Active Optical Technology: Recent Developments and Lessons Learned

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ABSTRACT

This paper provides an overview of the active optical technology developments supporting the Earth Science Division at NASA. It summarizes key results from a multiyear NASA investment program aimed at enabling new Earth science measurement capabilities, and a special program focused upon developing new techniques in the 1- and 2-micron wavelengths and improving reliability and longevity of future NASA active sensing instruments. Examples for Earth Science measurements such as atmospheric composition, altimetry, wind profiles, ozone levels, and vegetation change are discussed.

Keywords: technology development, remote sensing, active optical technology, lasers, lidar, Earth science

1. INTRODUCTION

Active optical technology has been important in a variety of remote sensing applications: light detection and ranging (*lidar*) techniques have been used to measure atmospheric aerosols and a variety of trace species, to profile winds, and to develop high resolution topographical maps.

Making these measurements from an orbiting satellite would provide great societal benefits. However, the space environment is a challenging one for the high power lasers that enable lidar measurements. Optical mounts must maintain precision alignment during and after launch. Outgassing materials in the vacuum of space lead to contamination of laser optics. Electronic components and optical materials must survive the space environment, including a vacuum atmosphere, thermal cycling, and radiation exposure. Laser designs must be lightweight, compact, and energy efficient. Many lidar applications require frequency conversion systems that have never been designed or tested for use in space.

A decade of investments by the NASA Earth Science Technology Office (ESTO) has contributed to the current mission concepts and technology heritage of planned active optical missions. The next section provides a brief overview of the NASA Earth Science technology investment program. In addition, a focused, interagency program to reduce risk and improve reliability associated with laser technology was also created; key results from the Laser Risk Reduction Program (LRRP) programs are summarized in the following section. Examples of key technology developments supporting priority Earth science measurements are provided in the final sections of the paper.

2. TECHNOLOGY DEVELOPMENT IN EARTH SCIENCE

The Earth Science Technology Office (ESTO) was created in March of 1998 to fund and manage a broad portfolio of emerging technologies, based upon science measurement objectives, for infusion into a range of future campaigns and missions. ESTO technology investments attempt to address the full science measurement process, from the instruments and components needed to make observations to the data systems and information products that make those observations useful.

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Since inception, ESTO has relied on open competition, a robust peer review process, and active project management to ensure that appropriate technologies are developed in a timely manner. Innovative ideas for advanced technology and instruments are solicited from the research community through regular, competitive, open solicitations. Until a consensus set of priority environmental measurements were developed by the National Research Council in its Decadal Survey report, funding priorities were based upon the measurement needs associated with six NASA Earth Science focus areas: Atmospheric Composition, Carbon Cycle and Ecosystems, Climate Variability, Earth Surface and Interior, Water and Energy Cycle, and Weather. Future measurement needs identified in NASA science roadmaps were translated into technology priorities, which became areas of emphasis in subsequent technology solicitations.

The Earth Science Technology program includes three distinct but related elements:

- **Advanced Component Technologies (ACT)—**provides component and subsystems technologies for instruments and platforms.
- **Instrument Incubator Program (IIP)—**provides new instrument and measurement techniques, including laboratory development and airborne validation.
- **Advanced Information Systems Technologies (AIST)—**provides innovative on-orbit and ground capabilities for the communication, processing, and management of remotely sensed data and the efficient generation of information.

Over the past twelve years, the Earth Science Technology Office has actively funded and developed hundreds of remote sensing technologies to support Earth science, including atmospheric, ocean surface, land surface, and ice and snow measurements. These remote sensing technologies include both active and passive optical and microwave systems. Many of these technology investments have led to complete, robust instruments; some are already flying on satellites and airborne platforms, or are otherwise deployed in science measurement campaigns. Additional investments support the advanced detectors, imagers, and other components critical to future remote sensing systems. All research tasks are summarized on the ESTO web site [1].

In 2007, the US National Research Council developed a consensus vision and priorities for future Earth science endeavors [2]. This Decadal Survey report advised, among other strategies, that costs and risks associated with future missions be reduced by “investing early in the technological challenges.” The study recommended a series of future remote sensing missions to obtain key environmental measurements.

The Earth Science Decadal Survey included a set of eighteen future remote sensing missions to obtain key environmental measurements. Fifteen of the missions were to be developed by NASA, and three were to be developed by the National Oceanic and Atmospheric Administration (NOAA) within the US Department of Commerce. The Climate Absolute Radiance and Refractivity Observatory mission has components to be developed by both NOAA and NASA.

The set of Decadal Survey missions for which NASA is responsible is shown in Figure 1. Many of the missions will require active sensing techniques, such as laser or radar instruments, and some will require combinations of active and passive measurement systems. Seven of the fifteen NASA missions will utilize active optical technology to make the required science measurements.

At the time the Decadal Survey was published, ESTO technology investments were already supporting many of the measurements to be made by the recommended notional missions. Immediately after publication of the Decadal Survey, ESTO made an additional 58 investments within its instruments, components, and information systems programs to further support and enable these measurement goals. A second round of investments in advanced instrument technologies has already taken place; additional awards for technology components and information systems are in progress. Figure 2 shows the applicability of each technology investment distributed across Decadal Survey missions.

The focus of ESTO oversight and review is successful infusion of these technology development awards into future missions, science campaigns and research experiments. With more than 500 completed technology investments and a current, active portfolio of nearly 100 projects, ESTO is driving innovation, enabling future Earth science measurements, and strengthening NASA’s reputation for developing leading edge technologies.

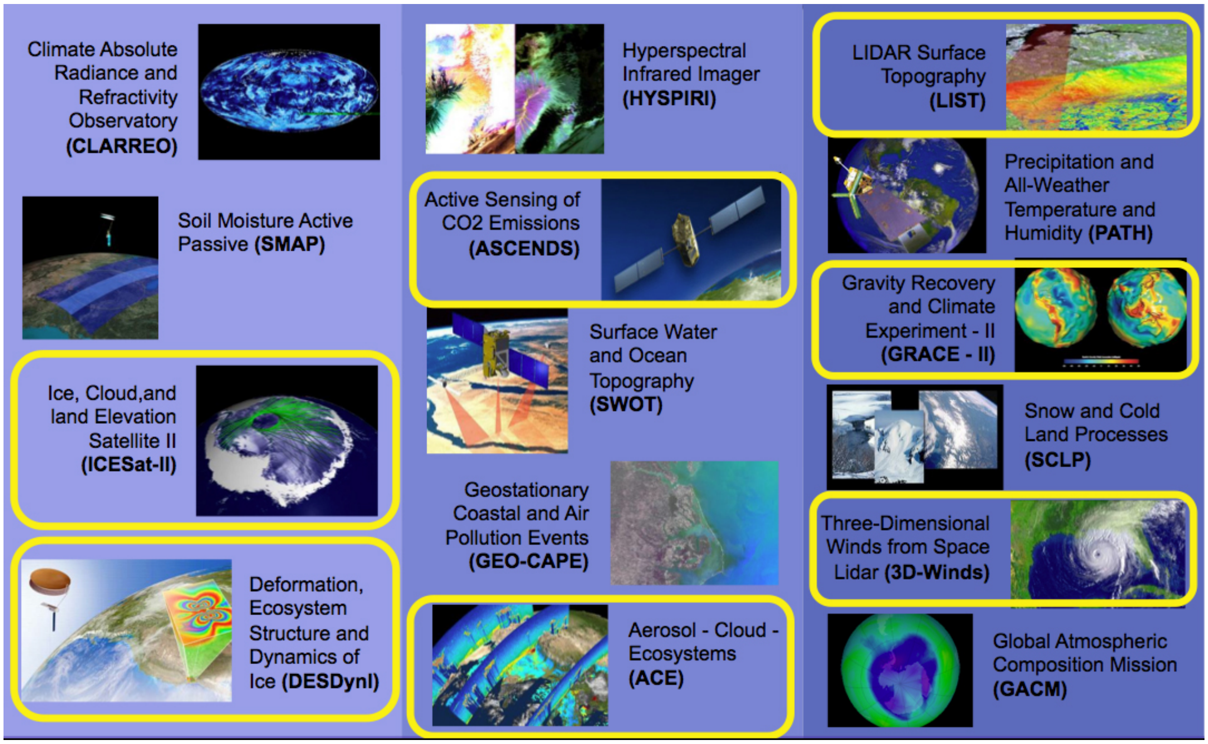

Figure 1. NASA Earth Science Decadal Survey Missions (missions using active optical techniques outlined).

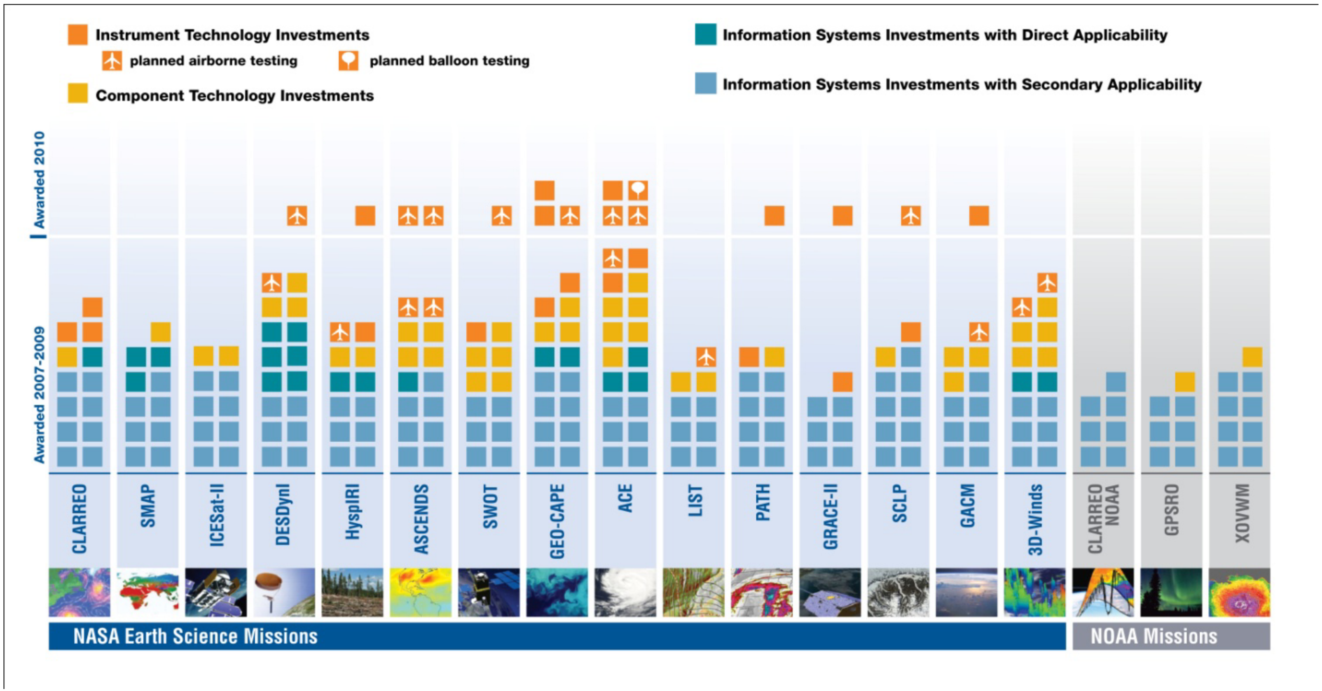

Figure 2. ESTO investments enabling the Earth Science Decadal Survey Missions. Each square is an individual investment in instruments (orange), components (yellow) or information technologies (blue). The squares across the center of the figure represent the investments made immediately after the Decadal Survey was released, and are shown in a column directly above the Decadal Survey mission upon which they focus. A second series of investment decisions is in process; the most recent instrument technology investments are shown in the top tier; investments planning to include airborne testing are shown with aircraft or balloon icons superimposed upon the relevant square.

3. REDUCING RISKS ASSOCIATED WITH LASER TECHNOLOGY

Between 2002 and 2009, NASA developed the Laser Risk Reduction Program (LRRP) in response to a major technology need for operational reliability in space. An external, multiagency Earth Science Independent Laser Review Panel had recommended that NASA intensively develop critical laser/lidar technology elements before mission approval: the LRRP program was created as the lead, non-classified, space-laser technology program for the United States government [3].

The LRRP program was organized to leverage expertise in 1-micron laser technologies at the NASA Goddard Space Flight Center and 2-micron laser capabilities at the NASA Langley Research Center; a number of industrial and academic partners also participated. The program specifically addressed the durability and long-term reliability issues of space-borne lasers, and included three basic areas of research: development of space qualified lasers, investigation of reliability issues and failure modes, and the development of ancillary hardware technologies for space-borne lidar systems.

The LRRP team investigated the root causes of failures in laser systems designed for space, and developed robust laser architectures that could be adapted to the specific requirements of future missions. As a result, significant advancements were realized in a range of key technologies:

- Laser architecture
- Laser materials and contamination control
- Pump diode packaging, testing, and lifetime
- Thermal engineering
- Radiation damage to laser materials
- Laser wavelength control
- Laser wavelength conversion

Results from the program have already delivered substantial benefits to NASA, by enabling the rapid development and deployment of the Lunar Orbiter Laser Altimeter (LOLA) instrument presently orbiting the moon on the Lunar Reconnaissance Orbiter mission. LRRP research advances are also expected to have significant impacts on mission reliability and cost reduction for several of the forthcoming Decadal Survey missions for the Earth Science community.

4. KEY MEASUREMENTS IN THE DECADAL SURVEY ERA

Active optical techniques may be used for a wide range of scientific measurements. Lidar allows day and night observation; the shorter wavelengths of laser light enable detection of molecules and aerosol particles. Almost half the missions identified by the Decadal Survey will include laser-based systems. Some of the measurements utilizing active optical techniques are discussed below, along with a few examples of relevant Earth Science Technology investments.

Aerosols. Studies of atmospheric composition require both the ability to characterize aerosols (optical thickness, size, and refractive index) and to understand aerosol transport. Several instrument systems are under development to better address these measurements. One, the Cloud-Aerosol Transport System (CATS) instrument, is a combination of a Doppler lidar and a high spectral resolution lidar. CATS will provide information about cloud and aerosol height, internal structure, and optical properties as well as derive wind motion, which enables studies of aerosol transport and cloud motion. The CATS instrument has recently been selected to fly on the NASA ER-2 aircraft.

Altimetry. Downward-looking active optical systems are important for a number of remote sensing measurements, including ice sheet mass, vegetation canopy, and topographic mapping. A team at the Goddard Space Flight Center [4] has developed an instrument using a single laser to generate multiple beams for high-resolution mapping. The system is a micropulse, photon-sensitive waveform recording system based on emerging laser transmitter and detector technologies.

Winds. Several systems are attempting to measure the profiles of wind speed by resolving the optical Doppler shift. The Optical Autocovariance Wind Lidar (OAWL) system uses a unique high resolution interferometric receiver and direct-detection to efficiently and accurately measure the profiles of wind speed by resolving the optical Doppler shift of aerosol backscatter from a pulsed laser at 355nm. Together with an etalon front end measuring the winds from molecular backscatter in clear air, the approach offers a single laser and wavelength architecture for measuring 3D-Winds profiling capability (aerosol and molecular backscatter winds). [5]

Ozone. Global ozone measurements are needed across the troposphere with high vertical resolution to enable comprehensive studies of continental and intercontinental atmospheric chemistry and dynamics. A compact ozone and aerosol lidar system is being developed to conduct global atmospheric investigations from the NASA Global Hawk Uninhabited Aerial Vehicle (UAV), and for enabling the development and test of a space-based ozone and aerosol lidar. The Global Ozone Lidar Demonstrator (GOLD) incorporates advanced technologies and designs to produce a compact, autonomously operating ozone and aerosol Differential Absorption Lidar (DIAL) system for a UAV platform. [6]

Vegetation Change. Interference and loss of data because of clouds is a significant problem for space-based lidars trying to make measurements near or at the Earth's surface. A new type of lidar – an electronically steerable flash lidar (ESFL) –produces three-dimensional views of forest and vegetation and provide estimates of biodiversity, carbon sequestration, distribution of foliage, and fuel for forest fires. The ESFL instrument, which utilizes multiple, independently steerable beams from a single laser, has recently been chosen to fly on the NASA Twin Otter aircraft to support additional Earth science campaigns. [7]

5. A SPECIFIC EXAMPLE: ACTIVE OPTICAL INVESTMENTS FOR CARBON DIOXIDE MEASUREMENTS

Several ESTO investments have been aimed at the goals of the Active Sensing of CO2 Emissions over Nights, Days, and Seasons (ASCENDS) mission of precise CO2 column measurements from space. No system has yet been able to make measurements at the accuracy levels required by the scientific community. Currently, ESTO investments fall into five general categories of potential approaches for measuring column CO2:

- 2.0 µm CW CO2 Laser Sounder (Menzies IIP-98, Phillips ACT-08)
- 1.6 µm Pulsed CO_2 Laser Sounder (Abshire ACT-99, IIP-04, IIP-07)
- 1.6 µm CW CO_2 Laser Sounder (Dobbs ACT-08)
- 2.0 µm Pulsed CO_2 DIAL (Ismail IIP-04, LRRP)
- A broadband lidar concept (Heaps IIP-08)

Sample progress on these systems is discussed below.

2.0 µm CW CO2 Laser Sounder. A team at the Jet Propulsion Laboratory have been evaluating the potential of a laser absorption spectrometer (LAS) to provide the high-accuracy CO2 mixing ratio measurements with the vertical and horizontal spatial resolution required for carbon cycle research. The LAS approach to global CO2 measurement utilizes cw illumination of the Earth's surface from orbit with subsequent analysis of the differentially attenuated multiwavelength surface backscatter signals to retrieve trace gas mixing ratios. Preferential weighting of selected altitudes within the total column is achieved by tuning the cw transmitter laser across a known, well-characterized pressure-broadened absorption line of the target species. Early experiments with an airborne LAS instrument in which discretely tunable laser sources were used demonstrated the utility of the technique to infer column-average mixing ratios of lower-tropospheric ozone. [8]

1.6 µm Pulsed CO_2 Laser Sounder. A team of researchers at the Goddard Space Flight Center [9] utilized a differential absorption lidar (DIAL) technique, using pulsed laser light operating on a selected CO2 absorption line in the 1572 nm band, and on a pair of O2 absorption lines near 765 nm in the Oxygen A-band. The DIAL technique is based on transmitting two wavelengths: an "on-line" wavelength that is absorbed by the gas of interest (in this case CO2 and O2 respectively) and an "off-line" wavelength that is not absorbed. The differential absorption between the two wavelengths (ratio of the measured backscattered energy) is a measure of the concentration of the gas in the path. The team has successfully developed a highly stable erbium doped fiber laser transmitter with 1 MHz frequency stability and demonstrated a photon counting detector at 1572 nm with a signal-to-noise ratio (SNR) of ~2400:1. In addition to developing these key technologies, the team also conducted laboratory demonstrations, ground-based field deployments, and engineering and science airborne test flights of the CO2 Laser Sounder instrument aboard the Lear-25 aircraft operated by the NASA Glenn Research Center.

1.6 µm CW CO_2 Laser Sounder. Researchers at ITT developed a lidar system using fiber laser technology, to demonstrate the applicability of modulation-coded continuous wave (cw) transmitter approaches as a viable alternative to the more common pulsed transmitter schemes, and to successfully complete airborne field trials of the instrument. Although the primary application identified for the prototype system was 3-D topographic mapping of ice sheets, the intent was to craft an instrument with modal flexibility such that it might also be used for 3-D topography of land and profiling of atmospherically entrained aerosol/cloud populations.

2.0 µm Pulsed CO_2 DIAL. Syed Ismail and colleagues at the NASA Langley Research Center developed a pulsed two-micron laser lidar system to provide detailed CO2 profiles over the most sensitive (0-5 km) region of the atmosphere while providing simultaneous aerosol and cloud distribution data. Advances in the 2-micron laser wavelength selection and stability allow precise interrogation of the CO2 feature around 2.053 microns, a line chosen for its absorption cross-section and relative freedom from water vapor interference. Significant improvements have also been made in the lidar receiver, with an optical redesign demonstrating a high S/N ratio from aerosol backscatter. Following a system performance check against in-situ sensors performed at Langley, the two-micron CO2 lidar team participated in a summer validation field deployment, coordinated by researchers at Penn State University, at a field test site in West Branch, Iowa. The testing was validated against in situ sensors on the tower as well as spiral overflights by NOAA CO2 research aircraft. [10]

Broadband Lidar Concept. William Heaps (GSFC) is developing an airborne laser measurement system for measuring CO2 changes in the lower atmosphere employing a newly available superluminescent light emitting diode (SLED) as the laser source, with an optical parametric amplifier (OPA) for laser amplification and a Fabry-Perot interferometer as its receiver. Using this approach, the goal of this effort is to reduce the number of individual lasers used in the system to a single laser and place much of the responsibility for wavelength control on the detector rather than the laser [11].

5. CONCLUSIONS

ESTO investments have, for several years, been mitigating the risk of nearly all the measurements recommended by the Earth Science Decadal Survey. In a few cases, including several active optical measurements such as those required by the ASCENDS mission, ESTO investments are enabling the conceptualization of the measurement recommendations. This is a testament to the best practices for technology development: competitive, peer-reviewed solicitations; active technology management; and broad-based, inclusive strategic planning. ESTO continues to monitor, and match investments to, the evolving needs of Earth science through engagement with the science community, development of technology requirements, and strategic planning for long-term investments. ESTO will continue to support these Earth science measurements with new investments and evolving state-of-the-art alternatives.

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