

# History of Laser Remote Sensing, Laser Radar, and Lidar

Dennis K. Killinger

Lidar and remote sensing grew from developments in optical spectroscopy, optical instrumentation, and electronics in the 1930s to 1950s. Starting in 1930, searchlights were directed upward and atmospheric scattering was measured with a separately located telescope. Starting in 1938, pulsed electric sparks and flashlamps were used in searchlights to measure cloud base heights. Middleton and Spilhaus introduced the term LIDAR (for Light Detection and Ranging) in 1953.

The laser revolutionized lidar and launched laser remote sensing. In 1962 Louis Smullen of MIT and visiting scientist Giorgio Fiocco (who had worked on radar at Marconi) detected backreflection from the Moon using 50-J, 0.5-ms pulses from a Raytheon ruby laser transmitted through a 12-inch telescope together with a 48-inch receiving telescope and a liquid-nitrogen cooled photomultiplier at MIT Lincoln Laboratory. (See Fig. 1.) The signal that returned after 2.5 s was very weak, including only about 12 photons, and had to be recorded by photographing a double-beam oscilloscope trace using “vast amounts of Polaroid film and time.” The project was called “Luna-See,” probably reflecting its difficulty. The following year a newly invented rotating mirror Q-switch shortened a 0.5-J ruby pulse to 50 ns for a series of lidar studies of the upper atmosphere. The first use of the term lidar referring to such a laser radar system was used by Goyer and Watson in 1963 and by Ligda in 1964.

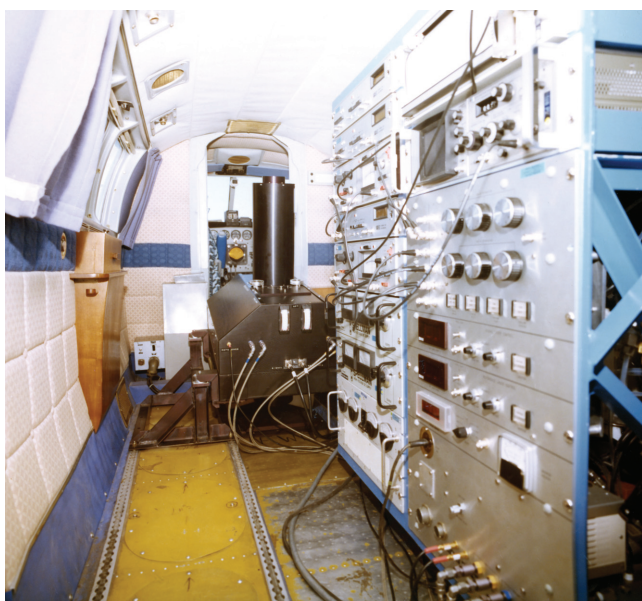
During the next decade advances in laser technology drove improvements in laser remote sensing. Richard Schotland in 1964 detected the concentration of a gas in the atmosphere for the first time by temperature-tuning the wavelength of a ruby laser across a water vapor absorption line. This was the first Differential-Absorption Lidar (DIAL) system.

Other groups went on to detect other species. After a detailed theoretical analysis of lidar techniques by Byer and Kildal in 1971, Hinkley and Kelley showed experimental detection of air pollutants using tunable diode lasers in 1971, and Byer and Garbuny detailed DIAL requirements for pollution detection in 1973. Karl Rothe and Herbert Walther’s group in Germany used DIAL with tunable dye lasers to detect NO<sub>2</sub> and in 1974–1976 Ed Murray, Bill Grant, and colleagues at SRI detected the gas with a tunable CO<sub>2</sub> laser. Menzies and Hinkley in 1978 measured atmospheric gases with a laser absorption spectrometer (LAS), two waveguide CO<sub>2</sub> lasers, and stripchart recorders mounted in a plane (see Fig. 2). In 1979, they measured atmospheric gases with the balloon-borne Laser Heterodyne Radiometer shown in Fig. 3. Sune Svanberg’s group at the Lund Institute mapped the mercury emission from coal-fired power plants in a seminal DIAL study in the 1980s, Jack Bufton at NASA Goddard measured atmospheric CO<sub>2</sub> in 1983, Ed Browell at NASA Langley measured water vapor and ozone in the atmosphere and the flow of Sahara Desert dust from Africa to the Southeast United States, and Nobuo Sugimoto and Kazuhiro Asai’s group measured similar Asian dust flow.

DIAL also performed landmark environmental observations. In 1993, Bill Heaps’ group at NASA Goddard and Stuart McDermid’s group at JPL tracked variations of stratospheric ozone levels in time and space for the first time, validating data suggesting an “ozone hole” collected by solar occultation instruments on NASA satellites in the 1980s. The satellite sensors had detected the hole years earlier but had not transmitted the data to the ground because the software considered the measured ozone levels too low to be accurate. The problem was



▲ **Fig. 1.** Photo of “Luna-See,” the first laser radar measurement of a laser beam backscattered from the Moon (white speck at the upper left) in May 1962 at Lincoln Laboratory by MIT Prof. Louise Smullen (left), Raytheon laser scientist Dr. Stanley Kass (middle), and visiting radar scientist Dr. Giorgio Fiocco (right). (Courtesy MIT Museum.)



▲ **Fig. 2.** Photo of 1978 JPL laser absorption spectrometer (LAS) lidar system mounted in a Beechcraft Queen Air aircraft. (Courtesy of R. Menzies, JPL.)

corrected by programing the satellite to transmit raw data for observations on and off the absorption line instead of just the ratio of the two.

The advent of tunable quantum cascade lasers, tunable optical parametric oscillators, and tunable solid-state and semiconductor lasers now have made DIAL measurements of atmospheric gases almost routine. DIAL instruments regularly monitor methane and CO<sub>2</sub> emissions to the atmosphere and measure ammonia and other gases for industrial process control. That’s a big advance from the 1960s, when ozone and smog levels in Los Angeles were monitored by timing the deterioration of a rubber band placed outside a window and stretched by a small weight.

John Reagan’s group at the University of Arizona began lidar mapping of atmospheric aerosols in the late 1960s, and others built on their effort. Pat McCormick and David Winker of NASA Langley flew

one of the first lidars in space, the Laser In space Technology Experiment (LITE) in 1994 on Space Shuttle mission STS-64, which mapped cloud-top heights and range-resolved distributions on a global scale. Lidar also proved valuable in observing particulates injected into the stratosphere by volcanic eruptions, which take about six months to mix with the atmosphere and remain airborne for about five years.

Hard-target lidar trackers and range finders were developed especially for military applications, with significant progress made by Al Jelalian's group at Raytheon, and Ingmar Renhorn and Ove Steinvall at the Sweden NDRI. Al Gschwendtner's group at MIT Lincoln Lab developed a high-speed imaging heterodyne Doppler lidar that could take full-view Doppler range-resolved images at a 30-Hz frame rate. Those heterodyne systems led to lidars with much higher pulse rates for scanning and mapping hard targets and terrain. Alan Carswell of the University of

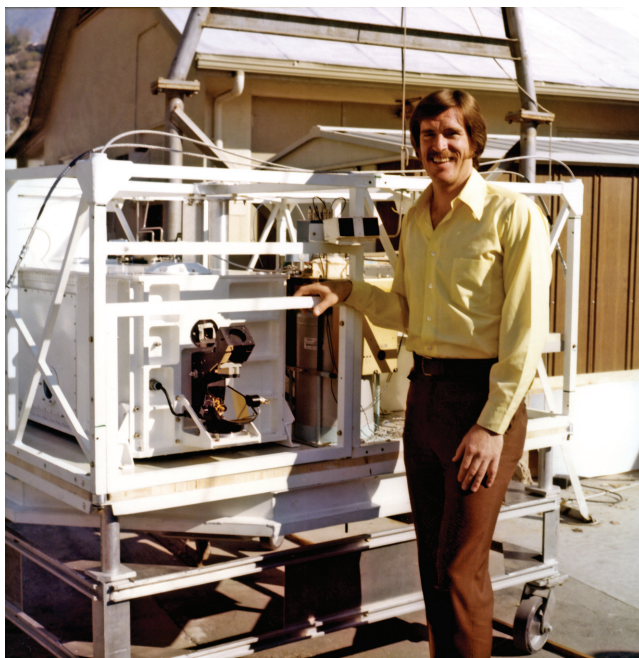
Toronto founded the Optech Corp., which developed suitcase-sized imaging lidar scanners that fire 200,000 pulses per second. Linked to a precision GPS network, these systems have compiled detailed 3D maps of urban buildings and discovered and mapped Mayan ruins hidden under jungle canopies using a foliage-penetrating lidar. Such precision mapping lidars have been so successful that they now perform most detailed geographical coordinate measurements. Another sign of their importance is that NIST has established a standards group for lidar mapping.

Laser-induced fluorescence (LIF) also can detect important species in the atmosphere. Doug Davis and Bill Heaps at Georgia Tech, Charlie Wang's group at the Ford Scientific Research Center, and the author in 1975 were the first to detect the OH free radical under ambient conditions at a concentration of 0.01 parts per trillion. OH is important as the major rate controller for chemical reactions that deplete ozone in the upper atmosphere.

Large flashlamp-pumped dye lasers often were used to produce frequency-doubled pulses near 282.5 nm, and operating them could be interesting. The large dye lasers quickly photobleached the dye, so 55-gallon drums of pure ethanol were used to extend the lifetime of the circulating solvent. Federal tax had to be paid on the pure drinking alcohol—about \$2000 a barrel—which was returned after dye was added and the liquid disposed of to show it had not been drunk. Recirculating the dye-alcohol solution stabilized fluid temperature, but the coaxial flashlamps had limited lifetimes and would explode after a few hundred hours. The Ford group had put the dye-alcohol pump downside of the flashlamp, so when the lamp exploded the pump just sucked in air. Unfortunately, Bell Labs had placed the dye-alcohol pump in front of the flashlamp, so it sprayed alcohol into the exploding flashlamp, causing a major fire. The arrangement was reversed in later laser designs.

In 1980, Jim Anderson of Harvard conducted a series of high-altitude balloon-borne laser measurements that confirmed the key roles of stratospheric OH and Freon in ozone depletion. Bill Heaps' group at NASA Goddard conducted similar measurements with a balloon-borne laser spectrometer, but in one case the parachute failed to deploy upon descent, creating what Heaps called the world's first "Lidar Pancake."

LIF lidar also studied the tenuous sodium layer that surrounds the Earth at an elevation near 90 km. Early lidar studies in 1972 by Gibson and Sandford, and in 1978 by Marie Chanin's group in



▲ Fig. 3. Photo of Bob Menzies and JPL laser heterodyne radiometer balloon instrument sitting in its gondola frame in 1979. (Courtesy of R. Menzies, JPL.)



France, measured sodium levels with a tunable yellow dye laser. They also observed gravity or breathing waves of the upper atmosphere, dynamic waves that travel around the world. Separate studies by L. Thomas' group in 1979, Chet Gardner's group at the University of Illinois in 1990, and C. Y. She's group in 1992 at Colorado State University showed that LIF excitation of the sodium layer could provide a beacon or "guide star" for adaptive optics compensation of atmospheric turbulence in ground telescopes. Most large ground-based telescopes now use laser-produced guide stars together with compensating optics to remove turbulence effects in milliseconds.

Lidar observations of the small Doppler shift in backscattered light arising from target velocity are challenging but can yield valuable results. In 1970, Milt Huffaker used a laser-Doppler system to detect aircraft trailing vortices. In the early 1980s, Freeman Hall and Mike Hardesty's group at NOAA and Christian Werner's group at DFVLR/Germany developed a coherent CO<sub>2</sub> laser system that mapped range-resolved wind-speed profiles near airports and within boundary flow geometries. Later, Sammy Henderson and Huffaker's group at Coherent Technologies Inc. developed coherent lidars based on solid-state laser systems near 2 μm. Direct-detection lidars developed during the past decade can also measure Doppler-shifted returns in ways that complement the coherent measurements. Now fiber-laser-based coherent Doppler lidars are mapping wind fields around wind turbines to increase efficiency of the blade pitch and direction.

Laser-induced-breakdown spectroscopy (LIBS) has also shown promise in the past decade for detecting chemicals at ranges from less than a meter out to a few hundred meters. Focusing a 0.1-J, 5-ns pulse through a telescope can produce dielectric breakdown in the air, yielding identifiable lines of atomic and ionized species in the plasma. It is a long way from the 3500-J, 1-μs CO<sub>2</sub> pulses Vladimir Zuev of the Tomsk Laser Institute in Siberia used to produce a plasma spark 2 km from the laser—earning him a semi-serious prize at the 1986 International Laser Radar Conference in Toronto for having made the world's longest cigarette lighter.

Conferences and workshops have played a vital role in the development of lidar and laser remote sensing. Much early and fundamental research was reported at Optical Society (OSA) Annual Meetings and March American Physical Society meetings in the 1960s, and at early CLEA/CLEO/CLEOS conferences in the 1970s. The International Symposium on Remote Sensing of Environment, first held in Ann Arbor in 1962, continues through today with an emphasis on passive satellite sensing.

One of the earliest conferences devoted to lidar was the 1968 Conference on Laser Radar Studies of the Atmosphere in Boulder, Colorado, chaired by Vernon Derr. It continues today as the International Laser Radar Conference (ILRC), run by the International Coordination Group on Laser Atmospheric Studies (ICLAS). One of the first conferences to look at the wide range of lidar techniques for species detection was the Workshop on Optical and Laser Remote Sensing, sponsored by the Army Research Office (ARO) in Monterey, California, in 1982 and chaired by Aram Mooradian and the author; Fig. 4 shows some attendees. An outgrowth of this was OSA's Topical Meeting on Optical Techniques for Remote Probing of the Atmosphere, first held in Incline Village/Lake Tahoe in 1983 and held biannually for the next several decades, sometimes changing emphasis and name. The Coherent Laser Radar Conference held first in 1980 in Aspen, Colorado, by Milt Huffaker is still going strong today with the most recent meetings in Barcelona, Spain, in 2013 and Boulder in 2015.

For the past five decades, laser remote sensing and lidar has been an outstanding and rewarding research career, often following the growth and expansion of the laser industry. It has seen the development of many worldwide collaborations among lidar colleagues and friends. Figures 5 and 6 shows a "lidar banquet dinner" at the 1994 17th International Laser Radar Conference in Sendai, Japan, with all participants obviously enjoying themselves.

Laser remote sensing has benefitted from the development of new lasers and improvements in their ease of use, compactness, cost, and reliability. Lidar systems in the 1970s occupied one or two optical tables, had laser lifetimes of hours, and relied on computer data acquisition systems operating at megahertz speeds. Over the past decade, lidar systems have started to use \$10 tunable LEDs, 10 GHz computers on a chip, and mini-spectrometers—shrinking systems so that portable suitcase systems are now routine.

Further reductions in size and cost are expected in the future. (Can we dream of tunable quantum cascade lasers for \$100?) Metamaterials and quantum-confined photonics will impact lasers and



▲ Fig. 4. Some attendees at the 1982 ARO Workshop on Optical and Laser Remote Sensing in Monterey, Calif. L-R: Dennis Killinger, Charles C. Wang, Gil Davidson, Paul Kelley, Norman Menyuk, and Phil Russell.



▲ Fig. 5. Good lidar friends attending a banquet dinner at the 17th International Laser Radar Conference in Sendai, Japan in 1994. (Left to right) bottom: Takao Kobayashi, Pat McCormick, Chet Gardner, Dennis Killinger, Jack Bufton; top: Akio Nomura, Osamu Uchino, Hiromasa Ito, Yasuhiro Sasano, Kazuhiro Asai, Toshikazu Itabe.





▲ Fig. 6. Humio Inaba, Rod Freulich, Jack Bufton, Kin Pui Chan, Mike Hardesty, and Dennis Killinger at 17th ILRC in Sendai, Japan, 1994.

detection techniques such as femtosecond absorption spectroscopy. It is hard to predict the future, but it is certain that major technical improvements will occur...they always have. As the technology continues to improve and laser remote sensing and lidar techniques become more widely accepted, we will find uses for lidar in applications not yet imagined.

It is sobering to recall that 40 years ago we thought that the main use of lidar and laser remote sensing was going to be akin to *Star Trek* where Spock scans the distant planet surface with a “laser” beam and tells the Captain that there are two humanoids on the planet’s surface and one has a bad kidney. Who would have guessed back then that one of the huge commercial successes for lidar today would be mapping of urban buildings and geological features, finding buried Mayan ruins, mapping wind fields for wind farms, detecting and mapping global climate change gases and pollutants in the atmosphere, and laser sensing of pharmaceuticals and chemicals at close ranges.