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Demonstration of coherent differential absorption lidar for wind and water vapor measurements using high-precision wavelength stabilization circuit

Kenya Yano[(a)], Eisuke Haraguchi[(a)], Hidenobu Tsuji[(a)], Masaharu Imaki[(a)], Satoru Yoshida[(b)], Tetsu Sakai[(b)], Tomohiro Nagai[(b)], Masahide Nishihashi[(b)], Eiji Oikawa[(b)], Shingo Shimizu[(c)], Takeshi Maesaka[(c)], Koichi Shiraishi[(d)]

[(a)] Mitsubishi Electric Corporation, Information Technology R&D Center 5-1-1 Ofuna, Kamakura, Kanagawa, Japan, 247-8501

[(b)] Meteorological Research Institute, Japan Meteorological Agency, 1-1 Nagamine, Tsukuba, Ibaraki, 305-0052, Japan

[(c)] National Research Institute for Earth Science and Disaster Resilience, 3-1 Tennodai, Tsukuba-shi, Ibaraki, 305-0006, Japan

[(d)] Fukuoka University, 8-19-1 Nanakuma, Jonan-ku Fukuoka 814-0180, Japan

Yano.Kenya@cw.MitsubishiElectric.co.jp

Abstract:

We have developed a differential absorption lidar (DIAL) that simultaneously measures water vapor and wind for heavy rain forecasting. In this paper, we summarize the development of a wavelength control unit that takes environmental resistance into consideration and the demonstration results of water vapor and wind lidar. Temperature tests of the wavelength stabilization circuit were conducted, and it is confirmed that the circuit was stable within 0 - 60°C with a frequency stability of ±10MHz and verify the performance of the DIAL with the prototype wavelength stabilization circuit. The DIAL was installed outdoors to measure water vapor in the vertical path. As a result of comparison with radiosonde measured in the same area, we confirmed that the accuracy was equivalent to the target measurement accuracy (2 g/m^3 or less).

1. Introduction

Water vapor is an important molecule in the atmosphere, not only for its natural greenhouse gas behavior, but also as a source of clouds and precipitation [1]. Water vapor in the troposphere influences the growth of cumulonimbus clouds that cause localized heavy rainfall. In Japan, heavy rain damage caused by quasi-stationary band-shaped precipitating systems is increasing, and it is difficult to predict with current observation technology. To predict such rainfall at an early stage, remote sensing methods for profiling water vapor concentration in the atmosphere have been studied. Among remote sensing techniques, lidar observations have an advantage in profiling water vapor. One of the advantages of coherent DIAL method is its high receiver sensitivity due to heterodyne detection technique. Furthermore, the heterodyne detection technique enables the simultaneous measurement of water vapor density and wind speed along the observation direction. This technique is suitable for monitoring cloud formation and predicting rainfall. In addition, the coherent DIAL is not affected by solar background noise because the detection is limited to the wavelength band of the laser. Recently, we proposed a 1.53-μm coherent DIAL for simultaneous observation of water vapor density and wind speed demonstrating its theoretical feasibility and experimental performance [2] in ground-based observations [3].

In this paper, we present a coherent DIAL with improved environmental resistance, and show the observation results. These observation results are an evaluation of water vapor measurement at a line of sight. In addition, we introduce a wavelength stabilization circuit that can precisely control the frequency even when the temperature fluctuates in the range of 0-60 degrees Celsius and show the observation results in the horizontal pass and vertical pass. Furthermore, the result of the comparison of measured water vapor density between DIAL and other sensors is presented.

2. Coherent DIAL Configuration

A photograph of the deployable prototype DIAL is shown in Fig. 1. Its size is 1100 mm x 900 mm x 800 mm and its weight is 150 kg. It has four wheels under the body for easy mobility. It operates on a standard power supply and requires a power capacity of AC 100 V / 15 A.

Figure 1. Coherent DIAL

The main performance of DIAL is shown in Table 1.

Table 1. DIAL specification

ON wavelength (λon)	1531.3828nm
ON wavelength stability	<+/- 0.5pm
OFF wavelength (λoff)	1531.5537nm
OFF wavelength stability	<+/- 5pm
Peak power	40W
Pulse width	500ns
Pulse repetition frequency	32kHz
Antenna aperture	70mm
Maximum range	1km
Water vapor measurement accuracy	<2g/m^3
Size, weight	W100 x D90 x H80 cm, 150kg
Operating temperature(outside)	0 ~ +40 degrees

To reduce the altitude dependence of absorption line intensity, the ON wavelength (λon) is not the peak of the water vapor absorption spectrum, but the area around 1531.3828 nm where the absorption coefficients at each altitude overlap [3]. To achieve the water vapor measurement accuracy of 5% (less than about 2 g/m^3) for the saturated water vapor density in summer season, the required wavelength stability for λon is less than +/- 0.5 pm (+/- 64 MHz). On the other hand, wavelength stability for λoff is less than +/- 5 pm. DIAL is designed to operate at an outside temperature of 0-40 degrees Celsius.

The system configuration block of the field-deployable prototype of the 1.53-µm coherent DIAL with serrodyne modulation is shown in Fig. 2[4]. DIAL consists of a wavelength lock (WL) unit, wavelength switch (WS) unit, signal processing (SP) unit, optical transmitter and receiver (OTRX) unit, optical amplifier (OA) unit, and telescope. Except for the WL unit and the WS unit, the DIAL shares functions with the wind measurement lidar.

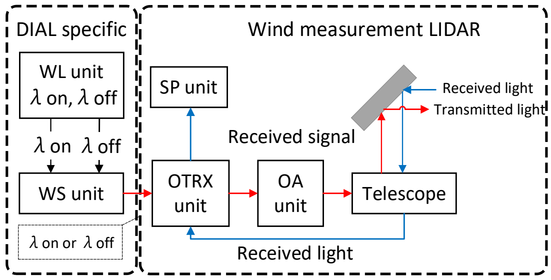

Figure 2. System configuration block, WL: Wavelength Lock, WS: wavelength switch, SP: Signal Processing, OTRX: Optical Transmitter and Receiver, OA: Optical Amplifier

System configuration of the WL unit is shown in Fig. 3. The WL unit consists of two units: one is the water vapor absorption line offset lock unit and the other is the HCN gas WL unit. The principle of wavelength locking is to lock to the wavelength band of the water vapor absorption line by conducting two types of wavelength locking.

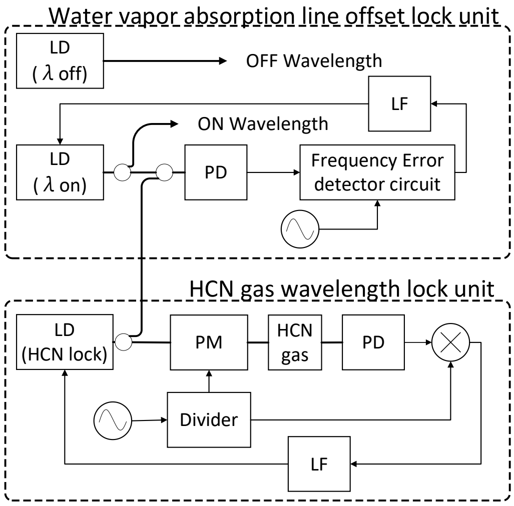

Figure 3. System configuration of wavelength lock unit, LD: Laser diode, PD: Photo detector, LF: Loop filter, PM: Phase modulator

3. Measurement Result

The diagram of the temperature test of the WL unit in the temperature bath is shown in Fig. 4. The WL unit and power supply unit are installed in a temperature bath. The analog-to-digital converter (ADC) is also installed in the temperature bath to monitor the control voltage. HCN and ON optical monitor ports are outside of the temperature bath and the wavelength is simultaneously monitored by an optical wavelength meter (WM). The intermediate frequency (IF) signal (868.086 MHz) after dividing for offset locking is monitored by a spectrum analyzer (SA).

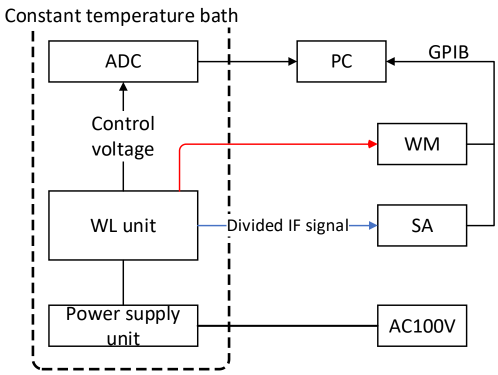

Figure 4. Diagram of temperature test in temperature bath

Both HCN lock and offset lock were confirmed to be within the control voltage dynamic range (±0.8 V) over the temperature range (0 - 60 degrees Celsius) and the target wavelength stability as shown in Fig. 5 and Fig. 6.

HCN wavelength stability is less than 0.2 pm, which is the wavelength measurement limit of WM. Also, offset lock stability is less than 3 MHz (0.025pm). Therefore, ON wavelength stability is less than 0.225 pm.

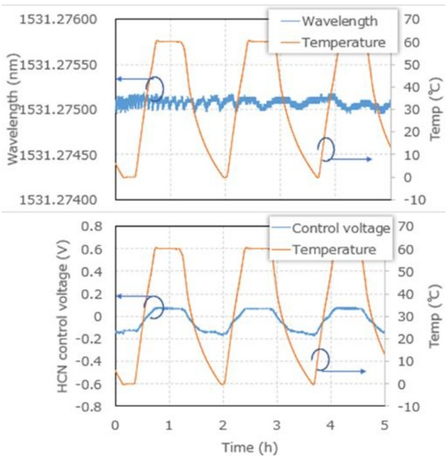

Figure 5. Temperature test of HCN synchronization

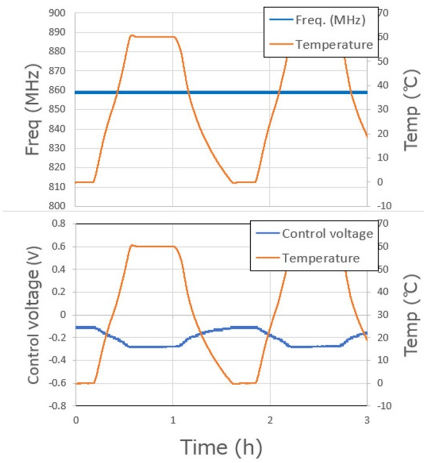

Figure 6. Temperature test of offset synchronization

After confirming the stability of the wavelength lock unit, horizontal path water vapor measurements were conducted at our company. The results of that observation are shown in Fig. 7 and Fig. 8. Water vapor measurements in horizontal pass were compared to a hygrometer and the (mean) difference was $0.8\ g/m^3$, within the target value of $2.0\ m^3$. In addition, the comparison of DIAL and theoretical Detectability is significantly correlated.

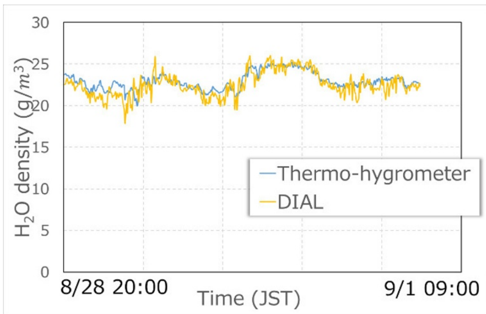

Figure 7. Horizontal pass result (2023/8/28 20:00 - 9/1 09:00)

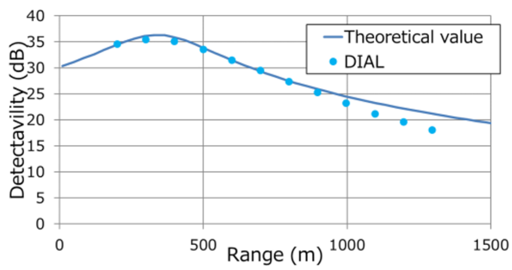

Figure 8. A-scope result in horizontal pass

Measurement in the vertical path was conducted at the Meteorological Research Institute in Tsukuba City. Water vapor observations using DIAL were done at a line of sight. The radiosonde for comparative verification was also launched at the same site.

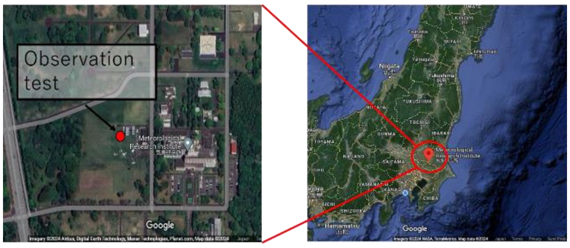

Figure 9. Location of vertical pass observation

The results of vertical profile are shown in Fig. 10 and Fig. 11. The water vapor decreasing was observed by cold front passed over Japan on 7th November.

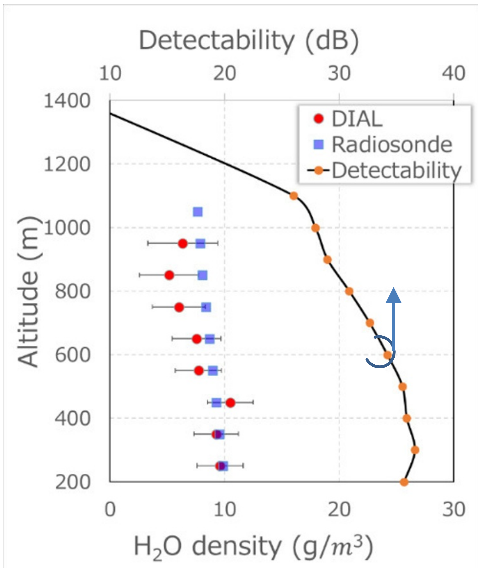

Figure 10. Vertical profile of water vapor density comparing radiosonde and DIAL and the DIAL detectability (2023/11/9 09:00)

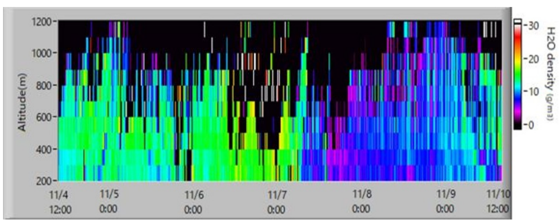

Figure 11. Vertical pass result (2023/11/4 12:00 - 11/10 12:00)

4. Conclusion

The WL unit was modified for environmental resistance, and the DIAL observation was verified. The temperature test combining the WL unit and each device was conducted, and stable operation was confirmed in the target temperature range from 0 to 60 degrees Celsius. The water vapor measurement in the horizontal path by the modified WL unit was in good agreement with the ground data with a measurement error of 0.8 g/m^3. The water vapor decreasing was observed by cold front passed over Japan on 7th November.

In the future, we will evaluate simultaneous measurements of wind as well as water vapor.

5. References

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