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## CURRENT 2- $\mu\text{m}$ DIAL MEASUREMENTS OF ATMOSPHERIC CO<sub>2</sub> AND EXPECTED RESULTS FROM SPACE USING NEW MCT APDs

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### INTRODUCTION

In the framework of CO<sub>2</sub> monitoring in the Atmospheric Boundary Layer (ABL), a ground-based 2- $\mu\text{m}$  Differential Absorption Lidar (DIAL) has been developed at the Laboratoire de Météorologie Dynamique (LMD) in Palaiseau. In order to derive flux information, this system has been set up with coherent detection, which allows to combine CO<sub>2</sub> density measurements with wind velocity measurements. On the other hand, new advances in the field of Mercury Cadmium Tellure (MCT) Avalanche Photodiodes (APDs) open the way for high-precision measurements in direct detection ultimately from space. In this study, we first report on state of the art measurements obtained with the current coherent DIAL system before presenting expected results for a similar laser transmitter equipped with MCT APDs. For this latter part, we use a numerical model which relies on APDs performance data provided by the Laboratoire d'Électronique et de Technologie de l'Information (LETI).

### I. LMD COHERENT DIAL

Since 2009, a Tm, Ho:YLF solid-state laser dedicated to 2  $\mu\text{m}$  DIAL applications has been developed at LMD by F. Gibert et al. A thorough analysis of this new transmitter performances was reported in early 2014 [5]. Current settings are reproduced in Tab 1. The first goal of this instrument was to enable high-precision carbone dioxide

Laser pulse energy	10 mJ
Double PRF	1 kHz
Wavelength ON/OFF	2050.96/2051.26 nm
Pulse duration/Width	40 ns / 10 MHz

Tab 1: LMD CDIAL transmitter features.

measurements within the ABL. Regarding CO<sub>2</sub> mixing ratio in the air, one has to keep in mind that CO<sub>2</sub> variation scales range from a 1-10 ppm for geophysical perturbations to hundreds of ppm for pollution sources. As the mean CO<sub>2</sub> mixing ratio is about 390 ppm, the suitable accuracy for geophysical concerns is a few ppm, that is an error of 1%. Despite all the efforts made to optimize the DIAL method [2], reaching such a bound remains a tremendous challenge. The necessary Signal to Noise Ratio (SNR) that is usually required for range-resolved measurement is around 1000. The huge number of independent samples that is required to reduce coherent lidar statistical error and get such SNR is the main limitation of this technique. Nevertheless, using a powerful Ho:YLF emitter (10 mJ/ 2 kHz), the LMD team made some preliminary atmospheric CO<sub>2</sub> DIAL measurements. Accuracy was about 1% with 10 min/ 100m time and space resolution (see Gibert et al. paper in this conference [6] and section III). These results will serve as a state of the art to derive the expected benefits of a new direct detection module with MCT APDs.

### II. Current MCT APDs performances and comparison with IPDA space requirements

To infer accurate CO<sub>2</sub> surface fluxes (the main goal for CO<sub>2</sub> lidar space mission), atmospheric CO<sub>2</sub> concentration should be determined with 1 ppm precision in total column [1]. The instrumental scaling has been widely documented in several studies for ESA and are summarized below in Tab. 2 [4][1].

MCT APDs are characterized by high linear avalanche gain, absence of avalanche break down and an ultra-low excess noise. In addition, they have quantum efficiencies (QE) higher than 80 % for wavelengths from the visible range to the infrared cut-off wavelength (2-5  $\mu\text{m}$  depending on the Cadmium composition) [7]. The comparison provided in Tab. 2 shows that MCT APDs meet the performance requirements for space monitoring of CO<sub>2</sub>, which is a promising prospect. Note that these detectors reliability in space environment will be tested in the next months.

Regarding lidar applications, first experiments will be held with ground-based lidars. The results obtained will assess the real potential and limits of these detectors. In this context, a macrodiode of 200  $\mu\text{m}$  diameter designed for 2- $\mu\text{m}$  DIAL application has been produced and tested at LETI at 1.5  $\mu\text{m}$ . It achieves a QEFR - which is the ratio of the quantum efficiency by the excess noise factor - of 70%, a bandwidth of 20 MHz and a Noise Equivalent

Parameter	Requirements	Current features
Satellite altitude (km)	450	450
Emitted energy ON/OFF (mJ)	75/25	10/10 (100/100)
Repetition frequency (Hz)	10	1000 (100)
Telescope diameter (m)	1	0.2
Detector quantum efficiency	0.6	0.8
Detector NEP (fW/ $\sqrt{Hz}$ )	$5 \cdot 10^{-14}$	$5.8 \cdot 10^{-14}$
Excess noise factor	1.5	1.3

**Tab 2:** Comparison between the IPDA requirements that were found in [1] and current features for LMD CDIAL transmitter and LETI MCT APDs.

Power (NEP) of  $74 \text{ fW}/\sqrt{Hz}$  for a reverse bias of 12 V and a gain  $M \approx 70$ . An improvement of 20 % of the NEP is expected at  $2 \mu\text{m}$  because the gain depends of the frequency and was designed to be optimal around  $2 \mu\text{m}$ .

### III. NUMERICAL MODELING FOR DIRECT DETECTION

In this paragraph we simulate the performances of a DIAL system which use the same LMD Ho:YLF transmitter and a direct detection with new MCT APDs.

#### A. The Lidar equation

The most simple form of the monochromatic lidar equation is provided in [8]. The wavelength dependency of all parameters is omitted but should be kept in mind. We have :

$$P(R) = \frac{K}{R^2} \beta(R) T(R) \quad (1)$$

where  $P$  is the optical power incident on the detector and received from a distance  $R$ . The term  $K$  accounts for the performances (energy per pulse, pulse length, optical efficiency, telescope area) of the lidar system while the term  $1/R^2$  expresses the spherical scattering.  $\beta(R)$  is the backscatter coefficient at range  $R$  and  $T(R)$  is the transmission over the distance  $R$  back and forth.

$$T(R) = \exp(-2(\tau(R) + \tau^0(R))) \quad \text{with} \quad \tau(R) = \int_0^R n(r) \tilde{\sigma}(r) dr \quad (2)$$

where  $\tau$  is the optical depth due to  $\text{CO}_2$  absorption and  $\tau^0$  the optical depth due to extinction and absorption by other species,  $n(r)$  is the  $\text{CO}_2$  concentration at range  $r$  and  $\tilde{\sigma}(r)$  is the absorption cross-section at range  $r$ . Recall that  $\tilde{\sigma}$  is a temperature, pressure and wavelength function.

#### B. Estimation of $K$

In order to derive an realistic estimate of  $K$ , we use  $\text{CO}_2$  experimental measurements at  $1,6 \mu\text{m}$  in direct detection presented at the 5th International workshop on  $\text{CO}_2/\text{CH}_4$  remote sensing (Kyushu University, March 2012) by Y.Shibata, C.Nagasawa and M. Abo (see Fig 1).

In the ABL,  $\beta(R)$  values can vary significantly because of aerosols strong influence on backscatterer coefficient. However in the free troposphere, backscattering is mainly due to molecules and is a well-quantified phenomenon [3]. Therefore, if we write (1) for the OFF wavelength of a DIAL ( $\tilde{\sigma} \approx 0$ ), we get :

$$\frac{P \cdot R^2}{\beta_{\text{Rayleigh}}(R)} = K \exp(-2\tau^0(R)) \quad (3)$$

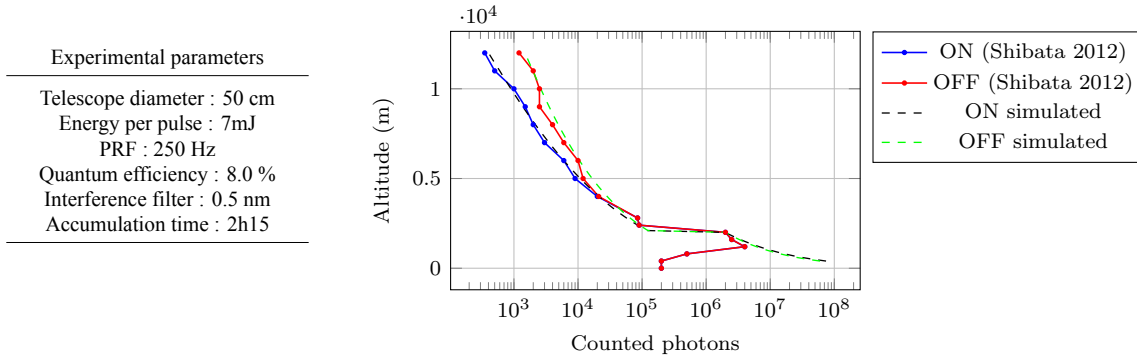
Even if it is not possible to rigorously distinguish between extinction influence and  $K$  influence, in clear sky conditions we will consider that  $\exp(-2\tau^0(R)) \approx 1$ . Therefore, the signal decrease in free troposphere will allow us to estimate  $K$ . The experimental and simulated data are presented in Fig 1. We obtain  $K = 5 \cdot 10^{-3}$ .

### IV. EXPECTED RESULTS FOR DIRECT DETECTION

#### A. Noise estimation

From (2), define the optical depth due to  $\text{CO}_2$  absorption :

$$\Delta\tau(R) := \tau_{\text{ON}}(R) - \tau_{\text{OFF}}(R) = \int_0^R n(r) (\tilde{\sigma}_{\text{ON}}(r) - \tilde{\sigma}_{\text{OFF}}(r)) dr \quad (4)$$



**Fig 1:** Experimental data obtained on 15/09/2011 and simulations. We have used the international standard atmosphere model for temperature and pressure, and the GEISA database for spectroscopic data. The top of the ABL is located around an altitude of 2.3 km. Experimental parameters are reminded in top left hand side corner. Notice that the overlap function is not modeled because we are interested in the signal decrease in the free troposphere.

In direct detection, one can show [2] that the relative standard deviation for  $\Delta\tau$  is given by :

$$\frac{\sigma(\Delta\tau)}{\Delta\tau} = \frac{1}{2\Delta\tau} \cdot \left( \frac{1}{\text{SNR}_{\text{ON}}^2} + \frac{1}{\text{SNR}_{\text{OFF}}^2} \right)^{1/2} \quad (5)$$

where  $\text{SNR}_{\text{ON/OFF}}$  is the signal to noise ratio for the ON/OFF wavelengths respectively. In this study, we consider that the background radiative noise and the speckle noise are negligible compared to the detector noise. The reason for that is that we want to assess the influence of detection noise on the measurement accuracy. As a consequence, we will only keep the shot noise and the detection noise:

$$\frac{1}{\text{SNR}_{\text{ON/OFF}}^2} = \frac{1}{N} + \frac{N_{\text{detector noise}}}{N^2} \quad (6)$$

where  $N$  is the total number of signal direct detected photons in the range gate while  $N_{\text{detector noise}}$  is the total number of noise direct detected photons in the range gate.

For range-resolved measurements, the error on the  $\text{CO}_2$  mixing ratio ( $X_{\text{CO}_2}$ ) equals the relative standard deviation on the local optical depth  $\delta\tau := \Delta\tau(R_2) - \Delta\tau(R_1)$  [2]. We have

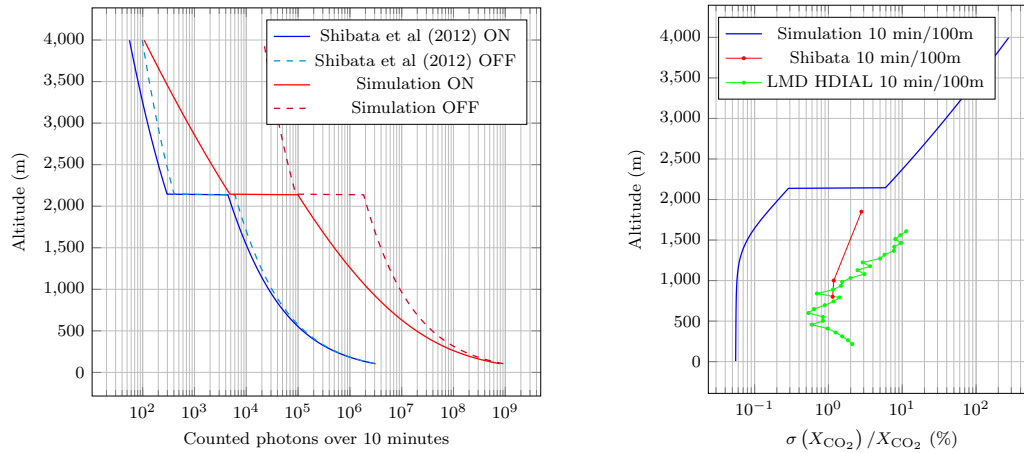
$$\frac{\sigma(X_{\text{CO}_2})}{X_{\text{CO}_2}} = \frac{\sigma(\delta\tau)}{\delta\tau} = \frac{1}{2\delta\tau} \cdot \sqrt{\frac{1}{\text{SNR}_{\text{OFF}}^2} + \frac{1}{\text{SNR}_{\text{ON}}^2}} \quad (7)$$

## B. Simulations

Putting together all the tools presented before, we present in Fig 2 a comparison between Shibata et al results, LMD CDIAL results and expected results if we assembled the LMD CDIAL transmitter, the LETI APDs and Shibata-like emission/detection devices (we take the same  $K$ ). We focus our concern on the ABL and the low free troposphere for this is the current limit for LMD CDIAL operability range.

## CONCLUSION

According to our current performances data, LETI MCT APDs should enable in the future remarkable  $\text{CO}_2$  monitoring at  $2 \mu\text{m}$ . In the next months, tests will be carried out at LMD for a ground-based lidar equipped with the current CDIAL transmitter. Simulations show that  $\text{CO}_2$  monitoring in the ABL and lower troposphere should be possible with extremely high precision/ lower time space resolution, therefore enabling better estimation of  $\text{CO}_2$  surface fluxes. On the other hand, further testing on the technologies involved with respect to space standards is to be undertaken for the APDs as well as for the laser transmitter [6]. This future work will assess the feasibility of a  $\text{CO}_2$  space mission with such technologies.



**Fig 2:** Simulated signals for LMD transmitter parameters (10 mJ, 1 kHz ON/OFF, 2.050  $\mu\text{m}$ ) and LETI APDs parameters (QEFR = 70 %, NEP = 56 fW/ $\sqrt{\text{Hz}}$ ). The calibrating parameter  $K$  found earlier is kept but we chose 20 cm as telescope diameter. Finally, as the backscatter coefficient for aerosols is lower at 2  $\mu\text{m}$  than at 1.6  $\mu\text{m}$ , a factor 1/2 was introduced to account for this phenomenon. Dashed lines correspond to OFF wavelength.

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