A REVIEW AND OUTLOOK FOR LIDAR SCIENCE INCLUDING SPACE PROGRAMS

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Abstract

Two long-duration Rayleigh/ Mie or aerosol/cloud lidars are now in Earth orbit, a winds lidar is being prepared for Earth orbiting in 2008, an aerosol/ cloud lidar is being built for Mars-based surface zenith measurements to be launched in 2008, and a laser altimeter system is on its way to orbiting Mercury. Lidars are routinely flying aboard aircraft for various studies like the characterization of the ozone hole, PSCs or volcanic clouds. They are an integral part of the instrument complement for these missions. Lidar networks are now a crucial part of regional weather and air quality forecasts. Raman (rational and vibrational), DIAL, multi-wavelength, and even hyperspectral lidars are now being used routinely. Even weblogs (or blogs for short) that show daily lidar and meteorological data are now common place. Bathymetry lidars are being used routinely from aircraft and low energy laser altimeters are being used to ‘paint’ very accurately the outlines of various targets from aircraft or ground platforms.

This paper will present a review of lidar from its earliest developments in the 1960s to the present time. It will incorporate data applications to illustrate the steady progress and the important place lidar has become in today’s remote sensing research. The paper will finish with a look into the future.

1. Introduction and History

In England in February 1935, a radar (for Radio Detection and Ranging) was first shown to work as a device to detect and range to aircraft by Robert Watson-Watt. In the 1950s many researchers were working on “optical masers” (as the laser was then called). Theoretical work was done by Schwalow and Townes who demonstrated the possibility of creating an amplifier of radiation similar to ones built earlier in the 1950s for microwaves. In 1959, G. Gould applied for a patent on the design principles for such a device and coined the phrase “Light Amplification by Stimulated Emission of Radiation”, or LASER. However it was T.H Maiman who on May 16, 1960, pumped with a flash lamp a ruby bar whose two faces were polished to act as a resonator and produced for the first time a coherent radiation source emitting in the visible part of the spectrum. He submitted a paper to the Physical Review Letters on these results, but it was turned down. Then he submitted his results to Nature who published it in their August 6, 1960 issue. Shortly after Maiman’s original finding the technique of “Q- switching” was introduced whereby the output pulse length was further shortened, producing millions of watts. Laser technology began its journey with Maiman’s discovery of the laser, and so did, therefore, lidar.

The first atmospheric lidar measurements began shortly after Maiman’s paper [Maiman, 1960]. The honor of the first lidar data paper goes to

Fiocco and Smullin for their September 1963 paper entitled “Detection of Scattering Layers in the Upper Atmosphere (60-140 km) by Optical Radar” [Fiocco and Smullin, 1963]. In that same year, Ligda presented a paper at a conference on laser techniques where he described meteorological applications of lidars [Ligda, 1963]. These and other early papers used the terms “laser radar” or “optical radar” to describe this new technique. The term lidar, was originally suggested in 1953, long before lasers by Middleton and Spilhaus in their book on “Meteorological Instruments” when describing ceilometry [Middleton and Spilhaus, 1953]. The term lidar, however, has become universally used to describe this new remote sensing technique using lasers and optics, partly because of its similarity with radar. Ground-based measurements continued with more and more sophistication in the 1960s and early 1970s until the present utilizing elastic backscatter, resonance fluorescence, Raman, bistatic, DIAL (Differential Absorption Lidar) and coherent lidar measurements. In the late 1960s and 1970s, a few airborne systems were developed which came into use allowing regional measurements and even satellite under flight correlative measurements To give a more global perspective, it wasn’t surprising that in the 1970s NASA put together groups to study the capabilities of lidar on satellite platforms. Because of the heavy weight and high power requirements for these early lidars, the obvious platforms for demonstrating lidar’s capabilities were Spacelab and Shuttle [AMPS, 1973; Shuttle Atmospheric Lidar Research Program, 1979]. Many other workshops were held in the subsequent years of the late 1970s and early 1980s. One of particular completeness was held in Europe in 1984 [SPLAT, 1984].

Finally, after some delays in its development, primarily due to the Shuttle Challenger mishap, the Shuttle flight of LITE (Lidar In-space Technology Experiment) took place for 11 days in September 1994 [McCormick, 2005]. This flight was truly a pathfinder mission for future space lidars, and ushered in a new era of remote sensing from planetary orbit. This flight showed the science community the exceedingly important data that a spaceborne lidar can provide. Previously, lidar active remote sensing techniques in the U.S. were not able to receive approval and funding for flight in competition with passive sensors, which have been used since satellites first orbited Earth. Passive sensors, however, have great difficulty with vertically resolving and uniquely determining tropospheric species as well as, geophysical parameters like temperature. It was obvious that the innate characteristics of lidars would provide a small footprint on the ground, i.e. high horizontal resolution, very high vertical resolution, a high sensitivity to aerosol measurements, and an excellent discrimination against noise because of laser spectral purity. Perhaps most importantly, these characteristics allow lidars to probe between clouds and penetrate through optically thin clouds and, therefore, profile the troposphere. Technology, however, held the lidars back from successfully obtaining long duration Earth-orbiting flights in the 1970s through the 1990s. Long-lifetime, laser power efficiency, cooling and weight issues had to be solved if lidars were to fly for long-duration on Earth-orbiting spacecraft. In the late 1980s and 1990s diode-pumped and long-lived ND-

YAG lasers, and light-weight optics and structures, changed drastically the feasibility for lidar flights. Coupled with the successes of LITE, and the successful laser altimeter flights of SLA (Shuttle Laser Altimeter) and MOLA (Mars Orbiting Laser Altimeter) [Abshire et al., 2000], lidars became competitive for spaceborne missions. Therefore, when new flight opportunities presented themselves, GLAS (Geo-science Laser Altimeter System) aboard Ice-Sat and CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Observations) were accepted for flight through the proposal process, as was ESA's Aeolus Mission with the atmospheric doppler lidar ALADIN aboard. Ice-Sat was launched in January 2002, and CALIPSO in April 2006. Aeolus is scheduled for launch in 2008.

Lidar has contributed greatly to our knowledge of the Earth's atmosphere, and Mars' and Earth's surface characteristics. Lidar measure-ments from the surface through the Earth's mesosphere are routinely made. Contributions include the determination of basic atmospheric variables of state like temperature, humidity, pressure and winds, as well as trace gases like ozone and water vapor. The planetary boundary layer diurnal variations, atmospheric turbulence, Polar Stratospheric Clouds, volcanic aerosols and forest fire smoke plumes and their global distributions, are all measured routinely by lidars. The morphology of particles in ice and water clouds, and even volcanic and dust events are easily made. Lidars have been instrumental in understanding meteorological phenomena like hurricanes, frontal passages, lee waves, gravity waves, mesospheric metallic ions and atoms, and clouds. Air quality measurements of aerosol and trace gases like sulfur dioxide are also important measurements by lidars. It is hard to imagine solving the myriad of atmospheric and climate problems without including lidar remote sensing from the ground, aircraft or space.

2. The Future

Presently, GLAS and CALIPSO are circling the Earth. The addition of data from the Aura constellation (the A-train), in the case of CALIPSO, will be a challenge and an attribute. The challenge is to incorporate these data into a more complete and understandable data set, and to use the data for various modeling studies. For example, the synergy is that it offers a much more complete description of direct and indirect forcing. Flying in formation, providing data unattainable by a single remote sensor, provides a paradigm for future satellite missions. These first spaceborne long duration missions utilize elastic backscatter only. Many studies, however, have taken place, which show the feasibility of utilizing the DIAL technique to make measurements of ozone and water vapor. Many conceptual studies that combined a backscatter aerosol and cloud experiment with a DIAL water vapor capability have been completed. The possibility of spaceborne DIAL systems flying in this first decade is technologically possible, but is problematic since NASA, JAXA or ESA haven't chosen a flight mission.

As lasers become more energy efficient, provide more useable wavelengths for increased profiling capability with eye-safe operation, and with increased lifetimes, other applications will become possible from aircraft and space. In addition to laser improvements, large deployable telescopes will allow new space applications. Laser altimeters that can provide cm-height resolutions and high repetition rates, and lasers with greater lifetimes and repetition rates are all now possible.

ESA has funded a wind lidar facility instrument, called Aeolus that is being developed and scheduled for launch in 2008. AEOLUS utilizes the Doppler shift in molecular backscatter associated with the wind profile. It measures in two wavelength bands on either side of the output frequency from the tripled wavelength of a Nd: YAG laser emitting at 355 nm.

The above improvements will enable future applications to be implemented in the subsequent decades like studies of the carbon cycle, circulation and forecasting through global tropospheric wind measurements, DIAL for constituent measurements and elastic backscatter for aerosol and cloud measurements. The implementation of these lidars in space will greatly enhance our understanding of atmospheric chemistry and climate. The future is indeed bright for spaceborne lidars, which are now taking their place alongside passive sensors, and fulfilling a myriad of measurement needs for the study of our Earth system. Groundbased networks of lidars operating within strict protocols of data analysis and availability will continue and become globally distributed in the near future. Numerous new applications and technology improvements, hyperspectral lidars, and steady improvements in autonomous operation and miniaturization will result in an even greater use of lidars in the future.

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