Optimization of an Optical Design for a Rotational Raman Lidar for Profiling the Accurate Atmospheric Temperature

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Abstract: Accurate thermodynamic profiling is crucial for predicting cloud developments leading to torrential rainfall. Here, we present the construction of a rotational and vibrational Raman lidar system aiming at profiling temperature and water vapor in the lower troposphere, utilizing a 266 nm laser. Our novel optical system for our rotational Raman detection incorporates a double-grating spectrometer and a linear array photomultiplier tube, which effectively shapes the spectrum and streamlines optical alignment. This design minimizes the impact of laser wavelength instability, allowing for using a non-seeded laser source. Furthermore, we enhance temperature estimation accuracy by integrating a relay lens that optimizes wavelength resolution across the optical detection and receiving systems. Our work introduces an optimized optical design for rotational Raman lidar, facilitating precise atmospheric temperature profiling.

1. Introduction

Accurate, high-temporal–spatial–resolution observations of thermodynamic profiles in the lower troposphere are crucial for understanding localized heavy rain processes, such as linear rainbands leading to water-related disasters, and for enhancing weather forecasting. Raman lidar stands as a well-established tool for measuring temperature and water vapor mixing ratio profiles with high spatiotemporal resolution [1-2]. In this study, we developed a Raman lidar system employing a laser wavelength of 266 nm. This technique offers the advantage of minimal daytime background noise, attributed to ozone layer absorption in the stratosphere [3]. The water vapor component of our observations showcased the capability to continuously acquire water vapor profiles at an observatory nestled within a forest throughout 2018 [4], and within an urban setting in 2020 [5]. Here, we introduce optimization of the optical design for a rotational Raman lidar to accurately profile atmospheric temperatures.

2. System setup

The experimental setup for the Raman lidar is illustrated in Figure 1. We utilize the fourth-harmonic output (266 nm) of a non-seeded Nd:YAG laser (Continuum Surelite III-10, USA), operating with a pulse energy of < 20–30 mJ. The divergence of the outgoing laser beam, post passage through the beam expander, measured at 0.17 mrad. An optical receiver, in the form of a custom-made Cassegrain telescope (Raymetrics, Greece), featuring a primary mirror diameter of 350 mm, was employed.

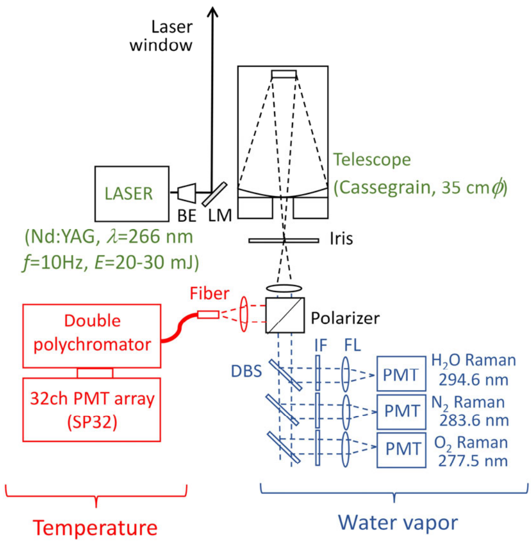

Figure 1. Schematic setup of temperature and water vapor Raman lidar. (BE: beam expander, LM: laser mirror; FL: focusing lens; ND: neutral density filter; DBS: dichroic beam splitter; IF: interference filter; PMT: photomultiplier tube)

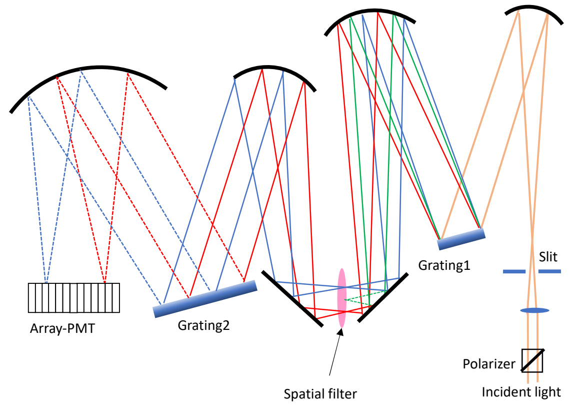

Figure 2. Schematic diagram of a polychromator consisted of a double-grating spectrometer and an array PMT.

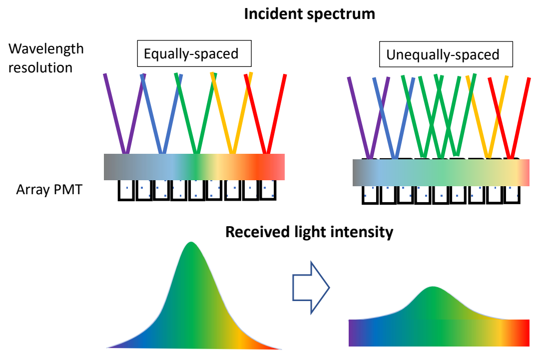

Figure 3. Received light intensities of a rotational Raman scattering observed from the spectrometers with equally spaced (left) and unequally spaced (right) resolutions.

The receiving system was divided into two parts: (1) a component for water vapor, comprising an interference-filter-based polychromator and a photomultiplier tube (PMT); and (2) a component for temperature, utilizing a double-grating spectrometer and a multispectral lidar detector (Licel SP32-HR, Germany). The SP32 is a 32-channel single photon counting system featuring a linear array PMT (Hamamatsu H7260, Japan). Each photocathode element pitch measures 1.0 mm, comprising an effective area of 0.8 mm × 7 mm with a 0.2 mm partition between each channel.

3. Optimization of the Optical Design for Temperature Measurement

The spectral detection component of the temperature lidar comprises a double-grating spectrometer and an array of PMT. The multispectral method enables the determination of the rotational Raman spectrum (RRS) shape, reducing uncertainties in laser wavelength stability and allowing for using a non-seeded laser.

The primary technical challenge of the rotational Raman technique is to sufficiently block the elastic backscatter signal in the rotational Raman channels. As illustrated in Figure 2, we employed two methods to attenuate the strong elastic backscattering by approximately 10^{-8} in the receiving optics. First, we used a polarization beam splitter to block a significant portion of the elastic scattering, leveraging the different polarization properties between elastic scattering from spherical particles and Raman scattering. Second, a spatial filter was implemented to eliminate the scattering of a specific wavelength in the double-grating spectrometer.

However, certain issues must be considered when using an array PMT for RRS detection. Firstly, all channels have the same dynamic range, which makes it challenging to simultaneously measure long-range signals with significant differences in intensity between the channels. Secondly, approximately 3% of crosstalk occurs between adjacent channels, which further complicates measurements. To address these challenges, we propose an optimization method, as illustrated in Figure 3, aimed at reducing the effects of dynamic range and crosstalk. Temperatures were estimated using RRS, where the intensities of the strong and weak signal wavelength bands differed by more than ten times. To accommodate this difference, an optical system employing an aspherical lens to create distortions was developed. The wavelength resolutions were unevenly spaced to disperse the wavelength regions with strong signals and concentrate them on the wavelength regions with weak signals. By reducing the difference in signal strength between channels, the effects of crosstalk can be partially mitigated, and the dynamic range of the PMT can be more effectively utilized to account for distance attenuation.

We assessed the accuracy of temperature estimation using the RRS detected in six assumed spectrometer patterns with varying wavelength resolutions, as depicted in Figure 4(a). The wavelength resolutions for Cases 1–2 were uniformly set across all channel at equal intervals, mirroring conditions during normal operation. For Cases 3–6, the resolutions were adjusted such that channels closer to the center (CH = 17) had finer resolutions, while those nearer the edges had coarser ones. Notably, Cases 5–6 featured higher wavelength resolutions near the center compared to Cases 3–4.

To assess spectral shape alterations induced by SP32-HR, we considered factors including the 0.2 mm dead space between each array-PMT channel, dead time, and crosstalk effects. Following guidance from the PMT catalog [6], we assumed crosstalk rates of 3% on the adjacent channel and 0.8% on channels two steps away from the target channel.

In the simulation, we utilized a scenario where the rotating Raman spectrum at 273 K was measured with the wavelength resolution illustrated in Figure 4(a). Initially, we acquired the calibration values necessary for the Raman lidar method when the channel exhibiting maximum signal intensity in the spectrum (CH-max) was set at 20 MHz. Subsequently, the observed signals were computed by introducing a normal distribution error of 1σ = 5% to the theoretical spectrum with the CH-max value varying from 2 to 100 MHz. Adjustments were made to the signal light intensity to account for the effects of dead time and crosstalk. Temperature estimation employing the observed signals with errors was conducted 100 times for each CH-max, and the temperature estimation bias and error were determined.

Figures 4(b) and 4(c) depict the simulation results of temperature bias and 1σ error for six cases. The x-axis denotes the value of the channel exhibiting the maximum intensity in the spectrum. The results illustrate that enhancing temperature estimation accuracy is achievable by suitably adjusting wavelength resolution at non-uniform intervals. Particularly, augmenting wavelength resolution near the central region of the spectrum, characterized by strong signal intensity, mitigated uncertainty arising from crosstalk from channels with high-signal level, thus enhancing temperature estimation accuracy. Case 6 underwent optimization to attain the highest temperature estimation accuracy.

An optical system featuring unequally spaced resolution was assembled using relay lenses. Figure 5 illustrates an optical design with characteristics akin to those of Case 6 in Figure 4(a). Under uniform illumination incident on the relay optics, the center channel darkens while both ends brighten. Figure 6 delineates the disparities in observed RRS signals contingent upon the presence or absence of relay lens optics. Halving the value of the channel exhibiting maximum signal intensity resulted in increased values at both ends with weak signals.

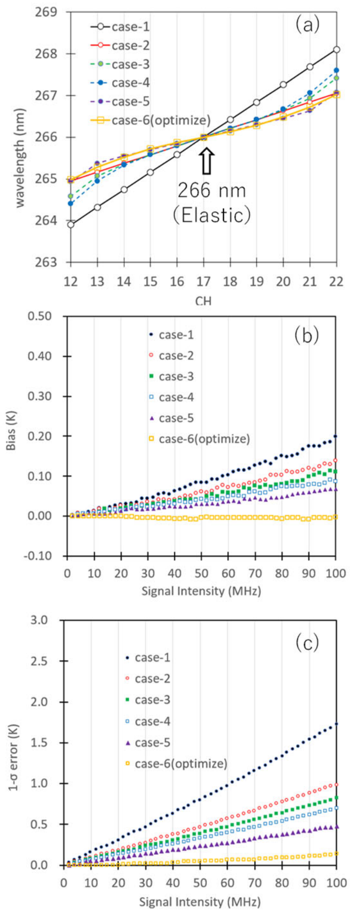

Figure 4. (a) Center wavelengths of each channel of the array-PMT for six different spectrometers with equally spaced or unequally spaced resolutions. Theoretical simulation of (b) the bias and (c) the 1-σ errors of the derived temperature for six different spectrometers caused by detector-specific parameters such as dead time and crosstalk.

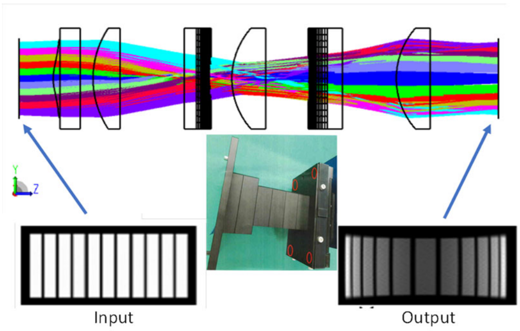

Figure 5. Optical design of the relay lens for adjusting the wavelength resolution of the spectrometer to unequal intervals.

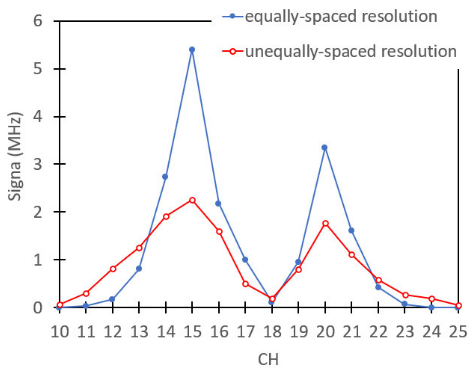

Figure 6. Variations in observed RRS signals depending on the presence or absence of the relay lens optics (August 8, 2023, 13:00–14:15JST, Shigaraki MU Observatory)

5. Summary

We constructed a rotational and vibrational Raman lidar system to profile temperature and water vapor in the lower troposphere, employing a laser with a wavelength of 266 nm. We proposed the optimization of the optical design for a rotational Raman lidar utilizing an array PMT, to accurately profile atmospheric temperatures. Currently, we are evaluating its performance based on these observations.

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