

Latest results of SCALE frequency comb LIDAR airborne experiment

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ABSTRACT

This paper concerns Frequency Comb LIDAR airborne experiment developed by CNES. This airborne demonstrator named SCALE has already flown in 2023 and 2024 and aims to demonstrate novel approach to CO₂ integrated-column measurement using a LIDAR system based on the dual-comb spectroscopy principle. Frequency Comb LIDAR relies on multiple optical frequencies evenly spaced along a target molecule's absorption line, offering more comprehensive spectral information compared to DIAL LIDAR. Instrument's theoretical model is assessed compared to real airborne data.

Keywords: laser, frequency comb, greenhouse gas, CO₂, airborne

1. INTRODUCTION

As the primary anthropogenic greenhouse gas, accurate and cost-effective monitoring of CO₂ cycles and fluxes is essential for a comprehensive understanding of climate dynamics. In the field of space-borne CO₂ research, passive spectrometers such as OCO₂ [1] (currently in operation), GOSAT-2 [2], MicroCarb [3] and CO₂M [4] (planned for future missions) are state-of-the-art instruments. However, passive dispersive spectroscopy in the SWIR domain presents certain limitations: instrument lineshape limits the spectral resolution, measurements can only be conducted during daylight hours, and high latitudes remain inaccessible. Moreover, aerosols can introduce significant biases, requiring additional measurement bands and complex optical atmospheric diffusion models for data correction. Given these various sources of bias, active measurement of greenhouse gases could bring complementary data and enhance our understanding of the global CO₂ column, particularly under conditions where passive spectroscopy is constrained, such as during night-time, along coastal edges, in the presence of clouds, and at high latitudes.

The ACDL (Aerosols and Carbon Detection Lidar) instrument on the DQ-1 satellite represents the first space-based CO₂ LIDAR combined with an aerosols channel, developed by the Chinese space agency [5]. Similar to the Merlin mission [6], which is dedicated to methane detection, the LIDAR onboard DQ-1 is an Integrated-Path Differential Absorption (IPDA) LIDAR system. Such type of instrument needs a highly accurate knowledge of the frequency emitted, leading to complex laser sources. To overcome limitations of classical DIAL systems, several teams proposed to use multi-wavelength emission systems [7–10] for future CO₂ LIDAR missions. Multi-frequency measurements can sample a gas absorption line, providing important information about the absorption line shape.

Regarding multi-frequency LIDAR for greenhouse gas monitoring, the ASCENDS experiment is the most accomplished experimental demonstration so far, with several flight campaigns [8,11] and a successive emission of up to 30 wavelengths, allowing high energy per laser shot and direct detection. However, albedo differences during the line scan can lead to errors. In this paper, we present the latest results obtained with SCALE (Short Comb Atmospheric Lidar Experiment) instrument, which combines multi-wavelength LIDAR measurement with simultaneous multi-wavelength emission and coherent detection, based on the dual-comb spectroscopy principle [12 -15].

2. SCALE INSTRUMENT

Optical architecture is depicted in Fig. 1, and main instrument parameters are synthesized in Table 1. The laser source is a cavity extended continuous-wave (cw) laser (PurePhotonics), emitting at 1572.389 nm. Long term optical frequency drift is avoided by continuously measuring the emitting wavelength with a lambda-meter (Bristol) and correcting it if necessary. The optical path is split by a 50/50 fibered coupler, and each path is phase modulated by electro-optic modulators (EOM, Exail) to create two optical frequency combs [16] with slightly different repetition rates obtained by different RF modulation frequencies (2.71 and 2.724 GHz).

In this paper, we use the dual-comb spectroscopy principle in an asymmetric configuration: one frequency comb is the local oscillator (LO) comb and stays onboard, and the other comb probes the atmosphere. The probe comb is 73.5 MHz frequency shifted by an acousto-optic modulator (AOM, Gooch & Housego). This AOM also temporally shapes the CW optical signal into 1.7 μ s FWHM length pulses, with a 5 kHz repetition rate. A first stage of Erbium Doped Fiber Amplifier (EDFA) amplifies the pulsed probe signal. A second stage of Erbium/Ytterbium-doped fiber amplifier (EYDFA, Lumibird) amplifies the probe comb up to 1 W average power. Coherent detection being the only way to separate comb teeth from each other's, monostatic optical architecture has been privileged. The telescope (Vaisala, 500 mm focal, 120 mm diameter) is used for both reception and emission.

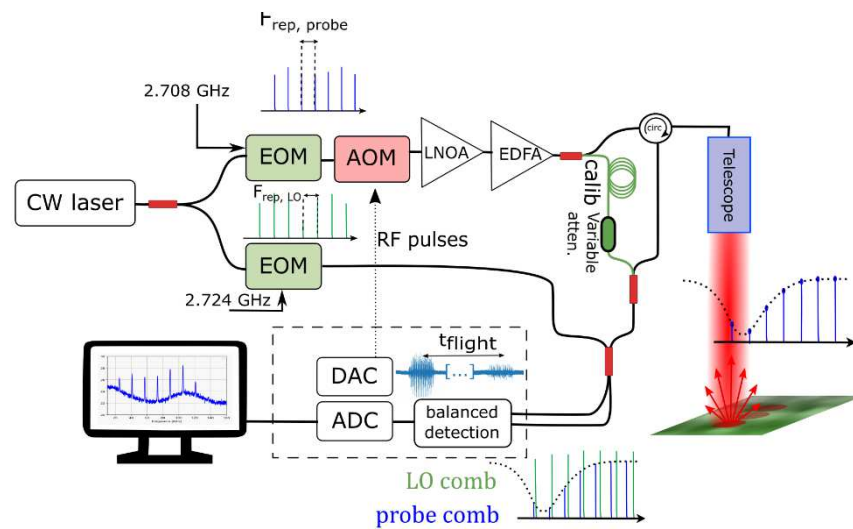


Figure 1: Optical architecture of the SCALE instrument

Infrared camera (Hamamatsu) with a 500 mm homemade lens and narrowband filter centered around the laser wavelength is co-aligned with the telescope. It provides the localization of the laser spot onto the landscape and types of targets for the Speckle study. After retrodiffusion on the ground, scattered light is collected by the telescope, and mixed on a balanced detector (Thorlabs, BDX3BF-SP1) with the LO comb in a shot-noise limited regime. RF combs obtained are filtered and amplified by custom-made analog electronic. Then, the signal is digitized at a 1 GS/sec rate and 14 bits by custom-made electronics based on the ZCU216 board, from AMD.

To normalize the comb shape at the emission, a tap isolator at the EDFA's output takes a small part of the optical signal (calibration pulse), which is delayed by a 4 km optical fiber, combined with the LO before detection. A variable attenuator after the delay line is used to adjust the amplitude of the calibration signal in the digitizer's dynamic range. Thus, the calibration pulse is temporally separated from the echo pulse and of the parasitic reflection on the airplane window and telescope lens. It shares the same detection chain as the echo one. Note that the architecture of the instrument is all-fibered.

Table 1

Instrument parameters		
Aircraft	height of flight	4000 – 6000 m
Emitter	Average Power	1 W
	Pulse Rate	Bottom margin)
	Central wavelfngth	1572.389 nm
	Pulse duration	1.7 μ s FWHM
	AOM frequency	73.5 MHz
	EOM A frequency	2.71 GHz
	EOM B frequency	2.724 GHz
Receiver	Telescope diameter	120 mm
	Local Oscillator power	9 mW
	Balanced PIN responsivity	1.2 A/W
	Sampling rate	1 Gsample / s

3. LEVEL 1 SIGNAL PROCESSING

Level 1 describes all the steps going from raw data to normalized optical transmission of the atmosphere. On the photodetector, the heterodyne current is composed of two successive interferograms, one for the calibration, and one for the echo signal. Figure 2 shows typical digitized interferograms and associated spectrograms for echo path (blue) and calibration path (green).

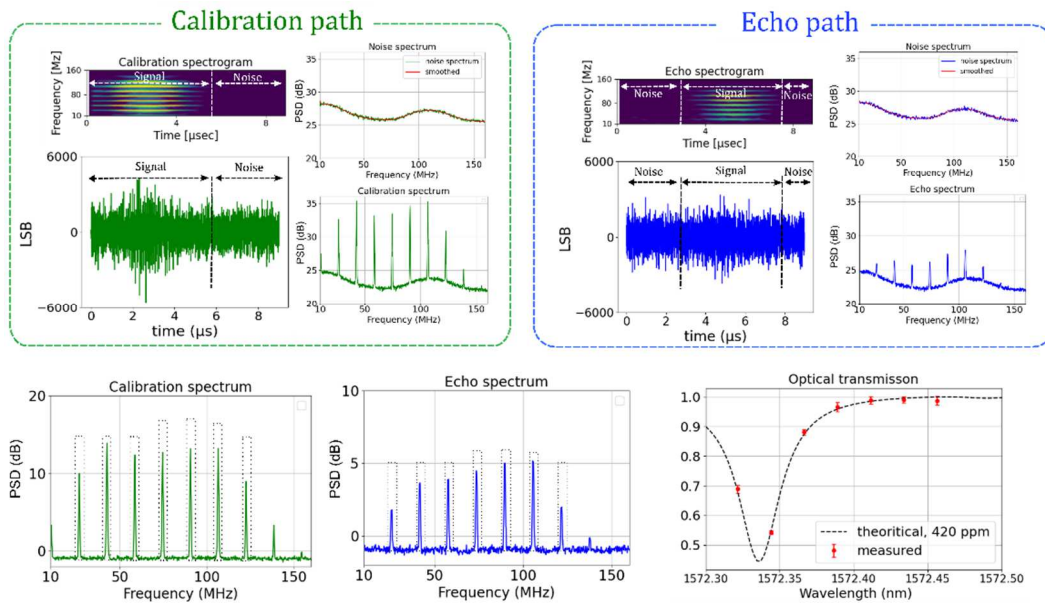


Figure 2: Level 1 post-processing steps for the calibration and the echo digitized signals

Data processing steps applied to the calibration and echo signal are detailed in **Erreur ! Source du renvoi introuvable..** For each LIDAR shot, echo and calibration interferograms are windowed around useful signal to limit shot noise integration in the spectra. Then, Fourier-transformed signals are incoherently averaged. Due to analog filters between the photodiode and the digitizer, the transfer function's gain is not constant on the bandpass. The aircraft's pitch and roll frequency-shifts the echo optical signal because of the Doppler effect. Therefore, transfer function gain correction is needed to compensate for the gain difference applied to the calibration and echo peaks of the same order.

After this step, spectra exhibit a flat baseline, as shown in Fig. 2 (bottom). Then, each RF comb line of averaged and gain-corrected spectra is integrated over a 3 MHz bandwidth. The transmission of the CO₂ absorption line is finally determined by dividing the integrated line values of the echo comb by the corresponding values of the calibration comb, as described by equation below.

$$T_k = \frac{\int_{\nu_k-1.5 \text{ MHz}}^{\nu_k+1.5 \text{ MHz}} |S_{echo}(\nu)|^2 d\nu}{\int_{\nu_k-1.5 \text{ MHz}}^{\nu_k+1.5 \text{ MHz}} |S_{calib}(\nu)|^2 d\nu}$$

4. INSTRUMENT UPGRADES

Since SCALE presentation at last ICSO conference [12], some upgrades have been implemented within the SCALE instrument, without modifying the global architecture and data processing presented on §2 and §3. Upgrades concern 3 points.

First of all, in the analog detection chain: balanced photodiode was changed from Thorlabs BDX3B to BDXQ1 in order to take benefit from the improved sensitivity from 0.8 A/W to 1.2 A/W.

Still in the analog detection chain we modify the RF gain chain filtering chain in order to get a more constant gain over the bandwidth of interest [5; 140] MHz. On the previous airborne campaign in 2024, we observed some slight variation in this gain frequency transfer function as a function of operation conditions. Having a better flatness should lead to the smaller gain transfer function with operating conditions. Moreover, during level 1 data processing, we have to correct from the transfer function. We expect to improve our correction with a flattened gain function. For illustration, we plot on Figure 3 the detection chain response to shot noise for the various airborne campaigns of SCALE. We can clearly see the change between 2024 and 2025, with un-flatness going from 3 dB to less than 1 dB over the bandwidth of interest.

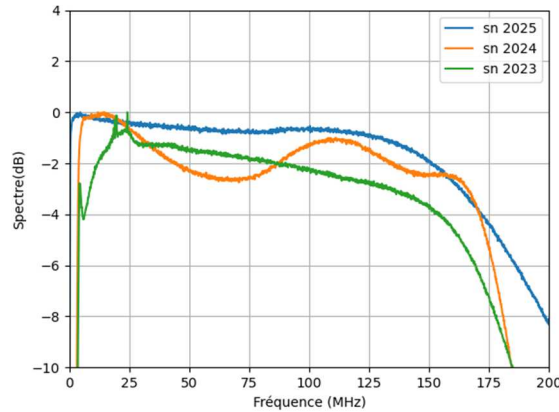


Figure 3: detection chain gain flatness for the 3 different SCALE airborne campaign. Characterized to chain response to Local Oscillator shot noise.

The last modification implemented concerns the comb generation system. The demonstrator is still using electro optical modulation, but we now use multifrequency modulation instead of single frequency modulation. The new system was developed through a contract with EXAIL. We demonstrated a 9 frequencies comb with evenly spaced frequencies (2.7 GHz), as shown on Figure 4. Over those 9 frequencies, optimum flatness is characterized at 0.5 dB. Rejection with first non-useful frequency is 4.5 dB. The total energy lost within non useful frequencies is measured at 0.65 dB. However this optimization is strongly dependent from operational stability, especially temperature.

In practice, laboratory as well as airborne measurements give flatness around 1 dB per optical frequency comb. Figure 5 present RF beatnotes measured in our laboratory using the two optical combs generated using this multi frequency electro optical modulation. We observe here a beatnote flatness around 2 dB.

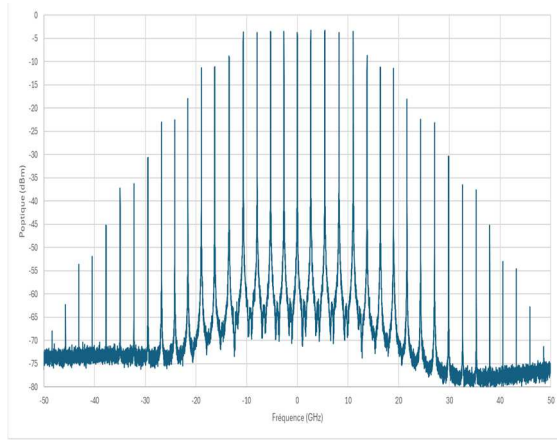


Figure 4: optimized 9 frequencies Comb using multifrequency modulation (Y in Log scale)

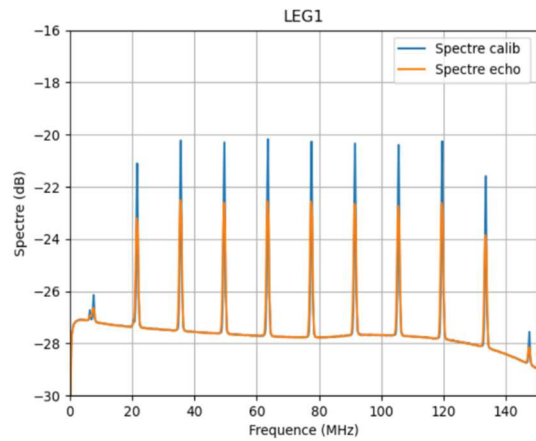


Figure 5: RF beatnotes PSD measured in laboratory, without absorption.

Main advantage with this modification is a well more homogeneous signal to noise ratio over the 9 RF beatnotes. Indeed beatnotes PSD is proportional to the square root of the product between local oscillator and probe signal. Improving comb flatness leads to a more homogeneous Signal to Noise Ratio over the beatnotes. We then expect a better CO₂ measurement through Bayesian inversion.

5. MODIFICATIONS VALIDATION

All modifications were tested in our laboratory. On top of that, we had the opportunity for a single flight within SAFIRE ATR 42 in March 2026. This flight took place above Toulouse, with real time CO₂ on ground measurements thanks to an EM27 based in CNES Toulouse. All the flight took place at a height between 5000 m and 6000 m. Examples of gain corrected Power Spectra Density (PSD) is given in Figure 6. Associated post level 1 processing absorption spectra is presented in blue in Figure 7. In this same figure, orange curve gives equivalent processing for 2024 campaign, therefore without instrument modifications presented in this paper. We do not observe any degradation in SNR for each beatnotes, plus the two new beatnotes obtained by going from a 7-tooth comb to a 9-tooth one.

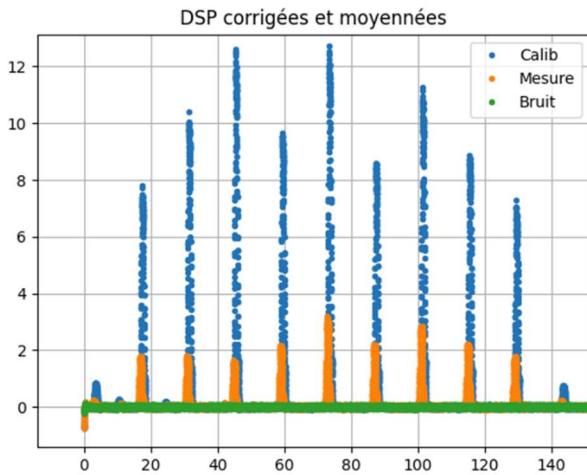


Figure 6: PSD example obtained during 2026 flight at 6000 m height

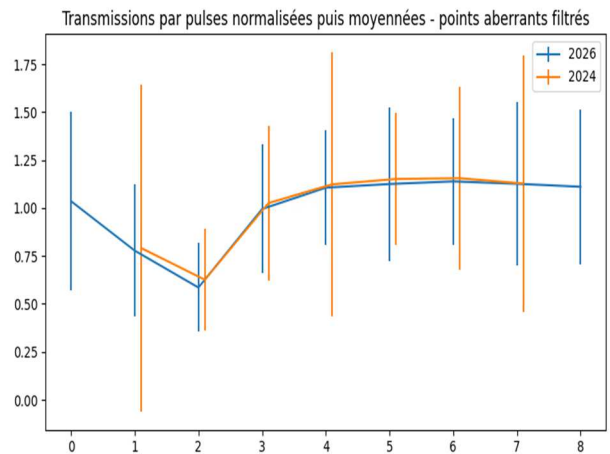


Figure 7: transmission obtained through level 1 data processing. In orange during 2024 airborne campaign, in blue during march 2026 campaign.

6. THEORETICAL VS AIRBONE SNR VALIDATION

The random error on the XCO₂ value retrieved after level 2 is dependent on the random error on the atmospheric transmission measured by the SCALE instrument. As explained in §3, for each peak of the optical comb, the atmospheric transmission is the ratio between the optical power of the light scattered and collected by the instrument P_{echo} , and the optical power of the calibration signal P_{calib} . As the signal calibration stays fibered in the instrument, it is not affected by radiometric issues, and we will assume that most uncertainties in the transmission come from the low quantity P_{echo} of scattered light collected by the telescope and injected in the single mode reception fiber.

In coherent lidar, the carrier-to-noise ratio is often used as an indicator of the lidar signal quality. On the heterodyne electrical signal, it is defined as the average signal power P_s over the average additive noise power P_{Noise} :

$$CNR = \frac{P_s}{P_{Noise}}$$

For a balanced detector, the electrical signal power is linked to the heterodyne current i_{het} :

$$P_{echo} \propto (i_{het})^2 = [2R\sqrt{P_{LO}P_{echo}}]^2$$

Where R is the photodiode responsivity [A/W]. The optical power P_{echo} is directly deduced from instrument, atmospheric and target parameters:

$$P_{echo} = R_{peak} P_{out} R_g \frac{D}{4h^2} T_{inj} T_{instr} T_{atm}^2 T_w^2 T_{telescope}^2$$

Values of parameters described in the previous equation are in Table 2 below.

Table 2

Signal to Noise Ratio calculation parameters		
Aircraft	height of flight	6000 m
Emitter	Average Power	1 W
	Pulse Rate	5 kHz
	Central wavelngth	1572.389 nm
	Pulse duration	1.7 μ s FWHM
	Approx % of tot. opt. pwr per peak	10 %
Atmosphere and target		
	Atmospheric transmission T_{atm}	0.95
	Airplane window T_w	0.9
	Ground surface reflectance R_g	0.1
Receiver	Telescope diameter	120 mm
	SM fiber injection rate T_{inj}	0.1
	Instrument transmission T_{instr}	0.1
	Local Oscillator power	9 mW
	Balanced PIN responsivity	1.2 A/W
	Bandwidth per peak	5 MHz

Coherent LIDAR are efficient in the shot-noise limited regime, achieved when the shot noise is dominant over all other noises (dark current, thermal noise of the detector). On the detector, the optical power of the scattered echo signal can be neglected regarding the optical power of the LO. Thus, the average additive noise P_{Noise} is driven by the shot noise of the LO photocurrent:

$$P_{Noise} = var(i_{shot\ noise}) = 2BqRP_{LO}$$

Where B is the bandpass, q is the electron charge, R is the detector sensitivity (A/W), and P_{LO} is the optical power of the local oscillator on the detector. One fundamental limitation of coherent LIDAR is that it can only detect scattered light in a single optical mode, which is the LO and the SM fiber's optical mode. With the Speckle effect, the optical power

superposing with the fiber's single mode is a random variable. The probability density function of this random variable follows an exponential function:

$$PDF_{P_{echo}}(P_0) = \frac{1}{\langle P_{echo} \rangle} e^{-\frac{P_0}{\langle P_{echo} \rangle}}$$

This PDF has an expectation of $\langle P_{echo} \rangle$ and a variance of $\langle P_{echo} \rangle^2$: for one LIDAR shot, the expected signal-to-noise ratio is equal to 1. Accumulating LIDAR shots is therefore necessary to increase statistics and have an accurate atmospheric optical transmission measurement. Finally, the precision on atmospheric transmission measurement is driven by the precision on P_s , whose SNR is a combination of instrument emission parameters, shot noise and Speckle statistics over a number N of LIDAR shots:

$$SNR = \frac{\langle P_s \rangle}{\sigma(P_s)} = \sqrt{N} \frac{CNR}{1 + CNR}$$

This SNR on the echo signal is compared to measured data during flight campaign on Figure 8. The variations observed in the echo signal for each of the beatnotes are close to those predicted by the theoretical SNR obtained in previous equations.

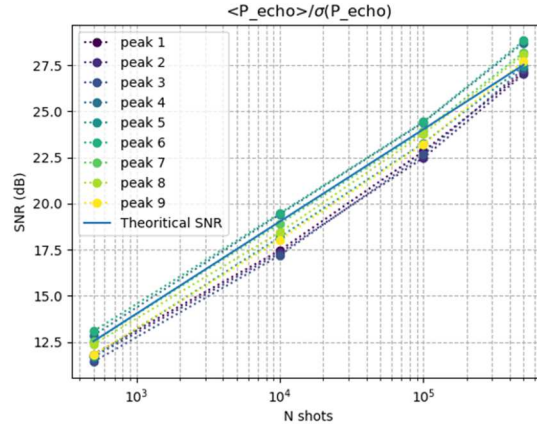


Figure 8: Theoretical Vs Measured SNR on the echo signal

7. CONCLUSION

The SCALE LIDAR was built with off-the-shelf telecom components, making it affordable and not requiring complex optical alignments or thermal control. It has been designed to demonstrate the concept of short comb LIDAR for GHG sensing, not to reach optimal performances of the concept. Nevertheless, obtained level 1 and level 2 performances give us satisfaction.

Level 1 post-processing methods were developed to compensate for the Doppler effect induced by the aircraft pitch and roll, and various effects of the analog detection chain gain. Since the instrument works with coherent detection, the wind speed and magnitude could be derived from the Doppler shift of the signal acquired before the ground echo, if reflection on aerosols occurs.

We presented the latest modifications of the instrument: implementation of new balanced photodetectors with better responsivity, changed in RF amplification gain homogeneity over the bandwidth of interest, new optical comb generation system, enabling better power distribution homogeneity over 9 frequencies. This new configuration was used for in-flight validation during a few hour flight over Toulouse within SAFIRE ATR42 in march 2026.

Using those in-flight data's shows good accordance in the radiometric Signal to Noise Ratio between echo optical power on one side, and heterodyne detection theory plus instrument definition on the other side. This good accordance is one critical block towards a satellite mission definition.

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