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# Impact of the selection of optical path differences for a spectral imager based on partially sampled interferograms

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**Abstract:** The imSPOC concept is a static Fourier transform spectral imager based on partially sampled interferograms. In this paper we investigate how the selection of optical path differences can impact the quality of the retrieved total CO<sub>2</sub> column. © 2023 The Author(s)

## 1. Context of the work

The emergence of hyperspectral concepts that are both sensitive and fast opens up new perspectives, in response to major challenges such as air quality monitoring or greenhouse gas emissions. The imSPOC concept (Patent number: FR16/56162) is a static Fourier transform spectral imager. Its compactness, robustness and lightness make it a promising concept for the measurement of greenhouse gases from space or air quality measurement. This concept is based on a paradigm shift since it allows acquiring only portions of interferograms, and not spectral radiances [1]. It is therefore necessary to transfer the optimal estimation algorithms into Fourier space: simulated interferograms are directly fit to the measured interferograms in order to retrieve total columns from its measurements. Within the framework of the European Space Carbon Observatory project (H2020 SCARBO), it was demonstrated that the relevant geophysical information (CO<sub>2</sub> column for one camera and CH<sub>4</sub> column for the other camera) is indeed present in the interferogram portions that were identified [2]. In parallel, two prototypes were built, one configured on the measurement of the CO<sub>2</sub> column, the other on the measurement of the total CH<sub>4</sub> column. To improve the designs of these cameras, it is important to have a codesign code that allows the propagation of instrumental errors to the gas columns. In order to improve future designs, the objective of the work presented in this paper is to evaluate the sensitivity of the CO<sub>2</sub> camera to the water vapor column which could be an interferent to CO<sub>2</sub>, its sensitivity to the temperature of the interferometric plate, and to give first elements on the evaluation of the impact of the step distribution of the interferometric plate which is directly related to the accessible optical path differences (OPD).

## 2. MEDOC, a codesign tool dedicated to imSPOC concept

The definition of the instrumental design requires to model correctly the instrumental response by taking into account many parameters, among which we can quote (i) the temperature of the interferometric plate, since this one has a direct incidence on its refractive index and thus on the optical path difference, (ii) the incidence angle of the ray as a function of its position on the thumbnail image, (iii) the position of the spectral filter and its width at half height, and (iv) the accessible OPD accessible  $\delta$  as a function of the thickness of the steps of the plate. This model is used to calculate the spectral transmission  $T_{cav}(\delta)$  of the plate. The associated integrated luminance  $I(\delta)$  can then be calculated as the radiance transmitted by the cavity integrated over the entire spectrum for a given OPD  $\delta$ :

$$I(\delta) = \int_{\sigma_{min}}^{\sigma_{max}} L(\sigma) F(\sigma) T_{inst} T_{cav}(\delta) d\sigma$$

Where  $L(\sigma)$  is the spectral luminance at the sensor input,  $F(\sigma)$  is the spectral response of the interference filter, and  $T_{inst}$  is the total instrument transmission of the instrument. The spectral luminance at the sensor input is calculated with a radiative transfer code (LBLRTM in the example that is presented here). The calculations were made for a solar occultation geometry. The atmospheric profile is the AFGL "US standard" profile. The MEDOC code, which acronym means "Model for IMSPOC design and data exploitation" was developed for this purpose. It allows coupling the input spectral radiances to the spectral imager instrumental response, and optimizing the instrumental parameters by minimizing their bias on the gas columns.

## 3. Methodology

The work focuses on the central pixel. Five configurations, represented on Fig. 1 have been tested. The first configuration (a) corresponds to the first airborne prototype: 80 steps are distributed to sample 4 times the same interference fringe which is insensitive to CO<sub>2</sub>, then to sample successively 4 times 3 interference fringes that are sensitive to CO<sub>2</sub> (Fig. 1 (e) and black dots in Fig 1(f)). Designs (b) to (d) correspond to 60 steps that can be realized with a new etching process allowing to sample 7 successive interference fringes but for which the step thickness is

poorly controlled and therefore irregular. Several configurations have been tested and the results are discussed below.

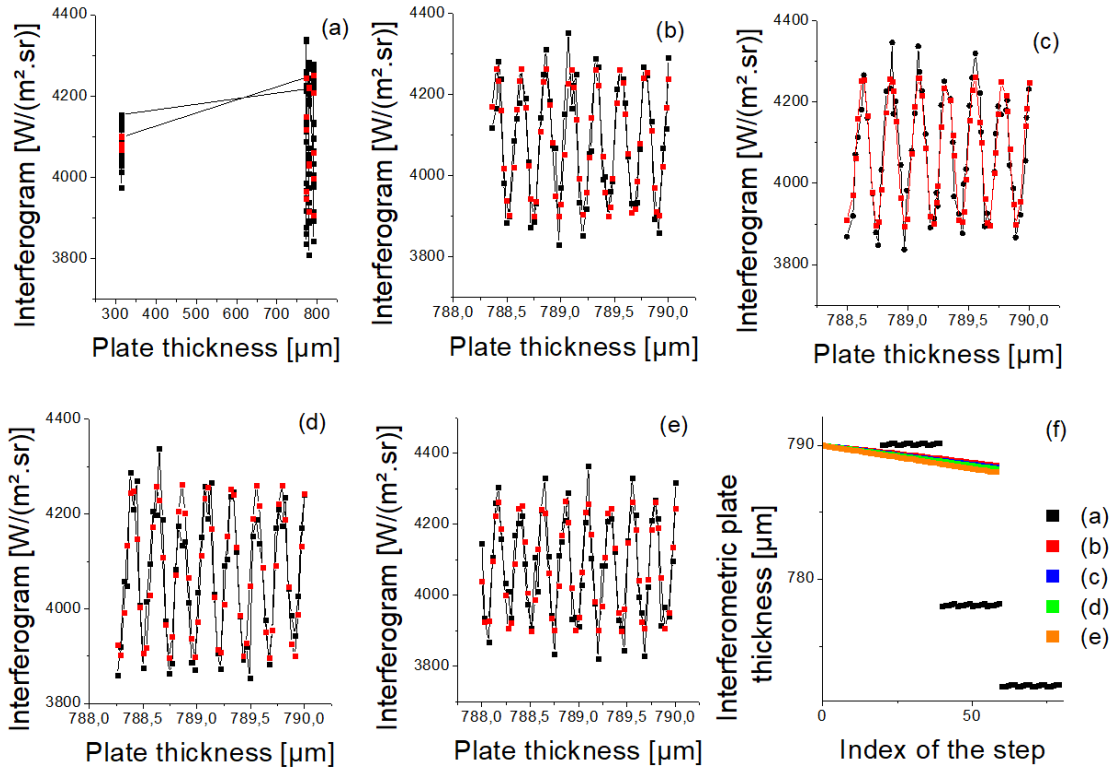


Fig. 1. (a) The step distribution as defined for the airborne prototype, (b) to (e) 5 realistic step distributions have been tested. The black curves give an example of noisy interferograms with a realistic signal-to-noise ratio and the red curves correspond to the fitted interferograms.

#### 4. Main results, conclusion and outlooks

To evaluate the impact of the parameters on the performances of CO<sub>2</sub> column restitution, a Levenberg Marquardt algorithm is coupled to the direct model. 100 iterations corresponding to the same interferogram with a different random noise have been performed. Statistics on the retrieved parameters are discussed below, as well as the average errors returned by the minimization algorithm for all the draws. The free parameters are the temperature of the plate and the CO<sub>2</sub> total column. For this study, no constraint on their variation range is applied and the minimized merit function is the quadratic difference between the noiseless interferogram and the noisy interferogram. The study showed that, with all the studied designs, the camera was not sensitive to a perturbation of the water column: a 20% disturbance of the total column of water vapor only disturbs the mean value returned for the CO<sub>2</sub> column by 1.5e-2%, which is 50 times smaller than the error bars associated with the CO<sub>2</sub> column by the inversion algorithm. In solar occultation setup, the results obtained are better for the configuration (a) for which we restore a total column that differs from the true value by 1.7 e-2 % with associated error bars of 1.8%. For the configurations (b) to (e), the absolute value of this deviation from its true value is on average 15 times higher, and the associated error bars are about 14% higher, without a real trend emerging between the different configurations. On the other hand, configurations (b) to (e) allow retrieving the temperature of the plate with a precision better than 0.2 % while this precision is 2 times greater with the configuration (a). This can be attributed to a better distribution of steps along the interferogram, but the results still need to be consolidated, by optimizing the step distribution, by treating more atmospheric situations and line of sight geometries.

[1] S. Gousset, L. Croizé, E. Le Coarer et al., “NanoCarb hyperspectral sensor: on performance optimization and analysis for greenhouse gas monitoring from a constellation of small satellites”, CEAS Space J., 11, pages 507–524 (2019)

[2] M. Dogniaux, C. Crevoisier, et al., “The Space CARBOn Observatory (SCARBO) concept: Assessment of XCO<sub>2</sub> and XCH<sub>4</sub> retrieval performance”. Atmospheric Measurement Techniques Discussions, 1-38.