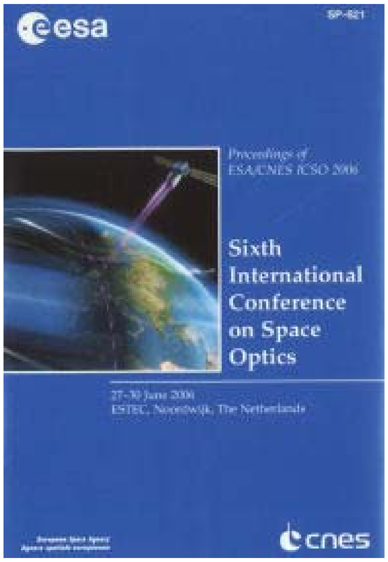

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FIRST CHARACTERIZATION OF A STATIC FOURIER TRANSFORM SPECTROMETER

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ABSTRACT

A new instrument concept for a Static Fourier Transform Spectrometer has been developed and characterized by CNES. This spectrometer is based on a Michelson interferometer concept, but a system of stepped mirrors generates all interference path differences simultaneously, without any moving parts. The instrument permits high spectral resolution measurements (≈ 0.1 cm^{-1}) adapted to the sounding and the monitoring of atmospheric gases. Moreover, its overall dimensions are compatible with a micro satellite platform.

The stepped mirrors are glued using a molecular bonding technique. An interference filter selects a waveband only a few nanometers wide. It limits the number of sampling points (and consequently the steps number) necessary to achieve the high resolution.

The instrument concept can be optimized for the detection and the monitoring of various atmospheric constituents. CNES has developed a version whose measurements are centered on the CO2 absorption lines at 1573 nm (6357 cm^{-1}). This model has a theoretical resolution of 40 pm (0.15 cm^{-1}) within a 5 nm (22.5 cm^{-1}) wide spectral window. It is aimed at the feasibility demonstration for atmospheric CO2 column measurements with a very demanding accuracy of better than 1%.

Preliminary measurements indicate that, although high quality spectra are obtained, the theoretical performances are not yet achieved. We discuss the causes for the achieved performances and describe foreseen methods for their improvements.

Key words: spectrometry; CO2; characterization; Static Fourier Transform Spectrometer.

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1. INTRODUCTION

CO2 is the main contributor to the global warming [1]. For a better understanding of the carbon cycle, there is a need to monitor current carbon fluxes at regional scales. This can be achieved with a dense sampling of atmospheric CO2 concentration, together with the knowledge of atmospheric transport. The dense sampling of CO2 can only be achieved through spaceborne remote sensing. However, it has been shown [2] that the satellite column concentration measurement must have a minimal precision better than 1 % to improve the current knowledge based on the sparse but very accurate ground measurement network.

Static Fourier Transform Spectrometry offers promising prospects to comply with the requirements of accurate measurements and compactness. Indeed, the concept presented in this paper enables to obtain precise measurements and furthermore to make these measurements onboard a satellite (dimensions and weight are compatible with a micro satellite platform). By limiting the spectral window to a narrow band sensible to CO2, one can reduce the amount of samples needed for the measurement and consequently use a static configuration. Finally the Static Fourier Transform Spectrometer has smaller dimensions and a more simple operation than a classical Fourier Transform Spectrometer.

CNES has developed a breadboard of this new kind of Static Fourier Transform Spectrometer in order to confirm the compatibility of the concept with the measurement of atmospheric CO2. The short term objective is to characterize and optimize the current configuration and then to sample a full year of atmospheric column concentration over our laboratory. A comparison to the concentration estimates derived from atmospheric transport models will be used to quantify the information content of the remote sensing measurements, and therefore to evaluate the instrument concept.

In the following, we present in more detail the interferometer and evaluate its characteristics based on laboratory and atmospheric measurements.

2. THE SPECTROMETER AND THE BREADBOARD

2.1. Description of the spectrometer and of its concept

2.1.1. Concept theory

The spectrometer developed by CNES relies on an innovative principle patented by Paul Vermande, CNES [3]. This principle consists in limiting the measurement spectral band so as to limit the sampling frequency and thus the required number of samples to achieve a given resolution. A limited number of interferogram samples makes it possible to use a static instrument, where stepped mirrors are used in place of a moving mirror as in classical Michelson interferometer.

This concept is based on the generalized Shannon theorem in the case of a narrow spectral band. Generally, to calculate the sampling frequency of a signal we refer to the maximal frequency of this signal. This approach is correct to acquire the signal in a spectral window whose limits are the null frequency and the maximal frequency. In this case, the minimal sampling frequency is $f_{samp} = 2 \times f_{max}$. In the case of a measurement within a narrow spectral band, which corresponds to absorption measurement in gas absorption lines, the generalized Shannon theorem states that the deciding factor is the width of the spectral interval of interest. The minimal sampling frequency is: $f_{samp} = 2 \times \Delta f$. The benefits to ease the measurement sampling become clearly valuable when the spectral width is much lower than the maximal frequency of the signal measured. Then one can considerably reduce the number of samples for the required resolution. For example, for the atmospheric CO2 measurement at 1.573 μm (6357 cm^{-1}), the acquisition of the whole spectral window would have required a sampling frequency of 2×6357 cm^{-1} $= 12700$ cm^{-1}, i.e. a sampling period equal to 0.8 μm (compared to the 150 μm optical thickness of the stepped mirrors). Therefore the constraints of sampling are considerably reduced for measurements in a narrow spectral band. With such sampling periods, a static measurement using stepped mirrors becomes possible.

The main advantages of a static measurement are i) to make the operation of the spectrometer easier, ii) to reduce the probability of failure due to the movement of a mirror and, iii) to obtain a compact and light instrument. These are major advantages when the instrument is designed for spaceborne observations.

2.1.2. The spectrometer

The design of the spectrometer is specially adapted to the measurement of integrated CO2 columns. After inversion, the measurements would provide the CO2 integrated concentration within the atmospheric column [4]. The concentration estimate relies on the absorption spectrometry technique.

The spectrometer is centered on a CO2 absorption line at 1573 nm (6357 cm^{-1}). Its analyzing window is 5 nm (22.5 cm^{-1}) wide. A spaceborne measurement would collect sunlight after a double atmospheric path. The depth of the absorption lines on the measured spectrum is directly related to the amount of CO2 along the light path, and therefore to the CO2 column concentration. Although the ground breadboard discussed in this paper collects sunlight after a single path in the atmosphere, the spectral signatures of the radiances are expected to be very similar to what a spaceborne instrument would collect.

For both the surface and spaceborne measurements, the spectrometer targets a square scene of 0.6 ° × 0.6 ° on infinity. The light flux comes into a classical Michelson interferometer except that the moving mirror is replaced by two fixed stepped mirrors (Fig. 1). The dimensions of the pupil of the spectrometer are 96 mm × 76 mm. After the interferometer the interference fringes are filtered and measured with a CCD camera. The camera has a telecentric lens which limits rays incidence on the filter and an InGaAs array detector. The filter is an interferometric thin layer filter of 5 nm wide. For the whole scene, an interferogram is obtained and the corresponding spectrum is derived through an inverse Fourier transform. The inversion of the spectra provides the CO2 concentration on the atmospheric column.

The spectrometer records interferograms composed of 456 samples (19 × 24 steps on the stepped mirrors). The sampling period is 150 μm, it corresponds to the optical height of the steps. A part of the interferogram is symmetrical (negative path differences). The maximal path difference is 6.5 cm. Such a sampling period permits, in theory, to derive measurements on a 30 cm^{-1} spectral window. For reasons of sampling conditions and for practical reasons linked with resampling, the spectra measured are contained in 22.5 cm^{-1}. Measurements are therefore oversampled. With a maximal path difference of 6.5 cm the theoretical resolution without apodization is 0.15 cm^{-1} which would allow to obtain 3 points by absorption line.

2.1.3. The rest of the breadboard

The CNES laboratory of spectrometry has developed the means to characterize and calibrate the spec-

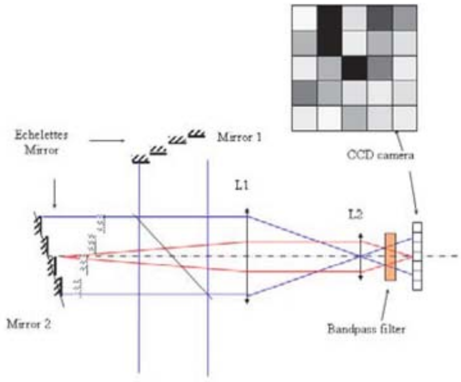

Figure 1. Principle diagram of the breadboard.

trometer. A mirror can be moved thanks to a nanometric motorized linear stage. This movement allows to test different configurations of measurement and to jam the fringes of interference for the uniformity calibration.

On the breadboard an area is dedicated to artificial light sources. We can use a monochromatic source (a tunable laser emitting in the whole band of the spectrometer) or a wide source (an incandescent lamp). The light is sent to an integrating sphere whose port is collimated to the infinity. Finally, the natural light source (the sun) can be targeted through the proper orientation of a mirror.

3. CHARACTERIZATION OF THE SPECTROMETER

The characterization is a part of the measurement procedure. Calibration and characterization are made before and during each interferogram acquisition. The quality of the measurements is quantified through the Signal to Noise Ratio (SNR). Theoretical computation states that the resolution of the spectrometer should be approximately 0.04 nm (0.15 cm^{-1}). This theoretical resolution is the inverse of the maximal path difference, it does not take into account neither the sources of noise nor the apodization (a triangular apodization is applied to the interferograms). The resolution of the spectrometer is reduced by several sources of noise whose main contributions derive from the photonic noise, the electronic noise (the photonic noise and the electronic noise are gathered in the radiometric noise) and the sampling noise.

3.1. Radiometric noise

As for any optical measurement, radiometric noise includes both the photonic noise and the electronic noise.

Moreover some other effects of stray light, specific to the spectrometer, can also produce systematic noise. Characterization of this kind of noise is in progress.

The radiometric noise is evaluated thanks to indirect methods. For example, in a lamp interferogram, the last samples are expected to have a null usable signal (once the mean subtracted). The ratio between the standard deviation and the mean of the signal on these last samples provides SNR on the interferogram.

The radiometric noise could be reduced by increasing the aperture of the spectrometer or by using a longer integration time. The modifications must be compatible with space applications (weight, movement. . .). Moreover the radiometric noise is less predominant than the sampling noise.

The first calibration shows a SNR for the interferogram better than 2000, which is compliant with the specification. Some improvements are tested to increase the SNR to 3000.

3.2. Sampling noise

The sampling noise has two sources: the resampling of the interferogram into a regular one and the thermal fluctuations.

- Intrinsically the sampling of the interferograms is not regular: the technique of construction of the stepped mirrors cannot ensure the regularity of the steps better than 1 μm. These defaults cannot be neglected from a point of view of the interferometric application. Yet it is possible to measure the irregularities in order to correct them with an interpolation so as to obtain a regular interferogram. The numerical Fourier transform applied to the interferograms need regularly spaced samples and the resampling tends to amplify the noise, with a net effect of decreasing the interferogram quality. A good choice of resampling parameters produces a noise amplification lower than 1.1 (10 % of increasing).
- The spectrometer is not thermally stabilized (it is simply placed in an air-conditioned environment). The thermal variations of this environment dilate the optical components, particularly the mirrors. The amplitude of the dilatations cannot be neglected. Yet, contrary to the defects of construction, this error

is not measurable before interferogram acquisition. These thermal fluctuations are constantly varying whereas the defects of construction are the same for all measurements. The temperature of the laboratory and of the interferometer is monitored to evaluate the foreseen quality of the measurements. Although the thermal fluctuations are significantly smaller than the defects of construction (around 1 nm), they have a strong impact because they are not monitored and cannot, therefore be corrected in the interferogram processing. Our results indicate that the thermal noise is the main source of noise for the acquisition of spectra.

To overcome this major difficulty, we are developing a system for the monitoring of the path differences simultaneously with the interferogram acquisitions. This system would use the absolute measurement of the path differences as a reference and would provide the relative variations corresponding to each spectrum measurement. The method for monitoring the path differences uses an interferometric system. The interferogram of a laser diode is regularly acquired and compared with a reference laser interferogram: the thermal fluctuations modify the state of interference in a way representative of the fluctuations. Such system is currently evaluated with our tunable laser, but cannot yet be operated simultaneously with the interferogram acquisition.

4. SPECTRA AND PROSPECTS

4.1. Laser spectra

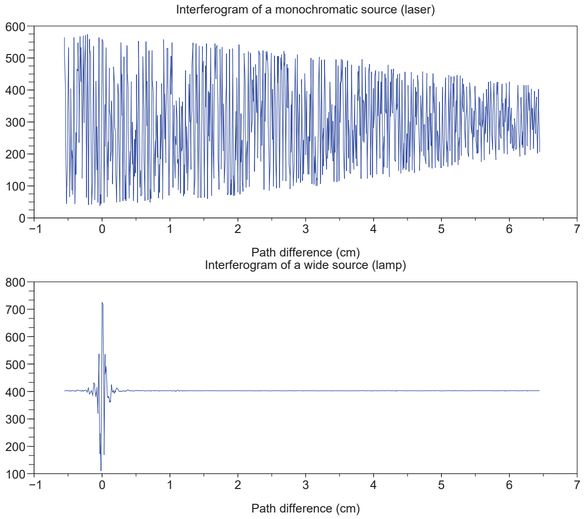

Figure 2. Interferograms of a monochromatic source (top) and of a lamp (down).

The theoretical interferometer through a Michelson interferometer of a monochromatic source is a sinusoid. Here the sinusoid is modulated by a decreasing function owing to the field of the spectrometer (Fig. 2). Fig. 3 shows a spectra obtained in front of a laser at 1573 nm (6357 cm^{-1}). The laser is announced to have a resolution of 0.1 pm (0.4×10^{-3} cm^{-1}). Thus the width of the line in the spectrum is due to the resolution of the spectrometer. On this spectra the resolution is approximately 0.15 nm which corresponds to a resolution of 0.6 cm^{-1} for a theoretical resolution of 0.15 cm^{-1}. Up to now we obtain a maximal Signal to Noise Ratio of 500 for laser spectra.

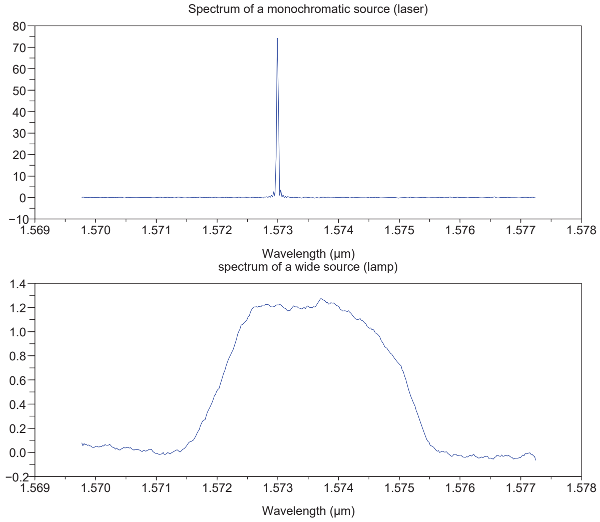

Figure 3. Spectra of a monochromatic source (top) and of a lamp (down).

4.2. Lamp spectrum

Like a CO2 spectrum, a lamp spectrum stretches on the whole spectral window. Because of the width of a lamp spectrum the interferogram decreases rapidly with the path difference (the fall of contrast due to the field of the spectrometer is now negligible) (Fig. 2). Fig. 3 shows a lamp spectrum. More exactly we show the spectrum of the lamp provided by the spectrometer through the bandpass filter. Therefore a lamp spectra is very close to the shape of the filter (a lamp have a flat spectra). Up to now we obtain a maximal SNR of 100 for the lamp spectra.

4.3. CO2 Spectrum

A CO2 measurement is far more difficult to manage. Indeed, the source (the atmosphere) is not a controlled source. The first difficulty lies in the

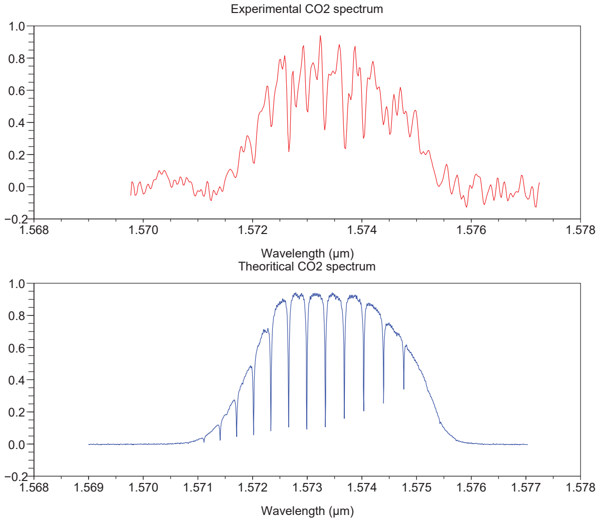

Figure 4. CO2 spectrum measured (top) and theoretical CO2 spectrum (down). The reasons for the poor quality of the experimental CO2 spectrum have been identified. The spectrometer has been realigned, therefore we expect to improve significantly the quality of the next spectra we will obtain and present.

knowledge of atmospheric conditions (clear sky is required). Second, we use a scattering board to reflect the sunlight to the laboratory. The optical properties of the board are not fully known. By directing the board we try to compensate the movement of the Sun in the sky due to the rotation of the Earth. The CO2 spectrum we present (Fig. 4) looks very noisy. A reason of the poor quality of the spectrum may be the fact that the spectrometer has been calibrated through a non suitable optical path. Indeed, the breadboard has one optical path dedicated to atmospheric measurements and one optical path dedicated to artificial sources measurements. Calibration of the spectrum (more precisely the calibration of the uniformity of the detector array) has been performed through the artificial sources path whereas the spectrum itself has been acquired through the atmospheric path. Consequently the atmosphere measurement is not corrected with the appropriate data (some corrections for the artificial sources may degrade outdoor measurements). Eager to see a CO2 signature, we decided to retrieve the spectrum from the interferograms. Although the result (Fig. 4) cannot be used to monitor CO2 with the proper accuracy, it is rather encouraging. Indeed despite measurement defects the spectra presents the same pattern as a theoretical spectrum with much noise. In particular we observe the CO2 absorption lines at the same wavelengths. Among the defects the stepped mirror array clearly seems to be shaded (Fig. 5): one can note the periodic perturbation particularly for the highest path differences which is probably due to the shade of a component. A recent realignment of the components of the spectrometer suppressed this problem but no atmospheric spectrum has since been acquired. Uniformity will be calibrated with the scattering board during the forthcoming CO2 measurements. We expect consequently a better quality of spectra for the next CO2 measurements.

4.4. Prospects

Several improvements of the spectrometer are planned. A completely molecular bonded interferometer is being built so that all optical components (not only mirrors) will be molecular bonded to the stand. The interferometer will have smaller dimensions (no more tunable mounts nor motor) and will be mechanically more stable. Finally the primary focus will be the reduction of the thermal deformations. In order to measure the thermal deformations a system is being defined. It will permit the monitoring of the path differences simultaneously with the measurements. Consequently interferograms will be reconstructed more precisely. The procedure of measurement of atmospheric CO2 will be completed and automatized. A campaign of measurement along one year is planed. Its objective is to record an annual cycle of atmospheric CO2 column concentration and to confront it with the results of atmospheric models in order to determine whether the spectrometer is adapted to a space measurement of CO2 column.

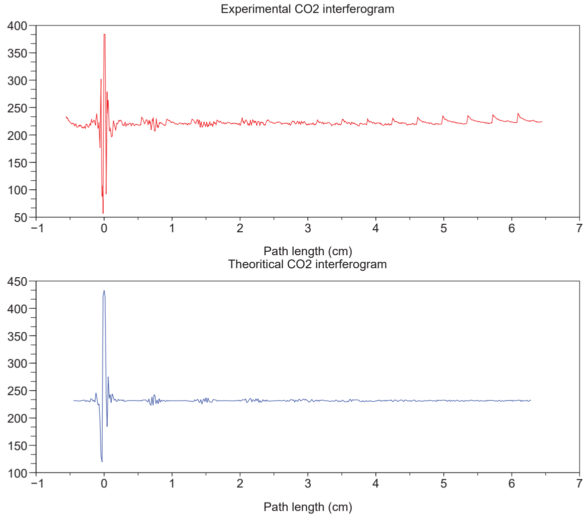

Figure 5. Measured CO2 interferogram (top), note the periodic perturbation particularly for the highest path differences which is probably due to the shade of a component. Theoretical interferogram (down).

Table 1. Performances of the spectrometer

Data type	**Measured SNR**	**Objective**
Lamp interferogram	$\geq$ 1000 (2000 at high path differences)	1000 to 2000
Lamp spectrum	100	150
Laser spectrum	$\geq$ 500	1000 to 2000

5. CONCLUSION

The Static Fourier Transform Spectrometer developed by CNES is really promising. It should enable to provide remote sensed measurements at low cost thanks to a simpler operation than the operation of the classical spectrometers. These prospects need to be confirmed by experimental measurements.

ACKNOWLEDGMENTS

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