

We thank the reviewers for the very fruitful comments and remarks, which helped us to improve the manuscript.

All the remarks from the reviewers have been addressed below, and changes in the manuscript have been done accordingly (highlighted in red).

Reviewer(s)' Comments to Author:

**Referee #1:**

This paper deals with simultaneous detection of ethane, methane and carbon isotopic composition of methane by means of mid-IR optical feed-back cavity enhanced absorption spectroscopy. The performance of the spectrometer (as obtained in the laboratory environment) in terms of sensitivity and measurement precision makes it suitable for in-situ measurements in ocean waters. In this respect, the scientific motivations are strong and very well highlighted.

The work is performed well and the paper is clearly organized and written, with figures of excellent quality. Therefore, the manuscript deserves publication.

I recommend the authors to consider the comments reported hereafter.

1 (comment from Referee): The spectral region of interest shows a manifold of lines. The authors are obliged to consider 46 absorption lines in the fit of a single spectrum, with a relatively large number of free parameters. To mitigate this issue, physical constraints are applied to some of the parameters, thus reducing the degrees of freedom for the fitting procedure. Since this is one of the key points of the article, more details should be provided. In particular, a careful reader would like to know: the total number of free parameters; the number of experimental points of the interlaced spectrum; the adopted lineshape model.

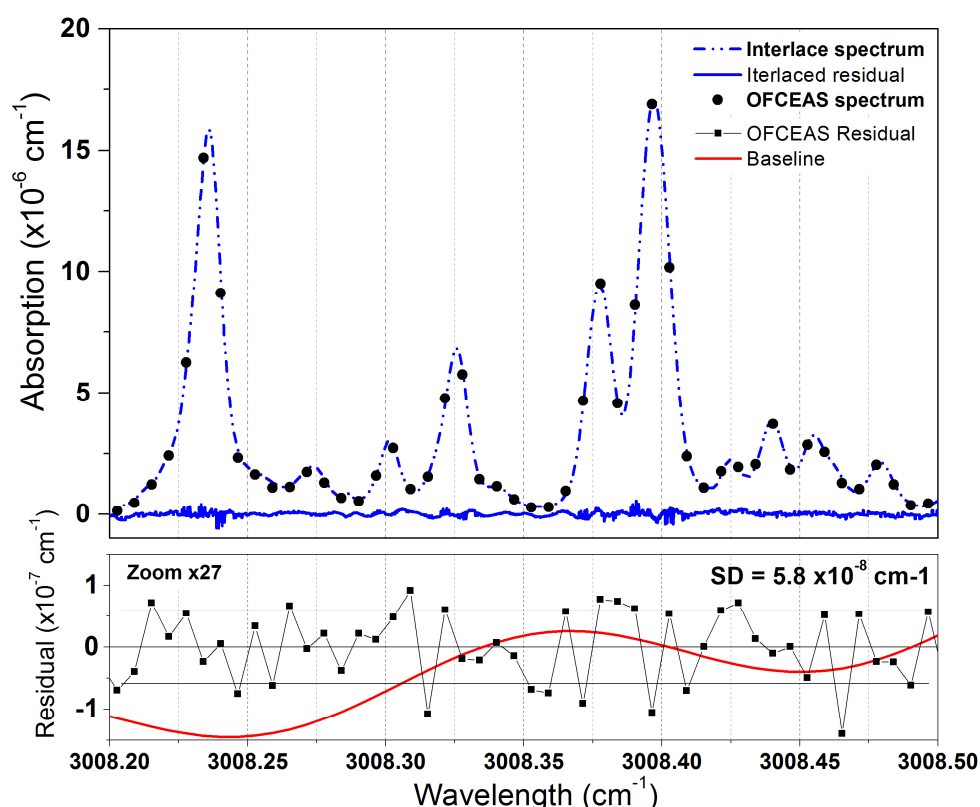
1 (author's response) : The adapted lineshape model is the speed-dependent Rautian. This information has now been added in the manuscript (page 4) together with the references to the used model. More details about the number of points used for the fit and the degrees of freedom (9 in total) have been added in this section. "In order to reduce the degrees of freedom of the fitting routine and allowing a real-time fit for each acquired spectrum, some of the parameters have been pre-optimized and fixed or linked together. The remaining free parameters are: 1) the spectrum position: the positions of all lines are linked together and only one parameter (which corresponds to the mode-shift) is used to adjust the fit with respect to the acquired spectra; 2) the four intensities of  $^{12}\text{CH}_4$ ,  $^{13}\text{CH}_4$ ,  $\text{C}_2\text{H}_6$  and  $\text{H}_2\text{O}$  from which concentrations are retrieved, and all lines belonging to one of these molecules are fixed in relative intensity to pre-optimized values, with a single intensity scaling parameter for all of them; 3) the coefficients of the polynomial function for drawing the baseline of the fit (here corresponding to three parameters for a second order polynomial function); 4) one extra parameter can be added per optical fringes that the operator may want to fit. In this case we only have one optical fringe which has been identified between the output cavity mirror and the signal photodiode. The Gaussian and Lorentzian widths as well as the  $v_{\text{vc}}$  parameter for Dicke narrowing are optimized line by line and then fixed to their optimum values. The total number of free parameters for the fit is 9 for a spectrum composed by 48 individual points."

2 (comment from Referee): This reviewer has the suspicion that the Voigt model has been used; if this is the case, I recommend the authors to give a look at the paper of Tennyson et al., Recommended

isolated-line profile for representing high-resolution spectroscopic transitions (IUPAC Technical Report), Pure and Applied Chemistry, 2014. I am sure that the use of the HTP model would lead to reduced residuals. However, Figure 2 should provide also the residuals for the interlaced spectrum.

2 (author's response) : In the fit routine we used (the Postfit developed by D. Romanini) the HTP model was not developed. However, this should lead to similar results that the speed-dependent Rautian profile used in this work. The difficulty here is more related to the relatively high congestion of absorption lines, which make the fit optimization not trivial.

We report the residual of the interlaced spectrum below (in blue) and we adapted figure 2 in the manuscript accordingly. As one can see, the interlaced residual still have some structure related to possible artefacts of the spectra interlacing and some imperfection of the fit optimization. This interlaced spectra is only used for improving the fit parameters which are fixed. During normal operation of the instrument the discrete OFCEAS spectra (black dots) is used.



3 (comment from Referee): Temperature stabilization and control of the V-shaped cavity are requested in order to obtain a high-quality interlaced spectrum. In fact, the authors explain that an increase of the spectral resolution is achieved by slightly scanning the temperature of the cavity (0.02°C of excursion), which causes a shift of the cavity mode positions with respect to the absorption lines. On page 3, they state that the cavity temperature is stabilized at 308.15 K, giving only two decimal digits. This means that the authors

can control the temperature at the level of 10 mK, which is NOT sufficient for a refined control of the cavity modes. Nevertheless, reaching the mK level is surely not an easy task. Moreover, the requested equipment would limit the portability of the spectrometer. Such a key point should be discussed.

3 (author's response) : This is indeed a key point that we now better explain in the manuscript. Reaching a temperature stability of the cavity better than 10 mK is challenging. By using a standard PID control and heating bands the temperature stability recorded by a PT1000 temperature probe are below 10 mK (the rms of the red curve in the top panel of Figure 3 is 1.5 mK). However, in this condition,

the shift of the cavity mode position with respect to the absorption line positions (mode shift) reaches several tens of MHz. Since the composition of the gas in the cell (and therefore the refractive index) did not change during the measurement, this shift is most probably due to artefacts of the electronic, mainly in the temperature reading but possibly also in the pressure. In order to avoid the shift of the cavity modes, we decided to lock their position with respect to the absorption lines. The position of the absorption lines becomes therefore our reference for maintaining the cavity comb always in the same position with respect to the acquired spectra. This allows a stability of the comb below 1 MHz, while we let the temperature reading fluctuating (by few tens of mK as shown in Figure 3). At page 6 we now added: “The aim of the lock is not to better stabilize the cavity temperature, but to acting on this temperature regulation in order to maintain the cavity comb always at the same position with respect to the position of the absorption lines and compensate for electronic drifts occurring on the circuit for reading pressure and temperature of the cavity.”

For further clarity we also added at page 4: “This interlacing is only used for fit optimization, while in normal operation the spectra are only composed by data points separated by the cavity FSR (187.4 MHz) with a total of 48 fitted spectral points.”

Regarding the temperature measurement, even if we can reach precision of 1.5 mK, on its absolute value we cannot have a better accuracy that 10 mK. That is why we state the temperature with only two digits. The temperature scans of 0.02°C are done in a relatively short time (<1 min), on which long term drifts mentioned above (due to artefacts by the electronic circuit) are negligible. Therefore this relative value of 0.02°C can be stated. In the Labview routine employed for interlacing the spectra is only required to have a linear mode shift evolution over more than one cavity FSR.

4 (comment from Referee): As for the dependence of the isotopic ratio on the methane concentration, this reviewer would suggest to consider the possibility of a side effect due to the choice of the wrong line shape model.

4 (author's response) : As mentioned above, the speed-dependent Rautian fit was used in this work. We did not try the HTP model as suggested by the reviewer since the model is currently not implemented in the fir routine. Nevertheless, we think that we are limited by the high density of absorption lines in the used spectral region more than by the model used for the fit.

Reviewer(s)' Comments to Author:

#### **Referee #2:**

This article presents an OF-CEAS based mid-IR interband cascade laser spectrometer for the simultaneous measurement of [CH<sub>4</sub>], [C<sub>2</sub>H<sub>6</sub>], and  $\delta^{13}\text{C}$ -CH<sub>4</sub>. It is targeted to concentration ranges for CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> as they are found in seawater. The manuscript is well written and structured, and the results are presented in a clear and concise fashion. I recommend publication in AMT after the authors have addressed a few minor points listed below.

1 (comment from Referee): page 2, line 27: in the text the ICL is said to be from Nanoplus, but in figure 1 you write NanoGiga.

1 (author's response) : It is indeed an ICL from Nanoplus. The figure have been corrected.

2 (comment from Referee): page 3, line 6: there are a few different procedures to compute the signal used to steer the piezo-mounted mirror (to control the OF phase) (e.g. "asymmetry" of the modes etc.). Which one is used here?

2 (author's response) : The phase locking is done by looking at the symmetry or the cavity mode. This has now be specified in the text "The phase error was retrieved by analyzing the symmetry of the cavity modes during the acquisition, as explained in (Morville et al., 2005). "

3 (comment from Referee): page 4, line 8: what lineshape do you use for the spectral fit? Voigt? Could some of the issues mentioned later (i.e. dependence of  $\delta^{13}\text{C-CH}_4$  on  $[\text{CH}_4]$ ) come from this choice?

3 (author's response) : Please see the answers to the Referee #1.

4 (comment from Referee): page 4, line 14: after the 200 spectra are acquired, how are they interlaced? I.e. how do you know by how much the cavity modes of the n-th spectrum are offset from the (n-1)th spectrum?

4 (author's response) : For the interlacing, we scan the cavity temperature by a bit more than one cavity FSR. For the interlacing to work well this scanning has to be as linear as possible in order to avoid artefacts in the spectrum. A dedicated labview routine is then identifying after how many consecutive spectra 1 FSR scan is achieved and it is homogenously distributing the spectra within this 1 FRS window. This has now been described in the manuscript "The interlacing is computed by a custom Labview routine that recognize after how many consecutive spectra a complete scan of the cavity FSR is complete. The spectra are then homogeneously distributed within the one FSR span to originate the interlaced spectrum."

5 (comment from Referee): page 4, line 31: is the exponent of your NEAS correct? should it not be -11 (per spectral point)?

5 (author's response) : The referee is correct. The values reported where not normalized by the root-square of the number of spectral elements. We further realized that the number of spectral elements used for the calculation should be 48 (as shown in figure 2). Therefore we now reported the correct values of  $1.28 \times 10^{-10}$  and  $2.6 \times 10^{-9} \text{ cm}^{-1} \text{ Hz}^{-1/2}$  per spectral element.

6 (comment from Referee): page 5, line 14: what are line "surfaces"?

6 (author's response) : It is the area underneath the absorption line. This is now specified in the manuscript (areas underneath the absorption line)

7 (comment from Referee): page 5, line 21: you say the positions of the cavity modes are "locked", but relative to what? To the time axis of each scan (i.e. the cavity modes should always occur at the same time relative to the start of the tuning ramp)?

7 (author's response) : The position of the cavity modes is locked with respect to the position of the absorption lines. This is now clearer in the manuscript.

8 (comment from Referee): page 5, line 27: I think you mean at 17h30 (not 14h30)

8 (author's response) : Yes. This has been corrected.

9 (comment from Referee): page 11, figure 1: solenoid (not solenoide)

9 (author's response) : Corrected

10 (comment from Referee): page 12, figure 2: subscript the "4" in  $\text{CH}_4$  in the caption.

10 (author's response) : [Corrected](#)

11 (comment from Referee): page 13, figure 3: you could use the same y-axis for the top panel (just a suggestion)

11 (author's response) : [Figure 3 has been modified accordingly.](#)

# Simultaneous Detection of C<sub>2</sub>H<sub>6</sub>, CH<sub>4</sub> and δ<sup>13</sup>C-CH<sub>4</sub> Using Optical Feedback Cavity Enhanced Absorption Spectroscopy in the Mid-Infrared Region: Towards Application for Dissolved Gas Measurements

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**Abstract.** Simultaneous measurement of C<sub>2</sub>H<sub>6</sub> and CH<sub>4</sub> concentrations, and of the δ<sup>13</sup>C-CH<sub>4</sub> isotope ratio is demonstrated using a cavity enhanced absorption spectroscopy technique in the mid-IR region. The spectrometer is compact and has been designed for field operation. It relies on optical-feedback assisted injection of 3.3-μm radiation from an Interband Cascade Laser (ICL) into a V-shaped high-finesse optical cavity. A minimum absorption coefficient of  $2.8 \times 10^{-9} \text{ cm}^{-1}$  is obtained in a  
15 single scan (0.1 s) over  $0.7 \text{ cm}^{-1}$ . Precisions of 3 ppbv, 11 ppbv, and 0.08‰ for C<sub>2</sub>H<sub>6</sub>, CH<sub>4</sub>, and δ<sup>13</sup>C-CH<sub>4</sub>, respectively, are achieved after 400 s of integration time. Laboratory calibrations and tests of performance are reported here. They show the potential for the spectrometer to be embedded in a sensor probe for *in situ* measurements in ocean waters, which could have important applications for the understanding of the source and fate of hydrocarbons from the seabed and in the water column.

## 1 Introduction

20 Methane (CH<sub>4</sub>) is the second most abundant anthropogenic greenhouse gas after carbon dioxide (CO<sub>2</sub>), but with a 25 times higher global warming potential. Monitoring and identifying the different sources of CH<sub>4</sub> is therefore important, for the future climate projections. Among these sources, one can distinguish biogenic and abiogenic processes. Methane is mostly produced through biological processes, with the decomposition of organic matter under anoxic conditions. The abiogenic processes include biomass burning and thermal breakdown of organic molecules at high temperature in deep reservoirs. CH<sub>4</sub> is the main  
25 component of natural gas, but heavier hydrocarbons (HCs) can also be present in natural gas such as ethane (C<sub>2</sub>H<sub>6</sub>) and propane (C<sub>3</sub>H<sub>8</sub>), depending on the gas origin. In addition the carbon isotopic composition of methane (δ<sup>13</sup>C-CH<sub>4</sub> hereafter) differs between biogenic and abiogenic sources. While biogenic gas has high concentration of CH<sub>4</sub> with respect to heavier HCs and a more negative δ<sup>13</sup>C-CH<sub>4</sub> (typically from -60 to -90 ‰), thermogenic gas is characterized by a lower ratio of CH<sub>4</sub>/C<sub>2</sub>H<sub>6</sub> and a less negative δ<sup>13</sup>C-CH<sub>4</sub> signature (-50 to -40 ‰). The combination of these two measurements leads to a quite unambiguous  
30 identification of the origin of natural gas (Claypool and Kvenvolden, 1983). A significant part of earth's HC reservoirs lies in

marine environments, at variable depth below the seafloor. Questions arise about their origin and fate, and notably about their contribution through leakage into the ocean. Such leakage contributes to the carbon balance of the oceans, to acidification after oxidation in the water column, and possibly to the atmospheric concentration of these HCs if gas flaring from the seabed reaches the ocean surface. Therefore it is important to document the origin and fate of methane and ethane present below the seabed and dissolved in the water column, for process understanding and for future climate and ocean acidity projections.

Standard techniques for dissolved gas measurements usually rely on discrete sampling of the water column using Niskin bottles, followed by laboratory analysis. This method has the advantage of being simple and easy to setup, but it suffers from possible artefacts of the measurements due to outgassing of sample during the ascent (particularly for deep water samples). In addition, it offers a limited spatial and temporal resolution for probing the variability and mixing of water masses. Thanks to significant efforts in miniaturization of analytical instruments, from mass spectrometers (MSs) to optical techniques, *in situ* measurements of dissolved gas composition are today feasible (Chua et al., 2016; Grilli et al., 2018; Wankel et al., 2013). Due to the complexity and size of isotopic ratio mass spectrometers (IRMSs), today the application of *in situ* MS is limited to the measurement of the abundance of dissolved gas species, while the isotopic analysis is most often still performed in the laboratory. On the other hand, modern optical spectrometers can offer similar performance for determining isotopic abundance as MSs, while being more compact and easier to use for *in situ* operations. Cavity based techniques such as cavity ring-down spectroscopy (CRDS) and cavity enhanced absorption spectroscopy (CEAS) offer detection of a variety of species, multispecies detection, and the access to the isotopic signature of small compounds in gas mixtures (Kerstel, 2004).

The optical feedback cavity enhanced absorption spectroscopy (OFCEAS) (Morville et al., 2003, 2014) used in this work, is a well-known technique belonging to the family of CEAS and widely employed in trace gas detection and related fields (Butler et al., 2009; Grilli et al., 2014; Landsberg, 2014; Lechevallier et al., 2018; Richard et al., 2018; Romanini et al., 2006). It relies on the optical locking of the laser emission to a resonance mode of a high finesse optical cavity and it has already been demonstrated for distributed feedback (DFB) lasers, quantum cascade lasers (QCLs) (Gorrotxategi-Carbajo et al., 2013; Maisons et al., 2010), and interband cascade lasers (ICLs) (Manfred et al., 2015; Richard et al., 2016). In this work we report a novel application for the simultaneous measurement of  $C_2H_6$ ,  $CH_4$ , and  $\delta^{13}C-CH_4$ , using an ICL radiation source in the mid-IR region that could be applied to the *in situ* measurement of these compounds in seawater.

## 2 Method

The OFCEAS spectrometer (Figure 1) is composed of an ICL diode laser (from Nanoplus GmbH), an infrared polarizer (ColorPol MIR), two aluminum steering mirrors, and two photodiodes (PCI-2TE-4), all mounted on a stainless-steel optical cavity block. The V-shaped cavity (6-mm internal channel diameter) is composed of two 40-cm long arms, resulting in a free spectral range (FSR) of the optical cavity of 187.4 MHz. The cavity mirrors (Lohnstar Optics) have a reflectivity of 99.9584%, which provides a ring-down time (lifetime of the photons inside the resonator) of 3.20  $\mu s$  ( $\sim 1$  km optical path length) in absence of intracavity absorption (i.e., if the cavity is filled with zero air). This design allows for feeding back to the laser only the

photons that are in resonance with the cavity, without any parasitic feedback, such as that from reflections off the entrance mirror. This modifies the laser dynamics, leading to spectral narrowing of the laser emission and forcing its oscillation to match the cavity resonance frequency (Morville et al., 2005). The optical feedback phase matching condition imposes that the laser is placed at a distance from the input mirror equal to an integer number of cavity-arm lengths (in this case equal to one).

5 Fine phase adjustment and continuous phase lock is obtained by a piezo-electric transducer (PZT) mounted on one of the two injection steering mirrors. **The phase error was retrieved by analyzing the symmetry of the cavity modes during the acquisition, as explained in (Morville et al., 2005).** The diode laser is stabilized in temperature and a current ramp is applied in order to produce a scan over a narrow frequency region (typically of a few tenths of nanometers, with a scanning rate of  $\sim 0.2 \text{ nm} \times \text{mA}^{-1}$  for ICL lasers) and to temporarily lock the laser emission to successive  $\text{TEM}_{00}$  longitudinal cavity transmission modes.

10 The interest of the technique is to achieve high signal to noise ratio thanks to the narrowing of the laser emission and therefore to a more efficient power coupling to the high-finesse cavity. It also provides an intrinsically linear frequency scale fixed by the cavity geometry ( $FSR = c / (2 N n L)$ ), where  $c$  is the speed of light,  $L$  the cavity arm length,  $N$  the number of arms and  $n$  the index of the media. The instrument is simultaneously recording the signal from the two photodiodes (before and after injection) in order to obtain transmission spectra that are subsequently converted to absorption units (absorption coefficients as a function of cavity transmission frequency or wavelength) using a measurement of the ring-down time performed at the

15 end of each scan (Morville et al., 2014). This ring-down event is produced by rapidly switching off the laser emission, and acquiring the exponential decay of the light leaking out of the cavity.

An OFCEAS spectrum acquisition covers more than 100 longitudinal cavity modes ( $0.7 \text{ cm}^{-1}$ ) and is repeated at a rate of 10 Hz. For a precise retrieval of the absorption profile, and therefore of the molecular density in the cell, the cavity is precisely

20 temperature and pressure stabilized at respectively  $\sim 308.15 \text{ K}$  and 30 mbar. The cell is heated by two resistive heating bands controlled via a PID regulation and a PT1000 sensor positioned at the center of the cell, glued on the stainless-steel block. A second PID loop is used for pressure regulation by acting on a solenoid proportional valve (FAS, Norgren Fluid Controls). The inner pressure in the optical cell is measured by a Wika, 0-250 mbar pressure gauge. The temperature and current of the laser and the temperature and pressure of the cell are controlled by a single electronic card developed by the company AP2E, which

25 by means of a micro-processor, also ensures the fast acquisition of the two photodiode signals (340 kHz per channel). The cavity with the optical assembly, reported in Figure 1, is suspended by two vibration-isolation dampers and placed in an insulated aluminium casing.

### 3 Spectral Region and Model Fit

In the infrared region, two fundamentals bands are available for detecting  $\text{CH}_4$ : the  $\nu_3$  mode between  $2800$  and  $3100 \text{ cm}^{-1}$  and

30 the  $\nu_4$  mode from  $1200$  to  $1300 \text{ cm}^{-1}$ . Several reasons make the  $\nu_3$  transition more suitable for trace gas sensing, and notably: (1) ICLs are today available at this wavelength and they require less effort to cool compared to room-temperature QCLs; and (2) photodetectors have better sensitivity in this spectral region. For this work, the selected laser is centred at  $3.325 \mu\text{m}$  and operates between  $8^\circ\text{C}$  and  $12^\circ\text{C}$ , allowing it to cover the spectral region from  $3005.4$  to  $3009.2 \text{ cm}^{-1}$ . This region has been



selected to best accommodate the absorption intensities of the species to be detected at a specific range of concentrations (around 200 ppmv for CH<sub>4</sub> and 30 ppmv for C<sub>2</sub>H<sub>6</sub>) and for the possibility to access the ‘best’ isolated absorption lines. For applications in dissolved gas measurements, the selected wavelength region offers access to water absorption lines, required for the characterization of the dissolved gas extraction system (Grilli et al., 2018).

- 5 The selected absorption window reports a relatively large overlap of absorption features, requiring a rigorous optimization of the fit parameters. Here, a multi-component fit routine is used where line parameters (intensity, position, Lorentzian and Gaussian widths and the  $v_{VC}$  parameter for collision-induced velocity change inducing a so called Dicke narrowing (Dicke, 1953)) are fitted for each absorption transition using a speed-dependent Rautian profile (Varghese and Hanson, 1984). ~~(some of the parameters are linked together between lines of the same species to reduce the number of degrees of freedom of the spectral fit procedure).~~
- 10 A total number of 46 absorption lines are included in the fit, with 17, 3, 23 and 3 lines for <sup>12</sup>CH<sub>4</sub>, <sup>13</sup>CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and H<sub>2</sub>O, respectively. In order to reduce the degrees of freedom of the fitting routine and allowing a real-time fit for each acquired spectrum, some of the parameters have been pre-optimized and fixed or linked together. The remaining free parameters are: 1) the spectrum position: the positions of all lines are linked together and only one parameter (which corresponds to the mode-shift) is used to adjust the fit with respect to the acquired spectra; 2) the four intensities of <sup>12</sup>CH<sub>4</sub>, <sup>13</sup>CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and H<sub>2</sub>O from which concentrations are retrieved, and all lines belonging to one of these molecules are fixed in relative intensity to pre-optimized values, with a single intensity scaling parameter for all of them; 3) the coefficients of the polynomial function for drawing the baseline of the fit (here corresponding to three parameters for a second order polynomial function); 4) one extra parameter can be added per optical fringes that the operator may want to fit. In this case we only have one optical fringe which has been identified between the output cavity mirror and the signal photodiode. The Gaussian and
- 20 Lorentzian widths as well as the  $v_{VC}$  parameter for Dicke narrowing are optimized line by line and then fixed to their optimum values. The total number of free parameters for the fit is 9 for a spectrum composed by 48 individual points. A typical spectrum is reported in Figure 2 for concentrations of 72 ppmv of methane and 20 ppmv for ethane in dry air. The temperature and pressure of the cell are 35°C and 30 mbar, respectively. The fit is optimized using an interlaced spectrum in order to increase the spectral resolution. The latter is obtained by slightly scanning linearly the temperature of the cavity (0.02 °C of excursion), which causes a shift of the cavity mode positions with respect to the absorption lines, due to the mechanical elongation of the cell together with a change in the refractive index of the gas sample. This interlacing is only used for fit optimization, while in normal operation the spectra are only composed by data points separated by the cavity FSR (187.4 MHz) with a total of 48 fitted spectral points. The interlacing is computed by a custom Labview routine that recognize after how many consecutive spectra a complete scan of the cavity FSR is complete. The spectra are then homogeneously distributed within the one FSR
- 30 span to originate the interlaced spectrum. For the spectrum of Figure 2 (experimental data: black and green lines), 200 consecutive spectra are interlaced to achieve a resolution of 935 kHz. In the top panel of the figure, the <sup>12</sup>CH<sub>4</sub> and <sup>13</sup>CH<sub>4</sub> (red and blue spectrum, respectively) are the simulated spectra according to the HITRAN 2016 database (Gordon et al., 2017). This has been carried out for a clearer visualization of the line positions of the two isotopologues. A disagreement between experimental data and the HITRAN database was found for the two superposed lines of <sup>12</sup>CH<sub>4</sub> at 3008.39 cm<sup>-1</sup>, which are

16.5% weaker in amplitude in the simulated spectra with respect to the experimental data. The arrows indicate the best isolated absorption lines, which are used for calculating the isotopic ratio of methane (red and blue spectra) and the ethane concentration (green spectrum). Optical interference fringes are visible on the baseline, with the major fringe corresponding to the optical path between the output cavity mirror and the photodiode. Improvement in the photodiode alignment and the use of an additional spherical mirror at the cavity output for focusing the light into the detector (as shown in Figure 1) significantly decreased the amplitude of the optical fringe.

The standard deviation of the fit residuals for the spectrum obtained with 72 ppmv of methane and 20 ppmv of ethane in dry air is  $5.8 \times 10^{-8} \text{ cm}^{-1}$  for a single acquisition, which corresponds to a precision of 140 ppbv, 1.3 ppbv, 37 ppbv and 1.5‰ for  $^{12}\text{CH}_4$ ,  $^{13}\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ , and  $\delta^{13}\text{C}-\text{CH}_4$ , respectively. For the determination of the precision of  $^{13}\text{CH}_4$ , its natural abundance was taken into account. A contribution from small imperfections of the fit parameters is still present, since the standard deviation of the absorption baseline in absence of absorber (i.e. cavity filled with 30 mbar of zero air) is  $2.8 \times 10^{-9} \text{ cm}^{-1}$  for a single acquisition. A more comparative way of describing the performance of the instrument consists of defining the figure of merit normalized by the square-root of the bandwidth of the measurement (10 Hz) and the number of spectral elements (48) (Moyer et al., 2008). This leads to a figure of merit (Noise Equivalent Absorption Sensitivity, NEAS) of  $1.28 \times 10^{-10} \text{ cm}^{-1} \text{ Hz}^{-1/2}$  per spectral element without account for fit imperfections and  $2.6 \times 10^{-9} \text{ cm}^{-1} \text{ Hz}^{-1/2}$  per spectral element for a typical spectrum of 72 ppmv of  $\text{CH}_4$  and 20 ppmv of  $\text{C}_2\text{H}_6$  in dry air.

#### 4 Results: The Performance of the Spectrometer

The stable carbon isotopic ratio ( $\delta^{13}\text{C}$ ) is normally expressed as a comparative measurement with respect to an international reference, in this case Vienna Pee Dee Belemnite (VPDB; for the *Belemnitella Americana fossil carbonate*). It is described by Eq. 1, in which  $R$  is the abundance ratio of each isotopologue in the sample material, and  $R_{\text{VPDB}}$  the corresponding abundance ratio in the standard material. In the linear absorption regime, the number density of the molecule is proportional to the absorption and related to it via the absorption cross-section. Therefore, the retrieval of the isotope ratio with respect to a standard gas of known isotopic composition is relatively straightforward (Kerstel, 2004). The  $\delta^{13}\text{C}-\text{CH}_4$  gas standards used for the experiments are from Isometric Instrument and certified on the VPDB scale with an uncertainty of  $\pm 0.2\%$ .

$$\delta^{13}\text{C} = \left( \frac{R}{R_{\text{VPDB}}} - 1 \right) \quad R = \frac{^{13}\text{C}}{^{12}\text{C}} \quad (1)$$

Because of the complexity of the spectral fit and the discretization on the wavelength or frequency scale dictated by the cavity FSR, the position of the cavity modes with respect to one of the absorption lines affects the results of the fit. This is due to small imperfections of the fit model relative to the real spectrum which is sampled by the cavity modes. As these move and trace out the real spectrum profile, the model spectrum defects translate into varying errors or biases of the fit parameters which are optimized to match the model to the data at each time. We thus observed a dependency of the retrieved line surfaces (areas underneath the absorption line) on the cavity mode positions with respect to the absorption features, which affects the

isotope ratio determination (also observed and discussed in Favier, 2017). The drift in the cavity mode position is mainly due to mechanical instability and temperature fluctuations. Pressure may also play a role: even if stabilized at  $\pm 10 \mu\text{bar}$  the sensor may experience drifts with respect to the absolute pressure due to, for instance, fluctuations of temperature. In order to compensate for these drifts, we locked the cavity modes position to the absorption lines position by dynamically acting on the cavity temperature. The aim of the lock is not to better stabilize the cavity temperature, but to acting on this temperature regulation in order to maintain the cavity comb always at the same position with respect to the position absorption lines and compensate for electronic drifts occurring on the circuit for reading pressure and temperature of the cavity. Figure 3 reports long term measurements for two situations: in red, where the temperature of the cavity is stabilized at  $35 (\pm 0.0015) ^\circ\text{C}$  and the cavity modes are free to move, and in black, where the cavity modes are locked by acting on the temperature setpoint (the shift reported corresponds to the MHz-size excursion of the cavity modes with respect to the absorption feature). Measurements were obtained by continuously flushing the cavity at a gas flow of 10 sccm (standard cubic centimeters per minute) with a sample containing 72 ppmv of  $\text{CH}_4$  and 20 ppmv of  $\text{C}_2\text{H}_6$  in dry air.

Without the locking of the cavity modes position we observed a drift of  $20 \text{ MHz h}^{-1}$  of the cavity modes, while with the servo loop a stabilization of the mode positions better than 620 kHz was obtained. In the unlocked dataset, a fluctuation in the temperature stabilization occurred around 17h30 local time, and the corresponding section of data has been removed for the analysis. The spectral fit was conducted for both situations and an Allan-Werle (AW) statistical analysis (Werle, 2010) was performed on the  $\delta^{13}\text{C}\text{-CH}_4$  signal (Figure 3). From the log-log plot, where the AW standard deviation ( $\sigma_{\text{AW-SD}} \delta^{13}\text{C}$ ) is plotted against the averaging time (t), a tenfold improvement of the long-term stability was observed which translates into an extension of the optimum integration time of the system for the case of temperature locking of the cavity mode positions.

Afterwards, the system was further improved with a better optimization of the fitting parameters and of the optical setup resulting in a reduction of the optical interference fringes. A second AW statistical analysis was therefore conducted on the simultaneous detection of  $\delta^{13}\text{C}\text{-CH}_4$ ,  $^{12}\text{CH}_4$ , and  $\text{C}_2\text{H}_6$  with the same experimental conditions as for Figure 3. More than four hours of continuous measurements were used to produce the log-log plot (Figure 4). At short times, the measurement is mainly dominated by white noise with the  $\sigma_{\text{AW-SD}}$  decreasing proportional to  $t^{-0.5}$ . The optimum integration time corresponds to 400 s, reaching precisions of 0.08 ‰, 11 ppbv, and 3 ppbv for  $\delta^{13}\text{C}\text{-CH}_4$ ,  $^{12}\text{CH}_4$ , and  $\text{C}_2\text{H}_6$ , respectively. For longer integration times, due to the rise of 1/f noise (drifts), the  $\sigma_{\text{AW-SD}}$  starts to increase, leading to a degradation of the precision. In order to fix the accuracy of the instrument at its optimal precision below 0.1‰ for the  $\delta^{13}\text{C}\text{-CH}_4$ , injection of a standard gas with a known isotopic composition should thus occur every 400 s. This allows overcoming the instrumental drifts, and to maintain the accuracy of the measurement at about the same level of precision obtained at the optimum integration time. If not, instrument drifts will dominate with a degradation of the accuracy as reported and explained below. A comparison of the two statistical analysis for the  $\delta^{13}\text{C}\text{-CH}_4$  measurements (between Figure 3 and Figure 4) highlights how the improvement on the optical setup allowed to shift the entire AW curve to lower values (with a decreasing of the  $\sigma_{\text{AW-SD}}$  by a factor of four), however we could not obtain the long integration time as reported in Figure 3. This is probably due to the fact that the arise of frequency dependent

noise is dominated by others instabilities, limiting the best precision of the  $\delta^{13}\text{C}\text{-CH}_4$  to a value close to 0.1‰. Nevertheless, the benefit of the improvements is clearly visible, with the improved setup approaching the same precision than the previous one ten times faster.

In Figure 5, the dependency of the isotopic ratio with the concentration of methane is reported. This dependency is not caused by isotopic fractionation due to the sample handling, but more probably related to the discretization of the spectra and the precise location of the measurement points with respect to residual optical fringes in the spectrum. The tendency is well reproducible, can be fitted with an exponential function and used for calibration propose. The same behaviour was also observed using the same technique but for  $\text{H}_2\text{O}$  and  $\text{H}_2\text{S}$  isotopic measurements (Favier, 2017; Landsberg, 2014), as well as with an instrument based on off-axis integrated cavity output spectroscopy (ICOS), as reported by Wankel et al., 2013. With a comparable amplitude variation of the absorption intensity, a similar effect (but less pronounced) was also observed with respect to  $\text{C}_2\text{H}_6$  concentrations. By monitoring the carbon isotopic ratio of methane with and without 22.5 ppmv of ethane in the gas mixture, a difference on the  $\delta^{13}\text{C}\text{-CH}_4$  of 2.55 ‰ was observed. For this relatively small effect, a linear correction was applied.

The reproducibility of the system was estimated by conducting three measurements per day during four days at two methane concentrations (9 and 90 ppmv in dry air). Before each measurement the system was completely switched off. No calibration using a standard gas was carried out before each measurement. Therefore, the resulting reproducibility corresponds to the intrinsic accuracy of the system affected by long term instabilities. Results are represented by the two histograms of Figure 5 showing the reproducibility for  $\delta^{13}\text{C}\text{-CH}_4$ , which is reported on a relative scale (i.e., with respect to an arbitrary reference value). At  $\text{CH}_4$  concentrations of 9 and 90 ppmv the isotopic ratio is retrieved with an accuracy of  $\pm 11.8$  ‰ and  $\pm 2.9$  ‰, respectively (both 1- $\sigma$ ). By injecting a standard gas before each measurement for calibration proposes, the accuracy at high concentrations should approach the expected precision of  $< 0.1$  ‰ after 5 min of integration.

For the purpose of further validating the stability of the system, long term measurements were made while regularly switching between two samples with different isotopic composition. The two standard mixtures that were used had a composition of 79.4 ppmv of  $\text{CH}_4$ , with a carbon isotopic composition of -54.5 ‰, and of 56.9 ppmv with  $\delta^{13}\text{C}\text{-CH}_4 = -38.3$  ‰ (with manufacturer certified uncertainties of  $\pm 0.2$  ‰). The gas flow was fixed at 2 sccm and the standard gas samples were switched every five minutes during 3 hours using a manual three-way two-position valve. In Figure 6, the measurements of the carbon isotopic ratio are reported. Since the two samples had different  $\text{CH}_4$  contents, a correction following the curve reported in Figure 5 was applied in order to account for the dependency of  $\delta^{13}\text{C}$  on the  $\text{CH}_4$  concentration. The -38.3 ‰ sample was employed as the “known” standard gas, and the isotopic composition of the second sample was then retrieved. Drifts on the isotopic signature of only 0.6 ‰ were observed after 3 hours of continuous measurements (which is in agreement with the AW analysis). The response time of the instrument at 2 sccm gas flow is estimated to be 15 sec (single exponential), entirely attributed to the renewal of the gas sample in the measurement cell. The standard deviation of the raw measurement (at 10 Hz) is  $\pm 1.9$  ‰, while after averaging the results over 20 s (blue curve) the noise decreases to  $\pm 0.5$  ‰.

## 5 Comparison with existing instruments

Depending on the application, different instrumental developments with a focus on a particular analytical aspect were carried out in the past. For instance, the concentration range will vary depending on the application: a high-sensitivity to measure in the low concentration range is required for environmental sensing (e.g. atmospheric measurements, paleoclimatology), while moderate sensitivity is required to measure in the high concentration range for dissolved gas measurements in seawater, leak detection, and for oil and natural gas exploration. Some applications would require low sample volumes (such as ice-core and dissolved gas analyses). Finally, different constraints such as compactness, robustness, and power consumption, may play a role depending on the measurement strategy (laboratory, on site, or *in situ* measurements). For this propose, a non-exhaustive comparison with some of the existing techniques for measuring  $\delta^{13}\text{C-CH}_4$  is reported in Table 1. The comparison highlights similar performances, albeit for different conditions, with precisions on  $\delta^{13}\text{C-CH}_4$  below 1 ‰. Up to now, the best performance in terms of precision and the amount of sample required remains IRMS technique, followed by the CRDS system developed by Picarro (Phillips et al., 2013; Schmitt et al., 2014). The QCLAS system of Eyer et al., 2016 based on a multi-pass cell, the ICOS from Los Gatos Research (Wankel et al., 2013), and the work reported here are more suitable for high methane concentrations. Our development aims at the measurement of dissolved gas in seawater, and therefore was optimized for relatively high methane concentrations of ~100 ppmv, achieving precision on the  $\delta^{13}\text{C-CH}_4$  below 1 ‰ after 1 s. This development sets itself apart by its compactness and portability as required for *in situ* measurements. Moreover, thanks to the low volume of the measurement cell, a small amount of sample ( $< 1 \text{ cm}^3$  of gas at STP) is required, making the spectrometer suitable for coupling to a membrane-based extraction system for *in situ* application in the water column under marine conditions.

## 20 Conclusion

In this work we presented a novel optical spectrometer, operating in the mid-IR region and based on the OFCEAS technique, for simultaneous measurement of  $\text{C}_2\text{H}_6$  and  $^{12}\text{CH}_4$  concentrations, and the  $\delta^{13}\text{C-CH}_4$ . The spectrometer achieved a minimum absorption coefficient of  $2.8 \times 10^{-9} \text{ cm}^{-1}$  over a single frequency scan (0.1 s) over  $0.7 \text{ cm}^{-1}$  at low levels of  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$  and  $5.8 \times 10^{-8} \text{ cm}^{-1}$  for a more typical gas mixture (72 ppmv of  $\text{CH}_4$  and 20 ppmv of  $\text{C}_2\text{H}_6$ ). Precisions of 3 ppbv, 11 ppbv, and 0.08 ‰ for  $\text{C}_2\text{H}_6$ ,  $^{12}\text{CH}_4$ , and  $\delta^{13}\text{C-CH}_4$ , respectively, were demonstrated for an optimum integration time of 400 s. A stability of  $\pm 2.9 \text{ ‰}$  for long term measurements of  $\delta^{13}\text{C-CH}_4$  was obtained without the need of regular injection of known isotopic composition standard gas. The latter is needed if an accuracy of the  $\delta^{13}\text{C-CH}_4$  measurement at the level of 0.1 ‰ is required. The dependency of the isotopic measurement on the composition of the gas mixture was characterized, with calibration curves for both  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$  concentration dependencies. The instrument has the required characteristics of compactness, precision, and time resolution to be coupled with a dissolved gas extraction system and to be integrated in an *in situ* sensor for continuously monitoring the dissolved gas composition in deep-sea and oceanic environments. A dissolved gas extraction

system similar to the one described by Grilli *et al.*, 2018 will provide an adjustable dilution of the gas sample by adding a zero-air carrier gas at the dry side of the extraction unit, therefore increasing the dynamical range of the sensor.

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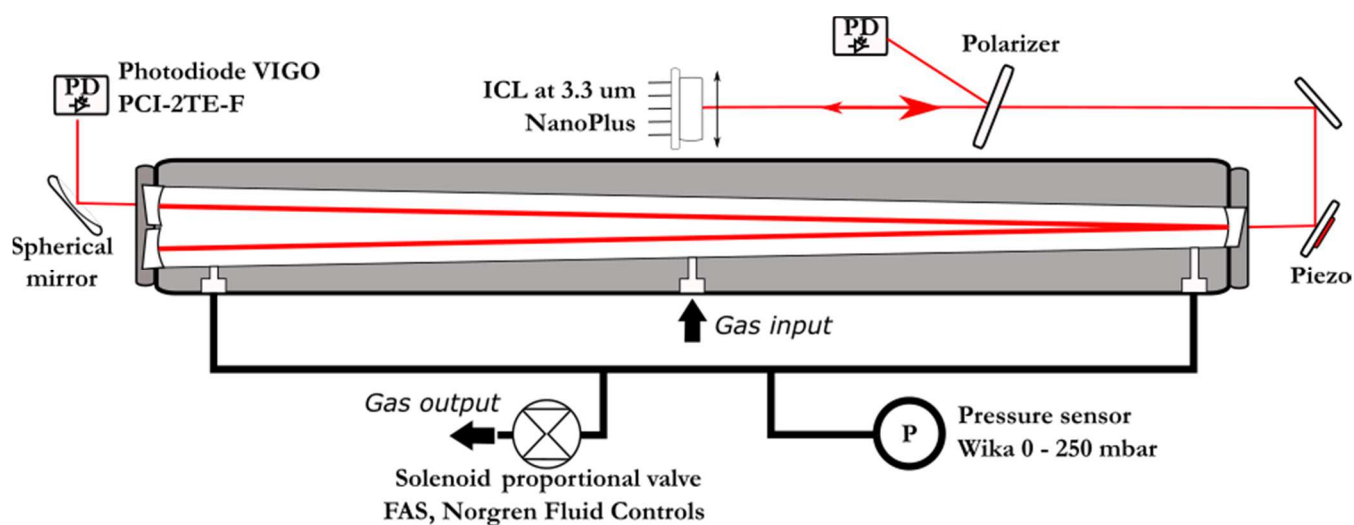


Figure 1 : Details of the optical setup with the laser injection and phase control (piezo mounted on the injection steering mirror assembly). The polarizer is tilted and its reflection used for acquiring the laser power spectrum before the cavity injection. At the cavity output, a spherical mirror is used to focus the light on the second (signal output) photodiode.

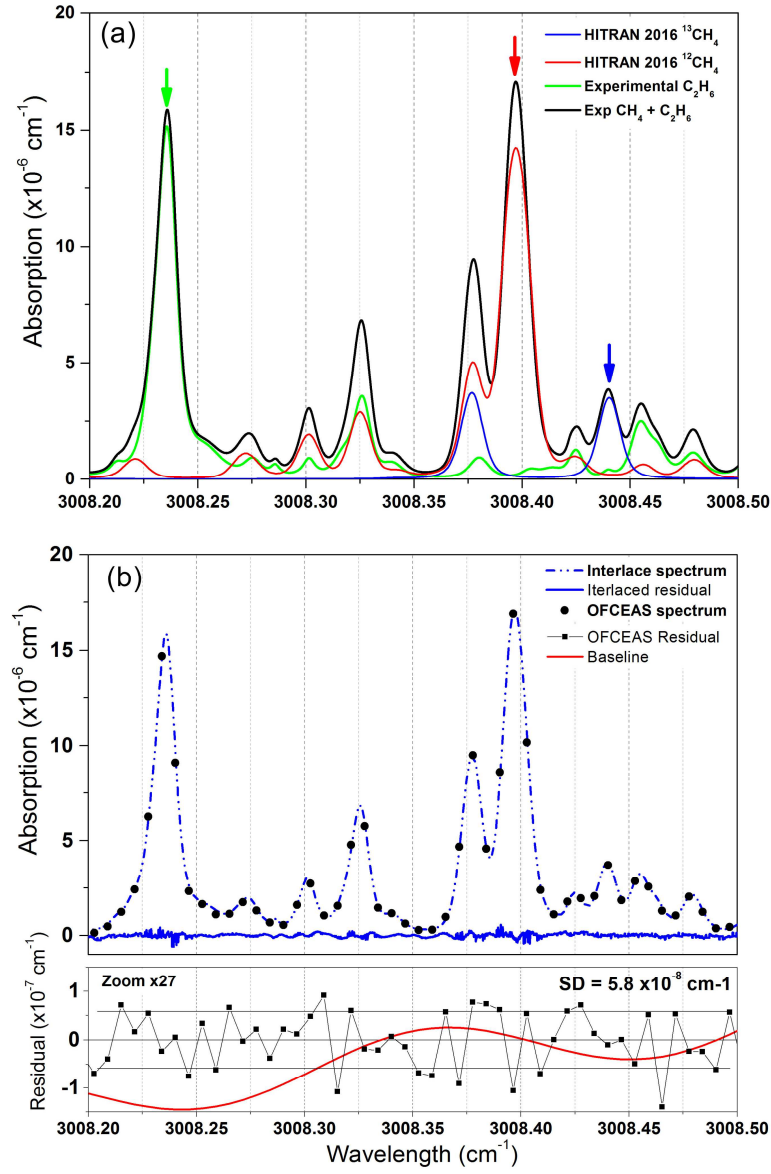


Figure 2 : (a) A combination of experimental interlaced spectra and spectra simulated using the HITRAN 2016 database at 30 mbar and 35°C. HITRAN profiles show the position of  $^{12}\text{CH}_4$  (red) and  $^{13}\text{CH}_4$  (blue) at 72 ppmv of  $\text{CH}_4$  in dry air. In green, the interlaced spectrum acquired with only 20 ppmv of  $\text{C}_2\text{H}_6$  in dry air in the cavity. The full experimental spectrum containing absorptions from the three species is reported in black. There is a disagreement for the two superimposed lines at 3008.39  $\text{cm}^{-1}$ , with a line intensity discrepancy between experimental data and the HITRAN 2016 database of ~16% on the amplitude of the absorption lines (this is outside the reported HITRAN 2016 uncertainties on the cross sections that are between 2% and 5%). (b) An example of an OFCEAS spectrum (black circles) and the corresponding interlaced methane-ethane absorption spectrum and its residue (blue lines). At the bottom, the residuals of the OFCEAS spectral fit for one acquisition (0.1 s) and the baseline curve (red) (generated by the fit) are reported.

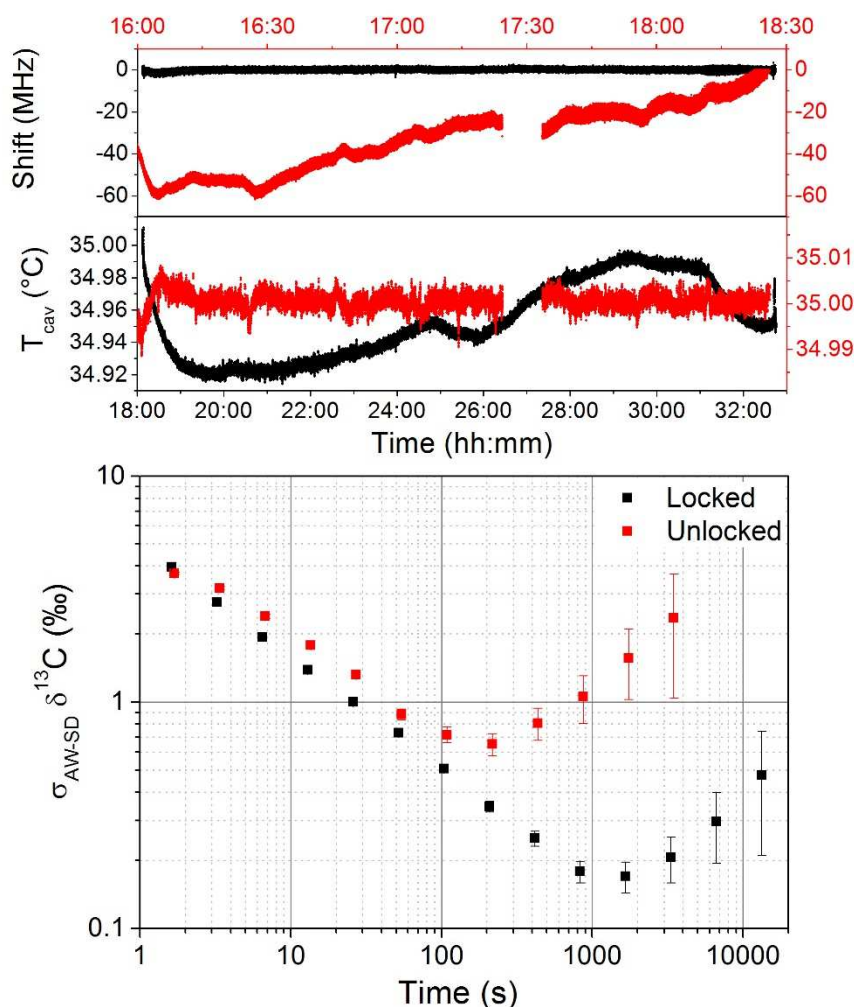


Figure 3. A comparison of the performance on the measurement of the  $\delta^{13}\text{C}\text{-CH}_4$  with (Black) and without (Red) the lock of the position of the cavity modes. Without the locking the temperature is stabilized at  $35 \pm 0.0015^\circ\text{C}$  and the mode position drifts of about  $20\text{ MHz h}^{-1}$ . By locking the mode positions by acting on the temperature setpoint, the mode positions are stabilized to 620 kHz. The advantage of the locking configuration is visible in the log-log plot, where the AW standard deviation of the  $\delta^{13}\text{C}\text{-CH}_4$  signal is shifted to slightly lower values, with a longer averaging-time stability. Both measurements were performed by continuously flushing the cavity with a 10 sccm gas flow of a synthetic air mixture containing 72 and 20 ppmv of  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$  in dry air, respectively.

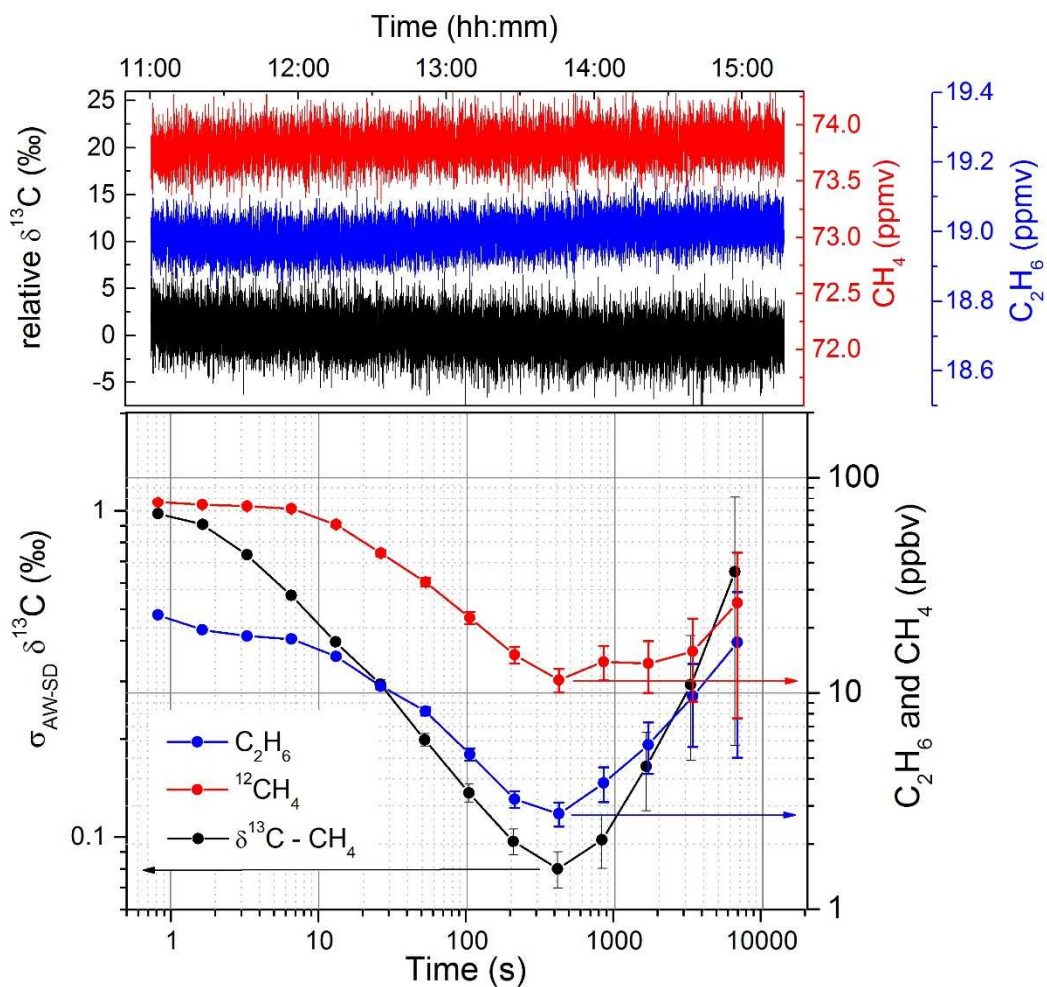


Figure 4 : The Allan-Werle standard deviation for a four-hour time series of measurement with 73.7 ppmv of methane (black) and 19 ppmv of ethane (blue) in dry air. The best integration time of the system corresponds to ~8 min and the achieved precision is 0.08 ‰, 11 **ppbv**, and 3 ppbv for  $\delta^{13}\text{C} - \text{CH}_4$ ,  $^{12}\text{CH}_4$ , and  $\text{C}_2\text{H}_6$ , respectively.

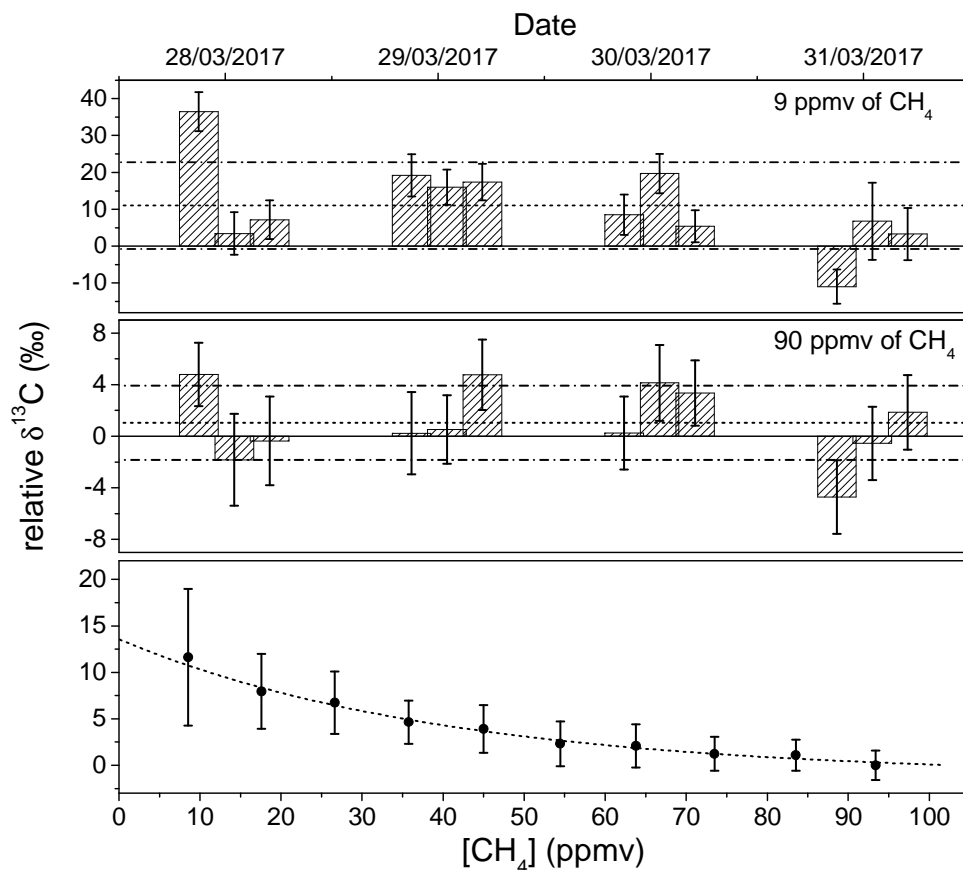


Figure 5. Bottom panel: the dependency of the relative  $\delta^{13}\text{C}$ -CH<sub>4</sub> on the CH<sub>4</sub> concentration. Two upper panels: Reproducibility between discrete measurements made three times a day during one week for 9 and 90 ppmv of CH<sub>4</sub> in dry air. Accuracies of  $\pm 11.8$  ‰ and  $\pm 2.9$  ‰ (represented by the dashed lines) were obtained for the two concentrations (1- $\sigma$ ). The instrument was not calibrated before each measurement using a gas standard. For high concentrations, such calibration would make the accuracy approaching the expected precision of 0.08 ‰ after 5 min of integration time.

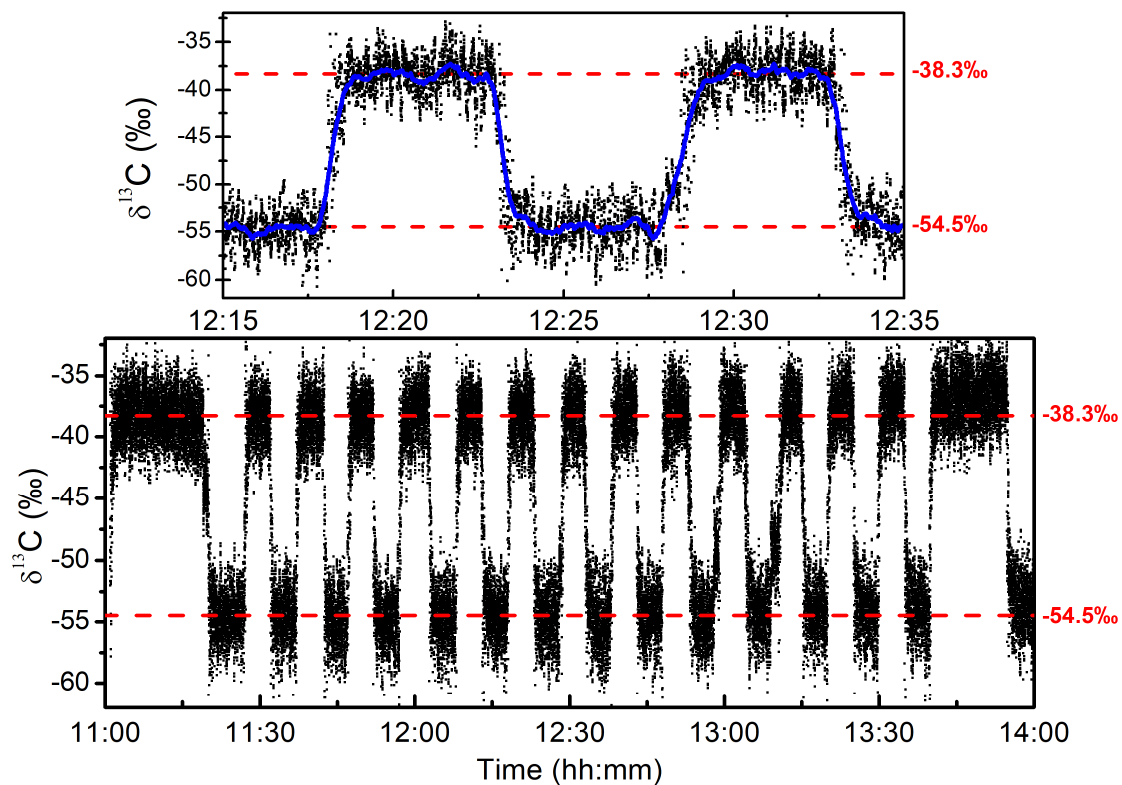


Figure 6 : Long-term measurements obtained by repeatedly switching between two methane samples in dry air having different stable carbon isotopic composition. The two samples are diluted gas standards from Isometric Instrument with specified  $\delta^{13}\text{C}\text{-CH}_4$  of  $-54.5 \pm 0.2\text{‰}$  (79.4 ppmv) and  $-38.3 \pm 0.2\text{‰}$  (56.9 ppmv).

**Table 1. Non-exhaustive comparison between some of the existing techniques for measuring  $\delta^{13}\text{C}\text{-CH}_4$** 

	Technique	Precision on the $\delta^{13}\text{C}\text{-CH}_4$	Remarks
Eyer <i>et al.</i> 2016	TREX-QCLAS (pre-concentration system coupled with a dual-QCL instrument with a multi-pass cell of 76 m)	0.1 ‰ in 10 min (750 ppmv of $\text{CH}_4$ )	Good performance at high concentration. It requires large gas volumes (0.5 L volume cell). Not adapted for application where low volumes of gas are available (e.g. ice-core, dissolved gases studies).
Wankel <i>et al.</i> 2013	ICOS (off-axis integrated cavity output spectroscopy), Los Gatos Research, Inc.	0.8 ‰ in 5 min (>1000 ppmv of $\text{CH}_4$ )	Proved for applications with small amount of sample (i.e. deep water measurements). Designed for high concentrations.
Phillips <i>et al.</i> 2013	CRDS (cavity ring-down spectroscopy), Picarro	0.8 ‰ in 5 min (>1.8 ppmv of $\text{CH}_4$ )	Designed for atmospheric measurements, it provides good reproducibility. Adapted to field measurements.
Schmitt <i>et al.</i> 2014	IRMS (isotope ratio mass spectrometer), IsoPrime	0.15 ‰ (atmospheric samples)	Best performances for low volume samples. Not adapted for field measurements.
This work	OFCEAS	0.1 ‰ in 5 min (72 ppmv of $\text{CH}_4$ )	Designed for <i>in situ</i> measurements and for low volume measurements. Degraded performances at low concentrations (atmospheric samples)