Eye-safe Atmospheric Lidar Measurements

ABSTRACT

Through the use of lidar, various details of atmospheric composition can be discerned. The National Center for Atmospheric Research developed an eye-safe lidar implementation for atmospheric investigation. Using stimulated Raman scattering (a third-order nonlinear process) the instrument output is eye-safe at approximately 1.5 µm. The instrument has a range of up to 9 km. It also has performance and durability advantages over many previously reported eye-safe lidar configurations. Eye-safe operation is necessary to broaden the available locations for measurements, including more populated areas and near airports.

OVERVIEW

Utilization of lidar to study the atmosphere is of interest to meteorologists to better understand boundary layers, aerosol distribution, and pollution, with respect to both range and time. With many instances of elastic backscatter lidar, however, the probing light is at a non-eye-safe wavelength and/or power. Hence, it is important to develop an eye-safe method.

Eye-safe operation would allow for the instrument to be operated in populated areas, and around airports. It is well-known that visible and near visible wavelengths focus light into the retina, making them particularly dangerous for the human eye. Using wavelengths that are not focused into the retina is one option for eye-safe lidar measurements.

An operation wavelength of ~1.5 µm was chosen for multiple reasons. First, this wavelength is in a region of the spectrum allowing for maximum energy while still being safe for the human eye (see **Figure 1**). Second, there are a multitude of commercially available detectors well-suited for acquiring signals at this wavelength that do not require specialized cooling. Finally, longer wavelengths have less molecular scattering and lower sky radiance contributions to the measured signal than eye-safe ultraviolet light. These factors lead to increased measurement contrast and a greater signal-to-noise ratio.

Stimulated Raman scattering (SRS) was used to shift the non-eye-safe pump beam to a longer, eye-safe wavelength. SRS is a third-order (i.e. weak) nonlinear scattering process, which excites molecular vibrations. These molecular vibrations induce a post-scattering wavelength shift. With knowledge of the scattering medium's vibrational characteristics and the wavelength of the pump beam, various allowable wavelength shifts can be calculated.

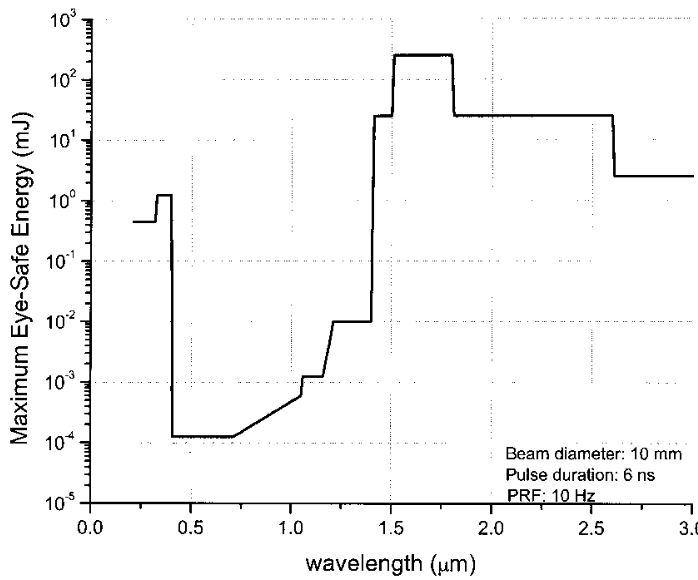

Figure 1. The maximum eye-safe energy varies as a function of wavelength. Operation around 1.5 µm allowed for maximum energy for the given parameters. Reprinted with permission from Ref. [1], *Applied Optics*.

Non-stimulated Raman scattering is also possible. This begins with the spontaneous emission of a photon from the medium. In this case, however, beam properties and power will vary. To avoid these undesirable fluctuations, a second laser (the seed laser) is used to stimulate particular Raman transitions and control spatial beam parameters.

The role of the seed laser is to enhance the preferred Raman scattering in a well-defined manner. When the seed laser interacts with the Raman medium, it effectively biases the scattering towards a specific shifted wavelength. Here, the first Stokes shifted wavelength was desired, so the seed laser's emission matched the first Stokes wavelength.

The use of a seed laser allowed for the elimination of variances in power and spatial beam properties. The seed laser "stimulates" the preferred Raman transition, thus the method being called stimulated Raman scattering, as opposed to Raman scattering.

The pump beam (emitting at a non-eye-safe wavelength of 1064 nm) was directed in an adjustable, multi-pass configuration through a gas cell filled with circulating methane (CH_4). **Figure 2** shows the experimental configuration used. The multi-pass configuration extends the path length through the medium. Adjusting the path length through the methane allowed empirical optimization of the Stokes-shifted output power. The gas cell was specifically designed to suppress other (non-first Stokes) wavelength shifts, further enhancing the optimization of the first Stokes wavelength. The pump beam, when scattered through methane, has an eye-safe first Stokes wavelength of 1543 nm.

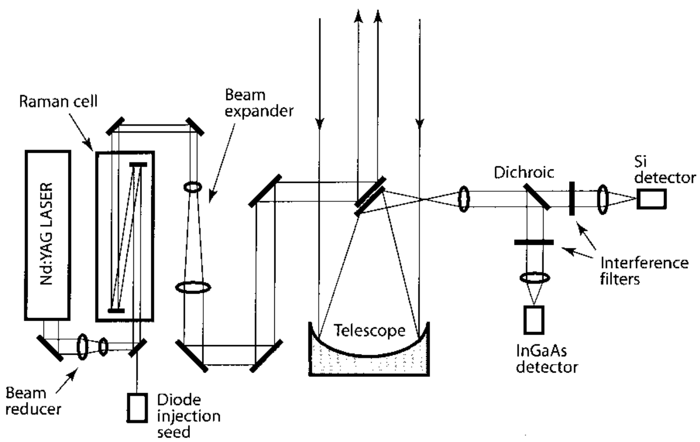

Figure 2. Experimental layout for the Raman-shifted lidar measurements. Reprinted with permission from Ref. [1], *Applied Optics*.

Once the system's wavelength was shifted to an eye-safe regime, the beam could then be used to acquire elastic backscatter lidar data.

PREVIOUS METHODS

Previous lidar systems pumping CH_4 to shift the wavelength encountered issues with gas cell window transparency. Since SRS is a third-order process, it requires a high energy density. To reach the requisite energy density threshold, these systems tightly focused the pump beam within the gas cell. The focused beam resulted in optical breakdown of the gas. Over time, this breakdown resulted in the cell windows becoming coated with a soot layer, degrading performance.

Methods not utilizing SRS have also been developed. Solid-state optical parametric oscillators (OPOs) have been used in some lidar systems as an alternative to SRS for shifting the wavelength to an eye-safe region. This is advantageous in that no methane needs to be handled. Unfortunately, OPOs result in high beam divergence at the powers required for lidar measurements, increasing the measurement difficulty.

With this information, the researchers chose to employ the SRS method. To avoid the sooting reported in previous systems, they used a higher power pump laser that was not focused in the cell.

CONTROLLING THE STOKES SHIFT

The dependence of the resulting shifted wavelength on the pump laser and the targeted Raman transition is given by

$$\frac{1}{\lambda_n^S} = \frac{1}{\lambda_p} - \frac{n}{\lambda_R} \qquad \textbf{(1)}$$

and

$$\frac{1}{\lambda_n^{AS}} = \frac{1}{\lambda_p} + \frac{n}{\lambda_R} \qquad \textbf{(2)}$$

where λ_n is the nth Stokes (S) or anti-Stokes (AS) wavelength, λ_p is the pump wavelength, and λ_R is the Raman transition's wavelength.

A pump wavelength of 1064 nm interacting with methane resulted in dominant Raman wavelengths of 1543 nm, 2.808 µm, and 812 nm [1]. These are the first Stokes, second Stokes, and first anti-Stokes wavelengths, respectively.

The researchers describe their method for reliably outputting the 1543 nm stimulated Raman scattered light as follows:

"Typically, the Stokes field is initiated by the spontaneous emission of a photon, and therefore the energy and spatial characteristics will fluctuate. To prevent these fluctuations one can seed the cell with a stable tunable Stokes wavelength laser. We injection seed our Raman cell with a continuous-wave 20-mW telecom diode laser (Mistsubishi FU-68PDF/520M45B). The laser has a center wavelength of 1543.73 nm and approximately 3-nm tunability."

Multiple steps were taken to ensure the first Stokes wavelength is the prevalent output from the pressurized gas cell. First, injection seeding was utilized, as described earlier. Secondly, specific optical consideration was made to suppress the second Stokes wavelength as well as the first anti-Stokes wavelength.

Wavelength Electronics laser diode driver WLD3343 and temperature controller WTC3243 were used to control the output of the seed laser. These modules matched the requirements for the seed laser. The low power required also enabled operation of the driver away from the upper and lower bounds of drive current, where noise contributions could be greater. Both laser current and temperature were used to fine-tune the output wavelength to stimulate the desired Stokes wavelength. Here, the precision temperature controller and laser diode driver allowed for tight wavelength control. Thus, the emission at 1543 nm from the gas cell was optimized.

In addition to injection seeding, other experimental parameters were also fine-tuned to maximize the efficiency of the 1543 nm output. These parameters include the pump laser's pulse energy, the gas cell pressure, and the path length within the gas cell.

BEAM QUALITY

Beam quality was also an important parameter for these measurements. The divergence of the beam (Θ) is given by

$$\Theta = \frac{2M^2\lambda}{\pi w_0} \quad \textbf{(3)}$$

where M^2 is the beam quality factor, λ the wavelength, and w_0 the radius of the beam waist.

To limit the divergence of the output beam and avoid the problems encountered with OPO systems, the researchers used two methods.

First, the beam quality was improved via the seed laser. It is important that the seed laser emits a nearly perfect Gaussian beam. It is known that current noise from the driver can influence spatial beam properties. Thus, the low noise provided from the driver helped ensure ideal beam properties. Without these optimal spatial characteristics of the seed laser, the output beam from the gas cell would deteriorate.

Second, after exiting the multi-pass cell, the resulting beam was expanded prior to being used to take measurements (see **Figure 2**).

Both methods help to limit the divergence of the beam, and thus give this configuration an advantage over OPO systems.

RESULTS

With the SRS-shifted lidar system, the researchers were able to obtain atmospheric composition data to a resolution of 53 m. The collected data's resolution was limited by the detector, not the transmission scheme.

They collected data using two different methods. One set of data presented was collected by pointing the lidar beam vertically, and the second set of data was collected by pointing the lidar beam at an angle of 3° above the horizon.

The vertical data collection shown in **Figure 3** took approximately 17 minutes with a net range of 700 m. Here, the researchers also collected data with the original pump beam operating at 1064 nm as a method of checking the collected data. The 1064 and 1543 nm data match very well, indicating that the eye-safe lidar system is operating as expected.

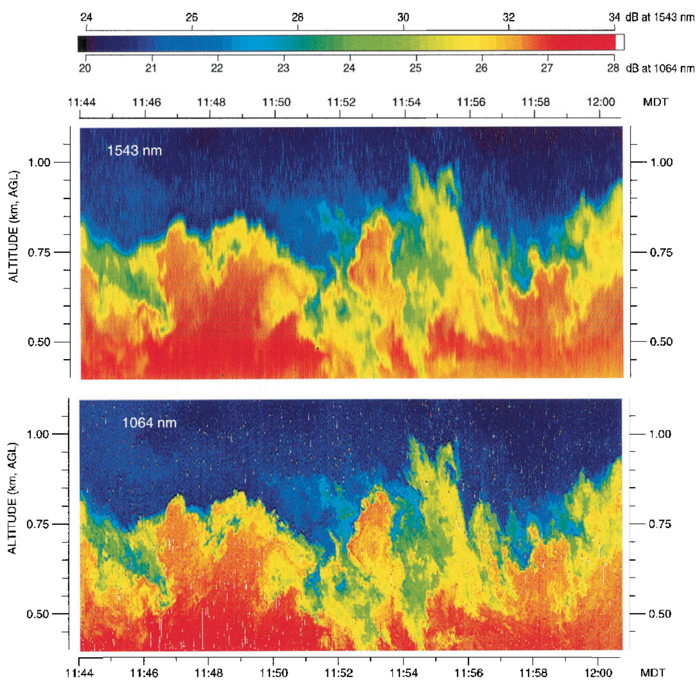

Figure 3. Vertically collected lidar data for the 1543 nm Raman-shifted beam (top) and 1064 nm pump beam (bottom). Reprinted with permission from Ref. [1], *Applied Optics*.

The horizontally collected data (shown in **Figure 4**) was able to discern coherent structures over approximately a 9 km range. The horizontal data was collected over 33 minutes with roughly a 9 km range.

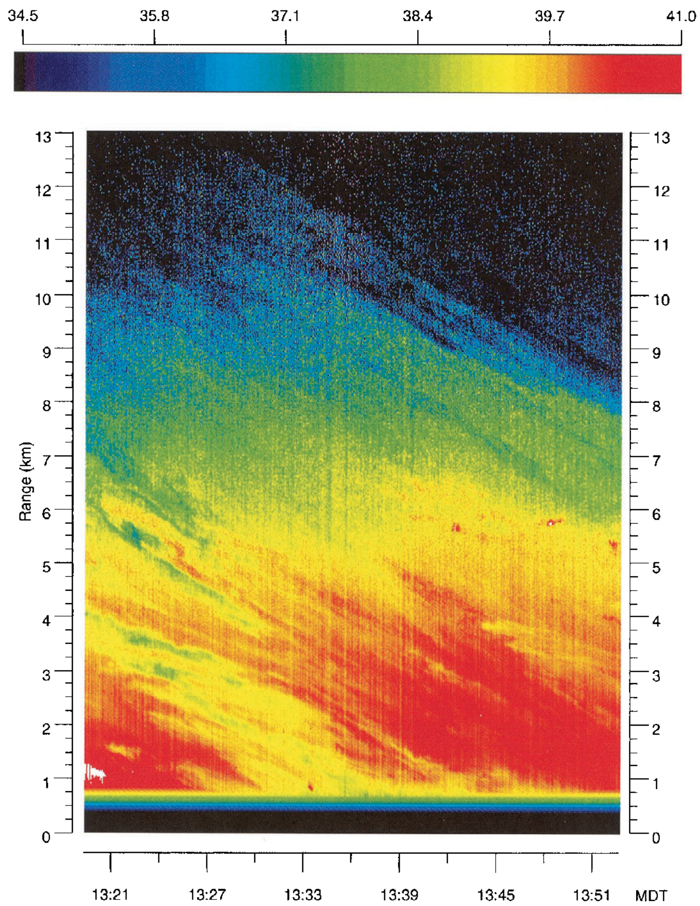

Figure 4. Lidar data collected horizontally with the Raman-shifted beam. Reprinted with permission from Ref. [1], *Applied Optics*.

In the presented data, information such as aerosol plumes and atmospheric layers are resolved. This type of information is important for research meteorologists.

WAVELENGTH SOLUTIONS

The researchers have shown an improved aerosol lidar system, which utilized higher pump pulse power than previous systems. This, in combination with diode laser injection seeding allowed eye-safe lidar measurements of atmospheric composition as a function of both distance and time.

The seed laser aided in the ability to collect this data, by optimizing the Stokes-shifted output beam. The use of a seed laser improved the beam quality, enhanced the conversion efficiency to the 1543 nm Stokes wavelength, and reduced the pulse-to-pulse energy fluctuations.

Wavelength's WLD3343 and WTC3243 were used to control the seed laser. The seed laser's output wavelength was a crucial parameter to control in order to optimize the beam output. The WLD laser driver, with 200 ppm current stability, paired with the WTC temperature controller with stability better than 1 mK, allowed for precise tuning of the wavelength.

REFERENCES

1. S.D. Mayor and S.M. Spuler, "Raman-shifted eye-safe aerosol lidar," Appl. Optics **43**(19), 3915-3924 (2004).

USEFUL LINKS

- WLD3343 Product Page
- WTC3243 Product Page

PRODUCTS USED
WLD3343, WTC3243

KEYWORDS
lidar, aerosol, elastic backscatter, Raman, Stokes, seed laser, methane, atmospheric sensing, eye-safe

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