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Development of Coherent 2-\(\mu\)m Differential Absorption and Wind Lidar with laser frequency offset locking technique and column-integrated CO\(_2\) measurement

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Outline

- Background and objectives
- Frequency offset-locking technique and specifications
- Estimation of XCO₂
- Horizontal experimental CO₂ measurement
- Experimental CO₂ measurement for the GOSAT data products validation
- Summary
Background and Objectives

**Background**
- CO$_2$ is one of the most important greenhouse gases.
- Spatial and temporal variations of the CO$_2$ concentration are important to understand the carbon cycle.
- Spaceborne measurement is a promising approach to globally measure the distribution of CO$_2$ concentration.
  - Active sensor mission: ASCENDS (2019?).
- Integrated path differential absorption (IPDA) lidar is one of the next-generation spaceborne sensors. 1.6-μm and 2-μm IPDA lidar systems have been developing by many research groups.

**Objectives of development of DIAL system**
- Development of reliable stable single-frequency Q-switched laser.
- Development of reliable detection technique.
- Development of algorithm.
- Development of airborne system.
  - Precursor of spaceborne IPDA lidar system.
  - Experimental study from moving.
- Demonstration of CO$_2$ measurement with a high accuracy.
**Frequency offset-locking technique I: $\lambda_{\text{Center}}$ laser**

- The $\lambda_{\text{center}}$ laser is set at the R30 absorption line center of CO$_2$ by using a CO$_2$ cell, external phase modulation and PID controller for PZT.
Frequency offset-locking technique I: $\lambda_{\text{Center laser}}$

Conditions:
- Frequency should be selected to maximize the slope at around the zero frequency offset.
- EOM needs a high frequency to establish a large monotone interval.

Left figure shows the simulated result of the relation between the frequency offset from the R30 absorption line center for the various frequency and the error signal output. Right figure shows the slope at the zero frequency offset. The frequency offset reaches a peak at around 150 MHz. The EOM operating at the frequency of 150 MHz was selected.
Frequency offset-locking technique I: $\lambda_{\text{center}}$ laser

Long-term laser frequency fluctuation of the $\lambda_{\text{center}}$ laser examined by recording the error signal using a data logger.

**Characteristics of $\lambda_{\text{center}}$ laser**
- Wavelength: 2050.967 nm
- Frequency stability: $<$ 160 KHz (-157 to +138 KHz)
- Time to locking: 6 msec
- Modulation frequency: 150.6 MHz
- CO2 gas cell: 20 Torr, 0.36 m x 3 pass

Tuning range of the $\lambda_{\text{center}}$ laser investigated using the error signal, and PZT diver’s DC voltage.
- Frequency of the $\lambda_{\text{center}}$ laser changes in proportion to -$6.78 \text{ MHz/1mV}_{\text{PZT driver’s DC}}$.
- $\Delta PZT_{\text{DC}} = 106.6 \text{ mV} \rightarrow 361 \text{ MHz}$
- Frequency offset: -361 MHz to +361 MHz
Frequency offset-locking technique II: $\lambda_{\text{On}}$ laser

$\lambda$-on laser is controlled to be locked for the $\lambda$-center laser. Difference in the frequency between the $\lambda$-center and the $\lambda$-on lasers is determined by the heterodyne and phase sensitive detections. Cavity length of the $\lambda$-on laser is controlled by adjusting PZT diver’s DC voltage. The phase locked loop (PLL) is used to control the DC voltage with a good precision.

**$\lambda$-Center**

**Characteristics of $\lambda_{\text{On}}$ laser**

- **Wavelength**: 2050.967 nm
- **Frequency stability**: $<100$ KHz (-157 to +138 KHz)
- **Frequency offset by PZT driver**: -543 MHz to +448 MHz
- **Frequency offset**: 2.5 GHz to 6.5 GHz
- **Time to locking**: 7 msec

Ramp and fire technique is used to establish the single-frequency Q-sw laser. The frequency stabilization of the single-frequency Q-sw laser was about 1 MHz. Total absolute frequency stability of the on-line laser depends on the frequency stability of the $\lambda_{\text{center}}$ laser, $\lambda_{\text{on}}$ laser, and pulse laser.

Total absolute frequency stability $= \sqrt{(0.16 \text{MHz})^2 + (0.1 \text{MHz})^2 + (1 \text{MHz})^2} \approx 1.02 \text{MHz}$
Specifications of Co2DiaWiL

Transmitter
Laser: Tm:Ho:YLF
Wavelength: 2051.004 to 2051.060 nm (On)
: 2051.250 nm (Off)

Pulse energy: 80 mJ/pulse
Pulse width: 140 nsec
Pulse Repetition: 30 Hz

Receiver
Clear diameter: 10 cmφ
Detector: InGaAs Balanced receiver

Data Processing
Signal processing: 8 Bit A/D
Sampling frequency: 500 MHz
Sampling points: 131072

Scanner
Clear diameter: 10 cmφ
Elevation angle: -20-200°
Azimuth angle: -10-370°
Scanning speed: 0°-60°/sec

We use a InGaAs PIN photodiode (DET1).

NICT
November 3, 2011 16th Coherent Laser Radar Conference
Examples of CNR for various laser frequency offsets

9000 shots pair @ 30Hz

Example of atmospheric returns corresponding to the off-line laser and the on-line laser for three laser frequency offsets, 2.5, 4.8, and 5.8 GHz. The CNR of the on-line laser decreases more moderately with increasing the laser frequency offset.
Horizontal experimental CO$_2$ measurement (3000 m-column range)

- + symbols show 1-minute DIAL results and black line shows 30-min running average of the DIAL results. Gray line shows data measured by the *in-situ* sensor.
- The precision for the 3000-m column range from 2616 to 5614 m (2998 m) and 900 shot pairs was 1%-2%.
- The root-mean-square of the absolute values of the differences between the 30-min averages by the two sensors was 3.5 ppm.

Surface data indicated that it was clear sky in the morning and cloudy in the afternoon. Convection was active in the morning, but less sunlight suppressed convection in the afternoon.
Estimation of XCO$_2$

\[
XCO_2 = \frac{\int_{R_1}^{R_2} n_{CO_2}(r) \cdot WF(r) \, dr}{\int_{R_1}^{R_2} WF(r) \, dr} = \frac{\tau_{CO_2}}{IWF} + \frac{\tau - \tau_{H2O}}{IWF} \cdot \int_{R_1}^{R_2} n_{air}(r) \cdot \Delta \sigma \, dr,
\]

\[
\tau = \tau_{CO_2} + \tau_{H2O} = \frac{1}{2} \log \left( \frac{P_{On}(R_1) \cdot P_{Off}(R_2)}{P_{Off}(R_1) \cdot P_{On}(R_2)} \right)
\]

\[x_{CO_2}: \text{ Dry-air volume mixing ratio of carbon dioxide}\]

\[n_{air}: \text{ Dry-air number density}\]

\[n_{CO_2}: \text{ CO}_2 \text{ number density}\]

\[\tau_{CO_2}: \text{ Differential absorption optical depth (DAOD) CO}_2 \text{ absorption in the range between } R_1 \text{ and } R_2.\]

\[\tau_{H2O}: \text{ DAOD due to the H}_2\text{O absorption in the range between } R_1 \text{ and } R_2\]

\[WF: \text{ Weighting function}\]

\[IWF: \text{ Integrated weighting function}\]

\[\Delta \sigma: \text{ Difference in the absorption cross sections at wavelengths of the on- and off-line lasers}\]

Error \(\Delta XCO_2\) is given using the DAOD, the WF, and meteorological data:

\[
\Delta XCO_2 = \sqrt{\left( \frac{\Delta \tau_{CO_2}}{IWF} \right)^2 + \left( \frac{\tau_{CO_2}}{IWF^2} \cdot \Delta IWF \right)^2}
\]

We used a radiosonde (Vaisala, RS92-SGP) to measure vertical profile of meteorological data. Total error of XCO2 estimated from accuracy of the radiosonde was <0.2 \%. 

November 3, 2011  16th Coherent Laser Radar Conference
Slant and vertical CO$_2$ measurements for the GOSAT data products validation

Column-integrated CO$_2$ measurements were conducted to contribute to the GOSAT project sensors on February 14, 20, and 23, 2010, and January 28, 31, February 3, and 7, 2011.

**Instruments at NICT**

- CO$_2$DIAL
  - 24 hours operation
  - EL = 0 deg (5 min), 16 deg (5 min), 90 deg (20 min) (2010)
  - EL = 16 deg (10 min), 90 deg (20 min) (2011)

- Mie Lidar, Ceilometer

- GPS Sonde (10JST, 12JST, 14JST)
  - Pressure, Temperature, RH, Wind speed and direction

- Automatic weather station
  - Pressure, Temperature, RH, Wind speed and direction

- In-situ NDIR
  - 24 hours operation

National institute for environmental studies (NIES) GOSAT Project conducted an airborne CO$_2$ measurement with Japan Aerospace Exploration Agency (JAXA).
Vertical profile of CO$_2$, measured by the airborne in-situ sensor on February 14 and 20, 2010

Airborne in-situ data provided by GOSAT validation team (NIES)

Altitude 0-400m: data measured by ground-based in-situ sensor
Altitude 400m-3km: data taken by airborne in-situ sensor over NICT (35.7N,139.5E).
Altitude 3km-7 km: data by airborne in-situ sensor over Kumagaya (36.2N,139.3E).
Altitude >7 km: constant value measured at altitude of 7km
Vertical profile of DAOD and SNR observed on February 14, 20, and 23, 2010

Slant measurement: EL=16 deg
Vertical measurement: EL=90 deg

\[ \text{SNR}_i(R_j) = \sqrt{N_L \cdot N_C} \cdot \frac{\langle P_1(R_j) \rangle}{\langle P_1(R_j) \rangle + \langle P_{N,i} \rangle}. \]

- \langle P_1(R_j) \rangle: Mean power of the backscattered signal
- \langle P_{N,i} \rangle: Mean noise power,
- \( N_C \): Number of coherent cell
- \( N_L \): Number of on- and off-line laser shots
XCO$_2$ measurement made on February 14, 20, and 23, 2010 and estimate of various error sources

<table>
<thead>
<tr>
<th>Integral interval</th>
<th>February 14, 2010</th>
<th>February 20, 2010</th>
<th>February 23, 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In-Situ</td>
<td>DIAL</td>
<td>GOSAT</td>
</tr>
<tr>
<td>0.4-1.0</td>
<td>406.187</td>
<td>408.3 ±4.2</td>
<td>402.387</td>
</tr>
<tr>
<td>0.4-2.0</td>
<td>401.754</td>
<td>-</td>
<td>399.220</td>
</tr>
<tr>
<td>0.4-3.0</td>
<td>398.870</td>
<td>416.7 ±4.7</td>
<td>397.445</td>
</tr>
<tr>
<td>0.4-10.5</td>
<td>394.720</td>
<td>390.6 ±5.1*</td>
<td>-</td>
</tr>
<tr>
<td>0.066-</td>
<td>383.063</td>
<td></td>
<td>388.229</td>
</tr>
</tbody>
</table>

* Cirrus

<table>
<thead>
<tr>
<th>Error source</th>
<th>Uncertainty</th>
<th>Measurement Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>±1 hPa</td>
<td>0.0%</td>
</tr>
<tr>
<td>Temperature</td>
<td>±0.5 ºC</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>RH</td>
<td>±5%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Frequency stability of Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-line</td>
<td>1.0 MHz</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Off-line</td>
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<td>0.0%</td>
</tr>
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GOSAT data ©JAXA/NIES/MOE
Vertical profile of DAOD and SNR observed on January 28, 31, and February 7, 2011

Slant measurement : EL=16 deg
Vertical measurement : EL=90 deg

\[
\text{SNR}_i(R_j) = \sqrt{N_L \cdot N_C} \cdot \frac{\left\langle P_i(R_j) \right\rangle}{\left\langle P_i(R_j) \right\rangle + \left\langle P_{N,i} \right\rangle}
\]

\( \left\langle P_i(R_j) \right\rangle \) : Mean power of the backscattered signal
\( \left\langle P_{N,i} \right\rangle \) : Mean noise power,
\( N_C \) : Number of coherent cell
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XCO₂ measurements made on January 28, 31, and February 7, 2011

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<th>January 31</th>
<th>February 7</th>
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<tbody>
<tr>
<td>0.4-1.0</td>
<td>401.8±5.0</td>
<td>405.6±10.5</td>
<td>405.3±6.1</td>
</tr>
<tr>
<td>0.4-2.0</td>
<td>398.0±5.6</td>
<td>394.5±9.5*</td>
<td>402.9±6.5</td>
</tr>
<tr>
<td>0.4-3.0</td>
<td>406.3±5.3</td>
<td>-</td>
<td>396.2±7.0</td>
</tr>
<tr>
<td>0.4-8.5</td>
<td></td>
<td></td>
<td>397.2±6.4**</td>
</tr>
</tbody>
</table>

* Integral interval is between 0.4 km and 1.9 km.
** Cirrus

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Summary

- A coherent 2-μm differential absorption and wind lidar with laser offset locking technique was developed to make the long-range CO$_2$ measurement. We examined the frequency stabilization of the λ-center and λ-on lasers and the single-frequency Q-switched laser.
  - The frequency stabilization of the λ-center laser was locked within about ±160 KHz.
  - The frequency stabilization of the λ-on laser was locked within about ±100 KHz for the λ-center laser.
  - The frequency stabilization of the single-frequency Q-switched laser with the ramp-and-fire technique was within about ±1 MHz.
  - The absolute frequency stability of the single-frequency Q-switched laser beam is <1.02 MHz.

- We made horizontal experimental CO$_2$ measurements to detection sensitivity of the Co2DiaWil.
  - The precisions for the 900 shot pairs and 3000-m column ranges were in the range of 1%-2%.
  - The root-mean-square of the absolute values of the differences between the 30-min averages by the two sensors for the 3000-m column range was 3.5 ppm.
  - Total errors due to the meteorological data was <0.5 % in the concentration on the CO$_2$ measurement.

- We made slant and vertical CO$_2$ measurements for the GOSAT validation in 2010 and 2011.
  - Precision of XCO$_2$ measurement in the boundary layer was 1 to 2%.
  - We estimated XCO$_2$ using the two cases of clouds observed in the upper troposphere:
    - Clouds observed around at altitude of 10.5 km on February 14, 2010: 390.6±5.1 ppm.
    - Clouds observed around at altitude of 8.5 km on February 7, 2011: 397.2±6.4 ppm.
  - We used the radiosonde (RS92-SGP) to measure vertical profile of meteorological data. Total error of XCO$_2$ estimated from accuracy of the radiosonde was <0.2 %.

- Future plans
  - Last April, new 5-year term program started.
  - We started to develop the airborne system for CO$_2$ and wind measurements and a fiber-laser-pumped laser system with middle/high repetition.
  - We will contribute to the Japanese ISS-JEM lidar observation of vegetation environment. We are organizing a working group on space-borne Doppler lidar as one of following spaceborne lidar missions.