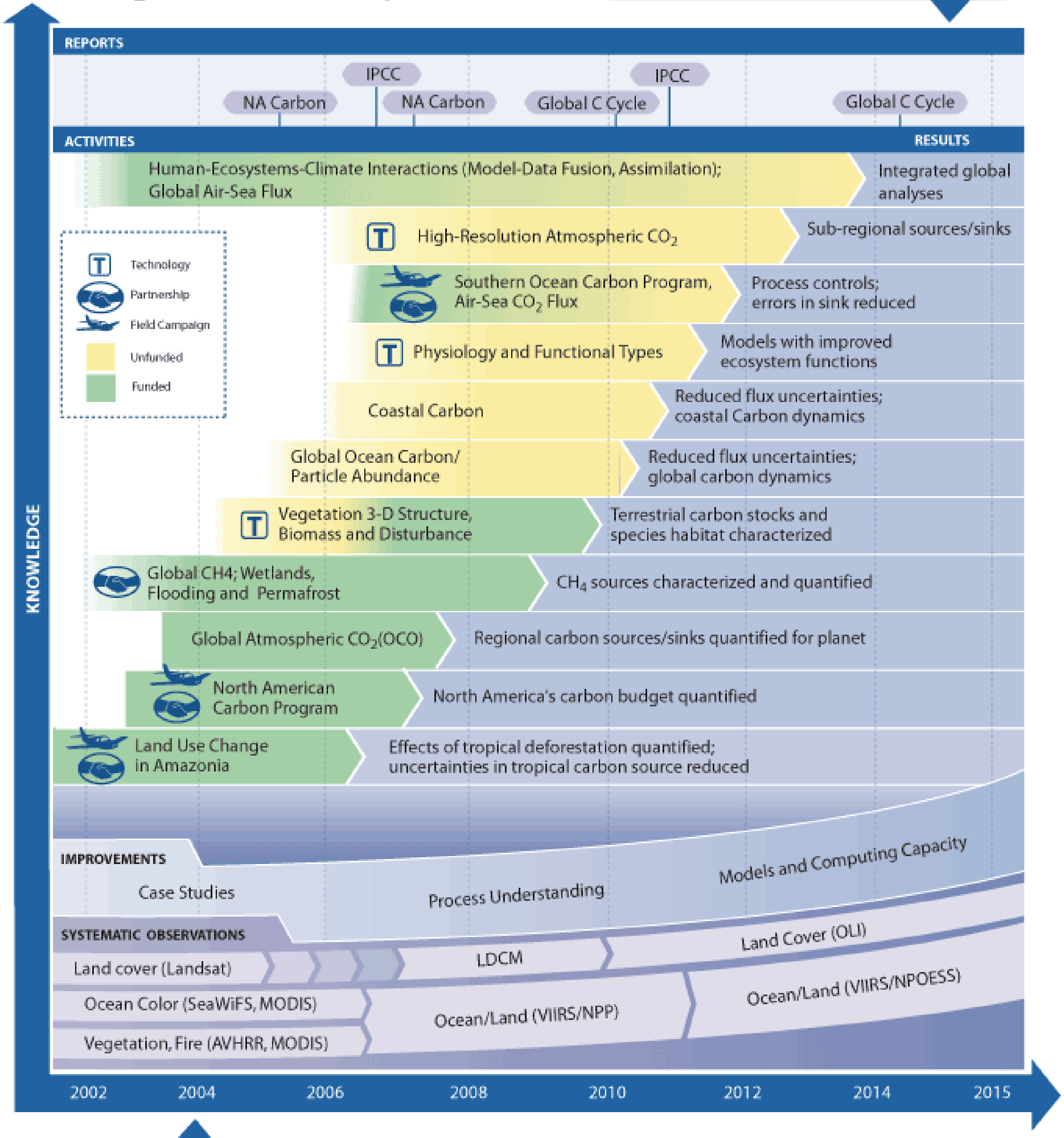
Halogen chemistry shown responsible for stratospheric O_3 losses; Tropospheric O_3 not well understood, but long-range transport and global change seem; Uncertainties in feedbacks between strat. O_3 recovery, trop. O_3 trends, & climate; Poor knowledge and modeling of the chemical evolution of aerosols

Version 2.0

Carbon Cycle and Ecosystems Roadmap

WHERE WE PLAN TO BE:

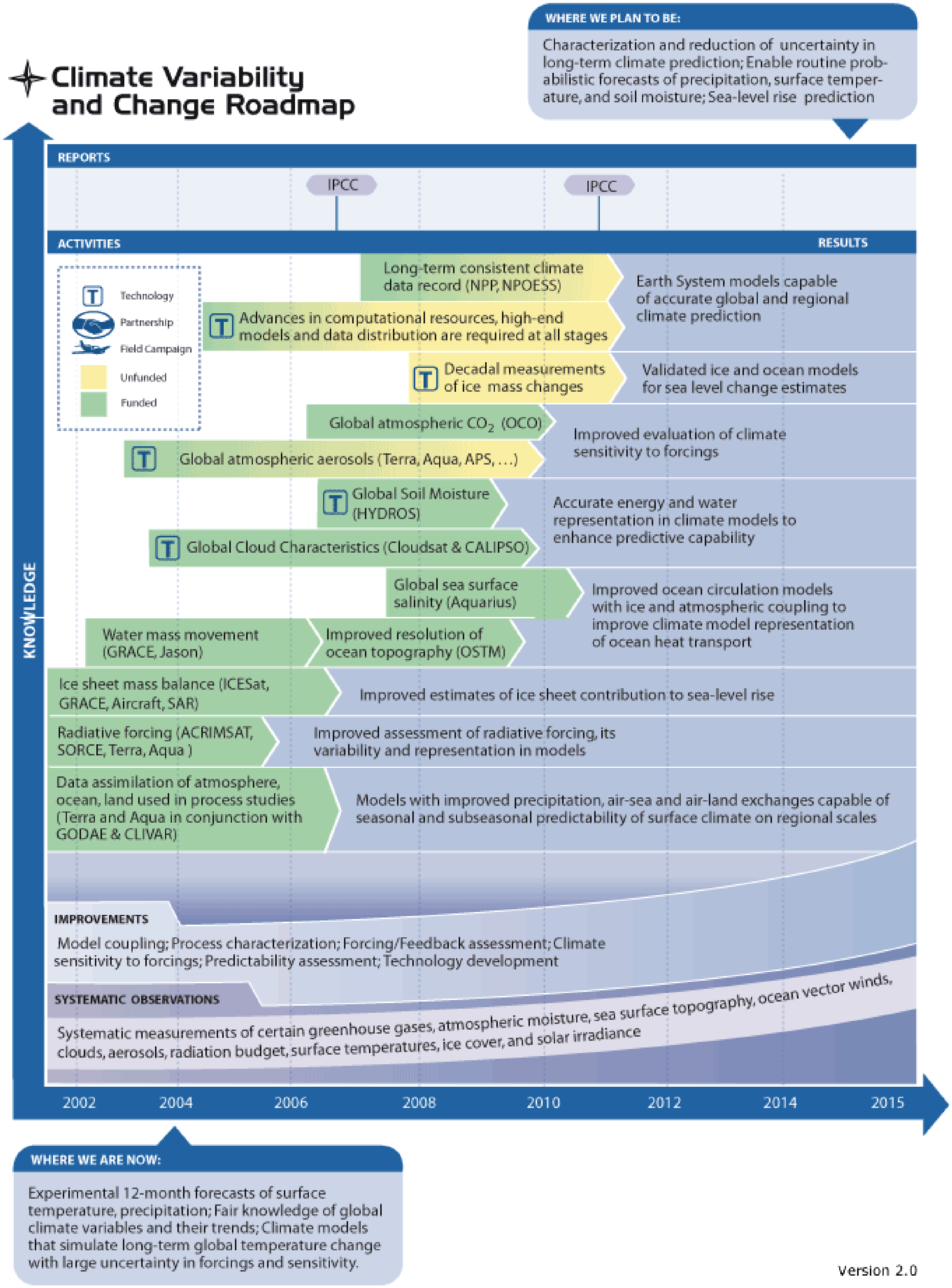
Global productivity and land cover change at fine resolution; biomass and carbon fluxes quantified; useful ecological forecasts and improved climate change projections



WHERE WE ARE NOW:

2002: Global productivity and land cover resolution coarse; Large uncertainties in biomass, fluxes, disturbance, and coastal events

Version 2.0



Climate Variability and Change Roadmap

WHERE WE PLAN TO BE:

Characterization and reduction of uncertainty in long-term climate prediction; Enable routine probabilistic forecasts of precipitation, surface temperature, and soil moisture; Sea-level rise prediction

REPORTS

IPCC

IPCC

ACTIVITIES

RESULTS

T Technology

Partnership

Field Campaign

🟨 Unfunded

🟩 Funded

Long-term consistent climate data record (NPP, NPOESS)

T Advances in computational resources, high-end models and data distribution are required at all stages

Earth System models capable of accurate global and regional climate prediction

T Decadal measurements of ice mass changes

Validated ice and ocean models for sea level change estimates

Global atmospheric CO_2 (OCO)

T Global atmospheric aerosols (Terra, Aqua, APS, …)

Improved evaluation of climate sensitivity to forcings

T Global Soil Moisture (HYDROS)

T Global Cloud Characteristics (Cloudsat & CALIPSO)

Accurate energy and water representation in climate models to enhance predictive capability

Global sea surface salinity (Aquarius)

Water mass movement (GRACE, Jason)

Improved resolution of ocean topography (OSTM)

Improved ocean circulation models with ice and atmospheric coupling to improve climate model representation of ocean heat transport

Ice sheet mass balance (ICESat, GRACE, Aircraft, SAR)

Improved estimates of ice sheet contribution to sea-level rise

Radiative forcing (ACRIMSAT, SORCE, Terra, Aqua)

Improved assessment of radiative forcing, its variability and representation in models

Data assimilation of atmosphere, ocean, land used in process studies (Terra and Aqua in conjunction with GODAE & CLIVAR)

Models with improved precipitation, air-sea and air-land exchanges capable of seasonal and subseasonal predictability of surface climate on regional scales

IMPROVEMENTS

Model coupling; Process characterization; Forcing/Feedback assessment; Climate sensitivity to forcings; Predictability assessment; Technology development

SYSTEMATIC OBSERVATIONS

Systematic measurements of certain greenhouse gases, atmospheric moisture, sea surface topography, ocean vector winds, clouds, aerosols, radiation budget, surface temperatures, ice cover, and solar irradiance

WHERE WE ARE NOW:

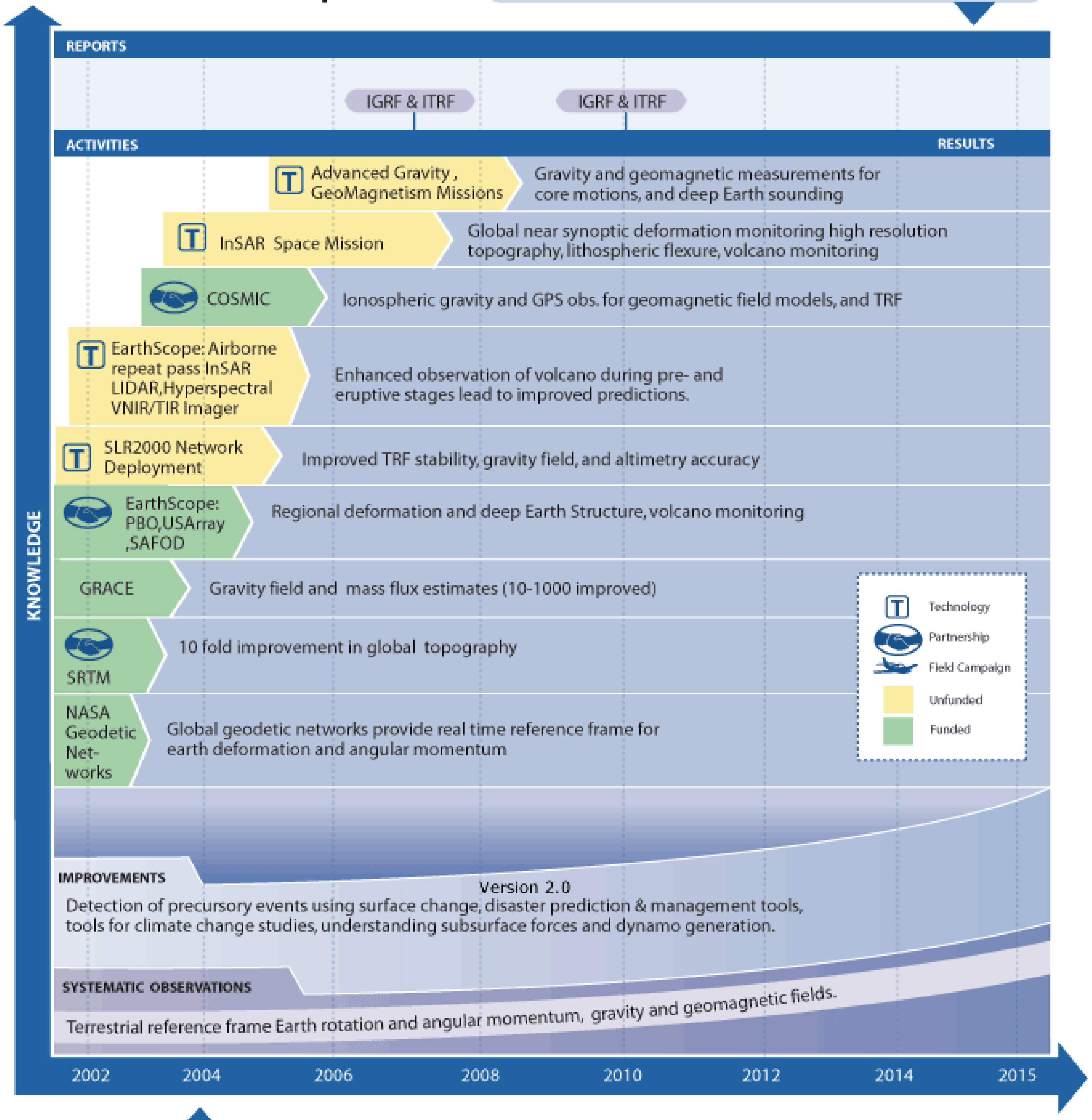
Experimental 12-month forecasts of surface temperature, precipitation; Fair knowledge of global climate variables and their trends; Climate models that simulate long-term global temperature change with large uncertainty in forcings and sensitivity.

Version 2.0

Earth Surface and Interior RoadMap

WHERE WE PLAN TO BE:

Understand plate boundary deformation & earth-quake hazards; How tectonics & climate interact ions shape the Earth's surface; Sea level changes from the interactions of ice masses, oceans, & the solid Earth



REPORTS

IGRF & ITRF

IGRF & ITRF

ACTIVITIES	RESULTS
T Advanced Gravity , GeoMagnetism Missions	Gravity and geomagnetic measurements for core motions, and deep Earth sounding
T InSAR Space Mission	Global near synoptic deformation monitoring high resolution topography, lithospheric flexure, volcano monitoring
🤝 COSMIC	Ionospheric gravity and GPS obs. for geomagnetic field models, and TRF
T EarthScope: Airborne repeat pass InSAR LIDAR, Hyperspectral VNIR/TIR Imager	Enhanced observation of volcano during pre- and eruptive stages lead to improved predictions.
T SLR2000 Network Deployment	Improved TRF stability, gravity field, and altimetry accuracy
🤝 EarthScope: PBO, USArray ,SAFOD	Regional deformation and deep Earth Structure, volcano monitoring
GRACE	Gravity field and mass flux estimates (10-1000 improved)
🤝 SRTM	10 fold improvement in global topography
NASA Geodetic Networks	Global geodetic networks provide real time reference frame for earth deformation and angular momentum

T Technology
🤝 Partnership
✈ Field Campaign
🟨 Unfunded
🟩 Funded

IMPROVEMENTS

Version 2.0

Detection of precursory events using surface change, disaster prediction & management tools, tools for climate change studies, understanding subsurface forces and dynamo generation.

SYSTEMATIC OBSERVATIONS

Terrestrial reference frame Earth rotation and angular momentum, gravity and geomagnetic fields.

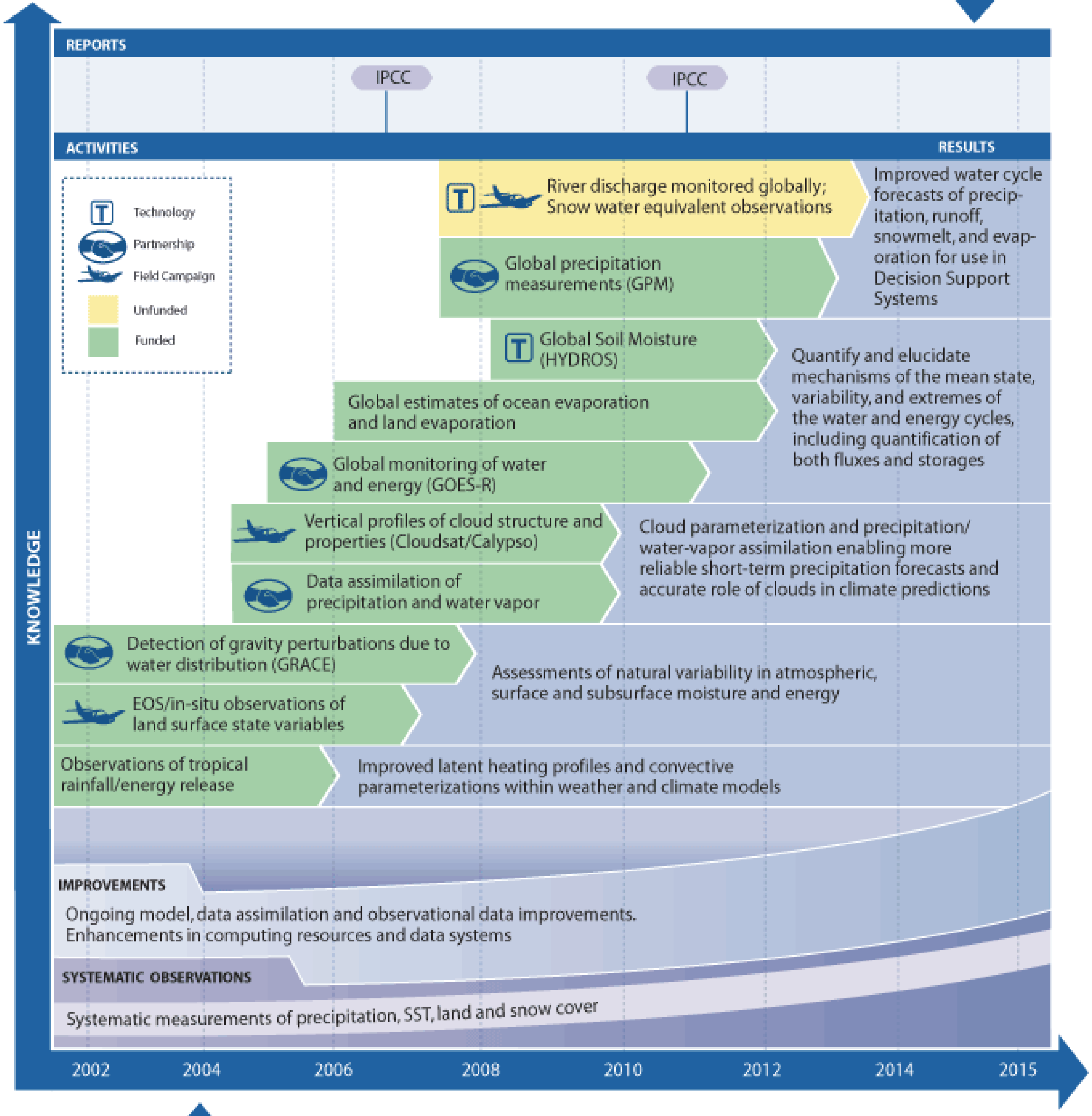
WHERE WE ARE NOW:

Space geodesy determines mm scale topography changes; Detection of Periodic and aseismic cm-scale strain events, and some seismic precursors. Postseismic stress changes linked to certain earthquakes; Volcanic inflation detected by InSAR reflect movement of magma at depth without seismic or eruptive signals.

Water and Energy Cycle Roadmap

WHERE WE PLAN TO BE:

Capability to observe, model, and predict the Water and Energy cycles, including regional scales and extreme events



REPORTS

IPCC (2006)

IPCC (2010)

ACTIVITIES

- T Technology
- Partnership
- Field Campaign
- 🟨 Unfunded
- 🟩 Funded

ACTIVITIES	RESULTS
River discharge monitored globally; Snow water equivalent observations	Improved water cycle forecasts of precipitation, runoff, snowmelt, and evaporation for use in Decision Support Systems
Global precipitation measurements (GPM)	
Global Soil Moisture (HYDROS)	Quantify and elucidate mechanisms of the mean state, variability, and extremes of the water and energy cycles, including quantification of both fluxes and storages
Global estimates of ocean evaporation and land evaporation	
Global monitoring of water and energy (GOES-R)	
Vertical profiles of cloud structure and properties (Cloudsat/Calypso)	Cloud parameterization and precipitation/water-vapor assimilation enabling more reliable short-term precipitation forecasts and accurate role of clouds in climate predictions
Data assimilation of precipitation and water vapor	
Detection of gravity perturbations due to water distribution (GRACE)	Assessments of natural variability in atmospheric, surface and subsurface moisture and energy
EOS/in-situ observations of land surface state variables	
Observations of tropical rainfall/energy release	Improved latent heating profiles and convective parameterizations within weather and climate models

IMPROVEMENTS

Ongoing model, data assimilation and observational data improvements. Enhancements in computing resources and data systems

SYSTEMATIC OBSERVATIONS

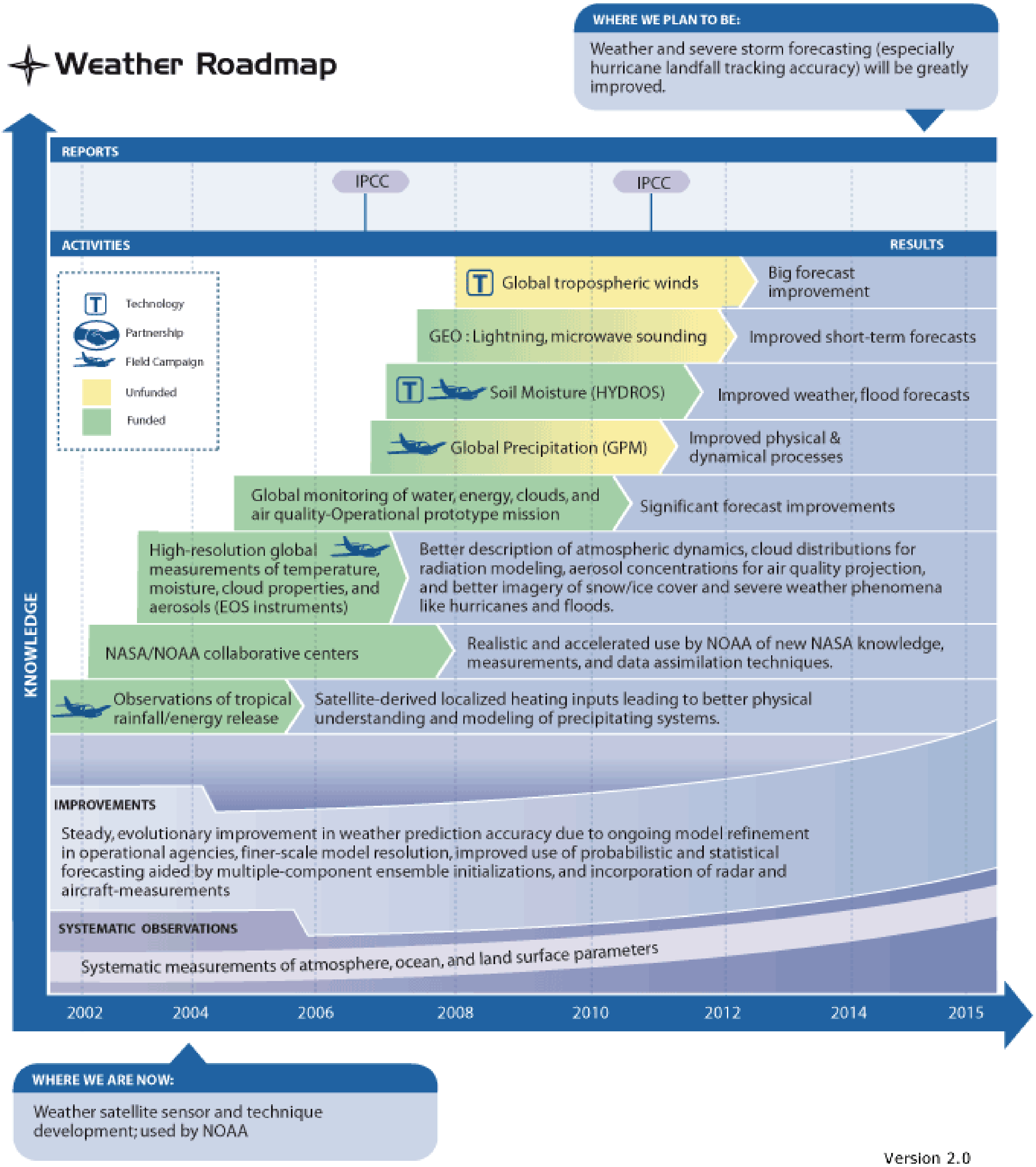
Systematic measurements of precipitation, SST, land and snow cover

WHERE WE ARE NOW:

Reservoirs and tropical rainfall well quantified Difficulty balancing the water budget on any scale Inability to observe and predict precipitation globally

Version 2.0

Weather Roadmap



WHERE WE PLAN TO BE:

Weather and severe storm forecasting (especially hurricane landfall tracking accuracy) will be greatly improved.

ACTIVITIES	RESULTS
T Global tropospheric winds	Big forecast improvement
GEO : Lightning, microwave sounding	Improved short-term forecasts
T Soil Moisture (HYDROS)	Improved weather, flood forecasts
Global Precipitation (GPM)	Improved physical & dynamical processes
Global monitoring of water, energy, clouds, and air quality-Operational prototype mission	Significant forecast improvements
High-resolution global measurements of temperature, moisture, cloud properties, and aerosols (EOS instruments)	Better description of atmospheric dynamics, cloud distributions for radiation modeling, aerosol concentrations for air quality projection, and better imagery of snow/ice cover and severe weather phenomena like hurricanes and floods.
NASA/NOAA collaborative centers	Realistic and accelerated use by NOAA of new NASA knowledge, measurements, and data assimilation techniques.
Observations of tropical rainfall/energy release	Satellite-derived localized heating inputs leading to better physical understanding and modeling of precipitating systems.

IMPROVEMENTS

Steady, evolutionary improvement in weather prediction accuracy due to ongoing model refinement in operational agencies, finer-scale model resolution, improved use of probabilistic and statistical forecasting aided by multiple-component ensemble initializations, and incorporation of radar and aircraft-measurements

SYSTEMATIC OBSERVATIONS

Systematic measurements of atmosphere, ocean, and land surface parameters

WHERE WE ARE NOW:

Weather satellite sensor and technique development; used by NOAA

Version 2.0

Appendix 1B: NASA ESTO Lidar Technology Working Group Members

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Winker, Dave	NASA/LaRC
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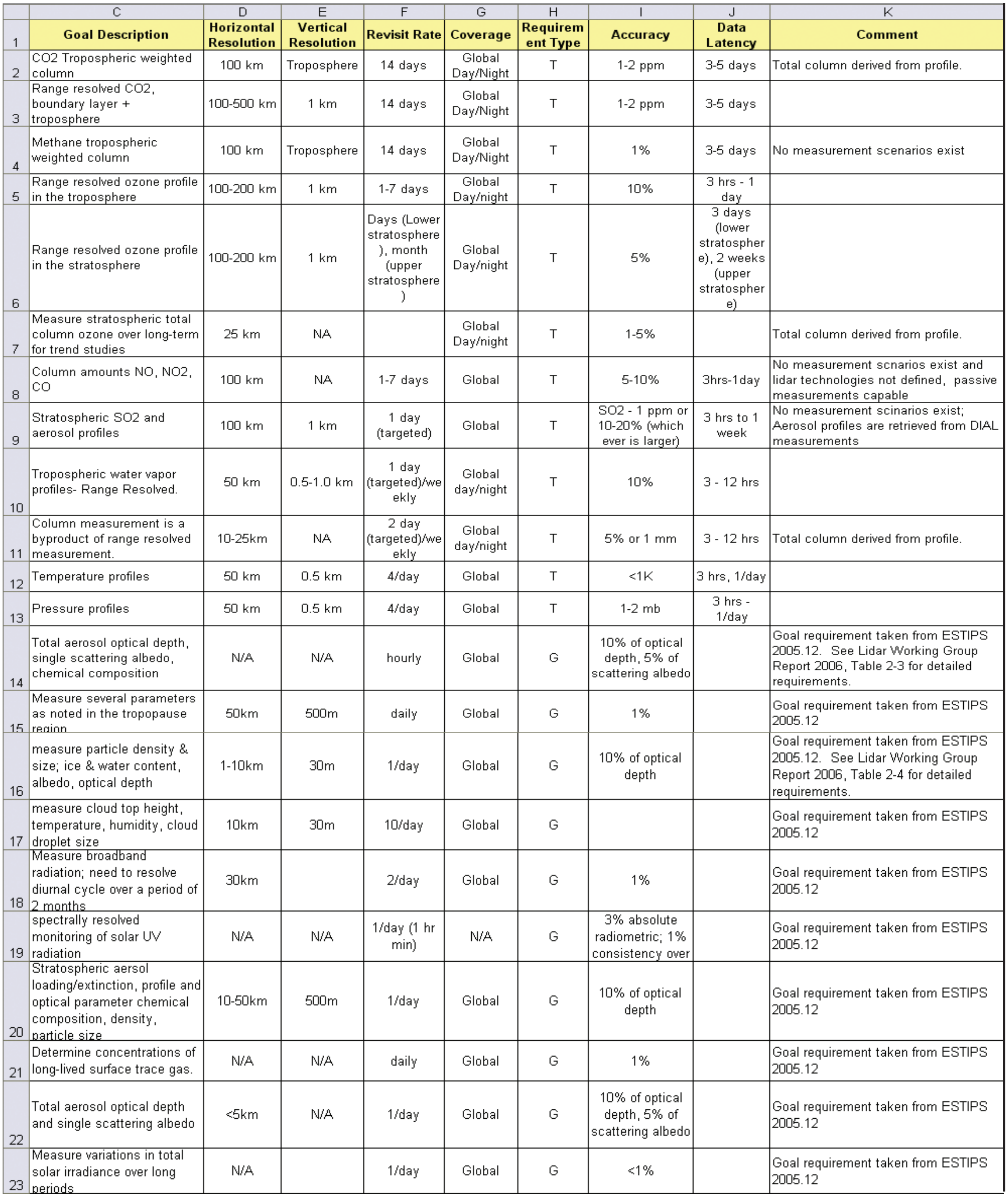
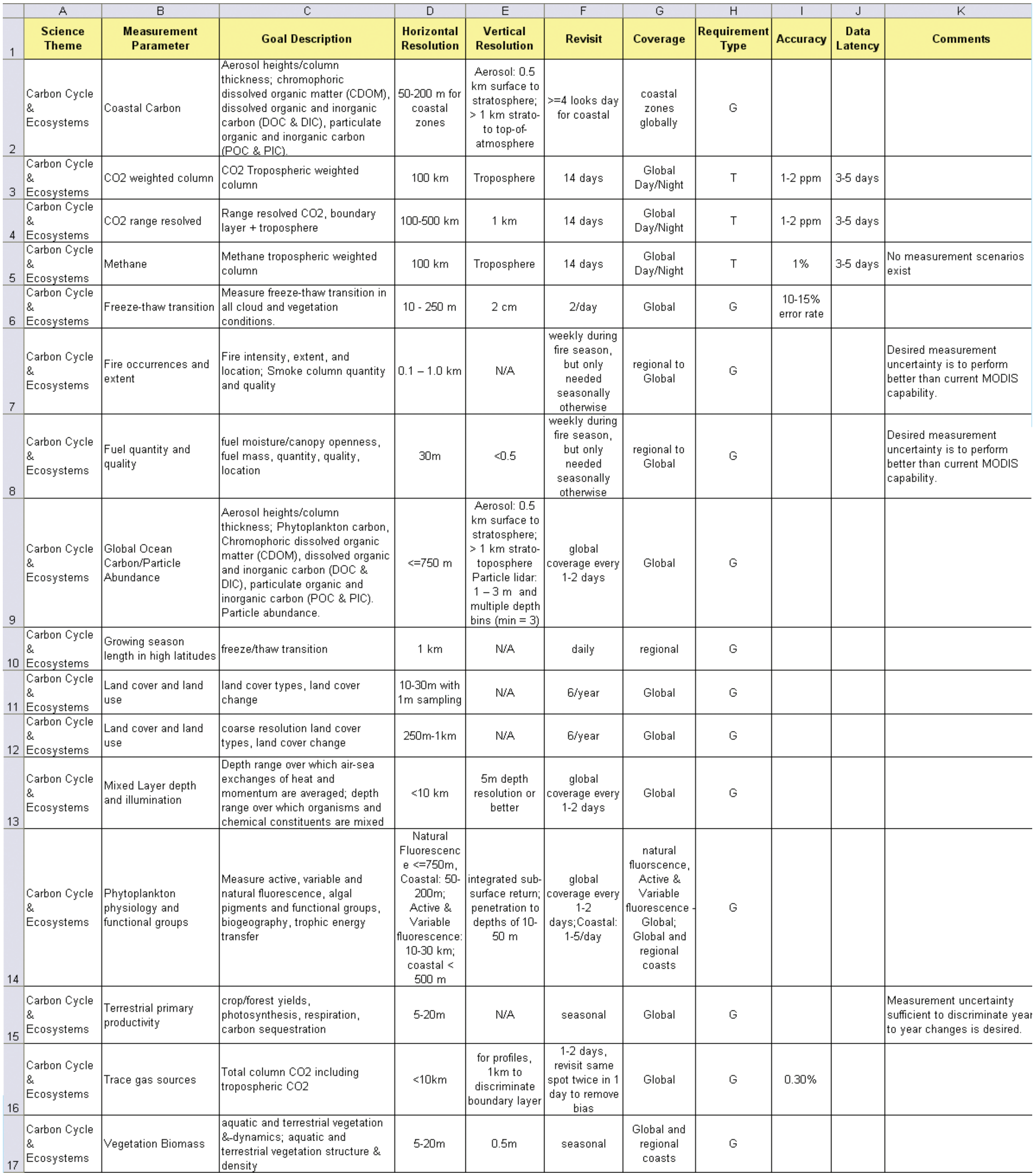
Appendix 2A: Atmospheric Composition Science Requirements



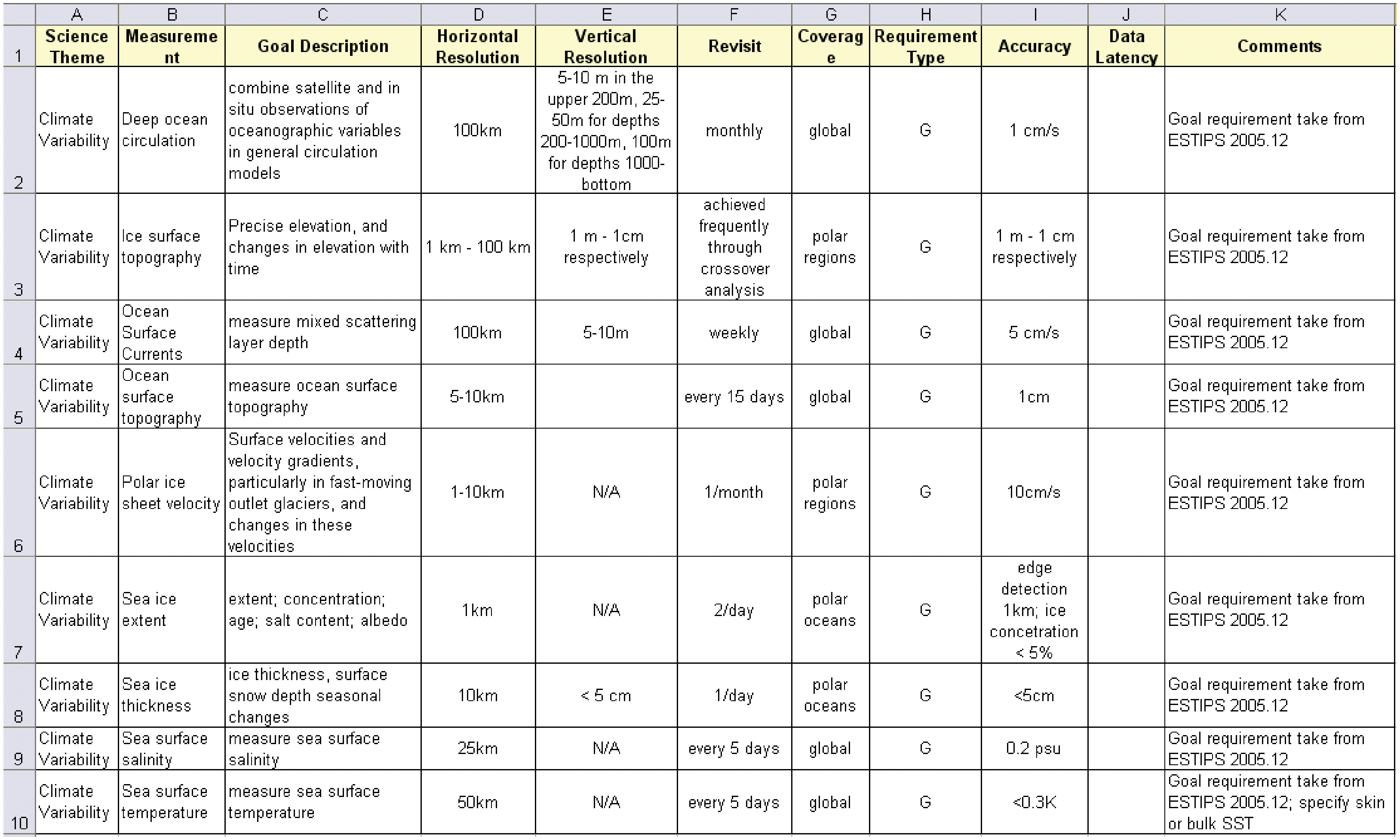
	C	D	E	F	G	H	I	J	K
1	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit Rate**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comment**
2	CO2 Tropospheric weighted column	100 km	Troposphere	14 days	Global Day/Night	T	1-2 ppm	3-5 days	Total column derived from profile.
3	Range resolved CO2, boundary layer + troposphere	100-500 km	1 km	14 days	Global Day/Night	T	1-2 ppm	3-5 days	
4	Methane tropospheric weighted column	100 km	Troposphere	14 days	Global Day/Night	T	1%	3-5 days	No measurement scenarios exist
5	Range resolved ozone profile in the troposphere	100-200 km	1 km	1-7 days	Global Day/night	T	10%	3 hrs - 1 day	
6	Range resolved ozone profile in the stratosphere	100-200 km	1 km	Days (Lower stratosphere), month (upper stratosphere)	Global Day/night	T	5%	3 days (lower stratosphere), 2 weeks (upper stratosphere)	
7	Measure stratospheric total column ozone over long-term for trend studies	25 km	NA		Global Day/night	T	1-5%		Total column derived from profile.
8	Column amounts NO, NO2, CO	100 km	NA	1-7 days	Global	T	5-10%	3hrs-1day	No measurement scnarios exist and lidar technologies not defined, passive measurements capable
9	Stratospheric SO2 and aerosol profiles	100 km	1 km	1 day (targeted)	Global	T	SO2 - 1 ppm or 10-20% (which ever is larger)	3 hrs to 1 week	No measurement scinarios exist; Aerosol profiles are retrieved from DIAL measurements
10	Tropospheric water vapor profiles- Range Resolved.	50 km	0.5-1.0 km	1 day (targeted)/weekly	Global day/night	T	10%	3 - 12 hrs	
11	Column measurement is a byproduct of range resolved measurement.	10-25km	NA	2 day (targeted)/weekly	Global day/night	T	5% or 1 mm	3 - 12 hrs	Total column derived from profile.
12	Temperature profiles	50 km	0.5 km	4/day	Global	T	<1K	3 hrs, 1/day	
13	Pressure profiles	50 km	0.5 km	4/day	Global	T	1-2 mb	3 hrs - 1/day	
14	Total aerosol optical depth, single scattering albedo, chemical composition	N/A	N/A	hourly	Global	G	10% of optical depth, 5% of scattering albedo		Goal requirement taken from ESTIPS 2005.12. See Lidar Working Group Report 2006, Table 2-3 for detailed requirements.
15	Measure several parameters as noted in the tropopause region	50km	500m	daily	Global	G	1%		Goal requirement taken from ESTIPS 2005.12
16	measure particle density & size; ice & water content, albedo, optical depth	1-10km	30m	1/day	Global	G	10% of optical depth		Goal requirement taken from ESTIPS 2005.12. See Lidar Working Group Report 2006, Table 2-4 for detailed requirements.
17	measure cloud top height, temperature, humidity, cloud droplet size	10km	30m	10/day	Global	G			Goal requirement taken from ESTIPS 2005.12
18	Measure broadband radiation; need to resolve diurnal cycle over a period of 2 months	30km		2/day	Global	G	1%		Goal requirement taken from ESTIPS 2005.12
19	spectrally resolved monitoring of solar UV radiation	N/A	N/A	1/day (1 hr min)	N/A	G	3% absolute radiometric; 1% consistency over		Goal requirement taken from ESTIPS 2005.12
20	Stratospheric aersol loading/extinction, profile and optical parameter chemical composition, density, particle size	10-50km	500m	1/day	Global	G	10% of optical depth		Goal requirement taken from ESTIPS 2005.12
21	Determine concentrations of long-lived surface trace gas.	N/A	N/A	daily	Global	G	1%		Goal requirement taken from ESTIPS 2005.12
22	Total aerosol optical depth and single scattering albedo	<5km	N/A	1/day	Global	G	10% of optical depth, 5% of scattering albedo		Goal requirement taken from ESTIPS 2005.12
23	Measure variations in total solar irradiance over long periods	N/A		1/day	Global	G	<1%		Goal requirement taken from ESTIPS 2005.12

Appendix 2B: Carbon Cycle and Ecosystems Science Requirements



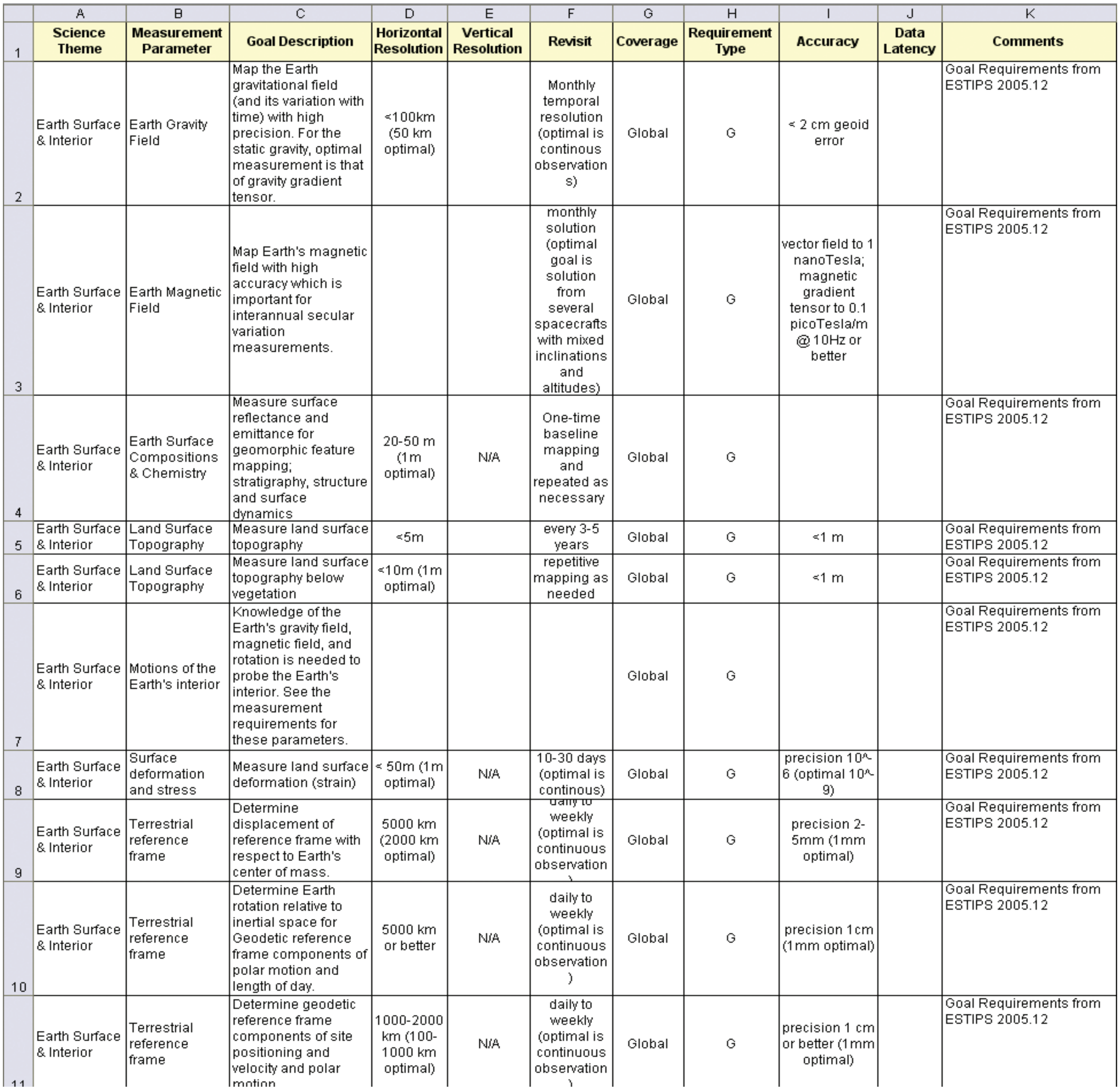
	A	B	C	D	E	F	G	H	I	J	K
1	**Science Theme**	**Measurement Parameter**	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comments**
2	Carbon Cycle & Ecosystems	Coastal Carbon	Aerosol heights/column thickness; chromophoric dissolved organic matter (CDOM), dissolved organic and inorganic carbon (DOC & DIC), particulate organic and inorganic carbon (POC & PIC).	50-200 m for coastal zones	Aerosol: 0.5 km surface to stratosphere; > 1 km strato-to top-of-atmosphere	>=4 looks day for coastal	coastal zones globally	G			
3	Carbon Cycle & Ecosystems	CO2 weighted column	CO2 Tropospheric weighted column	100 km	Troposphere	14 days	Global Day/Night	T	1-2 ppm	3-5 days	
4	Carbon Cycle & Ecosystems	CO2 range resolved	Range resolved CO2, boundary layer + troposphere	100-500 km	1 km	14 days	Global Day/Night	T	1-2 ppm	3-5 days	
5	Carbon Cycle & Ecosystems	Methane	Methane tropospheric weighted column	100 km	Troposphere	14 days	Global Day/Night	T	1%	3-5 days	No measurement scenarios exist
6	Carbon Cycle & Ecosystems	Freeze-thaw transition	Measure freeze-thaw transition in all cloud and vegetation conditions.	10 - 250 m	2 cm	2/day	Global	G	10-15% error rate		
7	Carbon Cycle & Ecosystems	Fire occurrences and extent	Fire intensity, extent, and location; Smoke column quantity and quality	0.1 – 1.0 km	N/A	weekly during fire season, but only needed seasonally otherwise	regional to Global	G			Desired measurement uncertainty is to perform better than current MODIS capability.
8	Carbon Cycle & Ecosystems	Fuel quantity and quality	fuel moisture/canopy openness, fuel mass, quantity, quality, location	30m	<0.5	weekly during fire season, but only needed seasonally otherwise	regional to Global	G			Desired measurement uncertainty is to perform better than current MODIS capability.
9	Carbon Cycle & Ecosystems	Global Ocean Carbon/Particle Abundance	Aerosol heights/column thickness; Phytoplankton carbon, Chromophoric dissolved organic matter (CDOM), dissolved organic and inorganic carbon (DOC & DIC), particulate organic and inorganic carbon (POC & PIC). Particle abundance.	<=750 m	Aerosol: 0.5 km surface to stratosphere; > 1 km strato-toposphere Particle lidar: 1 – 3 m and multiple depth bins (min = 3)	global coverage every 1-2 days	Global	G			
10	Carbon Cycle & Ecosystems	Growing season length in high latitudes	freeze/thaw transition	1 km	N/A	daily	regional	G			
11	Carbon Cycle & Ecosystems	Land cover and land use	land cover types, land cover change	10-30m with 1m sampling	N/A	6/year	Global	G			
12	Carbon Cycle & Ecosystems	Land cover and land use	coarse resolution land cover types, land cover change	250m-1km	N/A	6/year	Global	G			
13	Carbon Cycle & Ecosystems	Mixed Layer depth and illumination	Depth range over which air-sea exchanges of heat and momentum are averaged; depth range over which organisms and chemical constituents are mixed	<10 km	5m depth resolution or better	global coverage every 1-2 days	Global	G			
14	Carbon Cycle & Ecosystems	Phytoplankton physiology and functional groups	Measure active, variable and natural fluorescence, algal pigments and functional groups, biogeography, trophic energy transfer	Natural Fluorescence <=750m, Coastal: 50-200m; Active & Variable fluorescence: 10-30 km; coastal < 500 m	integrated sub-surface return; penetration to depths of 10-50 m	global coverage every 1-2 days;Coastal: 1-5/day	natural fluorscence, Active & Variable fluorescence - Global; Global and regional coasts	G			
15	Carbon Cycle & Ecosystems	Terrestrial primary productivity	crop/forest yields, photosynthesis, respiration, carbon sequestration	5-20m	N/A	seasonal	Global	G			Measurement uncertainty sufficient to discriminate year to year changes is desired.
16	Carbon Cycle & Ecosystems	Trace gas sources	Total column CO2 including tropospheric CO2	<10km	for profiles, 1km to discriminate boundary layer	1-2 days, revisit same spot twice in 1 day to remove bias	Global	G	0.30%		
17	Carbon Cycle & Ecosystems	Vegetation Biomass	aquatic and terrestrial vegetation &-dynamics; aquatic and terrestrial vegetation structure & density	5-20m	0.5m	seasonal	Global and regional coasts	G			

Appendix 2C: Climate Variability Science Requirements



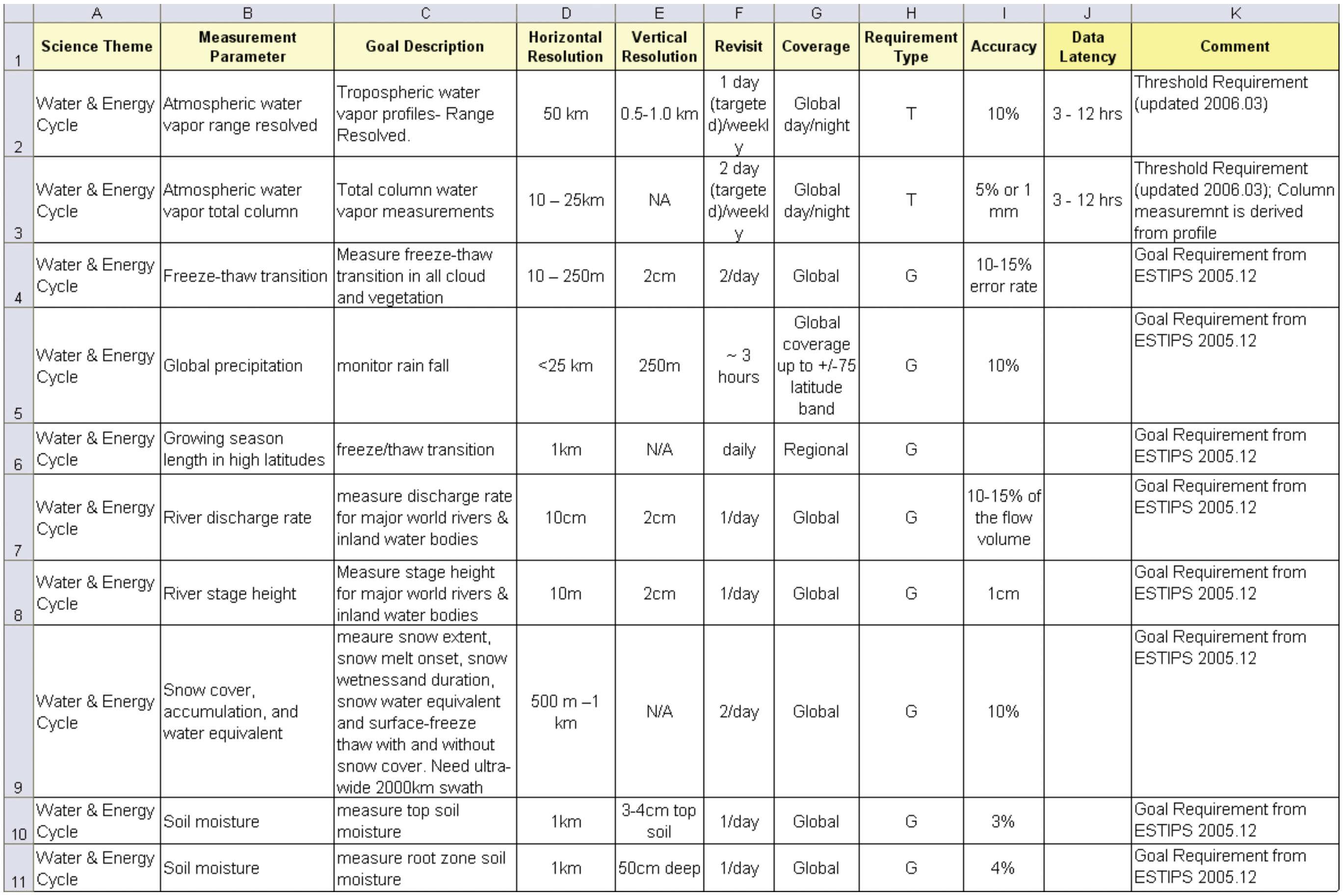
	A	B	C	D	E	F	G	H	I	J	K
1	**Science Theme**	**Measurement**	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comments**
2	Climate Variability	Deep ocean circulation	combine satellite and in situ observations of oceanographic variables in general circulation models	100km	5-10 m in the upper 200m, 25-50m for depths 200-1000m, 100m for depths 1000-bottom	monthly	global	G	1 cm/s		Goal requirement take from ESTIPS 2005.12
3	Climate Variability	Ice surface topography	Precise elevation, and changes in elevation with time	1 km - 100 km	1 m - 1cm respectively	achieved frequently through crossover analysis	polar regions	G	1 m - 1 cm respectively		Goal requirement take from ESTIPS 2005.12
4	Climate Variability	Ocean Surface Currents	measure mixed scattering layer depth	100km	5-10m	weekly	global	G	5 cm/s		Goal requirement take from ESTIPS 2005.12
5	Climate Variability	Ocean surface topography	measure ocean surface topography	5-10km		every 15 days	global	G	1cm		Goal requirement take from ESTIPS 2005.12
6	Climate Variability	Polar ice sheet velocity	Surface velocities and velocity gradients, particularly in fast-moving outlet glaciers, and changes in these velocities	1-10km	N/A	1/month	polar regions	G	10cm/s		Goal requirement take from ESTIPS 2005.12
7	Climate Variability	Sea ice extent	extent; concentration; age; salt content; albedo	1km	N/A	2/day	polar oceans	G	edge detection 1km; ice concetration < 5%		Goal requirement take from ESTIPS 2005.12
8	Climate Variability	Sea ice thickness	ice thickness, surface snow depth seasonal changes	10km	< 5 cm	1/day	polar oceans	G	<5cm		Goal requirement take from ESTIPS 2005.12
9	Climate Variability	Sea surface salinity	measure sea surface salinity	25km	N/A	every 5 days	global	G	0.2 psu		Goal requirement take from ESTIPS 2005.12
10	Climate Variability	Sea surface temperature	measure sea surface temperature	50km	N/A	every 5 days	global	G	<0.3K		Goal requirement take from ESTIPS 2005.12; specify skin or bulk SST

Appendix 2D: Earth Surface and Interior Science Requirements



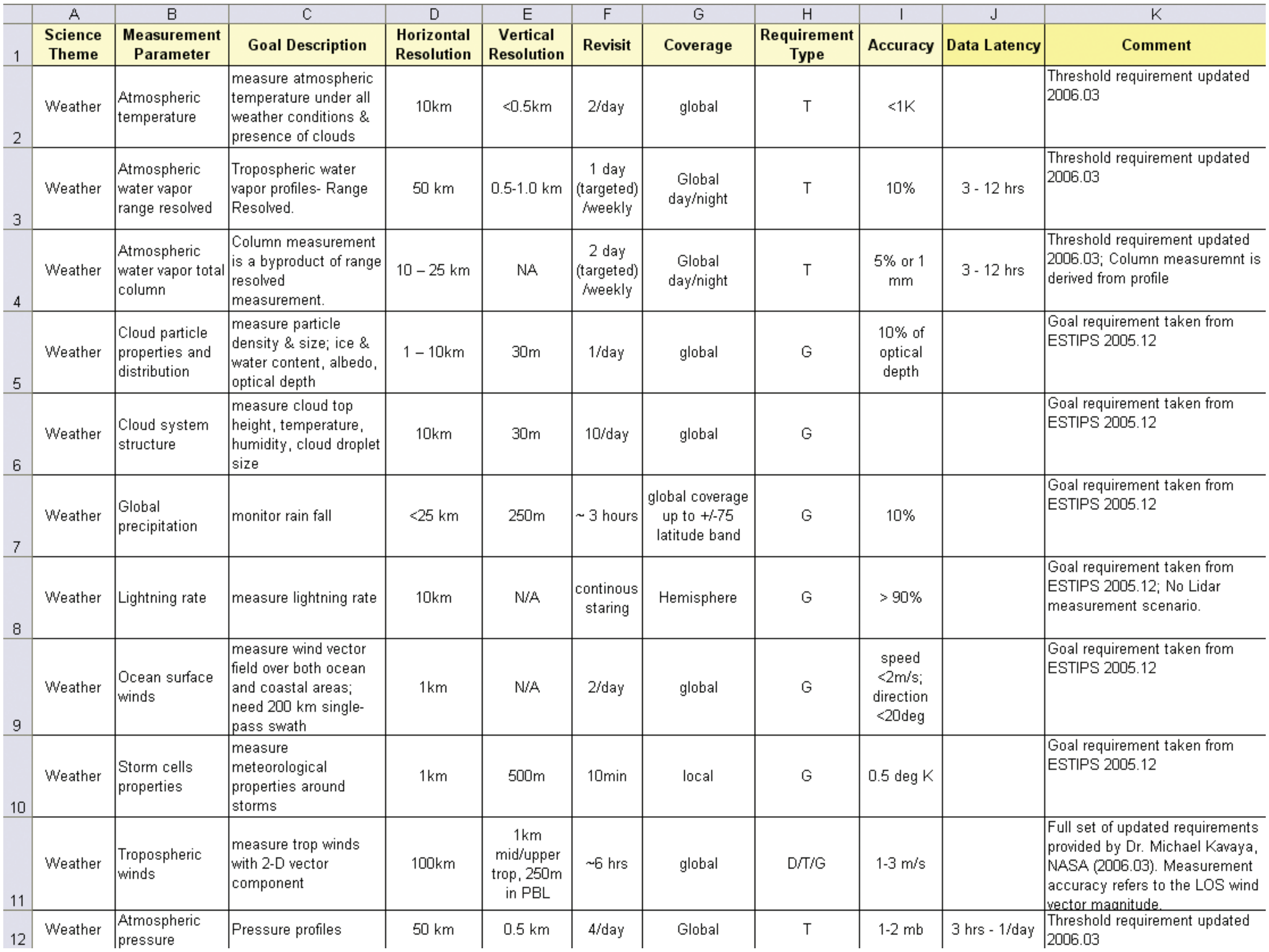
	A	B	C	D	E	F	G	H	I	J	K
1	**Science Theme**	**Measurement Parameter**	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comments**
2	Earth Surface & Interior	Earth Gravity Field	Map the Earth gravitational field (and its variation with time) with high precision. For the static gravity, optimal measurement is that of gravity gradient tensor.	<100km (50 km optimal)		Monthly temporal resolution (optimal is continous observations)	Global	G	< 2 cm geoid error		Goal Requirements from ESTIPS 2005.12
3	Earth Surface & Interior	Earth Magnetic Field	Map Earth's magnetic field with high accuracy which is important for interannual secular variation measurements.			monthly solution (optimal goal is solution from several spacecrafts with mixed inclinations and altitudes)	Global	G	vector field to 1 nanoTesla; magnetic gradient tensor to 0.1 picoTesla/m @ 10Hz or better		Goal Requirements from ESTIPS 2005.12
4	Earth Surface & Interior	Earth Surface Compositions & Chemistry	Measure surface reflectance and emittance for geomorphic feature mapping; stratigraphy, structure and surface dynamics	20-50 m (1m optimal)	N/A	One-time baseline mapping and repeated as necessary	Global	G			Goal Requirements from ESTIPS 2005.12
5	Earth Surface & Interior	Land Surface Topography	Measure land surface topography	<5m		every 3-5 years	Global	G	<1 m		Goal Requirements from ESTIPS 2005.12
6	Earth Surface & Interior	Land Surface Topography	Measure land surface topography below vegetation	<10m (1m optimal)		repetitive mapping as needed	Global	G	<1 m		Goal Requirements from ESTIPS 2005.12
7	Earth Surface & Interior	Motions of the Earth's interior	Knowledge of the Earth's gravity field, magnetic field, and rotation is needed to probe the Earth's interior. See the measurement requirements for these parameters.				Global	G			Goal Requirements from ESTIPS 2005.12
8	Earth Surface & Interior	Surface deformation and stress	Measure land surface deformation (strain)	< 50m (1m optimal)	N/A	10-30 days (optimal is continous)	Global	G	precision 10^-6 (optimal 10^-9)		Goal Requirements from ESTIPS 2005.12
9	Earth Surface & Interior	Terrestrial reference frame	Determine displacement of reference frame with respect to Earth's center of mass.	5000 km (2000 km optimal)	N/A	daily to weekly (optimal is continuous observation)	Global	G	precision 2-5mm (1mm optimal)		Goal Requirements from ESTIPS 2005.12
10	Earth Surface & Interior	Terrestrial reference frame	Determine Earth rotation relative to inertial space for Geodetic reference frame components of polar motion and length of day.	5000 km or better	N/A	daily to weekly (optimal is continuous observation)	Global	G	precision 1cm (1mm optimal)		Goal Requirements from ESTIPS 2005.12
11	Earth Surface & Interior	Terrestrial reference frame	Determine geodetic reference frame components of site positioning and velocity and polar motion	1000-2000 km (100-1000 km optimal)	N/A	daily to weekly (optimal is continuous observation)	Global	G	precision 1 cm or better (1mm optimal)		Goal Requirements from ESTIPS 2005.12

Appendix 2E: Water and Energy Cycle Science Requirements



	A	B	C	D	E	F	G	H	I	J	K
1	**Science Theme**	**Measurement Parameter**	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comment**
2	Water & Energy Cycle	Atmospheric water vapor range resolved	Tropospheric water vapor profiles- Range Resolved.	50 km	0.5-1.0 km	1 day (targeted)/weekly	Global day/night	T	10%	3 - 12 hrs	Threshold Requirement (updated 2006.03)
3	Water & Energy Cycle	Atmospheric water vapor total column	Total column water vapor measurements	10 – 25km	NA	2 day (targeted)/weekly	Global day/night	T	5% or 1 mm	3 - 12 hrs	Threshold Requirement (updated 2006.03); Column measuremnt is derived from profile
4	Water & Energy Cycle	Freeze-thaw transition	Measure freeze-thaw transition in all cloud and vegetation	10 – 250m	2cm	2/day	Global	G	10-15% error rate		Goal Requirement from ESTIPS 2005.12
5	Water & Energy Cycle	Global precipitation	monitor rain fall	<25 km	250m	~ 3 hours	Global coverage up to +/-75 latitude band	G	10%		Goal Requirement from ESTIPS 2005.12
6	Water & Energy Cycle	Growing season length in high latitudes	freeze/thaw transition	1km	N/A	daily	Regional	G			Goal Requirement from ESTIPS 2005.12
7	Water & Energy Cycle	River discharge rate	measure discharge rate for major world rivers & inland water bodies	10cm	2cm	1/day	Global	G	10-15% of the flow volume		Goal Requirement from ESTIPS 2005.12
8	Water & Energy Cycle	River stage height	Measure stage height for major world rivers & inland water bodies	10m	2cm	1/day	Global	G	1cm		Goal Requirement from ESTIPS 2005.12
9	Water & Energy Cycle	Snow cover, accumulation, and water equivalent	meaure snow extent, snow melt onset, snow wetnessand duration, snow water equivalent and surface-freeze thaw with and without snow cover. Need ultra-wide 2000km swath	500 m –1 km	N/A	2/day	Global	G	10%		Goal Requirement from ESTIPS 2005.12
10	Water & Energy Cycle	Soil moisture	measure top soil moisture	1km	3-4cm top soil	1/day	Global	G	3%		Goal Requirement from ESTIPS 2005.12
11	Water & Energy Cycle	Soil moisture	measure root zone soil moisture	1km	50cm deep	1/day	Global	G	4%		Goal Requirement from ESTIPS 2005.12

Appendix 2F: Weather Science Requirements



	A	B	C	D	E	F	G	H	I	J	K
1	**Science Theme**	**Measurement Parameter**	**Goal Description**	**Horizontal Resolution**	**Vertical Resolution**	**Revisit**	**Coverage**	**Requirement Type**	**Accuracy**	**Data Latency**	**Comment**
2	Weather	Atmospheric temperature	measure atmospheric temperature under all weather conditions & presence of clouds	10km	<0.5km	2/day	global	T	<1K		Threshold requirement updated 2006.03
3	Weather	Atmospheric water vapor range resolved	Tropospheric water vapor profiles- Range Resolved.	50 km	0.5-1.0 km	1 day (targeted) /weekly	Global day/night	T	10%	3 - 12 hrs	Threshold requirement updated 2006.03
4	Weather	Atmospheric water vapor total column	Column measurement is a byproduct of range resolved measurement.	10 – 25 km	NA	2 day (targeted) /weekly	Global day/night	T	5% or 1 mm	3 - 12 hrs	Threshold requirement updated 2006.03; Column measuremnt is derived from profile
5	Weather	Cloud particle properties and distribution	measure particle density & size; ice & water content, albedo, optical depth	1 – 10km	30m	1/day	global	G	10% of optical depth		Goal requirement taken from ESTIPS 2005.12
6	Weather	Cloud system structure	measure cloud top height, temperature, humidity, cloud droplet size	10km	30m	10/day	global	G			Goal requirement taken from ESTIPS 2005.12
7	Weather	Global precipitation	monitor rain fall	<25 km	250m	~ 3 hours	global coverage up to +/-75 latitude band	G	10%		Goal requirement taken from ESTIPS 2005.12
8	Weather	Lightning rate	measure lightning rate	10km	N/A	continous staring	Hemisphere	G	> 90%		Goal requirement taken from ESTIPS 2005.12; No Lidar measurement scenario.
9	Weather	Ocean surface winds	measure wind vector field over both ocean and coastal areas; need 200 km single-pass swath	1km	N/A	2/day	global	G	speed <2m/s; direction <20deg		Goal requirement taken from ESTIPS 2005.12
10	Weather	Storm cells properties	measure meteorological properties around storms	1km	500m	10min	local	G	0.5 deg K		Goal requirement taken from ESTIPS 2005.12
11	Weather	Tropospheric winds	measure trop winds with 2-D vector component	100km	1km mid/upper trop, 250m in PBL	~6 hrs	global	D/T/G	1-3 m/s		Full set of updated requirements provided by Dr. Michael Kavaya, NASA (2006.03). Measurement accuracy refers to the LOS wind vector magnitude.
12	Weather	Atmospheric pressure	Pressure profiles	50 km	0.5 km	4/day	Global	T	1-2 mb	3 hrs - 1/day	Threshold requirement updated 2006.03

Appendix 2G: Comments on Science Requirements for Wind

Comments on Science Requirements for Wind

Atmospheric Dynamics Science Subgroup:
Michael J. Kavaya, NASA/LaRC (Science Lead), Bruce M. Gentry, NASA/GSFC (Technology Lead), Robert M. Atlas, NOAA/AOML, Renny A. Fields, Aerospace Corp., Karen Moe, ESTO, Upendra N. Singh, NASA/LaRC, Gary D. Spiers, NASA/JPL

Introduction

The science and operational communities of the United States and other countries greatly desire global vertical profiles of horizontal vector winds for many applications; especially improved weather prediction; greater understanding of climate issues; and mitigation of weather hazard deaths, injuries, and costs. These three primary applications were ranked first, second, and fourth in a list of nine key societal benefits emphasized in a recent report by the cabinet-level National Science and Technology Council (NSTC)1. The report lists “wind profiles at all levels” as the highest priority observations for improved weather forecasting. The high value of wind measurements to improved weather prediction is highlighted by the fact that it is ranked as the highest priority unmet measurement by the National Polar-orbiting Operational Environmental Satellite System/Integrated Program Office (NPOESS/IPO), which is a joint office representing Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), and NASA2. A very strong case for the benefits of tropospheric wind profiling from space has been made in the scientific literature3-9. Wind measurements have been shown to promise a very positive economic benefit to the country10-11, as has improved weather prediction in general12. The 2006 NASA Strategic Plan lists 6 Strategic Goals, and Sub-goal 3A states that NASA’s Earth Science program should “improve prediction of climate, weather, and natural hazards” by “working to advance radar, laser, and light detection and ranging technologies to enable monitoring of such key Earth system parameters as land surface, oceans, ice sheet topography, and global tropospheric winds that could lead to advances in weather and severe storm prediction.”13 The benefits of the wind measurements, for the above three primary NASA applications, result from assimilation of the measurements into computer models used for weather forecasting and climate studies. The model outputs provide the improved weather forecasting, and climate studies are assisted since weather forecast results allow refinement of climate computer models. This assimilation of the wind data into models is to be contrasted to other benefits achieved by direct use of the wind measurements themselves. The DOD, for example, desires wind measurements for applications that both use and do not use model assimilation14-15. This bifurcation in the way that the wind data are used does not necessarily double the necessary technology development since the same lidar technology and techniques that would be advanced by NASA’s three primary applications can be envisioned to also enable the “direct use” applications.

Requirements for Vertical Profiles of Horizontal Vector Winds

The measurement requirements for global vertical profiles of horizontal vector wind have been steadily evolving since this potential use of Doppler lidar systems was first discussed in the 1970’s. In 2000, NASA formed the Global Tropospheric Winds Sounder (GTWS) mission formulation team to address a Congressional directive that NASA obtain global wind measurements through a commercial data buy approach16. One of the many activities undertaken by the GTWS team was to form a Science Definition Team (SDT) to determine the measurement requirements17. The GTWS SDT concentrated on measurement requirements for the “model assimilation” use of the data. NASA lidar technologists participated in the process to ensure that all of the requirements necessary to unambiguously define a Doppler wind lidar space mission were present18-21. Previous statements of wind measurement requirements had insufficient details to permit definition of the size of the Doppler wind lidar instrument. Ambiguities of several tens of dB were possible. The SDT developed both “Threshold” and “Objective” requirements, defined as “minimum requirements for wind data that would be useful for NOAA forecasting models and NASA science investigations” or “noticeable improvement,” and “optimum data specification” or “significant improvement,” respectively.

The Threshold and Objective requirements were released for comment on the World Wide Web (WWW) on 16 October 2001 jointly by the NASA Earth Science Enterprise (ESE) and the NOAA National Environmental Satellite Data and Information Service (NESDIS). The 21-page document was called the “Draft Global Tropospheric Winds Sounder (GTWS) Science and Operational Data Specification”. In addition to the requirements, the document contained definitions, explanations, and design atmospheres (see the definitions and explanations below, and see the design atmospheres in Appendix 2H). The design atmospheres comprise 9 tables covering 3 laser wavelengths for 3 aerosol conditions. The 3 laser wavelengths are 355, 1060, and 2051.8 nm.

Appendix 2G: Comments on Science Requirements for Wind

Table 1 lists the most familiar measurement requirements and Table 2 lists the remaining requirements. Errata in the original WWW listing of Oct. 2001 have been corrected and are shown in red in the tables and text. The definitions, explanations, and design atmospheres must accompany Tables 1 and 2 to represent a completely defined set of requirements for mission designs. In this way, various mission concepts with different technologies and/or techniques may be compared to each other with “equal requirements” and “equal atmospheres”.

In the years since the GTWS requirements were generated, it has become attractive to consider a demonstration wind mission in earth orbit that would demonstrate the lidar technology, the measurement technique, and the ability to scan the lidar beam as required by the need to measure two collocated line-of-sight (LOS) wind profiles (biperspective) at 4 (threshold) or 12 (objective) cross track distances (see Table 1) with a horizontally projected angle between the two perspectives of 30-150 degrees (see Table 2). The cost and risk of this demonstration mission could be kept down by relaxing the measurement requirements while preserving the primary validation objectives. As part of this Laser/Lidar Working Group, we developed a new set of “Demo” requirements in consultation with the members of the GTWS SDT, and with the members of the Working Group on Space-Based Lidar Winds (WGSBLW)22. These “Demo” requirements are also shown in Tables 1 and 2. Note that the requirements for vertical resolution and number of cross-track positions (wind tracks) have been eased, among others.

Table 1. Wind Measurement Requirements, Part 1

	Demo	**Threshold**	**Objective**	Units
Vertical depth of regard (DOR)	0-20	0-20	0-30	km
Vertical resolution:				
Tropopause to top of DOR	Not Req.	Not Req.	2	km
Top of BL to tropopause (~12 km)	2	1	0.5	km
Surface to top of BL (~2 km)	1	0.5	0.25	km
Number of collocated LOS wind measurements for horiz wind[A] calculation	2 = pair	2 = pair	2 = pair	-
Horizontal resolution	350	350	100	km
umber of horizontal wind[A] tracks[B]	2	4	12	-
Velocity error[C] Above BL	3	3	2	m/s
In BL	2	2	1	m/s
Minimum wind measurement success rate	50	50	50	%
Temporal resolution (N/A for single S/C)	N/A	12	6	hours
Data product latency	N/A	2.75	2.75	hours

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an “effective” horizontal wind measurement. The two LOS winds are reported to the user.

[B] The cross-track measurements do not have to occur at the same along-track coordinate; staggering is permitted.

[C] Error = 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 175/100/25 km square box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction as reported with the data.

BL = Boundary Layer

(original errata that have been corrected or clarification added)

Table 2. Wind Measurement Requirements, Part 2

	Demo	**Threshold**	**Objective**	Units
Vertical location accuracy of LOS wind measurements	1	0.1	0.1	km
Horizontal location accuracy of LOS wind measurements	5	0.5	0.5	km
Allowed angular separation of LOS wind pair, projected to a horizontal plane	30-150	30-150	30-150	degree
Maximum allowed horizontal separation of LOS wind pair	50	35	35	km
Maximum horizontal extent of each horizontal wind[A] measurement	175	100	25	km
Minimum horizontal cross-track width of regard of wind measurements	N/A	±400	±625	km
Maximum cross-track spacing of adjacent cross-track locations	N/A	350	100	km
Maximum design horizontal wind speed: Above BL Within BL	 50 50	 75 50	 100 50	 m/s m/s
Design 1σ wind turbulence level: Above BL Within BL	1 1	1.2 1	1.4 1	m/s
Max. LOS wind unknown bias error, projected to a horizontal plane	1	0.1	0.05	m/s
Minimum design a priori velocity knowledge window, projected to a horizontal plane (using nearby wind measurements and contextual information)	26.6	26.6	26.6	m/s
Design cloud field: Layer from 9-10 km, extinction coefficient Layer from 2-3 km, 50% of lidar shots untouched, 50% blocked	 0.14 50, random	 0.14 50, random	 0.14 50, random	 km^{-1} %
Aerosol backscatter coefficients: 2 vertical profiles provided	 Provided	 Provided	 Provided	 m^{-1}sr^{-1}
Aerosol backscatter: Probability density function (PDF) PDF width	Lognormal Provided	Lognormal Provided	Lognormal Provided	m sr m^{-1}sr^{-1}
Atmospheric extinction coefficient: 2 vertical profiles provided	 Provided	 Provided	 Provided	 km^{-1}
Orbit latitude coverage	N/A	80N to 80S	80N to 80S	Degree
Downlinked data	All	All	TBD	-

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an "effective" horizontal wind measurement. The two LOS winds are reported to the user.

(original errata that have been corrected or clarification added)

Table 1 shows that one of the requirements is a 50% minimum wind measurement success rate. In consultation with the GTWS SDT and the WGSBLW, this requirement has been clarified to not include the effect of thick clouds and to apply to each attempt at a biperspective LOS wind pair at each altitude layer defined by the vertical resolution and vertical depth of regard. It does, however, include the effect of the attenuating cloud layer. In order to understand the effect of thick clouds, a computer simulation enhanced as part of GTWS, and residing at Simpson Weather Associates (SWA)23, was used to examine the wind measurement performance of a “very large” Doppler lidar system (20 J pulse energy, 1 m optical diameter, 400 km orbit, 30 deg nadir angle). (These numbers have nothing to do with the required lidar for any notional mission.) The result is shown in Figure 1. The Doppler Lidar Simulation Model (DLSM) computer program simulates a Doppler wind lidar instrument in earth orbit with a realistic representation of earth’s atmosphere. The vertical axis is the height of the wind measurement in the atmosphere, and the horizontal axis is the percentage of each type of outcome of a measurement attempt. The horizontal lines indicate the vertical resolution. Colors encode the velocity error of measurement attempts that produce a wind measurement. Since the simulated lidar is so large, gray in this figure indicates lidar beam blockage by thick clouds. The effect of thick cloud blockage begins at about 14 km altitude and produces a blockage rate of about 35% at the surface. Since the requirement for 50% or higher success rate does not include cloud blockage, the black line show the resultant required success rate vs. altitude including the thick clouds of this modeled atmosphere.

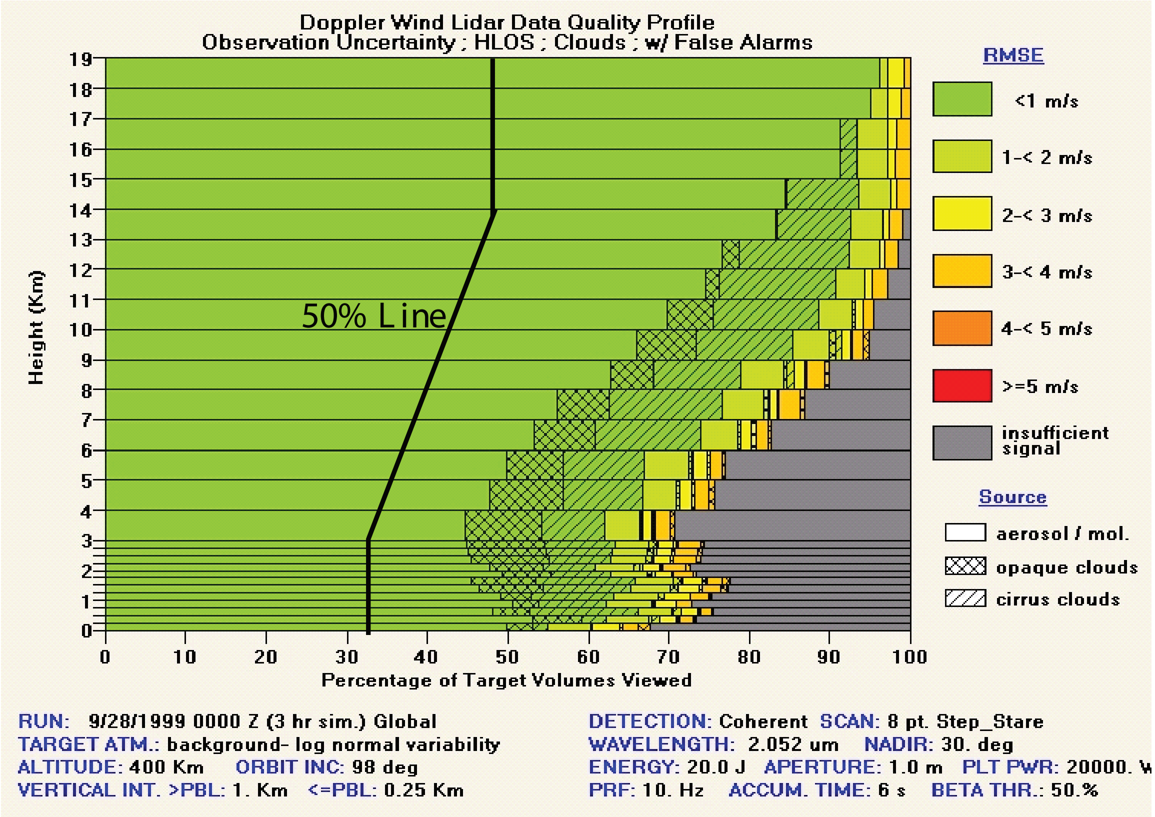


Figure 1. “Very Large Lidar” wind measurement performance revealing effects of thick clouds

Using the information of the thick cloud blockage, it is possible to present a subset of the wind measurement requirements in a visual format. Figure 2 shows a subset of the "Demo" requirements. The gray area shows the combination of the thick cloud blockage and the 50% minimum wind measurement success rate derived from Figure 1. The horizontal lines indicate required vertical resolution, and the required velocity accuracy is encoded in color using the same definitions as in Figure 1. The grid at the right of Figure 2 represents a top view of the orbiting lidar's scan pattern on the earth's surface over a 1400 km wide by 700 km long rectangle centered on the satellite's ground track. The colored ovals represent the collocated sets of forward (blue) and aft (red) shots comprising one biperspective vertical profile of "horizontal" winds. As stated in the requirements, the profiles are measured at two across-track positions (□400 km shown here for example) with an along track resolution (repeat distance) of 350 km.

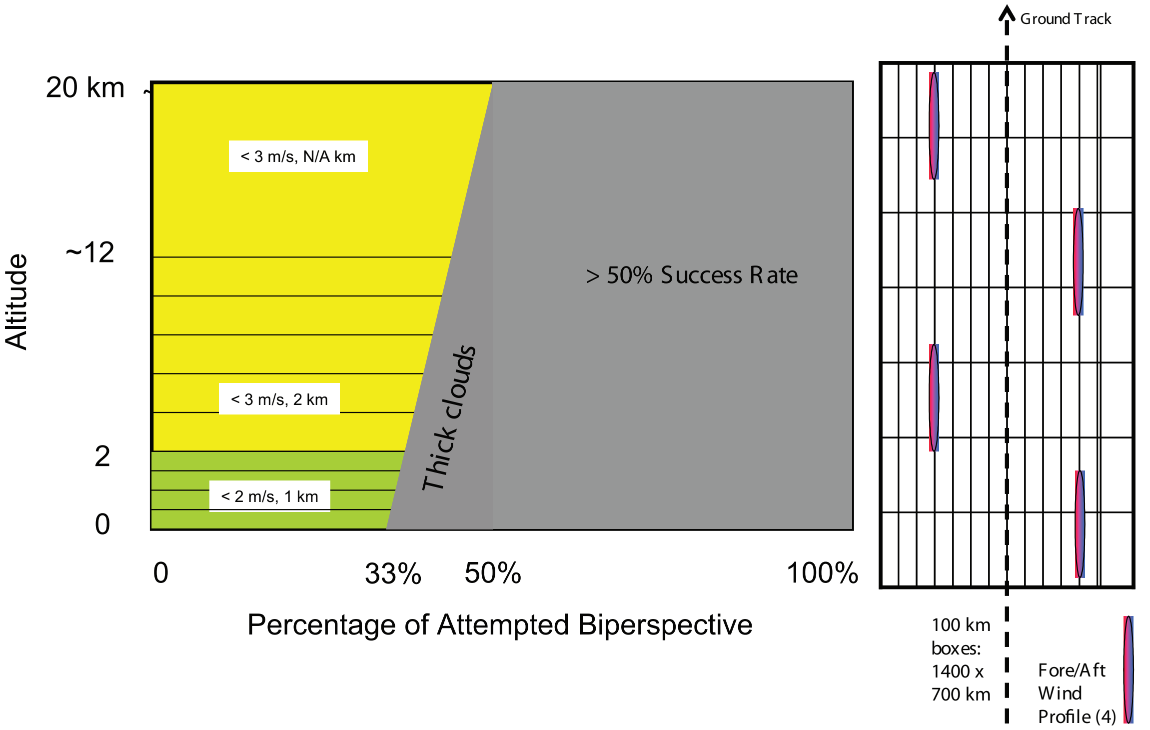


Figure 2. Depiction of demonstration wind measurement requirements

Figure 3 is a similar depiction of the "Threshold" requirements. The vertical resolution is stricter than the demonstration requirements by a factor of 2, but the success percentages vs. altitude remain the same. The number of cross-track positions is increased from two to four, also a factor of 2, and the cross-track "reach" ("width of regard") is mandated to be at least ±400 km, as shown. The factor of 2 increase in cross-track positions means that each vertical wind profile must occur in approximately half the time. The factor of 2 increase in vertical resolution difficulty means that each wind measurement must be made with half the range gate length in the atmosphere. A simple method to preserve Doppler wind lidar measurement performance in each of these cases would be to double the pulse repetition frequency (PRF) as compared to the demonstration requirements.

Using this approach to preserve performance for both vertical resolution and cross-track position requirement changes leads to a four-fold increase of laser PRF, laser electrical power, laser waste heat removal, pulse lifetime, and receiver data acquisition rate. For a coherent detection Doppler lidar, an alternative to doubling the PRF in each case would be to increase the laser pulse energy by 41%, or to increase the receiver collection area by 41%. Using these approaches for both cases would mean either a doubling of laser pulse energy, or a doubling of receiver collection area (increase in diameter by 41%). For a direct detection Doppler lidar, an alternative to doubling the PRF in each case would be to increase the laser pulse energy or receiver collection area by a factor of two. Using these approaches for both cases would mean a four-fold increase in either the laser pulse energy or receiver collection area (increase in diameter by a factor of 2). Any increase in laser pulse energy would proportionally increase the laser electrical power and laser waste heat removal. Any increase in receiver collection area causes an increase in mass, volume, and scanner complexity.

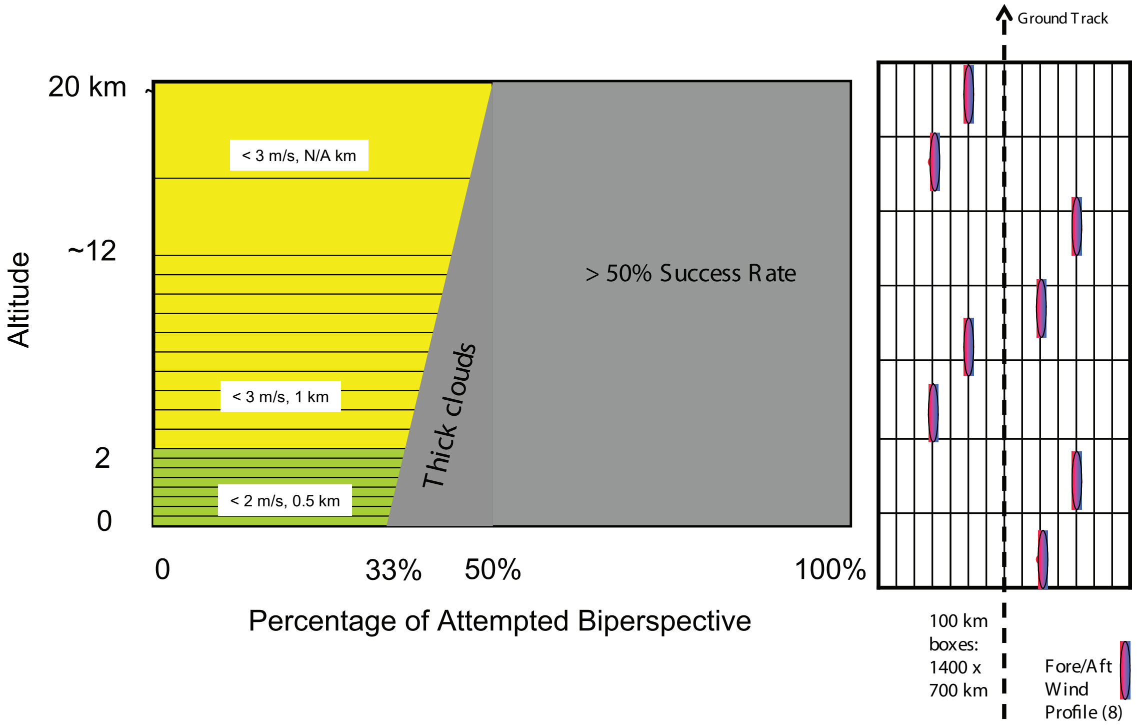


Figure 3. Depiction of the threshold wind measurement requirements

Figure 4 similarly shows the “Objective” wind measurement requirements. The vertical resolution has again doubled and is specified for the first time above the tropopause (~ 12 km). The vertical depth of regard has increased to 30 km. The velocity accuracy has gotten 1 m/s stricter at all altitudes. Perhaps most importantly, the number of cross-track positions has increased to 12 and the along-track repeat distance (horizontal resolution) has decreased to 100 km. Since we recommend both a “demo” and then a “threshold” space mission prior to an “objective” mission, and since the time horizon guideline for this Lidar Working Group was 15 years, we did not include any scenarios for an “objective” winds mission in this report.

It is interesting to compare the demo, threshold, and objective requirements to a similar graphical depiction of current wind observations. This is shown in Figure 5. The color encoding is the same as the above figures. Not all wind observations are depicted, but rather only those that produce a vertical profile (mainly radiosondes).

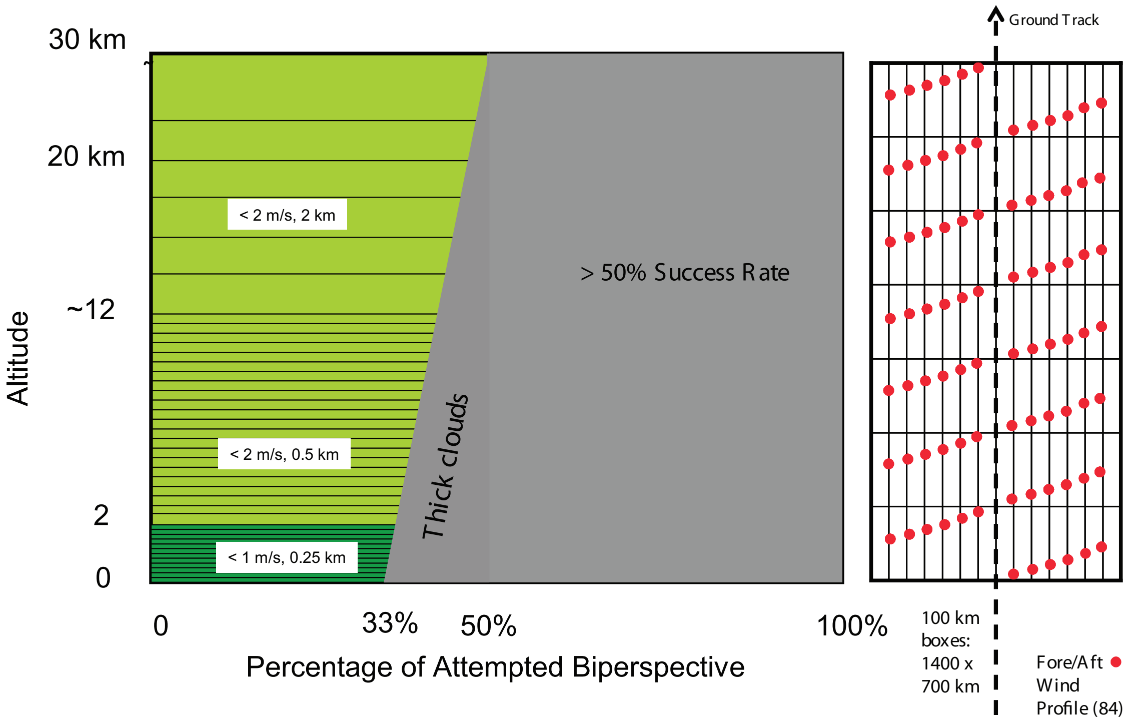


Figure 4. Depiction of the objective wind measurement requirement

The 30 mb pressure level on the vertical axis is about 23.4 km altitude. Whereas the horizontal axes in Figures 1-4 represent the Doppler lidar wind measurement success rate and the effect of thick clouds, the horizontal axis in Figure 5 assumes the earth's surface is divided into 300 km x 300 km boxes, and the percentage coverage of these boxes in 24 hours is shown. A simple calculation using the earth's surface area and the area of a 300 x 300 km box yields that there are about 5670 boxes on the earth. In 2004, there were an estimated 1700 radiosonde launches in the world per day. Since radiosonde locations launch twice a day, there were about 850 different radiosonde locations. Since each location would count as an observed box, a simple division predicts 15% coverage of the boxes on the earth. This agrees pretty well with Figure 5.

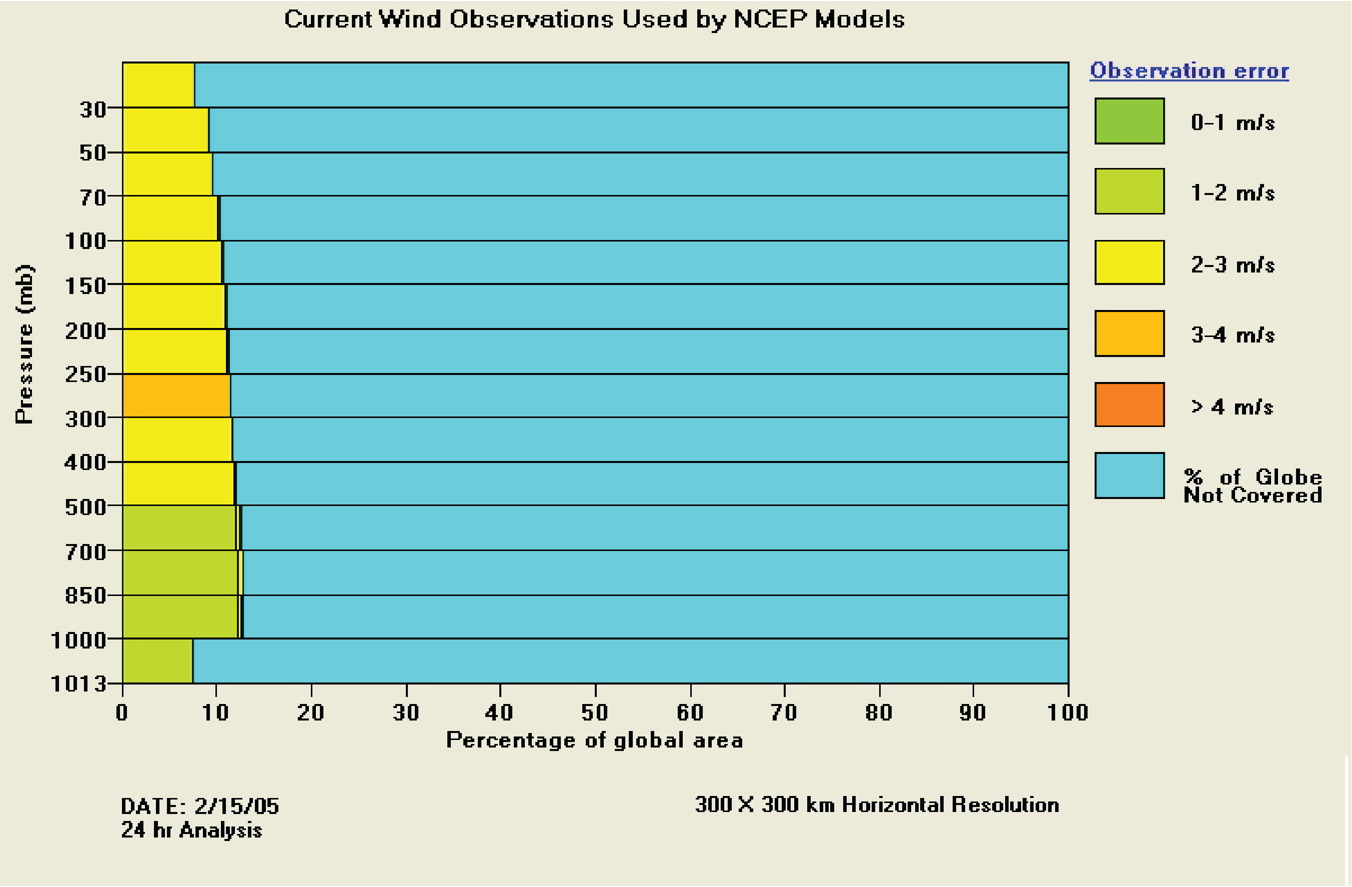


Figure 5. Current horizontal vector wind vertical profile observations in a 24-hour period

The DLSM software is capable of portraying the information in Figures 1-4 with the same type of figure of merit as the horizontal axis in Figure 5, by using the geometry of an actual orbit, and the scan pattern of the lidar. These figures are not included here.

Figure 6 shows an artist's concept of the vertical "sheets" of "horizontal wind" measurements with four tracks of winds measured per the threshold requirements.

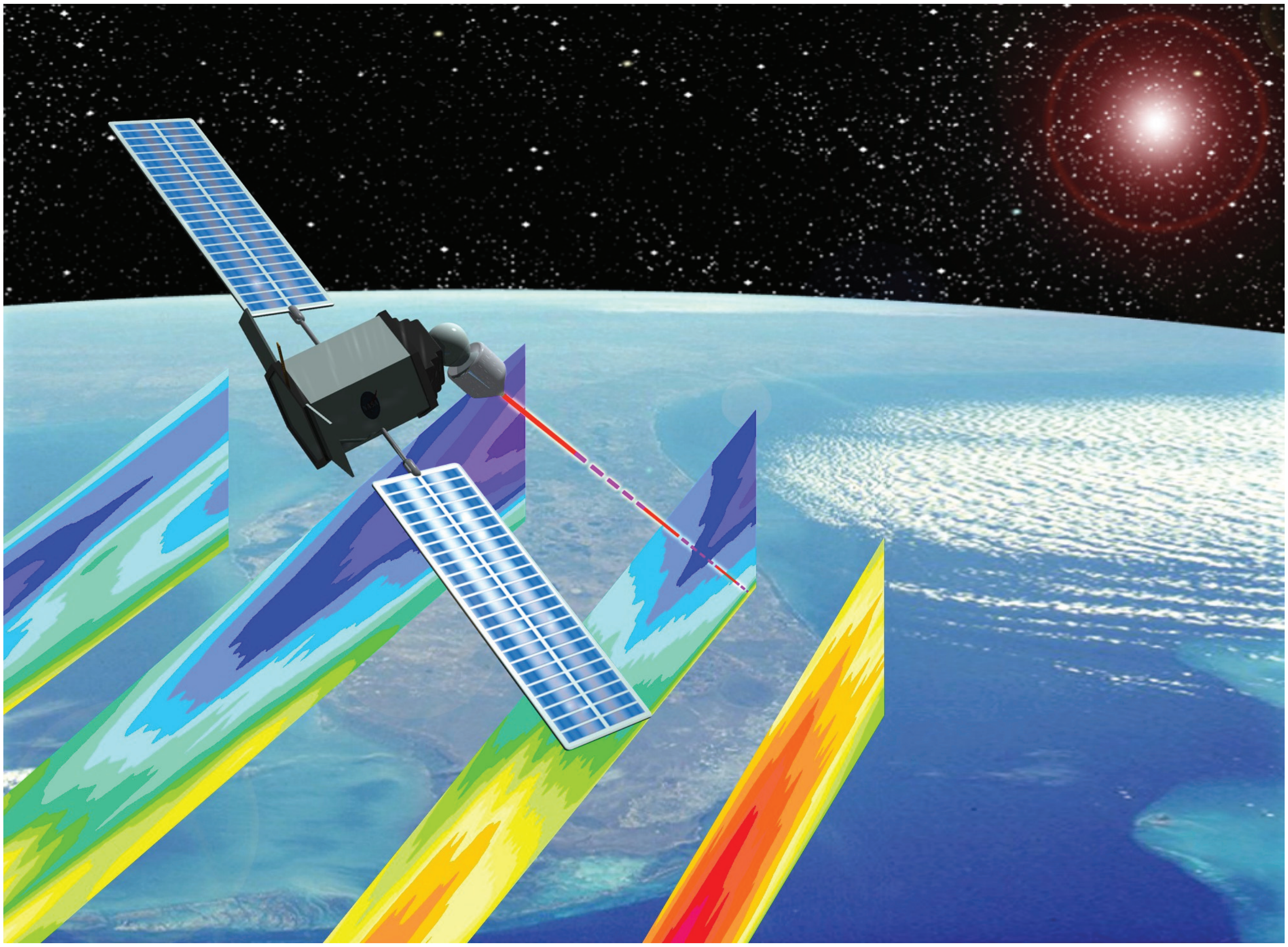


Figure 6. Artist's concept of four tracks of vertical wind profiles

Hybrid Doppler Wind Lidar Concept

There are two possible receiver approaches for the Doppler wind lidar technique of vertical profiling of horizontal vector winds. In one approach, the Doppler shift imparted to the backscattered photons by the molecules or aerosols moving with the wind is determined by optical components in the receiver that have different transmission coefficients for different optical wavelengths. The intensity of the light emerging from these optical components is measured by traditional optical detectors, and the measured intensities are used to calculate the wind speed from knowledge of the behavior of the receiver. In the second approach, the spectrum of the backscattered photons is translated from the very high optical frequencies to much lower MHz frequencies using an optical detector as a mixer and an auxiliary CW light beam as a mixing reference. The returned signal, after translation to much lower frequencies, is then digitized and processed in a computer to determine the wind velocity caused Doppler shift using frequency estimation techniques. The first approach is called direct or noncoherent Doppler lidar, and the second approach is called heterodyne or coherent Doppler lidar. Since the backscatter from molecules is proportional to the inverse fourth power of optical wavelength, shorter optical wavelengths are very helpful to utilize the molecules as a target. Since coherent detection lidar requires phase alignment between the CW light beam (local oscillator) and the backscattered photons, longer optical wavelengths permit relaxed alignment requirements. The required phase alignment also means that the transmitted laser beam should be diffraction limited to remain as small as possible in the earth's atmosphere so that the backscattered light will have sufficient transverse phase coherence. Because of the narrow beam requirement and eye safety considerations, coherent lidar is constrained to optical wavelengths above 1.5 microns. Finally, the two Doppler lidar techniques have different priorities in their detector parameters; dark current being very important for direct detection, and quantum efficiency being very important for coherent lidar. All of these considerations have led to two primary candidates for Doppler wind lidars in space: a coherent detection lidar at 2 microns using aerosol backscatter, and a direct detection lidar at 0.355 microns using molecular backscatter.

Another task undertaken by the GTWS mission was to utilize the Instrument Synthesis and Analysis Laboratory (ISAL) and the Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center (GSFC) in 2001 and 2002 to study the problem of wind measurement from space with a Doppler wind lidar. Both design teams analyzed both a coherent-detection and a direct-detection Doppler wind lidar, each meeting the GTWS requirements by itself. The result of the studies was that either type of lidar, meeting the requirements by itself, was very large and consumed a lot of electrical power. In both cases there was considerable technology that needed to be developed.

This result led to the investigation of the hybrid Doppler wind lidar approach. The concept was that each type of lidar would measure winds using its strengths, and let the other type of lidar complement it. In this way, both the coherent and direct lidars could be much smaller and yet together meet the requirements. The technology gap would be greatly reduced and a space mission could occur sooner. As will be seen in the next section, this concept proved to be correct.

Meeting the Wind Measurement Requirements

The DLSM software has been used to determine notional Doppler wind lidar mission parameters that meet the wind measurement requirements from different orbit heights. The performance of both a coherent and direct detection lidar is presented with the intent that the requirements are met by the combination of both lidar's measurements. Since the percentages of the earth at any time that are represented by background or enhanced aerosol models (see Appendix 2H) are not well known, we track performance under both conditions. With two types of lidar systems and two aerosol models, four performance plots are needed to understand the overall performance. Figures 7-10 show the performance of a hybrid Doppler wind lidar at 833 km (NPOESS orbit height), and a 30-deg scanner nadir angle for the conical step-stare scan pattern. The lidar parameters were chosen to meet the "demo" requirements. For example, the demo requirements call for 2 horizontal wind tracks (see Table 1). This would be accomplished using 4 lidar scanner azimuth angles to obtain 2 pairs of fore and aft views. Since the ground track of the spacecraft advances 350 km, the required horizontal resolution, every 53 s, the computer simulation permits 12 s of shot accumulation time for each LOS wind profile. The remaining 5 s are budgeted for scanner angle changes. Close scrutiny of Figures 7-10 and Figure 2 reveals that the 0.25 J, 5 Hz, 0.25 m receiver diameter coherent-detection lidar combined with the 0.337 J (0.75 J at 1 microns), 100 Hz, 0.75 m receiver diameter direct-detection lidar meets the demo requirements at all altitudes under background aerosol conditions, and exceeds the requirements under enhanced aerosol conditions.

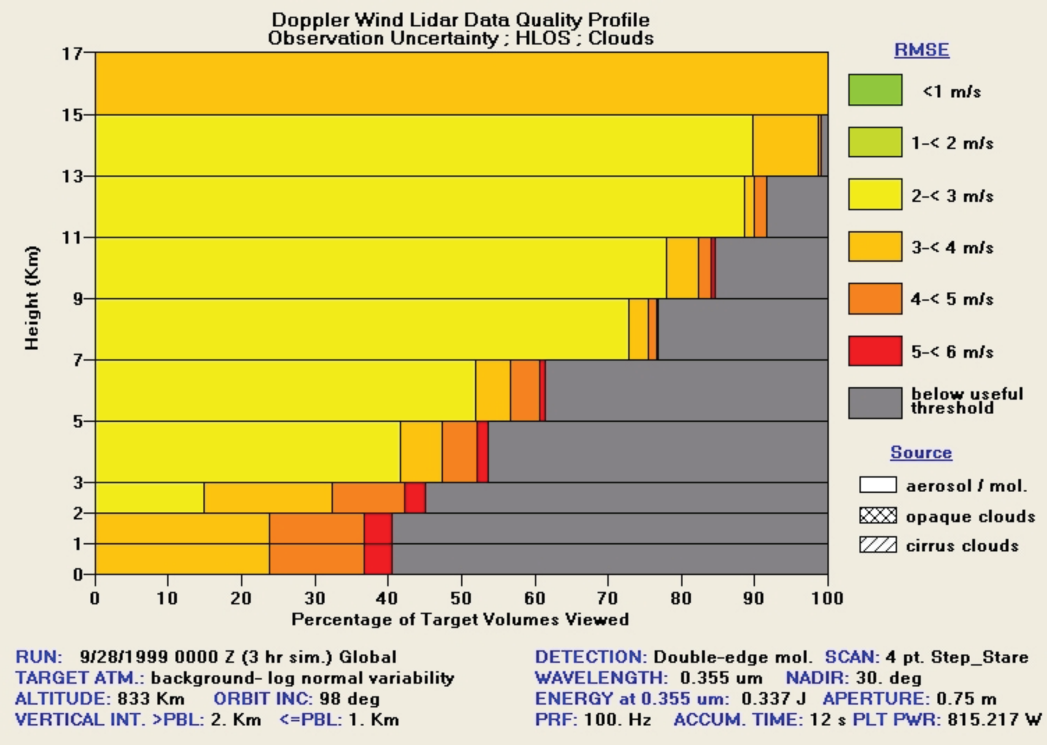


Figure 7. Direct detection lidar performance, background aerosol, 833 km, demo requirements

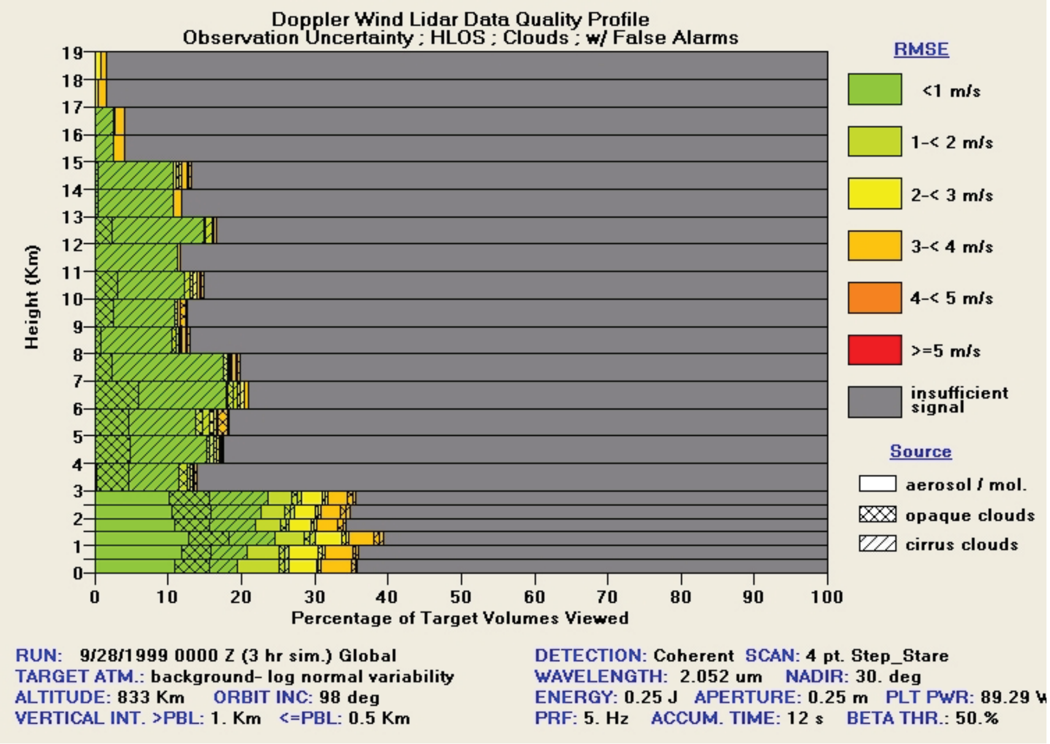
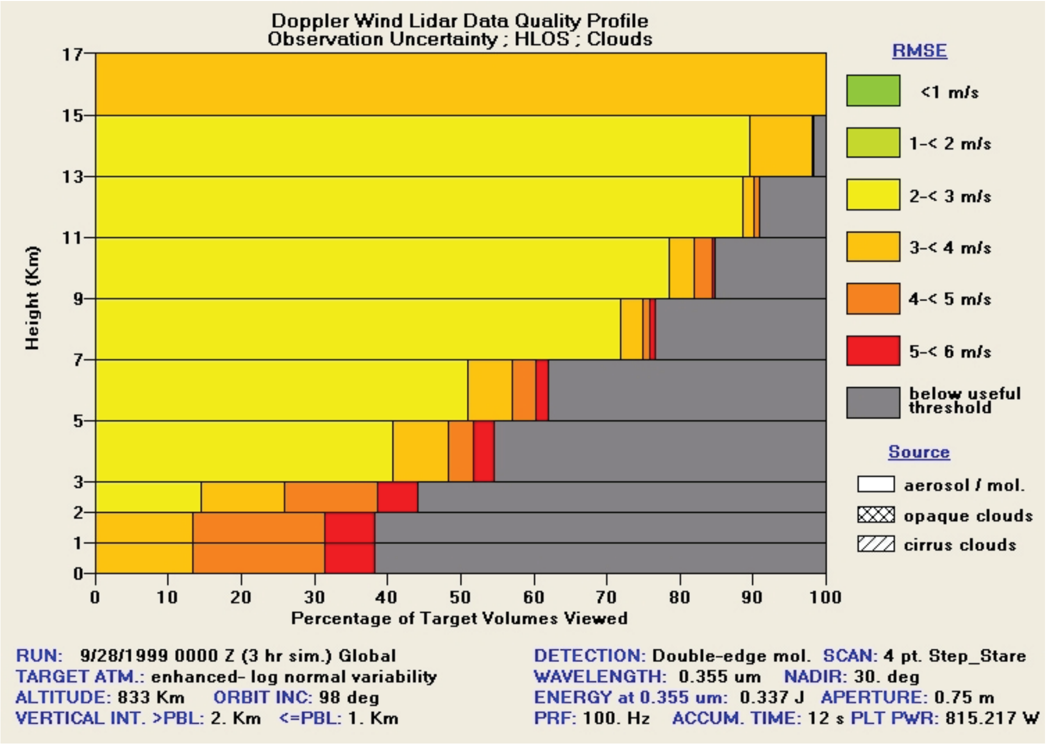


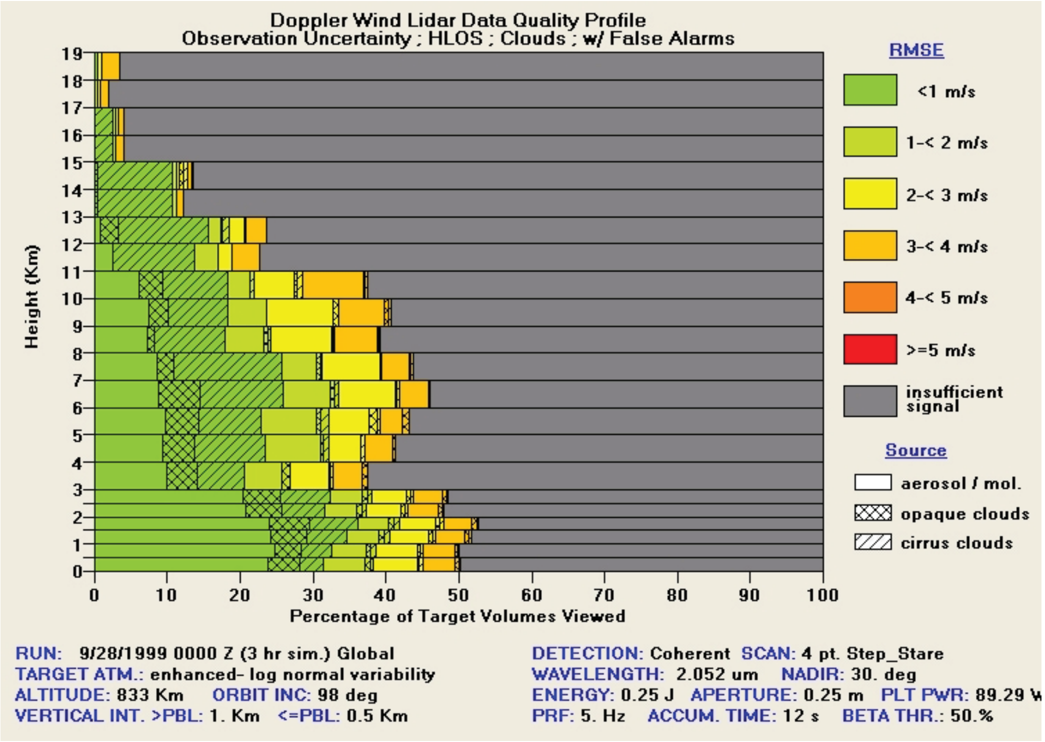
Figure 8. Coherent detection lidar performance, background aerosol, 833 km, demo requirements



RUN: 9/28/1999 0000 Z (3 hr sim.) Global
TARGET ATM.: enhanced- log normal variability
ALTITUDE: 833 Km ORBIT INC: 98 deg
VERTICAL INT. >PBL: 2. Km <=PBL: 1. Km

DETECTION: Double-edge mol. SCAN: 4 pt. Step_Stare
WAVELENGTH: 0.355 um NADIR: 30. deg
ENERGY at 0.355 um: 0.337 J APERTURE: 0.75 m
PRF: 100. Hz ACCUM. TIME: 12 s PLT PWR: 815.217 W

Figure 9. Direct detection lidar performance, enhanced aerosol, 833 km, demo requirements

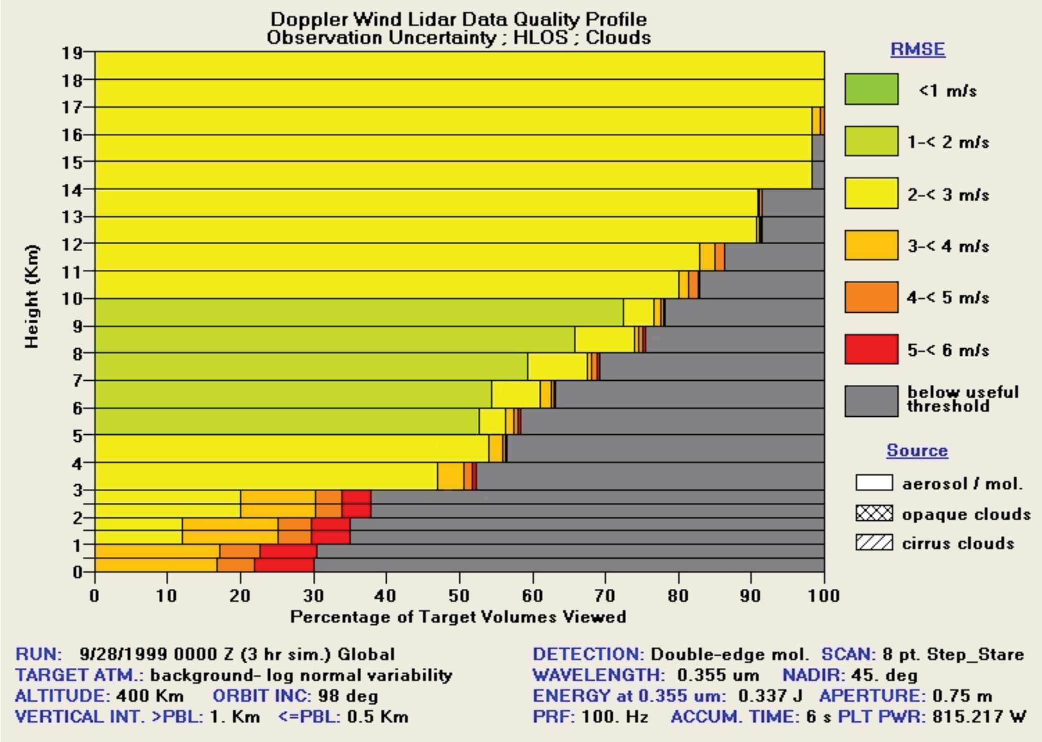


RUN: 9/28/1999 0000 Z (3 hr sim.) Global
TARGET ATM.: enhanced- log normal variability
ALTITUDE: 833 Km ORBIT INC: 98 deg
VERTICAL INT. >PBL: 1. Km <=PBL: 0.5 Km

DETECTION: Coherent SCAN: 4 pt. Step_Stare
WAVELENGTH: 2.052 um NADIR: 30. deg
ENERGY: 0.25 J APERTURE: 0.25 m PLT PWR: 89.29
PRF: 5. Hz ACCUM. TIME: 12 s BETA THR.: 50.%

Figure 10. Coherent detection lidar performance, enhanced aerosol, 833 km, demo requirements

Similarly, Figures 11-14 show the performance of a hybrid Doppler wind lidar at 400 km (NASA science mission), and a 45-deg scanner nadir angle for the conical step-stare scan pattern. The lidar parameters were chosen to meet the “threshold” requirements. Close scrutiny of Figures 11-14 and Figure 3 reveals that the 0.25 J, 10 Hz, 0.25 m receiver diameter coherent lidar combined with the 0.337 J (0.75 J at 1 microns), 100 Hz, 0.75 m receiver diameter direct lidar meets the threshold requirements at all altitudes under background aerosol conditions with the possible exception of the very lowest altitude layer. However, the simulation assumed a vertical resolution of 0.25 km and the requirement only needs 0.5 km. The hybrid lidar exceeds the requirements under enhanced aerosol conditions.



RUN: 9/28/1999 0000 Z (3 hr sim.) Global
TARGET ATM.: background- log normal variability
ALTITUDE: 400 Km ORBIT INC: 98 deg
VERTICAL INT. >PBL: 1. Km <=PBL: 0.5 Km
DETECTION: Double-edge mol. SCAN: 8 pt. Step_Stare
WAVELENGTH: 0.355 um NADIR: 45. deg
ENERGY at 0.355 um: 0.337 J APERTURE: 0.75 m
PRF: 100. Hz ACCUM. TIME: 6 s PLT PWR: 815.217 W

Figure 11. Direct detection lidar performance, background aerosol, 400 km, threshold requirements

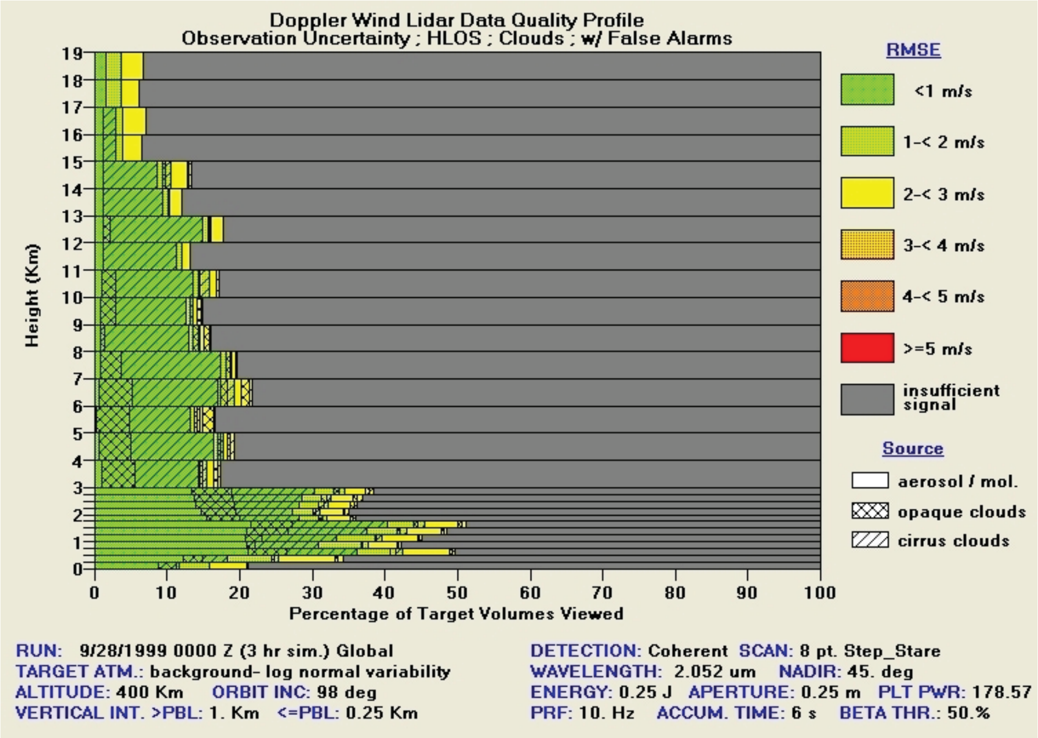


Figure 12. Coherent detection lidar performance, background aerosol, 400 km, threshold requirements

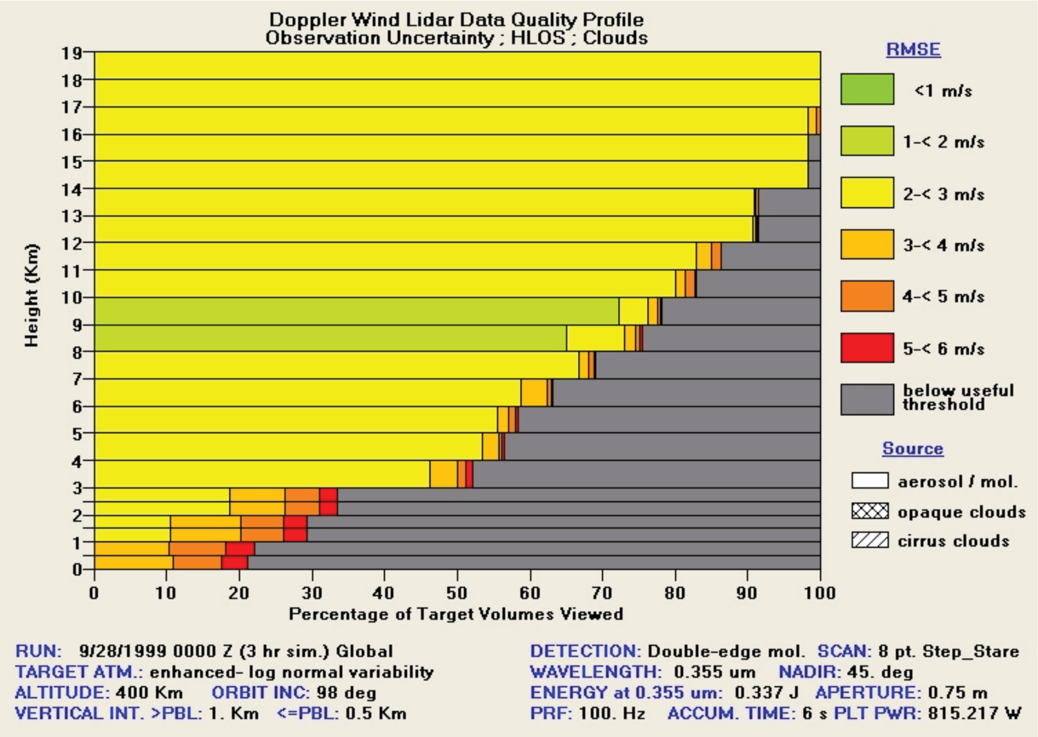


Figure 13. Direct detection lidar performance, enhanced aerosol, 400 km, threshold requirements

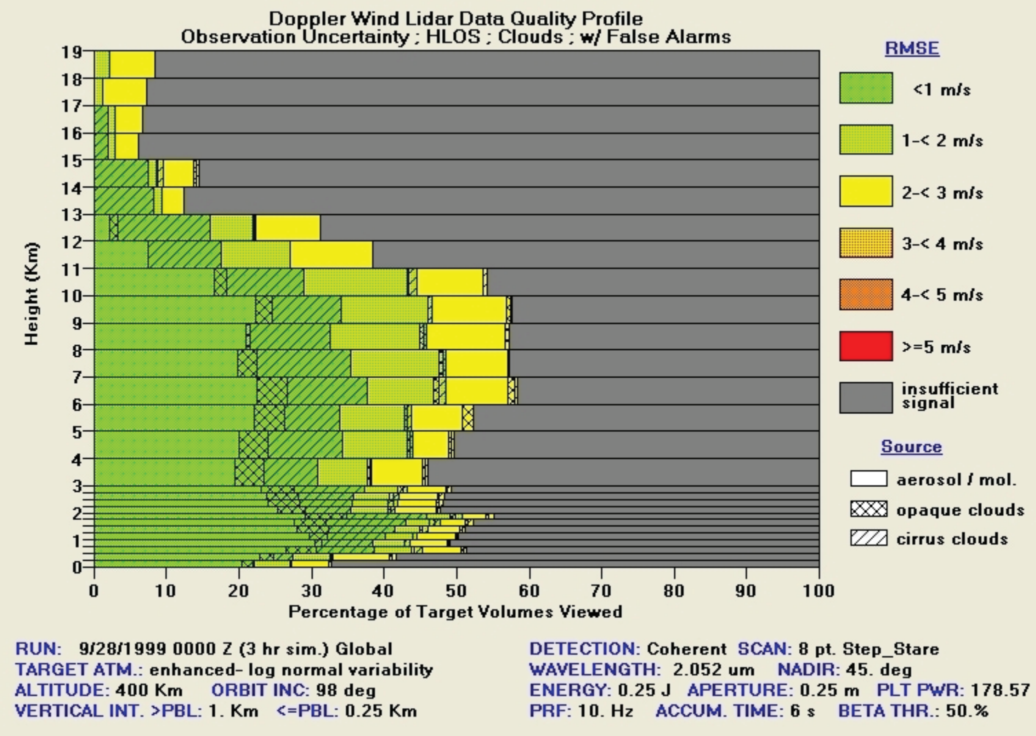


Figure 14. Coherent detection lidar performance, enhanced aerosol, 400 km, threshold requirements

Wind Measurement Requirements Definitions and Explanations (from the Oct. 2001 GTWS Requirements)

Additional GTWS Requirements:

Data level reported: All raw (level 0) data from the A/D (detector signal) should be downlinked.

Data spatial references: LOS sounding angles shall be referenced to local vertical; LOSH heights shall be referenced to local MSL.

Definitions and explanations associated with the GTWS Requirements Table:

The numbers in the requirements table are those that the GTWS Science Definition Team (SDT), with input from the GTWS workshop attendees, has determined to be necessary to assure a “useful” data product in terms of its likely impact on data assimilation and numerical weather forecasting models. It is understood that new Doppler Wind Lidar (DWL) observations will compete for usefulness with wind observations such as those from rawinsondes, ACARS, Cloud Track Winds, Water Vapor Winds, scatterometers and numerical model first guess fields. Winds derived from proposed future observing systems such as GIFTS are anticipated to be competitive with rawinsondes for accuracy and vertical coverage. The general guideline for specifying some of the threshold requirements is that any new DWL profiles should be provided globally and at roughly the same spatial and temporal density as provided by RAOBs today. This guidance applies mainly to the accuracy and horizontal resolution requirements. The cross track resolution and coverage is relaxed from this guidance in recognition of the difficulty of a single DWL to provide full global coverage in its first mission.

OBJECTIVE: These values represent the desired data requirement for space-based lidar winds. The SDT is confident that an instrument meeting the objective requirements would have a significant impact on both science and operational weather prediction in the 2005 – 2010 time frame.

THRESHOLD: These values represent the minimum data requirements for space-based lidar winds. A GTWS instrument that meets the threshold requirements would likely result in meaningful impact on science and operational weather prediction.

In addition to relaxing the “full global coverage” in the horizontal direction, the GTWS SDT also recognizes that there is a threshold for ‘usefulness” in the vertical coverage. For active optical sensors, clouds and aerosols determine where observations are possible and what the quality of those observations will be. The team further recognizes that requiring 100% of the requirements to be met 100% of the time when optically thick clouds are not a factor is not defensible in defining a threshold set of requirements. Thus the SDT has adopted the following guidance in defining threshold coverage:

- A threshold fraction of 50% of all the wind observations made by an orbiting DWL must meet the standards set in the GTWS requirements table.
- Individual observations that are judged to meet the requirements must be certified prior to their provision to the end user, i.e., each wind observation must be accompanied by a data quality flag that allows the user to discriminate between data of differing usefulness.
- Clouds will be present for many, if not most, of the occasions when a direct measure of the winds is likely to make a significant impact. Thus the GTWS requirements are expected to be met in the presence of “nominal” cloud coverage.

Depth of regard: The altitude limits (km) between which the DWL will be designed to process signals returned from the atmosphere. This does not imply that the DWL would be able to produce useful data products from the entire depth of regard at all times.

Vertical TSV Resolution: The vertical distance (not slant range) over which averaging may take place to return a data value that meets the accuracy requirement. The boundary layer (BL) is defined as the lowest region of the troposphere bounded by the earth’s surface and an elevated density inversion. For planning purposes, the depth of the BL is taken to be 2km.

Height assignment accuracy: The accuracy (RMSE) with which a LOS data value is assigned to the height that most properly represents the signal weighted mean of the averaged velocity information.

Target Sample Volume: (see explanation on Table) The cross-track and along-track distribution of TSVs need not be in a pattern of equal spacing. The look angles needed to meet the bi-perspective angle and spatial separation requirements will most likely dictate the TSV distribution. The general objective is to have the cross-track spacing of the TSVs be approximately the same as the along track spacing.

Horizontal TSV dimension: The maximum horizontal distance (km) over which DWL returns can be averaged to obtain a data value that meets the accuracy requirement. The geometry of the boundaries of the averaging region can range from a line to any two dimensional distribution whose maximum dimension is less than this requirement. Averaging over smaller distances may be acceptable if vertical coverage is not significantly compromised. (see additional comments in attachment 1)

Horizontal location accuracy: The allowable error in assigning a horizontal location for a single LOSH data value.

Horizontal resolution: The maximum horizontal distance (km) between data products meeting the TSV requirements. This resolution requirement applies to the along track direction.

Minimum X-track regard: The minimum width (km) of the “swath of regard” for the DWL. The distribution of lidar shots should not preclude the generation of several (>= number in ()) soundings in the cross-track direction. The cross track spacing between LOSH wind products should not exceed the horizontal resolution requirement. (See discussion under TSV)

Appendix 2G: Comments on Science Requirements for Wind

Number of LOS perspectives in TSV: The number of angularly independent LOS data products generated within a TSV. The angle between any independent LOSH data products must lie between 30 and 150 degrees. A related restriction is that all the lidar returns that have been used to obtain a single LOSH wind estimate must be taken with pointing angles that do not differ from each other by more than 20 degrees (<.02 in the cosine function). The horizontal distance between the LOSH wind observations in a perspective pair should not exceed 10% of the "Horizontal resolution" requirement.

Accuracy of LOSH (Velocity Error): The RMSE (m/s) of all LOSH wind component estimates represented to the model data assimilation routines by the instrument data system as meeting the accuracy requirement. This requirement is, in part, derived from the fact that for an observation to be used in a data assimilation scheme it will have to be assigned an observation error. It is expected that any DWL will be able to provide a data quality flag with each LOSH observation generated. The "accuracy" referred to in this requirement is the measurement accuracy of the instrument. It includes all known sources of error such as pointing knowledge, frequency jitter, signal processing uncertainty and atmospheric turbulence. The LOSH accuracy is defined as the total estimation error projected onto the horizontal plane for the average motion of the backscatter media within the measured volume along a LOS perspective. For example, a LOS estimation error of 1.5 m/s with a DWL using a 30 degree nadir scan angle would result in a 3.0 m/s uncertainty in the LOSH component. This accuracy requirement is expressed for both the BL and the rest of the troposphere. A set of "Design Atmospheres" will be provided to serve in establishing a point design. see attached examples in Attachment 1. (LOS projected to a horizontal plane (LOSH), accumulated N lidar shots, with atmospheric variability and platform and pointing and representativeness sources of error, single perspective)

Horizontal component bias: The maximum systematic instrument LOSH measurement error (m/s) that can occur without any known method for correction. For example, an uncorrectable bias might occur for a portion of an orbit when the pointing knowledge system drifted (non-linearly) without re-calibration.

Maximum horizontal speed: The maximum LOSH wind speed (m/s) that can be measured. The atmospheric targets related to these upper bound speeds are tropical cyclones, mid/upper tropospheric jets, and jets in the PBL.

Temporal resolution: The time (hours) between revisits of a TSV. A follow-up pass that comes within one half of a target resolution distance of a previous TSV will be considered a revisit. It is understood that the capability to revisit an area will be dependent on the orbit; hence this requirement is intended to preserve 12 hour resolution where possible. GTWS operations are to be provided during both the daytime and nighttime.

Data product latency: The maximum allowable time interval between the observation and the delivery of that information to the user.

Key: Original errata that have been corrected or clarification added.

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Appendix 2H: Design Atmospheres

Wind Measurement Requirements Design Atmospheres (from the Oct. 2001 GTWS Requirements)

Purpose

Having a common scattering target with internally consistent backscatter wavelength dependence enables meaningful "equal resource/equal target" comparisons of GTWS concepts that employ Doppler lidars. While the Science Definition Team (SDT) realizes that aerosol backscatter from the atmosphere will vary over several orders of magnitude, will vary over altitude, latitude and season and will also vary over space/time scales that are not readily modeled, the GLOBE, SABLE/GABLE backscatter surveys, and the AFGL MODTRAN aerosol data bases provide a nearly consistent picture of backscatter climatology. To establish a set of bounding profiles, the SDT has chosen (1) the "background" distribution of β(π) that appears in most stacked histograms of the GLOBE/SABLE/GABLE data sets and (2) the distribution of "enhanced" backscatter opportunities that are most apparent during the summer seasons and more common in the northern hemisphere (Srivastava, et al, 2001). The background mode value should not be interpreted as representing the minimum value of the aerosol cross section to be found. Rather, it represents a low cross section modal peak for aerosols in tropospheric air that does not have loading enhancement due to identifiable aerosol transport. There is a distribution of values and measurements indicating that the lowest aerosol cross sections can be an order of magnitude lower than the mode in some cases. The actual distribution of cross sections in the background mode is not well known. Measurements indicate that the background aerosol mode is present in large regions of the globe, mostly in the upper troposphere but can also be found in the boundary layer. The global distribution of these modes is not known, nor is the correlation of these modes with regions of ageostrophy. Therefore, these profiles should only be used to develop system point designs for concept evaluation and comparisons. It is expected that these profiles will be used to simulate the performance of a DWL concept for multiple levels within the troposphere and lower stratosphere. For example, for a shot reaching the altitude of 8 km in the "Background mode of GLOBE" atmosphere, the simulation of a .355 µm system scanned at 45° nadir should produce a distribution of velocity errors as a function of β(π) with a 2-way transmission of .498, a mean velocity of 25 m s-1, a layer mean shear of 15.0 E-3 s-1, and a "shot scale" turbulence with a standard deviation of 3.5 m s-1. The distribution would be for the "background" aerosol mode that has a geometric mean of 4.4 E-8 m-1 sr-1 and a width of ln(s) = .8. A complete description of the point design including the energy/pulse, prf, integration time, mirror diameter, etc. should accompany any presentation of the simulated results.

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Caveats*

1. These atmospheres are meant only for the purpose of enabling "equal target" comparisons of different DWL concepts and their potential LOS data products. Emphasis is on measurement accuracy and not representativeness or coverage. Furthermore, there is no claim to the frequency of occurrence of the two backscatter modes.

2. The wavelength dependency of the backscatter coefficient across the 1-2 orders of magnitude width of the background mode is thought to vary from λ-3 on the left side (lower on the left side (lower β) to λ-1.5 on the right side (higher on the right side (higher β)). A λ-2.5 was used in these tables going from 1.06 µm data to 2.0518 and .355 µm at and above 3 km. Since a different λ coefficient was used below 3 km, some smoothing of the resulting profiles has been done to make the transition more realistic. Even so, there are some "jumps" between the mid-troposphere and boundary layer values due in part to the use of different phase functions for the aerosol attenuation in those two regions.

3. Issues related to sampling and averaging (or co-processing) within regions of realistic wind variability are not addressed with these reference atmospheres. Significant differences will result from different scanning patterns and laser shot densities.

Definitions

Wavelength: expressed in micro-meters. Number in ( ) is the line (cm-1) used in FASCODE.

Background mode: based upon GLOBE data representing the “background” aerosol mode found in both northern and southern hemisphere data sets.

Enhanced mode: based upon GLOBE data taken during periods when aerosol backscatter was clearly enhanced over the background cases. Enhancement includes effects of elevated dust layers, convective pumping, biomass burning, etc.

MODTRAN: based upon the atmospheric transmission data for a maritime tropical air mass with 50 km visibility and 23 km visibility in the boundary layer.

Trans(2x): two way transmission from space (nadir looking) to the bottom of the layer and back (units: fraction)

Altitude (column 1): taken to be the top of the layer; data is assumed to be a point value for that altitude, except for surface wind which is taken to be at 10 m. For example the value of “B-back” = 0.490E-07 in the .355 tables (background mode) is to be interpreted as being at 3km. To obtain the average aerosol backscatter for the layer between 2 and 3 km, the value of 0.700E-07 at 2km should be used to compute the layer average of .595E-07. (units: km)

B-back (column 2): assumed to be the geometric mean of a lognormal distribution of GLOBE “background” aerosol mode data with ln(s) = .8 (units: m-1 sr-1). “s” is the distribution width.

B-enhan (column 2): values provided are the geometric layer mean of a lognormal distribution of the backscatter events that are in excess of the “background” aerosol mode of backscatter, sometimes referred to as the convective mode. The width of this distribution is ln(s) = 1.0.

B-MOD (column 2): values of aerosol backscatter from MODTRAN data bases.

A-totl (column 3): total attenuation coefficient (aerosol scattering, aerosol absorption, molecular scattering, and molecular absorption) based on FASCODE (units: km-1).

M-back (column 4): molecular backscatter $\beta(\pi)$ taken from MODTRAN (units: m-1 sr-1)

U (column 5): based upon global averages from ECMWF T106 Nature Run; exception is the jet superimposed at 10 km (units: m s-1) (the velocity should be assumed to be parallel to the horizontally projected laser beam)

Sigma (column 6): “reasonable” values of uncorrelated wind variability on scales less than 10 km (units: m s-1)

Cld (column 7): clouds are expressed in terms of their extinction coefficient (units: km-1). The physical thickness is assumed to be 1 km (eg. cloud listed at 10 km is located between 9 and 10 km). The percent coverage of the Target Sample Volume (TSV) is taken to be 100% for the cloud between 9 and 10 km and 50% for the cloud between 2 and 3 km. The cloud between 2 and 3 km is assumed to be composed of scattered small clouds that have horizontal dimensions equal to the spacing between individual lidar shots. Thus each shot has the same probability of being terminated by a cloud. (The 9-10 km cloud layer transmits 0.869 of a vertical laser beam, and the 2-3 km cloud layer transmits 0.0067. Therefore, the 2-3 km cloud layer effectively blocks half of the laser shots.)

A-ext (column 8): aerosol extinction coefficient derived using the same backscatter/extinction ratios as those used in MODTRAN (units: km-1)

M-scat (column 9): attenuation due to molecular scattering (units: km-1)

M-abs (column 9): attenuation due to molecular absorption (units: km-1)

Trans(2x) (column 10): two way transmission from space (nadir looking) to the bottom of the layer and back (units: fraction)

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Wavelength: 0.3550 ( 28169.02)

Background mode of GLOBE

z(km) B-back  A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.516E-08 0.280E-02 0.285E-06 15. 1.  0.00 0.188E-03 0.242E-02 0.190E-03 0.994E+00
24. 0.780E-08 0.320E-02 0.338E-06 15. 1.  0.00 0.284E-03 0.287E-02 0.492E-04 0.988E+00
23. 0.118E-07 0.380E-02 0.396E-06 15. 1.  0.00 0.429E-03 0.336E-02 0.800E-05 0.981E+00
22. 0.170E-07 0.462E-02 0.462E-06 15. 1.  0.00 0.618E-03 0.393E-02 0.690E-04 0.972E+00
21. 0.198E-07 0.560E-02 0.542E-06 15. 1.  0.00 0.720E-03 0.461E-02 0.273E-03 0.961E+00
20. 0.233E-07 0.670E-02 0.636E-06 15. 1.  0.00 0.847E-03 0.540E-02 0.449E-03 0.948E+00
19. 0.229E-07 0.770E-02 0.747E-06 15. 1.  0.00 0.833E-03 0.635E-02 0.521E-03 0.933E+00
18. 0.200E-07 0.878E-02 0.876E-06 15. 1.  0.00 0.727E-03 0.744E-02 0.612E-03 0.917E+00
17. 0.168E-07 0.102E-01 0.103E-05 15. 1.  0.00 0.611E-03 0.879E-02 0.806E-03 0.899E+00
16. 0.151E-07 0.119E-01 0.121E-05 15. 1.  0.00 0.549E-03 0.103E-01 0.110E-02 0.878E+00
15. 0.156E-07 0.136E-01 0.142E-05 18. 1.  0.00 0.568E-03 0.120E-01 0.101E-02 0.854E+00
14. 0.300E-07 0.160E-01 0.167E-05 22. 1.  0.00 0.109E-02 0.142E-01 0.715E-03 0.827E+00
13. 0.410E-07 0.185E-01 0.195E-05 26. 1.  0.00 0.149E-02 0.165E-01 0.429E-03 0.797E+00
12. 0.540E-07 0.211E-01 0.221E-05 28. 2.  0.00 0.196E-02 0.187E-01 0.450E-03 0.764E+00
11. 0.520E-07 0.235E-01 0.249E-05 35. 5.  0.00 0.189E-02 0.211E-01 0.543E-03 0.729E+00
10. 0.480E-07 0.261E-01 0.279E-05 50. 10. 0.14 0.175E-02 0.237E-01 0.636E-03 0.692E+00
9.  0.460E-07 0.294E-01 0.314E-05 40. 5.  0.00 0.189E-02 0.267E-01 0.868E-03 0.652E+00
8.  0.440E-07 0.329E-01 0.350E-05 25. 2.  0.00 0.193E-02 0.298E-01 0.121E-02 0.611E+00
7.  0.410E-07 0.373E-01 0.391E-05 18. 1.  0.00 0.204E-02 0.333E-01 0.204E-02 0.567E+00
6.  0.380E-07 0.407E-01 0.436E-05 16. 1.  0.00 0.204E-02 0.370E-01 0.161E-02 0.523E+00
5.  0.370E-07 0.469E-01 0.485E-05 14. 1.  0.00 0.212E-02 0.412E-01 0.355E-02 0.476E+00
4.  0.420E-07 0.521E-01 0.538E-05 13. 1.  0.00 0.302E-02 0.457E-01 0.342E-02 0.429E+00
3.  0.490E-07 0.587E-01 0.595E-05 12. 1.  5.00 0.452E-02 0.505E-01 0.368E-02 0.381E+00
2.  0.700E-07 0.627E-01 0.658E-05 11. 1.  0.00 0.316E-02 0.559E-01 0.370E-02 0.336E+00
1.  0.150E-06 0.711E-01 0.725E-05 10. 2.  0.00 0.585E-02 0.616E-01 0.358E-02 0.292E+00
0.  0.300E-06 0.823E-01 0.804E-05 2.  1.  0.00 0.106E-01 0.683E-01 0.337E-02 0.247E+00

Enhanced mode of GLOBE

z(km) B-enhan A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.516E-08 0.280E-02 0.285E-06 15. 1. 0.00 0.188E-03 0.242E-02 0.190E-03 0.994E+00
24. 0.780E-08 0.320E-02 0.338E-06 15. 1. 0.00 0.284E-03 0.287E-02 0.492E-04 0.988E+00
23. 0.118E-07 0.380E-02 0.396E-06 15. 1. 0.00 0.429E-03 0.336E-02 0.800E-05 0.981E+00
22. 0.170E-07 0.462E-02 0.462E-06 15. 1. 0.00 0.618E-03 0.393E-02 0.690E-04 0.972E+00
21. 0.198E-07 0.560E-02 0.542E-06 15. 1. 0.00 0.720E-03 0.461E-02 0.273E-03 0.961E+00
20. 0.233E-07 0.670E-02 0.636E-06 15. 1. 0.00 0.847E-03 0.540E-02 0.449E-03 0.948E+00
19. 0.229E-07 0.770E-02 0.747E-06 15. 1. 0.00 0.833E-03 0.635E-02 0.521E-03 0.933E+00
18. 0.200E-07 0.878E-02 0.876E-06 15. 1. 0.00 0.727E-03 0.744E-02 0.612E-03 0.917E+00
17. 0.168E-07 0.102E-01 0.103E-05 15. 1. 0.00 0.611E-03 0.879E-02 0.806E-03 0.899E+00
16. 0.151E-07 0.119E-01 0.121E-05 15. 1. 0.00 0.549E-03 0.103E-01 0.110E-02 0.878E+00
15. 0.156E-07 0.136E-01 0.142E-05 18. 1. 0.00 0.568E-03 0.120E-01 0.101E-02 0.854E+00
14. 0.300E-07 0.160E-01 0.167E-05 22. 1. 0.00 0.109E-02 0.142E-01 0.715E-03 0.827E+00
13. 0.410E-07 0.185E-01 0.195E-05 26. 1. 0.00 0.149E-02 0.165E-01 0.429E-03 0.797E+00
12. 0.540E-07 0.211E-01 0.221E-05 28. 2. 0.00 0.196E-02 0.187E-01 0.450E-03 0.764E+00
11. 0.700E-07 0.242E-01 0.249E-05 35. 5. 0.00 0.255E-02 0.211E-01 0.543E-03 0.728E+00
10. 0.200E-06 0.316E-01 0.279E-05 50. 10. 0.14 0.728E-02 0.237E-01 0.636E-03 0.683E+00
9. 0.230E-06 0.364E-01 0.314E-05 40. 5. 0.00 0.888E-02 0.267E-01 0.868E-03 0.635E+00
8. 0.250E-06 0.407E-01 0.350E-05 25. 2. 0.00 0.976E-02 0.298E-01 0.121E-02 0.586E+00
7. 0.300E-06 0.472E-01 0.391E-05 18. 1. 0.00 0.119E-01 0.333E-01 0.204E-02 0.533E+00
6. 0.350E-06 0.525E-01 0.436E-05 16. 1. 0.00 0.139E-01 0.370E-01 0.161E-02 0.480E+00
5. 0.375E-06 0.597E-01 0.485E-05 14. 1. 0.00 0.150E-01 0.412E-01 0.355E-02 0.426E+00
4. 0.400E-06 0.657E-01 0.538E-05 13. 1. 0.00 0.166E-01 0.457E-01 0.342E-02 0.373E+00
3. 0.425E-06 0.730E-01 0.595E-05 12. 1. 5.00 0.188E-01 0.505E-01 0.368E-02 0.323E+00
2. 0.600E-06 0.739E-01 0.658E-05 11. 1. 0.00 0.143E-01 0.559E-01 0.370E-02 0.278E+00
1. 0.150E-05 0.994E-01 0.725E-05 10. 2. 0.00 0.342E-01 0.616E-01 0.358E-02 0.228E+00
0. 0.300E-05 0.139E+00 0.804E-05 2. 1. 0.00 0.672E-01 0.683E-01 0.337E-02 0.173E+00

MODTRAN reference

z(km) B-MOD   A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.516E-08 0.280E-02 0.285E-06 15. 1. 0.00 0.188E-03 0.242E-02 0.190E-03 0.994E+00
24. 0.780E-08 0.320E-02 0.338E-06 15. 1. 0.00 0.284E-03 0.287E-02 0.492E-04 0.988E+00
23. 0.118E-07 0.380E-02 0.396E-06 15. 1. 0.00 0.430E-03 0.336E-02 0.800E-05 0.981E+00
22. 0.166E-07 0.460E-02 0.462E-06 15. 1. 0.00 0.602E-03 0.393E-02 0.690E-04 0.972E+00
21. 0.198E-07 0.560E-02 0.542E-06 15. 1. 0.00 0.721E-03 0.461E-02 0.273E-03 0.961E+00
20. 0.232E-07 0.670E-02 0.636E-06 15. 1. 0.00 0.846E-03 0.540E-02 0.449E-03 0.948E+00
19. 0.229E-07 0.770E-02 0.747E-06 15. 1. 0.00 0.834E-03 0.635E-02 0.521E-03 0.934E+00
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18. 0.205E-07 0.880E-02 0.876E-06 15. 1. 0.00 0.745E-03 0.744E-02 0.612E-03 0.917E+00
17. 0.168E-07 0.102E-01 0.103E-05 15. 1. 0.00 0.609E-03 0.879E-02 0.806E-03 0.899E+00
16. 0.151E-07 0.119E-01 0.121E-05 15. 1. 0.00 0.547E-03 0.103E-01 0.110E-02 0.878E+00
15. 0.156E-07 0.136E-01 0.142E-05 18. 1. 0.00 0.566E-03 0.120E-01 0.101E-02 0.854E+00
14. 0.175E-07 0.155E-01 0.167E-05 22. 1. 0.00 0.635E-03 0.142E-01 0.715E-03 0.828E+00
13. 0.204E-07 0.177E-01 0.195E-05 26. 1. 0.00 0.741E-03 0.165E-01 0.429E-03 0.799E+00
12. 0.253E-07 0.201E-01 0.221E-05 28. 2. 0.00 0.920E-03 0.187E-01 0.450E-03 0.768E+00
11. 0.315E-07 0.228E-01 0.249E-05 35. 5. 0.00 0.115E-02 0.211E-01 0.543E-03 0.733E+00
10. 0.449E-07 0.260E-01 0.279E-05 50. 10. 0.14 0.163E-02 0.237E-01 0.636E-03 0.696E+00
9. 0.746E-07 0.305E-01 0.314E-05 40. 5. 0.00 0.297E-02 0.267E-01 0.868E-03 0.655E+00
8. 0.138E-06 0.365E-01 0.350E-05 25. 2. 0.00 0.552E-02 0.298E-01 0.121E-02 0.609E+00
7. 0.256E-06 0.455E-01 0.391E-05 18. 1. 0.00 0.102E-01 0.333E-01 0.204E-02 0.556E+00
6. 0.318E-06 0.513E-01 0.436E-05 16. 1. 0.00 0.127E-01 0.370E-01 0.161E-02 0.502E+00
5. 0.383E-06 0.600E-01 0.485E-05 14. 1. 0.00 0.153E-01 0.412E-01 0.355E-02 0.445E+00
4. 0.762E-06 0.795E-01 0.538E-05 13. 1. 0.00 0.304E-01 0.457E-01 0.342E-02 0.380E+00
3. 0.143E-05 0.111E+00 0.595E-05 12. 1. 5.00 0.568E-01 0.505E-01 0.368E-02 0.304E+00
2. 0.347E-05 0.134E+00 0.658E-05 11. 1. 0.00 0.744E-01 0.559E-01 0.370E-02 0.233E+00
1. 0.553E-05 0.184E+00 0.725E-05 10. 2. 0.00 0.119E+00 0.616E-01 0.358E-02 0.161E+00
0. 0.882E-05 0.261E+00 0.804E-05 2. 1. 0.00 0.189E+00 0.683E-01 0.337E-02 0.955E-01

Wavelength: 1.0600 ( 9433.96)

Background mode of GLOBE

z(km) B-back  A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.713E-09 0.692E-04 0.329E-08 15. 1. 0.00 0.378E-04 0.280E-04 0.342E-05 0.100E+01
24. 0.108E-08 0.954E-04 0.390E-08 15. 1. 0.00 0.573E-04 0.331E-04 0.493E-05 0.100E+01
23. 0.163E-08 0.131E-03 0.457E-08 15. 1. 0.00 0.865E-04 0.388E-04 0.557E-05 0.999E+00
22. 0.229E-08 0.173E-03 0.534E-08 15. 1. 0.00 0.122E-03 0.454E-04 0.584E-05 0.999E+00
21. 0.274E-08 0.206E-03 0.626E-08 15. 1. 0.00 0.145E-03 0.532E-04 0.762E-05 0.999E+00
20. 0.321E-08 0.241E-03 0.735E-08 15. 1. 0.00 0.170E-03 0.624E-04 0.779E-05 0.998E+00
19. 0.317E-08 0.251E-03 0.862E-08 15. 1. 0.00 0.168E-03 0.732E-04 0.975E-05 0.998E+00
18. 0.283E-08 0.247E-03 0.101E-07 15. 1. 0.00 0.150E-03 0.859E-04 0.105E-04 0.997E+00
17. 0.231E-08 0.235E-03 0.119E-07 15. 1. 0.00 0.123E-03 0.101E-03 0.114E-04 0.997E+00
16. 0.208E-08 0.243E-03 0.139E-07 15. 1. 0.00 0.110E-03 0.118E-03 0.139E-04 0.996E+00
15. 0.215E-08 0.272E-03 0.163E-07 18. 1. 0.00 0.114E-03 0.139E-03 0.187E-04 0.996E+00
14. 0.241E-08 0.312E-03 0.192E-07 22. 1. 0.00 0.128E-03 0.163E-03 0.203E-04 0.995E+00
13. 0.281E-08 0.365E-03 0.225E-07 26. 1. 0.00 0.149E-03 0.191E-03 0.245E-04 0.994E+00
12. 0.349E-08 0.434E-03 0.255E-07 28. 2. 0.00 0.185E-03 0.216E-03 0.329E-04 0.993E+00
11. 0.330E-08 0.465E-03 0.287E-07 35. 5. 0.00 0.175E-03 0.244E-03 0.458E-04 0.993E+00
10. 0.320E-08 0.505E-03 0.323E-07 50. 10. 0.14 0.170E-03 0.274E-03 0.614E-04 0.992E+00
9. 0.310E-08 0.578E-03 0.362E-07 40. 5. 0.00 0.197E-03 0.308E-03 0.731E-04 0.990E+00
8. 0.300E-08 0.736E-03 0.405E-07 25. 2. 0.00 0.243E-03 0.344E-03 0.149E-03 0.989E+00
7. 0.280E-08 0.876E-03 0.452E-07 18. 1. 0.00 0.328E-03 0.384E-03 0.164E-03 0.987E+00
6. 0.250E-08 0.103E-02 0.503E-07 16. 1. 0.00 0.364E-03 0.427E-03 0.242E-03 0.985E+00
5. 0.250E-08 0.122E-02 0.560E-07 14. 1. 0.00 0.416E-03 0.475E-03 0.325E-03 0.983E+00
4. 0.290E-08 0.208E-02 0.621E-07 13. 1. 0.00 0.735E-03 0.528E-03 0.815E-03 0.979E+00
3. 0.340E-08 0.329E-02 0.687E-07 12. 1. 5.00 0.128E-02 0.583E-03 0.143E-02 0.972E+00
2. 0.700E-08 0.391E-02 0.759E-07 11. 1. 0.00 0.102E-02 0.645E-03 0.225E-02 0.965E+00
1. 0.500E-07 0.676E-02 0.838E-07 10. 2. 0.00 0.287E-02 0.711E-03 0.317E-02 0.952E+00
0. 0.100E-06 0.104E-01 0.929E-07 2. 1. 0.00 0.523E-02 0.789E-03 0.441E-02 0.932E+00

Enhanced mode of GLOBE

z(km) B-enhan A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.713E-09 0.692E-04 0.329E-08 15. 1. 0.00 0.378E-04 0.280E-04 0.342E-05 0.100E+01
24. 0.108E-08 0.954E-04 0.390E-08 15. 1. 0.00 0.573E-04 0.331E-04 0.493E-05 0.100E+01
23. 0.163E-08 0.131E-03 0.457E-08 15. 1. 0.00 0.865E-04 0.388E-04 0.557E-05 0.999E+00
22. 0.229E-08 0.173E-03 0.534E-08 15. 1. 0.00 0.122E-03 0.454E-04 0.584E-05 0.999E+00
21. 0.274E-08 0.206E-03 0.626E-08 15. 1. 0.00 0.145E-03 0.532E-04 0.762E-05 0.999E+00
20. 0.321E-08 0.241E-03 0.735E-08 15. 1. 0.00 0.170E-03 0.624E-04 0.779E-05 0.998E+00
19. 0.317E-08 0.251E-03 0.862E-08 15. 1. 0.00 0.168E-03 0.732E-04 0.975E-05 0.998E+00
18. 0.283E-08 0.247E-03 0.101E-07 15. 1. 0.00 0.150E-03 0.859E-04 0.105E-04 0.997E+00
17. 0.231E-08 0.235E-03 0.119E-07 15. 1. 0.00 0.123E-03 0.101E-03 0.114E-04 0.997E+00
16. 0.208E-08 0.243E-03 0.139E-07 15. 1. 0.00 0.110E-03 0.118E-03 0.139E-04 0.996E+00
15. 0.215E-08 0.272E-03 0.163E-07 18. 1. 0.00 0.114E-03 0.139E-03 0.187E-04 0.996E+00
14. 0.241E-08 0.312E-03 0.192E-07 22. 1. 0.00 0.128E-03 0.163E-03 0.203E-04 0.995E+00
13. 0.281E-08 0.365E-03 0.225E-07 26. 1. 0.00 0.149E-03 0.191E-03 0.245E-04 0.994E+00
12. 0.349E-08 0.434E-03 0.255E-07 28. 2. 0.00 0.185E-03 0.216E-03 0.329E-04 0.993E+00
11. 0.140E-07 0.103E-02 0.287E-07 35. 5. 0.00 0.743E-03 0.244E-03 0.458E-04 0.991E+00
10. 0.400E-07 0.246E-02 0.323E-07 50. 10. 0.14 0.212E-02 0.274E-03 0.614E-04 0.987E+00
9. 0.480E-07 0.257E-02 0.362E-07 40. 5. 0.00 0.219E-02 0.308E-03 0.731E-04 0.982E+00
8. 0.540E-07 0.300E-02 0.405E-07 25. 2. 0.00 0.251E-02 0.344E-03 0.149E-03 0.976E+00
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7. 0.600E-07 0.342E-02 0.452E-07 18. 1. 0.00 0.287E-02 0.384E-03 0.164E-03 0.969E+00
6. 0.700E-07 0.403E-02 0.503E-07 16. 1. 0.00 0.336E-02 0.427E-03 0.242E-03 0.961E+00
5. 0.780E-07 0.457E-02 0.560E-07 14. 1. 0.00 0.377E-02 0.475E-03 0.325E-03 0.952E+00
4. 0.760E-07 0.532E-02 0.621E-07 13. 1. 0.00 0.398E-02 0.528E-03 0.815E-03 0.942E+00
3. 0.700E-07 0.625E-02 0.687E-07 12. 1. 5.00 0.424E-02 0.583E-03 0.143E-02 0.931E+00
2. 0.200E-06 0.101E-01 0.759E-07 11. 1. 0.00 0.723E-02 0.645E-03 0.225E-02 0.912E+00
1. 0.500E-06 0.212E-01 0.838E-07 10. 2. 0.00 0.173E-01 0.711E-03 0.317E-02 0.874E+00
0. 0.100E-05 0.394E-01 0.929E-07 2. 1. 0.00 0.342E-01 0.789E-03 0.441E-02 0.808E+00

MODTRAN reference

z(km) B-MOD    A-totl    M-back    U Sigma Cld A-ext     M-scat    M-abs     Trans(2x)
25. 0.713E-09 0.692E-04 0.329E-08 15. 1. 0.00 0.378E-04 0.280E-04 0.342E-05 0.100E+01
24. 0.108E-08 0.952E-04 0.390E-08 15. 1. 0.00 0.572E-04 0.331E-04 0.493E-05 0.100E+01
23. 0.163E-08 0.131E-03 0.457E-08 15. 1. 0.00 0.866E-04 0.388E-04 0.557E-05 0.999E+00
22. 0.228E-08 0.173E-03 0.534E-08 15. 1. 0.00 0.121E-03 0.454E-04 0.584E-05 0.999E+00
21. 0.274E-08 0.206E-03 0.626E-08 15. 1. 0.00 0.145E-03 0.532E-04 0.762E-05 0.999E+00
20. 0.321E-08 0.240E-03 0.735E-08 15. 1. 0.00 0.170E-03 0.624E-04 0.779E-05 0.998E+00
19. 0.317E-08 0.251E-03 0.862E-08 15. 1. 0.00 0.168E-03 0.732E-04 0.975E-05 0.998E+00
18. 0.283E-08 0.247E-03 0.101E-07 15. 1. 0.00 0.150E-03 0.859E-04 0.105E-04 0.997E+00
17. 0.231E-08 0.236E-03 0.119E-07 15. 1. 0.00 0.123E-03 0.101E-03 0.114E-04 0.997E+00
16. 0.208E-08 0.242E-03 0.139E-07 15. 1. 0.00 0.110E-03 0.118E-03 0.139E-04 0.996E+00
15. 0.215E-08 0.272E-03 0.163E-07 18. 1. 0.00 0.114E-03 0.139E-03 0.187E-04 0.996E+00
14. 0.241E-08 0.312E-03 0.192E-07 22. 1. 0.00 0.128E-03 0.163E-03 0.203E-04 0.995E+00
13. 0.281E-08 0.365E-03 0.225E-07 26. 1. 0.00 0.149E-03 0.191E-03 0.245E-04 0.994E+00
12. 0.349E-08 0.434E-03 0.255E-07 28. 2. 0.00 0.185E-03 0.216E-03 0.329E-04 0.993E+00
11. 0.435E-08 0.521E-03 0.287E-07 35. 5. 0.00 0.231E-03 0.244E-03 0.458E-04 0.992E+00
10. 0.620E-08 0.664E-03 0.323E-07 50. 10. 0.14 0.329E-03 0.274E-03 0.614E-04 0.991E+00
9. 0.131E-07 0.102E-02 0.362E-07 40. 5. 0.00 0.642E-03 0.308E-03 0.731E-04 0.989E+00
8. 0.243E-07 0.169E-02 0.405E-07 25. 2. 0.00 0.119E-02 0.344E-03 0.149E-03 0.986E+00
7. 0.451E-07 0.276E-02 0.452E-07 18. 1. 0.00 0.221E-02 0.384E-03 0.164E-03 0.980E+00
6. 0.559E-07 0.340E-02 0.503E-07 16. 1. 0.00 0.274E-02 0.427E-03 0.242E-03 0.974E+00
5. 0.674E-07 0.410E-02 0.560E-07 14. 1. 0.00 0.330E-02 0.475E-03 0.325E-03 0.966E+00
4. 0.134E-06 0.791E-02 0.621E-07 13. 1. 0.00 0.656E-02 0.528E-03 0.815E-03 0.951E+00
3. 0.251E-06 0.143E-01 0.687E-07 12. 1. 5.00 0.123E-01 0.583E-03 0.143E-02 0.924E+00
2. 0.146E-05 0.508E-01 0.759E-07 11. 1. 0.00 0.479E-01 0.645E-03 0.225E-02 0.835E+00
1. 0.234E-05 0.803E-01 0.838E-07 10. 2. 0.00 0.764E-01 0.711E-03 0.317E-02 0.711E+00
0. 0.372E-05 0.127E+00 0.929E-07 2. 1. 0.00 0.122E+00 0.789E-03 0.441E-02 0.551E+00


Wavelength: 2.0518 ( 4873.77)

Background mode of GLOBE

z(km) B-back   A-totl    M-back    U Sigma Cld  A-ext     M-scat    M-abs     Trans(2x)
25. 0.256E-09 0.909E-05 0.233E-09 15. 1.  0.00 0.516E-05 0.198E-05 0.196E-05 0.100E+01
24. 0.387E-09 0.123E-04 0.275E-09 15. 1.  0.00 0.780E-05 0.234E-05 0.216E-05 0.100E+01
23. 0.587E-09 0.170E-04 0.323E-09 15. 1.  0.00 0.118E-04 0.274E-05 0.243E-05 0.100E+01
22. 0.822E-09 0.227E-04 0.377E-09 15. 1.  0.00 0.166E-04 0.320E-05 0.294E-05 0.100E+01
21. 0.984E-09 0.269E-04 0.442E-09 15. 1.  0.00 0.198E-04 0.376E-05 0.331E-05 0.100E+01
20. 0.115E-08 0.317E-04 0.519E-09 15. 1.  0.00 0.232E-04 0.441E-05 0.413E-05 0.100E+01
19. 0.114E-08 0.370E-04 0.609E-09 15. 1.  0.00 0.230E-04 0.518E-05 0.888E-05 0.100E+01
18. 0.102E-08 0.428E-04 0.715E-09 15. 1.  0.00 0.206E-04 0.607E-05 0.161E-04 0.100E+01
17. 0.831E-09 0.520E-04 0.844E-09 15. 1.  0.00 0.167E-04 0.717E-05 0.281E-04 0.999E+00
16. 0.747E-09 0.790E-04 0.984E-09 15. 1.  0.00 0.150E-04 0.836E-05 0.556E-04 0.999E+00
15. 0.773E-09 0.170E-03 0.115E-08 18. 1.  0.00 0.156E-04 0.981E-05 0.145E-03 0.999E+00
14. 0.867E-09 0.385E-03 0.136E-08 22. 1.  0.00 0.175E-04 0.115E-04 0.356E-03 0.998E+00
13. 0.700E-09 0.475E-03 0.159E-08 26. 1.  0.00 0.143E-04 0.135E-04 0.447E-03 0.997E+00
12. 0.620E-09 0.754E-03 0.180E-08 28. 2.  0.00 0.130E-04 0.153E-04 0.725E-03 0.996E+00
11. 0.590E-09 0.110E-02 0.203E-08 35. 5.  0.00 0.126E-04 0.172E-04 0.107E-02 0.994E+00
10. 0.550E-09 0.155E-02 0.228E-08 50. 10. 0.14 0.123E-04 0.194E-04 0.152E-02 0.991E+00
9.  0.540E-09 0.222E-02 0.256E-08 40. 5.  0.00 0.316E-04 0.218E-04 0.216E-02 0.986E+00
8.  0.530E-09 0.302E-02 0.286E-08 25. 2.  0.00 0.440E-04 0.243E-04 0.295E-02 0.980E+00
7.  0.510E-09 0.409E-02 0.319E-08 18. 1.  0.00 0.667E-04 0.271E-04 0.400E-02 0.972E+00
6.  0.450E-09 0.525E-02 0.356E-08 16. 1.  0.00 0.770E-04 0.302E-04 0.515E-02 0.962E+00
5.  0.440E-09 0.715E-02 0.395E-08 14. 1.  0.00 0.897E-04 0.336E-04 0.703E-02 0.948E+00
4.  0.510E-09 0.920E-02 0.439E-08 13. 1.  0.00 0.167E-03 0.373E-04 0.900E-02 0.931E+00
3.  0.560E-09 0.240E-01 0.485E-08 12. 1.  5.00 0.300E-03 0.412E-04 0.236E-01 0.887E+00
2.  0.350E-08 0.184E-01 0.537E-08 11. 1.  0.00 0.818E-03 0.456E-04 0.175E-01 0.855E+00
1.  0.250E-07 0.340E-01 0.592E-08 10. 2.  0.00 0.236E-02 0.503E-04 0.315E-01 0.799E+00
0.  0.500E-07 0.492E-01 0.656E-08 2.  1.  0.00 0.432E-02 0.557E-04 0.448E-01 0.724E+00

Enhanced mode of GLOBE
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z(km) B-enhan A-totl    M-back    U Sigma Cld  A-ext     M-scat    M-abs     Trans(2x)
25.  0.256E-09 0.909E-05 0.233E-09 15. 1.   0.00 0.516E-05 0.198E-05 0.196E-05 0.100E+01
24.  0.387E-09 0.123E-04 0.275E-09 15. 1.   0.00 0.780E-05 0.234E-05 0.216E-05 0.100E+01
23.  0.587E-09 0.170E-04 0.323E-09 15. 1.   0.00 0.118E-04 0.274E-05 0.243E-05 0.100E+01
22.  0.822E-09 0.227E-04 0.377E-09 15. 1.   0.00 0.166E-04 0.320E-05 0.294E-05 0.100E+01
21.  0.984E-09 0.269E-04 0.442E-09 15. 1.   0.00 0.198E-04 0.376E-05 0.331E-05 0.100E+01
20.  0.115E-08 0.317E-04 0.519E-09 15. 1.   0.00 0.232E-04 0.441E-05 0.413E-05 0.100E+01
19.  0.114E-08 0.370E-04 0.609E-09 15. 1.   0.00 0.230E-04 0.518E-05 0.888E-05 0.100E+01
18.  0.102E-08 0.428E-04 0.715E-09 15. 1.   0.00 0.206E-04 0.607E-05 0.161E-04 0.100E+01
17.  0.831E-09 0.520E-04 0.844E-09 15. 1.   0.00 0.167E-04 0.717E-05 0.281E-04 0.999E+00
16.  0.747E-09 0.790E-04 0.984E-09 15. 1.   0.00 0.150E-04 0.836E-05 0.556E-04 0.999E+00
15.  0.773E-09 0.170E-03 0.115E-08 18. 1.   0.00 0.156E-04 0.981E-05 0.145E-03 0.999E+00
14.  0.867E-09 0.385E-03 0.136E-08 22. 1.   0.00 0.175E-04 0.115E-04 0.356E-03 0.998E+00
13.  0.700E-09 0.475E-03 0.159E-08 26. 1.   0.00 0.143E-04 0.135E-04 0.447E-03 0.997E+00
12.  0.280E-08 0.796E-03 0.180E-08 28. 2.   0.00 0.553E-04 0.153E-04 0.725E-03 0.996E+00
11.  0.480E-08 0.118E-02 0.203E-08 35. 5.   0.00 0.943E-04 0.172E-04 0.107E-02 0.993E+00
10.  0.150E-07 0.183E-02 0.228E-08 50. 10.  0.14 0.293E-03 0.194E-04 0.152E-02 0.990E+00
9.   0.160E-07 0.270E-02 0.256E-08 40. 5.   0.00 0.512E-03 0.218E-04 0.216E-02 0.984E+00
8.   0.180E-07 0.356E-02 0.286E-08 25. 2.   0.00 0.587E-03 0.243E-04 0.295E-02 0.977E+00
7.   0.210E-07 0.473E-02 0.319E-08 18. 1.   0.00 0.704E-03 0.271E-04 0.400E-02 0.968E+00
6.   0.250E-07 0.602E-02 0.356E-08 16. 1.   0.00 0.840E-03 0.302E-04 0.515E-02 0.957E+00
5.   0.290E-07 0.804E-02 0.395E-08 14. 1.   0.00 0.978E-03 0.336E-04 0.703E-02 0.941E+00
4.   0.300E-07 0.101E-01 0.439E-08 13. 1.   0.00 0.108E-02 0.373E-04 0.900E-02 0.923E+00
3.   0.280E-07 0.248E-01 0.485E-08 12. 1.   5.00 0.115E-02 0.412E-04 0.236E-01 0.878E+00
2.   0.300E-07 0.198E-01 0.537E-08 11. 1.   0.00 0.226E-02 0.456E-04 0.175E-01 0.844E+00
1.   0.250E-06 0.462E-01 0.592E-08 10. 2.   0.00 0.146E-01 0.503E-04 0.315E-01 0.769E+00
0.   0.500E-06 0.737E-01 0.656E-08 2.  1.   0.00 0.288E-01 0.557E-04 0.448E-01 0.664E+00
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MODTRAN reference

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z(km) B-MOD   A-totl    M-back    U Sigma Cld  A-ext     M-scat    M-abs     Trans(2x)
25.  0.256E-09 0.910E-05 0.233E-09 15. 1.   0.00 0.516E-05 0.198E-05 0.196E-05 0.100E+01
24.  0.387E-09 0.123E-04 0.275E-09 15. 1.   0.00 0.780E-05 0.234E-05 0.216E-05 0.100E+01
23.  0.587E-09 0.170E-04 0.323E-09 15. 1.   0.00 0.118E-04 0.274E-05 0.243E-05 0.100E+01
22.  0.822E-09 0.227E-04 0.377E-09 15. 1.   0.00 0.166E-04 0.320E-05 0.294E-05 0.100E+01
21.  0.984E-09 0.269E-04 0.442E-09 15. 1.   0.00 0.198E-04 0.376E-05 0.331E-05 0.100E+01
20.  0.115E-08 0.318E-04 0.519E-09 15. 1.   0.00 0.233E-04 0.441E-05 0.413E-05 0.100E+01
19.  0.114E-08 0.370E-04 0.609E-09 15. 1.   0.00 0.229E-04 0.518E-05 0.888E-05 0.100E+01
18.  0.102E-08 0.427E-04 0.715E-09 15. 1.   0.00 0.205E-04 0.607E-05 0.161E-04 0.100E+01
17.  0.831E-09 0.520E-04 0.844E-09 15. 1.   0.00 0.168E-04 0.717E-05 0.281E-04 0.999E+00
16.  0.747E-09 0.790E-04 0.984E-09 15. 1.   0.00 0.151E-04 0.836E-05 0.556E-04 0.999E+00
15.  0.773E-09 0.170E-03 0.115E-08 18. 1.   0.00 0.156E-04 0.981E-05 0.145E-03 0.999E+00
14.  0.867E-09 0.385E-03 0.136E-08 22. 1.   0.00 0.175E-04 0.115E-04 0.356E-03 0.998E+00
13.  0.101E-08 0.481E-03 0.159E-08 26. 1.   0.00 0.204E-04 0.135E-04 0.447E-03 0.997E+00
12.  0.126E-08 0.766E-03 0.180E-08 28. 2.   0.00 0.253E-04 0.153E-04 0.725E-03 0.996E+00
11.  0.157E-08 0.112E-02 0.203E-08 35. 5.   0.00 0.315E-04 0.172E-04 0.107E-02 0.994E+00
10.  0.223E-08 0.158E-02 0.228E-08 50. 10.  0.14 0.449E-04 0.194E-04 0.152E-02 0.990E+00
9.   0.257E-08 0.228E-02 0.256E-08 40. 5.   0.00 0.946E-04 0.218E-04 0.216E-02 0.986E+00
8.   0.477E-08 0.315E-02 0.286E-08 25. 2.   0.00 0.176E-03 0.243E-04 0.295E-02 0.980E+00
7.   0.882E-08 0.435E-02 0.319E-08 18. 1.   0.00 0.325E-03 0.271E-04 0.400E-02 0.971E+00
6.   0.109E-07 0.558E-02 0.356E-08 16. 1.   0.00 0.403E-03 0.302E-04 0.515E-02 0.960E+00
5.   0.132E-07 0.755E-02 0.395E-08 14. 1.   0.00 0.486E-03 0.336E-04 0.703E-02 0.946E+00
4.   0.262E-07 0.100E-01 0.439E-08 13. 1.   0.00 0.967E-03 0.373E-04 0.900E-02 0.927E+00
3.   0.491E-07 0.255E-01 0.485E-08 12. 1.   5.00 0.181E-02 0.412E-04 0.236E-01 0.881E+00
2.   0.603E-06 0.510E-01 0.537E-08 11. 1.   0.00 0.335E-01 0.456E-04 0.175E-01 0.796E+00
1.   0.962E-06 0.850E-01 0.592E-08 10. 2.   0.00 0.534E-01 0.503E-04 0.315E-01 0.671E+00
0.   0.153E-05 0.130E+00 0.656E-08 2.  1.   0.00 0.851E-01 0.557E-04 0.448E-01 0.518E+00
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Key: original errata that have been corrected or clarification added

*sometimes spelled kavayats

Appendix 3: Lidar Technology Challenges

Measurement Parameter	Measurement Scenario	Assessment	Lidar Utility	Lidar Approach	Lidar Technique
Tropospheric Winds Storm Cell Properties	LWG-AD-AIR1	P	1	Doppler, Airborne, Scanning	Doppler
Tropospheric Winds	LWG-AD-SP1	P	1	Doppler, 400 km, Demo Mission, 100% duty cycle	Doppler
Tropospheric Winds	LWG-AD-SP2	P	1	Doppler, 833 km, Demo Mission, w/adaptive targeting	Doppler
Tropospheric Winds	LWG-AD-SP3	T	1	Doppler, 400 km, Threshold 3-yr Mission, w/adaptive targeting	Doppler
Atmospheric Temperature	69	G	2	UV Temperature	Backscatter
Cloud Particle Properties and Distribution Cloud System Structure Total Aerosol Amount Stratospheric Aerosol Distribution Aerosol Properties	116	G	2	Cloud and Aerosol Lidar	Backscatter
Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	180	P	2	Backscatter Lidar	Backscatter
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	182	P	2	Raman Lidar	Backscatter
Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution Total Aerosol Amount	LWG-AC-1	P	2	Cross-track Backscatter Lidar	Backscatter
Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount	LWG-AC-2	P	2	Backscatter Lidar	Backscatter
Aerosol Properties Stratospheric Aerosol Distribution Total Aerosol Amount	NRC-03	P	2	Aerosol Global Interactions Lidar	Backscatter
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	23	G	1	Laser Absorption Spectrometer (LAS)	DIAL
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	24	P	1	CO2 Dial	DIAL
Stratospheric Aerosol Distribution Atmospheric Temperature Total Aerosol Amount	70	P	2	IR-DIAL Temperature	DIAL
Atmospheric Temperature Atmospheric Water Vapor	72	P	2	IR-DIAL Temperature and Water Vapor	DIAL
Storm Cell Properties	81	P	2	Storm Cell DIAL	DIAL
Tropospheric Ozone and Precursors	113	T	2	UV DIAL	DIAL
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	179	G	1	Differential Absorption Lidar	DIAL
Tropospheric Ozone and Precursors	181	T	2	Differential absorption lidar	DIAL
Tropospheric Ozone and Precursors	185	T	2	IR Differential Absorption Lidar	DIAL
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	NRC-01	E	2	CAPES DIAL	DIAL

Science Subgroup	Responsible trans. person	Responsible DPO person	POC	Merged With	Power Generation (magnitude and efficiency)	Thermal Control and Management subsystem	Attitude Control and Determination Subsystem (including precision pointing)	Mechanical and Structural Subsystem	Precision Navigation and Orbit Determination	Formation flying of multiple platforms	1-100 W, 0.1-50 mJ 1-micron laser	100 W, 100 Hz 1-micron laser	1-100 W 1.5-micron fiber laser	20 W, 1 J 2-micron pulsed laser	Wavelength converters for the vis-UV	Wavelength converters for the IR	Other laser	Beam director
Atmos Dynamics	Kavaya	Kavaya																E
Atmos Dynamics	Kavaya	Kavaya			E	E	E	E	E			E		E	CR			E
Atmos Dynamics	Kavaya	Kavaya			E	E	E	E	E			E		E	CR			E
Atmos Dynamics	Kavaya	Kavaya			E	E	E	E	E			E		E	CR			E
Atmospheric Comp.	Heaps	Gentry			E	E						E			E			
Atmospheric Comp.	Ismail	Ismail		NRC-06						E	E				E			
Atmospheric Comp.	Gentry	Gentry	McGill, Welton	NRC-06														
Atmospheric Comp.	Heaps	Gentry										E			E			
Atmospheric Comp.	Gentry	Gentry	Welton, Winker								E							E
Atmospheric Comp.	Gentry	Gentry	McGill, Welton								E							
Atmospheric Comp.	Ismail	Ismail		2300-09								E			E			CR
Atmospheric Comp.	Spiers, Abshire	Spiers					E										E	
Atmospheric Comp.	Ismail	Ismail			E	E								E				
Atmospheric Comp.	Ismail	Ismail										E				E		
Atmospheric Comp.	Ismail	Ismail										E				E		E
Atmospheric Comp.	Ismail	Ismail														E		E
Atmospheric Comp.	Ismail	Ismail			E	E						E			E			
Atmospheric Comp.	Abshire, Krainak	Krainak		NRC-04									E		E	E		
Atmospheric Comp.	Heaps	Gentry									E				E			
Atmospheric Comp.	Heaps	Gentry																
Atmospheric Comp.	Ismail	Ismail		71								E				E		E

Appendix 3: Lidar Technology Challenges

Measurement Parameter	Measurement Scei	Assessment	Lidar Utility	Lidar Approach	Lidar Technique
CO2 and Methane Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount	NRC-02	G	2	Active Mission for Global CO2 Lidar	DIAL
CO2 and Methane Cloud Particle Properties and Distribution Total Aerosol Amount Surface Trace Gas Concentration Trace Gas Sources	NRC-04	G	2	Orbital Laser Sounder for Global CO2	DIAL
Phytoplankton Physiology and Functional Groups	17	G	1	Fluorescence Lidar Active-Passive Suite (FLAPS)	Backscatter
Coastal Carbon Global Ocean Carbon/Particle Abundance	27	G	1	Ocean Carbon and Particle Lidar	Backscatter
Mixed Layer depth and illumination	42	G	3	Ocean Mixed Layer Depth Lidar	Backscatter
Sea Ice Thickness	99	P	3	Direct Sea Ice Thickness Lidar	Backscatter
Earth Gravity Field	57	G	1	Quantum Gravity Gradiometer	Other
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	48	P	2	Ice and Land Topography Lidar	Ranging and Altimetry
Terrestrial Reference Frame	52	E	1	Laser Ranging Network	Ranging and Altimetry
Earth Gravity Field	56	G	1	Inter-spacecraft Gravity Gradiometer	Ranging and Altimetry
Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	186	P	2	Photon-counting, Imaging Lidar	Ranging and Altimetry
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	187	T	2	Waveform Recording, Multi-beam Lidar	Ranging and Altimetry
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	188	G	2	Wide Swath Imaging Laser Altimeter	Ranging and Altimetry
Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	LWG-OT-1	T	2	Narrow Swath Orbital Imager	Ranging and Altimetry
Vegetation Biomass Ice Surface Topography River stage height	LWG-OT-2	T	2	UAV High Resolution Imager	Ranging and Altimetry
Vegetation Biomass Land Surface Topography	NRC-07	G	2	Earth-Moon Laser Altimeter	Ranging and Altimetry
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	NRC-11	E	1	Biomass Monitoring Lidar	Ranging and Altimetry

Science Subgroup	Responsible trans. person	Responsible DPO person	POC	Merged With	Power Generation (magnitude and efficiency)	Thermal Control and Management subsystem	Attitude Control and Determination Subsystem (including precision pointing)	Mechanical and Structural Subsystem	Precision Navigation and Orbit Determination	Formation flying of multiple platforms	1-100 W, 0.1-50 mJ 1-micron laser	100 W, 100 Hz 1-micron laser	1-100 W 1.5-micron fiber laser	20 W, 1 J 2-micron pulsed laser	Wavelength converters for the vis-UV	Wavelength converters for the IR	Other laser	Beam director
Atmospheric Comp.	Spiers	Ismail											E		E			
Atmospheric Comp.	Abshire, Krainak	Krainak, Abshire		184									E		E	E		
Topo. and Oceans	Stabnow	Chekalyuk	DiGiacomo									E			E			
Topo. and Oceans	Stabnow	Chekalyuk	DiGiacomo	NRC-09							E	PE			E			
Topo. and Oceans	Spiers	Spiers													E			
Topo. and Oceans	Gentry	Gentry	Cahalan, Varnai		E							E			E			
Topo. and Oceans	Spiers	Spiers													E			
Topo. and Oceans	Blair	Blair		149, 150			E		E		E				E			E
Topo. and Oceans	Blair, Abshire	Blair									E							
Topo. and Oceans	Spiers	Spiers					E		E	E							E	E
Topo. and Oceans	Blair	Blair				CR	E	E	E		E				E			E
Topo. and Oceans	Blair	Blair									E							
Topo. and Oceans	Blair	Blair				E	E		E		E							E
Topo. and Oceans	Blair	Blair	Blair			CR	E	E	E		E							
Topo. and Oceans	Blair	Blair	Blair			E	E		E		E							E
Topo. and Oceans	Spiers	Spiers				E	E	E	E		E							E
Topo. and Oceans	Blair	Blair		NRC-08		CR	CR		CR		E							
Topo. and Oceans Atmospheric Comp.	Abshire, Krainak	Krainak, Abshire										E						

Appendix 3: Lidar Technology Challenges

Measurement Parameter	Aberration compensation	Alignment maintenance	Scanning Systems	Doppler Offset Compensation Technologies	Large Effective Area, Lightweight Telescopes (Including stray light control)	Mechanical Metering Structures	Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Narrowband Optical Filters	Detectors (Including Arrays) and Amplifiers	Optical High Resolution Spectral Analyzers	Detection Electronics, E.G., High speed ADC, multi-channel scaler, and boxcar averager	Science model-driven adaptive targeting	Formation flying	Spacecraft area network	On-board sensor control	Intelligent sensor health & safety	On-board near RT data production	Data compression	Space-qualified TB storage HW	Space-qualified HPC HW & programming tools	Airborne/ground lidar validation systems	Data Management / Service Oriendted Architecture	Model lidar data resampling techniques	Knowledge Discovery
Tropospheric Winds Storm Cell Properties		CR	E						CR		CR													
Tropospheric Winds		E	E		CR				CR		CR													
Tropospheric Winds		E	E		CR				CR		CR													
Tropospheric Winds		E	E		CR				CR		CR	E			E	E	E	E	E	E	E	E	E	E
Atmospheric Temperature																			E		E			
Cloud Particle Properties and Distribution Cloud System Structure Total Aerosol Amount Stratospheric Aerosol Distribution Aerosol Properties																			E		E	E	E	E
Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties																			E		E	E	E	E
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties												E							E		E	E	E	E
Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution Total Aerosol Amount					E		E												E		E			
Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount								CR	CR												E			
Aerosol Properties Stratospheric Aerosol Distribution Total Aerosol Amount					E	CR	E	E	CR	E									E		E			
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane		E			CR		CR		E			E			E	E	E	E		E				
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane					E			E	E			E			E	E		E	E	E	E			
Stratospheric Aerosol Distribution Atmospheric Temperature Total Aerosol Amount					E	E		E			E					E	E		E	E	E			

Measurement Parameter	Aberration compensation	Alignment maintenance	Scanning Systems	Doppler Offset Compensation Technologies	Large Effective Area, Lightweight Telescopes (Including stray light control)	Mechanical Metering Structures	Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Narrowband Optical Filters	Detectors (Including Arrays) and Amplifiers	Optical High Resolution Spectral Analyzers	Detection Electronics, E.G., High speed ADC, multi-channel scaler, and boxcar averager	Science model-driven adaptive targeting	Formation flying	Spacecraft area network	On-board sensor control	Intelligent sensor health & safety	On-board near RT data production	Data compression	Space-qualified TB storage HW	Space-qualified HPC HW & programming tools	Airborne/ground lidar validation systems	Data Management / Service Oriendted Architecture	Model lidar data resampling techniques	Knowledge Discovery
Atmospheric Temperature Atmospheric Water Vapor			E	E	E	E		E								E			E	E	E			
Storm Cell Properties												E			E		E		E	E	E	E	E	E
Tropospheric Ozone and Precursors					E	E		E																
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane									E			E			E			E	E	E	E			
Tropospheric Ozone and Precursors							CR											E	E		E			
Tropospheric Ozone and Precursors									CR									E	E		E			
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties					E	E	CR	E				E							E		E			
CO2 and Methane Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount					E	E	CR	E	E			E			E		E	E	E	E	E	E	E	E
CO2 and Methane Cloud Particle Properties and Distribution Total Aerosol Amount Surface Trace Gas Concentration Trace Gas Sources								CR	E			E			E		E	E	E	E	E	E	E	E
Phytoplankton Physiology and Functional Groups		PE			E		PE		PE	E	PE				E		E	E	E	E	E	E	E	E
Coastal Carbon Global Ocean Carbon/Particle Abundance		PE			PE		PE	PE	PE			E			E	E	E	E	E	E	E	E	E	E
Mixed Layer depth and illumination		PE			PE		PE	PE	PE						E		E		E	E	E	E	E	E
Sea Ice Thickness					E	E	E	E	E		E				E				E	E	E			
Earth Gravity Field															E					E				
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity					CR			CR	CR		CR			E	E			E	E	E				

Appendix 3: Lidar Technology Challenges

Measurement Parameter	Aberration compensation	Alignment maintenance	Scanning Systems	Doppler Offset Compensation Technologies	Large Effective Area, Lightweight Telescopes (Including stray light control)	Mechanical Metering Structures	Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Narrowband Optical Filters	Detectors (Including Arrays) and Amplifiers	Optical High Resolution Spectral Analyzers	Detection Electronics, E.G., High speed ADC, multi-channel scaler, and boxcar averager	Science model-driven adaptive targeting	Formation flying	Spacecraft area network	On-board sensor control	Intelligent sensor health & safety	On-board near RT data production	Data compression	Space-qualified TB storage HW	Space-qualified HPC HW & programming tools	Airborne/ground lidar validation systems	Data Management / Service Oriendted Architecture	Model lidar data resampling techniques	Knowledge Discovery
Terrestrial Reference Frame								CR			CR					E	E			E				
Earth Gravity Field													E	E	E					E				
Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height		E	E		E			CR	E		E			E	E		E	E		E				
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity		E			E			CR	CR		E							E	E	E		E	E	E
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity			E		E			CR	CR		E			E	E			E	E	E				
Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height		E			E			CR	E		E				E			E		E				
Vegetation Biomass Ice Surface Topography River stage height								CR	CR		E				E			E						
Vegetation Biomass Land Surface Topography		E	E		E			CR	CR		CR		E	E	E	E		E		E				
Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity					CR						CR			E	E			E	E	E	E			
Land Surface Topography Land Cover and Land Use Ice Surface Topography Sea Ice Thickness									E						E			E	E	E	E			

Appendix 4: Data Use Scenarios

Appendix

Data Use Scenarios

Data Use Scenarios depicting possible missions are presented here for:
Water Vapor DIAL
Tropospheric Winds Lidar
Wide Swath Land Imager Laser
Carbon Dioxide IR-IPDA

Water Vapor

Water Vapor Use Case
Data Use Scenario

Measurement Parameter

IR-DIAL Water Vapor
FTS-Temperature and DIAL Water Vapor

Lidar Approach:

Differential Absorption Lidar (DIAL) and Fourier Transform Spectrometer (FTS) for temperature

Interested Parties

Numerical Weather Prediction forecasters

Ground

- High resolution H2O profile data needed for model assimilation and numerical weather forecast to an improved hurricane track accuracy of 30 km to issue hurricane warnings and evacuations. A total time latency of 3 hours is allowed, from satellite overpass to the issuing of warnings.

Uplink

- The mission controller schedules data collection on the DIAL satellite.
- The mission controller commands the satellite and instrument controllers

Data Acquisition (Space)

Spacecraft

- The spacecraft is in a LEO orbit.
- The attitude control system points the satellite to the region of interest
- Power from the electrical power subsystem is supplied to the DIAL system

Instrument

- The instrument controller sends commands and triggers to the DIAL system to commence and synchronize operations in concert with subsystem resources. (Note: the system may run continuously)
    - One operation is to point the DIAL system
- The DIAL system starts conditioning the laser for operation. The laser tunes to the on and off-line positions and verifies they are at the specified spectral position.
- DIAL lidar laser (type: injection seeded OPO) transmits three pulsed beams (on-line (940 nm) wavelength, 2 of which water vapor absorbs, and off-line (delta=40-70 pm) wavelength that is less absorbed.
- The aft optics tunes the optical filters for maximum transmission; injection locking narrows line laser
- During laser operation the thermal subsystem dissipates the heat.
- Receiver system collects backscattered light with a telescope.
- A fiber optic cable is the transmission channel from the telescope to the detector.
- A narrowband filter provides background light rejection with high light throughput of the wavelength of interest. A photon counting Si:APD detector converts received light signals into electric pulses. The electric pulse is then fed into a digitizer.

Onboard Data Handling

- The instrument data is calibrated and quality control is assessed.
- Raw data is temporarily housed in onboard storage.
- Raw data is processed onboard. The processing includes: data editing, horizontal averaging, background correction, vertical averaging and differentiation, DIAL equation used for preliminary data reduction.
- The spacecraft data processor analyzes housekeeping data along with a small subset of backscattered returns to detect any faults
- Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags
- raw data (DIAL+FTS), DIAL averaged signal data and DIAL minimally reduced data are transmitted to ground. Only DIAL data is transmitted if downlink capability is exceeded

Downlink

- Raw data and preprocessed data are downlinked to the ground station(s)

Data Utilization (Ground)

Ground Data Processing & Dissemination

Quicklook

- Quicklook data are reviewed and commands sent to the onboard instruments to align optics, modify pointing, change correction coefficients, …

Level 0 data

- Level 0 processing compensates for optical losses in the atmosphere and the receiver system, temperature effects on the receiver system, …
- Calibration
- Level 0 data is sent to archival storage and to local storage
- Level 0 data is accessible and distributed to scientists
- Level 0 data is processed into level 1 data

Level 1 data

- Level 1 data is archived, accessible and ready for distribution
- Level 1 data is processed into level 2 data
- Archived data is searched using metadata

Modeling and Assimilation

- Model ingest and assimilation
- High level Numerical Weather Forecast runs

Wide Swath Land Imaging

Wide-Swath Imaging Lidar for Land, Ocean, and Ice Surface Mapping
Data Use Scenario

Measurement Parameter

Imaging Laser Altimeter for Earth Surface Mapping

Lidar Approach:

Spaceborne Scanning Laser Altimeter

Interested Parties

Ecologists, Geologists, Foresters, Climatologists

Appendix 4: Data Use Scenarios

Ground

- Global Mapping of Surface Topography and Vegetation Height and Structure, and Targeted Reimaging for Change Detection needed for the estimation of global biomass and monitoring changes in biomass. Mapping of global land topography, including sub-canopy, will contribute to numerous solid-Earth studies including monitoring natural hazards.
- Also, the operations scheme would be to spend probably 6 months in the 30% duty cycle mode - operating over all land/ice surfaces - then transition to a targeted imaging mode to fill in missing pieces and to re-image and monitor specific targets over multiple years. That might require something closer to a 10% overall duty cycle to extend mission lifetime. Then we would need algorithms and planning software to perform the targeted imaging.
- The mission controller schedules data collection for the Imaging Laser Altimeter.

Uplink

- The mission controller commands the satellite and instrument controllers, based on coastal crossings, determine the on/off times for operations - it is expected that there are 3-4 operations cycles/orbit.

Data Acquisition (Space)

Spacecraft

- The spacecraft is in a LEO orbit.
- The attitude control system points the satellite to the region of interest.
- Controlled off-nadir pointing is used for targeted acquisition of preplanned targets, with uploaded locations. Onboard processing software determines timing and off-nadir pointing required to acquire.
- Power from the electrical power subsystem is supplied to the Imaging Lidar system.

Instrument

- The instrument controller sends a block of timed commands to trigger the Imaging Lidar system to commence begin and end operations (Note: the system may run continuously). Realtime location information (for example, from onboard GPS) will be used to refine on/off times to account for errors in predicted orbit and coastal crossing times.
- The Imaging Lidar system begins an operational period by first conditioning the lasers for operation. A short warmup time is used to prepare lasers for optimum performance and to reduce any life-reducing shocks (i.e. thermal, mechanical) to the laser. The lasers are maintained at their operational temperature using backup heaters.
- Wide-swath Imaging lidar laser (type: seeded fiber amplifier) system transmits ~1000 beams at a 1064 nm wavelength.
- During laser operation the thermal subsystem dissipates the heat.
- The receiver system collects backscattered light with a telescope.
- A fiber optic cable is the transmission channel from the telescope to the detector.
- A narrowband filter provides background light rejection with high light throughput of the wavelength of interest.
- A Si:APD detector converts received light signals into electric pulses.
- The electric pulse is then fed into a digitizer.
- Digitizer operates constantly during active laser operations. The transmitted pulse shape is recorded and telemetered. One or more return pulse(s) per laser fire is recorded and telemetered.
- Precise time tags are also required on all of the critical data sets: 1) range 2) scan angle (if we are using a scanner) 3) platform attitude (roll, pitch, yaw) 4) instrument position (GPS lat, lon, altitude).

Onboard Data Handling

- The instrument data is calibrated and quality control is assessed.
- Digitizer operates constantly during active laser operations. The transmitted pulse shape is recorded and telemetered. One or more return pulse per laser fire is recorded and telemetered.
- Raw data is temporarily housed in onboard storage.
- Raw data is processed onboard: include return pulse finding, collection of detector noise statistics,
- The spacecraft data processor analyzes housekeeping data along with a small subset of backscattered returns to detect any faults
- Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags.

Downlink

- Raw data and preprocessed data are downlinked to the ground station(s).
- Downlink rate required (assuming a 10 minute downlink pass/orbit) is about 55 Mbps.

Data Utilization (Ground)

Ground Data Processing & Dissemination

Quicklook

- Quicklook data are reviewed and commands sent to the onboard instruments to align optics, modify pointing, change correction coefficients, etc.

Level 0 data

- Level 0 processing is performed.
- Calibration of data is performed.
- Level 0 data is sent to archival storage and to local storage.
- Level 0 data is accessible and distributed to scientists.
- Level 0 data is processed into level 1 data.

Level 1 data

- Level 1 data is archived, accessible and ready for distribution.
- Level 1 data is processed into level 2 data.
- Archived data is searchable using metadata.

Modeling and Assimilation

- Model ingest and assimilation produces maps of vegetation canopy height or biomass.
- Due to the low SNR of the individual footprints, we will have to average adjacent spots together to improve the SNR sufficiently to penetrate dense vegetation canopies. This will require massive processing to vertically geolocate and then superimpose adjacent waveforms together, then this super-waveform will be processed to extract ground topography and then recombined with the higher resolution canopy top topography to produce maps of canopy height.

Carbon Dioxide

Integrated Path Differential Absorption for Carbon Dioxide Data Use Scenario

Measurement Parameter

- Carbon Cycle & Ecosystems: CO2 and methane:Total column CO2 including tropospheric CO2
- Carbon Cycle & Ecosystems: Trace gas sources:Total column CO2 including tropospheric CO2

Lidar Approach:

2 micron cw integrated path differential absorption lidar

Interested Parties

Air Quality Control, Carbon Climate Change Researchers

Ground

- Data latency is not an issue - availability of data with 24 hrs would be acceptable.
- The mission controller schedules data collection from the lidar satellite.

Uplink

- The mission controller commands the satellite and instrument controllers.

Data Acquisition (Space)

Spacecraft

- The spacecraft is in a LEO orbit.
- The instrument is pointed slightly off nadir (~0.25 deg or 4 mrad), along the velocity vector to provide a Doppler shifted return signal.
- Pointing stability (0.4 mr) is required to keep the signal within the receiver bandwidth during signal capture.
- Power from the electrical power subsystem is supplied to the IPDA system. A key driver for power consumption is the thermal control subsystem that cools the lasers and diode pumps.

Appendix 4: Data Use Scenarios

Instrument

- The instrument controller sends commands and triggers to the IPDA system to commence and synchronize operations in concert with subsystem resources. (Note: the system may run continuously)
- During start-up the onboard reference laser is tuned and locked to a reference cell carried on board. The online and offline lasers are then offset tuned and locked with respect to this reference laser.
- The online and offline lasers are continuous (not pulsed) lasers and are transmitted out of the instrument. The output power and frequency of these transmitted lasers is constantly monitored and recorded internal to the system.
- The offline return signal offset frequency is monitored and used to adjust the receiver center bandwidth to accommodate for fluctuations in the spacecraft attitude that are smaller than 0.4 mr.
- During laser operation the thermal subsystem dissipates the heat.
- The receiver system collects backscattered light with a telescope.
- The return signals are mixed with a local optical oscillator on a detector.
- The heterodyne output from the detector is then fed into a digitizer.

Onboard Data Handling

- The instrument data is calibrated and quality control is assessed.
- Raw data is temporarily housed in onboard storage.
- Raw data is processed to assess SNR for instrument health purposes. More complex onboard processing requires ancillary data (Temperature Profile and Altimetry from systems on board or most likely from assets on other platforms flying in tandem) to be available but can potentially substantially reduce downlink data volume.
- The spacecraft data processor analyzes housekeeping data along with a small subset of backscattered returns to detect any faults
- Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags
- Raw and housekeeping data (monitor sensor data) are downlinked.
- If processing is done on board satellite cross-link may be required to obtain ancillary data necessary for processing.

Downlink

- Raw data and preprocessed data are downlinked to the ground station(s)

Data Utilization (Ground)

Ground Data Processing & Dissemination

Quicklook

- Quicklook data are reviewed and commands sent to the onboard instruments to align optics, modify pointing, change correction coefficients, etc.

Level 0 data

- Level 0 processing normalises the return signal with respect to the transmitted signal for each channel.
- Calibration of data is performed.
- Level 0 data is sent to archival storage and to local storage.
- Level 0 data is accessible and distributed to scientists.
- Level 0 data is processed into level 1 data.

Level 1 data

- Level 1 data is archived, accessible and ready for distribution.
- Level 1 data is processed into level 2 data.
- Archived data is searchable using metadata.

Modeling and Assimilation

- Model ingest and assimilation of data takes place.
- High level Numerical Weather Forecast runs are made.

Water Vapor
Data Use Scenario

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
Measurement Parameter:				
IR DIAL Water Vapor				
FTS Temperature; and DIAL Water Vapor				
Lidar Approach:				
Differential Absorption Lidar (DIAL) and Fourier Transform Spectrometer (FTS) for temperature				
Ground				
High resolution H2O profile data needed for model assimilation and numerical weather forecast to an improved hurricane track accuracy of 30 km to issue hurricane warnings and evacuations. A total 3-hr time latency is allowed (from satellite overpass) to issuing warnings.				
The mission controller schedules data collection on the DIAL satellite				
Uplink				
The mission controller commands the satellite and instrument controllers				commands
Data Acquisition (Space)				
Spacecraft				
The spacecraft is in LEO orbit.		orbit/altitude	400 km	
		orbit period	110 min	
		ground station coverage per orbit	10 min	
The attitude control system points the satellite to the region of interest	Attitude Control and Determination Subsystem (including precision pointing)	pointing accuracy	0.1 mr	
Power from the electrical power subsystem is supplied to the DIAL	Power Generation (magnitude and efficiency)	onboard power generation	4kW avg, 7kW peak	
Instrument				
The instrument controller sends commands and triggers to the DIAL system to commence and synchronize operations in concert with subsystem resources (Note: the system may run continuously)	Command & Control and autonomy for conditional data acquisition			
One operation is to point the DIAL system				
The DIAL system starts conditioning the laser for operation. The laser tunes to the on and off-line positions and verifies they are at the specified spectral position				
DIAL lidar laser (type: injection seeded OPO) transmits three pulsed beams (on-line (940 nm) wavelength 2 of which water vapor absorbs and off line (delta=40-70 pm) wavelength that is less absorbed)		pulse repetition frequency, pulse duration	0.5 J at 20 Hz, 30 ns	
The aft optics tunes the optical filters for maximum transmission; injection locking narrows line laser				
During laser operation the thermal subsystem dissipates the heat	Thermal Control and Management subsystem	thermal control (Watts dissipated)	5 kW	
Receiver system collects backscattered light with a telescope				
A fiber optic cable is the transmission channel from the telescope to the detector				
A narrowband filter provides background light rejection with high light throughput of the wavelength of interest				
A photon counting Si:APD detector converts received light signals into electric pulses				raw signals
The electric pulse is then fed into a digitizer		ADC	14 bit (three)	raw data
		data format		
		duty cycle	50%	
		resolution: vertical	0.5- 1.0 km	

Appendix 4: Data Use Scenarios

Water Vapor Data Use Scenario				
Data Use Scenario Steps	**Technology Challenge**	**Parameter**	**Value**	**Data Output**
		resolution: vertical	0.5- 1.0 km	
		resolution: horizontal	20-50 km	
		#channels	6 channels (1000, 14 bit, data points/per channel); 10 Hz	
		#water vapor profiles	200 per 10 min observation period	
Onboard Data Handling				
All raw data is temporarily housed in onboard storage.	Large on-board data storage	storage capacity	20 Gb	
		write/read throughput	? Mbps/? Mbps	
The spacecraft data processor analyzes housekeeping data along with (a small subset of?) the backscattered returns to detect any faults	Autonomous Sensor monitoring and control (anomaly detection; Health and Status)			
Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags				
Data that passes the initial quality checks is analyzed on-board to retrieve initial estimates of water vapor profiles and cloud and aerosol layer heights. The on-board lidar data processing operations include § background subtraction; § horizontal averaging; § vertical averaging; § division; § differentiation; and § layer detection. The DIAL equation used for preliminary data reduction on the processed data. The full resolution raw data is retained for downlink and ground processing.	Real time on-board processing (HW)	onboard processing	? MIPS	background corrected data with SNR estimates
	On-Board Data Processing Algorithms and Software	algorithm size; execution speed; data throughput		
The raw data (laser backscatter and FTS), DIAL averaged signal data, and DIAL-derived water vapor profiles are transmitted to the ground. If the available downlink capability is exceeded, only the DIAL data is transmitted.	satellite cross-links	capacity	? Mbps	
Downlink				
The operational data (i.e., data used to inform near real-time forecasting) is downlinked. The DIAL-derived water vapor profiles and layer boundaries are to be downlinked within 1 hour (TBR) of data acquisition for use in numerical weather prediction models.	data distribution; near real-time QA assessment	timeliness requirement	3 hours or less between raw data acquisition and derived data product use in numerical fore-cast models	water vapor profiles; layer heights

Water Vapor
Data Use Scenario

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
The science data is downlinked to the ground station(s). Science data consists of the full resolution raw data and all preprocessed data.	High Data Rate downlink	data rate	? Mbps	
	Communication real time downlink	data rate	? Mbps	
All data products retrieved on-board the satellite (e.g., DIAL-derived water vapor profiles and layer boundaries) are now accessible and distributed to scientists and modelers	data distribution			water vapor profiles; layer heights
Data Utilization (Ground)				
Ground Data Processing & Dissemination				
	Network Technologies: FireWire, Ethernet, etc.	networking configuration, throughput	config: star, thruput=? Mbps	
Quicklook				
Quicklook data are reviewed by scientists and mission planners. If necessary, commands are sent to the onboard instruments to optimize data acquisition efficiency (e.g., to align optics, modify pointing, change correction coefficients, etc.)	Data Quick Looks	data set size	? Mb	
		timeliness requirement	? Hours	
Level 0 data				
see http://observer.gsfc.nasa.gov/sec3/ProductLevels.html - Level 0 data products are "reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g. synchronization frames, communications headers, [and/or] duplicate data [are] removed"				raw data corrected for instrument artifacts
All raw data (DIAL+FTS) is converted to Level 0 format.	Data Pre-filtering			
el 0 data is sent to archival storage and to local storage.		networking configuration; throughput; storage capacity		
The Level 0 raw data (DIAL + FTS) is further processed into level 1 data				
Level 1 data processing (DIAL + FTS raw data only)				
see http://observer.gsfc.nasa.gov/sec3/ProductLevels.html - Level 1A data products are "time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to the Level 0 data." Level 1B data products are "Level 1A data that have been processed to sensor units"				
The laser backscatter profiles are range-corrected, geo-referenced, altitude registered, and background subtracted.	retrieval algorithms for Level 1 data products (algorithm development)			background subtracted, altitude registered data
The lidar calibration constant(s) are derived and applied to the profile	calibration of 940 nm backscatter data			attenuated backscatter profiles with error bars
The Level 1 data is now accessible and distributed to mission scientists.	data distribution; data visualization; QA assessment	timeliness requirement		
		distribution paths	internet, satellite downlink, ???	
The Level 1 data us sent to archival storage and to local storage.		networking configuration; throughput; storage capacity	? Mbps ? Tb	

Appendix 4: Data Use Scenarios

Water Vapor
Data Use Scenario

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
The Level 1 data is further processed to generate Level 2 data products.				corrected composite water vapor profiles with noise error and bias profiles as well as weighting functions
Level 2 processing data				
see http://observer.gsfc.nasa.gov/sec3/ProductLevels.html - "Level 2 data products are derived geophysical variables at the same resolution and location as the Level 1 source data."				
Profiles of cloud and aerosol optical properties are retrieved from lidar backscatter profiles produced in the Level 1 processing.	retrieval algorithms for Level 2 data products (algorithm development; use of chemical transport model to improve lidar ratio selection, optical property accuracy)	algorithm complexity		aerosol backscatter and extinction profiles; layer optical depths
The DIAL water vapor profiles are recomputed. The additional information resources available during ground processing (e.g., FTS data products, and/or profiles of aerosol extinction) will generate "climate quality" estimates with smaller error bars than are associated with the on-board retrievals.	data fusion (use of FTS data to improve accuracy)			
The Level 2 data is now accessible and distributed to mission scientists.	data distribution; data visualization; QA assessment	timeliness requirement		
		distribution paths	internet, satellite downlink	
The Level 2 data us sent to archival storage and to local storage.		networking configuration; throughput; storage capacity		
As a result of on-going validation and verification studies by science team members, coefficient files are updated, retrieval algorithms are improved, and software enhancements and bug fixes are implemented. With each new release of the production software, data reprocessing is initiated. Current processing continues using the latest version of the code; reprocessing begins with the first data acquired, and continues until all available Level 1 and Level 2 data products have been generated with the identical version of the production software.	automated staging and scheduling	networking configuration; throughput; storage capacity		
Data Distribution				
The Level 1 data is accessible and ready for public distribution.	subsetting; data distribution; data visualization			water vapor profiles with error estimates; layer boundaries; attenuated backscatter profiles with error estimates
The Level 2 data is accessible, and ready for public distribution.	subsetting; data distribution; data visualization			aerosol backscatter and extinction profiles with error estimates; layer optical depths with error estimates
	Virtual Data Products (on-demand products)			
Data users search archived data using metadata.	Data Discovery (meta-data search)	metadata	mission, ontology, keywords	
Modeling and Assimilation				
Model ingest and assimilation produces water vapor profiles with error estimates.	Model Ingest and Assimilation	algorithm	data product to grid mapping	water vapor profiles with error estimates
High level Numerical Weather Forecast runs produce weather forecasts and warnings.	Numerical weather forecast model runs and issue forecast			Issue Forecast and Warnings

Wide-Swath Imaging Lidar for Land, Ocean, and Ice Surface Mapping

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
Measurement Parameter:				
Imaging Laser Altimeter for Earth Surface Mapping				
Lidar Approach:				
Spaceborne Scanning Laser Altimeter				
Ground				
Global Mapping of Surface Topography and Vegetation Height and Structure, and Targeted Reimaging for Change Detection needed for the estimation of global biomass and monitoring changes in biomass. Mapping of global land topography, including sub-canopy, will contribute to numerous solid-Earth studies including monitoring natural hazards.				
Also, the operations scheme would be to spend probably 6 months in the 30% duty cycle mode - operating over all land/ice surfaces - then transition to a targeted imaging mode to fill in missing pieces and to re-image and monitor specific targets over multiple years. That might require something closer to a 10% overall duty cycle to extend mission lifetime. Then we would need algorithms and planning software to perform the targeted imaging.				
The mission controller schedules data collection for the Imaging Laser Altimeter				
Uplink				
The mission controller commands the satellite and instrument controllers, based on coastal crossings, determine the on/off times for operations - it is expected that there are 3-4 operations cycles/orbit.				# of commands
Data Acquisition (Space)				
Spacecraft				
The spacecraft is in LEO orbit.		orbit/altitude	400 km	
		orbit period	90 min	
		ground station coverage per orbit	10 min	
The attitude control system points the satellite to the region of interest	Attitude Control and Determination Subsystem (including precision pointing)	pointing accuracy	1 mr (control), 0.045 mr (knowledge 3 sigma)	
Controlled off-nadir pointing is used for targeted acquisition of preplanned targets, with uploaded locations. Onboard processing software determines timing and off-nadir pointing required to acquire.		off-nadir angle	+-10 degrees	
Power from the electrical power subsystem is supplied to the Imaging Lidar system	Power Generation (magnitude and efficiency)	onboard power generation	0.2kW avg, 0.3kW peak	
Instrument				
The instrument controller sends a block of timed commands to trigger the Imaging Lidar system to commence begin and end operations (Note: the system may run continuously). Realtime location information (for example, from onboard GPS) will be used to refine on/off times to account for errors in predicted orbit and coastal crossing times.	Command & Control and autonomy for conditional data acquisition	Autonomous decisions made per command;	Robustness of execution x Abstraction level of commands x complexity/ # of possibilities	
The Imaging Lidar system begins an operational period by first conditioning the lasers for operation. A short warmup time is used to prepare lasers for optimum performance and to reduce any life-reducing shocks (i.e. thermal, mechanical) to the laser. The lasers are maintained at their operational temperature using backup heaters.				
Wide swath Imaging lidar laser (type: seeded fiber amplifier) system transmits ~1000 beams at a 1064 nm wavelength		pulse repetition frequency, pulse duration	0.2 mJ at 750 Hz, 5 ns	

Wide Swath Imaging Lidar for Land, Ocean, and Ice Surface Mapping

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
During laser operation the thermal subsystem dissipates the heat	Thermal Control and Management subsystem	thermal control (Watts dissipated)	200 W	
Receiver system collects backscattered light with a telescope				
A fiber optic cable is the transmission channel from the telescope to the detector				
A narrowband filter provides background light rejection with high light throughput of the wavelength of interest				
A Si:APD detector converts received light signals into electric pulses				raw signals
The electric pulse is then fed into a digitizer		ADC	6 bit	raw data
		data format		
		duty cycle	~33%	
		resolution: vertical	0.05 m (single pulse), 0.5 m (multiple returns)	
		resolution: horizontal	10 m	
Digitizer operates constantly during active laser operations. The transmitted pulse shape is recorded and telemetered. One or more return pulse per laser fire is recorded and telemetered.				
Precise time tags are also required on all of the critical data sets: 1) range 2) scan angle (if we are using a scanner) 3) platform attitude (roll, pitch, yaw) 4) instrument position (GPS lat, lon, altitude)				
Onboard Data Handling				
The instrument data is calibrated and quality control is assessed.	Instrumentation to support Lidar Cal/Val	accuracy	10%	raw data including QC
Digitizer operates constantly during active laser operations. The transmitted pulse shape is recorded and telemetered. One or more return pulse per laser fire is recorded and telemetered.		Peak data rate	200 Mbps	
Raw data is temporarily housed in onboard storage	Large on-board data storage	storage capacity	2,000 Gb	
		write/read throughput	200 Mbps/? Mbps	
Raw data is processed onboard: include return pulse finding, collection of detector noise statistics,	Real time on-board processing (HW)	onboard processing	? MIPS	
	On-Board Data Processing Algorithms and Software	algorithm size, throughput		
The spacecraft data processor analyzes housekeeping data to detect any faults	Autonomous Sensor monitoring and control (anomaly detection; Health and Status)			
Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags				
Downlink				
Raw data and preprocessed data are downlinked to the ground station(s)	High Data Rate downlink	total daily data rate	0.5 Tbps	
Downlink rate required (assuming a 10 minute downlink pass/orbit)		data rate	55.55555556	Mbps
	Communication real time downlink	data rate	? Mbps	
Data Utilization (Ground)				
Ground Data Processing & Dissemination				
	Network Technologies: FireWire, Ethernet, etc.	networking configuration, throughput	config: star, thruput=? Mbps	
Quicklook				
Quicklook data are reviewed and commands sent to the onboard instruments to align optics, modify pointing, change correction coefficients, …	Data Quick Looks	data set size	? Mb	
		timeliness requirement	< 3 hours	
Level 0 data				

Wide Swath Imaging Lidar for Land, Ocean, and Ice Surface Mapping

Data Use Scenario Steps	**Technology Challenge**	**Parameter**	**Value**	**Data Output**
Level 0 processing	Data Pre-filtering			background corrected data
calibration				calibrated data
Level 0 data is sent to archival storage and to local storage		data storage size	________	
Level 0 data is accessible and distributed to scientists	Data Distribution	timeliness requirement	3 hours total; 1 hr for level 1, 2.0 hrs for assimilation and numerical forecast model run	calibrated and background corrected data
		distribution paths	internet, satellite downlink, ???	
Level 0 data is processed into level 1 data				
Level 1 data				
Level 1 data is archived, accessible and ready for distribution				
Level 1 data is processed into level 2 data				
	Data Processing Algorithms for Level 1 and 2 products (retrieval algorithm development)	algorithm complexity		
	Virtual Data Products (on-demand products)			
Archived data is searchable using metadata	Data Discovery (meta-data search)	metadata	mission, ontology, keywords	% relevancy to a data query
	Data Reprocessing			
Modeling and Assimilation				
Model ingest and assimilation produces maps of vegetation canopy height or biomass.	Model Ingest and Assimilation	algorithm	data product to grid mapping	maps of veg canopy Height (m) or Biomass kg C/ ha
				Ocean Height - data also used to derive Ocean Surface Temperature.
				Height of Ice surface
Due to the low SNR of the individual footprints, we will have to average adjacent spots together to improve the SNR sufficiently to penetrate dense vegetation canopies. This will require massive processing to vertically geolocate and then superimpose adjacent waveforms together, then this super-waveform will be processed to extract ground topography and then recombined with the higher resolution canopy top topography to produce maps of canopy height.				

IPDA for Carbon Dioxide

Data Use Scenario Steps	Technology Challenge	Parameter	Value	Data Output
Measurement Parameter:				
Carbon Cycle & Ecosystems: CO2 and methane:Total column CO2 including tropospheric CO2				
Carbon Cycle & Ecosystems: Trace gas sources:Total column CO2 including tropospheric CO2				
Lidar Approach:				
2 micron cw integrated path differential absorption lidar				
Ground				
Data latency is not an issue - availability of data with 24 hrs would be acceptable				
The mission controller schedules data collection from the lidar satellite				
Uplink				
ssion controller commands the satellite and instrument controllers				commands
Data Acquisition (Space)				
Spacecraft				
The spacecraft is in LEO orbit.		orbit/altitude	400 km	
		orbit period	92 min	
		ground station coverage per orbit	10 min	
Instrument is pointed slightly off nadir (~0.25 deg or 4 mrad) along the velocity vector to provide a Doppler shifted return signal.	Attitude Control and Determination Subsystem (including precision pointing)	pointing accuracy	0.4 mr	
Require pointing stability to keep signal within the receiver bandwidth during signal capture	Attitude Control and Determination Subsystem (including precision pointing)	pointing stability	0.4 mr	
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.	Power Generation (magnitude and efficiency)	onboard power generation	3-4 kW avg	
Instrument				
The instrument controller sends commands and triggers to the IPDA system to commence and synchronize operations in concert with subsystem resources (Note: the system may run continuously)	Command & Control and autonomy for conditional data acquisition			
During start-up the onboard reference laser is tuned and locked to a reference cell carried on board. The online and offline lasers are then offset tuned and locked with respect to this reference laser.				
The online and offline lasers are continuous (not pulsed) lasers and are transmitted out of the instrument. The output power and frequency of these transmitted lasers is constantly monitored and recorded internal to the system		pulse repetition frequency, pulse duration	2-5W each laser, CW (not pulsed)	
The offline return signal offset frequency is monitored and used to adjust the receiver center bandwidth to accommodate for fluctuations in the spacecraft attitude that are smaller than 0.4 mr				
During laser operation the thermal subsystem dissipates the heat	Thermal Control and Management subsystem	thermal control (Watts dissipated)	nominally same as power consumed.	
Receiver system collects backscattered light with a telescope				
The return signals are mixed with a local optical oscillator on a detector.				raw signals
The heterodyne output from the detector is then fed into a digitizer		ADC	14 bit (four)	raw data
		data format		
		duty cycle	100%	
		resolution: vertical	NA	
		resolution: horizontal	~100km	

IPDA for Carbon Dioxide				
Data Use Scenario Steps	**Technology Challenge**	**Parameter**	**Value**	**Data Output**
		horizontal #channels	5 channels (100MHz sampling on two, 10 MHz sampling on other 3, 14 bit, data points/per channel); CW	
Onboard Data Handling				
The instrument data is calibrated and quality control is assessed.	Instrumentation to support Lidar Cal/Val	accuracy	10%	raw data including QC
Raw data is temporarily housed in onboard storage	Large on-board data storage	storage capacity	2 Tb	
		write/read throughput	? Mbps/? Mbps	
Raw data is processed to assess SNR for instrument health purposes. More complex onboard processing requires ancillary data (Temperature Profile and Altimetry from systems on board or most likely from assets on other platforms flying in tandem) to be available but can potentially substantially reduce downlink data volume.	Real time on-board processing (HW)	onboard processing	? MIPS	SNR estimates
	On-Board Data Processing Algorithms and Software	algorithm size, throughput		
The spacecraft data processor analyzes housekeeping data along with a small subset of backscattered returns to detect any faults	Autonomous Sensor monitoring and control (anomaly detection; Health and Status)			
Detected faults are addressed by fault handling algorithms that recognize when laser power is not steady, and when the optical throughput and detector-signal processor system generates flags				
Raw and housekeeping data (monitor sensor data) are downlinked				
If processing is done on board satellite cross-link may be required to obtain ancillary data necessary for processing.	satellite cross-links	capacity	? Mbps	
Downlink				
Raw data and preprocessed data are downlinked to the ground station(s)	High Data Rate downlink	data rate	? Mbps	
	Communication real time downlink	data rate	? Mbps	
Data Utilization (Ground)				
Ground Data Processing & Dissemination				
	Network Technologies: FireWire, Ethernet, etc.	networking configuration, throughput	config: star, thruput=? Mbps	
Quicklook				
Quicklook data are reviewed and commands sent to the onboard instruments to align optics, modify pointing, change correction coefficients, …	Data Quick Looks	data set size	? Mb	
		timeliness requirement	? Hours	
Level 0 data				
Level 0 processing normalises the return signal with respect to the transmitted signal for each channel …	Data Pre-filtering			background corrected data
calibration				calibrated data
Level 0 data is sent to archival storage and to local storage		data storage size	? Tb	
Level 0 data is accessible and distributed to scientists	Data Distribution	timeliness requirement	3 hours total; 1 hr for level 1, 2.0 hrs for assimilation and numerical forecast model run	calibrated and background corrected data

IPDA for Carbon Dioxide				
Data Use Scenario Steps	**Technology Challenge**	**Parameter**	**Value**	**Data Output**
		distribution paths	internet, satellite downlink	
Level 0 data is processed into level 1 data				
Level 1 data				
Level 1 data is archived, accessible and ready for distribution				combined carbon dioxide profiles with noise error analysis
Level 1 data is processed into level 2 data				corrected composite carbon dioxide profiles with noise error and bias profiles as well as weighting functions
	Data Processing Algorithms for Level 1 and 2 products (retrieval algorithm development)	algorithm complexity		
	Virtual Data Products (on-demand products)			
Archived data is searchable using metadata	Data Discovery (meta-data search)	metadata	mission, ontology, keywords, ???	
	Data Reprocessing			
Modeling and Assimilation				
Model ingest and assimilation of data takes place.	Model Ingest and Assimilation	algorithm	data product to grid mapping	carbon dioxide profiles with error estimates
High level Numerical Weather Forecast runs are made.	Numerical weather forecast model runs and issue forecast			Issue Forecast and Warnings

Appendix 5A: Laser Transmitter Capability Breakdown Structure (CBS)

Technology	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
1-100 W, 0.1-50 mJ 1-micron laser	116 LWG-AC-1 LWG-AC-2	Backscatter lidar	1064 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.	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).
	180 LWG-AC-1 LWG-AC-2	Backscatter lidar		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.	
	27	Backscatter lidar		Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 and 1064 nm	
	181	DIAL		Tropospheric ozone profiles along aircraft flight track	Conductively cooled laser transmitters with 1-kHz PRF @ 290-330 and 1064 nm.	
	186	Laser altimeter		Map solid earth, ice and aquatic surface elevation	4 mJ/1 kHz, WPE >3%, pulselength 1 ns	
	187	Laser altimeter		Map solid earth and aquatic surface elevations, including vegetation height and vertical structure	50 mJ/100 Hz, <5 ns pulsewidth	
	188	Laser altimeter		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%	
	48, 149, 150 NRC-07 NRC-11	Laser altimeter		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)	
	LWG-OT-1	Laser altimeter		Map solid earth, ice and aquatic surface elevation	5-20 micro-J/>10 kHz, pulselength <1 ns, linewidth <2 pm, linearly polarized	
	LWG-OT-2	Laser altimeter		Map solid earth, ice and aquatic surface elevation from UAV	5-20 micro-J/10-100 kHz, pulselength 2-5 ns, linewidth <2 pm, linearly polarized	
100 W, 100 Hz 1-micron laser	71 NRC-01	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	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.
	71 NRC-01	DIAL	1064 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%. Nonlinear generation by OPO	
	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Doppler lidar		Tropospheric wind profiles	1 J/100 Hz, single frequency, WPE 6-8%	
	69	Backscatter lidar		Atmospheric temperature profiles	1 J/100 Hz, single frequency, WPE 6-8%	
	116 NRC-03	Backscatter lidar		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.	
	182	Backscatter lidar		Airborne profiling of cloud/aerosol optical properties	>300 mJ/>50 Hz @ 355 nm; ~1 J at 1064 nm fundamental	
	17	Backscatter lidar		Hyperspectral measurement of laser-stimulated emission and natural fluorescence from the ocean	1 J/20-100 Hz, single frequency @ 1064 nm, WPE 6-8%	
	27	Backscatter lidar		Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 and 1064 nm	
	NRC-14	Laser altimeter		Map polar ice sheets to characterize ice mass changes	100 mJ/100 Hz at 532 and 1064 nm	
1-100 W 1.5-micron fiber laser	70	IPDA-LAS	1520 nm	Atmospheric temperature profiles	>1 J/10 Hz double-pulsed @ 760-nm 2nd harmonic	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.
	NRC-02 179	IPDA-LAS	1570 nm	Lower tropospheric CO2 fluxes	10 W cw, 5-MHz long-term linewidth, tunable; fiber or 1064-nm pumped OPO	
	NRC-04	IPDA-LAS	1570 nm	Lower atmospheric CO2 fluxes	0.1 mJ/100 kHz, linewidth <10 MHz, pulselength 1000 ns, single freq.	
20 W, 1 J 2-micron pulsed laser	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Doppler lidar	2050 nm	Tropospheric wind profiles	0.5 J/10 Hz, single frequency, WPE 1.4%	1. Oscillator: 10 Hz, 100 mJ, >180 ns near-transform limited, M^2 < 1.2. 2. Amplifier 20 Hz, 1 J, >180 ns near-transform limited, ~2% WPE, M^2 < 1.2. 3. System: 500 Hz, 100 mJ, >180 ns near-transform limited, M^2 < 1.2. 4. 8-GHz tunable frequency-agile reference oscillator.
	24	DIAL	2050 nm	Tropospheric CO2 profiles	1 J/20 Hz double-pulsed with spectral purity >99.5%, wavelength stability <0.02 pm, WPE 3-5%	

Appendix 5A: Laser Transmitter Capability Breakdown Structure (CBS)

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
1. General oscillator exists in several configurations, further validation of space compatibility. (0.1 ns for scenario 186 is a unique challenge.) 2. Scenarios 186, 188, LWG-OT-1 are satisfied by 5W average power; 100W versions could be alternative sources for photon-counting measurement of ozone, water vapor and direct detection winds. TRL 4 versions exist and must be advanced thru TRL 6. 3. TRL 4 10-W versions exist and are rapidly evolving toward TRL 6. 100-W being addressed by DOD in FY06; would bring to TRL 4.	High-PRF systems not yet demonstrated in space.	4	6	2 Years	Near-term (4-5 years)	James Abshire	301-614-6081	James.B.Abshire@nasa.gov
1. Scenarios LWG-AD-SP1-3 require 10 kHz linewidth and 8-GHz frequency agility; polarimetric aerosol backscatter requires high degree of polarization purity. General oscillator exists in several configurations suitable for topographic systems, requires further validation of space compatibility. 2. Scenarios LWG-AD-SP1-3 require 1 J/30 ns @ 100 Hz. Polarization backscatter systems require 100 mJ/20 Hz with high polarization purity (scenario 116); topographic systems 50-100 mJ, 5W average power, particular attention to thermal management.	Joule-class diode pumped 1-micron systems are in early stages of development.	4	6	1-2 Years	Near-term (4-5 years)	James Abshire	301-614-6081	James.B.Abshire@nasa.gov
1. TRL 6 oscillator package exists but requires space qualification. 2. TRL 5 package exists but more development needed to meet amplitude stability requirement.	Space qualification of commercially derived optical communication equipment is high priority.	5	6	1-2 Years	Mid-term (5-8 years)	James Abshire	301-614-6081	James.B.Abshire@nasa.gov
1. Scenarios 24 and LWG-AD-SP1-3 require 100 mJ at 20 Hz (scenario 24 requires double-pulse operation). TRL 4 is SOA; needs advancement to TRL 6. 10mJ oscillator would satisfy 500 Hz wind and CO2 measurement. 2. LWG-AD-SP1-3 requires advancement to TRL 6 improvement for 500 mJ/pulse. 3. Scenario 24 requires development to 1-2 J, 20 Hz double pulsed for range-resolved CO2; 100 mJ/500 Hz for integrated path measurement of CO2 and coherent winds using high-PRF, low-CNR approach. 4. Frequency-agile reference oscillators are at TRL 5.	Joule-class diode pumped 2-micron systems are in early stages of development.	4	6	4-5 years	Mid-term (5-8 years)	Michael Kavaya	757-864-1606	Michael.J.Kavaya@nasa.gov

Appendix 5A: Laser Transmitter Capability Breakdown Structure (CBS)

Technology	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
Wavelength converters for the vis-UV	181	DIAL	290/330 nm	Tropospheric ozone profiles along aircraft flight track	1-kHz optical parametric oscillator (OPO), tunable 290-330 nm.	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.
	113	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)	
	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Doppler lidar	355 nm	Tropospheric wind profiles	340 mJ/100 Hz at 355 nm, single frequency with conversion efficiency from 1064 nm of 40% or better	3. 2x and 3x frequency multipliers for 1064-nm fundamental, average incident power handling 100W, 30-ns pulselength.
	LWG-AC-1 LWG-AC-2	Backscatter lidar	355 nm	Polarimetric multiwavelength cloud/aerosol properties	100 mJ/20 Hz, polarization purity >99% at 355 nm.	
	182	Raman lidar	355 nm	Airborne profiling of cloud/aerosol optical properties	>300 mJ/>50 Hz @ 355 nm; ~1 J at 1064 nm fundamental	
	180	Backscatter lidar	355 nm	Polarimetric multiwavelength cloud/aerosol properties from aircraft	50 micro-J/>1-kHz, linewidth ~5 pm @ 355 nm.	
	69	Backscatter lidar	355 nm	Atmospheric temperature profiles	>400 mJ/100 Hz at 355 nm. >40% harmonic conversion from 1064 nm	
	27	Backscatter lidar	532 nm	Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 nm	
	116 LWG-AC-1 LWG-AC-2	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.	
	17	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	
	48, 149, 150	Laser altimeter	532 nm	Land surface topography below vegetation	10-20 mJ/100-200 Hz at 532 nm, 4 ns pulsewidth.	
	NRC-14	Laser altimeter	532 nm	Map polar ice sheets to characterize ice mass changes	100 mJ/100 Hz at 532 nm	
Wavelength converters for the IR	70 NRC-04	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.
	56	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
	71 81 NRC-01	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. Nonlinear generation by OPO	Fixed on-/off-line OPOs in 940 nm range, 0.5 J/10 Hz.
	179	DIAL	1570 nm	Lower tropospheric CO2 fluxes	10 W cw, 5-MHz long-term linewidth, tunable; fiber or 1064-nm pumped OPO	Fixed on-/off-line OPOs in 1560-1575 nm range pumped by MHz-stability 1064-nm source.
Other laser	56	Laser interferometer	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
	23	IPDA-LAS	2050 nm	Lower tropospheric CO2 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 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE
	185	Active limb sounder	9.1-10.4 microns	Tropospheric ozone profiles	100-Hz PRF single mode, tunable 9.1-10.4 micron CO2 laser	Demonstrate reproducible tuning between on/off line wavelengths with settling time <10 ms, intraline tuning range ~10 cm^-1.
Beam director	LWG-AC-1	Backscatter lidar	355/532/1064 nm	Polarimetric multiwavelength cloud/aerosol properties	Up to 30-deg. cross-track scanning	
	186	Laser altimeter	532 nm	Map solid earth, ice and aquatic surface elevation	Up to 30-deg. cross-track scanning	Scanning accomplished by two transmissive, counter-rotating, optical wedges (Risley prism)
	NRC-07	Laser altimeter	1064 nm	Global surface topography of Earth and Moon, plus vegetation structure at Earth	30-km swath width at Earth and Moon	Cross-track scanning to attain 30-km swath from 1000-km Earth orbit and 500-km Lunar orbit results in maximum scan range of ~2 deg.
	188	Laser altimeter	1064 nm	Map solid earth and aquatic surface elevations, including vegetation height and vertical structure	10-km swath from LEO. Addressable beam positioning, no moving parts preferred, 1000 beam positions across 1-2 deg. field-of-regard	1. Optical phased array approach to eliminate moving parts.
	LWG-OT-2	Laser altimeter	1064 nm	Map solid earth, ice and aquatic surface elevation, including vegetation height and vertical structure	100-1000m swath from UAV	2. Backup approach is to use lightweight, low momentum scan mirror.
	LWG-AD-AIR1 LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Doppler lidar: **See Appendix 4D**				

Appendix 5A: Laser Transmitter Capability Breakdown Structure (CBS)

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
		4	6	2-3 years	Near-term (4-5 years)	Bill Heaps	301-286-5106	William.S.Heaps@nasa.gov
100 mJ/20 Hz at 532 nm, polarization purity >99% at 532 nm, linewidth 1 GHz or less (scenario 116), equivalent to ICESat/GLAS; for LWG-AD-SP1-3 verify increased doubler power handling, develop tripler from TRL 3 to TRL 6 (scenarios 69, 179, 180, 181, 182, NRC-03, NRC-04, NRC-02, 17, 27, 42, 56, 57, 99, 186, 48, 149, 150 are validated by current ICESat/CALIPSO performance).	Avoids direct generation of required vis/UV thru upconversion of 1-micron, which is more readily available from space qualified systems.							
Ruggedize for long-term alignment stability.	Provides high pulse energy alternative to fiber systems.	4	6	2-3 years	Mid-term (5-8 years)	Bill Heaps	301-286-5106	William.S.Heaps@nasa.gov
Laser frequency measurement system with accuracy <10^-5 Hz rms for averaging times of 100 seconds, over dynamic range of ~5 MHz	Instrument must continuously measure change in range between spacecraft separated by 50-100 kilometers with accuracy of 0.1 nm rms over 100 second averaging times, combined with reduction of accelerations due to non-gravitational forces to less than 10^-15 m/s**2 rms over 100 seconds.							
1. Demonstrate ~5W cw in a laboratory environment. 2. Demonstrate ~5W with required characteristics in a lab environment. 3. Demonstrate all characteristics in a space-qualifiable package.	Required characteristics demonstrated at 150-mW level on an operational basis in an aircraft instrument. Operation at ~800-mW level demonstrated in packaged laser with external frequency stabilization in a lab environment.							
	Long-term viability of CO2 gas laser technology in space demonstrated by Aura Microwave Limb Sounder OH-channel laser local oscillator							
1.5-km post spacing at the specified 100-Hz PRF implies that 30-km swath will be acquired in ~200 secs.	Laser altimeter swath must have significant overlap with that of co-manifested SAR.	4	6	4-5 years	Near-term (4-5 years)	J. Bryan Blair	301-614-6741	James.B.Blair@nasa.gov
Equipment performance benchmark is ultimately contingent on required slew-rate. This derives from number of positions required per unit time, which has not been specified.	Non-mechanical beam scanning concepts are still in their infancy, but present a highly attractive and advantageous capability once demonstrated.							

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Technology	Responsible Person	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
Alignment maintenance	**Kavaya, Gentry**	(CR) LWG-AD-AIR	Doppler Lidar, Airborne, Scanning	355 nm (direct)/ 2 micron (coherent)			
	Kavaya	(E) LWG-AD-SP1, (E) LWG-AD-SP2, (E) LWG-AD-SP3	Hybrid Doppler Lidar	2 micron (coherent) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low	5 microrad roundtrip (5 msec) lag angle compensation (coherent)	Develop optical lag angle compensator
	Gentry	(E) LWG-AD-SP1, (E) LWG-AD-SP2, (E) LWG-AD-SP3	Hybrid Doppler Lidar	355 nm (direct) channel	Measure tropospheric winds with 2D vector component using a hybrid	50 micorad active T/R boresite alignment (direct)	Develop acitive optical boresite alignment device
	Spiers	(E) 23 (ADD)	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 microradian standard deviation on a zero mean	
	Spiers	(E) 23	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	
	Blair	(E) LWG-OT-1				co-alignment of the transmitter beam and the detector array needs to be maintained to within ~ 5 microradian	
	Blair	(E) 186	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 microradian	
	Blair	(E) 187	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 microradian	Develop an active optical alignment system to monitor and maintain co-alignment between laser output beam and receiver FOV to within 10 urad relative angle.
	Spiers	(E) NRC-07 (Spiers)					
Scanning Systems		(CR) None					
	Kavaya	(E) LWG-AD-SP1, (E) LWG-AD-SP2, (E) LWG-AD-SP3	Hybrid Doppler Lidar	2 micron (coherent) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	30 deg to 45 deg nadir angle,> 25 cm diam., step-stare conical scanner	Develop >25 cm diffraction limited Si wedge Si wedge and step stare rotating mechanismincluding momentum compensation
	Gentry	(E) LWG-AD-SP1, (E) LWG-AD-SP2, (E) LWG-AD-SP3	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 deg to 45 deg nadir angle, 0.75 m diam., <50 microrad blur circle conical step-stare scanning telescope	Develop >75 cmholographic or diffractive optic telescope and step stare rotating mechanism including momentum compensation.
	Ismail	(E) 72	IR-DIAL Temperature and Water Vapor DIAL	760 to 940 nm	Range resolved measurements of water vapor and temperature including aerosol and cloud distributions.	+/- 10 degree continious cross track	Determine performance requirements for DIAL transmitter/reciever scanner system. Using requirements, leverate existing technology to develop a airborne version for
	Blair	(E) 186	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)	
	Blair	(E) 188	laser altimeter	1-micron	Wide-swath (i.e. 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean)	addressable FOV across 1 - 2 degrees	Develop solid-state approach of selecting individual fields-of-view at high switching rates.
	Spiers	(E) NRC-07					

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
	Lidar optics positions, spatial orientation and angles must remain aligned	3	4	2	2007	Bruce Gentry	301-614-6271	Bruce.M.Gentry@ nasa.gov
develop and demonstrate opto-mechanical methods to comensate for lag angle offset and image rotation	Lidar optics positions, spatial orientation and angles must remain aligned	2	6	4	2009	Michael Kavaya	757-864-1606	michael.j.kavaya@ nasa.gov
develop and demonstrate opto-mechanical methods to actively maintain far field laser beam and telescope FOV	Lidar optics positions, spatial orientation and angles must remain aligned	3	6	4	2009	Bruce Gentry	301-614-6271	Bruce.M.Gentry@ nasa.gov
	LOS winds from multiple azimuth agles are required to determine horizontal wind field. Matched to telescope aperture and requirements	4	6	4	2009	Michael Kavaya	757-864-1606	michael.j.kavaya@ nasa.gov
	LOS winds from multiple azimuth agles are required to determine horizontal wind field. HOE/DOE technology allows simplified combination of telescope andscanning function in one optical element.	3	6	4	2009	Bruce Gentry	301-614-6271	Bruce.M.Gentry@ nasa.gov
		3	5	2	2012	Syed Ismail	757 864-2719	s.ismail@ larc.nasa.gov
1) Identify relevant mission scenarios and extract detailed aperture, FOV, and other								

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Technology	Responsible Person	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
Large Effective Area, Lightweight Telescopes (Including stray light control)	**Chekalyuk**	(E) 17	Fluorescence Lidar	Laser beam: 532 nm (Optional: 355 and 532 nm, TBD) Detector: 520-800 nm (Optional: 370-	Measure water Raman, fluorescence and algal pigments	2-3 m (TBD) diameter/ ~200-300 μmrad (TBD) FOV, areal density: <25 Kg/m2	Develop a 2-3m (TBD) diameter lightweight telescope with deployable mechanism
	Spiers	(CR) 23	IPDA LAS for CO2	2.051 microns	lightweight 0.5 m telescope operating at 2 microns	0.5 m diffraction limited @2microns beam expander	
	Chekalyuk	(CR) 27	Ocean Particle and Aerosol Lidar	1064, 532nm	aerosol hights, phytoplankton carbon, particulate organic and inorganic carbon (POC & PIC), suspended sediments	1,2-1.5 m diameter/ ~60-150 μmrad FOV	Develop a 1-1.5 m diameter lightweight telescope
	Spiers	(CR) 42					
	Ismail	(E) 24	CO2 DIAL	2-micron	Range resolved CO2 mixing ratio in lower troposphere and aerosol distributions	3 m diameter/ ~100 mmrad FOV, areal density, <25 Kg/m2	1) Develop a 3m diameter telescope with deployable mechanisms and validate as part of a LIDAR ground based system. 2) Space based demonstation
	Ismail (Syed should this one be deleted?)	(E) 70					
	Ismail	(E) 72	IR-DIAL Temperature and Water Vapor DIAL	760 to 940 nm	Range resolved measurements of water vapor and temperature including aerosol and cloud distributions.	3m diameter deployable, ~100 mrad FOV, areal density <25 Kg/m2	1) Develop a 3m diameter telescope with deployable mechanisms and validate as part of a LIDAR ground based system. 2) Space based demonstation
	Gentry	(E) 99	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	1) Develop transmitter optics capable of producing 1 m spot on ice
	Ismail	(E) 113	Ozone DIAL	DIAL technique, 1st wavelegth 305 to 308nm,	Range resolved measurements of ozone including aerosol and	3 m diameter/ 0.3 mrad FOV, areal density <25 Kg/m2	1) Develop a 3m diameter telescope with deployable mechanisms and validate as part
	Blair	(E) LWG-OT-1	photon-counting laser altimeter	1-micron	single-photon range images across a 300 m swath	1 - 1.5 m diameter, < 10 microradian blur circle	see below (188)
	Blair	(E) 186	photon-counting laser altimeter	532 nm	single-photon range images across a 300 m swath	1 m diameter, 1 microradian blur circle (to minmize crosstalk between adjacent pixels)	see below (188)
	Blair	(E) 187	laser altimeter	1-micron	narrow swath profiles of 3-dimensional structure of land and vegetation	1.5 m telescope, 4 urad blur circle	see below (188)
	Blair	(E) 188	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 urad blur circle	Develop, light-weighted, 2 m diameter, thermally-stable, diffraction-limited telescope.
	Ismail	(E) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance	1.5 m segmented or deployable telescope	1) Develop a 1.5m diameter telescope with deployable mechanisms and validate as part of a LIDAR ground based system. 2) Space based demonstation
	?	LWG-AC-1				1 - 2 m aperture with +/- 30 deg FOV. The individual potential beams will have a much smaller IFOV.	
	Ismail	(E) NRC-02	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.	***Called Mike Dobbs 3/24/06, waiting for input***	
	Ismail	(E) NRC-07					
	Spiers	(CR) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance		
Mechanical Metering Structures	**Ismail**	(CR) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance		
	??? - not sure ... Chekalyuk	(E) 17	Fluorescence Lidar	Laser beam: 532 nm (Optional: 355 and 532 nm, TBD) Detector: 520-800 nm (Optional: 370-	Measure water Raman, fluorescence and algal pigments	???	???
	??? - not sure ... Chekalyuk	(E) 27	Ocean Particle and Aerosol Lidar	532nm	aerosol hights, phytoplankton carbon, particulate organic and inorganic carbon (POC & PIC), suspended sediments	???	???
	Ismail	(E) 70,					
	Ismail	(E) 72	IR-DIAL Temperature and Water Vapor DIAL	760 to 940 nm	Range resolved measurements of water vapor and temperature including aerosol and cloud distributions.	Syed to supply number	
	Ismail	(E) 113					
	Ismail	(E) NRC-01	high vertical resolution measurements of water vapor,	944 nm		Syed to supply number	
	Ismail	(E) NRC-02	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.	***Chris to get from Wallace Harrison***	

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

relevant parameters 1) Develop receiver

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
1) Identify critical technological solutions and components (TRL3) 2. Component laboratory validation (TRL4) 3. Component validation in relevant environments (TRL5) 5. Assemeble and a laboratory test the telescope system 6. Demontsrate and valida	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	6	4	2012	Alex Chekalyuk	757-824-2401	chekaluk@osb.wff.nasa.gov
1. Component laboratory validation (TRL4) 2. Component validation in relevant environments (TRL5) 3. Assemeble and a laboratory test the telescope system 4. Demontsrate and validate the telescope in relevant environments		3	6	2	2009	Michael Behrenfeld	541-737-5289	behrenfm@science.oregonstate.edu
	ESTO is has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for there mechanical stability	2	5	4	2015	Syed Ismail	757 864-2719	s.ismail@larc.nasa.gov
	ESTO is has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for there mechanical stability	2	5	4	2015	Syed Ismail	757 864-2719	s.ismail@larc.nasa.gov
	Transmitted laser spot on the icemust have size comparable to sea ice thickness, ~1 m	1	6	4	TBD	Robert Cahallan	301 614-5390	Robert.F.Cahalan@nasa.gov
	ESTO is has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms	2	5	4	2012	Syed Ismail	757 864-2719	s.ismail@larc.nasa.gov
1) Design a thermally-stable, diffraction-limited telescope with a 2 m aperture 2) Fabricate engineering model telescope 3) Environmentally test telescope	Large aperture (1.5- 2 m) required to meet signal-to-noise requirements of system.	4	6	3	2010	Vibart Stanley Scott III	301-614-6280	Stan.Scott@nasa.gov
	ESTO is has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for there mechanical stability	2	5	4	2012	Syed Ismail	757 864-2719	s.ismail@larc.nasa.gov
						Syed Ismail	757 864-2719	s.ismail@larc.nasa.gov
???	???	???	???	???	2012			
???	???	???	???	???	2009	Michael Behrenfeld	541-737-5289	behrenfm@science.oregonstate.edu

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Technology	Responsible Person	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)							
	Spiers	(CR) 23	IPDA LAS for CO2	2.051 microns	radiation resistant efficient 2 micron transmitting fibers	polarisation maintaining, radiation tolerant 2 micron single mode fiber with transmission efficiency > 95%/m	
	Chekalyuk	**(E) 17**	Fluorescence Lidar	Laser beam: 532 nm (Optional: 355 and 532 nm, TBD) Detector: 520-800 nm (Optional: 370-800 nm, TBD)	Narrow-band notch filter to reduce laser backscatter to the level comparable with fluorescence and Raman components in the laser-stimulated backscatter signal	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
	Ismail	(CR) NRC-02	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.	***Chris to get from Wallace Harrison***	
	Spiers	(E) 42					
	Genrty	(E) 99	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	optical fiber bundles to guide 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 field-of-views	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.
	Ismail	(E) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance		
Narrowband Optical Filters	Spiers	(CR) 42					
	Blair	(CR) 52					
	Blair	(CR) 186	photon-counting laser altimeter	532 nm	single-photon range images across a 300 m swath		
	Blair	(CR) 187	laser altimeter	1-micron			
	Blair	(CR) 188	laser altimeter	1-micron	Wide-swath (i.e. 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography		
	kKrainak, Abshire	(CR) NRC-04					
	Spiers	(CR) NRC-07					
	Blair	(CR)[48,49,150]	laser altimeter	1-micron			
	Ismail	(E) 24	CO2 DIAL	2.05 µm	Range resolved CO2 mixing ratio in lower troposphere and aerosol distributions	200 pm, 60% transmission	
	Ismail	(E) 70		760 nm		?	
	Gentry	(E) 99	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
	Ismail	(E) 113		308/320 nm		.2 nm FWHM	
	Ismail	(E) NRC-03	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%	
	Ismail	(E) NRC-02	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.	***Chris get from Wallace Harrison***	
Detectors (Including Arrays) and Amplifiers	Kavaya, Gentry	(CR) LWG-AD-AIR,	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	Develop and demonstrate detectors
	Kavaya	(CR) LWG-AD-SP1, (CR) LWG-AD-SP2, (CR) LWG-AD-SP3	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	Develop and demonstrate detectors
	Gentry	(CR) LWG-AD-SP1, (CR) LWG-AD-SP2, (CR) LWG-AD-SP3	Hybrid Doppler Lidar	355 nm (direct) channel	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	Develop and demonstrate detectors
	Ismail	113 (ADD)	UV DIAL	305-320 nm	height-resolved measurements of tropospheric ozone along a thin line associated with the ground track of the satellite	PMT with QE > 40% photon counting with internal gain 10^6, dark current <10 cps single photon sensitivity,	
	Blair	(CR) [48,49,150]	laser altimeter	1-micron	3-dimensional measures of the Earth's surface (land, ice, and ocean) topography		
	Gentry	(CR) 185	IR occutation measurement of O3 aqnd precursors from high altitude UAV	9.5 microns	Make range resolved measurements of tropospheric ozone using an IR occultation technique		
	Blair	(CR)186	photon-counting laser altimeter	532 nm	single-photon range images across a 300 m swath		
	Blair	(CR) 187	laser altimeter	1-micron			
	Blair	(CR) 188	laser altimeter	1-micron	Wide-swath (i.e. 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography		
	Ismail	(CR) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance		
	Spiers	(CR) NRC-07					
	Spiers	(E) 23	IPDA LAS for CO2	2.051 microns	radiation tolerant 2 micron heterodyne detector	radiation tolerant, >1 mm2 area, heterodyne detector for 2 micron wavelength, details TBD	
	Ismail	(E) 24	CO2 DIAL	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.	
	Spiers	(E) 42					
	Gentry	(E) 99	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	High QE>60% single photon counting detector array	
	Krainak	(E) 179					
	Blair	(E) 186	photon-counting laser altimeter	532 nm	single-photon range images across a 300 m swath		
	Blair	(CR) 187					
	Ismail	(E) NRC-02	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.	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/sec	
	Krainak, Abshire	(E) NRC-04				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/sec	

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
1) Identify critical technological solutions (TRL3) 2. Filter design, assembling and laboratory validation (TRL4) 3. Filter demontsration and validation in relevant environments (TRL5-6)	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	6	3	2012	Alex Chekalyuk	757-824-2401	chekaluk@osb.wff.nasa.gov
		2	6	4	TBD	Robert Cahallan	301 614-5390	Robert.F.Cahalan@nasa.gov
	Narrowbandwith required for background rejection. Wide acceptance angle needed to capture multiple off axis beams required to sample multiple scattering.	2	6	4	TBD	Robert Cahallan	301 614-5390	Robert.F.Cahalan@nasa.gov
	0.355 detector QE improvement permits relaxation of laser and optics requirements; 5-element detectors at 2 microns will improve alignment maintenance options	2	4	2	2007	Bruce Gentry	301-614-6271	Bruce.M.Gentry@nasa.gov
	5-element detectors at 2 microns will improve alignment maintenance options	2	6	4	2009	Michael Kavaya	757-864-1606	michael.j.kavaya@nasa.gov
1. Identify new photocathode materials for PMTs with higher QE between 300 and 400 nm. 2. Examine new solid state avalanche photodiodes suitable forsinglephoton counting (Geiger mode) operatiion: high QE low dark counts 3. New CCD detectors with high QE, high speed and low read noise (<1 e/s)	0.355 detector QE improvement permits relaxation of laser and optics requirements;	2	6	4	2009	Bruce Gentry	301-614-6271	Bruce.M.Gentry@nasa.gov
						Bruce Gentry	301-614-6271	Bruce.M.Gentry@nasa.gov
		2	6	4	TBD	Robert Cahallan	301 614-5390	Robert.F.Cahalan@nasa.gov

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Technology	Responsible Person	Measurement Scenarios	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement	Task
	Kramak, Abshire	(E) NRC-14					
Optical High Resolution Spectral Analyzers		(CR) None					
	Chekalyuk	(E) 17	Fluorescence Lidar	Laser beam: 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	Develop a space-qualified LSE spectral detector/analyzer that meets or exceed the listed requirements
	Ismail	(E) NRC-03	High Spectral Resolution Lidar (HSRL) for aerosol characterization	Transmitter 1-micron; receiver 355 and 532 nm	3-D measurement of aerosol microphysical properties, absorbtion and abundance	Resolution of 1GHz FWHH over range of 20GHz centered at laser wavelength of either 355 or 532 nm; etendue >100mm-mrad; transmission >70% +/-0.1%/hr; freq drift <1 MHz/hr	
Detection Electronics, E.G., High speed ADC, multi-channel scaler, and boxcar averager	Kavaya, Gentry	(CR) LWG-AD-AIR	Doppler Lidar, Airborne, Scanning	355 nm (direct)/ 2 micron (coherent)	Measure wind structure in and around storm cells using an airborne Doppler wind lidar		
	Kavaya	(CR) LWG-AD-SP1, (CR) LWG-AD-SP2, (CR) LWG-AD-SP3	Hybrid Doppler Lidar	2 micron (coherent) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit		
	Gentry	(CR) LWG-AD-SP1, (CR) LWG-AD-SP2, (CR) LWG-AD-SP3	Hybrid Doppler Lidar	355 nm (direct) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit		
	Blair	(CR) 52					
	Blair	(CR) [48,49,150]	laser altimeter	1-micron	3-dimensional measures of the Earth's surface (land, ice, and ocean) topography	low power(<50W),10 bit, 1 Gsamp/s digitizer	see below (187)
	Spiers	(CR) NRC-07					
	Blair	(CR) NRC-11	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	see below (187)
	Ismail	(E) 70					
	Blair	(E) LWG-OT-1				20 channel, 0.5 nsec resolution, multi-stop digital timing device; 20 Mcount/sec capability	
	Blair	(E) 186	photon-counting laser altimeter	532 nm	single-photon range images across a 300 m swath	100 channel, 0.5 nsec resolution, multi-stop digital timing device; 20 Mcount/sec capability	
	Blair	(E) 187	laser altimeter	1-micron		low power(<50W),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.
	Spiers	(E) 42				High speed ADC	
	Blair	(E) 188	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, 500-1,000 Msamp/s, 6-8 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.

Appendix 5B: Receiver Capability Breakdown Structure (CBS)

Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
1) Identify critical technological solutions and components (TRL3) 2. System design, assembling and laboratory validation (TRL4) 3. Demontsrate and validate the system in relevant environments (TRL5-6)	Although there are commercial prototypes, none of them meets the specified quantitative requirements and is a space-qualified product. This development is enabling for the FLAPS measurement scenario	2	6	3	2012	Alex Chekalyuk	757-824-2401	chekaluk@osb.wff.nasa.gov
		2	4	2	2007	Bruce Gentry	301-614-6271	Bruce.M.Gentry@nasa.gov
		2	6	4	2009	Michael Kavaya	757-864-1606	michael.j.kavaya@nasa.gov
		2	6	4	2009	Bruce Gentry	301-614-6271	Bruce.M.Gentry@nasa.gov
1) Select radiation-tolerant and latchup immune 10-12 bit, 1 Gsamp/s A/D chip that uses < ~5W 2) Design low-power, backend processor for return pulse identification and pulse processing 3) Integrate and test	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 groudn returns in a single pulse in the presence of variable atmospheric attenuation and surface albedo variations.	4	6	2	2009	Bryan Blair	301-614-6741	James.B.Blair@nasa.gov
1) Design a low-power, high speed A/D system coupled with real-time signal analysis hardware capable of identifying return pulses at rates on the order of 100,000 returns/s. 2) Prototype digitizer system and characterize performance 3) Environmentally test digitizer	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 idenfication is required to sustain the high rep-rate data collection.	3	6	2	2010	Bryan Blair	301-614-6741	James.B.Blair@nasa.gov

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

	A	B	C	D	E	F	G	H
1	**Technology**	**Lidar TC Capability**	**Measurement scenario**	**Use Case**	**Needed Functional Product**	**Quantitative Req'ts**	**Task**	**Subtask**
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)	NRC-11, NRC-14, LWG-AD-SP3, 180, 116, LWG-AC-1, 2300-09, 182, LWG_AC-2, 69, 99, 17, 27, 42, NRC-02, NRC-01, 24, 179, 181, 185, 70, 72, NRC-04, 81, NRC-09	Land, Water, Winds Jason	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	OSSE based sensor web design environment; Develop such a system using existing commodity equipment; leverage fiber laser amplifiers from Telco and other similar systems	Produce sensor web based validation campaign with data assimilation and instrument/orbit trade capability
3						1). Aerosols (0.1 um to 100 um), 2). Molecular identification (O3, CO2, Water Vapor)	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.	1a) Develop a set of requirements for ground and airborne instruments based on Lidar community inputs obtained via a workshop. 1b) Acquire instruments through acquisition process (POD or AO) 2a) Develop a set of calibration requirements that include spatial and temporal co-registration issues and instrument functions. Also require that the calibration activity resolve differences between ground-based and space-base
4	**Intelligent sensor health & safety**	Technology to enable autonomous monitoring & control of lidar H&S (laser performance/ degradation, laser life optimization strategy)	23, LWG-AD-SP3, NRC-07, 24, 27, 52, 70, 73	C02, Land Jason	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.	1a) Work with the Lidar developers and determine critical sensing needs. 1b) Pick a particular Lidar system and demonstrate the use of the sensors in increasing instrument performance or extending laser life. 2a) Determine the Lidar degradation modes and create software models that describe the effects. 2b) Develop "cost model" for optimal Lidar operation that, for instance, optimizes laser life or optimizes Lidar performance.
5						instrumentation suite to monitor H&S	develop integrated prototypes based on a common base module that contains the processor/memory/ADC/interface	development of rad-tolerant versions

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

	A	B	C	D	E	F	G	H
6						Monitor and summarize health and status.	Prototype monitoring and diagnosis software. Parts run onboard and parts on the ground.	Development of trends database for lasing system diagnostics such as pump beam misalignment vs. energy input, beam profile monitoring with Quad CCD detector, OPO control loop, etc
7						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: a,b,c	Prototype diagnosis and response software (onboard)	Develop algorithms for graceful degradation of laser by controlling duty cycles
8						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.	
9	**On-board sensor control**	Sensor control to enable autonomous data acquisition & support formation flying (precision pointing, fault handling)	23, 56, 57, 81, 99, 186, 188, 48, 149, 150, LWG-AD-AP3, NRC-07, NRC-11, NRC-15, 24, 179, NRC-02, NRC-04, 27, LWG-OT-1, LWG-OT-2, 187, NRC-14, 42, NRC-09	Land, CO2, Winds Jason	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	
10						Localize detected events with accuracy equal to pointing accuracy.	Prototype event localization software; assumes spacecraft localization system (see above)	Develop a data management system onboard to provide information to sub systems effectively
11						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	Develop algorithms for 1) Detect, 2) instrument pointing and commanding, 3) realtime support
12						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.	
13	**Spacecraft area network**	Inter-Spacecraft level network (spacecraft area network) standards	56, 186, 188, 48, 149, 150, NRC-07, NRC-11, NRC-16	CO2 Jason (Khorrami)	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 tech. does not allow interaction between instruments. In the future instruments should share information.	Demonstrate feasibility by prototyping in an Instrument Development Lab or testbed environment

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

	A	B	C	D	E	F	G	H
14	**Formation flying**	Metrology & control	56, NRC-07…57	Gravity Jason (Folkner)	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.	1) ranging measurement noise <100 pm rms	1a) develop space-qualified single-mode 30 mW laser	1a) space-qualified single-mode 30 mW
15						2) laser frequency stabilization, Allan deviation 1E-13	2a) develop space-qualified laser frequency reference, including required fiber injection and electro-optic modulator	2ai) develop space-qualified optical reference cavity
16								2aii) develop space-qualified electro-optical modulator
17								2aiii) develop space-qualified fiber injection optics
18						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	3a) test mass and positions sensor available from Europe
19							3b) develop diagnostics for noise measurement and extend life of 5 mN Hall or Xe-ion engine	3bi) perform noise measurement of 5 mN Hall or Xe-ion engine
20								3bii) develop thrust diagnostic measurements to characterize noise in 5 mN Hall or Xe-ion engine
21								3biii) develop processes for extending life of 5 mN Hall or Xe-ion engine to 5 years
22							3c) develop extended life of precision low-thrust electric propulsion system	3ci) develop extended life of precision low-thrust electric propulsion system
23						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	4a) develop software and hardware for inversion of 200,000 by 200,000 matrix for gravity field estimation
24								4b) develop computing platform for inversion of 200,000 by 200,000 matrix in under 48 hours
25	**On-board near RT 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	52, 70, 186, 17, NRC-02, NRC-04, 23, LWG-AD-SP3, 81, 27, 42, NRC-09	Winds, Water Mark, Mike	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) a range resolution 500 m or better (b) water vapor uncertainty 10% or less	1. development of a integrated, parallel-processing algorithm suite implementing all numerical methods required for DIAL retrieval: 1. background subtraction; 2. horizontal and vertical averaging; 3. numerical differentiation;	1) Realtime on board database technology; 2) Reconfigurable software, 3) formalization of data policy

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

	A	B	C	D	E	F	G	H
26	**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)	81, LWG-AD-SP3, 182, NRC-02, NRC-04, 24, 179, 27, NRC-01, 23	Winds, CO2, Water Mike	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.	Autonomous Plan & Execution commanding script generation
27	**Space-qualified TB storage HW**	Rad-hardening & space packaging of high volume solid state storage modules to support flight processing	NRC-11, NRC-14, LWG-AD-SP3, 180, 116, LWG-AC-1, 2300-09, 182, LWG_AC-2, 69, 99, 17, 27, 42, NRC-02, NRC-01, 24, 179, 181, 185, 70, 72, NRC-04, 81, NRC-09, 188, 187, 48, 149, 150	Land, CO2, Sam	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	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	NASA should do a 3 month study to determine current SOA in both ground based and spaceborne non-volatile solid state flash memory. The study should determine the technology lag between ground and space and develop recommendations for NASA on how to shorten that gap and how to achieve TB scale non-volatile SS flash in space by 2010. Key issues are to understand how to
28	**Space-qualified HPC HW & programming tools**	Rad-hardening & space packaging of flight computers & chip programming tools to support flight processing	23, 56, 57, 81, 99, 186, 188, 48, 149, 150, LWG-AD-AP3, NRC-07, NRC-11, NRC-15, 24, 179, NRC-02, NRC-04, 27, LWG-OT-1, 187, NRC-14, 52, 70, 73, 17, 42, NRC-09	Sam	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	(1) 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.	(a) commercial technology characterization; (b) effects of scaling and low-power technology; (c) novel material science investigation; (d) develop hardening techniques for deep submicron technology; (e) demonstrate deep submicron technology for gate array, SRAM, FPGAs, DSPs, and microprocessors; (f) develop advanced hardened controller technology for system upset and recovery; (g) develop radiation hardened system-on-
29	**Model lidar data resampling techniques**	Algorithms and software to resample lidar data to model grids and other assimilation tools	182, 116, 180, 81, LWG-AD-SP3, 187, NRC-02, NRC-04, 17, 27, 42, NRC-09	Land ask Joe	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.	1) Modification / Extensions to Earth Science Modeling Framework 2) Sampling techniques that optimize information content per sampling rate. 3) Standard methods in SensorML compatible format to reproject from sensor to common grid format per domain. 4) Methods to resample data to arbitrary, coarser resolutions for global models (land & ice processes)
30	**Knowledge Discovery**	Knowledge Discovery	182, 116, 180, 81, LWG-AD-SP3, 187, NRC-02, NRC-05, 17, 27, 42, NRC-09	Land ask Joe	Techniques to enable rapid use of Lidar measurements by analysis and decision support systems.	1.0) First principle forward models (Physical model) and machine access to them. 2.0) Data driven models: model accuracy & robustness, number of training data needed. 3) Weather forecast for Air pollution, hurricane in < 3 hr	1.1) Sensor model parametric representation of the sensor response. 1.2) 3-D photon propagation model atmosphere into canopy/surface and back. 1.3) Describe and access models using SensorML. 2.1) Training examples: physical measurements of land types and lidar data. 2.2) Re-enforcement learning methods to build models.	1.1.1) Construct 1st P model and calibrate extensively 1.1.2) SensorML adapted to represent model description and machine access to model. 1.2.1) Computational resources needed to run a forward model. 1.2.2) methods to archive in a machine extractable and executable readable way the model and data for remote use. 1.2.3) Methods to edit and update the model 2.1.1) Science program executes field experiments to collect data.

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

I	J	K	L	M	N	O	P	Q	R	S	T	U
Explanation	**TRL at Start**	**TRL at End**	**Dev Period**	**Year Needed**	**LOE**	**HW Cost Estimate**	**Error In Estimate**	**Estimate Source**	**POC**	**Comments**	**Measurement Parameter(s)**	**Scenario Uniquess** (can the measurement be accomplished only via this technique?)
This task provides a simulation based testing and validation capability to optimize science return and to meet timing requirements for wind	2/3	7	5	2010	25	1,000	Med	Comparison to other program	Jason		1. Land Surface Topography 2. Land Cover and Land Use 3. Vegetation Biomass 4. Ice Surface Topography 5. Sea Ice Thickness 6. Ocean Surface Topography 7. Cloud Particle Properties and Distribution 8. Phytoplankton	Yes
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	7	4	2010	6	Task 1) is an industrial development effort. The cost of the instrument development depends on the requirements. A cost estimate can be established at the time data is gathered from the Lidar community. Costs can	Med	Comparison to other program	Jason (Menzies, Buehler)		1. Land Surface Topography 2. Land Cover and Land Use 3. Vegetation Biomass 4. Ice Surface Topography 5. Sea Ice Thickness 6. Ocean Surface Topography 7. Cloud Particle Properties and Distribution 8. Phytoplankton physiology & functional groups 9. Ocean	Yes
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	6	5 years	2009	2	0.1	Med	Comparison to other program	Jason (Castano, Buehler)		1. Trace gas sources 2. CO2 and methane 3. Land Surface Topography 4. Land Cover and Land Use 5. Vegetation Biomass 6. Tropospheric wind 7. Terrestrial reference frame 8. Aerosol Properties and distributions 9. Water vapor profiles 10. Ozone profiles	Yes, greatly increases laser reliability
	2/3	6	5 years	2012	10	1000	Low	Best Guess	Jason		1. Trace gas sources 2. CO2 and methane 3. Land Surface Topography 4. Land Cover and Land Use 5. Vegetation Biomass 6. Tropospheric wind 7. Terrestrial reference frame	Yes, greatly increases laser reliability
	4	6	3	2012	10	0	Med	Comparison to other program				
	4	6	4	2012	8	600	Med	Comparison to other program				
Demonstrate performance in the target (flight-like) environment.	3	6	3	2012	8	600	Med	Best Guess				
	3	6	4	2010	12	1000	Med	Comparison to other program	Jason		1. Land surface topography 2. Tropospheric wind 3. Gravity field 4. CO2 and methane 5. Sea ice topography 6. Phytoplankton physiology & functional groups 7. Ocean carbon/particles 8. Mixed layer depth	Yes, precise pointing is critical with critical timing requirements
Localization of detected events must exceed pointing accuracy to enable detected target to be sensed on later pass	3	6	3	2010	3							
Goal based control system is desired	4	6	5	2012	5		Med	Comparison to other program				
Onboard event detection is in regular use on ASE. Event	4	6	2		2	??						
Need proof of concept and demo of the prototype. May be able to get funding from future projects	3	6	2 years	2009	2	0.25	medium	Based on JPL experience	Jason		1. Land surface and sea ice topography, 2. Gravity field	Yes, Gravity, No. However, it levies a lot harder ground data system load.

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

I	J	K	L	M	N	O	P	Q	R	S	T	U
1a) Cost of US EM ~$3M. NASA/SIM project will probably fund development	3	6	2	2009	3	0.5	low	JPL proposal	Folkner	Low priority since units are available commercially from Europe		
2ai) need cavity with extreme dimensional stability yet survive launch vibration	3	6	2	2009	3	0.5	low	based on Langley Sunlit cavity	Folkner			
2aii) EOM needed to compare laser frequency to cavity	3	6	2	2009	2	0.5	low	based on JPL ATIP	Folkner			
2aiii) need fibers and fiber positioners to intact light to cavity while withstanding launch vibration and radiation environment	3	6	1	2009	2	0.3	low	based on JPL ATIP	Folkner			
3a) cost of developing US supplier estimated to be ~$30M, based on RFI response fro NASA/LISA project	6	6	3	2009	n/a	n/a	n/a	n/a	Folkner	European sensor for LISA Pathfinder will be delivered for I&T in 2007		
3bi) noise of thruster that counters high drag force has never been used in drag-free control loop	3	6	1	2009	2	1	medium	Experience with similar needs for ST7	Folkner			
3bii) in two-stage propulsion system, noise in main thruster needs to be measured so that smaller thruster can be commanded to compensate	4	6	1	2009	3	1	medium	Experience with similar needs for ST7	Folkner			
3biii) 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	6	3	2009	8	3	high	Based on cost of Air Force contract to extend life from 60 to 120 days	Folkner			
3ci) micro-newton thrusters with 90 day life developed for NASA/ST7 project; 5 year life needed	3	6	2	2009	8	1	medium	Based on development for ST7 with expanded reservoir	Folkner			
4a) inversion of matrix is needed to optimizing mission design; currently exceeds file handling capability	n/a	n/a	1	2009	1	0	medium	Experience with parallelizing estimation software	Folkner	Not for flight		
4b) inversion of matrix is needed to optimizing mission design; currently exceeds takes ~10 days on Beowulf cluster	n/a	n/a	2	2009	2	1000	medium	Cost of expanding Beowulf clusters	Folkner	Not for flight		
water vapor profiles required within 3 hours of measurement for effective use in weather forecasting models	4	7	3	2008	5	100	medium	algorithm design and development efforts for LASE	Mark			

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

I	J	K	L	M	N	O	P	Q	R	S	T	U
Simulation environment will help determine optimal configuration of future LIDAR instruments/platforms	3	6	5	2010	6	20K + access to high-end computing platforms	high	Based upon 2001-03 studies funded by RASC, ESTO, EO-1 CASPER software	Seablom	Assumption is that existing technologies for all the elements and sub-elements of a model-driven targeting capability already exist, but an effort is needed to provide linkage and the ability to perform extensive testing (positive feedbacks in the system could wreck overall performance).		
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	4	7	4 years	2010			high	Engineering Judgement	Charles Le/JPL 818.354.4633 Charles.Le@jpl.nasa.gov	As stated the issue is to understand the technology discrepancy between what is being developed for the ground based commodity market and what is required to shorten the gap with what is available in space. Current space qualified hardware lags in storage volume and uses too much power to reasonable scale to TB sized storage. Current USB flash is		
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	2	5	5 years	2010			high	Engineering Judgement				
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	6	2	2009		0	low			lidar data should be accessible via domain grid projections, not sensor and data should be stored at highest resolution with resampling/aggregation offered by NASA server on-the-fly or cached.		
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	3	6	2	2009		0	low			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		

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

V	W	X	Y	Z	AA
Science Impact? (High=dramatic leap in understanding or Medium=incremental understanding) In both cases, explain the science impact if this technology is developed)	**Scenario Relevance?** (designate T=meets threshold science requirements, G=meets goal science requirement, E=exceeds goal science requirements)	**Measurement Timeliness** according to roadmaps (Now= immediate development needed, Later=Can wait 2-3 years, Latest=Can wait 4-5 years; correlate with scenario ID)	**Technology Criticality** (E=enabling, CR=Cost Reducing)	If "CR" in column G, explain the return on investment. How is cost reduced and by how much?	**Risk** (Does this technology development reduce the risk of mission failure? If yes, explain.
High, utility of early data validation is enormous (esp. winds), also aids instruments health monitoring (early baseline on performance established); necessary to achieve data calibration analogous to Landsat products	G, improved understanding of science	now, validation will be a significant factor, can also help refine mission concept	E		Risk is having 2 year data validation delay ala IceSat
High, utility of early data validation is enormous (esp. winds), also aids instruments health monitoring (early baseline on performance established); necessary to achieve data calibration analogous to Landsat products	G, improved understanding of science	now, validation will be a significant factor, can also help refine mission concept	E		Risk is having 2 year data validation delay ala IceSat
Medium	G, improved understanding of science	Later, proprietary interface is sufficient	E, CR	Will extend instrument life for lower risk lasers	Trade off between laser reliability vs. control & monitoring system
Medium	G, improved understanding of science	Later, proprietary interface is sufficient	E, CR	Will extend instrument life for lower risk lasers. Minimize instrument down-time due to faults.	Trade off between laser reliability vs. control & monitoring system
Medium, provide higher precision and relevant data	E, vastly improves model	Now, requires long term development	E, CR	Reduce GDS processing, operations cost	Enable stricter instrument health monitoring and control
Medium, complete data for understanding structure, high resolution data for additional science	G, improved understanding of science	Later, also take advantage of industry	E		

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

Scenarios

Measurement Parameter	Measurement Scenario		Measurement Parameter	Measurement Scenario
Tropospheric Winds	LWG-AD-SP1		Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	23
Tropospheric Winds	LWG-AD-SP3		Tropospheric Ozone and Precursors	181
Tropospheric Winds	LWG-AD-SP2		Tropospheric Ozone and Precursors	185
Tropospheric Winds Storm Cell Properties	LWG-AD-AIR1		Tropospheric Ozone and Precursors	113
Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution Total Aerosol Amount	LWG-AC-1		Coastal Carbon Global Ocean Carbon/Particle Abundance	27
Aerosol Properties Stratospheric Aerosol Distribution Total Aerosol Amount	2300-09		Earth Gravity Field	57
Atmospheric Temperature	69		Earth Gravity Field	56
Atmospheric Temperature Atmospheric Water Vapor	72		Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	LWG-OT-1
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	182		Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	186
Atmospheric Water Vapor Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	NRC-01		Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	NRC-11
Cloud Particle Properties and Distribution Cloud System Structure Total Aerosol Amount Stratospheric Aerosol Distribution Aerosol Properties	116		Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	48, 149, 150
Cloud System Structure Cloud Particle Properties and Distribution Aerosol Properties	180		Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	187
CO2 and Methane Cloud Particle Properties and Distribution Total Aerosol Amount Surface Trace Gas Concentration Trace Gas Sources	NRC-04		Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	188
CO2 and Methane Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount	NRC-02		Mixed Layer depth and illumination	42
Storm Cell Properties	81		Phytoplankton Physiology and Functional Groups	17
Stratospheric Aerosol Distribution Atmospheric Temperature Total Aerosol Amount	70		Sea Ice Thickness	99
Stratospheric Aerosol Distribution Cloud Particle Properties and Distribution Total Aerosol Amount	LWG-AC-2		Terrestrial Reference Frame	52
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	24		Vegetation Biomass Ice Surface Topography River stage height	LWG-OT-2
Surface Trace Gas Concentration Trace Gas Sources CO2 and Methane	179		Vegetation Biomass Land Surface Topography	NRC-07
			Land Surface Topography Land Cover and Land Use Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	NRC-14

Appendix 5C: Data Utilization and Acquisition Capability Breakdown Structure (CBS)

Guidelines

Parameter	Description
Technology	This column should reflect the technologies identified in Lidar Challenges
Measurement Scenario	This column should reflect the measurement scenarios as defined in the lidar measurement scenarios taken from ESTIPS and should be referenced in the "Lidar_Challenges.xls" spreadsheet for all applicable scenarios.
Instrument Type	This column should reflect the instrument type(s) for which the technology applies (e.g. Wind Lidar, DIAL, etc.)
Waveband	State the frequency or waveband for the required measurement.
Needed Functional Product	Describe the final functional data product required, i.e, what is measured.
Quantitative Requirement	Describe the specific levels of performance required by the technology to achieve the desired measurements. This can be a level of sensitivity of the instrument or it can be additional parameters like the amount of data storage required, or a certain mass or power requirement, etc.
Task	Identify the task (and potential subtask) required to mature the technology to the target Technology Readiness Level (TRL). Try to identify specific events that will demonstrate how the technology achieves the required TRL level. Please refer to the "TRL Description" worksheet for a further definition, and examples, of TRL.
Subtask	If necessary for clarification purposes, identify subtasks needed to support the required task.
Explanation	Please explain how the task contributes to the advancement to the next TRL level.
TRL @ Start	Choose the TRL level of technology at the beginning of the task.
TRL @ End (up to 6)	Choose the target TRL at the end of the task. Progression of the TRL beyond level 6 is not required for the technology development effort.
Development Period (years)	Please state the time required to mature the technology to the target TRL level.
Year Needed (at least 3 years before mission launch)	Please state the year in which the technology will have to achieve a TRL of 6 assuming that the technology needs to reach TRL 6 three years prior to launch.
Level of Effort (person-years)	Please estimate the labor level of effort required for the task. Please estimate the effort required in person years (i.e. one person year of effort is expended when on person works full-time on an effort for one year).
Hardware Cost Estimate ($M)	Please estimate the cost of any hardware or other contracts associated with the maturation of the technology to the target TRL level. If possible, please identify the cost in million of fiscal year 2004 dollars.
Error In Estimate	Please select low, medium or high for the inherent error in your estimate. Please select low if you believer that the final cost will be within 25% of your estimate; medium if within 50%; or high if 75% of greater.
Estimate Source	Please identify the source of the estimate. The source of the estimate can be engineering judgement, bottoms-up expert opinion, comparison to other programs, best-guess or other method. If more detail is available, including the cost of analogous projects, please provide the supporting data as part of the
POC	Person responsible for filling the other fields on this line
Comments	Any additional discussion or clarification regarding the technology or capability development.

Appendix 6A: Laser Transmitter Prioritization

Technology Challenge (from TC master heading)	**Technology Capability**	**Technology Utility** (list scenario IDs that this technology will enable)	**Measurement Parameter(s)**	**Scenario Uniqueness** (can the measurement be accomplished only via this technique?)	**Science Impact?** (High=dramatic leap in understanding or Medium=incremental understanding. In both cases, explain the science impact if this technology is developed)
1-100 W, 0.1-50 mJ 1-micron laser	100 mJ/20 Hz at 532 and 1064 nm. Polarization purity >99% at 532 nm, divergence 100 microrads, injection-seeded linewidth 1 GHz or	116 LWG-AC-1 LWG-AC-2	Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution	Yes	High: Improved resolution vertical distribution of aerosols and characterization of their optical properties is critical to full understanding of the radiation budget
	Conductively cooled laser transmitters with >1-kHz PRF, linewidth ~5 pm, pulse energy ~50 micro-J @ 355 and 1064 nm.	180 LWG-AC-1 LWG-AC-2	Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution	Yes	High: Improved resolution vertical distribution of aerosols and characterization of their optical properties is critical to full understanding of the radiation budget
	4 mJ/1 kHz @ 1064 nm, WPE >3%, pulselength 1 ns	186	Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	Yes	High: Ice-sheet topography and sea-ice thickness for mass balance and dynamics knowledge are critical to cryosphere program
	0.1 mJ/75 kHz @ 1064 nm, pulselength ~5 ns, WPE ~10%	188 48	Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	Yes	High: Vegetation 3-D structure is critical to carbon cycle & ecosystems program; ice-sheet topography and sea-ice thickness for mass balance and dynamics knowledge are critical to cryosphere program
	5-20 micro-J/>10 kHz @ 1064 nm, pulselength <1 ns, linewidth <2 pm, linearly polarized	LWG-OT-1	Land Surface Topography Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	Yes	High: Ice-sheet topography and sea-ice thickness for mass balance and dynamics knowledge are critical to cryosphere program
100 W, 100 Hz 1-micron laser	1 J/100 Hz, single frequency @ 1064 nm, WPE 6-8%	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Tropospheric Winds	Yes	High: Tropospheric wind profiles remain the highest priority unaccommodated NPOESS
	1 J/20-100 Hz, single frequency @ 1064 nm, WPE 6-8%	17	Phytoplankton Physiology and Functional Groups	Yes	High: Accurate oceanic biome inventory is critical to carbon cycle & ecosystems program
1-100 W 1.5-micron fiber laser	10 W cw, 5-MHz long-term linewidth	179 NRC-02	CO2 and Methane	Yes	High: High-resolution measurement of carbon dioxide (CO2) mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems
	0.1 mJ/100 kHz, linewidth <10 MHz, pulselength 1000 ns, single freq.	NRC-04	CO2 and Methane	Yes	High: High-resolution measurement of CO2 mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems program
20 W, 1 J 2-micron pulsed laser	0.5 J/10 Hz, single frequency, WPE 1.4%	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Tropospheric Winds	Yes	High: Tropospheric wind profiles remain the highest priority unaccommodated EDR
	1 J/20 Hz double-pulsed with spectral purity >99.5%, wavelength stability <0.02 pm, WPE 3-5%	24	CO2 and Methane	Yes	High: High-resolution measurement of CO2 mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems program
Wavelength converters for the vis-UV	340 mJ/100 Hz at 355 nm, single frequency with conversion efficiency from 1064	LWG-AD-SP1 LWG-AD-SP2 LWG-AD-SP3	Tropospheric Winds	Yes	High: Tropospheric wind profiles remain the highest priority unaccommodated EDR
	100 mJ/20 Hz, polarization purity >99% at 355 and 532 nm	LWG-AC-1 LWG-AC-2	Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution	Yes	High: Improved resolution vertical distribution of aerosols and characterization of their optical properties is critical to full understanding of the radiation budget
	~500 mJ/20-100 Hz at 520-532 nm with conversion efficiency from 1064 nm of 50%	17	Phytoplankton Physiology and Functional Groups	Yes	High: Accurate oceanic biome inventory is critical to carbon cycle & ecosystems program
	20 mJ/100 Hz or higher at 532 nm with conversion efficiency from 1064 nm of 50% or better	48	Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography Cloud Particle Properties and Distribution River discharge rate River stage height Polar ice sheet velocity	Yes	High: Vegetation 3-D structure is critical to carbon cycle & ecosystems program; ice-sheet topography and sea-ice thickness for mass balance and dynamics knowledge are critical to cryosphere program
Wavelength converters for the IR	10 W cw @ 1.6 microns, 5-MHz long-term linewidth, tunable 1064-nm pumped OPO	179	CO2 and Methane	Yes	High: High-resolution measurement of CO2 mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems program (complementary with scenarios 23, NRC-02, and NRC-04)
Other laser	5 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE	23	CO2 and Methane	Yes	High: High-resolution measurement of CO2 mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems program (complementary with scenarios 179, NRC-02, and NRC-04)
Beam director	Up to 30-deg. cross-track scanning	LWG-AC-1	Aerosol Properties Cloud Particle Properties and Distribution Stratospheric Aerosol Distribution Total Aerosol Amount	Yes	High: Improved resolution vertical distribution of aerosols and characterization of their optical properties is critical to full understanding of the radiation budget
	Addressable beam positioning, no moving parts preferred, 1000 beam positions across 1-2 deg. FOV	186 188	Land Surface Topography Land Cover and Land Use Vegetation Biomass Ice Surface Topography Sea Ice Thickness Ocean Surface Topography River Discharge Rate River Stage Height	Yes	High: Vegetation 3-D structure is critical to carbon cycle & ecosystems program; ice-sheet topography and sea-ice thickness for mass balance and dynamics knowledge are critical to cryosphere program

Scenario Relevance? (designate T=meets threshold science requirements, G=meets goal science requirement, E=exceeds goal science requirements)	**Measurement Timeliness according to roadmaps** (Now= immediate development needed, Later=Can wait 2-3 years, Latest=Can wait 4-5 years; correlate with scenario ID)	**Technology Development Criticality** (E=enabling, CR=Cost Reducing)	**If "CR" in column G, explain the return on investment. How is cost reduced and by how much?**	**Risk** (Does this technology development reduce the risk of mission failure? If yes, explain.)
G	Latest	E		Technical approach has heritage through LITE and CALIPSO
G	Latest	E		Technical approach has heritage through LITE and CALIPSO
E	Later	E		Photon counting has not been validated and carries more risk with respect to vegetation structure, but if successful enables a less stressing transmitter option
E	Later	E		Photon counting has not been validated and carries more risk with respect to vegetation structure, but if successful enables a less stressing transmitter option
E	Later	E		Photon counting has not been validated and carries more risk with respect to vegetation structure, but if successful enables a less stressing transmitter option
T: Assessment supported by multiple point design studies for winds	Now	E		Technology is mandatory for mission success
T	Latest	E		Technology is mandatory for mission success
G	Later	E		Airborne validation pending
G	Later	E		Airborne validation scheduled in FY08 (IIP)
T: Assessment supported by multiple point design studies for winds	Now	E		Technology is mandatory for mission success
T	Later	E		Technology is mandatory for mission success
T	Now	E		Technology is mandatory for mission success
G	Latest	E		Technical approach has heritage through LITE and CALIPSO
T	Latest	E		Technology is mandatory for mission success
E	Later	E		Risk reducing: 532 nm is for aerosol channel, which is required to compensate optical path length changes due to clouds and aerosols along altimeter line-of-sight
G	Later	E		Risk reducing: Nonlinear generation is alternative to direct generation by conventional fiber techniques
G	Later	E		Airborne validation scheduled in FY06
G	Latest			Increases coverage to better match that of passive aerosol sensors
E	Later	E		This technology would greatly enhance the resolution and accuracy of land cover structure

Appendix 6B: Receiver Prioritization

Technology Challenge (from TC master heading)	**Technology Capability**	**Technology Utility** (list scenario IDs that this technology will enable)	**Measurement Parameter(s)**	**Scenario Uniquess** (can the measurement be accomplished only via this technique?)
Alignment maintenance	5 microrad roundtrip (5 msec) lag angle compensation (coherent) and 50 microrad active transmitter/receiver boresite alignment (direct)	LWG-AD-SP1, LWG-AD-SP2, LWG-AD-SP3,	Tropospheric winds	Yes
	50 microradian standard deviation on a zero mean on ground for two beams with different wavelengths	23	CO2	
	co-alignment of the transmitter beam and the detector array needs to be maintained to within ~ 5-10 microradian	LWG-OT-1, 186, 187, 23	Ice surface topography, Vegetation biomass, CO2	Yes
Scanning Systems	Conical or step-stare capability with full-azimuth coverage at 30-50 deg. nadir angle	LWG-AD-SP1, LWG-AD-SP2, LWG-AD-SP3	Tropospheric winds	Yes
	addressable FOV across 1 - 2 degrees	188	Vegetation biomass	Measurement may be accomplished by InSAR, but with less vegetation vertical structure definition
Doppler Offset Compensation Technologies				
Large Effective Area, Lightweight Telescopes (Including stray light control)	1.5-2m telescope, 4-20 urad blur circle	LWG-OT-1, 187, 188	Vegetation biomass, Ice surface topography	Measurement may be accomplished by InSAR, but with less vegetation vertical structure definition
	3 m diameter/ ~100 μmrad FOV, areal density, <25 Kg/m2	24, 17	CO2, Phytoplankton Physiology and Functional Groups (may require further analysis for PPFG only)	Yes
	1.5 m segmented or deployable telescope	NRC-03	Aerosol vertical distribution	
	1 - 2 m aperture with +/- 30 deg FOV. The individual potential beams will have a much smaller IFOV.	LWG-AC-1	Aerosol vertical distribution	
Mechanical Metering Structures				
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	?	NRC-03, LWG-AC-1	Aerosol vertical distribution	

Science Impact? (High=dramatic leap in understanding or Medium=incremental understanding) In both cases, explain the science impact if this technology is developed)	**Scenario Relevance?** (designate T=meets threshold science requirements, G=meets goal science requirement, E=exceeds goal science requirements)	**Measurement Timeliness according to roadmaps** (Now= immediate development needed, Later=Can wait 2-3 years, Latest=Can wait 4-5 years; correlate with scenario ID)	**Technology Criticality** (E=enabling, CR=Cost Reducing)	**If "CR" in column G, explain the return on investment. How is cost reduced and by how much?**	**Risk** (Does this technology development reduce the risk of mission failure? If yes, explain.
High: Tropospheric wind profiles remain the highest priority unaccommodated Environmental Data Record (EDR)	T	Now	E		This technology is mandatory for mission success
High.	G	Later	E		
High: Enabling mission technology	T	Now	E		Mission success depends on alignment of telescope to transmitter to maintain performance requirements.
High: Tropospheric wind profiles remain the highest priority unaccommodated Environmental Data Record (EDR)	T	Now	E		This technology is mandatory for mission success
High: High vertical/horizontal resolution DEMs with vertically-resolved vegetation structure are critical to carbon cycle & ecosystems program	E	Later	E		This technology would greatly enhance the resolution and accuracy of land cover structure and could possibly render coherent change detection feasible
High: High vertical/horizontal resolution DEMs with vertically-resolved vegetation structure are critical to carbon cycle & ecosystems program	E	Later	E		This technology would greatly enhance the resolution and accuracy of land cover structure and could possibly render coherent change detection feasible
High	G	Later	E		This technology is mandatory for mission success.

Appendix 6B: Receiver Prioritization

Technology Challenge (from TC master heading)	**Technology Capability**	**Technology Utility** (list scenario IDs that this technology will enable)	**Measurement Parameter(s)**	**Quantitative Req'ts**	**Scenario Uniqueness** (can the measurement be accomplished only via this technique?)
In-situ (air, ground) lidar validation systems	*1 In-situ (airborne, gnd) Lidar systems (small, inexpensive and easy to operate remotely)	NRC-11, NRC-14, LWG-AD-SP3, 180, 116, LWG-AC-1, 2300-09, 182, LWG_AC-2, 69, 99, 17, 27, 42, NRC-02, NRC-01, 24, 179, 181, 185, 70, 72, NRC-04, 81, NRC-09	1. Land Surface Topography 2. Land Cover and Land Use 3. Vegetation Biomass 4. Ice Surface Topography 5. Sea Ice Thickness 6. Ocean Surface Topography 7. Cloud Particle Properties and Distribution 8. Phytoplankton physiology & functional groups 9. Ocean	combine with 21 sensor web	Yes
Intelligent sensor health & safety	*5 Intelligent Sensor for automated H&S/fault handling	23, LWG-AD-SP3, NRC-07, 24, 27, 52, 70, 73	1. Trace gas sources 2. CO2 and methane 3. Land Surface Topography 4. Land Cover and Land Use 5. Vegetation Biomass 6. Tropospheric wind 7. Terrestrial reference frame	instrumentation suite to monitor H&S	Yes, greatly increases laser reliability
On-board sensor control	*3 On-board sensor control (planning, execution, fault handling) precision pointing	23, 56, 57, 81, 99, 186, 188, 48, 149, 150, LWG-AD-AP3, NRC-07, NRC-11, NRC-15, 24, 179, NRC-02, NRC-04, 27, LWG-OT-1, LWG-OT-2, 187, NRC-14, 42, NRC-09	1. Land surface topography 2. Tropospheric wind 3. Gravity field 4. CO2 and methane 5. Sea ice topography 6. Ocean carbon/particles 7. Mixed layer depth	precision pointing	Yes, precise pointing is critical with critical timing requirements
On-board near RT data processing	*4 Science data processing (Pattern recognition, Event detection, on-board calibration)	52, 70, 186, 17, NRC-02, NRC-04, 23, LWG-AD-SP3, 81, 27, 42, NRC-09	1. Tropospheric wind 2. Aerosols 3. Water Vapor (71) 4. Phytoplankton physiology & functional groups 5. Ocean carbon/particles 6. Mixed layer depth CO2 profiles (23) surface topography (186, 187) aerosol profiles (HSRL-2300-09)	only lidar can detect wind sheer lidar can help to detect wind shear, pollution events to enable adaptive targeting of satellite/satellite suite and augment real-time forecasting applications; near real time recognition of scientifically and/or ecological	Yes, specific to phytoplankton blooms (HABs), plumes (volcano, pollution, wind sheer, moisture gradient events) Yes, necessary to meet <3 hr data to model requirement Yes, specific to aerosol, water vapor, and ozone profiles
Science model-driven adaptive targeting	*2 Science model-driven adaptive targeting	81, LWG-AD-SP3, 182, NRC-02, NRC-04, 24, 179, 27, NRC-01, 23	1. Tropospheric wind 2. Aerosols 3. Water Vapor 4. CO2 and methane & Methane 5. Surface trace gas concentration 6. Trace gas sources 7. Coastal carbon 8. Global ocean carbon/particle abundance	determine & acquire next target within 3 hours	Yes, in order to meet a stringent time requirement, autonomous way to command the spacecraft is necessary to fill data gaps for a decision support system
Space-qualified TB solid state storage	* 6 Space qualified Terabyte solid state storage	NRC-11, NRC-14, LWG-AD-SP3, 180, 116, LWG-AC-1, 2300-09, 182, LWG_AC-2, 69, 99, 17, 27, 42, NRC-02, NRC-01, 24, 179, 181, 185, 70, 72, NRC-04, 81, NRC-09, 188, 187, 48, 149, 150	1. Land Surface Topography 2. Land Cover and Land Use 3. Vegetation Biomass 4. Ice Surface Topography 5. Sea Ice Thickness 6. Ocean Surface Topography 7. Coastal Carbon 8. Global ocean carbon/partical abundance 9. Phytoplankton physiology & functional gro	use microwave report	Yes,
Space-qualified HPC HW & programming tools	* 7 Space Qualified FPGAs, HPC computers, clusters and programming tools	23, 56, 57, 81, 99, 186, 188, 48, 149, 150, LWG-AD-AP3, NRC-07, NRC-11, NRC-15, 24, 179, NRC-02, NRC-04, 27, LWG-OT-1, 187, NRC-14, 52, 70, 73, 17, 42, NRC-09	1. Land surface topography 2. Tropospheric wind 3. Gravity field 4. CO2 and methane 5. Trace gas and CO2 6. Crustal motion 7. Aerosols & Water Vapor 8. Sea ice topography 9. Phytoplankton physiology & functional groups 10. Ocean carbon/particles 11. Mixed	use microwave report	yes

Science Impact? (High=dramatic leap in understanding or Medium=incremental understanding) In both cases, explain the science impact if this technology is developed)	**Scenario Relevance?** (designate T=meets threshold science requirements, G=meets goal science requirement, E=exceeds goal science requirements)	**Measurement Timeliness according to roadmaps** (Now= immediate development needed, Later=Can wait 2-3 years, Latest=Can wait 4-5 years; correlate with scenario ID)	**Technology Criticality** (E=enabling, CR=Cost Reducing)	**If "CR" in column G, explain the return on investment. How is cost reduced and by how much?**	**Risk** (Does this technology development reduce the risk of mission failure? If yes, explain.
High.	G	Now	E		
High.	E	Latest	E		
High: HSRL is the only known technique that can measure aerosol extinction and backscatter independently.	T	Now	E		
High: High-resolution measurement of CO2 mixing ratio variances in the lower troposphere are critical to carbon cycle & ecosystems program	G	Now	E		This technology is mandatory for mission success
High: Discrimination of phytoplankton functional groups is critical for carbon cycle and ecosystems program.	G	Now	E		This technology is mandatory for mission success
High: HSRL is the only known technique that can measure aerosol extinction and backscatter independently.	T	Now	E		
High: High vertical/horizontal resolution DEMs with vertically-resolved vegetation structure are critical to carbon cycle & ecosystems program	E	Later	E		This technology would greatly enhance the resolution and accuracy of land cover structure and could possibly render coherent change detection feasible
High: High vertical/horizontal resolution DEMs with vertically-resolved vegetation structure are critical to carbon cycle & ecosystems program	E	Later	E		This technology would greatly enhance the resolution and accuracy of land cover structure and could possibly render coherent change detection feasible

Technology Challenge (from TC master heading)	**Technology Capability**	**Technology Utility** (list scenario IDs that this technology will enable)	**Measurement Parameter(s)**	**Scenario Uniquess** (can the measurement be accomplished only via this technique?)
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Narrow-band notch filter to reduce laser backscatter to the level comparable with fluorescence and Raman components in the laser-stimulated backscatter signal. 1-3 nm half-height or better, D>5, 90% transmission or better in 380-800 nm range.	17	Phytoplankton Physiology and Functional Groups	Yes.
Narrowband Optical Filters	200 pm, 60% transmission	24	CO2	
Narrowband Optical Filters	Bandpass daylight rejection etalon filter: <50 pm FWHM, T>70%	NRC-03	Aerosol Properties Stratospheric Aerosol Distribution Total Aerosol Amount	Yes
Detectors (Including Arrays) and Amplifiers	1.5 and 2 micron detectors	23, 179, 24, NRC-02, NRC-04	CO2	Yes
Optical High Resolution Spectral Analyzers	Space-qualified spectral analyzer, 520-800 nm range, 1-3 nm resolution, gated with 50-100 ns pulses, capable of photon counting, high QE, low noise	17	Phytoplankton Physiology and Functional Groups (may need further analysis)	Yes
Optical High Resolution Spectral Analyzers	Resolution of 1GHz FWHH over range of 20GHz centered at laser wavelength of either 355 or 532 nm; etendue >100mm-mrad; transmission >70% +/-0.1%/hr; freq drift <1 MHz/hr	NRC-03	Aerosol Properties Stratospheric Aerosol Distribution Total Aerosol Amount	Yes
Detection Electronics, E.G., High speed ADC, multi-channel scaler, and boxcar averager	low power,12 bit, 1 Gsamp/s, 9 channel digitizer.	187	Vegetation biomass, Ice surface topography	Measurement may be accomplished by InSAR, but with less vegetation vertical structure definition
	20 - 100 channel, 0.5 nsec resolution, multi-stop digital timing device; 20 Mcount/sec capability	LWG-OT-1, 186	Vegetation biomass, Ice surface topography	
	streaming digitizer, 500 Msample/sec, 8 bits, with integrated pulse finding and time tagging.	188	Vegetation biomass, Ice surface topography	Measurement may be accomplished by InSAR, but with less vegetation vertical structure definition

Science Impact? (High=dramatic leap in understanding or Medium=incremental understanding) In both cases, explain the science impact if this technology is developed)	**Scenario Relevance?** (designate T=meets threshold science requirements, G=meets goal science requirement, E=exceeds goal science requirements)	**Measurement Timeliness according to roadmaps** (Now= immediate development needed, Later=Can wait 2-3 years, Latest=Can wait 4-5 years; correlate with scenario ID)	**Technology Criticality** (E=enabling, CR=Cost Reducing)	**If "CR" in column G, explain the return on investment. How is cost reduced and by how much?**	**Risk** (Does this technology development reduce the risk of mission failure? If yes, explain.
High, utility of early data validation is enormous (esp. winds), also aids instruments health monitoring (early baseline on performance established); necessary to achieve data callibration analogous to Landsat products	G, improved understanding of science	now, validation will be a significant factor, can also help refine mission concept	E		Risk is having 2 year data validation delay ala IceSat
Medium	G, improved understanding of science	Later, proprietary interface is sufficient	E, CR	Will extend instrument life for lower risk lasers	Trade off between laser reliability vs control & monitoring system
Medium, provide higher precision and relevant data	E, vastly improves model	Now, requires long term development	E, CR	Reduce GDS processing, operations cost	Enable stricter instrument health monitoring and control
High, fill data gaps for vastly improved prediction High (although what's really high is the practical impact of improved forecasting of such things as hurricane tracks and air quality)	T, provides some additional capability G, improved understanding of science (aerosol, water vapor, and ozone profiles)	now	E		
High, fill data gaps for vastly improved prediction; substantial impact in predictive skill has already been demonstrated via OSSEs (Atlas, et al).	T, will help to meet the acquisition time requirement	Later, demo missions are planned for feasibility with loose time requirement	E		It will enhance mission capability
High, enable new science	G, improved understanding of science		E		
High, enable new science	G, improved understanding of science	now	E		

Appendix 6D: Data Utilization and Acquisition Roadmaps

Data Acquisition - Autonomy

Capability	Today	2006-2010	2011-2015	2016-2020
Airborne/Ground Lidar validation systems	Instrument level models Manual data ingestion from in situ instrument > 1wk for validation > 1 month for calibration	OSSE based sensor web framework (TRL 4) Demonstration of validation GDS (TRL 6) Decision Support validation (TRL 5)	Seamless data ingestion into weather model (TRL 6) Instrument degradation prediction Simulation based validation	Self reconfiguring sensor web Model directed sensor targetting (accurate error bars on data quality flags)
Intelligent sensor health & safety	Fixed set of condition monitoring based on on board engineering sensors Ground based diagnostic (~ 1 day turn-around)	Real-time H & S monitoring Flexible suite of monitoring instrumentation Complete database of laser instrument characteristics	Real-time H & S diagnosis and Response (TRL 6)	Real-time H & S prognosis (when will it fail)
On-board sensor control	Cyclic scheduling execution, rate monotonic analysis Static feature recognition; tens of minutes Pointing based on ground base commanding sequence	Deadline-based scheduling Composite or dynamic feature recognition and response; tens of second Prototype diagnosis and response algorithms (TRL 6)	Control analysis based on timeliness constraints Sensor fusion, 1 sec, onboard registration Integrated control sensor manipulation (TRL 6)	Real-time sensor control for Model directed follow-up sensing Accurate sensors with precise attitude control in real-time to meet 0.25 degree pointing accuracy

Data Acquisition - Processing

Capability	Today	2006-2010	2011-2015	2016-2020
On-board near real time data processing	FPGA based preprogrammed raw data processing Analog to digital conversion Data compression (rudimentary interferogram)	Level 1 and 2 data production for quick look data generation (TRL 6) Formalization of data policy for data products, compression, calibration for on board processing Onboard database and data management (TRL 6)	Reconfigurable data product processing Fault tolerant software	Goal directed autonomy (TRL 6) Parallized architecture based data processing
Space-qualified TB storage HW	Non-volatile Storage: ~100 GB SQ USB: 1 - 10 GB Power: 2mW	Capacity: ~1 TB 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 deg C Includes EDAC - Error Detection And Correction	SQ versions of high speed flash memory (non-volatile) Capacity: 100 TB USB interface (TRL 8)	Capacity: 10- 100 TB Power < 10 W
Space-qualified HPC HW & programming tools		RH: FPGA 10 – 20 watts per system 1000 - 2000 MIPS at TRL 6 reprogrammable FPGA in flight Instrument micro controllers: 100 MIPS @ 3 W, TRL 6 Symmetrical Multi Processing: 4-6 Nodes TRL 6	RH: Integrated Avionics Platform, 10 – 20 watts 10 000 MIPS multiprocessor TRL 6 Multiple FPGA each with Multiple PPC CPU Radiation Tolerant micro controllers, TRL 6 LAN Distributed Computing 8 – 16 nodes TRL 6	RH: Flight qualified Avionics, TRL 8 Multiple CPU Fault Tolerant, TRL 7 Embedded reconfigurable low-power processing, TRL 8 Rad. Tolerant embedded micro controllers, TRL 8 Distributed Computing TRL 8
Data compression	*don"t need to include*			

Appendix 6D: Data Utilization and Acquisition Roadmaps

Data Acquisition - Utilization

Capability	Today	2006-2010	2011-2015	2016-2020
Science model-driven adaptive targeting	Manual scheduling based on science requests Analysis is done ad hoc by using different models	OSSE to simulate LIDAR data (TRL 5) Model and data assimilation system to provide data products in near real time (< 1 day) Algorithms for targeting scheme for data capture Delivery and evaluation of science data products	Simulation of end-to-end adaptive targeting environment (TRL 5) Data assimilation in real time (TRL 6) Automatic schedule generation (TRL 6)	
Model Lidar data resampling techniques	Assimilation of satellite data with representation of atmospheric forcing for near global 1-deg ocean circulation model using HEC. TRL 4	1/6-deg model resolution of global ocean domain coupled to atmospheric circulation model for seasonal-to inter annual forecasts. TRL 6	Multiple high resolution coupled models driving advanced instrument design, observations, and mission planning. TRL 7	Coupled models using multiple assimilation sources producing science quality data products in near real-time. TRL 9
Data Management/Service Oriented Architecture	Small percentage of archived data utilized in science data processing, yet a acquisition goals are growing. (TRL 3) << 1 Teraflops Theoretical Peak	Distributed data management tools feed models using >25% of relevant archived data sets. TRL 5 5 Teraflops Theoretical Peak	HEC-based data mining tools feed HEC visualization systems in a scalable way. TRL 8 10 Teraflops Theoretical Peak	GRID gets real-time instrument data streamed into models using >50% of relevant archived data. TRL 9 Within top 5% of HPC Top500 list