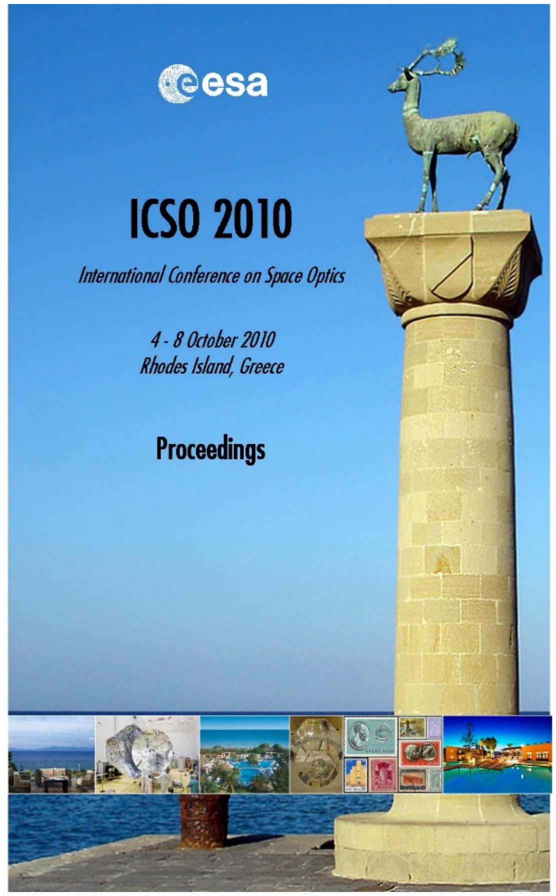
# International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

*Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas*

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International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105655F · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2552111

# CONCEPTION AND DEVELOPMENT OF A STATIC FOURIER TRANSFORM SPECTROMETER BREADBOARD

F. Brachet[1], C. Buil[1], L. Roucayrol[1], E. Baldit[1], E. Cansot[1], L. Soulat[1]
[1]*Centre National d'Etudes Spatiales, 18 avenue Edouard Belin, 31401 Toulouse cedex 09, France*

## I. INTRODUCTION

Global atmospheric chemistry monitoring from space is a key to follow up air quality and provide the repeatable global coverage needed to explain the different mechanisms explaining global warming effects. Space observations with high revisit frequency allow following air mass and pollution clouds movements, both over continents and oceans.

Whereas sounders like IASI (Infrared Atmospheric Sounding Interferometer) on board MetOp satellite are mostly designed for meteorological applications, CNES started studying alternative concepts to dedicate new instruments to some selected molecular species. A patent released in 1998 by CNES [1] is at the basis of a static configuration of Michelson interferometers, sampling each interferogram at once. New perspectives to reduce existing instruments in terms of mass, volume and complexity and to create constellations of small satellites or micro-satellites were opened.

CNES either proposed this concept for $CO_2$ concentration monitoring (Carbosat and Minicarb missions) in the near infrared or CO and $O_3$ atmospheric profiles retrieval (SIFTI instrument on TRAQ mission [2]) in the thermal infrared. Though TRAQ was finally not selected by ESA, a validation of this concept has been undertaken in parallel with SIFTI phase A studies with the development of a breadboard called MOPI (which stands for 'Maquette Optique de Performances Infrarouges' in French, approximately translated into 'Optical Breadboard for Infrared Performances').

In this paper, we will first describe the instrumental concept. The second part will detail the different conception choices made to design MOPI and, finally, the third part will present the next steps awaited for this breadboard.

## II. THE CONCEPT OF STATIC FOURIER TRANSFORM SPECTROMETER

The concept developed by CNES for several years now is based on a modified Michelson interferometer with a pair of staircase mirrors. Using staircase mirrors instead of plane mirrors as in the classical configuration both releases the constraint of development of a high frequency sampling mechanism and the need for smearing compensation due to a temporal acquisition. The interferogram is acquired spatially in one go with a detection matrix.

As a matter of fact, the two crossed staircase mirrors form an OPD array. This interferometer can consequently be seen as a multitude of small classical Michelson interferometers at a fixed OPD in parallel. The OPD array is then imaged on a detector array adapted to the spectral band, as shown on Fig. 1.

The key element in the interferometric core is certainly the two staircase mirrors, assembled by molecular adhesion. Each assembled glass plate and thus each facet can be positioned with a +/- 2 µm *rms* accuracy. The interferogram is therefore irregularly sampled and cannot be directly inversed with Fourier transform. A re-sampling processing, as exposed in [3], is necessary, requiring a nanometric knowledge of each facet position. These OPD measurements can be obtained thanks to an on board metrology laser or extrapolated from on ground calibration, assuming a solid behavior of each mirror. For more details on the concept, see [4].

## III. MOPI BREADBOARD CONCEPTION AND DEVELOPMENT

MOPI can be seen as a functional breadboard of SIFTI instrument. Considering the beginning of SIFTI's phase A in parallel with the conception of MOPI and the delivery time of one year for its main elements (staircase mirrors, lenses, detector …) some choices have been anticipated and have necessarily led to a limited representativeness of the breadboard towards the instrument resulting from the phase A.

MOPI's objectives are mainly to establish the impact of thermal infrared specificities on the concept. Among them, physical phenomena such as diffraction, which was negligible in the near infrared, are of major importance in the thermal infrared with the small apertures represented by the mirrors facets. Such optical phenomena are not easy to model since this concept mixes both interferometry and imagery with radiometry. MOPI breadboard is also a test bench dedicated to calibration procedures testing. It will consequently remain evolving, by means of discrete opto-mechanical elements. Calibration is one of the difficulties of this concept, since this static interferometer is necessarily imperfect and needs a detector array. Pixels response non uniformity becomes crucial to distinguish between instrumental response and scientific phenomena. OPD measurements are also necessary to compensate for irregular OPD sampling and retrieve spectra from interferograms with an inverse Fourier transform. Different calibration measurements have consequently to be done before and after each scientific measurement.

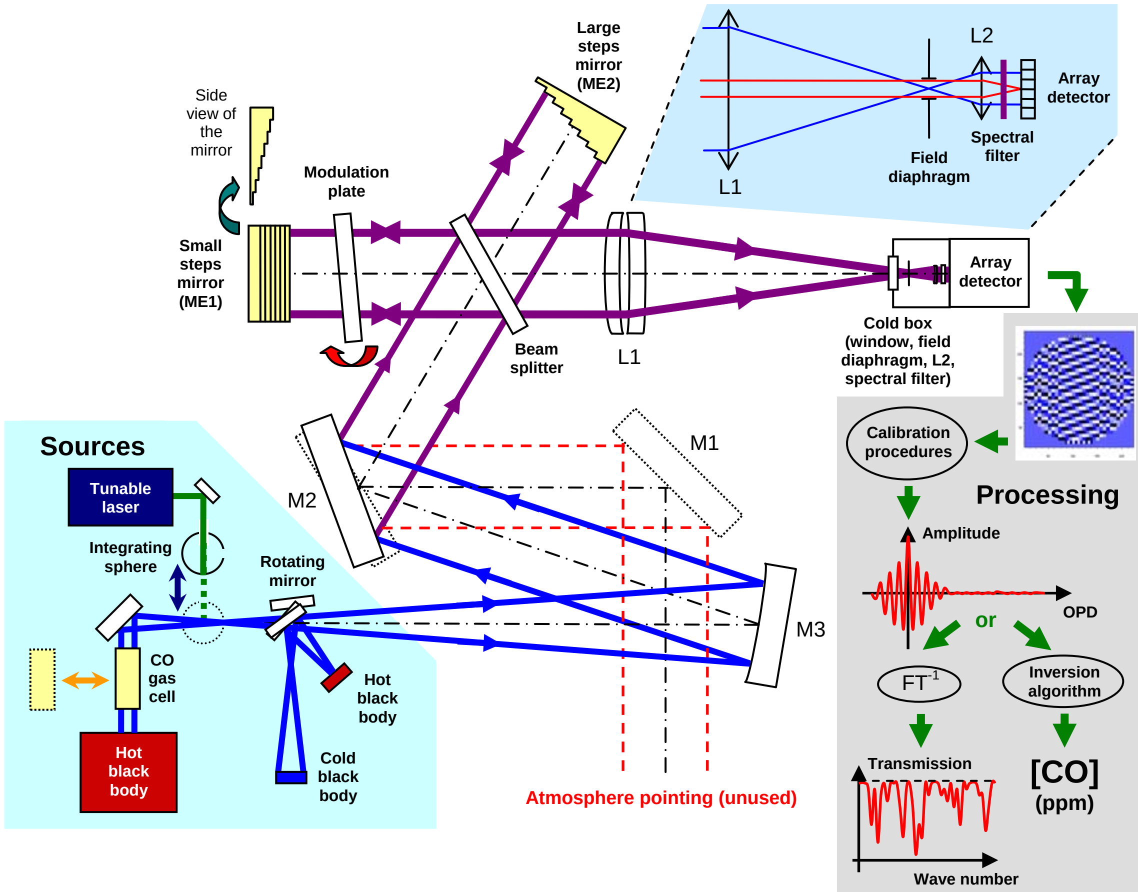


**Fig. 1.** Complete optical system schematics of MOPI breadboard. The OPD array is imaged on the detector *via* the afocal combination of L1 and L2 lenses. The field diaphragm selects the viewing angle of the system and thus the on ground pixel size. To homogenize the filter response for all the facets images, the filter has been placed in a telecentric position. As in classical Michelson interferometer, a compensation plate is added in one of the interferometer arm to compensate the beam splitter's thickness and allows phase modulation. The different sources are represented on the lower left corner, whereas the processing is on the right, to retrieve either spectra and/or CO concentration from the interferograms.

The two spectral bands of SIFTI's instrument have been restricted to the single B2 band around 4.6 µm (corresponding to CO) for MOPI. Environmental background's influence in B1 band (around 9.6 µm) would have required cooling the whole breadboard down to a cryogenic temperature. In the B2 band, only one lens, the spectral filter and the field diaphragm have to be cooled down.

Let's see now each principal element of this bench in more details (see the picture on Fig. 3).

Light sources: atmospheric measurements by pointing the self-emitting atmosphere in the infrared were originally intended. For the sake of repeatability of the measurements, reference sources were preferred. They consist in CO gas cells with a black body. A set of gas cells has been filled and characterized with different calibrated concentrations. A tunable laser centered in B2 band has also been provided for OPD measurements, spectral characterizations and instrument function measurements. Its wavelength is continuously monitored thanks to a wavemeter.

Staircase mirrors: they are made of 30 x 30 steps of Zerodur assembled with molecular adhesion. The two mirrors are different to create a regular OPD progression of 8 cm. One mirror consists in small regular steps, which height defines the sampling period of the interferogram, whereas the mean height of the large steps of the other mirror is equal to the range of the small steps. Only the mean height since the progress is irregular to create a circular pupil (technological validation). Fig. 3 shows a simulation of MOPI pupil with a laser source.

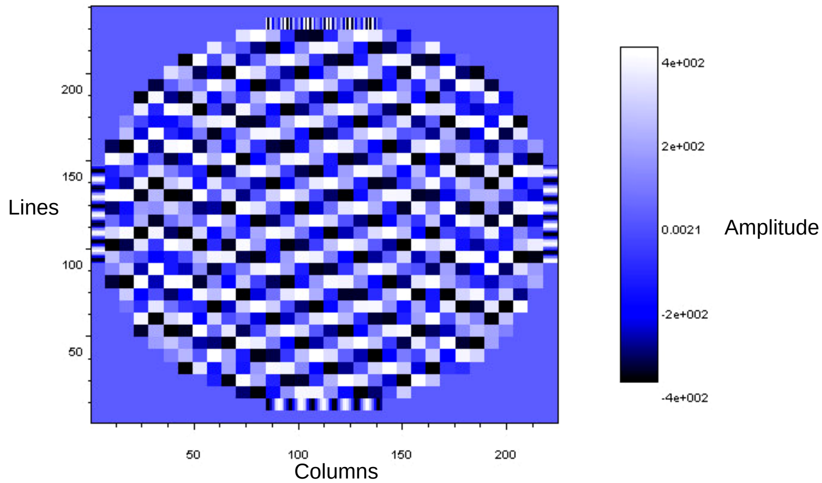


**Fig. 2.** Simulation of a laser source interferogram with MOPI. Each cross section between two facets creates a sub-pupil corresponding to one point of the interferograms (mean value). In this simulation, the staircase mirrors are considered as perfect mirrors, without any tilt or OPD errors, hence a perfect contrast on each sub-pupil. Zero Path Difference is located on the center line, on the left. The pupil has been chosen circular and is surrounded by tilted plates (partly visible on each side) for calibration procedures.

Detector and cold box: a 320 x 256 HgCdTe detector has been supplied with a 30 µm pitch. Its window has been removed when connecting the detector with a specific cold box dedicated to cool the nearest optics down to liquid nitrogen temperature.

Optics: while mirrors are classically made of Zerodur, the beamsplitter and the different lenses of the afocal are made of ZnSe or ZnS with antireflective coatings. With a pupil of 100 mm, they are necessarily bulk and have required specific mechanics. Considering the compensating plate, its mount has been put on a commercial rotating stage in order to allow phase modulation. In fact, phase modulation was identified as a way to reduce inter-pixel offsets, stray light fluctuations and more generally noise effects, if they can be considered as constant during measurements. Instead of a single one, four interferograms are successively acquired with a phase variation of $\lambda_{mean}/4$ in-between, where $\lambda_{mean}$ is the mean wavelength of the spectral band. Subtraction and addition of couples of interferograms allows both to reduce background effects and biases and to double the samples number. This process increases stability and performances of the reconstruction algorithm. Yet the concept loses a part of its static design. Nevertheless the complexity of a several centimeters long mechanism and a few microns piezoelectric motion system are not comparable. The benefits and means of phase modulation are detailed in [5].

Test bench and damping elements: considering the high level of stability needed for an interferometer, special care has been taken during the breadboard conception (use of super-Invar for the bench, Invar for certain mechanical parts, a seismic pod ... The breadboard is also divided into three parts separated by partitions. The first one is the interferometric core, which consists in the two staircase mirrors, the beam splitter and the compensation-modulation plate. A second zone is dedicated to detection and cold box. The third one consists in a collimator to create a uniform lighting of the staircase mirrors. It is fed with the light coming from either a hot or cold black body, the gas cell illuminated with a warmer black body or the tunable laser through an integrating sphere.

## III. NEXT STEPS

MOPI's integration is now over after some difficulties with the cold box. Each major element has been put on the bench. A few sub-systems characterizations and calibrations remain to be done before acquiring the first interferogram. A spectral characterization of the detector has also to be realized with the cold box and the tunable laser before using it. Image acquisition programs are now functional, but global calibration and acquisition procedures remain to be optimized.

MOPI should be operational for scientific measurements at the beginning of 2011.

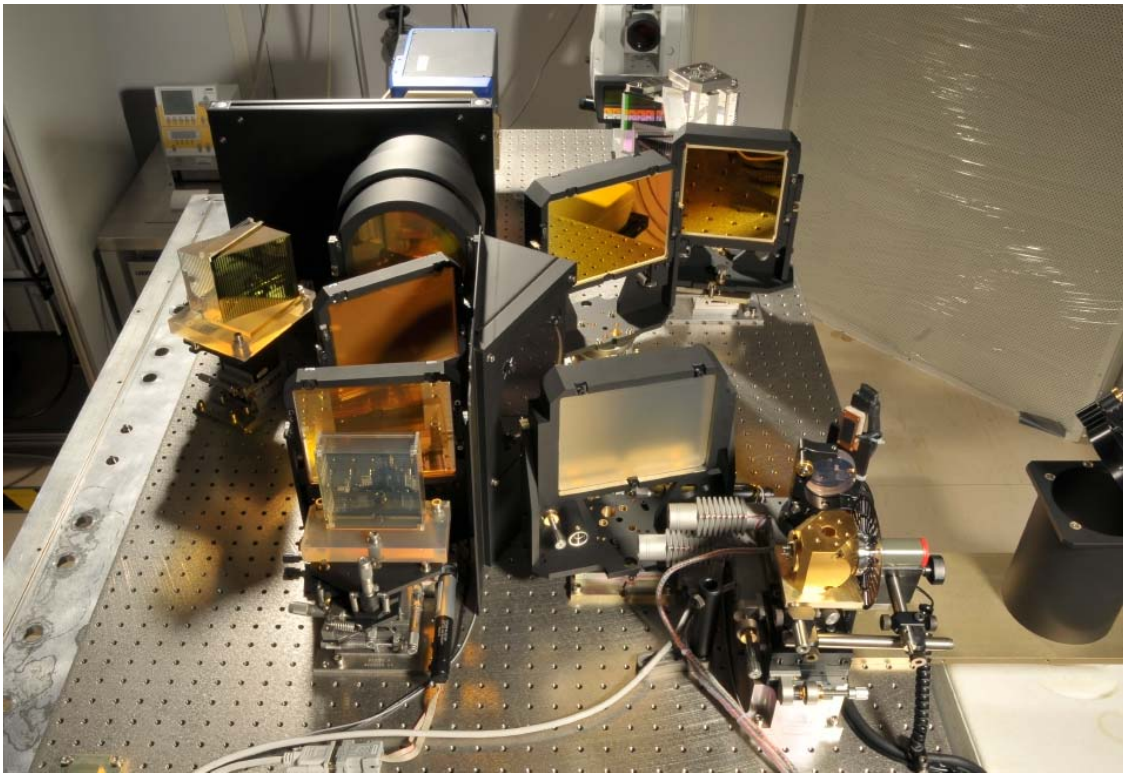

**Fig. 3.** Picture of the main bench of MOPI. The interferometric core (staircase mirrors, beam splitter and modulation plate) is on the foreground, on the left. The commercial detector used on the beginning of the measurements is on the background. The right part of the bench consists in the calibration part. The cold box was not implemented at the time the picture was taken.

In parallel, some simulations have been made to identify the impact of diffraction on the interferogram pictures. The two main effects were observed. Firstly, the diffraction between neighboring steps of one single mirror creates a grid pattern visible on the base line of the interferogram (no interferences on this part of the interferogram). Secondly, there is a diffusion of the modulated signal of a sub-pupil to its eight neighboring sub-pupils. Treating both effects in the calibration chain, including a special diffusion correction algorithm allows to manage the diffraction problem, which makes us confident concerning the concept adaptability to thermal infrared.

## IV. CONCLUSION

CNES has been developing static Fourier transform spectrometers for years now. After validating this concept in the near infrared, a new breadboard called MOPI will be soon operational to study the impact of thermal infrared specificities on the concept and compare scientific measurements with instrumental models. Physical phenomena such as diffraction will be studied, as well as correction algorithms. This concept could open new ways towards optimized instruments dedicated to a few chemical species in the context of global atmospheric chemistry monitoring from space.

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