A BISTATIC LIDAR RECEIVER TO OBSERVE LOWER TROPOSPHERIC AEROSOL PROPERTIES

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Abstract

The scattering of optical radiation in the visible, ultraviolet and infrared regions of the spectrum has a major impact on commercial air traffic and on many military systems. It has become critically important, with modern systems, that the electro-optical environment be properly characterized. We have been able to demonstrate that the rotational and vibrational Raman backscatter can be used to determine the extinction profile through optical scattering regions such as clouds. But a method is still needed to determine extinction profiles within the first several hundred meters above the Earth's surface through aerosol layers.

We have developed a bistatic remote receiver that utilizes a linear photodiode array to image the radiation scattered from any high power CW or pulsed laser system. By observing the angular scattering variation from a given aerosol layer, additional information contained in the scattering angle phase function can be obtained. A technique has been developed to estimate particle size and distribution widths (of spherical scatterers) by placing two or more of these instruments perpendicular and parallel to the scattering plane. Polarizers are also used to measure the cross polarization to determine the amount of multiple scattering and nonsphericity of the particles in the scattering volume. The information on the particle size and distribution width along with absolute extinction measurements from Raman lidar should allow extension of the extinction and transmission calculations to a wider range of wavelengths.

Background

The challenge is to remotely measure the extinction and transmission through regions of the atmosphere without having to assume any relationship between backscatter and extinction. Lidar techniques show the best promise for describing the local electro-optical environment. However, most of the past applications of lidar have failed to provide satisfactory results because the techniques used have generally focused on measurements of the backscattered radiation at the laser fundamental wavelength. The extinction can be related to the backscattered energy by the equation $\beta(r)=C(r)\alpha(r)^k$, where $\beta(r)$ is the backscattered intensity, $\alpha(r)$ is the extinction and $C(r)$ and k are frequently assumed constant. But $C(r)$ is a function of range and k is different for each scatterer, so given only the backscatter intensity $\beta(r)$, the extinction $\alpha(r)$ can not be reliably obtained. This presents a problem for techniques relying on the inversion of a single-ended lidar return to obtain range dependent atmospheric extinction coefficients. This technique will only be useful for regions of the atmosphere with uniform scatterers and small extinction coefficients, like those found in stratospheric aerosols [1,2]. A more reliable method using lidar to measure atmospheric extinction has been developed independently by M. R. Paulson, 1987 and G. J. Kunz, 1987. This lidar inversion algorithm uses a double ended lidar technique where the relationship between the backscatter and extinction coefficients is eliminated by comparing the backscatter signal returned from a volume common to each lidar located at opposite ends of the propagation path. The double ended lidar technique is presented to show that the β/α ratio in general is not constant with range and that the technique of inverting a single ended lidar return (Klett inversion) can produce inaccurate extinctions. Figure 1 shows plots of extinction calculated from both single-ended [C(r) assumed constant] and double-ended lidar backscattered returns (Richter and Hughes, 1991).

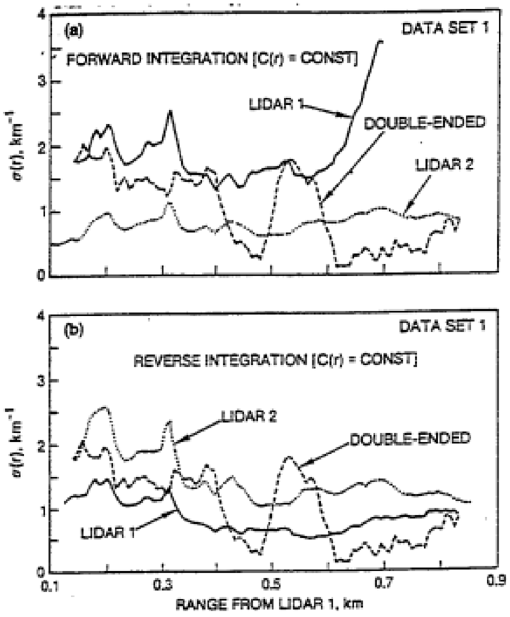

Figure 1. Comparison of extinction coefficients versus range calculated using forward and reverse integration on a single-ended lidar return and using the double-ended lidar technique. (from Richter and Hughes, 1991) [5]

These data sets show very clearly how unreliable standard inversion techniques are at obtaining extinction from a single backscattered lidar return. However, if the values of C(r) are known as a function of range and allowed to vary, standard single-ended lidar returns could be inverted to reliably obtain extinction coefficients. More information is needed about the scatterers so that C(r) can be calculated for each range bin. The ratio of the 532 nm to the 355 nm backscatter for a two-color lidar return is theoretically proportional to C(r). But this has yet to be used in an inversion algorithm to accurately and uniquely calculate extinction (Rau, 1994). The double-ended lidar technique is a proven method for measuring the extinction along a path, but it is not a practical solution for instantaneous measurements above altitudes of a few meters and for locations where instruments can not be located at each of the end points. The scattering properties are much too complicated for the simplistic single-ended backscattered inversion approach and much more information is needed to characterize the processes.

Instrumentation

The only way to collect scattered radiation at angles other than 180° from a lidar system is to set up a bistatic receiver located some distance from the laser. We have developed a unique bistatic receiver that can remain fixed with respect to the laser (e.g. it does not have to scan up and down the laser beam). The scattering volume's height is derived from the location of the laser's image on a photodiode array. This type of receiver is small, about the twice the size of a regular SLR camera, making it ideal as a permanent fixture at many locations. This type of receiver is also independent of the laser/lidar system and requires no electrical connection to the laser source. Multiple receivers could be set up on ships and at airports to continually monitor atmospheric aerosol variability.

The bistatic receiver collects an image of the radiation scattered from the first few kilometers of the atmospheric path to help determine atmospheric particle size distributions. The instrument is a straight forward use of a linear photodiode array detector in the image plane of a standard 35 mm SLR camera. The receiver is a hand held unit composed of three parts, a Ricoh XR-10m SLR camera, a digital control and data storage box, and a power source (either a 6 v battery, or an extension cord). This receiver is essentially a very sensitive, high resolution digital camera. The camera images the laser light onto an EG&G monolithic linear photodiode array. The array has 1024 photodiode elements with a 25 μm center-to-center spacing. Each element has a 100:1 aspect ratio of 25 μm x 2.5 mm making it easy to image the laser beam onto the array. The data collection process starts with a remote start switch. The embedded micro-computer reads the input and starts a series of events defined by the data acquisition and control program. The scattered laser light is filtered by a 10 nm bandwidth, 532 nm filter and focused onto the photodiode array by a 50 mm lens. First, the array is cleared and then the shutter is opened for about ten seconds (200 laser shots). The data is digitized with a 12 bit, 100 kHz digitizer and transferred directly to RAM. A background sample is then digitized with the shutter closed and also stored directly to RAM. The background is subtracted from the signal and saved to a PCMCIA solid state memory. One data sample requires about 55 seconds, and 1000 samples can be saved to one PCMCIA card. At the end of the night, the data can then be saved to a standard 3.5" floppy disk.

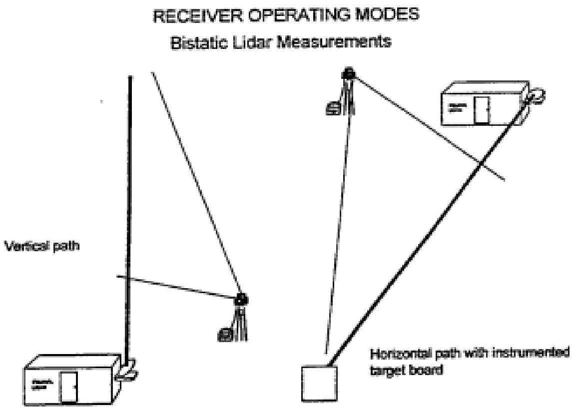

Figure 2. The lidar and bi-static receiver will be operated both vertically and horizontally. By operating a receiver with a linear array off-axis from the laser beam, phase information can be collected about the scatterers.

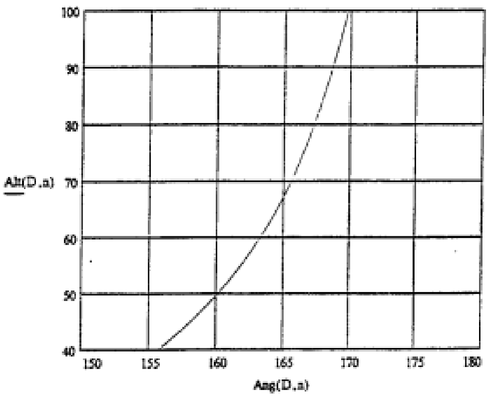

Figure 3. Plot of altitude versus angle for a receiver located 18 m from the laser transmitter. This plot shows the maximum range of angles that can be observed with the laser pointed vertical. Altitude is in meters.

Figure 2 shows the two modes of operationfor the lidar and bistatic receiver. All measurements thus far have been obtained with the laser pointed vertical. The horizontal mode of operation is also important so that ground based measurements can be compared with the lidar data. In this mode of operation an instrumented target board can be used to directly measure the total extinction between it and the laser source. The data inversion process is more difficult in the vertical mode of operation because the end point of the laser is not well defined. The camera is positioned so that the infinity point of the laser is imaged onto the last few pixels of the array. The last pixel with a signal is assigned a value of infinity for its altitude, and the inversion is processed downward. Because of the geometry, the last pixel has a range of about 8 km to infinity, and the first pixel has a range size of about 1 cm. This means that an error in assignment of the end point could cause large errors at high altitudes, but relatively small errors within the first kilometer. Figure 3 shows a plot of altitude versus angle for the vertical mode and with the receiver positioned 18 m from the laser. This plot shows the range of scattering angles that would be observed from a 60 m thick layer between 40 and 100 m. Lidars normally measure only the backscattered radiation at 180 degrees. The bistatic receiver will be able to observe scattered radiation at angles between 155 and 170 degrees with this geometry. It will be shown latter that there is valuable information contained in this small range of angles. The optimal position of the receiver will be slightly different depending on the height of the aerosol layer. But the maximum range of observed angles will always be 15 degrees. For the same aerosol layer between 40 and 100 m, the spatial resolution is less than 0.6 m, and is as small as 0.17 m at 40 m altitude. The height resolution for this type of instrument is very small because it is dependant not on electronic timing, but on geometry.

Initial Results

Figure 4 is a plot of unprocessed data from the photodiode array. The ordinate is digitized voltage minus background and the abscissa is the pixel number out of 1024. This data was collected

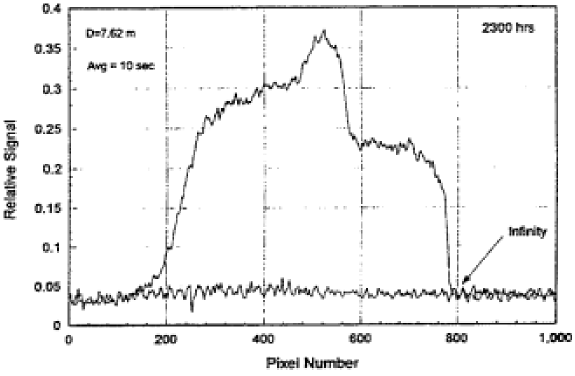

Figure 4. Raw data collected at Penn State with a bistatic receive, using a linear photodiode array on March 14, 1995.

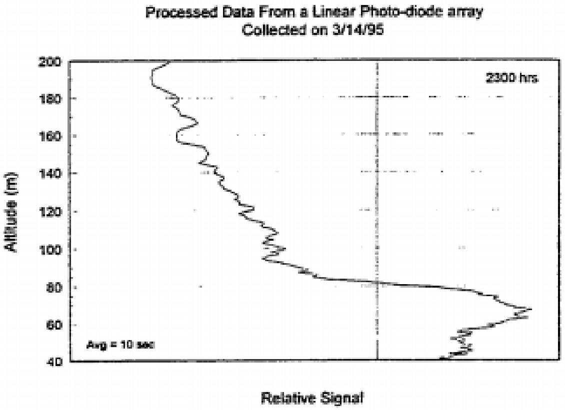

Figure 5. First measurements from a bistatic receiver collected on March 14, 1995. The integration time was 10 seconds. The spatial resolution through the layer is less that 0.4 m.

using the LAPS (Lidar Atmospheric Profile Sensor) laser on March 14, 1995 in State College, PA. The data were averaged for 10 seconds (300 laser pulses), and the receiver was located 7.62 m from the laser. There were no clouds that night so the last pixel with signal was assigned an altitude of infinity for data processing. The data must be processed to provide a profile of relative signal versus altitude. As the altitude increases the scattering volume also increases, due to the geometry of a bistatic receiver intersecting the laser. Therefore, the relative signal must be corrected for the size of the volume being measured. A (R^2) correction must also be applied due to the increasing distance between the scatterers and the receiver.

Figure 5 shows a plot of the data from Figure 4 with these corrections applied. It can now be seen that the aerosol layer is between about 60 and 80 m. To obtain the maximum angle range for a layer at this height, the receiver should have been placed 18 m not 7 m from the laser. The height resolution in the layer is between 0.2 and 0.4 m. Aerosol profiles with this resolution and this close to the ground are very difficult to obtain with any other instrument. Monostatic lidars are not able to reliably measure aerosol scattering closer than about 1500 m from the surface because their telescopes are generally far field instruments. Many more data sets like these will be collected to verify the operation of the instrument and to determine the best method for obtaining particle size and distribution.

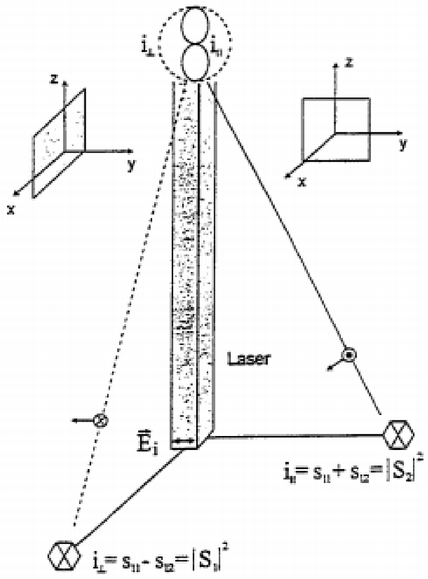

Figure 6. Geometry for a bistatic lidar setup to show which components of the electric field will be measured at each location.

Data Analysis

Figure 6 shows the geometry for a bistatic lidar setup to illustrate which scattering matrix elements must be calculated to model and predict the results of the bistatic receiver. The laser beam propagates vertically into the atmosphere with its electric field polarized in the y-z plane. We would observe the scattered radiation from two separate locations, one perpendicular to the scattering plane and one parallel to the scattering plane. At the top of Figure 6 the radiation pattern for a dipole radiator is drawn to show which components of the electric field are observed at each measurement location. For the perpendicular component no variation is seen, but for the parallel component the standard variation of a dipole radiator is measured. Of course this is the simplest case, the radiation pattern for most scatterers is much more complicated as will be shown later. The ratio of these two components would then provide unique information about the size and distribution of the scatterers.

A simple and limited model has been developed to determine if this technique is feasible. This model uses a fortran subroutine from Bohren and Huffman, 1983 called "bhmie" to calculate the scattering matrix elements S_1 and S_2. A single mode

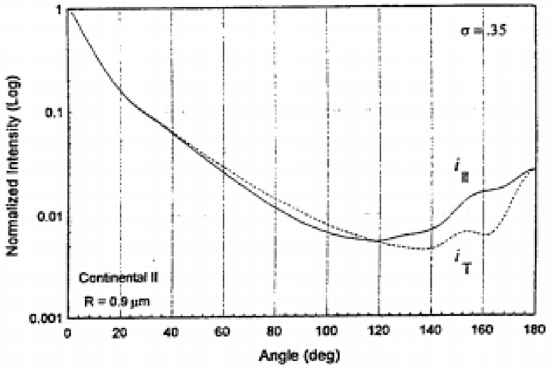

Figure 7. The two components of scattered radiation according to Mie theory calculated for a single log-normal size distribution.

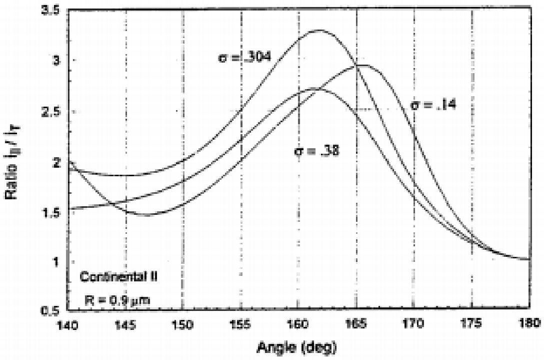

Figure 8. Ratio of the two electric field components plotted in Figure 7. Three different size distribution widths were chosen to see how much the ratio would vary.

log-normal distribution is used to calculate the scattering between angles of 140 and 180 degrees. This simplifies the calculation because the relative number densities between the three modes of a trimodal distribution can not be ignored. For example, a few large diameter scatterers could dominate the effects of many smaller diameter scatterers. In other words, the largest mode with only 1000 scatterers could cause much more extinction than $1x10^6$ scatterers in the smallest mode.

Figure 7 is a plot of the parallel and perpendicular scattering components between 0 degrees (forward scatter) and 180 degrees (backscatter) for the scattering geometry in Figure 6. A single log-normal distribution was used with a standard deviation of 0.35 and a mean radius of 0.9 μm, typical values for "Continental type II" aerosols. The distribution of sizes smooths all the fine structure out of the curves. However, a sizable difference in the scattering intensity still remains between 120 and 180 degrees. Figure 8 shows the ratio of the parallel to the perpendicular component of scattered radiation. The bistatic lidar will be able to observe angles between 155 and 170 degrees. Different standard deviations were plotted to estimate how much variation would result in the measured ratio. It should be noted that the ratio peaks between 2.5 and 3.5 for a scatterer of radius 0.9 μm.

A few assumptions must be made before any inversion algorithm can determine size distributions from these bistatic measurements. The scatterers must be assumed to be spherical, if they are not spheres this measurement technique could determine how non-spherical they are. A polarizer is placed on the receiver to look for electric field components perpendicular to the one being transmitted. If there is a large return from the "cross polarized" component it can be assumed that either there is strong multiple scattering or the particles are not spheres. The index of refraction for the inversion will be estimated from the geography and meteorological conditions (e.g. is the data collected at sea). In order to measure a range of angles from an aerosol layer without moving the instrument to many different locations, it will be assumed that the layer consists of a uniform particle distribution. Using the above assumptions, a method will be used to invert or fit the returns from the two components to a model to obtain particle size and distribution for the scattering layer.

Acknowledgements

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