

Preparing a future CO₂/H₂O and wind space lidar mission: from scientific objectives to technological breakthroughs.

Focus on direct detection at 2 μ m using frequency conversion.

Fabien Gibert^{*a}, Dimitri Edouart^a, Claire Cénac^a, Paul Monnier^a

^a Laboratoire de Météorologie Dynamique (LMD), CNRS, École polytechnique, 91128 Palaiseau cedex, France

ABSTRACT

Following recent technical advances both in hybrid/bulk all-amplifier built emitter at 2 μ m and in IR up-conversion detection, an ambitious CO₂ (H₂O) and wind space lidar mission has been considered at LMD. Numerical simulations showed that a 1% precision of CO₂ mixing ratio in the first kilometre in the atmosphere above the ground over a satellite pathway of 50 km is now achievable. Additional products of the mission, H₂O and wind profiles, enable to give some necessary additional data for CO₂ signal processing and for transport model parametrizations in order to infer accurate and precised CO₂ surface fluxes at regional scale. To prove the concept, an experimental set-up has been built at LMD integrating new emitter and detector schemes at 2 μ m and is currently in atmospheric test. Preliminary DIAL atmospheric measurements show an Off-line SNR larger than 10 dB in horizontal LOS at a distance of 10 km with time and space resolution of 30 s and 15 m respectively.

Keywords: CO₂, H₂O, wind, Lidar, DIAL, upconversion detector, space mission

1. INTRODUCTION

In the framework of global warming mitigation, there is a strong need to quantify sources and sinks of CO₂, ultimately from space. Global estimates of CO₂ mixing ratio in synergism with a transport model has the potential to infer surface fluxes following a so-called top-down approach. A space-based lidar in IPDA (integrated path) or DIAL (range-resolved differential absorption) modes is a unique tool to get a required precision around 0.25% and an even better accuracy which is the key point for such measurements.

The usual technique considered for space-borne CO₂ lidar is the IPDA (current ACDL CO₂ mission and forthcoming MERLIN CH₄ one) as it enables to have a sufficient signal to noise ratio using the ground reflectivity of the laser pulses. However, an ideal mission should provide: 1) a concentration measurement in the boundary-layer (first km above the ground) close to surface sources and sinks, 2) some constraints to the transport model as this latter represents a significant uncertainty in optimized surface flux retrievals - vertical structure of the atmosphere and horizontal wind speed - 3) other information such as the water vapor and the temperature profiles to mitigate regional biases. This is of particular importance to reduce the uncertainty on surface flux estimates by atmospheric inversion [1]. In the same idea, the required precision on IPDA measurement is usually more stringent (around 1 ppm, i.e. 0.25 % [2, 3]) compared to a mean DIAL measurement in the boundary layer (around 4 ppm, i.e. 1%).

Recent advances in critical technological parts of a CO₂ lidar, i.e. laser source and efficient low noise detection in the near infrared enables to re-consider more ambitious scenarios than a simple IPDA mission. Numerical simulations have been performed at LMD to assess the feasibility of a CO₂/H₂O and wind DIAL/Doppler space lidar mission. The description of such mission, its objectives and performances are presented. In addition, the current status of technology developments, resulting from several past and ongoing European and national projects, features a suitable architecture for the emitter and the receiver of such a lidar mission. LMD is especially involved in 2- μ m pulsed laser source development for CO₂/¹³CO₂/H₂O DIAL [4], coherent detection for wind speed and direct detection using both HgCdTe avalanche photodiode [5] and nonlinear frequency conversion which are the basic bricks of the instrument. Concerning the direct detection of the lidar at 2 μ m, a ground-based CO₂ DIAL has been developed at LMD lab integrating a frequency upconversion system (2 μ m towards 700 nm) and first measurements are provided in this paper that represents a breakthrough in Lidar detection in the NIR.

2. CO₂ (H₂O) AND WIND DIAL/DOPPLER SPACE LIDAR MISSION DEFINITION AND PERFORMANCES

2.1 Lidar mission scenarios

Different scenarios for space-borne CO₂ lidar measurement may be considered from the most ambitious to the lowest one. Target is for DIAL measurement in the first kilometre of the atmosphere, i.e. in the boundary layer (ABL) using particles scattering, breakthrough is for IPDA measurement using the ground reflectivity plus a vertical structure information of the atmosphere (typically the ability to measure the ABL height and the horizontal wind speed profile) and threshold is for a standard IPDA measurement with the typical specifications of ACDL (CO₂ Chinese lidar mission, 2022) or MERLIN (CH₄ French-German lidar mission, scheduled in 2029). The different scenarios are gathered in **Erreur ! Source du renvoi introuvable.**

In order to measure the horizontal wind speed profile, the laser/telescope line of sight should be oriented 20° off nadir cross orbit path similarly to the scheme of ADM-Aeolus mission. In addition, a sun synchronous 6h-18h orbit similar to MERLIN lidar mission should be considered to limit the background parasitic light on the lidar detection. A low altitude orbit (400 km) is also chosen to obtain a sufficient signal to noise ratio, especially for the target mode which relies on aerosol backscatter signal.

Table 1. Scientific objectives of a space-borne CO₂ lidar mission and specifications of measurements in terms of precision, accuracy, horizontal and vertical resolutions; ^a Correspond to A-SCOPE and current ACDL specifications of a CO₂ lidar mission; ^b The DIAL measurement provides a mean CO₂ concentration in the first kilometre of the atmosphere, i.e. in the atmospheric boundary layer. In the free troposphere, the vertical resolution should be lower depending the content of particles. The same should apply for H₂O DIAL profile; ^c Wind speed measurement using coherent detection requires significant aerosol content (typically 0-4 km altitude and clouds)

	Target			Breakthrough	Threshold ^a
CO ₂ Lidar	DIAL			IPDA	IPDA
Additional measurements	- Aerosol/cloud profiles - Canopy structure/reflectivity - Horizontal wind speed profile - H₂O profile			- Aerosol/cloud profiles - Canopy structure/reflectivity - Horizontal wind speed profile	- Cloud altitude - Canopy structure/reflectivity
	CO ₂ ^b	H ₂ O	Wind ^c		
Precision	4 ppm (1%) (DIAL) < 1 ppm (IPDA)	10 % (DIAL)	< 1 m/s	< 1 ppm	1 ppm
Horizontal resolution	50 km (DIAL) 10 km (IPDA)	50 km	10 km	50 km	50 km
Vertical resolution	1 km (DIAL) weighted column (IPDA)	< 1 km	< 200 m	weighted column	weighted column

2.2 Lidar main equations

The IPDA measurement is a weighted integrated measurement. It relies on the reflected laser pulses by a scattering surface (ground, cloud). For this method, a precise instrument calibration for the On and Off-line emission and reception parameters that may vary along the measurement (like the emitted pulse energies shot by shot) is necessary. The CO₂ differential absorption optical depth is calculated using the observed lidar optical return power at both wavelengths assuming the contribution from other gases (i.e. H₂O in our case) is negligible:

$$DAOD = \frac{1}{2} \ln \left(\frac{P_{Off}}{P_{On}} \right) \quad (1)$$

The DAOD is converted into vertically-integrated dry mixing ratio of CO₂, $\langle X_{CO_2} \rangle$, which is the measurement that may be used for assimilation in atmospheric transport models:

$$\langle X_{CO_2} \rangle = \frac{\int_0^{P_{surf}} X_{CO_2}(p) WF(p) dp}{\int_0^{P_{surf}} WF(p) dp} = \frac{DAOD}{IWF} \quad (2)$$

where IWF is the integrated weighting function between the platform and the scattering surface, p is the atmospheric pressure, P_{surf} is the surface pressure and $WF(p)$ is the weighting function under humid air conditions:

$$WF = \frac{\sigma_{On} - \sigma_{Off}}{g(m_{dry} - m_{H_2O} X_{H_2O})} \quad (3)$$

where m_{dry} and m_{H_2O} denote the molecular masses of water vapor and dry air molecules, X_{H_2O} is the dry air volume mixing ratio of water vapor (number of water vapor molecules divided by the number of air molecules without water molecules), g is the acceleration of gravity and $\sigma_{On} - \sigma_{Off}$ is the differential absorption cross section for the selected wavelength pair that is a function of pressure and temperature.

The DIAL measurement is a range-resolved measurement. It is theoretically free from instrumental calibration although this is not true in practice as many non-linear disturbances from the detection chain should be considered carefully to reach a 1% precision on the measurement. The useful signals are the optical power backscattered by the particles and molecules in a sounding volume, i.e. a range gate. The lidar measurement concerns the CO₂ differential absorption coefficient:

$$\alpha(r) = d(DAOD)/dr \quad (4)$$

Note that $\alpha(r)$ must be corrected by H₂O absorption (optical depth) if it is not negligible. The range resolved CO₂ dry mixing ratio is obtained through the range resolved weighting function:

$$X_{CO_2}(r) = \alpha(r)/WF(r) \quad (5)$$

where $WF(r) = n_{dry}(r)(\sigma_{On} - \sigma_{Off})$ and $n_{dry}(r)$ is the dry air density.

To infer the CO₂ dry mixing ratio, the DIAL and IPDA measurements rely on spectroscopic data and meteorological data. Both IPDA and DIAL require knowledge of pressure, temperature and water vapor profiles although they are not so sensitive to their precisions and accuracies. Usually, meteorological profiles from NWP centres are sufficient. For example, the IPDA measurement requires the estimate of the scattering surface pressure:

$$P_{surf} = P_{NWP} \exp\left(-\frac{g \cdot m_{dry}}{T_{NWP} \cdot R} (SSE - Z_{NWP})\right) \quad (6)$$

where the SSE, the scattering surface elevation, comes from direct lidar range measurement and additional data from the satellite altitude and attitude.

One may write for the relative random error (RRE) on IPDA $\langle X_{CO_2} \rangle$ measurement:

$$RRE(\langle X_{CO_2} \rangle) = \sqrt{RRE(DAOD)^2 + RRE(IWF)^2} \quad (7)$$

and on DIAL $X_{CO_2}(r)$ measurement:

$$RRE(X_{CO_2}) = \sqrt{RRE(\alpha)^2 + RRE(IWF)^2} \quad (8)$$

The first terms in Eqs (7) and (8) are due to the CO₂ lidar DAOD and absorption coefficient measurements. Possible errors come from instrument signal to noise ratio (SNR) but also from non-perfect knowledge of instrumental parameters (frequency position, spectral purity, pulse energy especially for the IPDA configuration) and of platform pointing parameters (distance between the platform and the scattering surface, attitude of the platform). This should be considered in a global error budget. In this analysis, it is assumed (and this is a bit optimistic) that the error requirement on X_{CO_2} is the same as for the DAOD (IPDA) or the absorption coefficient (DIAL) which are linked to the instrument signal to noise ratio (SNR). In further work and a more detailed study, we will have to consider that the error budget has actually to be equally shared between instrumental and geophysical errors, i.e. DAOD and IWF. Using Eqs. (1) and (4) and assuming that the errors on On-line and Off-line emitted energies are negligible and the RRE on Off and On-line signals are independent (On-line and Off-line signals time separation low enough so that their probing volumes/surface are identical), the relative

random error on IPDA measurement may be written with the instrument return power signal to noise ratios (SNR) at On and Off wavelengths:

$$RRE(\langle X_{CO_2} \rangle) = \sqrt{SNR_{On}^2 + SNR_{Off}^2} / (2 \cdot DAOD) \quad (9)$$

Assuming that Off or On-line SNR does not change over a range gate of δr , a similar equation may be written for the DIAL error:

$$RRE(X_{CO_2}) = \sqrt{2} \sqrt{SNR_{On}^2 + SNR_{Off}^2} / (\alpha \cdot \delta r) \quad (10)$$

In this study, only direct detection is considered for DIAL/IPDA measurements as it is the more efficient solution with respect to the emitter as concluded in A-SCOPE study. Coherent detection will be only considered for radial horizontal wind speed measurements. Assuming the speckle noise and the background noise (optical filter narrow enough) are negligible, the SNR is then limited by the shot noise and the noise equivalent power of the detection (NEP) (usually the case) and may be written [6]:

$$SNR = \frac{P}{\sqrt{2h\nu PB + NEP^2 B}} \quad (11)$$

where B is the detection chain bandwidth, proportional to the inverse of the time gate, e.g. $B = 1/(2\delta t) = c/(4\delta r)$, and where noise factor and the quantum efficiency of the detector are equalled to one.

2.3 Spectroscopy in the 2- μ m domain

In order to get a boundary layer or high-pressure sensitivity in the space borne IPDA measurement, one may take advantage of the narrowing of absorption line as the pressure decreases with altitude. This requires the use of a strong absorption line and a laser line positioning on the wing of the absorption line. In addition, other conditions must be fulfilled: the total optical depth due to absorption has to be close to unity to optimize IPDA or DIAL statistical error [7], the absorption line has to be rather insensitive to temperature variation and interference with other trace gas absorption has to be avoided. Such absorption line has been found in the 2 μ m spectral band, i.e. the R30e line of the 20013 $\leftarrow$ 00001 band of $^{12}CO_2$, centred at 4875.748732 cm^{-1} . Figure 1 shows ACS (absorption cross section) calculated with line intensities from HITRAN2020 database [8] in the 2.06- μ m spectral region. These were obtained with a multispectrum fitting approach using a modified Voigt line shape to include line mixing and quadratic speed dependence. This database has been improved for air-broadening, air-pressure shift coefficients and their temperature dependence with recent CRDS lab measurements for $^{12}CO_2$ [9] and for $^{13}CO_2$ absorption lines [10] (Table 2). The residuals obtained after the multi-spectrum fit procedure are usually lower than 0.05 % for the absorption lines considered in this study. Figure 1 shows the On-line and Off-line positions around the R30 CO_2 absorption line chosen in this study. DIAL or IPDA instrument usually use a frequency reference system (FRS) to lock the laser wavelengths on dedicated positions. In these numerical simulations, the FRS is locked on a low-pressure CO_2 absorption cell in the centre of the CO_2 R30 absorption line at 2050.967 nm. Off-line is located in a free absorption window around 2051.250 nm and On-line position on the wing of the R30 CO_2 absorption line around 2051.02 nm. We also indicated the ability to use the nearby H_2O absorption lines for simultaneous CO_2 and H_2O DIAL or IPDA measurements. Note that $^{13}CO_2$ lidar measurements from space are also possible in this spectral domain and may be an additional product to consider for carbon cycle studies.

Table 2. Main $^{12}CO_2$ and $^{13}CO_2$ absorption line parameters used in this study. S: line intensity at 296 K weighted by standard isotopic abundance; E'': lower energy level of the transition; γ_0 : air broadening coefficient at 296 K; n_{γ_0} : temperature dependence exponent; δ_0 : air-pressure shift coefficient at 296 K. Line intensity values and uncertainties are taken from HITRAN2020 database [8]. Values and uncertainties for γ_0 , n_{γ_0} , δ_0 are from [9,10]. One-sigma uncertainties are given in parenthesis in the unit of the last digit.

	ν (cm^{-1})	λ (nm)	S ($cm/molecule$)	E'' (cm^{-1})	γ_0 ($m^{-1} atm^{-1}$)	n_{γ_0}	δ_0 ($m^{-1} atm^{-1}$)
$^{12}CO_2$ R30	4875.7487	2050.9670	1.510×10^{-22} (0.1-1%)	362.7882	6.890(2)	0.744(3)	-0.520(1)
$^{12}CO_2$ R24	4871.7917	2052.6329	2.225×10^{-22} (0.1-1%)	234.0833	7.049(2)	0.738(3)	-0.493(2)
$^{13}CO_2$ P18	4872.3027	2052.4176	9.59×10^{-24} (1-2%)	133.4456	7.360(7)	0.700(4)	-0.527(2)
$^{13}CO_2$ P14	4875.8434	2050.9272	9.58×10^{-24} (1-2%)	81.9440	7.649(6)	0.69	-0.510(2)

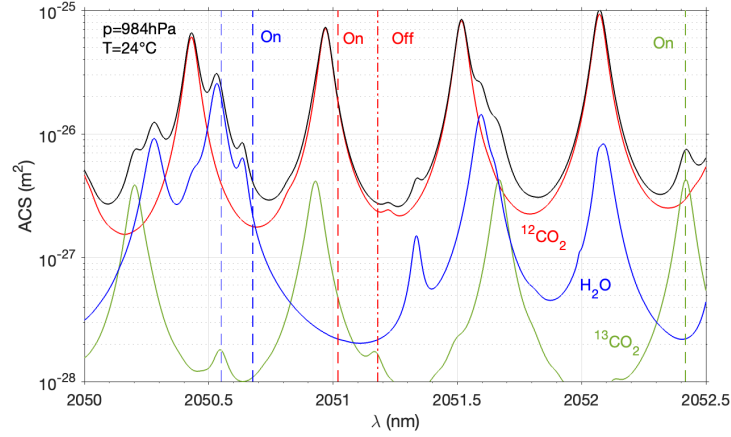


Figure 1. Absorption cross-section (ACS) for $^{12}\text{CO}_2$, $^{13}\text{CO}_2$ and H_2O for pressure 984 hPa and temperature 24°C (Voigt profile). H_2O ACS have been multiplied by a factor of 25 with respect to mixing ratios in the atmosphere (CO_2 : 0.04%, H_2O : 1%). $^{13}\text{CO}_2$ ACS is multiplied by the VPDB isotopic ratio 0.01118. The DIAL wavelengths chosen in this work are indicated.

2.4 Numerical simulations for space-borne $\text{CO}_2/\text{H}_2\text{O}$ DIAL

In these numerical simulations we consider a satellite altitude, speed and off-nadir angle of 400 km, 7 km/s and 20° respectively. The present numerical simulations use standard atmospheric conditions for temperature, pressure, humidity and particles extinction and backscatter coefficients from the ESA RMA model. A constant profile of 420 ppm is assumed for CO_2 . The nominal conditions correspond to free-cloud condition, a flat terrain and a ground reflectivity of 0.03 sr^{-1} (surface albedo is 0.1). The lidar emitter delivers 30/10 mJ On/Off pulses at a shot-pair repetition rate (PRF) of 500 Hz. 20% of the pulses are dedicated to H_2O DIAL measurement whereas the other part is used for CO_2 DIAL/IPDA measurements (PRF= 400 Hz for CO_2). The CO_2 On-line is shifted 3.6 GHz out of the R30 CO_2 absorption line centre. The detector NEP is 0.5 fW/rHz in agreement with HgCdTe avalanche photodiode performances [6]. Other possibility to obtain such NEP relies on parametric conversion from the 2- μm domain to the visible at 0.7 μm (see section 3) where standard low noise internally amplified detectors (photomultiplier PMT) exist but this will decrease the total efficiency of the system (efficiency for the conversion may be 50%) [11]. The overall optical transmission of the instrument (transmitter and receiver) is 50%. The telescope diameter is fixed to 1.5 m similar to ADM-Aeolus mission.

The total transmitter power was limited (for the target scenario) to the reasonable but also challenging level of 20 W (16W for CO_2 and 4W for H_2O) and the minimum horizontal resolution was chosen to be 50 km for the DIAL measurement. The telescope field of view is chosen to be larger than the laser divergence and is reduced so that the background noise is lower than the detector noise. With these parameters, a single shot On and Off-line SNR of around 10 is obtained in the ABL. The precision of a mean DIAL X_{CO_2} estimate in the first kilometre of the ABL is about 3.5 ppm (0.8 %) (8 ppm for the first 200 m range gate) (Fig. 2e). The IPDA mean X_{CO_2} precision is 0.4 ppm with a horizontal resolution of 5 km.

Atmospheric H_2O vertical profile remains a main interest for a space-based lidar mission as it is the main driver for life on the Earth but also for climate as it is the first greenhouse gas ahead of CO_2 . As shown in Figure 2, a lidar in the 2 μm spectral range has the potential to make simultaneous measurements of water vapor and carbon dioxide. This enables to study the link between the water vapor and carbon cycles. In addition to these geophysical interests, H_2O mixing ratio has to be quantified to make bias corrections in CO_2 optical depth/ absorption measurements and in dry air density estimate as well. The main difficulty to DIAL/IPDA H_2O measurement is the strong variability over several orders of magnitude of its mixing ratio with the latitude and the altitude from the polar to the tropical air mass (Fig. 2f) which has led the scientific community to propose a multi-wavelength H_2O -absorption coefficient DIAL architecture [12]. In our numerical simulations, we keep only two wavelengths but we optimize the lidar parameters for the tropical atmospheric conditions, knowing that the lower water vapour absorption in the temperate or polar region will increase the statistical error (which will just require a larger pulse-pair averaging) but will not prevent us to make a useful measurement. Using only a part of the total laser emitter power (30/10 mJ at 100 Hz) and keeping the same parameters as for the target scenario in Table 1, a 15% of precision may be achieved in the boundary layer with a 200 m and 50 km vertical and horizontal resolutions both for tropical ($X_{\text{H}_2\text{O}} = 30 \text{ mmol/mol}$ in the ABL) and temperate ($X_{\text{H}_2\text{O}} = 4 \text{ mmol/mol}$ in the ABL) regions. The same precision may be obtained in the free troposphere with a lower vertical resolution (kilometre range) (Fig. 2j).

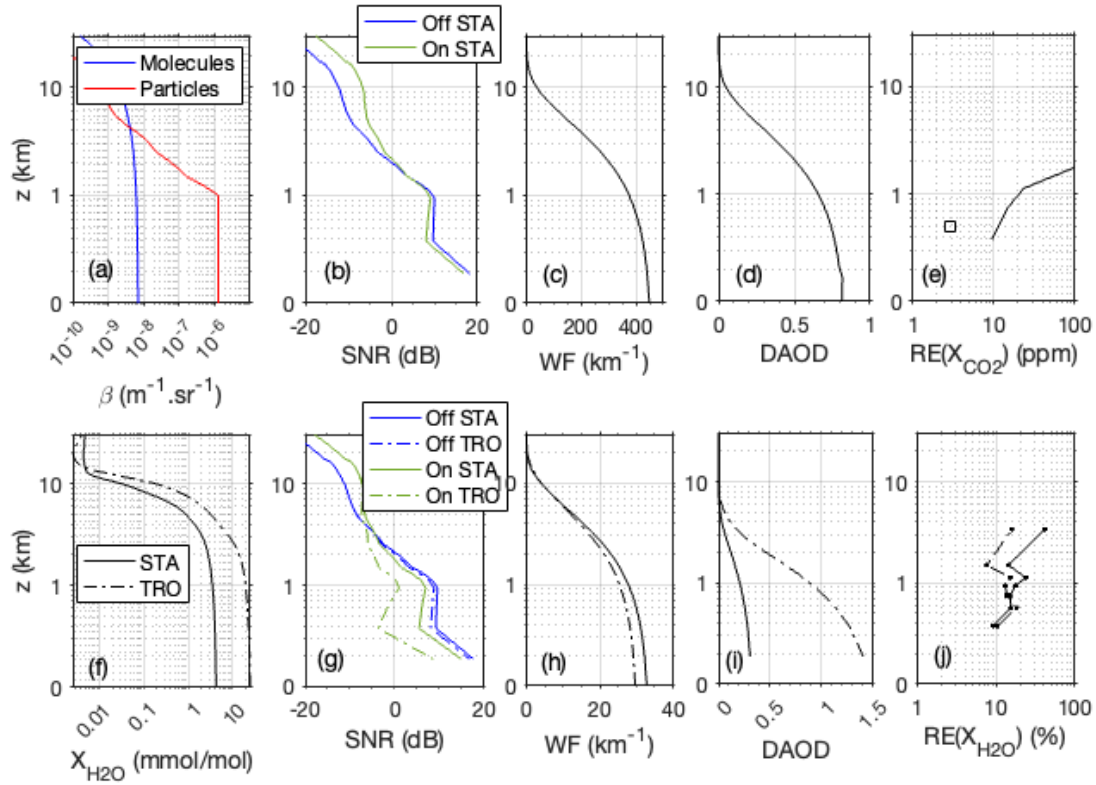


Figure 2. (a-e) CO₂ DIAL. (a) Particles and molecules backscatter coefficient (b) Off and On-line single shot signal to noise ratios (c) Weighting function (d) CO₂ differential absorption optical depth (DAOD) (e) Random Error (RE) on DIAL X_{CO₂} profile measurement for a vertical resolution of 200 m (solid line) and 1 km (marker). (f-j) H₂O DIAL. (f) X_{H₂O} mixing ratio profiles in temperate (STA) and tropical (TRO) regions (g) Off and On-line single shot signal to noise ratios (h) Weighting function (i) H₂O differential absorption optical depth (DAOD) (j) Random Error (RE) on DIAL X_{H₂O} profile measurement (dashed and dotted line is for tropical and solid line for standard atmosphere). The vertical resolution evolves from 200 m to 3 km.

2.5 Numerical simulations for additional horizontal wind speed profile with coherent detection

As mentioned in the introduction, in addition to CO₂ column-integrated or range-resolved measurements, the horizontal wind speed profile will give some important constraints on the transport model that will be used to estimate CO₂ surface fluxes. Such measurement may be achieved in direct (ADM-Aeolus ESA mission) or coherent detection. In coherent detection, the received optical field is mixed with a part of the emitter seeder on a quadratic detector. The beat-wave frequency components of the detector output current, proportional to the amplitude of the received optical field, is then digitized. In the spectral domain, the coherent detection gives the backscatter signal power (area of the spectrum) and a frequency shift with respect to the laser emitted frequency) due to the motion of the sounded volume/surface with respect to the lidar onboard the satellite (Doppler effect). A carrier to noise ratio in the range gate, defined as the ratio of the averaged signal power to the averaged noise power not accounting for speckle noise, may be written:

$$CNR = \gamma_H \eta N_C / M \quad (12)$$

where γ_H is the heterodyne efficiency, N_C is the number of photons received during a single coherence time τ_c and $M \cong 2\delta r / (c\tau_c)$ is the number of speckle (for IPDA $M \cong 1$) or coherent time in the time gate.

Assuming a Gaussian spectrum and a Levin frequency estimator, the variance on radial wind speed is estimated with [13]:

$$var(V_r) = \frac{\left(\frac{\lambda}{2} f_2 \cdot F_e\right)^2}{M_e \cdot CNR \cdot \frac{\delta v_L}{B} \cdot g} \quad (13)$$

where $g = \frac{1}{\sqrt{2\pi}} \int_B \frac{\alpha_1 v^2 e^{-v^2}}{(1 + \alpha_1 e^{-v^2/2})^2} dv$, $\alpha_1 = \frac{CNR \cdot \delta v_L}{\sqrt{2\pi} f_2}$ and $f_2 = \frac{\delta v_L}{2 F_e \sqrt{2 \ln(2)}}$.

F_e is the sampling frequency, $B = F_e/2$ is the bandwidth of the coherent detection over which is calculated the CNR, $M_e = F_e \cdot \delta r$ is the number of acquisition points in the range gate, $\delta v_L = 2 \ln(2) / (\pi \tau_c)$ is the laser linewidth assuming the laser pulse duration equals the coherence time.

Assuming the same instrumental parameters as in Table, $\gamma_H = 0.2$, $B = 50$ MHz and a 10 mJ / 200 ns / 500 Hz laser onboard the satellite, a 0.5 m/s radial wind speed precision is obtained up to $z = 4$ km with a 10-km, 200-m horizontal and vertical resolution respectively (Fig. 3). Note that with a pulse energy of 10 mJ, the CNR is larger than -20 dB up to $z = 4$ km which may provide at the same time the vertical backscatter profile of the atmosphere (Breakthrough case in Table 1). In that case, the breakthrough case in Table 1 can relax the condition on the direct detection detector NEP to the one of the threshold case (typically NEP = 50 fW/rHz), the direct detection being used only for the CO₂ IPDA measurement.

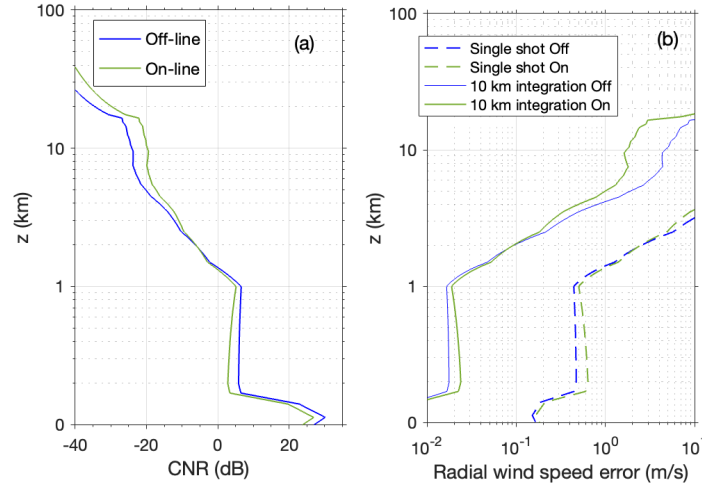


Figure 3. Numerical simulations for space-based lidar in coherent detection. (a) Carrier to noise ratio (b) Radial wind speed error.

3. EXPERIMENTAL TEST OF A 2 μ M CO₂ DIAL WITH DIRECT DETECTION USING A UPCONVERSION DETECTOR

3.1 Experimental set-up

In order to evaluate the feasibility of such a lidar mission, a 2- μ m CO₂ DIAL instrument with direct detection including an up-conversion detector (UCD) has been achieved at LMD (Fig. 4). The hybrid fiber-bulk emitter built with only amplifiers has been described in [4]. Few modifications appear in the current set-up. The emitter uses a seeder module with two narrow linewidth external cavity laser diodes (custom model CHEETAH from Sacher Lasertechnik). the On-line seeder is locked to the P14 ¹³CO₂ absorption line center using a frequency reference system (FRS) built with a 80-cm path gas cell filled with pure ¹³CO₂ at 5 hPa and a Pound-Drever-Hall (PDH) technique. The Off-line is locked at 2051.18 nm using a phase-locking loop and a beat frequency monitoring with respect to the On-line seeder. The spectral precision of each wavelength presents an Allan deviation better than 1 MHz between 10 s and 10 min (Gibert et al. 2018). In addition, the accuracy of each wavelength is within 1 MHz. After a 4x1 double stage fibered switch (Agiltron) (measured cross-talk isolation larger than 45 dB), the seeder power is amplified through a CW Thulium doped fiber amplifier (TDFA) (model CTFA from Keopsys). The laser pulses of 300 ns are shaped using an acousto-optic modulator AOM (model Brimrose – 50 MHz). An electro-optical modulator and a double-stage optical fibered-coupled switch (Agiltron – not represented in Fig. 4) is added to reject (by 50 dB) the long settling time CW power after the pulse. The pulse repetition rate is 2 kHz as a compromise to have a large number of samples and keep a sufficient Carrier to Noise Ratio (CNR). The wavelength switch is fixed at 20 Hz (switch every 100 pulses at fixed wavelength) as a compromise to limit switch disturbance on the measurements and keep identical atmospheric aerosol backscatter signal for the two wavelengths. A custom Holmium

pulsed fibered amplifier (model THALYS-2051nm-0.2W from Cybel) enables to deliver a maximum of 17 W peak power ($\sim 5 \mu\text{J}$ for a 300 ns pulse duration) without parasitic stimulated Brillouin scattering (SBS) effect. The laser pulses are then amplified in a free space multi-pass Ho:YLF amplifier. Six 0.5%-Holmium doped 50-mm long Ho:YLF rods pumped by two 50-W linearly polarized Thulium fiber lasers (model TLR-50-1940-LP from IPG Photonics) are used to obtain a mean 20 W output power at $2.05 \mu\text{m}$ (10 mJ @ 2 kHz). Both high cross-talk isolation from the double stage optical switch and high side mode suppression from the amplifiers (Lahyani et al. 2024) give an overall spectral purity larger than 45 dB. This laser architecture enables flexible characteristics of the laser: pulse duration, energy and repetition frequency (PRF). A coherent detection with a 50-mm diameter aperture lens (optimal heterodyne efficiency for horizontal measurement close to the surface over a distance of 2 km), a balanced extended InGaAs photodiode detection (Discovery Semiconductors Inc.) and a two-channels data acquisition and real time signal processing system (model Waverider-250 from LICEL) completes the set-up. The direct detection consists in a 50-cm diameter telescope, several optics to optimize the coupling of atmospheric backscatter beam inside the UCD (custom system from NLIR). A narrow optical filter (0.3 nm FWHM at 700 nm, OD6 over 200-1100 nm), a PMT (H16722P-40 from Hamamatsu) and a 16 bit-80 MHz ADC (TR80-16bit-3U from LICEL) enables to acquire the signal both in analogic and photon counting modes and makes real time signal shot averaging. Each signal at 3.75 m and 4 s time and space resolution are then stored to be further analyzed.

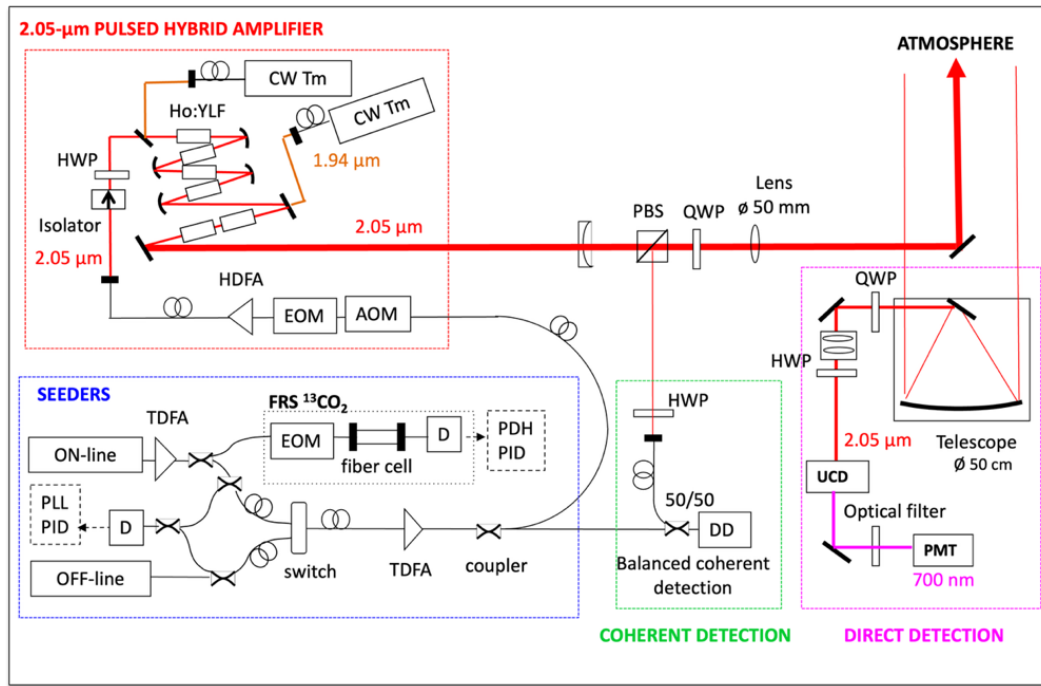


Figure 4. Lidar experimental set-up. FRS : frequency reference system, EOM et AOM : electro and acoustic-optical modulators, HDFA and TDFA : Holmium and Thulium fiber amplifiers, PDH and PLL: Pound-Drever-Hall and Phase-Locking-Loop techniques for wavelength position monitoring, HWP and QWP :half and quarter wave plate, PBS : polarizer beam splitter, UCD: upconversion detector, PMT: photomultiplier.

3.2 Characteristics of the UCD at $2 \mu\text{m}$ and NEP estimate

The UCD is broadly similar to the one described in [11] with some optimizations (increased pump power by 50%, limited bandwidth centred at $2.05 \mu\text{m}$). The pump beam waist inside the 25-mm-long-PPLN crystal used for the frequency conversion is $150 \mu\text{m}$ ($\text{FOV} = 11.8 \text{ mrad}$). The etendue of the UCD, $A\Omega \cong \pi W^2 \cdot \pi \text{FOV}^2$, is then $31 \mu\text{m}^2 \text{rad}^2$ which gives a $\text{FOV} = 7 \mu\text{rad}$ at telescope entrance (50 cm telescope diameter). Assuming an emitted beam waist of 2 cm, the overlap between the laser beam and the telescope FOV is never full and the optical efficiency of the detection is dramatically reduced to few percent (Fig. 5a).

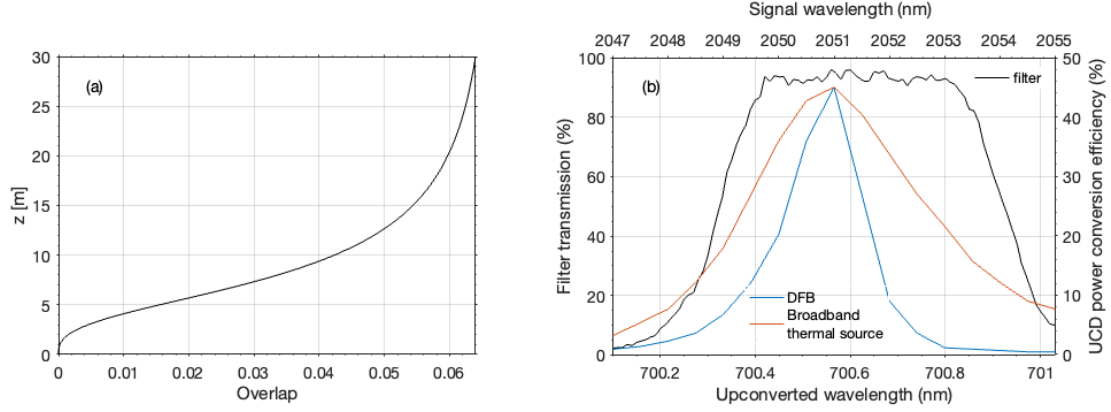


Figure 5. (a) Overlap function of the lidar direct detection (b) Optical filter transmission and UCD power conversion efficiency using a narrow band DFB and a broadband thermal source.

The optical bandwidth of the UCD is approximately FWHM= 1.5 nm centred at 2051 nm once measured with the current scanning of 2-MHz linewidth distributed feedback laser diode (DFB). Adding the fact that a linear polarization is necessary at the input of the UCD, the background noise (sun induced radiometric flux) is negligible and cannot be measured in practice, after a 0.3 nm narrow optical filter centred at 700.6 nm (Fig. 5b).

The UCD noise is mainly due to upconverted spontaneous parametric downconversion (USPDC) noise. The laser pump at 1064 nm induces a broadband parametric fluorescence and unwanted IR photons that are spectrally upconverted in the narrow bandwidth of the UCD around the upconverted wavelength of interest, i.e. 700.6 nm. In order to quantify the noise from the UCD module, different experiments are made using the same data acquisition system (ADC): (i) ADC only (ii) PMT and ADC (iii) PMT, ADC and UCD without infrared signal. The different signals are sampled at 40 MHz and averaged over 4 s. The RMS UCD noise is expressed by [11]:

$$NEP = U_{RMS} \sqrt{N_{shots}} / (\eta_{up} \eta_{opt} SMR_f \sqrt{B}) \quad (4)$$

Using the upconversion efficiency $\eta_{up} = 0.4$, the optical coupling efficiency $\eta_{opt} = 0.85$, the PMT anode sensitivity $S = 150 \text{ mA/W}$ at 700 nm, the PMT gain $M = 3 \cdot 10^6$, the ADC input resistance $R_f = 50 \Omega$ and bandwidth $B = 20 \text{ MHz}$ and measuring $U_{RMS} = 7 \mu V$ for a number of shots averaged $N_{shots} = 2000$, the NEP of the UCD is estimated to be around 9 $\text{fW/Hz}^{1/2}$.

3.3 Preliminary atmospheric measurements, SNR and CO₂ DAOD

For these experiments, the DIAL Online was locked to the center of the ¹³CO₂ absorption line at 2050.93 nm on the wing of R30 ¹²CO₂ absorption line to reduce the absorption along the LOS of the lidar. Figure 6a shows the logarithm of Off-line range-corrected backscatter signal with a quasi-horizontal LOS at a time and space resolution of 30 s (30000 shots averaged) and 15 m, respectively. Figure 6 b-d shows profiles of Off and On-line range-corrected backscatter signals, the SNR and the DAOD. With such resolution, the On-Line SNR is larger than 10 dB up to a distance of 5 km. Off-line signal is detectable up to 20 km. The DAOD has an expected linear increase as a function of the distance up to 8 km which suggest a rather constant CO₂ mixing ratio along the lidar LOS although the first kilometers seem to be disturbed by different overlap functions for On and Off-line signals. Investigations are ongoing to infer an accurate and precised CO₂ mixing ratio profile with this experimental set-up.

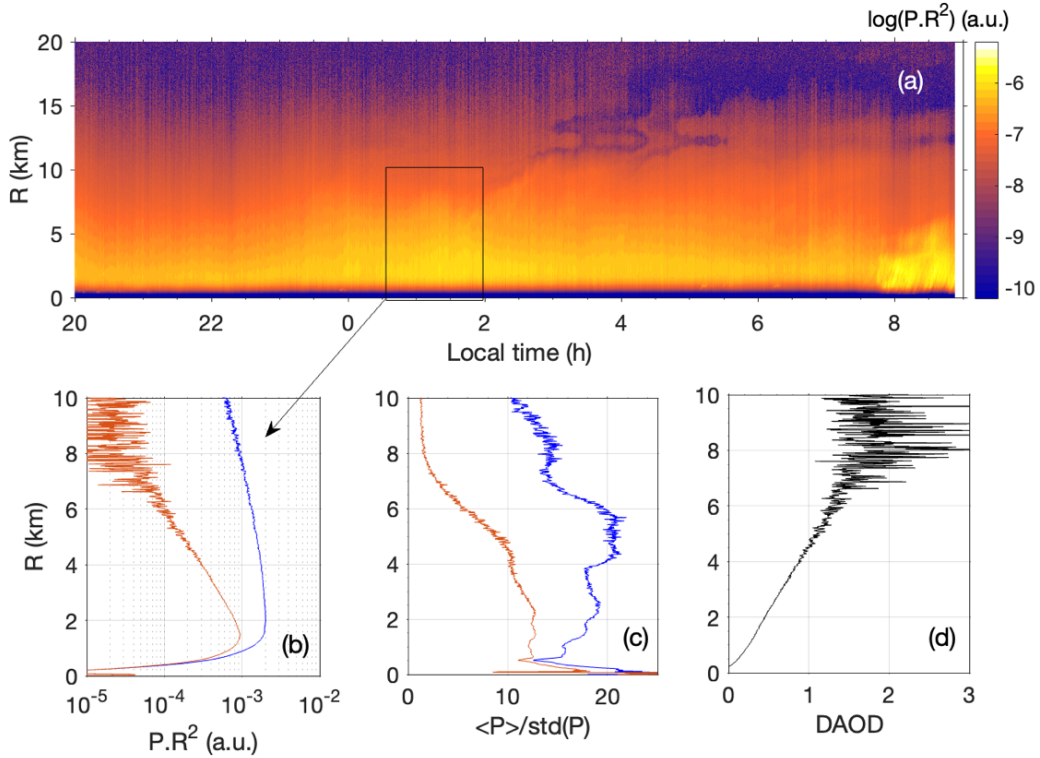


Figure 6. (a) Logarithm of Off-line range-corrected backscatter signal in quasi horizontal LOS along 11 hours of measurements with time and space resolution 30 s and 15 m. (b) Off-line and On-line range-corrected backscatter signal profiles at the local time 00:30 h. (c) Off-line and On-line SNR profiles calculated over 1h30 (rectangle). (d) DAOD at the local time 00:30 h.

4. SUMMARY

Following recent technical advances both in hybrid/bulk all-amplifier built emitter at $2\ \mu\text{m}$ and in IR up-conversion detection, an ambitious CO_2 (H_2O) and wind space lidar mission has been considered at LMD. Numerical simulations showed that a 1% precision of CO_2 mixing ratio in the first kilometre in the atmosphere above the ground is now achievable. Additional products of the mission, H_2O and wind profiles, enable to give some necessary data for CO_2 signal processing and for transport model parametrizations in order to infer CO_2 surface fluxes. To prove the concept, an experimental set-up has been built at LMD integrating new emitter and detector schemes at $2\ \mu\text{m}$ and is currently in atmospheric test. Preliminary DIAL atmospheric measurements show an Off-line SNR larger than 10 dB in horizontal LOS at a distance of 10 km with time and space resolution of 30 s and 15 m respectively.

ACKNOWLEDGEMENTS

The CO_2 lidar space mission study has been made in the framework of HALLOA – Hybrid Amplifier laser for Lidar OperAtions project funded by the European Union, project ID: 101189970, <https://doi.org/10.3030/101189970>. The DIAL experimental set-up and especially the up-conversion system benefited from the funding of the French National Agency (ANR) in the framework of France 2030 CABESTAN, The carbon cycle at land-sea interface in the context of tidal zones and wetlands of the Atlantic and Channel coasts, project ID: 22-PEXF-0007.

REFERENCES

- [1] Lauvaux, T. and Davis, K. J., “Planetary boundary layer errors in mesoscale inversions of column-integrated CO₂ measurements”, *J. Geophys. Res. Atmos.*, 119, 490–508, (2014), doi:10.1002/2013JD020175
- [2] Rayner, P.J. and O’Brien, D.M., “The utility of remotely sensed CO₂ concentration data in surface source inversions”, *Geophys. Res. Lett.*, 28(1), 175-178, (2001)
- [3] A-SCOPE (Advanced Space Carbon and Climate Observation of Planet Earth), ESA report for Assessment, SP-1313/1, (November 2008)
- [4] Gibert F., Edouart, D., Mondelain, D., Cénac C. and Yver, C., “d¹³C carbon isotopic composition of CO₂ in the atmosphere by Lidar – A preliminary study with a CDIAL system at 2-μm”, *Atmospheric Measurement Techniques*, 19, 1927–1941, (2026), doi.10.5194/amt-19-1927-2026
- [5] Dumas, A., Rothman, J., Gibert, F., Edouart D., Lasfargues, G., Cénac, C., le Mounier, F., Pellegrino, J., Zanatta, J.-P., Bardoux, A., Tinto F. and Flamant, P.H., “Evaluation of a HgCdTe e-APD based detector for 2 μm CO₂ DIAL application”, Vol. 56, No. 27 / *Applied Optics*, 7577 – 7585, (2017)
- [6] Sun, X., Abshire, J.B., Beck, J.D., “HgCdTe e-APD detector arrays with single photon sensitivity for space lidar applications”, *Proc. of SPIE Vol. 9114*, 91140K-1, (2014)
- [7] Bruneau, D., Gibert, F., Flamant, P.H. and Pelon, J.: Complementary study of differential absorption lidar optimization in direct and heterodyne detection, *Appl. Opt.*, 45, 4898-4908, (2006)
- [8] Gordon, I.E., Rothman, L.S., Hargreaves, R.J., Hashemi, R., Karlovets, E.V., Skinner, F.M., Conway, E.K., et al., “The HITRAN2020 Molecular Spectroscopic Database”, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 277: 107949, (2022)
- [9] Mondelain, D., Campargue, A., Fleurbaey, H., Kassi, S., Vasilchenko, S., “Line shape parameters of air-broadened ¹²CO₂ transitions in the 2-μm region, with their temperature dependence”, *J. Quantitative Spectroscopy Radiative Transfer*, 298, 108485, (2023), doi: 10.1016/J.jqsrt.2023.108485
- [10] Mondelain, D., Campargue, A., Gamache, R.R., Hartmann, J.-M., Gibert, F., Wagner, G., Birk, M., Röske C., “Isotopologue dependence of the CO₂-air broadening and shifting coefficients: experimental evidence and comparison with theory for ¹³CO₂ and ¹²CO₂”, *J. Quant. Spect. Radiative Transfer*, 333, 109271, (2025), doi: 10.1016/j.JQSRT.2024.109271
- [11] Meng, L., Fix, A., Wirth, M., Hogstedt, L., Tidemand-Lichtenberg, P., Pedersen, C., Rodrigo, P. J., “Upconversion detector for range-resolved DIAL measurement of atmospheric CH₄”, *Opt. Express* 26, 3850, (2018)
- [12] WALES ESA Report for Assessment—The WALES Candidate Earth Explorer Core Mission. ESA SP-1257(2), 91 pp., (2001)
- [13] Rye, J. and Hardesty, R.M., “Discrete spectral peak estimation in incoherent backscatter heterodyne lidar. I: spectral accumulation and the Cramer-Rao Lower Bound”, *IEEE Transactions on Geoscience and remote sensing*, 31, 16-31, (1993)