

SIFTI : a Static Infrared Fourier Transform Interferometer dedicated to ozone and CO pollution monitoring

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Abstract

Measuring pollutant concentrations in the boundary layer of the atmosphere is a major challenge for air quality. Infrared sounding, providing vertically resolved profiles for several trace gases in the troposphere, is a must for pollution observation. In this framework, CNES is currently leading a phase-A study for SIFTI, a Static Infrared Fourier Transform Interferometer devoted principally to ozone and CO measurements in the thermal (TIR) and short-wave infrared (SWIR).

We will first describe the high-level mission requirements, including orbital considerations like the revisit frequency or the need for cloud-free observations. Instrument specifications, like spectral band position, spectral resolution, radiometric noise, are then derived from the precision needed in CO and ozone profile retrievals. The sensitivity of the profile retrievals, given in terms of vertical sensitivity and errors, to instrument performances are studied using the optimal estimation theory.

The instrument concept proposed by CNES (Centre National d'Etudes Spatiales, the French space agency), an interferometer with no moving part, based on scaled mirrors, is a simple and efficient solution to meet these requirements and obtain very high resolution spectra (better than 0.1 cm^{-1}) with a high signal-to-noise ratio. Spectra are measured within two thermal infrared bands (for CO and O₃) and one optional shortwave infrared band (for CO and CH₄) for synergetic more accurate SWIR/TIR inversion of CO profile. Thanks to an intelligent pointing mechanism based on real-time analysis of observations from an imbedded infrared imager, the probability of clear sky is dramatically increased. An optimization of the instrument, based on an irregular but well-chosen sampling of the interferogram, opens the way to still higher quality profiles.

Introduction

Measuring pollutant concentrations in the boundary layer of the atmosphere is a major challenge for air quality. Infrared sounding, providing vertically resolved profiles for several trace gases in the troposphere, is a must for pollution observation. In particular, current infrared sounders like

IASI (Infrared Atmospheric Sounding Interferometer) provide operational quantitative products for CO, ozone, and CH₄ (Turquety et al. 2004). More elaborated research products from advanced infrared sounders include molecules like SO₂, C₂H₄, CH₃O₃H (Clerbaux et al. 2008) or dust aerosols (Peyridieu et al. 2008). However, current sounders are primarily designed for meteorological and climate applications. In order to improve their ability to provide relevant data for pollution survey, CNES is currently leading a phase-A study for SIFTI, a Static Infrared Fourier Transform Interferometer especially devoted to ozone and carbon monoxide (CO) measurements in the thermal (TIR) and short-wave infrared (SWIR).

In this paper, we will first give the science objectives of a typical satellite air quality remote sensing mission. From this high-level needs, we will derive both the geometric requirements (when and where to observe the atmosphere) and the instrument requirements applying to SIFTI. The expected product performances are then shown for both the ozone and CO vertical profiles. In the last part, the static interferometric concept, the retained solution to reach the instrument requirements, is detailed.

Science objectives

The first science objective of the SIFTI mission covers the air quality and tropospheric composition on a global and regional scale. As air quality relates to human health, it focuses on mega-cities. This implies also to observe the atmosphere as close as possible to the surface. Diurnal cycle of atmospheric pollution shows very sharp variations of pollutant concentrations (e.g. for ozone). So, frequent observations (roughly every one hour) are of great interest to improve air quality forecast. The long range transport of pollutants is another key parameter for tropospheric composition.

Another major objective of the mission concerns the localization and quantification of sources and sinks of trace gases. These are determined from atmospheric models based on emissions that actually rely on still poor inventories. Satellite-based remote sensing observations of gas concentrations must distinguish between the boundary layer (from the surface to a few hundreds of meters or kilometres) and be accurate enough to bring benefit to chemistry and transport models through assimilation. Note that CO is a tracer for combustion processes and biomass burning and proves very useful for improving the estimated biomass emissions. Sinks for pollutants are mainly depending on the oxidising capacity of the atmosphere, which is controlled by ozone. CO and NO_x also play a role as ozone precursors.

The last challenge of the mission is to contribute to study the link between the tropospheric composition and global change, through the measurement of tropospheric ozone and optionally methane (30% of greenhouse effect together). Stratospheric ozone is a first importance climate variable, while CO and CH₄ oxidation is an important source of CO₂.

Geometric requirements : when, where?

The geometric requirements are driven by the high revisit frequency need. A time period of the order of one hour is necessary to monitor the rapidly evolving pollution peaks. A classical sun-synchronous orbit provides one observation every 12 hours and thus does not satisfy this need. A geostationary orbit provides this requirement for part of the globe. However, the very high

altitude of the geostationary orbit (36,000 km) reduces the radiation flux entering the instrument and significantly reduces the signal-to-noise compared with a low Earth orbit, considering a given pupilla diameter. Therefore, an original drifting orbit has been proposed by CNES. Its altitude is 720 km, and its angle with respect to the equator is 55° . Combined with a field of view spanning from -50° to $+50^\circ$ with respect to nadir, such an orbit ensures in the mid-latitudes up to 5 revisit per day (see Fig. 1). The time period between two visibility passes over the same point is 90 minutes, and the hours of passes drift by a few minutes every day, as represented in Fig. 2. Consequently, the 5 revisits span over 6 hours possibly during day-time only, possibly during both day-time and night-time, and possibly during night-time only. Together with a sampling point every 50 km at nadir, the orbit also ensures a good regional covering, adapted to the spatial variability of the pollution.

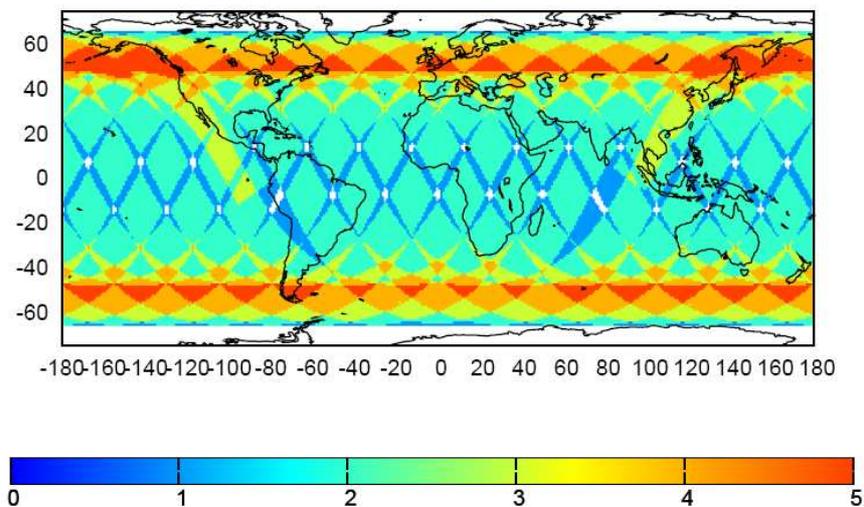


Fig. 1 : number of passes per 24 h for the drifted orbit of the mission.

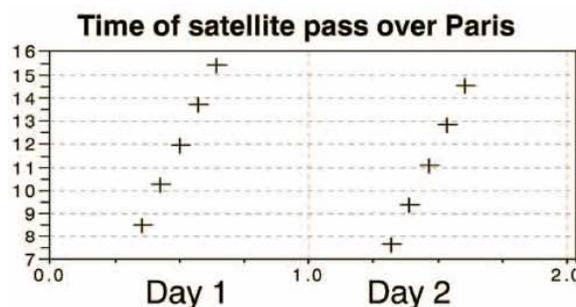


Fig. 2 : local time of the 5 satellite passes over Paris for day 1 (from 8.30 a.m. to 3.30 p.m.) and day 2.

The geolocalisation need is 1 km. It comes from the potential use of SIFTI in synergy with other instruments on the same platform, for example a UV-VIS spectrometer for NO_2 and O_3 measurement and/or a directional polarised spectrometer for aerosols. The SIFTI geophysical products must be well localised also for their use in atmospheric models.

For a given orbit, the number of useful observations is maximised through spatial sampling, a wide swath, a small pixel size (between 10 and 12 km) to reduce the risk of cloud contamination, possibly cloud-clearing algorithm (research in progress) and “intelligent

pointing”. This later strategy relies on a mechanism allowing a slight modification of the pointing direction to avoid clouds in the field of view (Fig. 3).

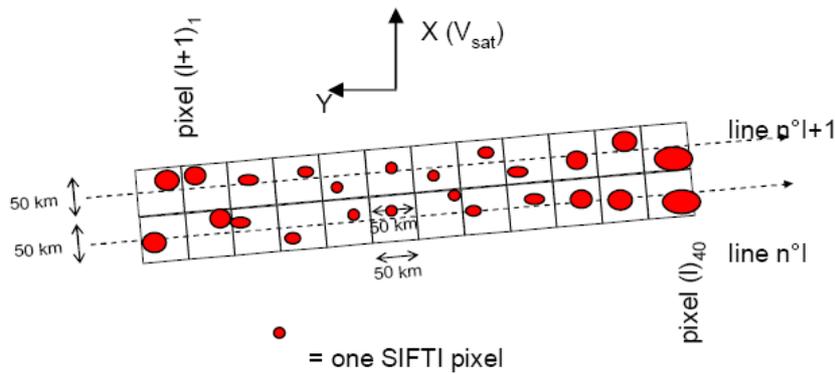


Fig. 3 : spatial distribution of SIFTI pixels using the intelligent pointing option.

An optional cloud imager, CLIM, with 2 bands in the thermal infrared domain, will provide cloud cover information within the SIFTI instantaneous field of view. Real time cloud analysis, based on these CLIM measurements, will be used to anticipate the optimal viewing direction for SIFTI with respect to this cloud cover. The potential gain in cloud-free footprints using this intelligent pointing strategy (with respect to a regular scanning pattern) depends strongly on the observed scene. For a typical orbit over Europe, the gain of intelligent pointing, evaluated thanks to a 2-bands version of the MAIA algorithm (Lavanant et al. 2007) is roughly 1.5 (see Fig. 4).

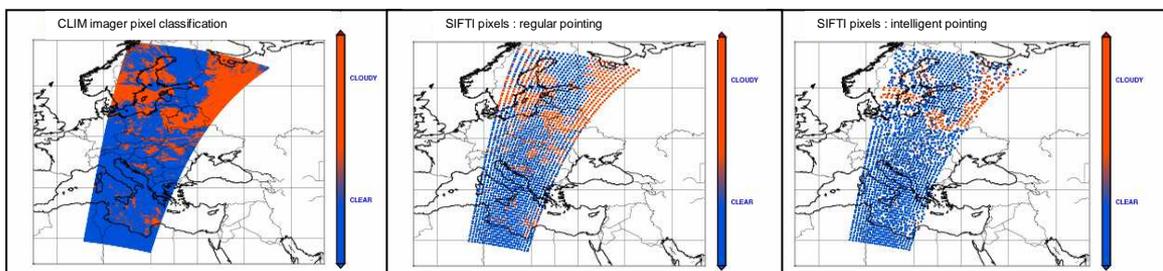


Fig. 4 : simulation of the gain of the intelligent pointing for one orbit : CLIM imager pixel classification (on the left), SIFTI pixels classification using regular pointing mode (in the middle), SIFTI pixels classification using intelligent pointing mode (on the right). Red=cloudy, blue=clear.

Instrument requirements

The spectral band position is determined by the target molecules: O₃ and CO (see Fig. 5), with some care to reduce the water vapour contamination. The SIFTI spectral band “B1” is dedicated to ozone measurement and covers 25 to 30 cm⁻¹ in the 1030-1070 cm⁻¹ range (about 9.5 μm). The SIFTI spectral band “B2” is dedicated to carbon monoxide measurement and covers 25 to 30 cm⁻¹ in 2140-2180 cm⁻¹ (about 4.6 μm). Finally, a third band, located in the short-wave

infrared domain, is studied as a possible option : band “B3” dedicated to CO and CH₄, from 4270 to 4300 cm⁻¹ (about 2.3 μm).

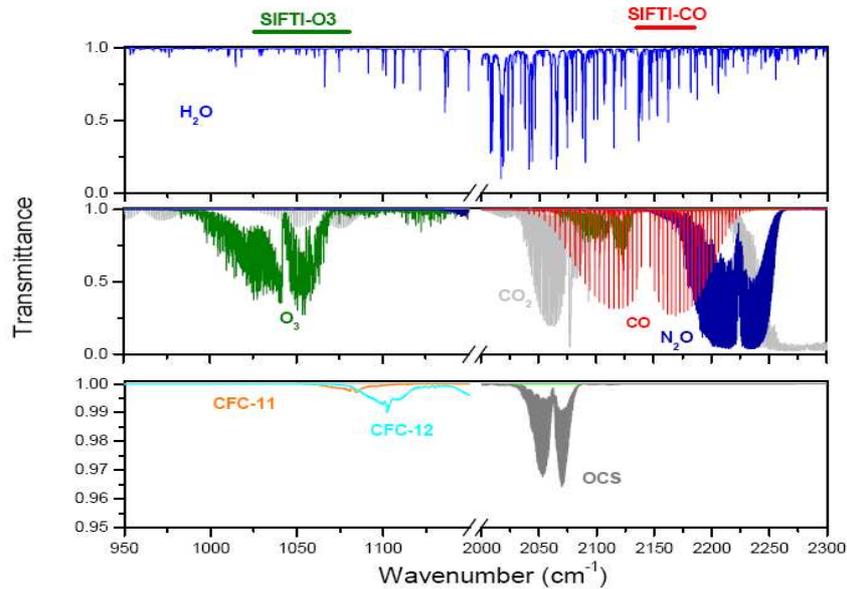


Fig. 5 : main absorbing molecules in the thermal infrared and position of SIFTI spectral bands.

The apodised spectral resolution is 0.125 cm⁻¹, the spectral sampling being 0.0625 cm⁻¹. The purpose of such a high spectral resolution is to be compatible with CO narrow lines, in order to observe the line wings and probe the lower troposphere.

Next, the instrument noise requirements are very high too: the Noise equivalent difference Temperature (NedT) at 280 K should be between 0.08 K and 0.1 K for B1, and between 0.12 and 0.2 K for B2.

Expected product performances

SIFTI is expected to produce high quality concentration profiles. The vertical resolution is such that it provides 5 to 7 independent pieces of information (DOFS, Degrees Of Freedom for Signal, (Rodgers, 2000)) for ozone, and 2.5 to 4 for CO with band B2, 1.5 for CO with band B3. It should be noticed that one of this piece of information is located in the boundary layer. The accuracy of the retrieved profile leads to a final error of the tropospheric column of the order of 4 to 14% for ozone from B1, and 2 to 8 % for CO from B2, depending on the geophysical situation. Fig. 6 shows the averaging kernels for SIFTI and the a priori and a posteriori variability of CO and O₃ profiles, computed with the 4A/OP radiative transfer code (Scott and Chédin 1981, Chaumat et al. 2007) for radiative transfer calculation, and with tools developed at CNES for the inverse model, based on optimal estimation (Rodgers, 2000). As compared to currently flying sensors, the error on the profile is reduced up to the surface, proving the interest of SIFTI for air quality.

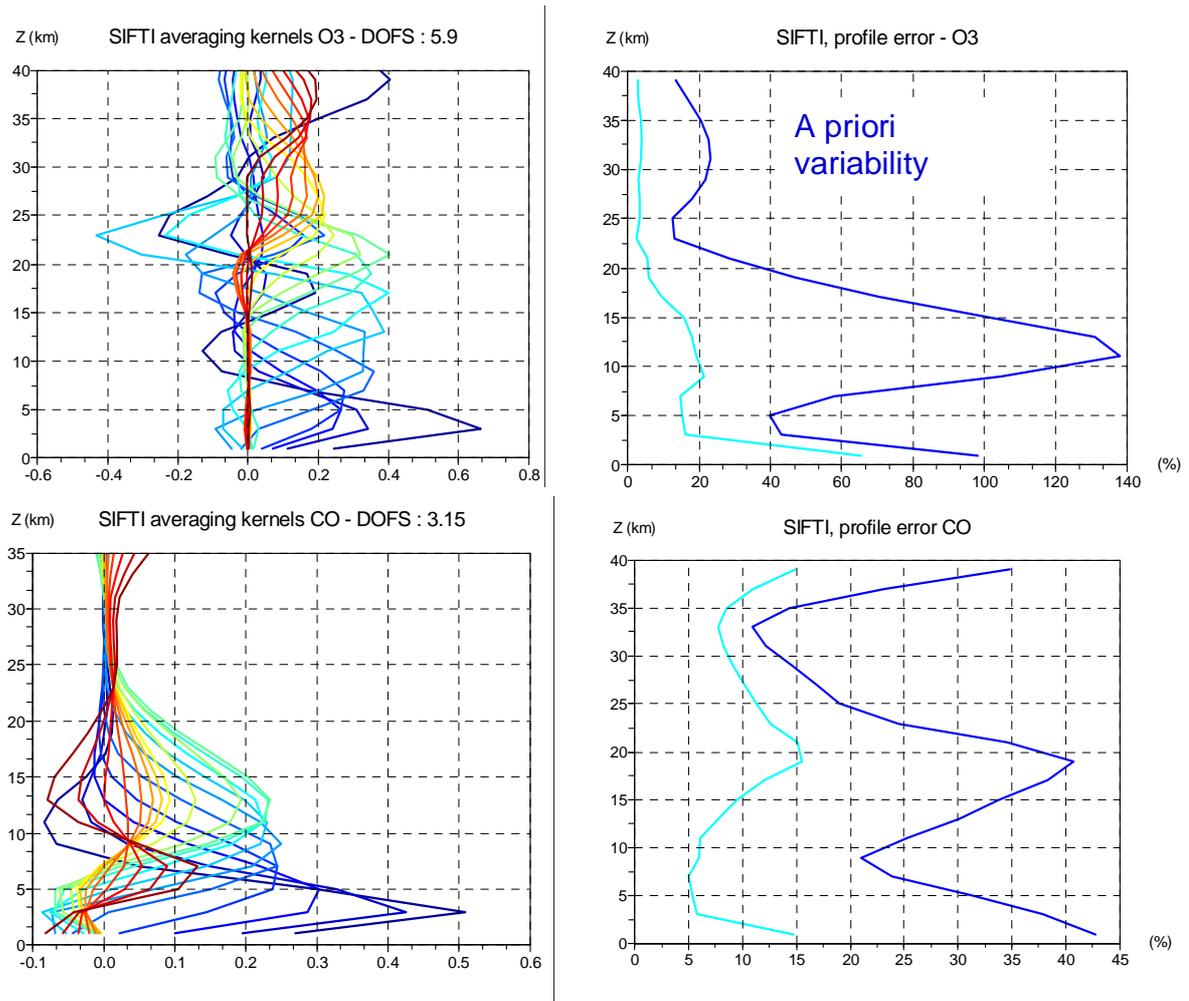


Fig. 6 : example of averaging kernels (on the left) and error profile (on the right) for O₃ profile from SIFTI B1 (upper panels) and CO profile from SIFTI B2 (lower panels).

SIFTI also offers promising retrievals of carbon monoxide in the troposphere thanks to the TIR/SWIR synergy. CO can be retrieved by combining the radiances spectra from the thermal and short-wave infrared domains. Fig. 7 shows that the TIR retrieval is more accurate than the SWIR retrieval, even close to the surface. However, combining both spectral domains improves the CO profile retrieval in the boundary layer: in that example, adding the SWIR band, the statistical error for the 0-1 km layer decreases from 23% to 16%.

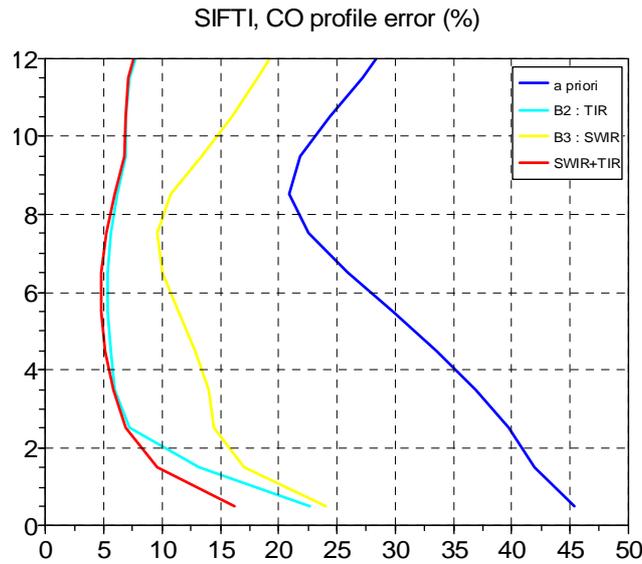


Fig. 7 : CO profile error (%) from the surface to 12 km. Blue = a priori variability, yellow = SWIR retrieval, cyan = TIR retrieval, red = combined SWIR+TIR retrieval.

Static interferometry concept

The principle of static interferometry relies on a CNES patented concept: the moving mirror in classical Michelson interferometry is replaced by a stepped mirror. Temporal acquisition of the interferogram is replaced by spatial acquisition onto a detector matrix (see Fig. 8 and Fig. 9). The main advantage of static interferometry is its reliability, as there is no moving mirror and no dynamic perturbation.

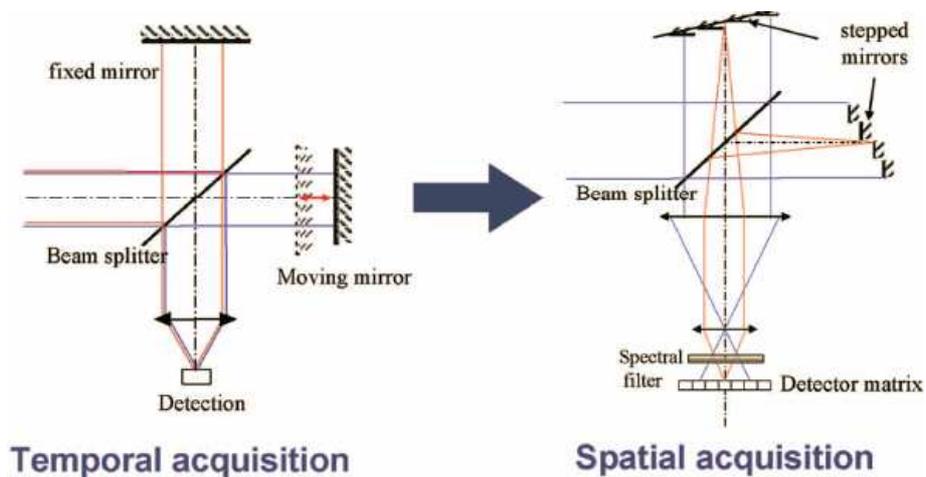


Fig. 8 : from dynamic interferometry to static interferometry.

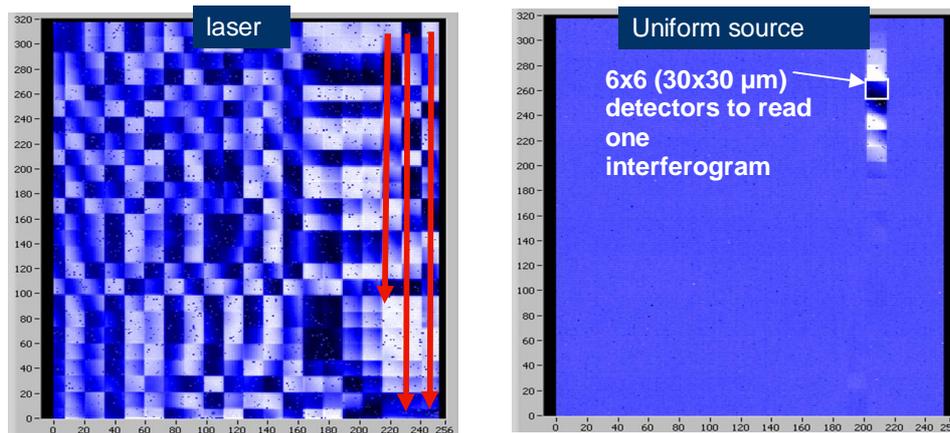


Fig. 9 : examples of spatial acquisition of interferograms on a detector matrix (from CNES breadboard). The red arrows show the reading direction of the interferogram.

Such a concept permits very high spectral resolution: the maximal optical path difference is given by the depth of the stepped mirrors (Fig. 10). For SIFTI, it is 8 cm optical, as compared to 2 cm for IASI, thus leading to a spectral resolution 4 times better. Facets are obtained by crossing the steps of two mirrors. In the manufacturing of the mirrors, the technology of molecular adherence allows as many facets as about one thousand in a 100 mm × 100 mm surface. The interferometric fringes are built on these facets, and are read by imaging them onto a 2D detector array. There is no over-sampling of the interferogram, which implies that the number of channels in the spectrum is limited to about one thousand too. The concept is thus limited to narrow spectral bands. However, for gas retrieval, it is well adapted. The first difficulty of the concept is the need for a very good knowledge of Optical path Difference (OPD) (a few nm) which implies on-board monitoring of the mirror position thanks to an algorithm or a laser. The second difficulty is the accurate radiometric inter-calibration of the matrix detectors. More details on the instrument might be found in Hébert et al. (2006).

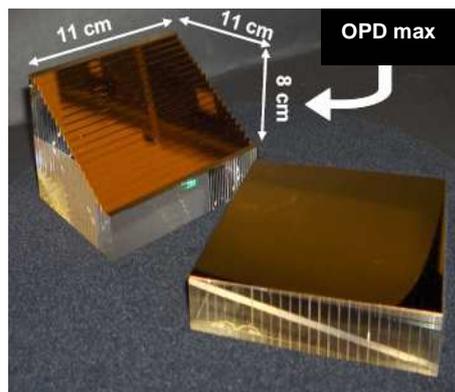


Fig. 10 : the stepped mirrors of a static interferometer breadboard developed at CNES.

Future way forward

Moreover, this concept also opens the way to a new processing strategy of the data: a direct retrieval of geophysical products from interferogram data, with an optimisation of the interferogram sampling. CO periodic line comb produces a periodic fringe pattern in the interferogram (Fig. 11). So, the idea is to acquire and to use only interesting Optical Path

Difference (OPD) samples with irregular steps in the scaled mirrors. As a theoretical simulation, an optimal selection of samples for SIFTI B2, based on information content, has been conducted : only 87 different OPD positions are selected (among thousands of possible positions), some of them several times, mainly where CO signature is strong (Fig. 11). The direct retrieval of gas profiles on the irregular optimised interferogram shows better performances than the retrieval from a regular interferogram, or its equivalent spectrum. For instance, we see on Fig. 12 that we obtain 4.1 DOFS for the retrieval from regular sampling, and 5.7 from the optimised sampling. To obtain the same performance (5.7 DOFS) with regular sampling, we should reduce the noise by a factor of 2.12. Conversely, if we decide to keep the performance constant (4.1 DOFS), an optimised interferometer requires only 220 interferogram samples (versus 971 in the regular case) which conducts to a simpler and smaller instrument.

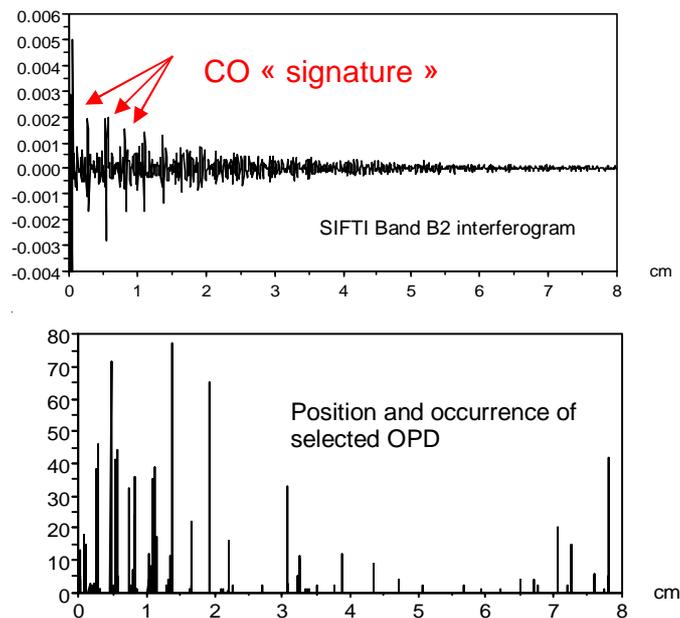


Fig. 11 : SIFTI band B2 interferogram (top), and position and occurrence of selected OPD (bottom) for interferogram retrieval with optimised sampling.

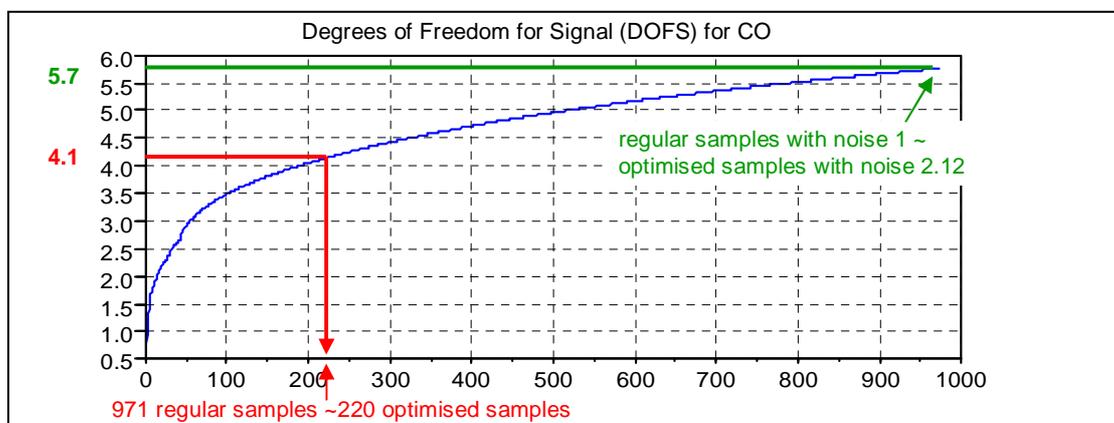


Fig. 12 : performance of the CO retrieval (DOFS) as a function of the number of optimally selected interferogram OPD samples, from 0 to 971.

Conclusions

For a mission dedicated to air quality and pollution monitoring, an original drifting orbit leading to 5 revisits per day in the mid-latitudes and a global coverage has been proposed. The geometric requirements are driven by the need to maximise the number of useful observations. For this purpose, an “intelligent pointing” strategy, based on on-board processing of an imager, permits to avoid clouds. The SIFTI instrument, an infrared interferometer, thanks to its very high spectral resolution (0.125 cm^{-1} apodised) and its very low noise, provides high quality profiles for ozone and carbon monoxide. The accuracy of CO retrieval in the boundary layer can be improved with a combined SWIR/TIR retrieval. The instrument concept is a static interferometer, with stepped mirrors instead of moving mirrors, which is very reliable for space applications. A possible optimisation of the interferogram samples opens the way to higher quality profiles for CO.

We established here that infrared sounding is a must for pollution monitoring, as it can provide ozone and carbon monoxide concentrations, both fundamental molecules for air quality. Moreover, we have seen that it gives access not only to gas total column but also to vertical profiles, with information down to the surface. The orbit and geometric optimisation presented here, as well as the high performance instrument concept, should find a place in the way towards operational atmospheric chemistry, for instance as planned in the European Union Global Monitoring for Environment and Security (GMES) program.

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