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Yann Ferrec, Florence de la Barrière, Laurence Croizé, Silvère Gousset, Etienne Le Coarer, et al..
Overview of the NanoCarb GHG sensor project. OPTRO 2022 10th International Symposium on
OPTRONICS IN DEFENCE AND SECURITY., Jun 2022, Versailles, France. hal-03838361

HAL Id: hal-03838361

<https://hal.science/hal-03838361>

Submitted on 3 Nov 2022

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OVERVIEW OF THE NANOCARB GHG SENSOR PROJECT

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KEYWORDS: atmosphere, greenhouse gases, hyperspectral imaging, Fourier transform spectrometer, Fabry-Perot interferometer, satellite constellation

ABSTRACT:

NanoCarb is a compact snapshot imaging spectrometer in the shortwave infrared, dedicated to the measurement of greenhouse gases, like CO₂ or CH₄. It was developed in the framework of the H2020 Scarbo project by Onera and UGA, and two avenues of research were investigated: a preliminary design for a space mission, and the development of two airborne prototypes. The former proved the relevance of Nanocarb as a compact payload for a constellation of minisatellites dedicated to GHG monitoring with a sub-daily revisit, while the airborne prototypes proved the manufacturability of such a microspectrometer. Even though more experiments and signal processing improvements are still to be done to quantitatively prove the performance of Nanocarb GHG sensor, the current results confirm the interest to pursue the development of Nanocarb.

1. NANOCARB GHG SENSOR

1.1. ImSpoc design

ImSpoc (Imaging Spectrometer On Chip) is an imaging spectrometer based on a multicam design [1,2], that is with a lenslet array, to form a mosaic of images of the scene (we call them thumbnails) on the common focal plane array (FPA). We obtain the spectrometry function by adding a specific filter in front of each microlens. The feature of ImSpoc is to use Fabry-Perot interferometer as spectral filters, in a multiplex mode, that is with a spectral range far larger than the free spectral range of the Fabry-Perot (see Figure 1). The filter array is then a step-case plate, which can be made of glass or air. If the Fabry-Perot finesse is low, the interferometer is close to a two-wave interferometer and ImSpoc is then a Fourier-transform imaging spectrometer [3]. Main assets of ImSpoc are firstly to be compact: the interferometric core (interferometric plate and lenslet array) is a few millimetres deep and is set just in front of the FPA. Secondly, it is very robust since there is no moving part, and compacity also helps for thermal regulation (very few thermal

gradients in the interferometric core). Thirdly, compared with a multicam camera using narrow-band spectral filters, ImSpoc benefits from a multiplex advantage. Lastly, ImSpoc is snapshot, which allows it to monitor time-varying scenes, and it also eases signal processing and constraints on scene scanning.

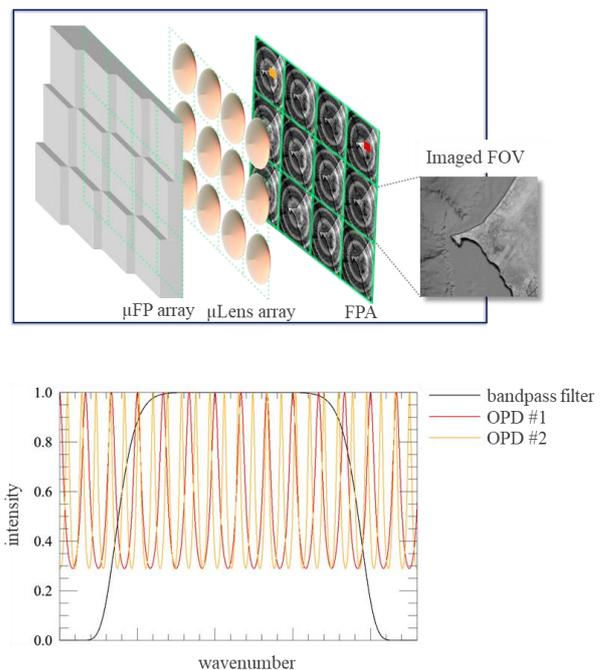


Figure 1. Top: layout of ImSpoc, with the Fabry-Perot array, the lenslet array and the FPA, on which the scene is duplicated. The red and orange dots indicate two pixels viewing the same point of the scene, but through distinct Fabry-Perot thickness. Bottom: spectral response of these two pixels. The bandpass filter (not represented on the top layout) is much wider than the free spectral ranges of the Fabry-Perot.

Limitations are the difficulty of manufacturing the Fabry-Perot array, the reduced signal collection compared to non-snapshot systems, and the reduced size of the hyperspectral cube, since its total numbers of points (spectral and spatial) is equal to the number of pixels of the FPA. However, these last two limitations are shared with all other snapshot imaging spectrometers.

1.2. Partial interferograms for gas measurement

The Nanocarb GHG sensors are based on the

ImSpoc design, but their specificity is to measure only a small part of the interferogram. Indeed, most of spectral signature of GHG have periodic features. In the Fourier space –that is in the interferogram domain– this means that most of the relevant geophysical information are concentrated at few optical path differences (OPD). Thus, measuring the interferogram only at these OPD is enough to get the required information about the gas column [4,5,6]. This is a way to overcome the aforementioned third limitation of ImSpoc. (see Figure 2).

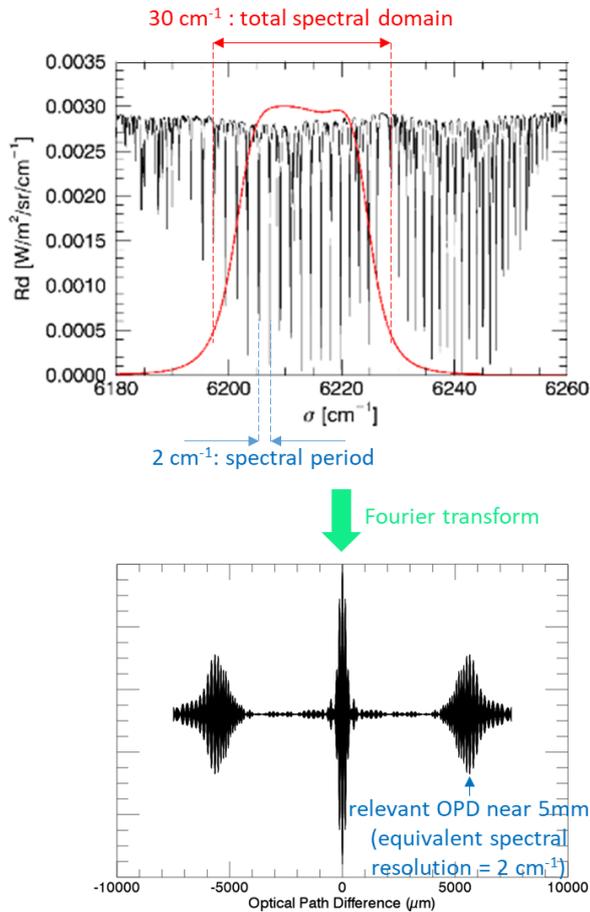


Figure 2. Top: spectral radiance that would be observed from the top of atmosphere near 1607 nm (6220 cm^{-1}), the spectral lines due to CO₂ absorption are clearly visible. In the spectral range delimited by the filter (red-plotted), they are quasi-periodic with a 2 cm^{-1} period. Bottom: interferogram from the above plotted spectral radiance limited by the filter, the periodicity of the spectral lines makes that most of the information is concentrated around 5 mm OPD.

2. THE H2020 SCARBO PROJECT

2.1. Scientific motivations and state-of-the art

Thanks to its compacity and its ability to target efficiently a specific GHG, Nanocarb is a promising solution as a payload for monitoring GHG from space. Space-based optical cameras are indeed a well-established tool for monitoring GHG, and current institutional missions include GOSAT [7] and GOSAT-2 [8], OCO-2 [9] and OCO-3 [10],

Sentinel 5P Tropomi [11], and GaoFen5-GMI [12]. In Europe, planned missions include Microcarb [13], Sentinel 5 [14], and CO₂M [15]. Besides these public missions, several privately funded missions are already operational or in development, such as GHG Sat [16], MethaneSat [17] or Carbon Mapper [18], but at very high spatial resolution (a few tens of meters), and thus exclusively concentrating on the local scale.

None of current missions provide observations enabling to assess anthropogenic CO₂ emissions with desired quality, and although future missions under development like CO₂M are a big step forward towards this goal, the lack of frequent enough observations (and cloud cover) may be a strong limitation. Indeed, routine estimation of emissions needs intraday revisit, given the diurnal variations of fossil GHG emissions.

2.2. Scarbo mission proposition

Between 2018 and 2021, the H2020 Space CARBOn Observatory (SCARBO) project [19] was to explore ways to take up this challenge by proposing a complementary mission filling the intraday revisit gap, focusing on CO₂ and CH₄. The main macroscopic mission specifications are listed in Table 1.

Table 1. level 2 (L2, total column concentration) product requirements

	XCO ₂	XCH ₄
random error	0.5 / 1 ppm	3 / 6 ppb
systematic error	0.2 / 0.5 ppm	1 / 5 ppb
horizontal resolution	2 / 6 km ²	
swath	150 / 240 km	
vertical resolution	total column	
temporal coverage	sub-daily	

The challenges for the Scarbo mission are to reach simultaneously:

- high accuracy measurements;
- high observation frequency;
- high spatial resolution;

at an affordable cost. The observation frequency calls for a satellite constellation of about 24 satellites in low Earth orbit, to ensure one access per day for the whole hot spots identified, and two accesses per day for 70% of them, without roll capacity. However, from an economic point-of-view, the choice of a constellation leads to small satellites (150 kg class), and thus to compact payloads. Moreover, the need for high accuracy measurements involves measuring aerosols, since a misknowledge of these latter may generate significant biases. Therefore, the Scarbo payload includes an aerosol instrument, Spex, developed by SRON [20], and a GHG instrument, Nanocarb. The first part of the work about Nanocarb was to design a payload that may be compliant with the aforementioned requirements. This will be described in next Section. The second part of the

work was to increase Nanocarb technology-readiness level (TRL). This will be described in Section 4.

3. PRELIMINARY NANOCARB DESIGN FOR A SPACE MISSION

At Nanocarb level, the Scarbo project was a preliminary design of a space-based payload, with an associated performance model, and the development of basic components, to mitigate the technological risk for a space mission.

3.1. Optical design

We chose the short-wave infrared (SWIR) as the spectral domain, because it has been demonstrated that it is well suited for anthropogenic GHG measurement [21]. More precisely, as a starting point, we chose the spectral bands of CarbonSat, that is to say two CO₂ bands around 1609 nm and 2066 nm, one CH₄ band around 1645 nm, and one band for O₂ around 764 nm. In order to reach the required swath and spatial resolution, and due to the limited size of SWIR FPA, we decided to design one Nanocarb camera in each band.

The chosen FPA was the HgCdTe NGP from Lynred [22] for the SWIR bands, and the Si Capella CIS120 from e2v for the visible band [23].

Spectral band and OPD optimization was then performed through a simplified L1 performance model [24], taking into account H₂O effect on interferograms and the spectral shift of the filter with the angle of incidence. To reduce bias due to H₂O, several OPD ranges have been selected (see Table 2).

Table 2. Spectral bands and OPD of the four Nanocarb cameras

central wavelength	FWHM	OPD		
764 nm	2 nm	1.4 mm		4.2 mm
		O ₂ aerosols		
1609 nm	6 nm	2.3 mm	2.8 mm	5.6 mm
		H ₂ O	CO ₂	CO ₂
		0.9 mm	1.1 mm	2.1 mm
1645 nm	19 nm	H ₂ O	CH ₄	CH ₄
		5.6 mm		12 mm
		CO ₂ aerosols		
2066 nm	8 nm	5.6 mm		12 mm
		CO ₂ aerosols		

About the imaging performance, we fixed the ground sampling distance (GSD) at 1.2 km for a 600 km satellite altitude, so that the spatial resolution be compliant with the requirement of Table 1. Thumbnails are 170 pixels wide in the across-track direction, thus the swath is about 200 km. The optical system consists in the lenslet array (with diaphragm array) and in a front afocal lens with an intermediate focal plane where we set a field stop (see Figure 3). A good optical quality was reached, with a point-spread-function (PSF) diameter close to the pixel size. Note that this may cause aliasing, which will have to be taken into account in the data processing chain (see

Section 5.2). A rough tolerancing estimation shows that afocal alignment is very tolerant in reference to the lenslet array. Nevertheless, the interferometric core is very compact, and thermally regulated with the FPA, thus current optomechanical tolerances are compliant with a mini-satellite environment.

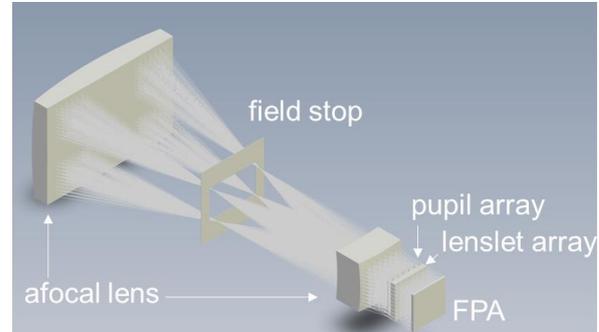


Figure 3. Space Nanocarb optical system for the SWIR bands. The Fabry-Perot array is not shown in the figure because it depends on the spectral band. The overall length of this system (not including mechanical mount and electronics) is about 161 mm.

A mechanical design for the Nanocarb camera was also performed: with this first and still preliminary design, we obtain a volume for the four Nanocarb cameras about 20x20x25 cm³ and a mass about 7 kg.

3.2. L2 performance estimation

From the optical definition of Nanocarb, we estimated the radiometric performance of L1 data, that is to say interferograms after non-uniformity correction and frame registration. Even though this radiometric model is slightly optimistic, since we assumed perfect non-uniformity and bad pixels correction, it should not be far from what could be experimentally reached, thanks to a careful experimental characterization of the instrument.

L2 performance estimation were then derived at LMD (Palaiseau, France) from this L1 performance model, using the optimal estimation inverse method. This work was done considering only Nanocarb data, and Nanocarb and Spex data. More details on this L2 performance estimation can be found in [25].

The main results are that:

- Spex data do improve XCO₂ and XCH₄ retrieval from Nanocarb interferograms;
- with the model assumptions, random errors are below 1 ppm for XCO₂ and 6 ppb for XCH₄.

This study thus confirms that the partial interferogram contain significant information about the targeted gas concentration, and that Nanocarb fulfill the requirement for the Scarbo mission.

4. NANOCARB AIRBORNE PROTOTYPES

At the beginning of the Scarbo project, Nanocarb technological readiness level (TRL) was only 2, i.e. "technology concept formulated". Thus, an effort has been made to increase this TRL, by developing prototypes and acquiring experimental data.

4.1. Camera design and trade-offs

It is important to stress that in the four years of the Scarbo project, it was unrealistic to develop a payload similar to the one described in the previous Section. Our goal was to initiate technological developments to pave the way for the future space payload. We thus had to find trade-offs between performance and project constraints.

A first trade-off was made about the FPA. We had indeed to choose an affordable and off-the-shelf FPA. We thus used the InGaAs Snake FPA from Lynred [26]. Compared with the NGP, it is smaller (640x512 pixels) and has a shorter cut-off wavelength. The 2066 nm band was therefore not accessible.

The main technological effort was led towards the manufacture of the interferometric plate. We decided to develop only two cameras, one for CO₂ at 1609 nm and one for CH₄ at 1645 nm. Moreover, we targeted only two OPD intervals for CO₂ and one for CH₄. The technological challenge was indeed high enough: engraving a Silicon plate with steps about 1 mm wide but a few tens of nanometers deep. This was successfully achieved at LTM (Grenoble, France), and a photograph of the Silicon plate can be seen on Figure 4.

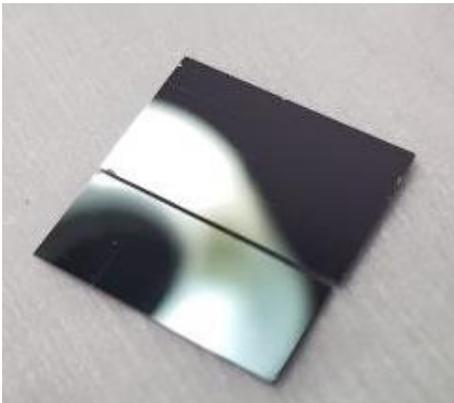


Figure 4. Silicon plate for the CO₂ airborne Nanocarb camera. This plate is in two pieces, one for each main OPD interval. Each of these pieces is itself graved with 50 nm steps, barely visible in the photograph.

The spectral filter is custom in order to fit with the required spectral band, but the used materials are standard. Consequently, the effective refractive index is about 1.8, which means that the spectral shift with the angle of incidence is more significant than the one used for the space-mission design.

The optical system has a total focal length of 3 mm, so that the instantaneous field-of-view (iFOV) is 5 mrad. There are 8x10 thumbnails of 64x64 pixels, however only 50x50 pixels can be used without edge effects: the field-of-view (FOV) is then $\pm 7.2^\circ$. Consequently, at an altitude height of 10000 m, the GSD is 50 m and the FOV swath is 2.5 km, thus larger than the pixel of the space mission. Table 3 lists the main characteristics of the Nanocarb airborne cameras, which are also described in [27].

Table 3. Main characteristics of the airborne Nanocarb cameras

	Nanocarb CO ₂	Nanocarb CH ₄
spectral band (on-axis)	[1606-1612] nm	[1635-1653] nm
iFOV	5 mrad	
useful pixels per thumbnail	50x50	
FOV	$\pm 7.2^\circ$	
frame rate	20 Hz	
camera mass	<1.9kg	
camera volume	9x10x26 cm ³	

4.2. Airborne campaigns

These cameras were integrated in a Falcon 20 from Safire (Cugnaux, France) for an airborne campaign, initially planned in May 2020 but delayed to October 2020 due to the Covid19 pandemic. The scientific payload was made up of the Spex polarimeter from SRON and of the Nanocarb cameras. Figure 5 shows these cameras inside the aircraft.

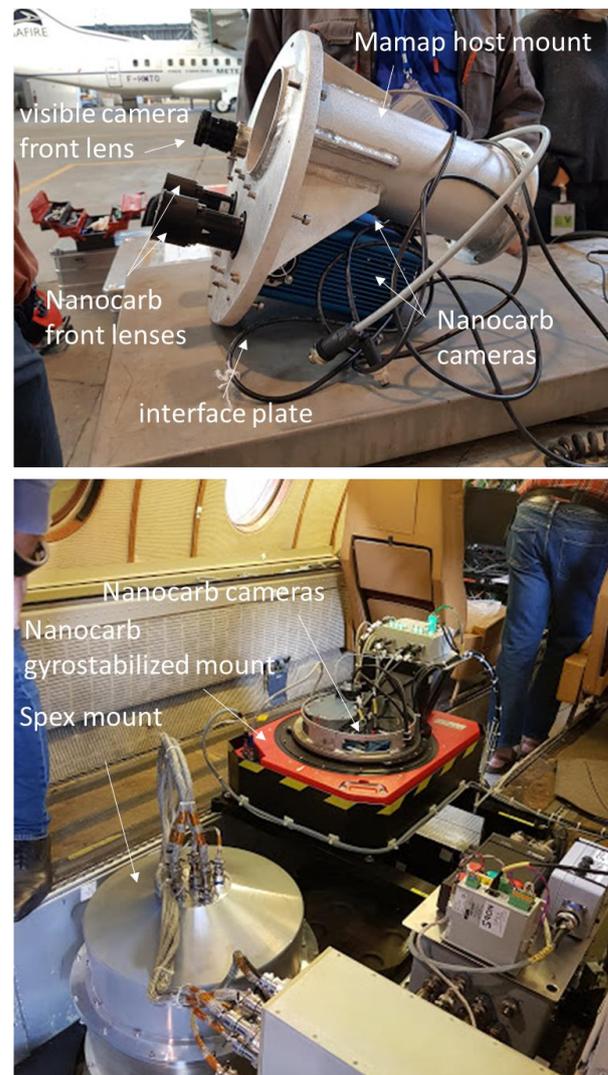


Figure 5. Integration of Nanocarb cameras into the Falcon20. Mamap is a spectrometer from the University of Bremen [28], which unfortunately could not participate to this campaign due to Covid 19 restrictions.

For Nanocarb, the goal of this airborne campaign was threefold:

- to demonstrate the proper functioning and the stability of a Nanocarb camera under airborne conditions;
- to acquire airborne experimental data to help the development of the image processing chain;
- to demonstrate the ability of these Nanocarb prototypes to detect a significant CO₂ plume.

In order to reach the third goal, we planned to fly over the coal power plant of Bełchatów in Poland. Unfortunately, weather conditions were too bad in autumn 2020 over Bełchatów, as well as over other large coal power plants like Neurath, Germany. We thus could not experimentally demonstrate Nanocarb performance over a CO₂ plume. Nevertheless, the other two objectives were successfully attained. Indeed, Nanocarb cameras have correctly operated, laboratory characterizations have not put in evidence any major deviations before and after the airborne campaigns, and a lot of images –unfortunately not over CO₂ plume– were acquired and useful to develop the image processing chain. Figure 6 shows example of image acquired by Nanocarb CO₂ camera, and Figure 7 three interferograms. On these plotted interfeograms, the measured signal-to-noise ratio (SNR) is between 50 and 70, while the expected SNR was between 70 and 95. This 30% discrepancy comes from imperfect non-uniformity correction of the FPA and from dusts on the aircraft window. This moderate SNR is greatly compensated by the huge amount of data in the interferogram of one scene point. Indeed, each OPD interval is sampled with 20 thumbnails in a single frame, and the total number of frames where this scene point appears is about 200 (depending on the aircraft speed, the frame rate and the camera field-of-view). Results are more deeply described in [29].

These data have also been used to test inversion of experimental partial interferograms by LMD (France). Nevertheless, the lack of reference data and of significant GHG gradient in the scene, makes difficult to derive quantitative estimation of airborne Nanocarb performance from these data. First L2 analysis has emphasized a strong correlation between albedo and XCO₂ estimation, but this would not prevent to detect the CO₂ plume from a coal power plant. We hope that we will demonstrate this ability with future airborne campaign.

5. PERSPECTIVES

Data acquired during this campaign are still used to improve the signal processing chain and to better estimate Nanocarb image quality, at level L1 and L2. Furthermore, other research avenues are envisaged, whether from data acquisition, data processing, or hardware development.

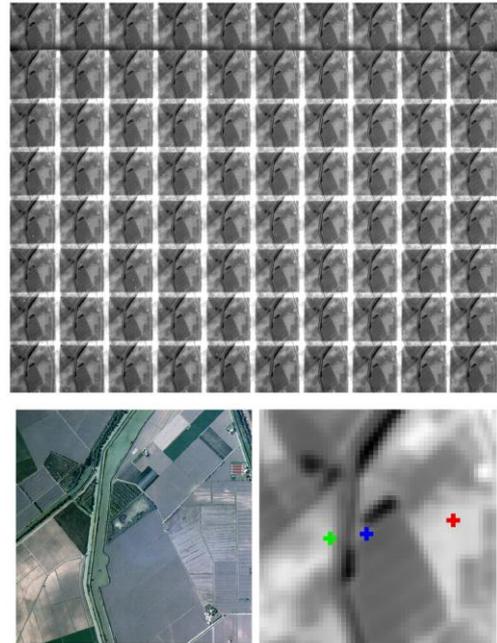


Figure 6. Top: raw image acquired by Nanocarb CO₂ camera. Bottom: on the left, image from the context visible camera, and on the right the Nanocarb “panchromatic” image (sum of all the thumbnails). The coloured crosses indicate the point, the interferogram of which are plotted on Figure 7.

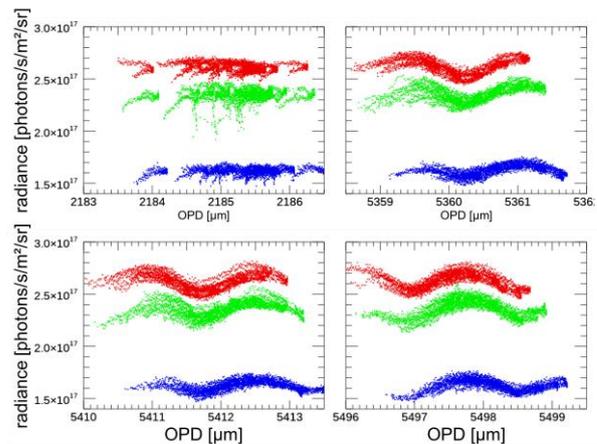


Figure 7. Interferograms of the points marked on Figure 6, after registration of multiple frames from the whole sequence. The OPD range of the top left figure is outside CO₂ signature. Some outliers appear, but are very few in number compared to the number of points.

5.1. Data acquisition

As stressed above, the October 2020 airborne campaign did not provide data with CO₂ plume. Moreover, due to the tight schedule of the project, it was not possible to perform other tests with the Nanocarb cameras. Now that we have proved that the Nanocarb cameras work properly, we plan to perform more experiments to focus on gas concentration estimation, with three steps. The first will be in laboratory, with a gas cell, so that the scene is very well known and simple, entirely described with very few parameters quasi-perfectly monitored. The second step will be observations in solar occultation configuration: the scene geometry

is still simple, but the sounded air column is more complex. We will rely on reference instruments to validate Nanocarb L2 results. The third step is to fly again over GHG plume.

5.2. Signal processing development

From a signal processing point-of-view, work will be done at L1 and at L2 levels. At L1 level, we will improve thumbnails (and possibility) frame registration. Indeed, the pixel pitch of current SWIR FPA is 10 or 15 μm . With f-number lower than 10 for instance, it means that the image will be aliased. This may cause artefacts during thumbnail registration. We will thus investigate the possibility to use super-resolution techniques for thumbnail registration and interpolation, taking advantage of the significant redundancy between the thumbnails, while paying attention to preserve the information of each interferogram.

At L2 level, speeding up of the interferogram inversion is required for a future space mission, due to the huge amount of data that such a constellation would acquire. We propose to develop methods to accelerate this inversion, for instance by performing inversion directly in the interferogram space, and possibly by coupling this inversion currently-developed deep-learning approaches.

5.3. Mission definition

From an instrumental point-of-view, the Nanocarb payload of Section 3.1 may be reviewed, building on what we have learned during the Scarbo project and on the tools we developed. Several points have to be discussed. The first one is the spectral parameters: the L2 performance estimation for the space mission showed that inversion use only few information from some spectral bands and OPD intervals. It may be more relevant to give up these bands or to redefine the Fabry-Perot parameters to focus on more informative spectral content. This work will rely on a new inversion code, called Medoc (*Modèle d'Exploitation des Données pour ImSpoc*) [30], that has been purposely developed as a design support tool for Nanocarb-like cameras.

The second point to discuss is the way to decrease sensitivity to the scene albedo. A solution could be to add either an hyperspectral imager [31], to provide lower resolution spectra but on an extended spectral interval, or at least a single spectral band close but outside the absorption band of CO_2 and CH_4 , to provide information about albedo decorrelated from GHG concentration. This may be obtained with an additional imager, or by dedicating one or a few thumbnails from Nanocarb to such a spectral band. There again, a tool like Medoc will be useful to validate the relevance of these additional spectral bands.

Thirdly, polarization effects must be tackled: at present, they are only second order effects in relation to Nanocarb development, but for a future space mission they have to be carefully evaluated.

Lastly, we are currently investigating the gain brought by hybrid payloads, combining both active and Nanocarb-like instruments.

5.4. Hardware development

As mentioned in the introduction of Section 4.1, hardware components of the current prototypes have to be improved to reach the performance required by a space mission. About the Silicon plate, more robust technological processes are being developed, like grayscale lithography process [32]. Another key component is the spectral filter. As can be seen in Table 2, the spectral bands are quite narrow. It is thus important to use filter with an effective index as high as possible, to reduce the spectral shift with the angle of incidence. A solution would be to use high refractive index material like Silicon for the multilayer coating [33].

Lastly, another key component of the Nanocarb GHG sensor is the FPA. Larger InGaAs FPA than the one used for the airborne prototypes are now available [34,35], but still with a cut-off wavelength at about 1670 nm at 20°C, thus excluding the 2066 nm CO_2 band. We will thus have to evaluate the best solution from a system point-of-view (including space qualification and cost aspects), either to give up this spectral band, to use smaller but spectrally extended InGaAs FPAs [36], or to use HgCdTe FPA like our initial hypothesis for the space mission design.

6. CONCLUSION

Nanocarb is a promising solution for compact payload dedicated to GHG monitoring. Indeed, the H2020 Scarbo project (2018-2021) proved that the association of an aerosol instrument (Spex) and of a GHG instrument based on the Nanocarb design, makes a payload well-fitted for a constellation of small satellites, with the required performance for a scientifically relevant mission (sub-daily revisit, XCO_2 random error lower than 1 ppm and XCH_4 lower than 6 ppb).

The Scarbo project was also an opportunity to experimentally develop the Nanocarb concept, with an effort led towards the manufacturing of the interferometric plate and the development of two airborne prototypes in a tight schedule. Despite the lack of airborne data over a CO_2 plume, the results are satisfactory since they prove the good functioning of these Nanocarb cameras. We plan to use them for more field tests, and to improve them, either to increase performance for CO_2 and CH_4 monitoring, or to detect other molecules, while maintaining the prospect of a space mission.

7. ACKNOWLEDGMENT

The development of Nanocarb is the fruit of a team project, involving far more people than the few listed as co-authors of this proceeding. We thus thank Mathieu Chambon, Christophe Coudrain, Roland Domel, Rémi Gouyon, Philippe Perrault, and Jean-

Baptiste Volatier from Onera, and Quentin Balmand, Jumana Boussey, H el ene Ehrhardt, C ecile Gourgon, Zoltan Hubert, and Eric Stadler from UGA.

We also gratefully thank our partners in the Scarbo project, first of all Laure Brooker and Saturnino Val Serra from ADS for the coordination of the project, Guillaume Bonnery (ADS) for the preparation of the H2020 proposition, and Matthieu Dogniaux and Cyril Crevoisier from LMD for the L2-performance estimation. During the four years of the project, the discussions with the other partners were also extremely interesting and fruitful, and we sincerely thank Safire, the University of Bremen, the SRON, and Noveltis. We also thank Pierre Rochus for his relevant comments along the project.

Scarbo project has received funding from the European Union's H2020 research and innovation program under grant agreement No 769032.

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