Preliminary study on ground based coherent differential absorption LIDAR for vertical profiling of water vapor density using 1.53 µm wavelength

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Abstract: We performed preliminary study on a ground based coherent differential absorption lidar (DIAL) for vertical profiling of water vapor density using 1.53 µm laser wavelength. We assumed the atmospheric condition using the fast atmospheric signature code (FASCODE), and estimated the measurement accuracy using coherent lidar equation. Simulation results show a 10% accuracy of water vapor density from an altitude of 0.1 km to 4.5 km with 10 minutes average.

Keywords: Water vapor, Differential absorption, Coherent

1. Introduction

Water vapor in the atmosphere affects growing cumulonimbus which causes localized heavy rainfall, therefore the measurement of water vapor density profile is required for the early prediction of this rainfall. Height profile of water vapor measurement using incoherent differential absorption lidar (DIAL) technique was reported in Ref. 1 and 2. The continuous height profile measurement was demonstrated, however, the measurement accuracy was influenced by solar background light. On the other hand, coherent DIAL technique can overcome this issue and was reported in Ref. 3 and 4. The good agreement result on water vapor density in comparison with that of radiosonde soundings was shown.

Since late 1990s, we have been developing the wind sensing coherent Doppler LIDARs with 1.5 µm wavelength. The LIDAR with 1.5 µm wavelength has advantages such as its compactness and reliability by using telecom products. Here, we consider to apply this technology to DIAL, and perform preliminary study on a ground based coherent DIAL for vertical profiling of water vapor density using 1.53 µm laser wavelength. In the followings, we discuss the concept, configuration, and simulation results of the lidar.

2. SYSTEM CONFIGURATION

The system configuration is shown in Fig. 1. A CW laser lights with 1.5 µm wavelength from two laser diodes are locked to the ON and OFF wavelength for water vapor. Either ON or OFF wavelength lights are selected by an optical switch. Selected laser light is modulated with a pulse waveform, is amplified, and is transmitted to the atmosphere. A part of the CW light is tapped and used for a local signal light for heterodyne detection. The received lights are converted into electrical signals by a photodetector. The received signal is analog-to-digital converted and spectral analysis and accumulation is performed in the signal processor. A coherent lidar has an advantage in daytime measurement compared with incoherent lidar because the influence of background light is greatly low. In addition, the lidar can simultaneously measure wind speed and water vapor density.

A differential absorption optical depth DAOD and water vapor density n are derived from a ratio of the normalized measured intensities of the two wavelengths, and are written by
where $P_{\text{off}}(z)$ is received power of OFF wavelength in electric domain and $P_{\text{on}}(z)$ is received power of ON wavelength in electric domain at range $z$. $\Delta z$ is range resolution of the lidar, $k_{\text{on}}$ and $k_{\text{off}}$ are absorption coefficient of ON wavelength and OFF wavelength, respectively. If the absorption coefficient is constant, the random relative error of the water vapor density $\Delta n/n$ is expressed by

$$\frac{\Delta n}{n}(z_i) = \left( \frac{1}{\text{SNR}_{\text{on}}(z_i)} \right)^2 + \left( \frac{1}{\text{SNR}_{\text{off}}(z_i)} \right)^2 + \left( \frac{1}{\text{SNR}_{\text{on}}(z_{i+1})} \right)^2 + \left( \frac{1}{\text{SNR}_{\text{off}}(z_{i+1})} \right)^2 \cdot \frac{1}{\text{DAPD}(z_i)}$$

... (3)

where $P_{\text{shot}}$ is shot noise power in electric domain and $N$ is number of laser shot. The first term in a denominator is the signal-to-noise ratio (SNR) depend on the shot noise, and the second term in a denominator is the SNR depend on the speckle noise.

3. WAVELENGTH SELECTION

The main requirements for ON wavelength selection in 1.5 $\mu$m wavelength region are (i) strong line intensity and high weighting function near the ground in the region of the band of optical amplifier, and (ii) low temperature dependence of absorption. Figure 2 shows the line intensity of water vapor absorption lines for 700 nm - 2100 nm range (upper) and 1520 nm - 1570 nm range (bottom). Although an absorption coefficient of 1.5 $\mu$m wavelength region is lower than one of 0.8 $\mu$m wavelength region which has been used widely in the past literature, it is suitable for long range measurement. In the band of
optical amplifier, the strong line intensity is in shorter wavelength, and the value is $3.066 \times 10^{-24}$ (cm/molecule) at 1531.374 nm wavelength.

Figure 2: Line intensity of water vapor for 700-2100 nm range (upper) and 1520-1570 nm range (bottom).

Temperature dependence of the line intensity is expressed by

$$ S_T(T) = S(T_{296}) \cdot \frac{Q(T_{296})}{Q(T)} \cdot \exp \left( \frac{h \cdot c \cdot \nu}{k \cdot T} \left( \frac{1}{T_{296}} - \frac{1}{T} \right) \right) \cdot \left\{ \frac{1 - \exp \left( \frac{h \cdot c \cdot \nu}{k \cdot T} \right)}{1 - \exp \left( \frac{h \cdot c \cdot \nu}{k \cdot T_{296}} \right)} \right\}, \quad \cdots (5) $$

where $S(T_{296})$ is line intensity at temperature of 296 K, $Q(T)$ is the total internal partition sum, $h$ is Plank constants, $c$ is speed of light, $k$ is Boltzmann constant, $E''$ is the lower-state energy of the transition, and $\nu$ is the wavenumber of the spectral line transition in vacuum.

Figure 3 shows the temperature dependence of the water vapor line intensity. The line color of red, orange, yellow, green, and blue is the line intensity in 1.5 μm wavelength region. The white color line is the line intensity in 0.8 μm wavelength region which is used for the typical incoherent DIAL system [2]. The minimum temperature dependence is 1531.374 nm in the 1.5 μm wavelength region, and we selected this wavelength as the ON wavelength.
4. **CALCULATION RESULTS OF RANDOM RELATIVE ERROR IN WATER VAPOR DENSITY MEASUREMENT**

We calculated the random relative error of the water vapor density by using eq. 3. The system parameters are described as follows. On and OFF wavelength are 1531.374 nm and 1531.555 nm, respectively. The output laser energy is 1.6 mJ, pulse width is 650 ns which correspond to about 100 m range resolution, and repetition frequency is 5 kHz. The receiver diameter is 150 mm, and system efficiency is -4 dB. The number of laser shot is 30,000 for each wavelength, which correspond to the 10 minutes observation time. About the atmospheric model, U.S. standard atmosphere 1976 is used, and the height profile model of aerosol backscatter coefficient from Ref. 5 and water vapor density from Ref. 6 are used. These are shown in Fig. 4 (a) and (b).

Calculation results of the received power in electrical domain and relative error of water vapor for 100 m, 300 m, and 500 m range resolution are shown in Fig. 4 (c) and (d). Simulation results show a 10 % accuracy of water vapor density from an altitude of 0.1km to 4.5km with 10 minutes averaged. These results indicate that coherent DIAL has the potential of the water vapor density measurement for weather forecast of localized heavy rainfall.
Figure 4. Height profile model of aerosol backscatter coefficient (a), water vapor mixing ratio (b), the received power for $\lambda_{on}$ and $\lambda_{off}$ at 100 m range resolution (c), and the relative error of water vapor for 100 m, 300 m, and 500 m range resolution (d).

5. REFERENCES