NASA Laser Remote Sensing Technology Needs for Earth Science in the Next Decade and Beyond

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ABSTRACT

In late 2005 the NASA Earth Science Technology Office convened a working group to [illegible]dal-term technology needs for Earth science active optical remote sensing objectives. The outcome [illegible]ded to guide future NASA investments in laser remote sensing technologies. This paper [illegible]ndings and places them in context with the conclusions of the National Research [illegible]ds, completed in 2007.

Keywords: Lidar, laser radar, laser altimetry, Ea[illegible]

1. I[illegible]

In 2003 the NASA Earth Science Technology O[illegible]echnology requirements that would be necessary for mountin[illegible] was then formulated. The resulting report identified and quantifi[illegible] mapped them to the future science measurements that were t[illegible] parallel technology focus areas:

- Active Remote Sensing I (laser radar/lidar technol[illegible])
- Active Remote Sensing II (radar technologies)
- Passive Remote Sensing I (optical technologies)
- Passive Remote Sensing II (microwave and radio-fre[illegible])
- *In-situ*, unconventional, and non-spacebased sensing t[illegible]tform technologies

Since the publication of the original report, a series of technology specific working groups has been established to delve deeper into the requirements of each individual technology focus area and provide explicit recommendations for infusion into future ESTO research and development solicitations. The working group that was convened to evaluate laser sensing technologies had the advantage of carrying out its task within the timeframe of the National Research Council (NRC) decadal survey of future Earth and environmental science and applications needs, which was commissioned jointly by NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey in 2004. Because of this confluence, the ESTO Lidar Technology Requirements Working Group was aware of the NRC committee's measurement priorities (in terms of science impact, societal benefit, *etc.*) and was able to align its technology investment recommendations with those priorities. Hence, the findings contained in the Lidar Working Group report[2] mirror to a large degree the recommendations contained in the decadal survey report[3].

Particular attention was paid to the structure of the working group. The composition of the group included three technology subgroups focused on the topics of laser transmitters; detection, processing and optics (receivers); and data acquisition and utilization, while three science subgroups focused on the atmospheric composition, atmospheric dynamics, and oceans and topography application areas.

In order to capture relevant information from the widest possible knowledge base, inputs from the broader external science and technology communities beyond the working group membership were solicited by means of an open

Community Forum which was held early in the process. Information acquired through this mechanism[4] was then incorporated into the technology evaluation and roadmapping development.

2. METHODOLOGY

The exhaustive technology requirements definition process commenced with an evaluation of the science requirements, as extracted from the NASA Earth Science Research Strategy document. From this a set of measurement scenarios and use cases were derived from which technology challenges could be identified and flowed down ultimately to a roadmap timeline of priority technology developments. This progression is represented in Figure 1.

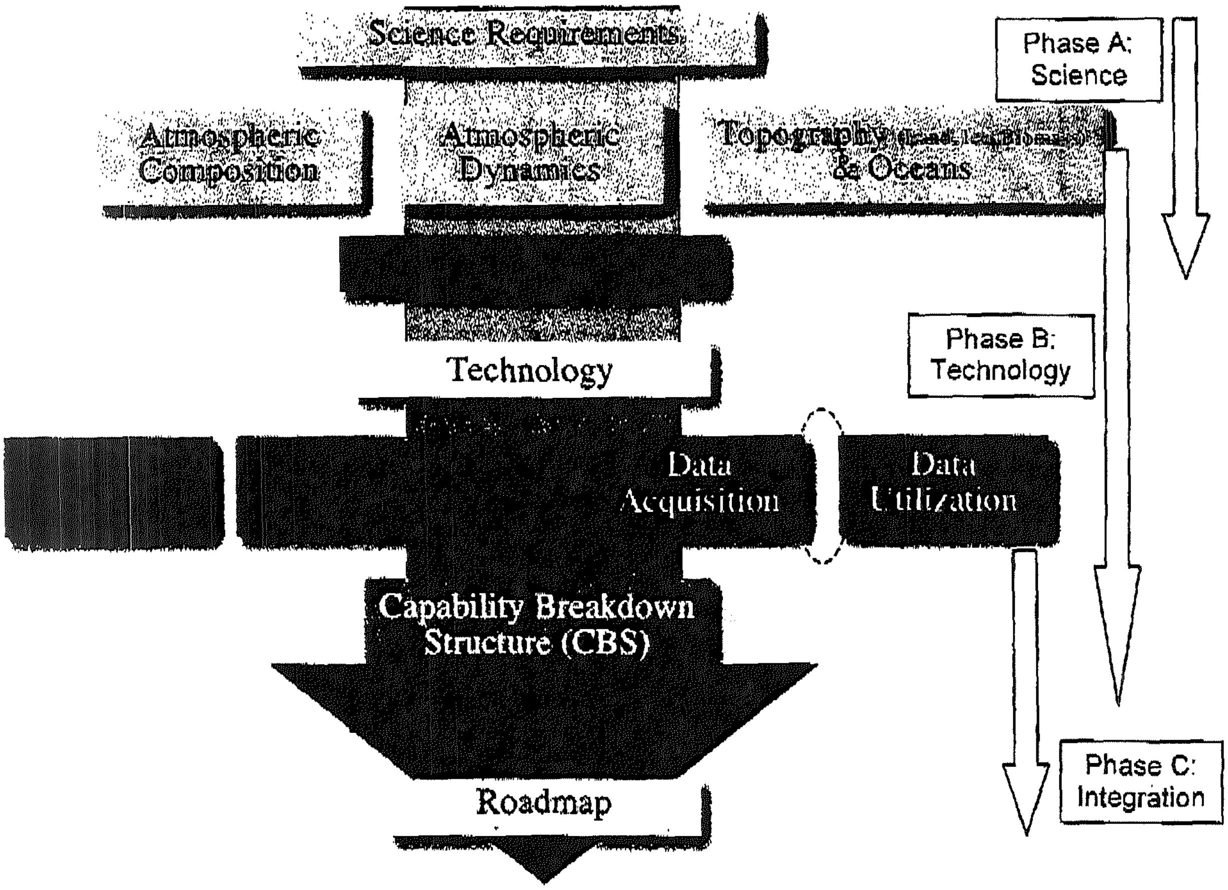

Fig. 1. Schematic depiction of the technology requirements definition process.

When recommending development timelines or immediacy of technology investments, the group took several prioritization factors into account. The prioritization criteria developed by the working group are as follows (in order of assigned importance):

- Scientific impact
- Societal benefit
- Measurement scenario utility
- Technology development criticality
- Technology utility
- Required measurement timeline
- Mission risk reduction

Here, we treat only the three highest priority criteria[a] and refer the reader to the working group report for a discussion of the remaining criteria[2].

2.1 Scientific Impact

Scientific impact is defined as the degree to which the proposed measurement *via lidar technique* will improve our scientific understanding of the Earth System and help to answer the overarching questions explicit in the NASA Earth Science Research Strategy. The key factor to consider here is the *scientific impact achieved because of the uniqueness of the lidar measurement technique*. Lidar techniques make significant and unique contributions to our scientific understanding specifically for the following measurements:

- *Tropospheric Winds,* where timely measurement on a global scale is impossible using any other currently known methodology. Yet, and despite its acknowledged importance, measurement of the 3D tropospheric wind field globally from space has remained an elusive goal. High spatiotemporal resolution knowledge of the tropospheric wind field is vital for understanding the weather system and for accurate prediction of severe weather events such as hurricanes[5].
- *Tropospheric CO_2 Profile*, where the desired horizontal and vertical resolution is not feasible with any other technique than active optical sensing. Determining the CO_2 profile in the atmosphere will have a major impact on our understanding of changes in this primary greenhouse gas and its impact on the Earth system. In order to properly characterize the magnitude and location of CO_2 sources and sinks, it is essential to acquire high resolution measurements within the lowermost layers of the atmosphere, *i.e.*, the planetary boundary layer and free troposphere[6].
- *High Resolution Ice Sheet Topography and Velocity*, where the value of high vertical resolution laser altimetry has been amply demonstrated by the ICESat (Ice, Cloud, and land Elevation Satellite) mission. Complemented by Interferometric Synthetic Aperture Radar (InSAR) 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[7].
- *Vegetation 3D Structure, Biomass and Disturbance*, where lidar systems offer very high range resolution compared to either passive electro-optic or microwave techniques. High vertical resolution measurements are key to accurate profiling of the vegetation canopy and the assessment of change in forest structure[8].
- *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.

2.2 Societal Benefit

Societal benefit can be judged by 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 predictions). A primary intent of the NASA Earth Science Division is investment in Earth science application areas with clear benefit to mankind, since science research to improve life on Earth has been a high priority of NASA and is explicitly stated in its charter.

Recent natural disaster events in the U.S. and the world at large have made it clear that the ability to predict the onset and progress of severe weather events is not only critical for improving the quality of life on Earth, but also is now recognized as important to national security (as evidenced by the 2007 U.S. Congressional call for a National Intelligence Estimate on this topic[9]). For example, the landfall of Hurricane Katrina (2005) notoriously resulted in at least 2000 fatalities, displaced many thousands more, and threatened the oil refineries in the Gulf of Mexico region, thereby causing severe adverse economic consequences as well as exposing the vulnerability of the U.S. homeland security system. Had accurate and advanced hurricane path and intensity forecasts been available, some of these extreme adverse consequences could have been avoided, or at least mitigated, through the issuance of timely warnings.

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[a] Our top two prioritization criteria (scientific impact and societal benefit) accord with the top two criteria applied by the Decadal Survey committee.

In this particular regard, accurate knowledge of the 3D global tropospheric wind field is essential for accurate numerical weather forecasting and severe weather prediction capability[10]. For this reason, obtaining the tropospheric wind profiling capability offers arguably the most immediate societal benefit.

A series of Observing System Simulation Experiments (OSSEs) carried out at NASA Goddard Space Flight Center, the National Centers for Environmental Prediction, and the NOAA 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[5]. 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, improved wind measurements would 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 atmospheric CO_2 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 climatic impact they may have on regional and global scales.

To assess changes in the Earth's long-term climate, accurate measurements of CO_2 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 CO_2 profiling capability is one of the main goals of the U.S. Climate Change Science Program.

2.3 Measurement Scenario Utility

If a lidar approach was identified as the *primary* or *unique* approach for making the proposed measurement, then this was a key determinant in establishing the fundamental utility of a given measurement scenario. Another important factor was whether the scenario met or exceeded threshold or goal science requirements, or otherwise met the requirements for a demonstration mission. Using these criteria as a filter, the following measurements emerged as priority applications:

- Tropospheric Winds
- CO_2 Vertical Profile
- Vegetation Biomass
- High Resolution Ice Surface Topography
- Phytoplankton Physiology and Functional Groups
- Ocean Carbon/Particle Abundance
- Terrestrial Gravity Field
- Terrestrial Reference Frame

The value of lidar for several of these applications has already been discussed above. For the remainder, we note that lidar is required for ocean carbon/particle abundance because passive 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 zones. The improved spacecraft-to-spacecraft range measurements provided by free-space laser interferometry applied to a next-generation GRACE (Gravity Recovery and Climate Experiment)[11] type mission are desired to enable Earth gravity field observations to less than 100-km grid scale and 10-day resolution with an accuracy of less than 1-cm equivalent surface water height[b]. An improved satellite laser ranging network will provide a factor of 5-10 improvement in Earth reference frame knowledge and satellite precision orbit determination over current capability.

[b] Current GRACE Ka-band observations are ~400-km and 30-day resolution with an accuracy of approximately 2-3 cm equivalent surface water height.

1. *Technology Development Criticality:* Whether the development of the proposed technology enables new measurement capabilities or provides incremental improvement in the measurement quality.
2. *Technology Utility:* The degree to which the technology makes a significant contribution to more than one measurement application. The utility can be measured by the number of different measurement scenarios the technology enables.
3. *Measurement Timeline:* Determined by the time horizon when a particular measurement is needed, as articulated in the NASA Earth Science Research Strategy.
4. *Risk Reduction:* The degree to which the new technology mitigates the risk of mission failure.

3. TECHNOLOGY REQUIREMENTS

The working group considered individual system requirements on a holistic level, including science impacts and end-to-end technology needs. One expression of this policy was that information system technology needs were evaluated in tandem with the sensor technologies, so that three separate technology subgroups were tasked with collating data on laser transmitter technologies, receiver technologies, and information system technologies. The top-level prioritized technology summaries and associated derived performance requirements now follow.

3.1 Prioritized Transmitter Technology Needs

An overview of the transmitter technology priorities is given in Figure 2. Here, each technology is traced to the measurement application, outlining different transmitter technology options required for each application. The highest priority technologies in this area are then classified as follows:

1. *1-100W, 0.1-50 mJ, 1-μm Laser:* These low pulse energy, moderate-to-high pulserate systems are oriented toward applications for ice surface topography and 3-D vegetation structure.
2. *100 W, 100 Hz, 1-μm Laser:* These high pulse energy, low pulserate systems are essential for tropospheric wind measurement (direct detection Doppler retrieval), ice mass, and phytoplankton physiology measurement applications.
3. *1-100 W, 1.5-μm Fiber Laser:* These systems have heritage in the telecom industry and are primarily desired for lower tropospheric CO_2 measurement. However, a limited number of these systems have been space qualified, although their in-space performance and reliability statistics are minimal.
4. *5-20 W, 2-μm Laser:* These systems are applicable to tropospheric vector wind (coherent Doppler retrieval) and lower tropospheric CO_2 measurement.
5. *Wavelength Converters:* These systems are essential for direct detection Doppler wind, ice mass, CO_2, and phytoplankton physiology measurements. This category includes target wavelengths in the UV, visible, and shortwave-IR spectral regions.
6. *Beam Director:* Reliable, repeatable, high-slewrate beam scanning technologies are essential for the tropospheric vector wind and 3-D biomass vegetation structure missions.

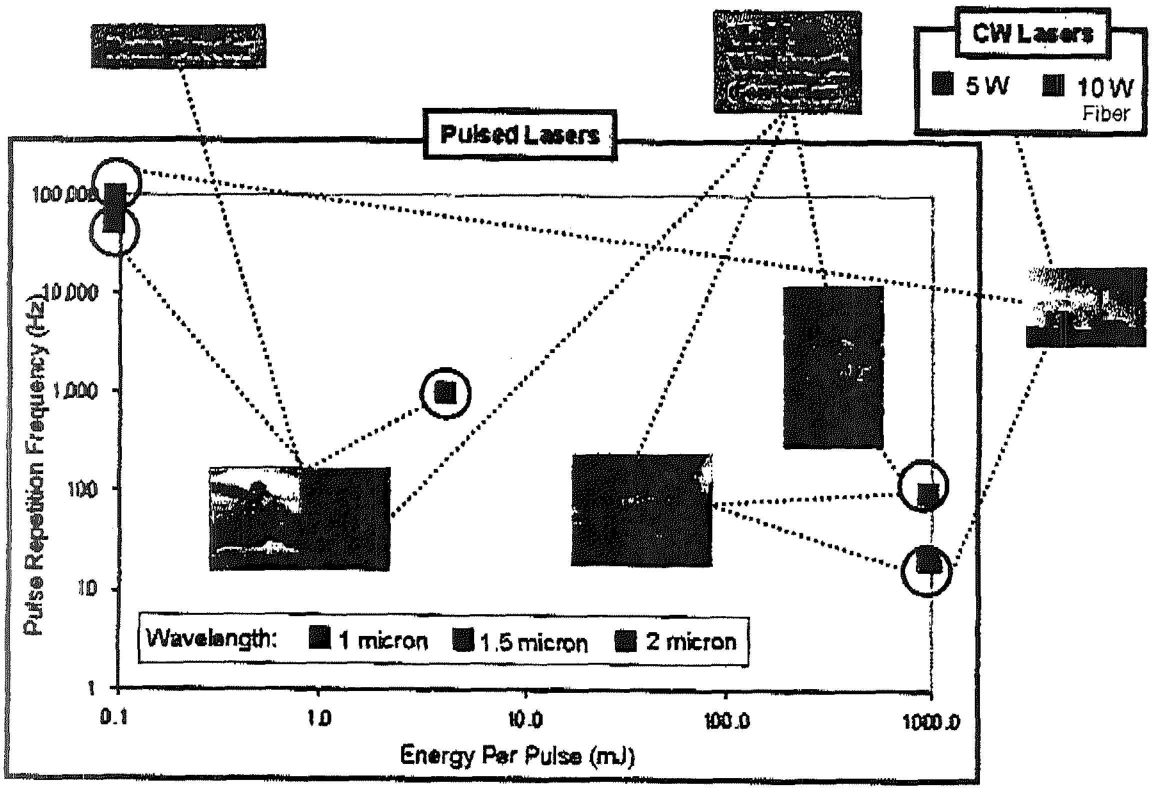

Fig. 2. Transmitter technology science applications summary and flowdown to performance requirements.

3.2 Prioritized Receiver Technology Needs

High priority receiver technologies are summarized in Figure 3, in which each technology is again traced to the measurement application, outlining different receiver technology options required for each application. The highest priority receiver technologies are classified accordingly:

1. *Alignment Maintenance:* This technology is essential for tropospheric winds. The requirement varies for different measurements and varies from approximately 5-50 mrad.
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.
3. *Large, Lightweight Telescopes (<25 kg/m²):* Telescope apertures in the range 1-2 m in diameter are required for certain altimetry measurements. Apertures up to 3-m diameter are required in the case for CO_2 and phytoplankton physiology measurements.
4. *Detectors (Including Arrays), Amplifiers and Electronics:* 1.5- and 2-μm detectors with high quantum efficiency are needed for CO_2 measurements. These technologies will also permit relaxation of laser power requirements. Next generation high-speed analog-to-digital converters are needed for altimetry measurements.
5. *Optical Filters and Specialty Optics:* Special requirements in this technology class enable CO_2 and phytoplankton measurements.

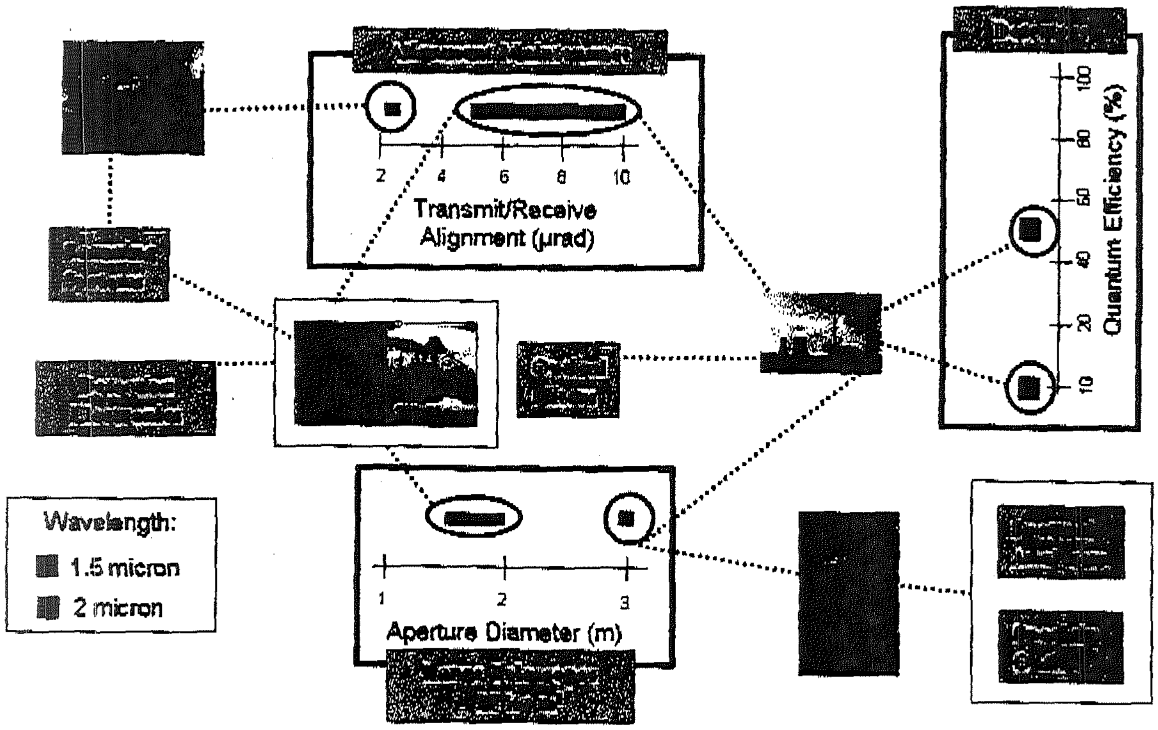

Fig. 3. Receiver technology science applications summary and flowdown to performance requirements.

3.3 Prioritized Information System Technology Needs

In Figure 4 priority technologies are mapped against representative science scenarios and illustrated with requirements for data processing time and data volume. Each color-coded box in the three data acquisition and utilization (DAU) technology tables represents a specific priority technology. The accompanying graphs indicate ranges of requirements for data processing time and data volume for each technology area. In addition, each technology is traced to the measurement application, outlining different choices of DAU technologies for each discrete application. The highest priority technologies in this area are classified according to[c]:

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. OSSEs (Observing System Simulation Experiments) are 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 pulserate or high degree of alignment stability greatly benefit from this technology intended to increase lidar life. Biomass and CO_2 measurement 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 CO_2 measurement.

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[c] Although seven priorities were identified, we address only four areas here, since storage, processors, and on-board computing technologies are already either funded under existing programs or are currently being advanced by industry.

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 line-of-sight) and for instrument catastrophic failure avoidance. This technology is relevant to ice mass and CO_2 measurement.

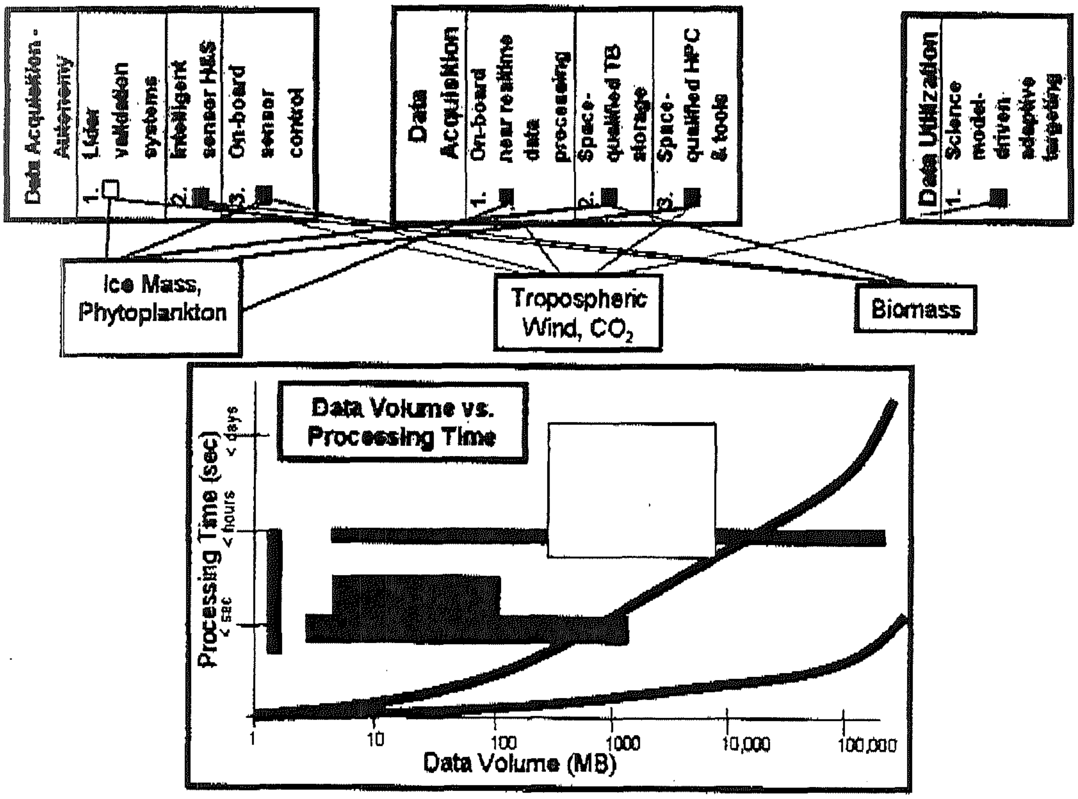

Fig. 4. Information system technology science applications summary and flowdown to performance requirements.

Three distinct timing requirements for information processing needs were identified:

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.

4. RELATIONSHIP TO 2007 EARTH SCIENCE AND APPLICATIONS DECADAL SURVEY

4.1 NRC Decadal Survey Conclusions

The NRC Earth Science Decadal Survey report recommends 3 missions for execution by NOAA and 14 by NASA[3] with mission implementation timelines ranging from the near-term (2010-2013), to mid-term (2013-2016), and finally to the long-term (2016-2020). Of the 17 recommended Earth science missions, six stipulate a requirement for laser remote sensing technology and one retains laser sensing as an option:

- **ICESat-II** to measure ice sheet topography changes for climate change diagnosis using a laser altimeter (near-term).
- **DESDynI** (Deformation, Ecosystem Structure, and Dynamics of Ice) to measure surface and ice sheet deformation for understanding natural hazards and climate, and vegetation structure for ecosystem health using a laser altimeter and an L-band InSAR (near-term).
- **ASCENDS** (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) for measuring diurnal, all-latitude, all-season CO_2 column-integrated measurements for climate emissions diagnosis using a multifrequency laser (mid-term).
- **ACE** (Aerosol/Cloud/Ecosystem) for measuring aerosol and cloud profiles for understanding of climate change and the water cycle using a backscatter lidar (mid-term).
- **LIST** (Lidar Surface Topography) to measure land surface topography for landslide hazards and water runoff using a laser altimeter (long-term).
- **GRACE-II** to measure high temporal resolution gravity fields for tracking large-scale water movement using spacecraft-to-spacecraft laser (or microwave) ranging (long-term).
- **3D-Winds** to map tropospheric wind vector profiles for weather forecasting and pollution transport (long-term).

It is important to recognize that many of the same technologies are applicable to planetary and lunar science measurements. This speaks to the importance and growth of laser remote sensing in the next few decades.

4.2 Intersection of Working Group Findings with Decadal Survey Recommendations

The ESTO Lidar Working Group final report[2] was released approximately six months prior to publication of the Earth Science and Applications Decadal Survey report[3] and recommended technology development for the following measurements that overlap with the missions recommended by the Decadal Survey:

- **Tropospheric Winds** (designated **3D-Winds** by the Decadal Survey). The ESTO group recommended immediate technology development in this area to address the technology challenges associated with this measurement. This is in concurrence with the decadal survey recommendation of a demo 3D-wind demo mission by 2016, since the technology development requires a maturing phase to approach readiness for space flight. However, we stress that investments in the hybrid (direct and coherent detection) approach[12] must begin *immediately* in order to make the 2016 launch feasible.
- **Ice Mass** (designated **ICESat-II** by the Decadal Survey). The group recommended technology developments for improving the measurements already achieved by ICESat[13] for a mid-term implementation. However, it is clear from the decadal survey report that the panel favors flying an ICESat-II mission in the near-term with little or no modification to the technology already flown. In this case, the technology development investment would be minimal to fly what would essentially be a re-build of ICESat.
- **CO_2** (designated **ASCENDS** by the Decadal Survey). The working group recommended investment in a set of competing technology approaches and a trade study to mature the most promising technology.
- **Biomass** (designated **DESDynI** by the Decadal Survey). The working group recommended investment in technologies for the vegetation laser altimeter for a longer term implementation than that indicated in the decadal survey.

The technology recommendations emanating from the ESTO working group report thus have the potential to enable 7 out of 17 (or 40%) of the missions recommended by the Earth Science Decadal Survey report.

5. THE PATH FORWARD AND FOLLOW-ON ACTIVITIES

In response to the Earth Science Decadal Survey recommendations, NASA has convened a series of working groups charged with defining high fidelity requirements for the four missions that the survey panel urged be executed in the near-term (2010-2013). Two of these involve laser remote sensing (*i.e.*, ICESat-II and DESDynI) and stand to gain immediate benefit from the Lidar Working Group's efforts.

While the Earth Science Decadal Survey recommended that the 3D-Winds demonstration mission not be considered for implementation until the long-term (*i.e.*, 2016-2020), NASA and NOAA nevertheless recently formed a joint working group to tightly coordinate focused technology development for research leading to an operational mission. This effort is expected to aggressively leverage technology from industry and other U.S. government programs.

Progress achieved by related international programs, in particular the European Space Agency's Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus) development[14], offer scope for future collaborative opportunities in global laser remote sensing. This would further build on the fruitful relationship exemplified by the joint NASA/Centre National d'Etudes Spatiales CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) mission, which is a multi-instrument Earth-orbiting platform that includes as its centerpiece a two-color polarimetric aerosol/cloud profiling lidar[15].

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