Response to Dr. Robert T. Menzies

We appreciate your helpful, thoughtful, and meaningful comments and the time and effort put in to help with regard to our manuscript. We hereby addressed our point-by-point response to reviewer's comments.

Title, abstract and conclusion of the paper were reconsidered based on comments of Dr. Robert T. Menzies have been revised with focusing on the coherent IPDA lidar CO_2 measurement. The title has been changed as follows: Ground-based integrated path coherent differential absorption lidar measurement of CO_2: foothill target return. The abstract and conclusion have been revised.

Our final goals are to measure column-averaged mixing ratio of CO_2 with the 2-μm coherent IPDA lidar from space at the horizontal resolution of 100 km x 100 km. Our purposes are to study a 2-μm lidar for future airborne lidar measurement and to examine the detection sensitivity of a 2-μm coherent IPDA lidar. It is very important to make a precise range measurement between the foothill target and a specific range (altitude) and to detect the position of aerosols and clouds in order to achieve the XCO_2 measurements with a high precision. The IPDA lidar with a Q-switched laser and a range-gated receiver has also a great advantage in terms of reducing uncertainty due to the presence of aerosols and clouds. We believe that a Q-switched laser and a range-gated receiver should be used for these reasons.

Specific Comments:

Abstract:

(1) Why do your results indicate that a Q-switched laser is important? What unique properties of a Q-switched laser are essential? Also, in what measurement context are you assuming that "it is better to simultaneously conduct both hard target and atmospheric return measurements…"? I assume that you're thinking of ground-based local/regional measurements in urban areas, not global measurements from Earth orbit. Please clarify.

All sentences of explanation have been revised as follows:

The 2-μm coherent IPDA lidar can detect the CO_2 volume mixing ratio change of 3 % with in the 5-minutes signal integration. In order to detect the position of foothill target, to measure a range with a high SNR, and to reduce uncertainty due to the presence of aerosols and clouds, it is important to make a precise range measurement with a Q-switched laser and a range-gated receiver.

(2) The statement is made both here and in the Conclusions that a lidar with high prf laser (few tens of kHz) is (or "may be") necessary for 1-2 ppm precision. Why? Do you consider it important or essential to obtain CO2 measurements on time scale of a few seconds rather than ~5-10 minutes?

Our goal is to measure column-averaged mixing ratio of CO_2 with a precision of 1-2 ppm at the horizontal resolution of 100 km x 100 km from space. In order to observe temporal and spatial variations in the CO_2, the science measurement requirement is the XCO_2 measurement with a precision of 1-2 ppm. The distance 100km corresponds to 14 seconds if a spacecraft speed is 7km/sec. In case of the coherent IPDA lidar CO_2 measurement, our results indicated that increase of number of laser shot decrease the relative error. The coherent IPDA lidar need to use a laser with high pulse repetition frequency.

Sentence of explanation has been changed as follows:
The results indicated that a coherent IPDA lidar with a laser operating at a high pulse repetition frequency of a few tens of KHz is necessary for measuring XCO_2 measurement with a precision of 1-2 ppm in order to observe temporal and spatial variations in the CO_2.

1. Introduction:
(1) lines 27,28: referring to the passive sensor: "…..therefore, it tends to overestimate the optical depth of aerosols and to underestimate that of thin clouds.? This is not correct as written. Please clarify.

Reference "Morino et al. 2011; Yang et al. 2013" have been addeded:
Morino, I., Uchino, O., Inoue, M., Yoshida, Y., Yokota, T., Wennberg, P. O., Toon, G. C., Wunch, D., Roehl, C. M., Notholt, J., Warneke, T., Messerschmidt, J., Griffith, D. W. T., Deutscher, N. M., Sherlock, V., Connor, B., Robinson, J., Sussmann, R., and Rettinger, M. ,: Preliminary validation of column-averaged volume mixing ratios of carbon dioxide and methane retrieved from GOSAT short-wavelength infrared spectra, Atmos. Meas. Tech. 4, 1061–1076, 2011.
Yand, D., Lie, Y., and Cai, Z.,: Simulations of Aerosol Optical Properties to Top of Atmospheric ReflectedSunlight in the Near Infrared CO2 Weak Absorption Band, Atmos. Oceanic Sci. Lett., 6, 60-64, 2013.

Sentence of explanation has been replaced as follows:
...therefore, the retrieval procedures sometime overestimate/underestimate the optical depth of aerosols and thin clouds (Morino et al. 2011; Yang et al. 2013). Those presences cause an error of the total integrated path of CO_2 measurements. The overestimation/underestimate of the total optical depth due to CO_2 absorption may result in regional biases.

(2) "A differential absorption lidar is not affected by the presence of aerosols and clouds….." This is not true as stated. Aerosols and clouds provide backscattered signals to a DIAL system. This should be re-worded or removed. You must be referring to an IPDA system here.

A sentence of explanation has been replaced as follows:
The IPDA lidar can measure the total column-averaged mixing ratio of trace gas using return signal from the Earth's surface or from thick clouds.

2. Coherent 2-micron differential absorption and wind lidar:

(1) The 1 MHz absolute frequency stability of the injected pulsed laser is very good, certainly sufficient for high-precision CO2 measurements.

A sentence of explanation has been added as follows:

which is sufficient for CO_2 measurement with a high precision.

(2) “The interferences due to the presence of other atmospheric gases are almost negligible.” This is ambiguous. Please be quantitative, maybe by providing a statement that they contribute less than a particular equivalent CO2 DAOD. Water vapor is likely the most probable. Since your weather station provides Relative Humidity, do you account for water vapor in your analysis?

Sentences of explanation have been changed as follows:

The interferences due to the presence of other atmospheric gases except for the water vapor are almost negligible. The water vapor has to be taken into account in order to estimate the correct optical depth. The interference due to water vapor (relative humidity = 10 % to 70 %) could bring an error of 0.1 % to <0.3 % in the CO_2 volume mixing ratio derived from the IPDA lidar measurement.

3. Estimation of CO2 and Error Analysis:

(1) Equation (2): Another factor $ct_p/2$, where t_p is pulse duration, is needed in this equation to account for the fact that the distributed aerosol backscatter is coming from an integrated column at any given time. Although not stated, this reviewer assumes the usual units for beta, $\beta(R)$, i.e. $m^{-1}sr^{-1}$.

Equation (2) has been corrected.

Unit and a sentence of explanation have been added as follows:

$\beta(R)$ (m^{-1} sr^{-1}) is the backscattering coefficient of the atmosphere, c ($m\ s^{-1}$) is the light velocity and t_p (s) is the laser pulse duration.

(2) Equation (5): Define N_{air}.

A sentence of explanations has been corrected as follows:

A By applying Eq. (1) to ranges R_1 and R_2 and to the on- and off-line wavelengths, absorption cross sections $\sigma_i(r)$ (m^{-2}) and the dry air number density N_{air} (m^{-3}),…

(3) Equation (5): “The CO_2 volume mixing ratio…” Is this the dry air CO_2 volume mixing ratio?

A sentence has been corrected to “the dry air volume mixing ratio of CO_2…”

(4) State explicitly that sigma, σ, depends on p, T.

A sentence of explanation has been added as follows:

The difference between the absorption cross sections σ depends on both pressure and temperature.

4. Ground-based in situ measurements

(1) "…which leads to a total error of 0.1% in the CO2 volume mixing ratio…." Cite your equation (10). This applies to the atmosphere near the NICT building; however variability in these atmospheric parameters along the measurement path may result in additional uncertainty.

Reference "Kanda et al., 2005" has been added:

Kanda, M., Moriwaki, R., and Kimoto Y.: Temperature Profiles Within and Above an Urban Canopy. Boundary-Layer Meteorol. 115, 499-506, 2005.

Sentences of explanation have been changed as follows:

The total error of 0.1 % is for the atmosphere near the NICT building. However, the f1uctuations of temperature might have been larger than 1 ºC due to the heterogeneous radiative properties of the surface over the 7km measurement pass. For instance the temperature difference between within and above the canopy is about 1 ºC in an urban area of Tokyo (Kanda et al., 2005), which corresponds to an error of 0.5 %. Thus, although the R30 absorption line of CO_2 is rather insensitive to temperature, the f1uctuations of temperature along the 7km measurement path result in additional uncertainty. Spectroscopic errors also include error on the parameter values (pressure broadening and line strength).

5. Experimental hard target measurement:

(1) "We used the range resolution of 150m to avoid speckle-induced intensity fluctuation for determining a correct range." Please clarify this with some additional text.

Sentences of explanation have been added as follows:

Figure 3(c) indicates two different modes in the detection of the foothill target return. The slope angle was assumed to be about 12º from the topographic data around the target area. If there were 5-meter-height trees around the target area and if the laser beam would pass through the trees, the length from the tree to the ground surface would correspond to be about 23.5m (=5 m/tan 12º). The two different modes suggest that the foothill target returns are a mix of trees and ground surface reflection.

Sentences of explanation have been changed as follows:

We used the range resolution of 150 m for determining a correct range to ignore uncertainties of ± 0.012 km due to effects of the speckle-induced intensity fluctuation and to the two different modes.

(2) Page 8590, line 3: I believe this would be improved by stating "…..for the three shot pair cases."

A sentence of explanation has been changed as suggested.
"…..for the three shot pairs." have been changed to "…..for the three shot pair cases." as suggested.

(3) lines 7-10, beginning with "The relative error of the DAOD…" Please explain/clarify. …two times lower than the minimum..??

We tried to qualitatively explain the relation between the relative error of the DAOD and range. In order to mention it clearly, a sentence of explanation has been changed as follows:
The relative error of the DAOD at the range of 7.12 km was about two times lower than the minimum relative errors at the range between 1 km and 7 km.

(4) line 19: "Therefore the N_C for the hard target return is limited to improving the SNR." Please clarify the intending meaning of this statement.

A sentence of explanation has been changed as follows:
The improvement of the signal-to-noise ratio for the coherent IPDA lidar due to Nc is limited if the Nc is small.

(5) lines 25-28: Please clarify. I assume you believe that increasing the number of shot pairs in the measurement will continue to decrease the relative random error, with a laser having a prf of a few tens of kHz being necessary in order to attain the goal of 1-2 ppm relative error within a convenient measurement duration

A sentence of explanation has been changed as follows:
Increasing the number of shot pairs in our experimental measurement will decrease the relative random error. The coherent IPDA lidar with the laser at a pulse repetition frequency of a few tens of KHz is necessary in order to reach the goal of 1-2 ppm relative error with and horizontal resolution of 100 km x 100 km for spaceborne observation (Ehret et al. 2008, NASA Science Definition and Planning Workshop Report 2008).

(6) Page 8591, line 14: Here you state that you used the slope method. What alternate algorithm would be practical for detecting/identifying localized plumes at locations along your path? What is your estimate of the minimum detectable localized rise in CO_2 due to an emission plume?

Our final goals are to measure column-averaged mixing ratio of CO_2 with the 2-µm coherent IPDA lidar and to examine the detection sensitivity of a 2-µm coherent IPDA lidar.

A sentence of explanation has changed and added as follows:

The CO_2 volume mixing ratio for the foothill target return was obtained with a DAOD (Eq. (5)) between 0.974 and 7.12 km and Eq. (6). The CO_2 volume mixing ratio for the atmospheric return was estimated from a slope of 40 range-gated bins for a range between 0.974 and 6.97 km. The distribution of CO_2 volume mixing ratio can be measured by using the slope method. The CO_2 volume mixing ratio change of 3 % is detectable by 5-minutes (or 4500 shot pairs) measurements in both methods. Though more localized plume can be detectable in the DIAL measurement with atmospheric return, IPDA results are more stable. We compared the detection sensitivity of the IPDA lidar measurement with that of the DIAL measurement, in which the CO_2 volume mixing ratio for the atmospheric return was estimated by using the slope method.

(7) Page 8592, lines 16-21: I assume that your "..fluctuation of the DAOD due to the decrease in the CNR" refers to the variable atmospheric aerosol backscatter coefficient, the value of which depends on the variable aerosol sources and the atmospheric conditions. Please clarify.

A sentence of explanation has been added as follows:

Precision depends strongly on the backscattering coefficient of the atmosphere and the atmospheric condition.

6. Conclusions:

As stated in my general comments, the conclusions should be strengthened, made more meaningful, by tying your results to some high-level objectives of an application (e.g. precision, measurement time scale, spatial resolution), whether it's ground-based urban studies, global-scale measurements from Earth orbiting platform, or some other application.

Conclusions have been revised as follows:

The XCO_2 measurement from the space requires a bias-free high precision of 1-2 ppm with a horizontal resolution of 100 km x 100 km. The IPDA lidar is one of candidate spaceborne sensors to measure the column-averaged mixing ratio of CO_2 using return signal from the Earth's surface. We need to discuss the detection sensitivity of a 2-µm IPDA lidar using a coherent detection with using a direct detection. In this paper, we used the coherent IPDA lidar with a 2-µm single-frequency Q-switched laser with laser frequency offset locking. Experimental horizontal CO_2 measurements were conducted using foothill target (trees and ground surface) and atmospheric (aerosol) returns in the western part of Tokyo on December 11, 27 and 28, 2010. The CO_2 concentration was first measured with the 2-µm coherent IPDA lidar. The foothill target is located about 7.12 km south of NICT. The results obtained from the foothill target return were examined in detail and compared with those measured from the atmospheric return and the *in situ* sensor. The range measured using the 2-µm coherent IPDA lidar showed a large fluctuation related mainly to speckle-induced intensity fluctuation. The results of the range measurement showed the characteristics of mix reflection by the trees and the ground surface. For coherent lidar, it is difficult to measure the range with a high precision better than 1 m due to the long laser pulse width. Our results showed that the 2-μm coherent IPDA lidar can measure a range with the precision of 0.012 km corresponding to the laser pulse width of 150 nsec. Our results also indicated that the 2-μm coherent IPDA lidar has a potential for detecting the ground surface return from the backscattered signal. The PDF in negative exponential function can be expected if the signal is backscattered only from the ground surface. The results showed the Nc=1.9. The precisions of the 2-μm coherent IPDA lidar CO_2 measurement after the integration of 900, 4500 and 27000 shot pairs were 6.5, 2.8, and 1.2%. As described by Ehret et al. (2008), the results also indicated that a laser operating at a high pulse repetition frequency of a few tens of KHz is necessary for the coherent IPDA lidar XCO_2 measurement at the target horizontal resolution of 100 km x 100 km from space. The averages values of the 2-μm coherent IPDA lidar measurements were about 5 ppm lower than the 5-min running averages of the *in situ* sensor, because of the spatial difference, the f1uctuation of temperature, and the natural variability of CO_2 along the observed line of sight. Statistical comparisons indicated that there were no bias between foothill target and atmospheric return measurements. We can obtain more stable data from the 2-μm coherent IPDA lidar. The CO_2 volume mixing ratio change of 3 % is detectable by the 2-μm coherent IPDA lidar if the signal is integrated during 5 minutes. The calibration of the on- and off-line return powers was carried out at a range of 0.974 km. Our result showed that the bias of the optical depth was negligible if the SNRs of on- and off-line backscattered signals were very high. In order to detect the foothill target and to measure a specific range with a high SNR, it is important to make a precise range measurement using a Q-switched laser and a range-gated receiver. The precise range measurement leads to the XCO_2 measurement with a high precision. The IPDA lidar with a Q-switched laser and a range-gated receiver has a great advantage in terms of reducing uncertainty due to the presence of aerosols and clouds.

Last sentence: "….has a great advantage in terms of discussing uncertainty due to the presence of aerosols and clouds." ?? Do you mean to say "reducing uncertainty"?

A sentence of explanation has changed as follows:

The IPDA lidar with a Q-switched laser and a range-gated receiver has a great advantage in terms of reducing uncertainty due to the presence of aerosols and clouds.