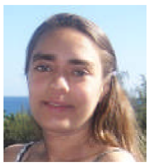
Laser Radar: A Technique for Studying the Atmosphere

Nimmi Sharma



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Laser radar, also called lidar, is proving to be a powerful technique for helping us to understand the world in which we live. It can provide information on topography, vegetation canopies, and on characteristics of Earth's atmosphere. This article describes how laser light scattering can be used in lidar systems to help visualize the structure of our atmosphere and to address a wide variety of important scientific questions from air pollution to climate issues. The article focuses on two specific examples of ground-based elastic lidar, the Micro Pulse Lidar System and the CLidar system, to provide an introduction to the methods of atmospheric lidar measurements and their applications.

1. Introduction

The atmosphere of our planet affects every living thing. From the quality of the air we breathe to regulation of the temperature of our entire ecosystem, atmospheric processes and constituents play an important part in sustaining life in air, on land, and even in water. Through local, regional and global effects such as pollution transport and rainfall patterns, they affect not only sustainability of life, but also quality of life. Knowledge of the makeup of the atmosphere and the dynamic changes in this vast system is important for understanding ongoing patterns of change and predicting future effects of those changes.

It is extremely challenging to take direct measurements of the atmosphere over a wide range of altitudes, times and locations. Direct atmospheric sampling can be accomplished via aircraft or balloon-borne instruments which travel up through the atmosphere and pull in samples at various altitudes. However, these techniques are often limited as they typically provide a single sample at discrete altitudes at one time. Remote sensing techniques, which study the atmosphere indirectly by investigating the

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interaction of the atmosphere with a probe such as a light wave, provide a means of gathering information on the entire vertical extent of the atmosphere over time. Laser radar is one such remote sensing technique which is gaining prominence as a highly useful tool for atmospheric studies.

Laser radar, also known as lidar[1] (an acronym for LIght Detection and Ranging), scatters pulsed or continuous laser light off targets of interest, detects the return 'echo' of the light, and uses that light and other information such as the time of the echo return to determine the distance to the target and to gain information on target properties. Lidar systems are being used from the ground to measure air pollution. They are also used to study parts of the Earth other than the atmosphere. Lidar systems have been mounted in aircraft and pointed downwards to map the topography of ice sheets (monitoring changes from global warming) and to study the heights and coverage of treetops and other vegetation (also affected by atmospheric processes). They have even been flown in space. Some lidar systems also measure winds and detect specific chemicals of interest in the air.

[1] S Veerabuthiran, *Resonance,* Vol.9, No.3, pp.23–32, 2004.

In this era of growing environmental awareness, one of the most promising applications of lidar lies in its ability to map aerosol locations and amounts in the atmosphere. Aerosols[2] are small particles suspended in the atmosphere which may be either natural or man-made. Examples include sea spray, pollen, soot and volcanic ash. Aerosols play an important role in the thermal balance of the Earth and may impact global warming in a complex manner which depends on aerosol types, concentrations, and altitudes. More information on atmospheric aerosols is needed to help climate modelers predict atmospheric changes. Aerosols can also affect precipitation patterns and can serve as tracers for atmospheric dynamics.

[2] See G Nagendrappa, An appreciation of Free Radicals, *Resonance,* Vol.10, Nos.2,3,4 and 7, 2005.

> Elastic backscatter systems send out laser light and measure the fraction of the light that is elastically scattered (with no wavelength shift) back in the direction of the instrument.

The simplest types of lidar systems are monostatic elastic backscatter lidars. Monostatic systems have a laser transmitter and detector positioned at the same location. Elastic backscatter systems send out laser light and measure the fraction of the light

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that is elastically scattered (with no wavelength shift) back in the direction of the instrument. Traditional monostatic systems typically employ detectors which are able to measure the time of flight, from transmission to scattered return, of the laser pulse to detect the altitude of the scatterer as well as the scattered intensity. The Micro Pulse Lidar (MPL) systems used in the United States National Aeronautics and Space Administration's (NASA's) global lidar network (MPLNet) are examples of these types of instruments. They can provide information on cloud base heights, aerosol optical depth, and structure of the atmospheric boundary layer. Since light is scattered from all constituents in the atmosphere including air molecules (nitrogen, oxygen, etc.), aerosol particles, and clouds, the detected signal intensity of the scattered light contains contributions from all these components. For aerosol measurements, it is necessary to separate out the contributions from clouds and air molecules. Two examples of lidar systems which provide information on atmospheric aerosols will be discussed in detail: the Micro Pulse Lidar, a monostatic system, and the CLidar, a bistatic system.

2. Micro Pulse Lidar

Micro Pulse Lidar systems provide a good example of monostatic lidar. As a global network of these MPL systems exists, their data can be combined to help yield a broader picture of the atmosphere over a wide range of locations. For ground-based Micro Pulse Lidar systems, a 527 nm green laser is pointed vertically and pulsed at a rapid frequency of 2500 Hz with a low power of approximately 10 μJ per pulse. The system has an altitude resolution of 15 meters. The laser is beam-expanded and is transmitted out from a telescope which also serves to collect the returning scattered laser light. See *Figure* 1. The system is capable of continuous daytime and night-time operation. The data may be graphed as a plot of signal intensity versus altitude and time, and displayed as a two-dimensional color image with altitude on the vertical axis, time on the horizontal axis and the intensity of the signal at each altitude and time denoted by a colormap, as shown in *Figure* 2.

Figure 1. Micro Pulse Lidar System.

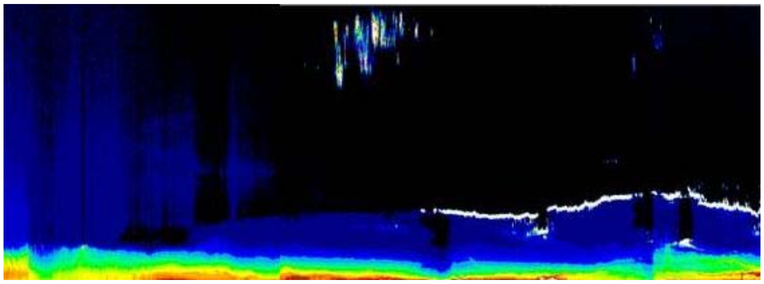

Figure 2. Micro Pulse Lidar data taken over a 24-hour time span. Clear air with low signal intensity is seen in black and dark blue. A stratified layer of low-altitude aerosols with moderate signal intensities is clearly visible in the first few kilometers of the atmosphere. A high-altitude cloud appears in the middle of the time sequence. Strongest signal-returns are indicated in white and correspond to a lower-lying cloud deck which settled over the instrument later in the run and persisted until the end of the experiment.

The returned signal due to light scattered at a range r from the instrument, in photoelectrons per microsecond, n_r, is given by:

$$n_r = O_r\, C\, E\, B_r\, T^2/r^2 + n_{br} + n_{ar})/D_r,$$

where O_r is the overlap correction at range r which adjusts for signal lost near the instrument due to differing fields of view for the transmitter and detector, C is the system calibration constant that is set by overall optical efficiency of the instrument, E is the laser pulse energy, B_r is the backscatter cross-section at range r for the air molecule or aerosol particle, T is the atmospheric transmittance which includes both aerosol and molecular transmittance, n_{br} is the background signal at range r due to non-laser light (sunlight, etc.), n_{ar} is the afterpulse correction for range r which corrects for instrument artifacts following the firing of a laser pulse, and D_r is the detector deadtime correction which accounts for the finite counting speed of the detector. Typically, the quantity of interest in the measurements is the portion of the transmittance that is due to aerosols at every altitude. This can also be expressed in terms of the aerosol optical depth at each altitude.

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Instrument calibrations of detector deadtime, instrument afterpulse and instrument overlap must be performed to characterize these instrument effects so that they can be removed from the data. Detector deadtime can be calibrated by the detector manufacturer. The MPL's detection and timing system may be envisioned as a sequence of 'time bins', where photons scattered from the lowest 15 meters of the atmosphere 'fall' into the first time bin, those scattered from the next 15 meters 'fall' into time bin 2, and so on. Detector afterpulse results when light from the laser pulse

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firing is scattered internally in the instrument optics and reaches the detector, not only causing a large signal in the first time bin, but also resulting in the 'bleeding' of photoelectrons into subsequent time bins (with successively lower and lower intensities) which produces spurious signals that appear to come from higher altitudes. This artifact may be quantified by taking a set of data with the laser blocked at its outlet. The resulting data show the characteristic 'afterpulse' curve of intensity versus range which can then be used to subtract out the afterpulse signal. Correction for the fact that, due to the monostatic optical configuration, the MPL instrument only 'sees' scattering from the entire volume illuminated by the laser when a certain distance from the instrument is exceeded, is called the overlap correction. This needs a more involved experimental calibration, since it requires data to be taken in a homogeneous atmosphere.

Atmospheric structure changes dramatically in the vertical direction, with most aerosols staying in the first few kilometers of the atmosphere. Therefore the overlap correction is performed by obtaining lidar data with the MPL laser pointing horizontally over a clear path length of homogeneous atmosphere that extends for at least 12 km. A plot of these data as the natural log of the signal multiplied by the square of the range from the instrument versus the range is linear at far ranges, and falls off in the near ranges. By calculating the amount by which the near range signals should be raised to fall on the same line as the distant signals, the system overlap correction may be determined, which is then applied to correct vertical aerosol data. The overlap calibration must be conducted repeatedly over time, requires a specialized experimental location where long unobstructed horizontal paths are available, and also introduces some uncertainties into the data from the first few kilometers of the atmosphere.

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To quantify the aerosol component of the signal, additional information from another instrument is required. Often MPL systems are used in conjunction with sunphotometers. A sunphotometer simply points at the sun and measures the amount of solar radiation at the desired wavelength which reaches the instrument. As the incoming solar radiation at the top of the atmosphere is well known, the sunphotometer provides a measurement of the aerosol transmittance of the entire column of atmosphere above it (total column aerosol transmittance). A constant ratio of extinction to backscatter is often assumed. Data are taken on a relatively clear, cloudless day with both the MPL and a sunphotometer. Since most aerosols lie in the lower atmosphere, a 'fitting' region of altitudes above the aerosol layer is then selected in which it is assumed that all scattering is due to air molecules only (e.g., 7–12 km). The signal is then corrected for aerosol attenuation in the ranges below using the estimated optical depth from the sunphotometer. Once the aerosol and molecular transmittances at the bottom of the fitting layer have been computed, an iterative process is used to solve for the extinction to backscatter ratio value, which is then used to solve for the aerosol transmittance at every altitude (not simply the total over the entire atmosphere) and to compute the aerosol optical depth as a function of altitude. The results of this analysis then serve as inputs for a wide variety of atmospheric studies on topics such as pollution, rainfall and climate.

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3. The CCD CAMERA Lidar System

The majority of lidar systems in use are monostatic.They have the advantages of constant altitude resolution and constant scattering angle[3]. However they face challenges in the lowest regions of the atmosphere due to uncertainties in the overlap correction function. As these low altitude regions are typically the areas of highest aerosol concentrations, good instrument performance in this portion of the atmosphere is important. In addition, monostatic systems typically require sensitive timing circuitry combined with detection and electronics components which must perform linearly over a large dynamic range since the signals they measure vary by several orders of magnitude over the altitudes studied. This contributes to the high cost of typical systems and to the limited proliferation of lidar technology. Requirements of specialized experimental sites for performing overlap calibrations also present challenges. Bistatic lidar systems where the detector is

[3] The angle between the direction of the laser light transmission and the direction of the scattered return light, which is 180° for monostatic backscatter systems.

spatially separated from the laser have been developed to address these issues. One such system is the CCD Camera Lidar (CLidar) system [1].

The CLidar system consists of a vertically pointing high power green laser which is imaged from the side by a CCD camera[4] with wide-angle optics. The camera is located at a known and substantial distance from the laser. From the pixel intensities in the image, the aerosol scatter is determined, and geometry rather than timing is employed to determine the altitude of the scatterers. Over the entire vertical range of the atmosphere, the intensity of the returned signal varies by several orders of magnitude less than that of a monostatic lidar signal. Therefore expensive timing systems and high dynamic range electronics are not required. The system is designed to provide excellent altitude resolution in the near-ground region which allows for accurate comparison with ground level air sampling instruments such as *nephelometers*[5].

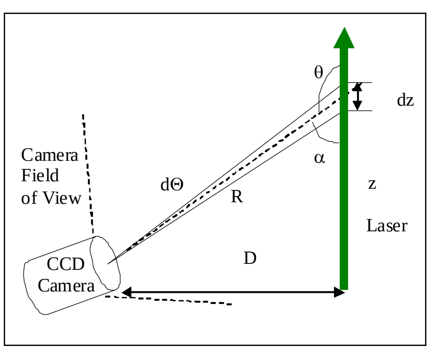
[4] See *Vasant Natarajan,* The 2009 Nobel Prize in Physics: Honoring Achievements in Optics That Have Changed Modern Life, *Resonance,* Vol.15, No.8, 2010.

[5] A nephelometer is an instrument which draws in an air sample from a single location (usually from an inlet above a building roof) and sends the sample to a chamber within the instrument where it is illuminated by a light and the sample's scattering is directly measured.

The CLidar system is depicted in *Figure* 3. Wide-angle optics allow the entire laser beam to be imaged at once so that data may be obtained from every altitude at the same time. An optical filter which passes only a narrow band of light around the laser wavelength cuts down on background light. The system operates only at night. For a typical CLidar system, a camera exposure of a few minutes is sufficient.

[6] The image of the laser beam on the CCD camera chip covers many pixels. Each pixel on the CCD camera can be thought of as a small telescope with field of view $d\Theta$ which looks at light from the altitude range dz.

Figure 3. CLidar System showing CCD imaging system located D meters from the laser.



An air parcel at height z, with altitude range dz, located at a range (slant distance) R from the camera is *imaged by a pixel*[6] with field of view $d\Theta$. The scattering angle, which is the angle between the direction of the transmitted and returned light, is given by θ. The energy E_r received by a pixel in the CCD image is:

$$E_r = K_1 E_1 A\, T_{atmz} T_{atmR}\, \beta(\theta, \phi, z) dz/R^2. \qquad (1)$$

E_L is the total laser pulse energy during the image exposure time; A is the effective area of the collecting optics; T_{atmz} and T_{atmR} are the atmospheric transmittances along the outgoing and return paths; $\beta(\theta,\phi,z)$ is the scattering coefficient for a scattering angle θ and a polarization angle (direction between the plane of the electric field vector of the laser light and plane containing the transmitted and returned light) ϕ, at altitude z. Here dz is the length of beam imaged on the pixel (which also gives the altitude resolution of the system). K_1 is the calibration factor which describes the optical efficiency of the system [1].

The CLidar altitude resolution is highest at low altitudes and degrades at higher altitudes since the length of laser beam imaged in each pixel grows in a manner approximately proportional to the square of the range R. Therefore pixel intensities representing scattering at high and low altitudes do not vary by large amounts since where the atmosphere is most densely populated with scatterers (low altitudes), only a small region is imaged in each pixel, and where there are few scatterers (higher altitudes), larger altitude ranges are incorporated into a single pixel. This has the effect of substantially lowering the dynamic range requirements for system electronics and thus allowing measurements to be obtained with simple off-the-shelf components. In addition, for a prototype system where the camera is located approximately 160m from the laser and the optics are selected to give a 0.2^{o} field of view per pixel, the system has an altitude resolution near the ground of less than one meter. This allows for detailed comparisons with other instruments on the ground. There is no overlap correction required. Bistatic systems however, do present challenges of their own in data interpretation, due to the dependence of the signal on polarization and scattering angles.

The data are contained in the CCD image of the beam. A sample (unfiltered) image is shown in *Figure* 4.

The image is analyzed quantitatively using IDL (Interactive Data Language) software. First the beam center (highest intensity track) is determined, then the perpendicular to the center is calculated and pixels along the perpendicular line are interpolated and fit to a Gaussian profile. The signal is taken to be a constant multiplied by the width and height of the Gaussian. Regions of the

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Figure 4. CCD image of laser beam without background light filter showing stars and the milky way.
Courtesy: John Barnes, National Oceanic and Atmospheric Administration, USA.

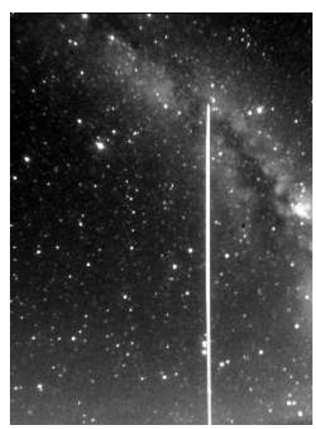

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image near the beam are used for background subtraction. As is done with monostatic lidar, an altitude region which is assumed to be aerosol-free is selected and the signal is normalized to match the calculated scattering due to air molecules in this aerosol-free region. The molecular signal is then subtracted from the data to generate the aerosol scattering signal, and the ratio of aerosol to molecular scattering can be determined. With monostatic lidar the scattering angle is the same (180^o) for every altitude. This is not the case for bistatic systems including the CLidar system, since the scattering angle changes for every altitude due to the geometry of the experimental setup. Thus aerosol phase functions (equations relating aerosol scattering efficiency to the angle at which the light was scattered) must be assumed or measured to derive additional aerosol parameters [2].

4. Conclusion

Both monostatic and bistatic lidar are providing new insights into our atmosphere and the constituents which help shape our weather and climate. The applications for lidar are growing as new technologies enhance ease and affordability. Lidar studies are currently being conducted worldwide at universities, research institutions, and governmental facilities such as NASA and NOAA in the US. Lidar studies require a strong background in optics, electricity and magnetism, and an interest in interdisciplinary areas such as meteorology and earth sciences.

Suggested Reading

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[5] http://en.wikipedia.org/wiki/CLidar

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[7] A Kovalev and William E Eichinger, *Elastic Lidar: Theory, Practice, and Analysis Methods*, John Wiley & Sons, 2004.

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