National Institute of Information and Communications Technology

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Development of Coherent 2-μm 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 XCO_2
- Horizontal experimental CO_2 measurement
- Experimental CO_2 measurement for the GOSAT data products validation
- Summary

Background and Objectives

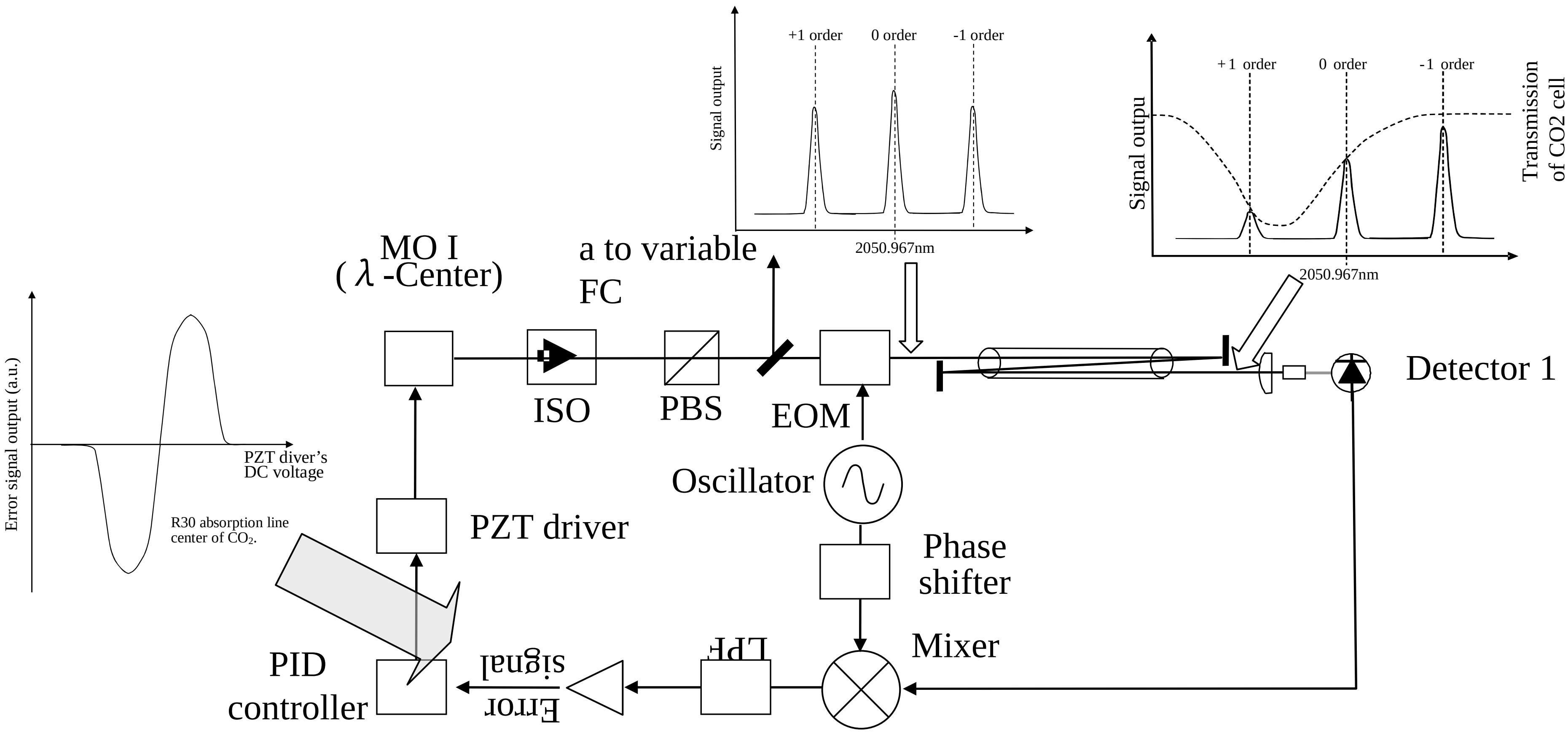
Background

- 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.
  - Passive sensor mission: GOSAT(2009), OCO-2 (2013).
  - 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.

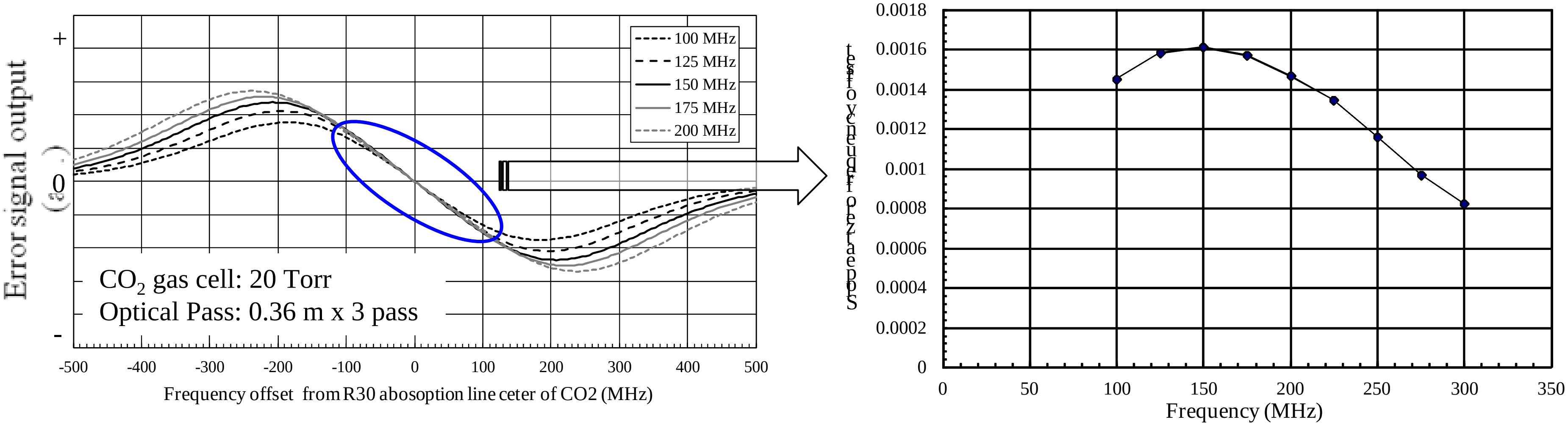
Frequency offset-locking technique I: λ_{Center} laser



λ_{Center} laser:

- The λ_{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: λ_{Center} laser



Conditions:

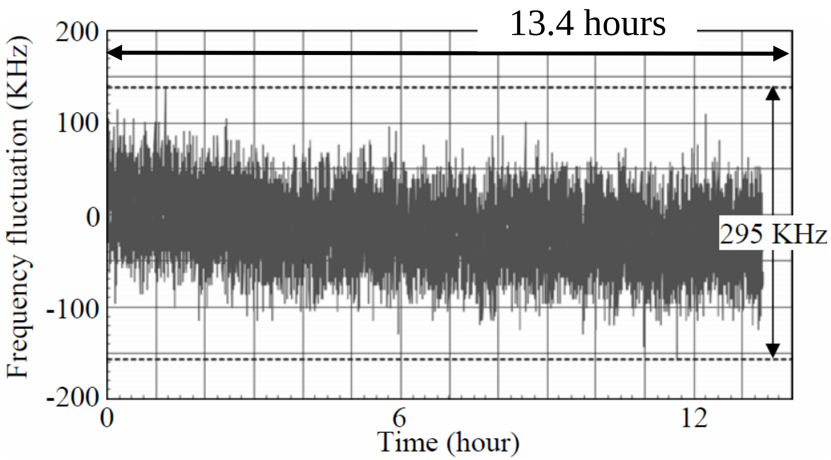
- Frequency should be selected to maximize the slope at around the zero frequency offset.
- EOM needs a high frequency to establish large monotone interval.

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.

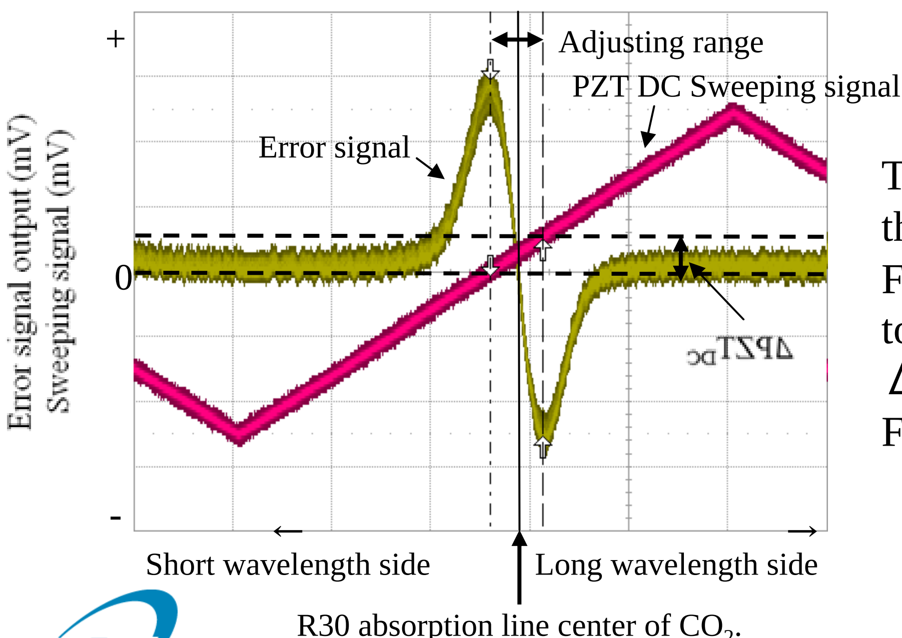
Frequency offset-locking technique I: λ_{Center} laser



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

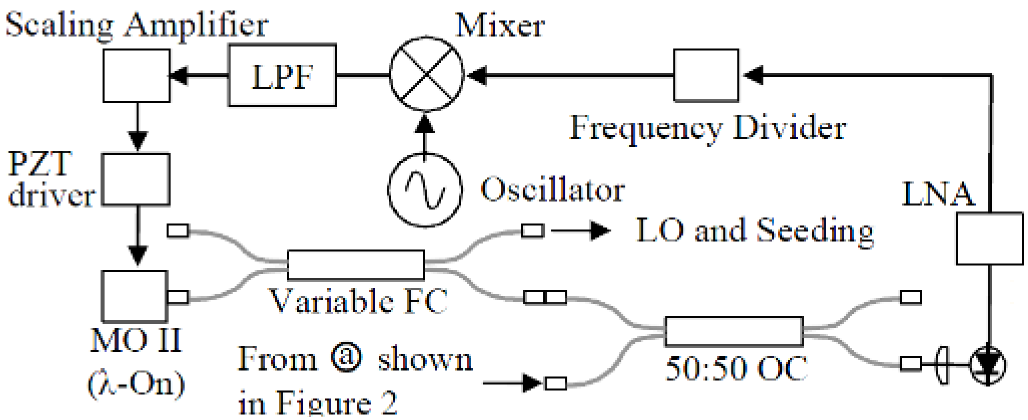
<u>Characteristics of λ_{center} laser</u>

Wavelength : 2050.967 nm
Frequency stability : <160KHz (-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 λ_{center} laser investigated using the error signal, and PZT diver's DC voltage.
Frequency of the λ_{center} laser changes in proportion to -6.78 MHz/ 1mV$_{\text{PZT driver's DC}}$.
ΔPZT_DC= 106.6 mV → 361 MHz
Frequency offset : -361 MHz to +361 MHz

Frequency offset-locking technique II: λ_{On} laser



λ-Center

λ-on laser is controlled to be locked for the λ-center laser. Difference in the frequency between the λ-center and the λ-on lasers is determined by the heterodyne and phase sensitive detections. Cavity length of the λ-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.

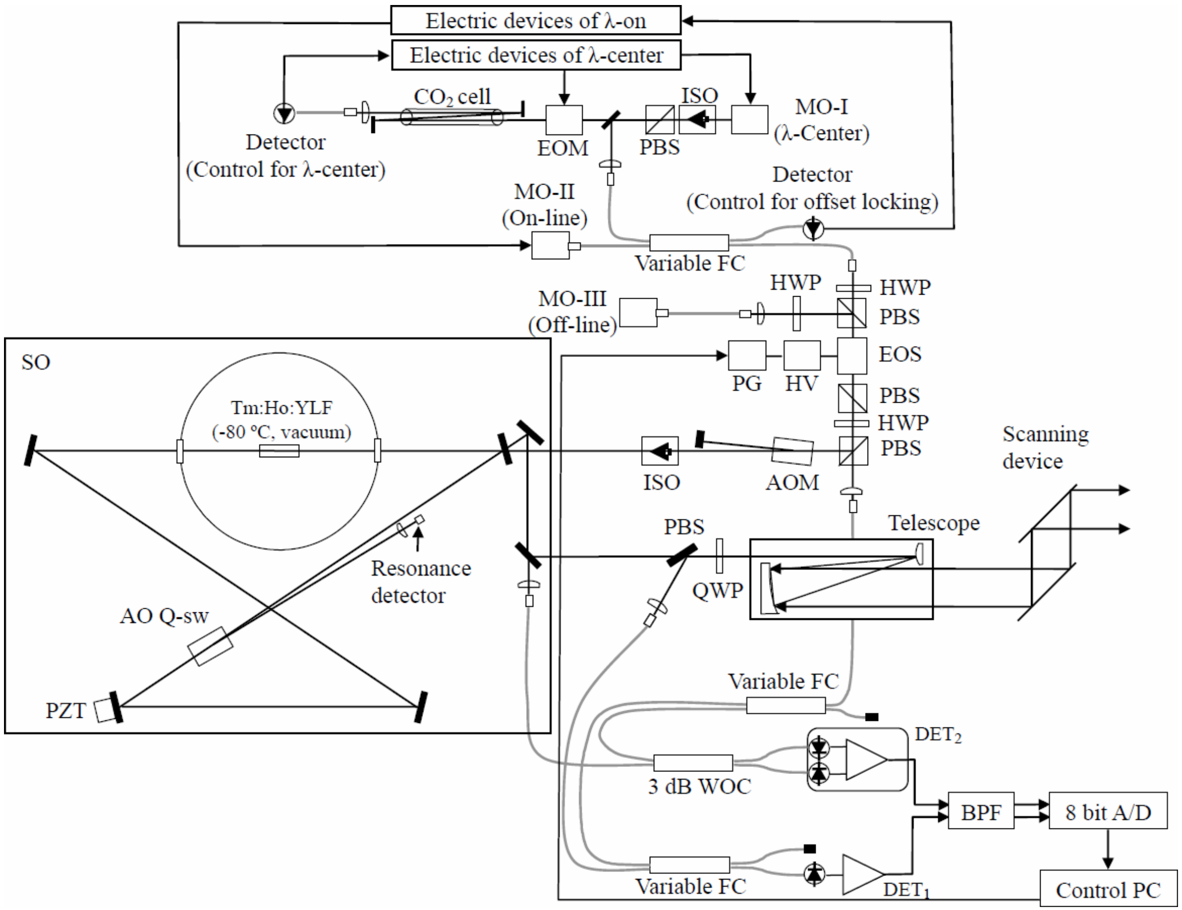
	Characteristics of λ_{on} laser
Wavelength	: 2050.967 nm
Frequency stability	: <100KHz (-157 to +138 KHz)
Frequency offset by PZT driver	: -543 MHz to +448 MHz
Frequency offset	: 2.5 GHz to 6.5 GHz
Time to locking	: 7 msec

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 1MHz.

Total absolute frequency stability of the on-line laser depends on the frequency stability of the λ_{center} laser, λ_{on} laser, and pulse laser.

$$\text{Total absolute frequency stablitiy} = \sqrt{(0.16\text{MHz})^2 + (0.1\text{MHz})^2 + (1\text{MHz})^2} \cong 1.02\text{MHz}$$

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

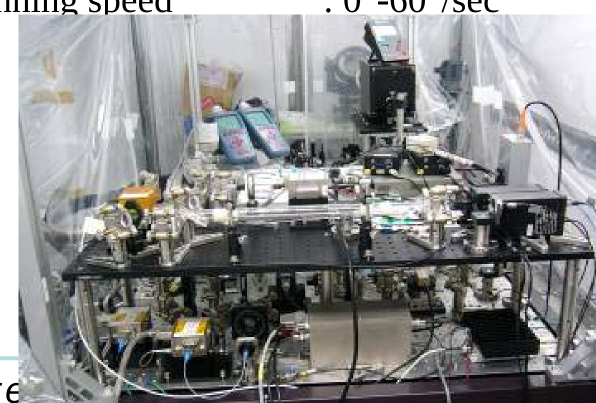
Clear diameter : 10 cmϕ

Elevation angle : -20-200°

Azimuth angle : -10-370°

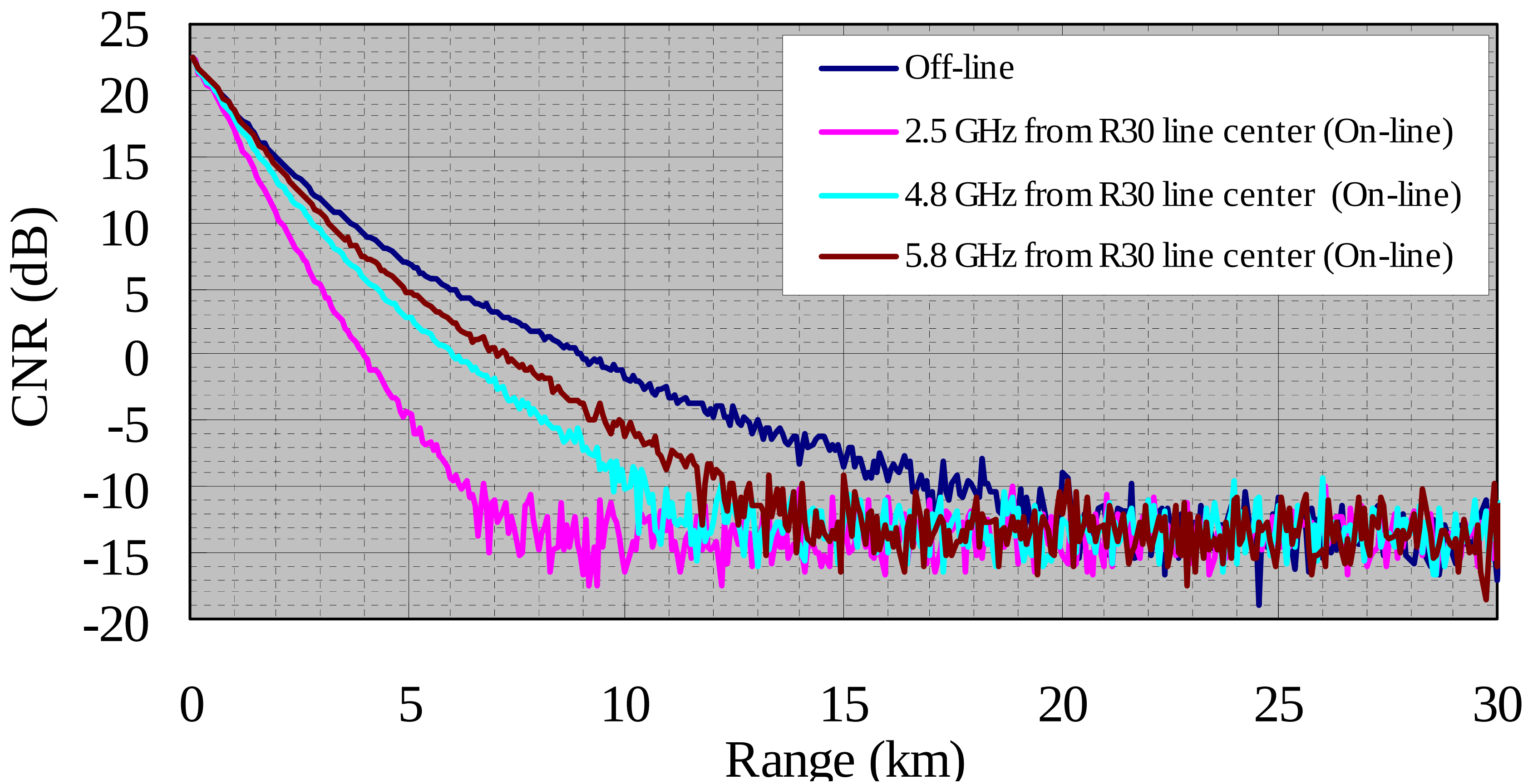
Scanning speed : 0°-60°/sec

We use a InGaAs PIN photodiode (DET_1) .



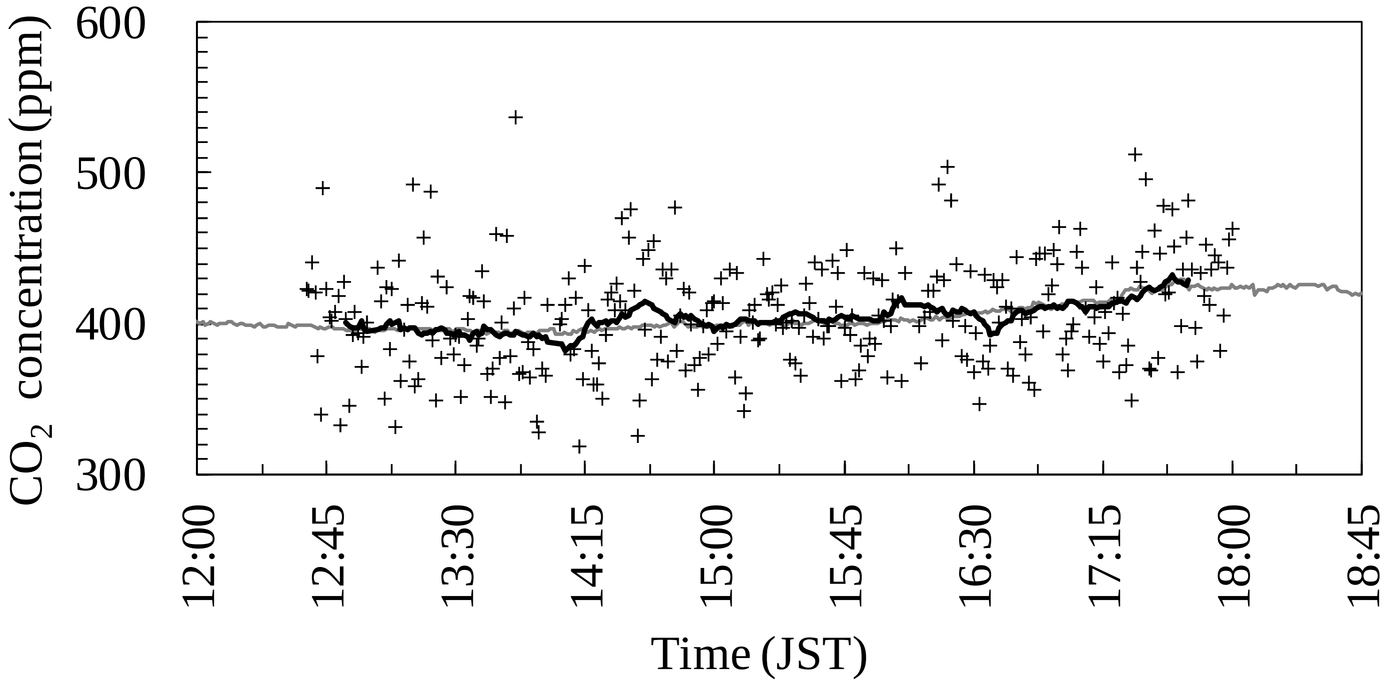
Examples of CNR for various laser frequency offsets

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

$$XCO_2 = \frac{\int_{R_1}^{R_2} n_{CO_2}(r)\cdot WF(r)\,dr}{\int_{R_1}^{R_2} WF(r)\,dr} = \frac{\tau_{CO_2}}{IWF} = \frac{\tau - \tau_{H_2O}}{\int_{R_1}^{R_2} n_{air}(r)\cdot \Delta\sigma\,dr}, \qquad \tau = \tau_{CO_2} + \tau_{H_2O} = \frac{1}{2}\cdot \log\left(\frac{P_{On}(R_1)\cdot P_{Off}(R_2)}{P_{Off}(R_1)\cdot P_{On}(R_2)}\right)$$

- x_{CO2}: : Dry-air volume mixing ratio of carbon dioxide
- n_{air} : Dry-air number density
- n_{CO2} : CO_2 number density
- τ_{CO2} : Differential absorption optical depth (DAOD) CO_2 absorption in the range between R_1 and R_2.
- τ_{H2O} : DAOD due to the H_2O absorption in the range between R_1 and R_2
- WF : Weighting function
- IWF : Integrated weighting function
- $\Delta\sigma$: Difference in the absorption cross sections at wavelengths of the on- and off-line lasers

Error ΔXCO_2 is given using the DAOD, the WF, and meteorological data:

$$\Delta XCO_2 = \sqrt{\left(\frac{\Delta\tau_{CO_2}}{IWF}\right)^2 + \left(\frac{\tau_{CO_2}}{IWF^2}\cdot \Delta IWF\right)^2} = \sqrt{\left(\frac{\Delta\tau_{CO_2}}{IWF}\right)^2 + \frac{\tau_{CO_2}}{IWF}\cdot\left(\left(\frac{\Delta IWF}{IWF}\right)_P^2 + \left(\frac{\Delta IWF}{IWF}\right)_T^2 + \left(\frac{\Delta IWF}{IWF}\right)_{RH}^2\right)}.$$

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 %.

Slant and vertical CO_2 measurements for the GOSAT data products validation

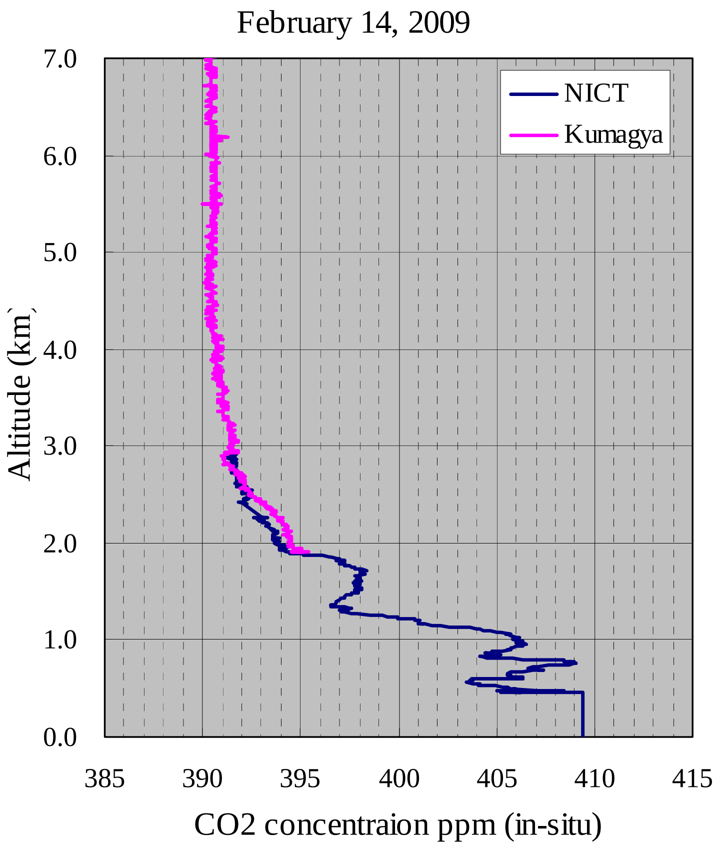
Column-integrated CO_2 measurements were conducted to contribute to the GOSAT project sensors on February 14, 20, and 23, 2010, and January 28, 31, February 3, and 7, 2011.

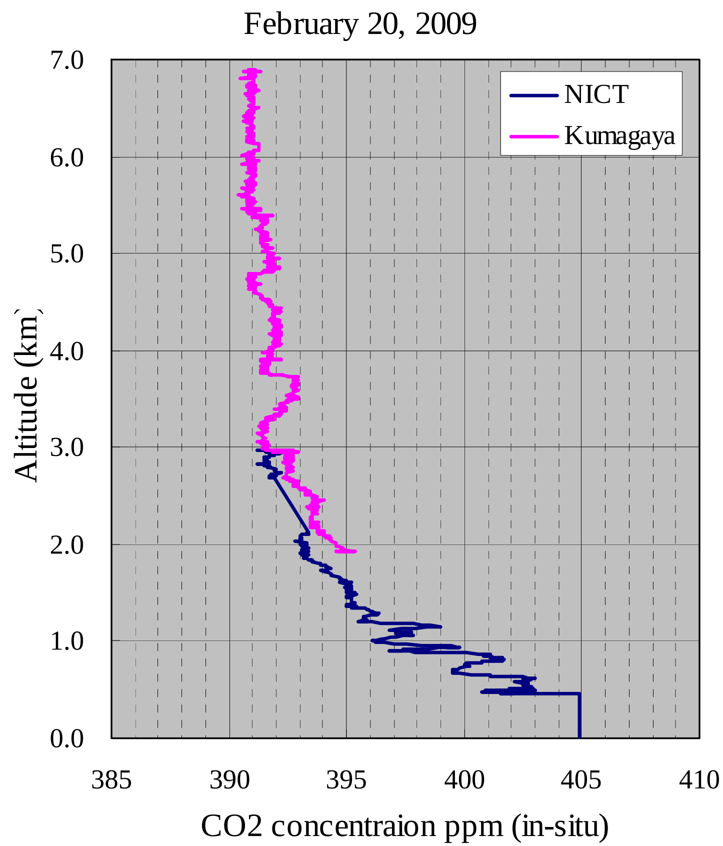
Instruments at NICT

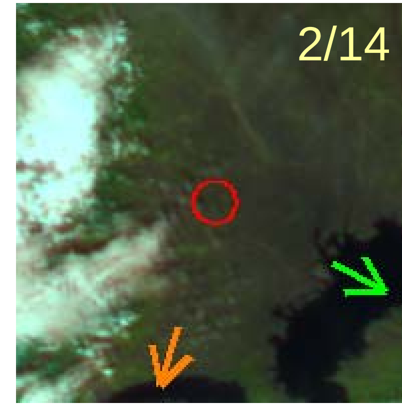
- CO_2DIAL
  - 24 hours operation
  - EL= 0 deg (5 min), 16 deg (5 min), 90 deg (20 min) (2010)
  - EL= 16 deg (10 min), 90 deg (20 min) (2011)
- Mie Lidar, Ceilometer
- GPS Sonde (10JST, 12JST, 14JST)
  - Pressure, Temperature, RH, Wind speed and direction
- Automatic weather station
  - Pressure, Temperature, RH, Wind speed and direction
- In-situ NDIR
  - 24 hours operation

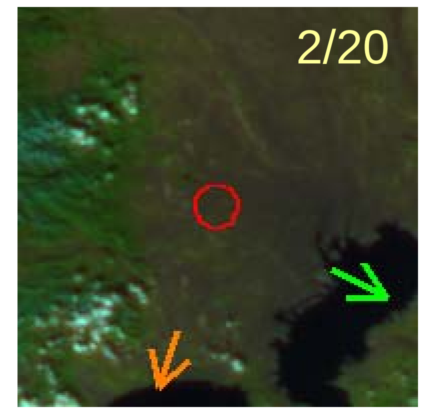
National institute for environmental studies (NIES) GOSAT Project conducted an airborne CO2 measurement with Japan Aerospace Exploration Agency (JAXA).

Vertical profile of CO_2, measured by the airborne in-situ sensor on February 14 and 20, 2010









Picture from GOSAT ©JAXA/NIES/MOE

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

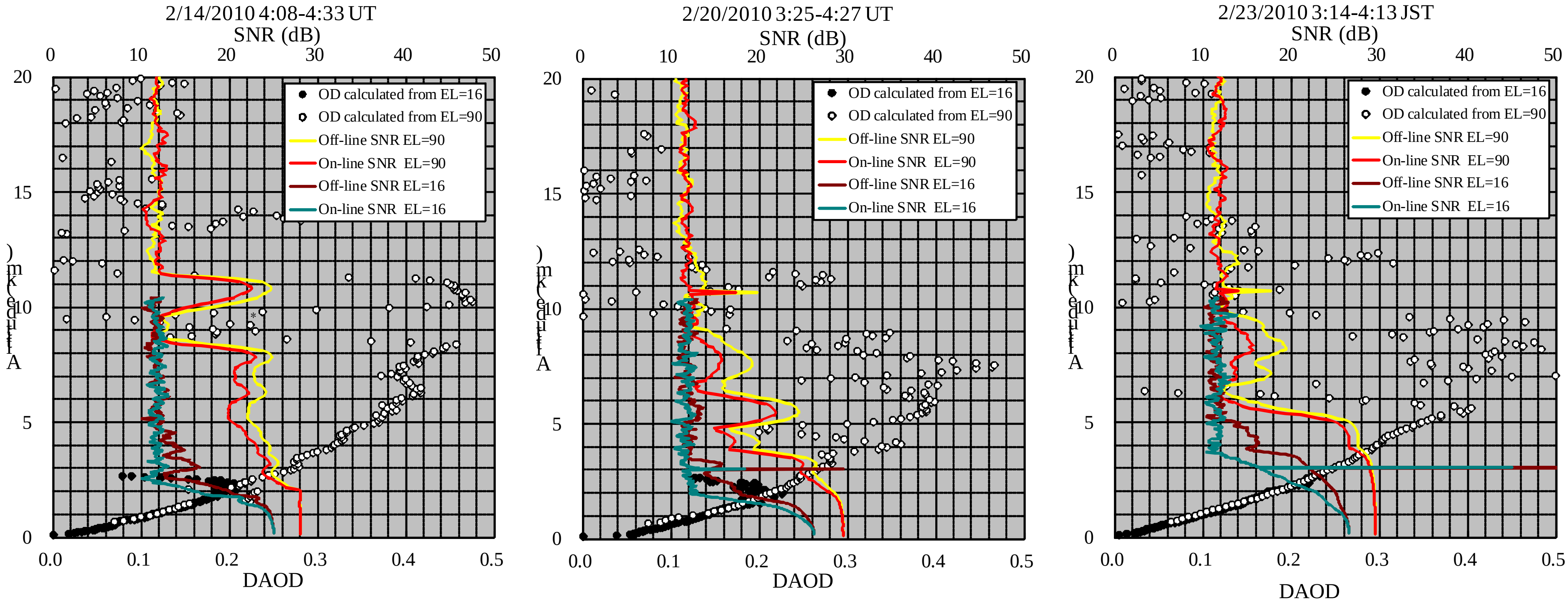
Altitude 0-400m: data measured by ground-based in-situ sensor

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

$$\mathrm{SNR}_i(R_j) = \sqrt{N_L \cdot N_C} \cdot \frac{\left\langle \overline{P_i(R_j)} \right\rangle}{\left\langle \overline{P_i(R_j)} \right\rangle + \left\langle \overline{P_{N,i}} \right\rangle}.$$

$\left\langle \overline{P_i(R_j)} \right\rangle$: Mean power of the backscattered signal

$\left\langle \overline{P_{N,i}} \right\rangle$: Mean noise power,

N_C: Number of coherent cell

N_L: Number of on- and off-line laser shots

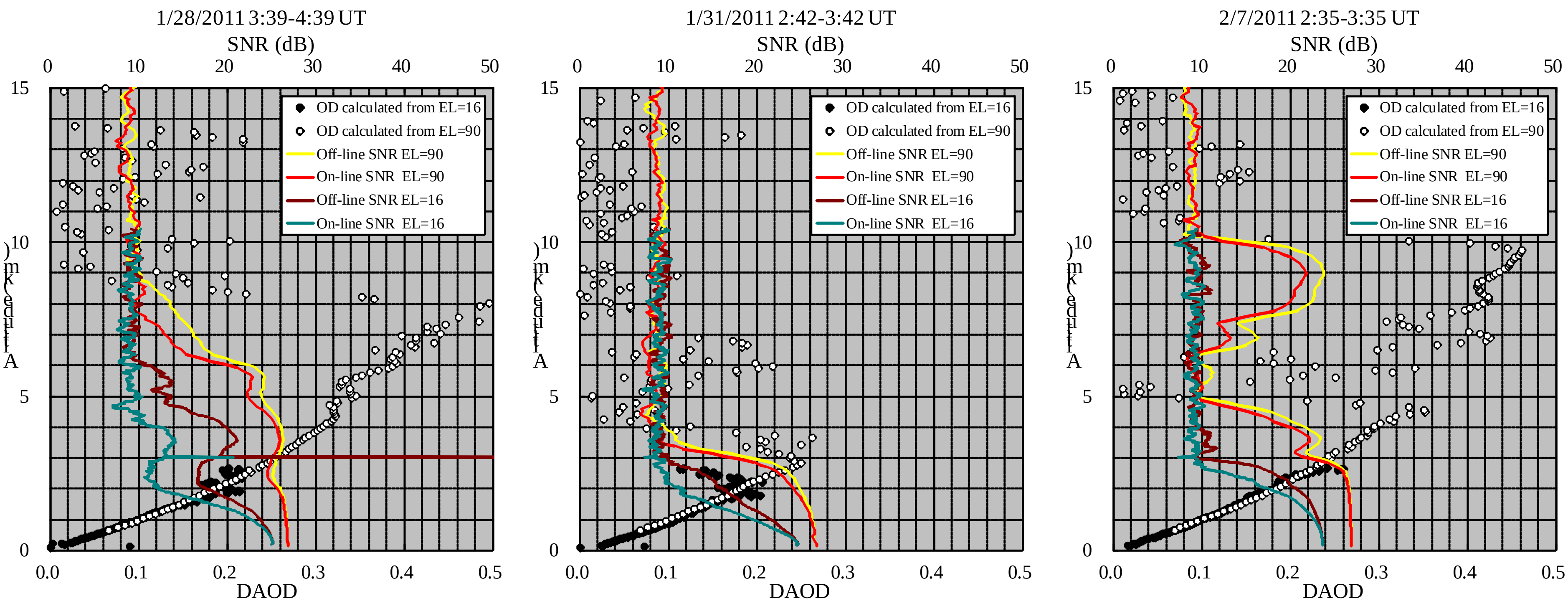
XCO_2 measurement made on February 14, 20, and 23, 2010 and estimate of various error sources

	February 14, 2010			February 20, 2010			February 23, 2010	
Integral interval	In-Situ	DIAL	GOSAT	In-Situ	DIAL	GOSAT	In-Situ	DIAL
0.4-1.0	406.187.	408.3±4.2		402.387	401.7±4.6		No data	399.9±4.4
0.4-2.0	401.754	-		399.220	393.0±4.0		No data	404.4±4.7
0.4-3.0	398.870	416.7±4.7		397.445	-		No data	397.9±4.5
0.4-10.5	394.720	390.6±5.1*		-	-		No data	-
0.066-			383.063			388.229		

* Cirrus

Error source	Uncertainty	Measurement Error
Meteorological elements Pressure Temperature RH	 ±1 hPa ±0.5 ºC ±5%	 0.0% < 0.1% < 0.1%
Frequency stability of Laser On-line Off-line	 1.0 MHz 1.0 MHz	 < 0.1% 0.0%

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

$$SNR_i(R_j) = \sqrt{N_L \cdot N_C} \cdot \frac{\langle \overline{P_i(R_j)} \rangle}{\langle \overline{P_i(R_j)} \rangle + \langle \overline{P_{N,i}} \rangle}.$$

$\langle \overline{P_i(R_j)} \rangle$: Mean power of the backscattered signal

$\langle \overline{P_{N,i}} \rangle$: Mean noise power,

N_C: Number of coherent cell

N_L: Number of on- and off-line laser shots

XCO_2 measurements made on January 28, 31, and February 7, 2011

Integral interval	January 28	January 31	February 7
0.4-1.0	401.8±5.0	405.6±10.5	405.3±6.1
0.4-2.0	398.0±5.6	394.5±9.5*	402.9±6.5
0.4-3.0	406.3±5.3	-	396.2±7.0
0.4-8.5			397.2±6.4**

* Integral interval is between 0.4 km and 1.9 km.

** Cirrus

Error source	Uncertainty	Measurement Error
Meteorological elements		
Pressure	±1 hPa	0.0%
Temperature	±0.5 ºC	< 0.1%
RH	±5%	< 0.1%
Frequency stability of Laser		
On-line	1.0 MHz	< 0.1%
Off-line	1.0 MHz	0.0%

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 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.