

BROAD BANDWIDTH LIDAR FOR STANDOFF BIOAEROSOL SIZE DISTRIBUTION

James B. Gillespie, David L. Ligon, Paul M. Pellegrino, and Nicholas F. Fell, Jr.
U.S. Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783-1197
jgillesp@arl.mil

ABSTRACT

We are examining the possibility of using a broad bandwidth lidar system to estimate size distributions of aerosol clouds that may possess respirable biological particles. An optical parametric oscillator has been specially designed and fabricated for broad bandwidth operation in the 1.4 to 1.8 micrometer spectral region. We have determined the spectral bandwidth, output, and pumping power characteristics of this device as a potential lidar source. We have developed a Monte Carlo technique to analyze backscattering data that would result from our hyperspectral lidar. Lidar simulation results show good estimates of size distributions for respirable size aerosols.

1. INTRODUCTION

Current methods of stand off detection of bioaerosols involve either point sensors in remote locations, or use of planned lidar systems. Two types of lidar considered are (a) ultraviolet (UV) laser induced fluorescence systems that can detect the presence of biological particles and (b) elastic backscattering lidar systems that can detect the presence and perhaps the shape of an aerosol plume. The UV lidar systems lack specificity in that they can only detect a spectrally broad spectrum—usually the emission of triptophan, an amino acid found in biological cells. UV systems are also generally do not operate in an eye safe mode of operation. The UV system has limited range at night and will not operate satisfactorily in the daytime because of the presence of background light. The elastic backscattering lidar systems have longer range, will operate in the daytime, and are eye safe. From a practical standpoint however, there will be aerosol plumes present almost everywhere in the environment; so there is a complete lack of any specificity. We have been developing a third type of lidar technology for standoff detection of biological aerosol plumes—a hyperspectral, broad bandwidth lidar. This type of lidar would emit a pulse of “laser” light that is several hundred nanometers in spectral bandwidth and centered at 1.55 micrometers so it can be eye safe. The backscattered return from an aerosol plume would be collected and dispersed spectrally on a detector array so that backscattering versus wavelength could be analyzed for particle size information (and perhaps refractive index information). This type of system combines two new technologies: (1) inverse Monte Carlo (IMC) signal analysis of the backscattered light and (2) a new broad bandwidth optical parametric oscillator (OPO) laser source for the 1.5 micrometer spectral region. This type of lidar could be hyperspectral, if required, by simply collecting the return light at high resolution. For the application at hand, the high resolution is not essential, but the spectral width is important. This system will have daytime operation capability and will be eye safe. It also will have some specificity in that the aerosol size distribution can be estimated. The determination of the size of the aerosol particles is important because biological endospores are typically one to a few micrometers in size while most background aerosols are submicrometer in size with the exception of fog type water droplets which are one to ten micrometers, or greater than 40 micrometers in size. Soil-derived aerosol particles are typically much greater than ten micrometers in diameter. Detection of an aerosol plume that has a significant concentration of particles in the 1 to 10 micrometer size range would be cause for concern and act as an alert to probe the aerosol with a more specific point sensor. We have demonstrated feasibility of

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the our notional hyperspectral lidar system though a computer simulation based on a Monte Carlo method to solve the inverse scattering problem. We have obtained and characterized an OPO device which can be used for the source of the system.

2. THEORY

This work originated from an effort to remotely size atmospheric aerosols using multi-wavelength, multi-angle light scattering data. Since a lidar only receives backscattering. We investigated the applicability of the method to one angle with many wavelengths. This section summarizes the results of a Monte Carlo method to invert lidar scattering data.

2.1 INVERSE MONTE CARLO METHOD

For a system of particles in the single scattering regime, we can write the volume extinction coefficient as a Fredholm integral of the first kind:

$$c(l) = N_0 \int_0^{\infty} K_{ext}(r, l) g(r) dr ,$$

where N_0 is a scaling parameter (in our case it is the total particle density), K_{ext} is the Mie Kernal function, r is the particle radius, and $g(r)$ is is probability distribution function for the aerosol (corresponding to the normalized size distribution). The spectral backscatter coefficient can be written in the same form, and for computer computations it can be approximated by a sum over a discreet set of M radii

$$b(l) = N_0 \sum_{i=1}^M K_{back}(r, l) f(r)$$

where K_{back} is the Mie backscatter kernel and $f(r)$ is the size distribution. The standard problem is to solve for the backscatter coefficient knowing the size distribution, number density, and the Mie kernel. The inverse problem is to experimentally collect backscattering data and then determine the size distribution. The above expression is for a number distribution. By adding a weighting term

$$w(r) = 4/3\pi r^2 ,$$

we can determine a volume size distribution. The use of the weighting function makes this method more stable for inversion. The resulting volume distribution can then be converted to a number distribution for plotting purposes.

Standard inversion methods require much data and are computationally intensive (sometimes several hours of computer time). They are also very sensitive to propagation of errors because of the matrix methods involved. There are usually problems of uniqueness because of incomplete data sets and noise in the data. For scattering, the kernel can be multivalued causing additional uniqueness problems.

The Monte Carlo approach to solving the inverse scattering is a mathematical brute force, random-walk, curve fitting approach using physics through the application of Mie theory. It also uses practical assumptions and constraints. Briefly, walkers representing the particle sizes are distributed on a grid. A walker is moved on the grid and scattering computations are made and compared to the experimental data set. If there is improvement (through comparison to a chi-squared error analysis), the walker stays in the new position and another walker is moved. If there is no improvement the walker is returned to its position and another walker is moved. The process is repeated until a predetermined error constraint is

obtained. When a fit to within 5% of the input data is obtained, the process ends and the resulting size distribution is considered to be the estimate of the actual size distribution. This method is described by Ligon, et al.¹. A flow chart of the IMC process is shown in the figure below.

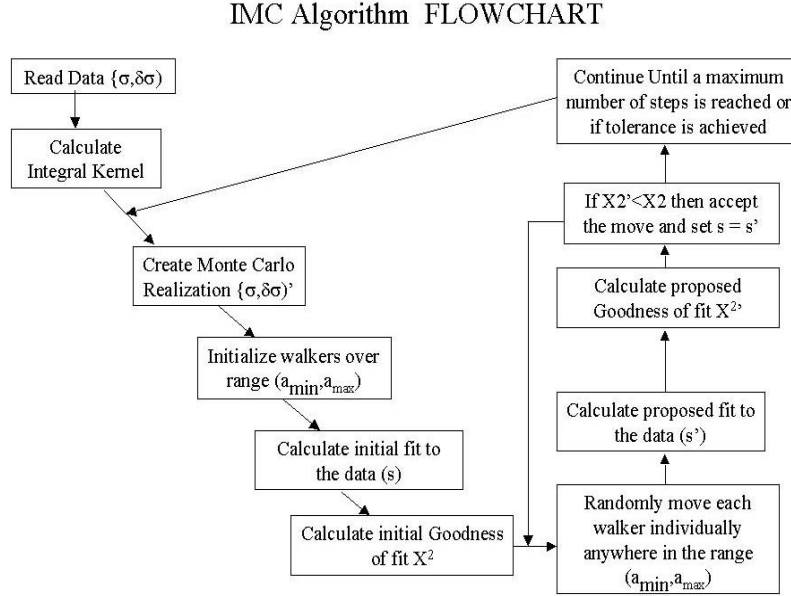


Figure 1. The flow chart for the Inverse Monte Carlo method.

INVERSION FOR LIDAR

The use of multi-wavelength lidar measurements allows for the characterization of aerosol properties from retrieved backscatter coefficients²³. The retrieval of aerosol properties from multi-wavelength lidar is a two-step process. The first step involves retrieval of the spectral backscatter coefficient, aerosol extinction coefficient, or both from the lidar signal. The second step is to retrieve from these values the aerosol properties such as refractive index, and size distribution. In previous work, we developed a novel inverse Monte Carlo algorithm that was shown to be effective in retrieving the aerosol properties from spectral backscatter and extinction measurements⁴. The exact nature of the inversion methodology for our broadband lidar is still in progress, however some salient features can be discussed.

One standard for for the lidar equation for the return power, $P(r)$, is given by

$$P(z) = P_0 \frac{c t}{2} \frac{A}{z^2} h b(z) \exp \left[-2 \int_0^z a(z) dz \right]$$

where: $h(z, l)$ is the receiving efficiency (overlap) of the lidar, A is the receivers aperture area, $b(z, l)$ is the backscatter coefficient at range z and wavelength λ (principally due to aerosols), and the two-way transmission is

$$T(z, l) = \exp \left[-2 \int_0^r a(z, l) dz' \right]$$

is the atmospheric transmission to the range z for the atmospheric volume extinction coefficient a which has contributions from both atmospheric aerosols and molecular absorption by atmospheric gases. The inversion is complicated by the fact that we are interested in determining properties of aerosol clouds that may be composed of more than one type of aerosol at different ranges. One possible choice of inversion procedures incorporates a modified form of the constrained slope method on the quantity

$$\ln[S(z, l)] = \ln \left[\frac{P(z)z^2}{A} \right] = \ln[h(z, l)b(z, l)] - 2 \int_0^r a(z, l) dz$$

in which the value $\ln[h(z, l)b(z, l)]$ is determined from a metropolis optimization algorithm given a constraint on the allowable range for the extinction coefficient α and an estimate of the molecular contribution to the extinction.

3. EXPERIMENTAL

There are two aspects to the experimental work, a computer simulation to demonstrate that backscattering from an aerosol can be successfully inverted to yield a good estimate of the aerosol size distribution and an experimental characterization of the broad bandwidth laser source.

3.1 AEROSOL BACKSCATTER INVERSE MONTE CARLO SIMULATION

We examined the Monte Carlo inversion method using synthetically generated scattering data. This section is a brief summary of a more complete analysis recently published in reference 4. Using Mie scattering theory we calculated the extinction and backscatter coefficients for 3 different log-normal distributions of water droplets for the wavelength range 0.4 to 0.8 micrometers at 41 evenly-separated wavelengths in the interval. The distributions chosen correspond to three regions: Region I, a distribution with modal radius smaller than the minimum wavelength in the data set; Region II, a distribution with modal radius within the wavelength region of the data set and Region III, a distribution with modal radius greater than the maximum wavelength in the data set. The particular modal widths chosen for these distributions were selected in order to keep the same standard deviation for each distribution. We assumed an error of 1% in the generated data and used a boot strap method for 50 different realizations of the data for error analysis.

Figure 2 shows the results of an inversion for a broadly distributed, bi-modal aerosol. This is for the 1.5-micrometer spectral region. For this case the log normal distribution parameters for the first mode are: modal radius = 1.5-micrometers and the modal width is 0.2. For the second mode the parameters are: modal radius = 2.5-micrometers, and the modal width is 0.25. Five percent noise was used on the data. The calculated fit is in good agreement with the simulated data. Simulations worked well even for noise levels of 33%. In general, if the size distribution was completely contained within the broad output then the size distribution was very accurately obtained. If the size distribution was for particles that were all larger than the wavelengths, then we could only determine where the distribution was located. We could determine the index of refraction by iterating the entire process over a range of refractive indices and observing the minimum chi-squared value.

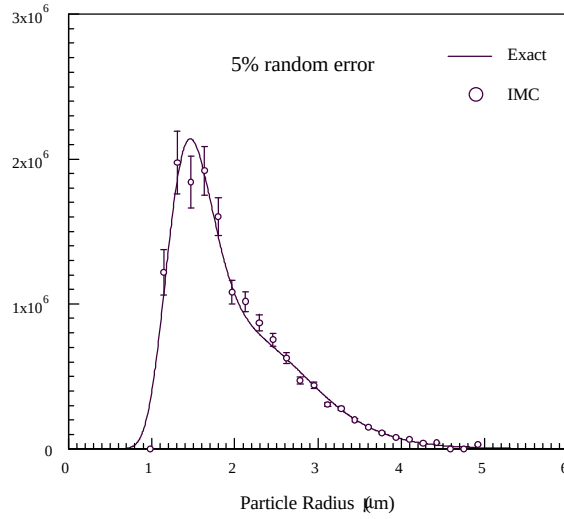


Figure 2. Bi-modal broad distribution.

3.2 BROAD BANDWIDTH SOURCE

The source for the proposed hyperspectral lidar system is a BBO optical parametric oscillator (OPO) that was specially designed for broad bandwidth operation by scientists at DERA in the United Kingdom⁵. This device is based on a visible broad bandwidth device patented for a white light laser⁶. It is pumped with a 532-nm Nd:YAG laser.

The OPO cavity is 2.54 cm long and is designed to resonate the OPO signal (700 to 950-nm). The crystal was extensively modeled to design the BBO crystal and the cavity. Both high and low signal to pump angle phase matching configurations were investigated. It was found that the high angle solution produced an unwanted blue component in the light; so the low angle solution was used. The pump angle was about 23.8 degrees and the signal angle was about 21.4 degrees. The Cavity consists of a high reflector (99%) at one end and an output coupler (95%) at the other. The idler beam (in the 1.4 to 1.8 micrometer spectral region) will be the source for the laser. The beam divergence of the idler was recollimated using a grating, and the beam divergence was 0.2-mr in the horizontal and 7.9-mr in the vertical. Figure 3 shows the wavelength structure of the signal beam in the 720 to 920-nm region. Because there was no suitable detector for the idler, the idler spectrum was theoretically calculated from the signal spectrum. The resulting calculations indicate that the idler is greater than 220-nm broad. The entire 1.4 to 1.8 region can be obtained by tuning the OPO.

The slope efficiency and power output levels were characterized for the OPO system. The OPO was pumped with three Nd:YAG lasers. First the system was tested at DERA with an injection seeded laser the idler had a 14.3% energy efficiency and the signal was 4.5%. The pump threshold was 44.8-mj per pulse. When installed at the Army Research Laboratory, two unseeded Nd:YAG lasers were tried, one in a Schwartz ElectroOptic (SEO) Ti:sapphire laser and a Big Sky laser. The results are shown in figure 4.

The SEO had a threshold of about 60-mj per pulse with 23% energy efficiency and the Big Sky was about 90-mj with 11% energy efficiency.

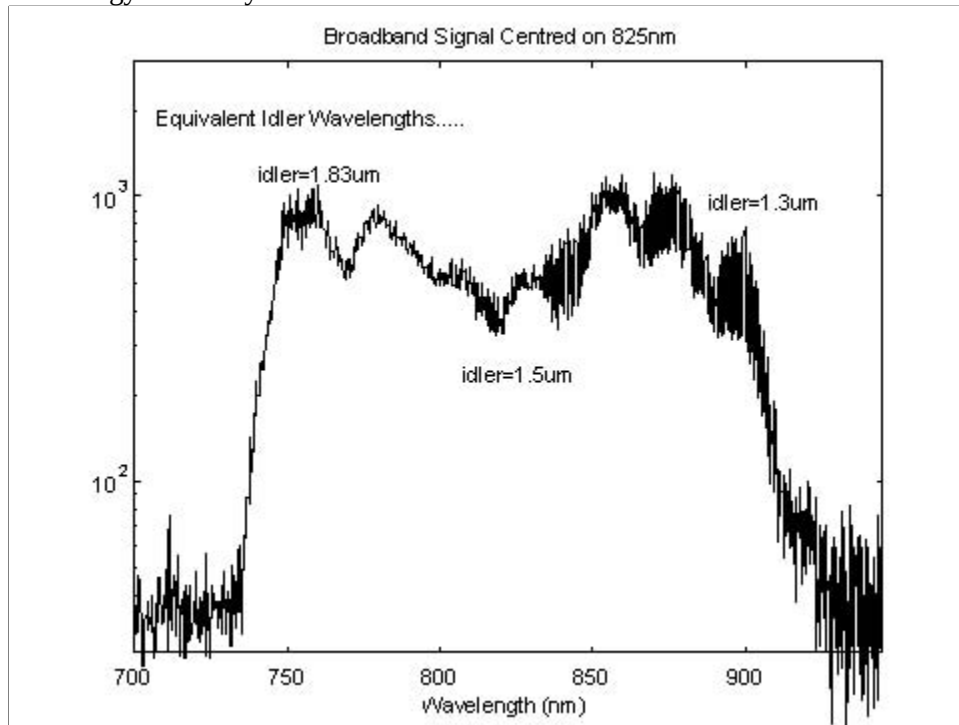


Figure 3. The wavelength spectrum of the OPO signal.

The OPO cavity oscillated and produced broad output in the 1.5 micrometer region as predicted by the modeling work. A collimator was necessary to correct for the beam dispersion. The current power output is about 7-mj per pulse for the system as configured.

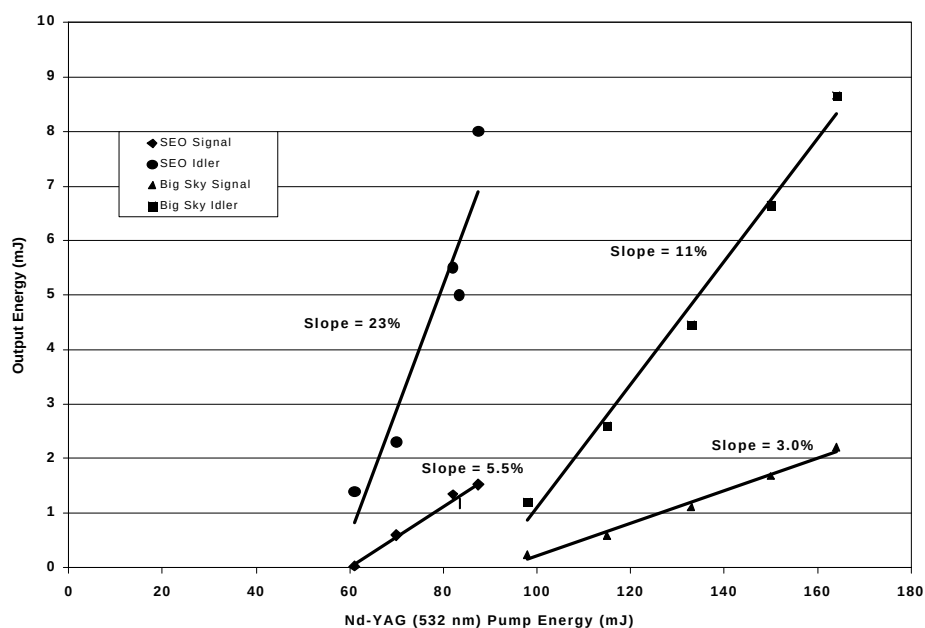


Figure 4. The slope efficiency plot for the SEO laser and the Big Sky laser.

4. CONCLUSIONS

We have designed a notional hyperspectral lidar system for standoff determination of aerosol size distributions. The lidar system is based on two new technologies: a broad bandwidth “laser” OPO source that operates in the 1.5-micrometer spectral region and an inverse Monte Carlo algorithm for analyzing the data. The hardware aspect of the system is currently a laboratory breadboard system, and aerosol experiments will commence shortly. The broad bandwidth laser has been characterized and will emit pulses of broad bandwidth light that are greater than 220-nm broad with 7-mj of power. The IMC analysis method has been rigorously tested and simulations on backscatter from aerosols have shown great promise. The inverse Monte Carlo method is very fast—typically two minutes on a desktop workstation for the entire analysis. One must assume a refractive index; however there are techniques to estimate this from the data using an iterative method. The simulation results in Section 3 demonstrate that the IMC is a stable method for inversion of scattering data. This stability comes from application of a boot strap error method. Noise levels of up to 33% can be handled successfully. The method works best when the size distributions are narrow, or wholly contained within the source spectral region; however even when the size distribution is outside the excitation region, meaningful information on the particle size is obtained. The second part of the software development is an actual lidar simulation in which the atmospheric transmission and the backscatter coefficients are analyzed. This second part is well underway and simulations have been performed. The lidar aspect may involve a calibration reflector in the near field of the lidar to provide enough information for all the required information.

5. ACKNOWLEDGMENTS

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