Improve Lidar SNR in Biaxial Systems: Simulation to Examine the Overlap Function and the Receiver Aperture Alignment

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Abstract: Lidar daylight measurements are limited by sky background noise (BGN). Reducing the BGN is essential to improve Lidar signal-to-noise ratio (SNR). The main objective of this paper is to optimize the signal to noise ratio in a biaxial Lidar system by improving the geometrical design of Lidar receiver. A series of simulations and modeling to calculate the overlap area between both the transmitter and the receiver field of view (FOV) was conducted for a vertically pointing Lidar to determine optimal receiver aperture shapes within four different lidar ranges. Results show that varying receiver aperture shape, position, and size, that accommodate all backscattering return signals over a given Lidar range, while at the same time minimizing detected BGN, will maximize Lidar SNR. This approach of improving Lidar SNR can be translated to an improvement in Lidar attainable range for backscatter schemes including Raman Lidar and Differential Absorption Lidar (DIAL).

Keywords: Biaxial Lidar, FOV, Background noise, SNR, Overlap Factor, Aperture, Simulation, Matlab.

1. Introduction

The impacts of aerosol in the human health with diseases such as lung cancer, bronchitis, and asthma have been essential motivations to record aerosol properties and transportation. Additionally, many studies investigate the relationship between the traffic pollution and the damage in human brain and analyze the effects of traffic pollution on the genome of a newborn, and prematurity and preeclampsia issues [1]. Light Detecting and Ranging (Lidar or Laser Radar) is an active optical remote sensing instrument widely used for probing the earth’s atmosphere. Lidar system is capable of providing vertical distribution of aerosol and cloud [2, 3]. Lidar has been applied to study stratospheric aerosols [4], tropospheric aerosols [5], and climate gases such as stratospheric ozone [6]. Lidar consists of three basic subsystems: the transmitter, receiver, and electronics subsystems [7]. The typical monostatic configuration of lidar systems can be classified into two categories, coaxial and biaxial. The main disadvantages in the coaxial configuration, where the coaxial alignment between transmitted beam and the receiver’s FOVs is maintained, are: (a) the detector saturation problem due to optical obstacle, and (b) the near field optical distortions for shorter range, where part of the signal is blocked by the secondary mirror. Biaxial lidar, where the transmitter and receiver are located adjacent to each other, is a practical solution to overcome the coaxial configuration problems. On other hand, the recorded data from the biaxial lidar is negatively affected by the geometrical factor (GF) at shorter range, as shown in figure 1. This effect makes near field measurements impossible (figure 1, 2). In this study, we examine the potential of improving SNR for vertically pointing biaxial lidar systems by optimizing detector aperture geometry and design through a series of simulations and modeling using Matlab for four different lidar ranges. To realize the effect of GF $\xi(R)$ in the return lidar signal, the lidar Equation can be written as [8]:

$$P(\lambda_k, R) = P_0 \frac{A_0}{R^2} \xi(\lambda_k, R) \beta(\lambda_k, R) \frac{\epsilon L}{2} \exp \left( -2 \int k(\lambda_k, R) dR \right)$$  \hspace{1cm} (1)
Where, \( p(\lambda_z, R) \) is the total scatter laser power received from a distance \( R \), \( p_x \) represents the average power in the laser pulse, \( A_r/R^2 \) describes the solid angle of the receiver optics (\( A_r \) is the area of the telescope primary mirror), \( \xi(\lambda_z) \) denotes the receiver’s spectral transmitter factor, \( \beta(\lambda_z, R) \) is the volume backscatter coefficient, \( c_\tau \) represents laser pulse length (\( c \) is speed of light, \( \tau \) is Laser pulse rectangular duration), \( k(\lambda_z, R) \): Atmospheric extinction coefficient. The smaller the value of \( \xi(R) \) is the smaller the return signal and the smaller SNR particularly for low altitudes. GF can be defined as the ratio of the energy transferred to the photodetector to the energy reaching the telescope primary mirror, \( E_{det}/E_{can} \). This reduction in the detector response to the return signal is caused by a lack of perfect overlap between the receiver telescope’s FOV and the transmitter laser beam. In the following section, we describe the problem and discuss the calculations. The overlap effect of the GF including the receiver field stop position and size, and their effect in lidar SNR improvement will be introduced. Then Lidar simulation results will be introduced.

2. Problem Description and Calculations

The standard configuration for most lidar systems is to place a ‘round’ aperture at the focal point of the receiver telescope. It is also commonly assumed that once the lidar receiver FOV and transmitted beam are completely overlapping, the efficiency of collection is unity. However, this analysis does not properly take into account the shifted position of the collected backscattering signals on the image plane from the telescope focal point at the receiver. As shown in figure 1 & 2, the image displacement is range dependent and it is due to the distance ‘\( b_o \)’ between the laser and telescope optical axis. In our calculations, the telescope is represented by a lens with diameter ‘\( t_o \)’ and ‘\( f \)’ focal length. The farther the lidar object (\( z=R_{max} \)), the smaller the sounding image (\( Im_t \)). Numerous papers implemented a wedge-like shape aperture design to overcome this shifted problems. In this paper we analyze the effect of changing the size, shape, and alignment of a round aperture in the lidar SNR. As shown in Fig. 3, we assume the optical vertical axis \( z \) the ground level (\( x \)-axis), where the location of the telescope primary mirror and the transmitted laser beam, is at \( R=0 \). The range ‘\( R \)’ increases, there will be a point ‘\( R_i \)’ where the first intersection between the left boundary of the laser beam FOV and the right boundary of the telescope FOV. Then at (\( z = R_i \)), a complete overlap is formed. But this is not the effective overlap function. The effective FOV is based on, \( D_o \), the field stop diameter (\( \phi_{eff} = D_o / f \) the shaded area in this case) [9]. The actual overlap started at (\( z = R_i \)) and finally the effective overlap is completed at (\( z = R_o \)). At short distances (\( z < R_o \)) the ratio of the overlapping area (\( OL_{area} \)) to the image area (\( Im_{area} \)) that formed near to ‘\( f \)’ is equal to zero: \( \xi(R) = OL_{area} / Im_{area} = 0 \), where \( OL_{area} = 0 \). This is making near field observations impossible (effective telescope area: \( A_{off}(R) = A_o \xi(R) = 0 \) [11].
In the case of a small round aperture \( (D_o = 2 \text{ mm diameter}) \) is placed at the telescope focal point \( f_o \), the overlap function \( \xi(R) \) is very small for any object in ranges of \( (R_1 < z < R_3) \), where at \( R_3 \) there is an arbitrary object which has a large sounding image and very far from \( f \) in the imaging plan (see Fig. 3) [11]. Design of a unique aperture to cover certain desired ranges becomes feasible. In our calculation, a Matlab code was created to simulate the biaxial Lidar system performance using the lidar design parameters in Table 1, and equations from Table 2 [12]. Then, the size and position of the sounding image at the telescope were also calculated for four different ranges. Using the size and position of the sounding image, apertures were proposed to accommodate the entire backscattering signal and, at the same time, eliminate the BGN, then improve the SNR. To visualize this improvements, the GF was calculated as well.

3. Results and Analysis

![Figure 3. Biaxial Lidar: overlap between effective FOV of telescope (diameter = \( t_o \)) and laser beam (initial diameter = \( L_o \)) and aperture (diameter = \( D_o \)) [11]](image)

![Figure 4. Images position, proposed aperture size and shape, and the corresponding comparison of the geometric factor of the new and old aperture in (a) Short Range, (b) Mid-low Range, (c) Mid-Range, and (d) Long Range](image)
The simulation of the Lidar system shows that the telescope and laser beam overlap starting after 40 meters of altitude. We examined the GF for four different ranges: Short Range: from 0.05km up to 3km, Mid-low Range: from 3km to 15km, Mid-Range: from 15km to 30km, and Long Range: from 30km to 50km (the maximum altitude of the Lidar). Figure 4 is the graphical representation of the results summarized in Table 3 (the size and position of the sounding image) for four cases. The black circumference represents an initial proposed aperture of radius 1mm at the focal point of the telescope, while the red figure represents the new proposed aperture. The comparison of GF between the traditional aperture and the GF obtained with the new aperture shows a significant improvement. Table 3 summarized the proposed apertures position (center), size, shape, area, and the GF for each of the four cases.

### Table 3. Results for Aperture Size and GF

<table>
<thead>
<tr>
<th>Range (km)</th>
<th>Image $R_{\text{max}}$ Radius (mm)</th>
<th>Image $R_{\text{min}}$ Radius (mm)</th>
<th>Aperture Center</th>
<th>Aperture Shape</th>
<th>Aperture Area (mm$^2$)</th>
<th>Geometric Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 - 3</td>
<td>1.3735</td>
<td>1.6967</td>
<td>(-8.85, -172.4)</td>
<td>Trapezoid</td>
<td>930.71</td>
<td>5.1 x 10$^{-3}$</td>
</tr>
<tr>
<td>3 - 15</td>
<td>1.3695</td>
<td>1.3735</td>
<td>(-0.15, -3.061)</td>
<td>Complex</td>
<td>11.535</td>
<td>0.437</td>
</tr>
<tr>
<td>15 - 30</td>
<td>1.3690</td>
<td>1.3695</td>
<td>(0, -0.75)</td>
<td>Ellipse</td>
<td>7.213</td>
<td>0.816</td>
</tr>
<tr>
<td>30 - 50</td>
<td>1.3688</td>
<td>1.3690</td>
<td>(0, 0.408)</td>
<td>Ellipse</td>
<td>6.456</td>
<td>0.911</td>
</tr>
</tbody>
</table>

4. Conclusions

In the effort of improving the SNR in biaxial Lidar system by optimizing the geometrical factor of the Lidar receiver, we propose a change in the receiver aperture shape, positions and size for different ranges (that accommodate all backscattering return signals over a given Lidar range, while at the same time minimizing detected BGN). Using this proposed design, a series of simulations and modeling to calculate the GF of a vertically pointing Lidar shows significant improvements in GF, hence improves lidar SNR, in mid and high ranges compared to less improvement in short and mid-low ranges. In this study, the GF in biaxial Lidar system was analyzed as a parameter to improve the SNR. Our results have shown vast improvements at different ranges. In the low range, 0.05-3km, GF was increased by using a trapezoidal aperture when it was nearly impossible to attain a good signal at that altitude. Yet the size and position of the aperture are too big, therefore it is impossible to be implemented at the low range. In the Mid-low range, 3-15 km a complex aperture is proposed to better fit all the images at this range. An overlap factor of 43.7% was achieved within this range. For Mid (15-30km) and High (30-50km) ranges elliptical shaped apertures have been tested and showing changes in the GF (81.6% and 91.1%, repetitively).

5. References


