Response to Anonymous Referee #2

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 anonymous referee #2. Those 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.

Return signals from foothill target were examined in detailed. The results indicated that some return signals have two peaks. I agree with the reviewer's presumption. Some return signals consist in a mix of trees and ground surface. The term of "hard" target must be used with great caution. In the revised paper, we replace the term of "hard" target by the term of foothill target. The instrumental calibration and speckle number issues were discussed in Section 5 as suggested.

Specific comments:

Abstract:

l. 11-12: <<precision of 1-2 ppm>>. For what kind of application such a precision is needed? This will surely explain why a high PRF laser system is then needed for such measurements.

Our final 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 7 km/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 $CO_2$.

l. 15: <<was about 5 ppm lower>>: if the authors want to address an accuracy better than 1%, the accuracy of spectroscopic data and their fluctuations with meteorological data should be addressed.

We will discuss the accuracy of spectroscopic data in Section 4.

A sentence of explanation has been replaced as follows:

The $CO_2$ volume mixing ratio obtained by the Co2DiaWiL measurements for the foothill target and atmospheric returns was about -5 ppm lower than the 5-min running averages of the *in situ* sensor. Not only actual difference of sensing volume or the natural variability of $CO_2$ but also the f1uctuations of temperature could arise due to this difference.

l. 17: <<no differences>>. I guess that the authors mean <<no biases>>

Term “no differences” has been replaced to “no biases”.

l. 23-25: <<simultaneously conduct both hard target and atmospheric return measurements>>. This should not be a recommended objective of $CO_2$ lidar measurements as IPDA measurements are generally not used when range-resolved measurements are available. The raison for simultaneous IPDA and DIAL measurements should be more developed in the paper. Any IPDA calibration issue?

The IPDA calibration issue is discussed later.

All sentences of explanation have been corrected 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.

<u>Introduction</u>

l. 27: <<it tends to overestimate the optical depth of aerosols...>> This is not the optical depth of aerosols or clouds which is concerned but more the optical depth due to $CO_2$ absorption and the error due to aerosols and clouds.

Aerosols and clouds entails a reduction of the total integrated path of $CO_2$ measurements for passive sensors. In this way the total optical depth due to $CO_2$ absorption is underestimated and regional biases may occur.

Reference “Morino et al. 2011; Yang et al. 2013” have been changed.

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.

Sentences of explanation have been added:
...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.

l. 5 p. 8582 <<is not affected>>: unlike passive sensors, aerosols and clouds don't produce a reduction of optical depth for IPDA measurements. However, due to their associated extinction effect on the laser beam, they still affect the signal to noise ratio.

A sentence of explanation has been removed according to Dr. Menzies's suggestion.

l. 26 p. 8582<<Gilbert et al.>> please remove the <<l>> (Gibert et al.)

References have been corrected.

l. 3 p. 8583: <<hard target>> the authors may be careful using the term of hard target.
A definition of hard target is definitively needed in this paper. Some dense clouds can also be considered as hard target as only one temporal speckle will be seen in a temporal range gate. Also the surface might not be considered as a hard target as some propagation of the laser beam is still possible through the canopy.

Following comments of anonymous referee #2, return signals from foothill target were examined in detailed. The results indicated that some return signals have two peaks. I agree with the reviewer's presumption. Some return signals consist in a mix of trees and ground surface. The term of "hard" target must be used with great caution. In this revised paper, we decided to replace the term of "hard" target by the term of foothill target.

2. Coherent 2-µm differential absorption and wind lidar
3. <u>Estimation of CO2 and error analysis</u>
l. 5 p. 8587: <<temporal cross correlation coefficient as 0>>: the authors should consider that the correlation coefficients are different for atmospheric and ground target return power signals. This might have an impact on the precision of the IPDA measurements comparing to the DIAL measurements (see for example the papers from Killinger et al, 1981, 1983 and others). This should be addressed or at least mentioned.

Sentences of explanation have been changed as follows:

In this paper we assume the temporal cross correlation coefficient as 0 to avoid practical difficulties. The temporal correlation coefficient for the foothill target return would be different from that for atmospheric return. The difference of the temporal correlation coefficient might have an impact on the precision of the IPDA measurement comparing to the DIAL measurement.

4. Ground-based in-situ measurements

l. 5: <<a total error of 0.1% in the CO2...DIAL measurements>>: although the R30 CO2 absorption line is rather insensitive to temperature fluctuations, one can claim that the f1uctuations of temperature in the surface layer are larger than 1ºC due to the heterogeneous radiative properties of the surface (building, river, forest, altitude variations) over 7km as mentioned by the authors. This should be discussed by the authors.

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).

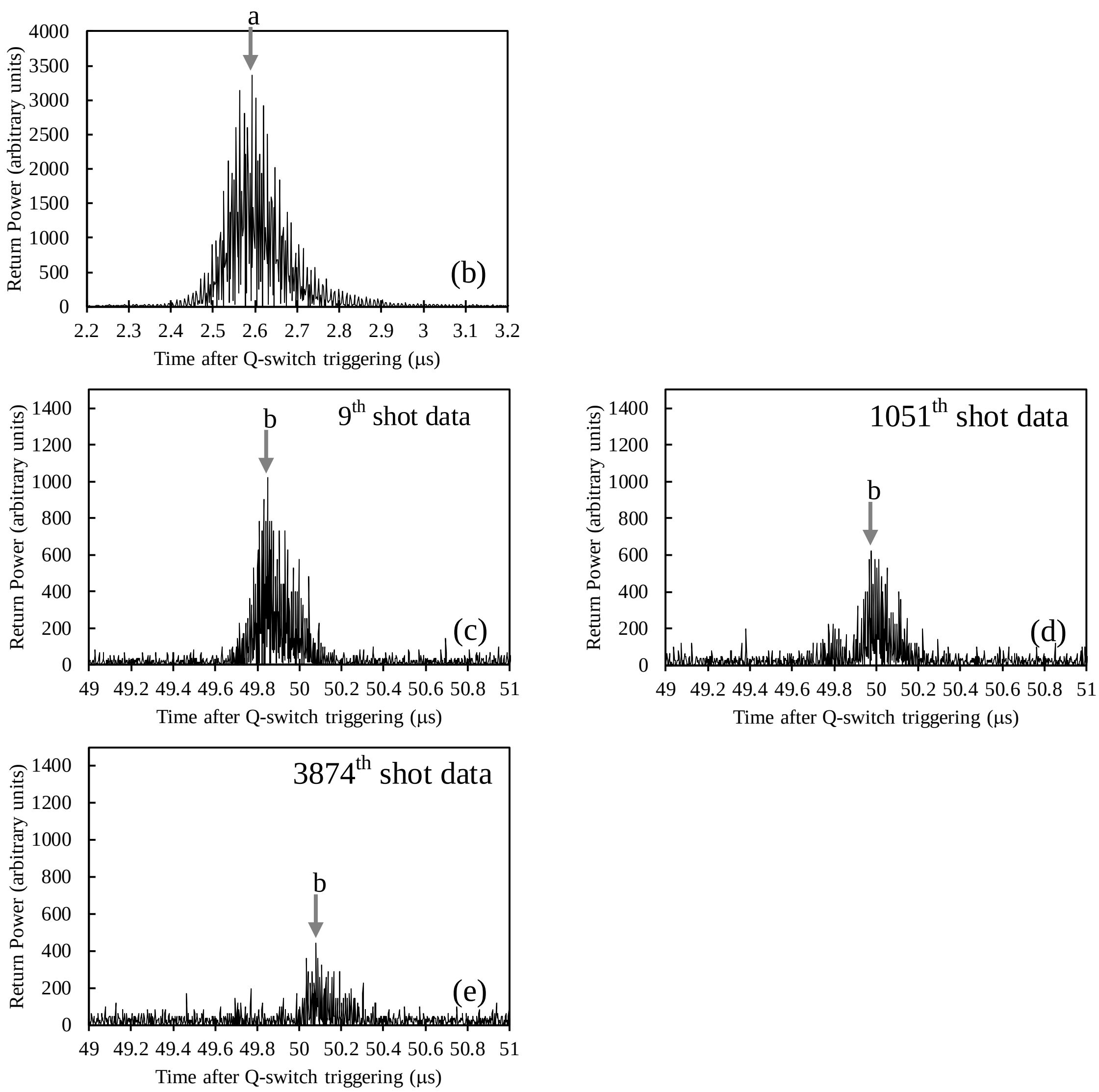
5. Experimental hard target measurements

l. 21 <<hard target surface>>: please define what is this <<hard target>>: ground surface, forest, building... later, the authors wrote <<swaying branches>> so the reviewer assumes that the target consist a mix of trees and ground surface.

As mentioned above, I agree with the reviewer’s comments that the return signals consist in a mix of trees and ground surface. The terms of “hard target” have been replaced to the term of foothill target.

Fig. 2c: the reviewer thinks that Fig. 2c does not give more information than Fig. 2a. Instead, a similar zoom on the emitted and the reflected pulses should be shown. Please make a zoom in Fig. 2b and a similar zoom for the reflected pulse in Fig. 2c so that we will have some information about the change in the shape of the return pulse. This will help to characterize the <<hard target>>.

Figures 2b and 2c have been magnified as suggested. Figure 2(d) has been added and a sentence of explanation has been added.




l. 4 p. 8589 and fig. 3a and b: <<speckle induced f1uctuations>> how is calculated the range using the hard target return signal? any fit of the data?

A sentence of explanation has been mentioned in line 26 p.8588- line 1 p.8589.
The intermediate-frequency (IF) signal is given by 8-bit digital data (-128 to 127, center 0). The square of "IF 8-bit digital data" was calculated, and the maximum value was investigated in a range gate. We define the point (time) of the maximum as the range of the foothill target.

Fig. 3c: Fig. 3c seems to show two different modes in the detection of the range of the hard target. This should indicate that the <<hard target>> is a mix of trees and ground surface. Please discuss that in the paper.

Sentences of explanation have been added as follows:

Figure 3(c) indicates two different modes in the detection the foothill target return. The slope angle was assumed to be about $12^{\circ}$ 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 $12^{\circ}$). The two different modes suggest that the foothill target returns are a mix of trees and ground surface return.

A sentence of explanation has been also added 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.

l. 23-25: please clarify

Sentences of explanation have been changed and added as follows:

Though the power at the range of 7.12 km may include the contribution from the atmospheric return, it is 0.1% of the power of the foothill target at most.

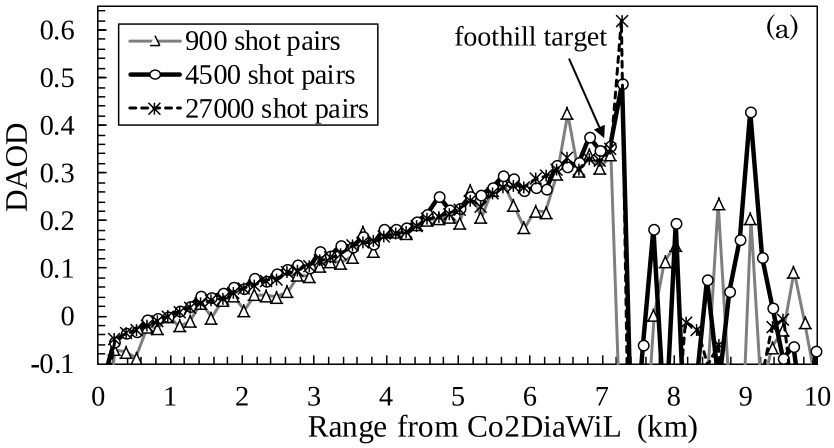
Fig. 5a: Fig. 5a shows that a negative optical depth is obtained at a range of 0 which raises the issue of calibration of absolute measurement of optical depth. This calibration is necessary to obtain accurate optical depth and CO2 mixing ratio measurements with the IPDA method. Gibert et al. (JTECH 2008) used the DIAL technique and the slope method in order to correct instrumental biases in IPDA optical depth measurements in free troposphere clouds.

Please comment on this calibration issue and develop in this paper how accurate IPDA measurements of CO2 are made here.

Sentences of explanation have been added as follows:

Fig. 5a shows negative optical depths for the three shot pair cases at a range of 0 km, which raises the issue of calibration of absolute measurement of optical depth. The calibration is necessary to obtain an accurate optical depth with the IPDA lidar measurement. Gibert et al. (2008) suggested that the bias of the optical depth is negligible for high SNRs of on- and off-line backscattered signals. In this paper, the calibration was carried out at a range of 0.974 km. The optical depths are computed with respect to the position. The bias of the optical depth was calculated using Eq. (C5) described by Gibert et al. (2008). The SNRs of on- and off-line backscattered signals for the 900 shot pairs were >40 at ranges of 0.974 km and 7.12 km. The calculated bias of the optical depth was $-5.2\text{x}10^{-7}$. The low bias of the optical depth does not affect the measurement of the optical depth in our IPDA lidar experiments.

Figure 5(a) has been changed:




l. 27-29: <<TheDAOD…7km>>: please remove this sentence. The next sentence means the same thing and is more clear to the reviewer.

A sentence of explanation has been removed as suggested.

l. 16 p. 8590: for a pure hard target, the reviewer expects to have a PDF in negative exponential and not a lognormal law. The reviewer suspects that two speckles are obtained due to the characteristics of the hard target (mix of trees and ground)

I agree with the reviewer's comment. Sentences of explanation have been changed as follows:
If signal were backscattered only by the ground surface, we could expect to have a PDF in negative exponential function. The result suggests that the PDF is composed of several speckles due to the reflection by mix target of trees and ground surface. The PDF shape is better represented by a gamma function.

l. 17: <<the calculated Nc for atmospheric return>>. This depends not only on the pulse width but also on the turbulence in the atmosphere. The reviewer suggests that the authors make an experimental PDF calculation for atmospheric return with their data and compare it with the one of the hard target. Also, some theoretical considerations for Nc might be welcome here.

The calculated $N_C$=6.7 for the atmospheric return was wrong. The calculated $N_C$ for the atmospheric return was corrected.

A sentence of explanation has been corrected and added as follows:
The calculated $N_C$ for the atmospheric return amounts to 10.1 using a pulse width of 150 ns and a range

gate duration of 1000 ns, and Eq. (4) described by Gibert et al. (2006). The experimental value of $N_C$ for the atmospheric return was 9 to 10. In the present experiment, we cannot say anything about the effects of the turbulence, although the Nc for atmospheric return depends not only on the pulse width but also on the turbulence in the atmosphere.

l. 20: please clarify and rewrite the sentence

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.

l. 27: please indicate the duration of measurements that is considered here and for what kind of application.

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).