Enabling Laser and Lidar Technologies for NASA's Science and Exploration Mission's Applications

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Abstract – **NASA's Laser Risk Reduction Program, begun in 2002, has achieved many technology advances in only 3.5 years. The recent selection of several lidar proposals for Science and Exploration applications indicates that the LRRP goal of enabling future space-based missions by lowering the technology risk has already begun to be met.**

I. INTRODUCTION

NASA entered a new era in the 1990's with the approval of several space-based remote sensing missions employing laser radar (lidar) techniques. Following the steps of passive remote sensing and then active radar remote sensing, lidar (light detection and ranging) sensors were a logical next step, providing independence from natural light sources, and better spatial resolution and smaller sensor size than radar sensors. The shorter electromagnetic wavelengths of laser light also allowed signal reflectance from air molecules and aerosol particles. The smaller receiver apertures allowed the concept of scanning the sensor field of view. However, technical problems with MOLA I, LITE, MOLA II, VCL, and SPARCLE during that decade led to concern at NASA about the risk of lidar missions. An external panel was convened to make recommendations to NASA. Their report in 2000 strongly advocated that NASA maintain in-house laser and lidar capability, and that NASA should work to lower the technology risk for all future lidar missions. NASA then formed an Integrated NASA Lidar Systems Strategy Team (INLSST), chaired by U. N. Singh at LaRC and W. S. Heaps at GSFC, to make specific recommendations for implementing the external panel's advice. Their plan for a NASA Laser Risk Reduction Program (LRRP), to be lead by LaRC and GSFC with participation and collaboration from industry and academia, was approved by NASA's Administrator in June 2001. Funding of the LRRP began in 2002.

II. THE LRRP CONCEPT

The LRRP implemented the recommendations to work on lidar technologies before mission approval and to

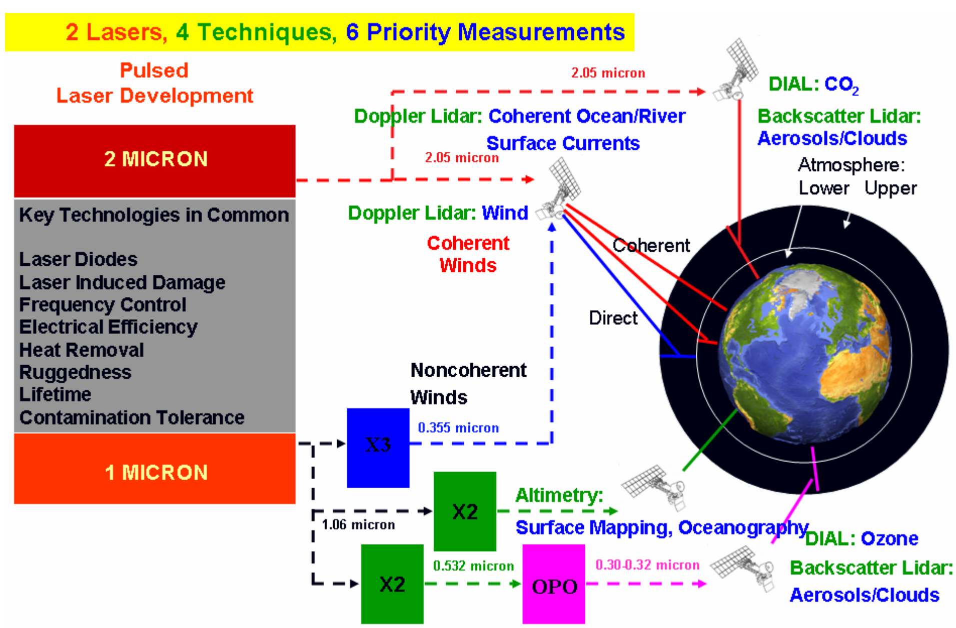

Figure 1. Connection between technology development and 6 priority measurements

maintain in-house capability by using the strengths in 1-micron solid-state lasers at GSFC and the strengths in 2-micron solid-state lasers at LaRC to work on fundamental issues concerning these two laser technologies, as listed on the left side of Figure 1. With additional work on wavelength conversion technologies, the four lidar techniques of altimetry, Doppler, Differential Absorption Lidar (DIAL), and basic lidar backscattered signal strength profiling would be able to make 6 high priority earth science measurements: surface and ice mapping, horizontal vector wind profiles, river currents, CO_2 profiles, O_3 profiles, and aerosols/clouds. Figure 2 depicts the enabled lidar techniques and measurements. Through collaboration and communication between LaRC and GSFC of questions, capabilities, and results, the advancement of the commonly needed areas of laser and wavelength conversion development would proceed faster and without duplicated effort. The goal of the LRRP is to advance the technologies to the point that science mission proposals could be confident of acceptable risk upon selection.

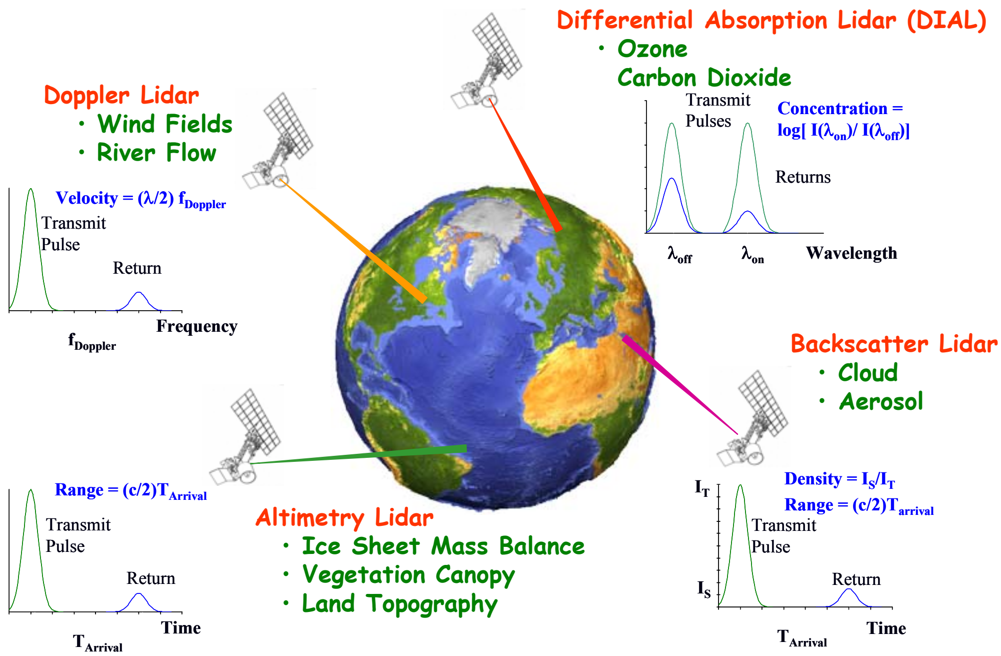

Figure 2. Depiction of four techniques of lidar remote sensing using two lidar technologies

III. LRRP TASKS AT LARC

The main thrust of the LRRP effort at LaRC has been the development and risk reduction of the solid-state, diode-pumped, 2-micron pulsed laser. The Ho:Tm:LuLF based laser will enable the measurement of wind, CO_2, aerosols, clouds, and river flow. LaRC is the world leader in high pulse-energy 2-micron laser technology. However, the laser needed development in the areas of pulse energy, beam quality, heat removal, efficiency, and packaging. Another thrust at LaRC has been the laser diode arrays that are used to pump the 2-micron laser. The external panel, as well as NASA engineers, were very concerned about the lack of several commercial vendors providing space qualified LDAs, and the ability of the LDAs to have long life in space. This concern has been validated by the technical problems with the LDAs that occurred after launch of the ICESAT mission in 2003. Both LaRC and GSFC have been working on LDAs in parallel, with emphases on the specific LDAs needed to pump the 2 and 1 micron laser, respectively. A third LaRC thrust has been in technologies to convert the 1 micron photons of the Nd:YAG laser to UV wavelengths needed for the DIAL measurement of ozone. Efficient and reliable conversion to pulse energies near 200 mJ with small components is desired. This task also was shared by LaRC and GSFC, with LaRC concentrating on high pulse energy techniques, and GSFC concentrating on high pulse repetition frequency techniques. An additional LRRP task at LaRC involved advancement of the receiver technologies for both coherent and direct detection lidar remote sensing at 2 microns. Any improvement in the detection efficiency allows either better measurement sensitivity with the same size laser and receiver mirror, or the same measurement sensitivity with a smaller laser and/or mirror. Since the laser and mirror sizes translate into cost, power, mass, volume, and heat removal; improved detection efficiency translates into a large mission benefit. Table 1 shows a summary of the LRRP thrusts at LaRC.

Table 1. LRRP Thrust Areas at LaRC

Thrust Area	Areas of Risk Reduction	Enabled Measurements
Pulsed Laser	Pulse energy Heat removal Efficiency Beam quality Damage Contamination Lifetime Packaging	Earth: Wind, CO_2, Aerosols, Clouds Mars: Wind, Density, Dust
Pump Laser Diode Arrays	Materials Architecture Lifetime Space qualification Availability	All 2 micron laser measurements above
Wavelength Conversion to UV	Efficiency Pulse energy Damage Lifetime	Ozone, Aerosols, Clouds
2-Micron Direct Detector	Responsivity Noise Active area	Direct detection CO_2, Aerosols, Clouds
2-Micron Coherent Receiver	Quantum efficiency Packaging	Earth: Wind, CO_2, Aerosols, Clouds Mars: Wind, Density, Dust

Space only permits a sampling of the accomplishments to be mentioned here.

IV. SELECTED ACCOMPLISHMENTS

There has been a lot of hard work and many outstanding accomplishments to date by the outstanding LaRC team of technicians, engineers, and scientists involved with LRRP.

Pulsed Laser

The 2-micron laser activity which has been carried on under the LRRP builds on the coherent detection lidar technology developed for the SPARCLE (SPAce Readiness Coherent Lidar Experiment) Shuttle mission to measure winds. At that time, 100 mJ of single-mode 2-micron pulse energy was the state-of-the-art [1]. Since then a new laser material with a 20% efficiency improvement over prior art has been formulated and demonstrated [2-4], exceeding 1 J pulse energy in a single pulse and 1.5 J in a double pulse in recent tests [5-6]. Besides high energy and efficiency, another key requirement for space is conduction only cooling (as opposed to liquid cooling) of the laser structure. An all conductively-cooled laser architecture was recently demonstrated with more than ~100 mJ pulse energy and near diffraction limited beam quality [7].

Serendipitously, there is a very strong carbon dioxide (CO_2) absorption line within the tuning range of this 2-micron laser and this presents the opportunity to simultaneously measure CO_2 along with wind, aerosols, dust, etc. The temperature profile can be obtained also by using both temperature independent and temperature dependent CO_2 absorption lines. By transmitting both an on- and an off-resonant laser wavelength, the DIAL technique can measure CO_2 concentration profiles.

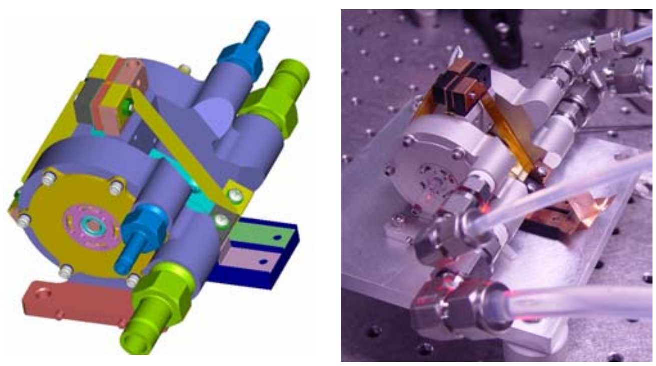

Figure 3. Drawing and photograph of the diode-pumped laser oscillator head

Several steps towards such a multi-use lidar application have already been accomplished. Frequency control and locking of the laser wavelength to the CO_2 absorption line has been demonstrated [8-10]. Double pulse operation of the 2-micron laser has been accomplished, which extracts more optical energy from the laser, thus raising efficiency, and opening the possibility of obtaining both DIAL laser wavelengths from each laser firing [11]. Recently, a DIAL measurement of CO_2 was performed with the resonant and off-resonant DIAL wavelengths alternated at a 5-Hz rate, thus simulating the advantages of the double pulse laser technique. Since this technique greatly reduces the error from atmospheric fluctuations, a best ever precision of 1.5% for a CO_2

measurement was produced, though from a static platform [12]. Since CO_2 comprises ~95% of the Martian atmosphere its measurement can be used to infer density profiles. The Martian troposphere is 40 km in depth and the altitude variations of CO_2 could exceed two orders of magnitude. The strength of the 2-micron absorption lines in CO_2 permits the use of off-line center DIAL techniques, leading to much greater dynamic range of the measurement, so that vertical profiling of density is possible through a significant portion of the atmospheric column.

Current activities on the pulsed laser include completion of an all-conductively-cooled amplifier, phase conjugate mirror development for improved beam quality of the amplifier output, and compact, rugged packaging.

Pump Laser Diode Arrays

As indicated in Table 1, the pump laser diode arrays (LDA) are crucial to successfully utilizing the solid-state pulsed laser technology in space. Several of NASA's space lidar missions have had trouble with the LDAs, most recently the ICESat mission. Recently, it was learned that the upcoming European Space Agency (ESA) Atmospheric Dynamics Mission (ADM) is also having technical problems with the LDAs. These missions all employ 1-micron lasers. The pulse duration needed to pump the 2-micron laser is 7 times longer than needed by the 1-micron laser, thereby increasing the LDA thermal transients and possibly decreasing lifetime. Both LDA Characterization and Lifetime Test Facilities have been designed, assembled, and put into intensive service. The lifetime facility can test up to 12 LDAs simultaneously. The experience at GSFC in setting up

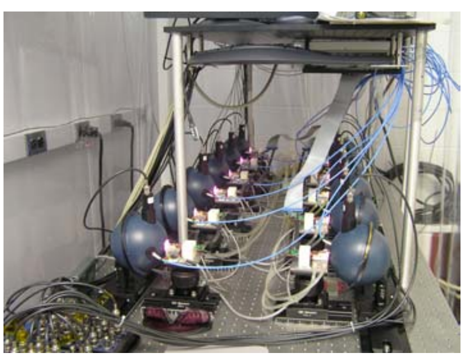

Figure 4. LDA lifetime test facility at LaRC

similar facilities was leveraged by LaRC. LaRC has also worked heavily with industry to discuss the characterization and lifetime results of current LDAs, and to discuss ways to improve the LDAs [13]. Failure mechanisms being considered include laser bar material defect, thermal cycling, solder creep/migration, solder de-bonding, and bond wire failure. An improved LDA architecture using diamond in the LDA package in place of the standard BeO/Cu was developed by teaming with Northrup Grumman/CEO. Test show that the thermal resistance has been reduced by 17%, which should translate into a large improvement in lifetime.

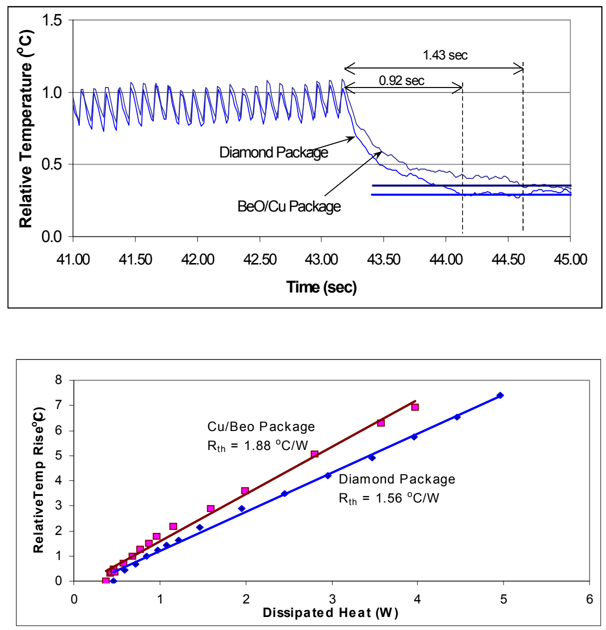

Figure 5. LDA data showing reduced thermal resistance

Wavelength Conversion to UV

The LaRC approach for generating the two UV wavelength (308 & 320 nm) laser pulses necessary to profile ozone concentration is to use Optical Parametric Oscillator (OPO) and Sum Frequency Generation (SFG) nonlinear optics technologies. LaRC has teamed with Sandia National Lab and Fibertek to accomplish this. Fibertek is fabricating a > 1J Nd:YAG laser for LaRC with the strict beam qualities needed to pump the nonlinear optical processes. Sandia has perfected models of the nonlinear processes and used these models to invent a novel OPO architecture (see Figure 6), and to provide guidance for the overall UV generation system. Up to 190 mJ pulse energy at 320 nm has already been demonstrated. Integration and demonstration of the components is planned at LaRC.

V. LRRP TECHNOLOGY SPINOFFS

Figure 7 depicts how the technologies being developed at LaRC and GSFC by the LRRP plus some additional lidar technologies may be combined to enable several measurements desired by NASA's Science Mission Directorate (SMD) and Exploration Systems Mission Directorate (ESMD). Not shown in the figure are many applications for other US Agencies, such as NOAA, DOD, EPA, Homeland Security, etc. During FY04, LaRC and GSFC teamed on a proposal to the ESMD. LaRC proposed to apply the 2-micron laser technology, and the coherent detection wind measurement and CO_2 measurement techniques for demonstrating a prototype Mars Orbiter Lidar for obtaining wind, density, and dust climatologies of Mars. This proposal was selected. Also during FY04, the SMD requested Instrument Incubator Program (IIP) proposals to advance technology in the TRL 3-5 range. Of the 5 proposals selected from LaRC, 4 proposals received assistance from the LRRP technology development at LaRC and GSFC. A tropospheric wind proposal benefited from the LRRP effort at LaRC on the 2-micron laser, the LDAs, and the heterodyne receiver. A CO_2 proposal benefited from the advancement at LaRC of the same laser and LDAs, and also from the direct detection detector advancement and

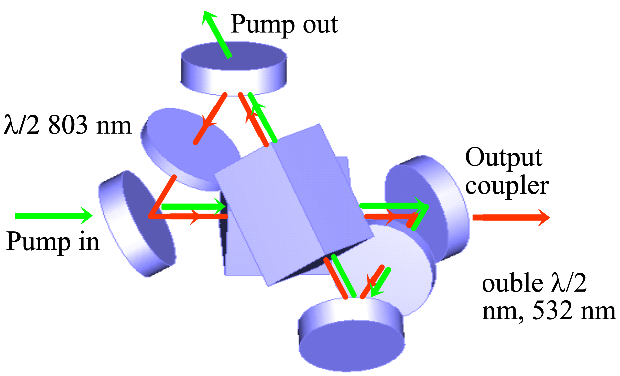

Figure 6. Novel OPO arrangement invented at Sandia

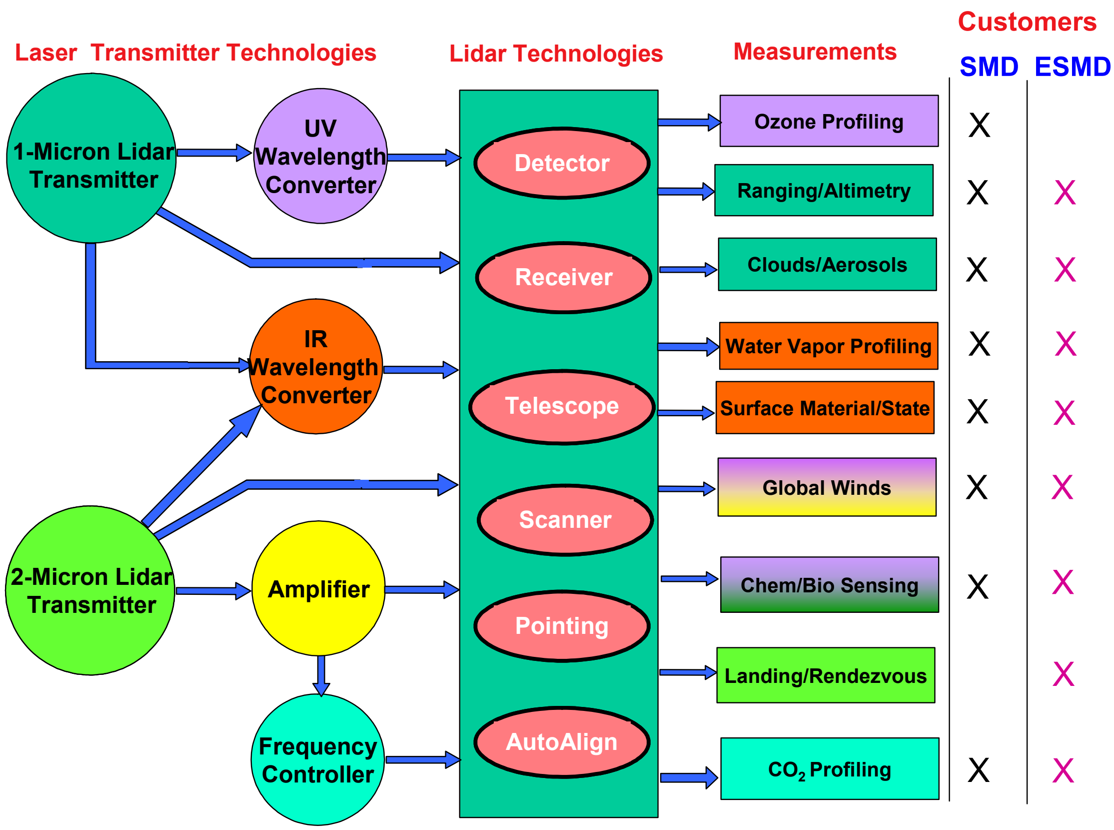

Figure 7. Flow of LRRP technologies to NASA's desired measurements

the CO_2 measurement demonstrations. Two selected IIP proposals at LaRC are for ozone measurement. One benefited from the wavelength conversion to UV activities at LaRC, and the other benefited from the complementary activities at GSFC.

VI. CONCLUSIONS

NASA responded to concerns about the perceived risks of future space-based lidar missions by commissioning an external review panel. The panel made excellent recommendations which NASA implemented through the LRRP. The collaboration between LaRC, GSFC, industry and academia has proved to work well, and the LRRP activities have been shown to be very valuable. Several proposals have already been selected which benefited from LRRP advances. Continuation of the LRRP for a few more years would permit many activities, such as the LDA improvement, space qualification, and availability task, and the radiation and contamination tasks, to take advantage of the teams and laboratories in place to provide a large benefit to NASA for a small cost.

VII. ACKNOWLEDGEMENTS

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