SIFTI, a sounder based on a new instrument concept: static Fourier transform interferometry

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Abstract: The SIFTI instrument is presented, in particular the program, the mission, and the concept of this new type of sounder, and its preliminary performances. Developed by CNES for the monitoring of atmospheric pollution (ozone and carbon monoxide), the concept is based on static Fourier transform interferometry, which permits to get an interferogram with no translation mechanism in the interferometer. Very good radiometric performances are foreseen, and a high spectral resolution is obtained. The concept is well suited to get high performance spectra in narrow bands.

Introduction

In 2005, CNES participated to a Netherlands – France joint proposal to the ESA's Earth Explorer call for ideas, consisting in an air pollution monitoring mission called TRAQ. The TRopospheric Air Quality mission as been exposed for instance by Phulpin et al. (2006). The payload of TRAQ comprises 3 instruments, among which the SIFTI instrument (Static Infrared Fourier Transform Interferometer) is in charge of the infrared part of the spectrum. Complementary to the other instruments, i.e. TROPOMI (PI: P. Levelt, KNMI) and OCAPI (PI: D. Tanré, LA), SIFTI (PI: C. Camy-Peyret, LPMAA) is based on a new technique of interferometer, namely the "static" interferometry. Developed by CNES since the middle of the 90' (Vermande et al. 2000), static interferometry was the object of a patent released by CNES in 1998, and its first application was the project of an instrument dedicated to CO_2 sounding, at 1.6 µm, as detailed by Rosak and Tinto (2003). The extension of its principle to the thermal infrared was the basis of SIFTI. Indeed, the principle of static interferometry is well suited to narrow band spectra measurements, and gives the opportunity of an instrument whose design and sizing is optimized for this mission.

Air quality mission

Scientific questions about pollution require information and data about species responsible for primary pollution: NO_2, O_3, CO, SO_2 and micro particles, which are the direct causes of toxic effects, and about species like H_2CO or methane.

The sounding of CO and O_3 within the troposphere, including the boundary layer, with at least one independent piece of information in the [0 – 3 km] layer, is mandatory for an air quality mission. For that purpose, infrared sounding is complementary to UV-VIS technique. UV-VIS shows quite constant weighting functions, which is favourable to estimation of total column amount. Moreover UV-VIS has been widely used for O_3 profiles with higher sensitivity in the stratosphere. In the infrared, these functions have peaks in the troposphere. Moreover, the infrared allows measurements by night. These two techniques are anyway complementary, as shown by Clerbaux et al (2003). In this context, the purpose of SIFTI observations is the retrieval of CO and O_3 profiles, down to the boundary layer. On the other hand, the TROPOMI spectro imager is dedicated to H_2CO, SO_2 and NO_2, and OCAPI, a polarising multiviewing imager, shall retrieve the aerosol characteristics.

For the infrared measurements, the need to obtain as much information as possible requires dealing with the cloud cover, i.e. increasing the probability to stare between clouds. The first condition to achieve this is to limit the size of the pixel on ground to 10 km at nadir. Note that for aerosol observations with OCAPI, a resolution of 2 to 4 km is required. A powerful way to increase the efficiency of sounding with respect to cloud cover would be an agile scanning, as proven by Lavanant and Phulpin (2006). Agile scanning is the means to stare the line of sight of the sounder, in real time, in areas favourable to declouding, in each Field Of Regard along the swath. In any case, an embedded imager called CLIM would provide pieces of information necessary to correct the soundings from cloud effects.

The weak maturity of the troposphere sounding is such that a probatory mission is justified. Thus the system definition should be limited to a single "mini sat" type satellite, and a ground segment. The geographical zones to cover being concentrated between 40N and 65N latitudes, for example the European continent, an inclined drifting orbit was proposed by CNES. Its 54° inclination, at the altitude of 720 km, allows a revisit time of 100 minutes. The local time of passes is drifting by 19 mn per day. Consequently, periods of up to 18 days will benefit from 5 passes per day during daytime, thanks to the wide swath of the instruments, as depicted in Figure 1

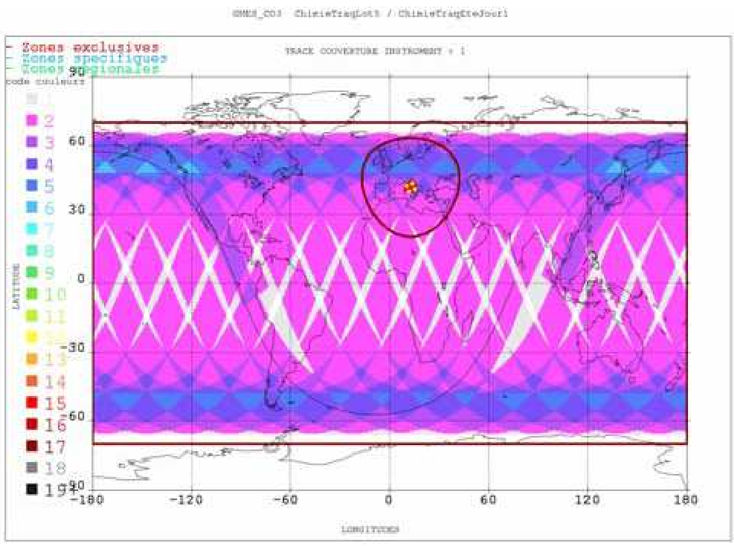

Figure 1: SIFTI daily coverage at day 15

Apart from these periods, the set of 5 passes will drift from or to the night. Conversely, daytime passes will drift to other longitudes. Thus this orbit will insure, with only one satellite, global earth coverage and a short revisit interval, and a survey of all diurnal conditions.

Note that, SIFTI observations being made in the infrared, both night-time and daytime measurements are useful; so, the 5 passes in mid-latitudes provide 5 useful infrared observations per 24h whatever the day of the year.

Mission requirements for SIFTI

The level 2 specifications for the SIFTI products are summarized in Table 1:

Table 1: SIFTI level 2 product requirements. (*): one point in the boundary layer

Species	Product	DOFS	Absolute Uncertainty
O_3	Stratospheric profile[12 – 50 km]	4	1 - 4 %
	Tropospheric profile [0 – 12 km]	2.3 (*)	10 – 30 %

CO	Tropospheric profile [0 – 12 km]	2.5 (*)	6 – 12 %
	Column [0 – 12 km]	1	3 – 15 %
CH_4	Tropospheric profile [0 – 12 km]	TBD	0.4 – 2.5 %

The scientific objective of a space mission for the global monitoring of pollution is to reach a better understanding of the impact of anthropogenic activities and of natural phenomena on the troposphere composition, over Europe, especially through the measurements of diurnal, seasonal, annual … variations of the implied species. As for the infrared part of the spectrum, covered by SIFTI, the first step is to demonstrate the feasibility of the CO and O_3 profile retrieval. That is to say to get 4 to 6 degrees of freedom for concentrations in the depth of the atmosphere. The first measurement point (in the low troposphere) is of most importance. The accuracy needed in the vertical profiles is of the order of 10 to 20 %.

Scientific investigators of SIFTI have gathered requirements for the infrared sounder in a "SIFTI Mission Requirement Document". The main ones are the following.

The instrument measures atmospheric spectra in two nominal bands: 30 cm^{-1} wide in B1 band = [1030 – 1070 cm^{-1}] i.e. (9.71 – 9.35 µm), and in B2 band = [2140 – 2180] i.e. (4.67 – 4.59 µm). For the sake of simplicity, spectrum as seen by the instrument can be considered as the one of a black body at the same temperature as the earth surface, multiplied by a "pseudo-transmission" of the atmosphere. Figure 2 shows the average atmospheric "pseudo-transmission" in the mission bands.

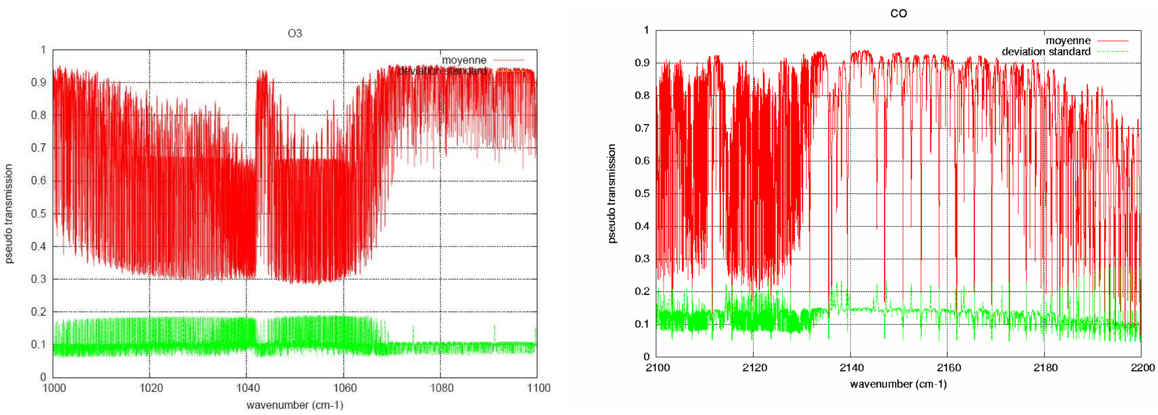

Figure 2: SIFTI pseudo-transmission in B1 (left) and B2 (right) (in red lines). Statistical variation among 232 atmospheric situations (in green lines).

An optional third band is envisaged in SIFTI. It would be [4270 – 4300 cm^{-1}] (2.34 -2.32 µm). This band provides the total column amount of CO, thus it allows a more accurate retrieval of the profile given by B2 band. Having this SWIR band within SIFTI would benefit to the collocation of B3 and B2, which is crucial in retrieving CO in a synergetic approach. On the other hand, implementing it in TROPOMI would be beneficial in terms of spatial sampling, since TROPOMI is basically an imager with a Spatial Sampling Distance of 5 km. The debate is still open. Moreover, this third band will provide also lines of methane.

Background on static Fourier transform interferometry at CNES

The principle of static Fourier transform interferometry was proposed by CNES in the 90', in parallel to the development of IASI, to circumvent the intrinsic difficulty of a mechanism in a scanning Michelson interferometer. It was found that a static interferometer was well adapted to narrow spectra sounding from space, because it allows high spectral resolution in a simplified on board hardware. CNES released a patent in 1998, which addresses these two themes.

The first application of static FTS was a project of an instrument dedicated to CO_2 sounding at 1.6 µm. The MOLI instrument, for the Carbosat mission, aims at being a low cost and robust payload for an accurate and global monitoring of CO_2, as presented by Rosak and Tinto. A dedicated breadboard allowed the validation of the principle, the technology and the performances of MOLI. Figure 3 shows a photograph of the breadboard.

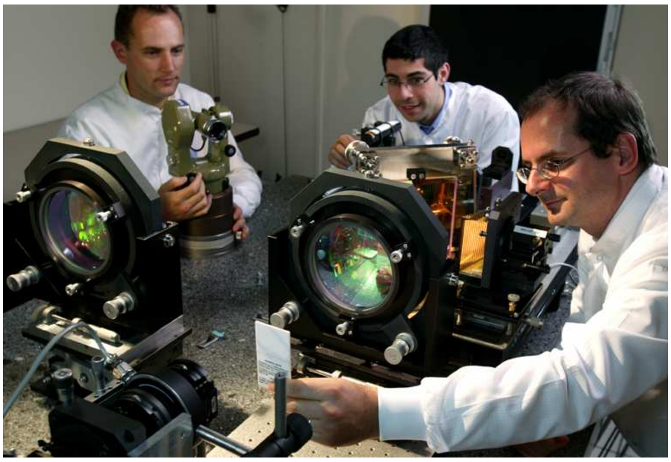

Figure 3: breadboard of MOLI in CNES facilities

The latest validations obtained on this breadboard are exposed by Lacan et al (2006).

Among all the technical validations, the manufacturing of the facet mirrors was validated in the frame of the MOLI breadboard. Each mirror has the shape of stairs, one with large steps, the other one with small steps. The range of the small steps is equal to one large step. The two step mirrors are crossed, so as to form about one thousand intersections. Each of them has a different Optical Path Difference, which provides about one thousand samples in the interferogram. The accuracy of sample positioning is ± 2 µm today. Figure 4 shows the stepped mirrors developed for the MOLI breadboard.

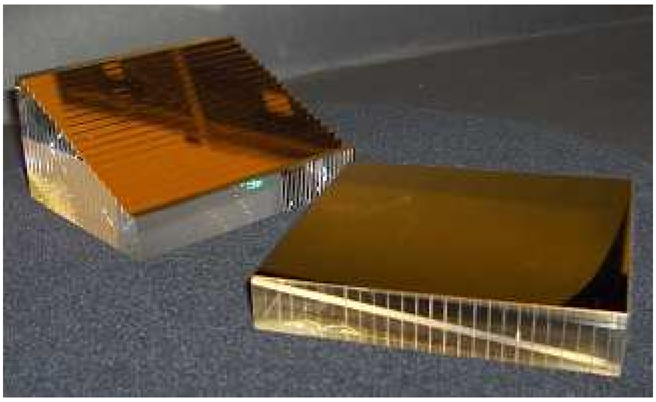

Figure 4: prototypes of step mirrors for MOLI breadboard (CNES R&T)

In 2005, the TRAQ mission raised the need for an infrared sounder, in narrow spectral bands but with a high spectral resolution and a low noise. The static Fourier interferometry was found to be a good candidate for this instrument, that was called SIFTI, standing for "Static Infrared Fourier Transform Interferometer". Thus CNES led a phase 0 study to adapt the principle to the infrared. Besides, the design of the platform and of the orbit of TRAQ, the results were gathered with those of KNMI for TROPOMI, and with an Astrium study under a CNES contract, for a response to the ESA's Earth Explorer call for ideas. This proposal has been selected with five other missions for a phase 0 system study by ESA, CNES initiated a phase A for SIFTI. Numerous modelling and preliminary design were necessary in 2006 to specify the instrument and identify the tasks to be done. The phase A started in March 2007, with Thales Alenia Space – France as the prime contractor. It should last two years, so as to be coherent with the Earth Explorer schedule. However, the goal of the phase A was determined to reach the design of an optimized instrument in terms of cost, mass and volume, in order to remain compatible with any mini-sat type satellite. So other programmatic contexts can still be envisaged.

In parallel to the industrial phase A, CNES has started the development of an infrared breadboard called MOPI. The goal of MOPI is, eventually, to validate the performance models of CNES and Thales Alenia Space, in real conditions.

Principle of static Fourier transform interferometry

In a dynamic Michelson interferometer, a moving mirror scans the stroke continuously, up to the Maximum Optical Path Difference (MOPD). MOPD is straightforward from the desired unapodized spectral resolution:

$$MOPD = \frac{1}{2.\delta\sigma_{unapo}}$$

In the case of SIFTI, MOPD = 8 cm. In a static interferometer, the moving mirror is replaced by a stepped fix mirror, as illustrated by Figure 5.

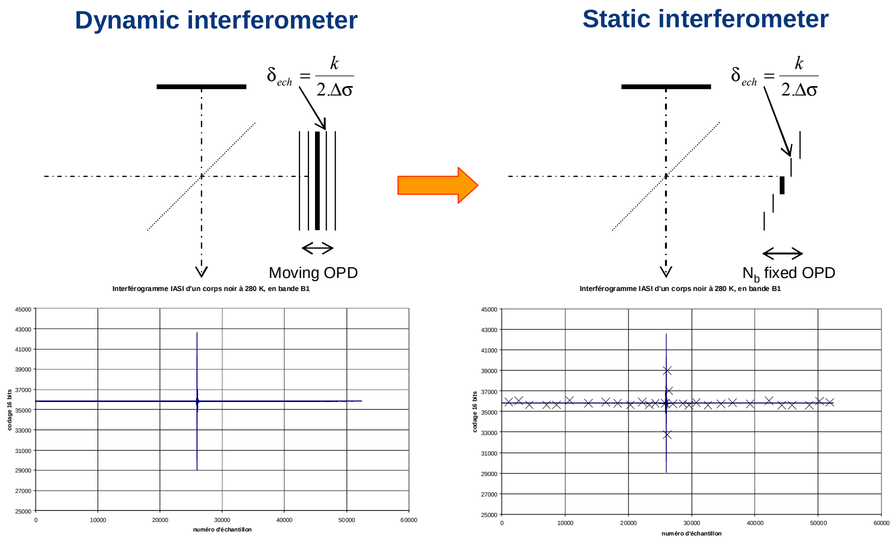

Figure 5: from dynamic to static FT interferometer

As explained above, the facets are obtained by crossing the steps of to mirrors. In the manufacturing of the mirrors, the technology of molecular adherence allows many facets, up to about one thousand in a 100 mm × 100 mm surface. Applying the generalized Shannon's theorem, it is possible to accept a spectral bandwidth [σ_{min} ; σ_{max}] if the sampling step of the interferogram is

$$\delta x_{sample} = \frac{1}{2.(\sigma_{max} - \sigma_{min})}$$

The bands being quite narrow, double-sided interferograms are not necessary, so the interferograms are scanned from $-\varepsilon$ to MOPD. ε is defined to allow some low resolution calibrations and corrections. It is of the order of few mm.

Note that in an interferometer like IASI, the sampling step is $\delta x_{sample} = \frac{1}{2.\sigma_{max}}$, so that it can restore the entire bandwidth [0 ; σ_{max}]. With respect to that, it can be considered that SIFTI's interferogram are undersampled, but, if the input flux spectrum is rendered null outside the bandwidth of interest, the sampling of interferograms is in fact optimized. To achieve this condition, a high rejection rate narrow filter is placed in the beam. One filter is required for each band, and is set in the detection box, in front of the detectors. The edges of the filters must be as steep as possible in order to maximize the free spectral range (or useful bandwidth), in which the signal amplitude is high, width respect to the total bandwidth, in which the spectrum is restore without aliasing, as illustrated by Figure 6.

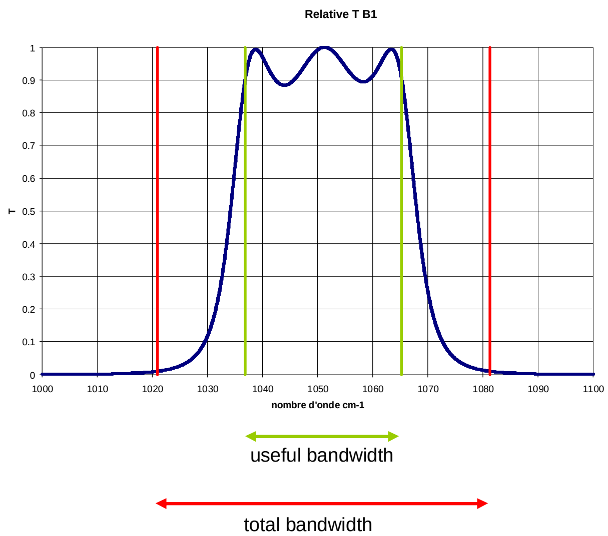

Figure 6: useful and total bandwidth

Another aspect to deal with is the accuracy of the sampling position. The technology allows an accuracy of ± 2 µm RMS on the position of the facets, in terms of OPD. This irregular sampling would not allow a direct Fourier transform. It is however possible to restore the spectrum by a re-sampling processing as presented by Rosak and Tinto (2003). This processing requires a good knowledge of these positions, within a few nanometres, like in any FT interferometer. Thus an accurate monitoring of the OPD, based on stabilized lasers, is necessary before applying the so called "resampling" algorithm.

As the interferograms are folded on the stepped mirrors, they can be red by a 2D detector array, after the image of the facets is formed by adequate optics on the detector, as shown in Figure 7.

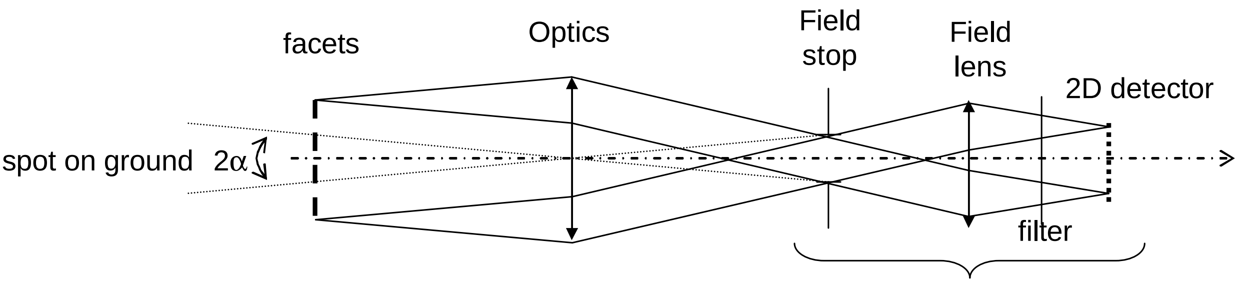

Figure 7: reading the interferograms

The field stop defines the size of the pixel on ground. The filter is in telecentric position in order to homogenise the incidence angles on it for all the pixels.

Figure 8 gives an example of an interferogram, as it is red by the 2D detector array.

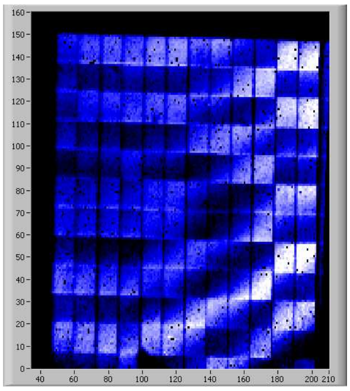

Figure 8: example of interferogram on the detector

Several bands can be addressed by the interferometer. This requires splitting them from another with dichroics, before the narrow optical filters and the detectors. Figure 9 gives a possible optical layout in the detection box.

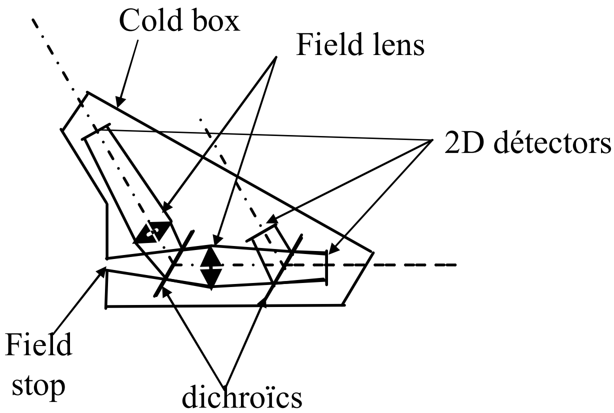

Figure 9: possible layout in the detection box

Because of the infrared wavelength, the detection box and the detectors must be cooled down.

The interferograms are digitized and sent to the ground. The data flow is intrinsically as low as possible thanks to the optimized sampling step. Processing the Fourier transform on board would be of no help with that respect.

Data processing

In order to lower the effects of different noises and fluctuations, several processing of the acquisitions are implemented.

The radiometric calibration is the most classical one. It aims at calibrate the spectra in terms of radiance temperatures. For that, SIFTI looks periodically at an internal black body and at deep space. Then we apply the following equation to every atmospheric spectra N(σ) to get the actual emitted radiance B(σ):

$$B(\sigma) = B_{BB}(\sigma, T_{BB}).\mathrm{Re}\left(\frac{N(\sigma) - N_{CS}(\sigma)}{N_{BB}(\sigma) - N_{CS}(\sigma)}\right)$$

where N is a measured spectrum, B_{BB} is the Planck function for the black body (which temperature T_{BB} must be accurately monitored), "BB" stands for black body and "CS" for cold space. This calibration occurs after Fourier transforms. Both can be made on ground.

The need for resampling implies to get the actual position of each OPD. This can be made by a reference sub-system based on a very stable laser which provides, parallel to the interferograms and possibly at the same time, a set of relative positions of each facet. This data set is injected in the processing.

Phase modulation is an innovative way to reduce the effect of inter-pixel offsets, stray light fluctuations and to reduce noise effects. Let us call λ_{av} the medium wavelength of the spectral band. Four interferograms are acquired during the integration time, separated by an OPD of $\lambda_{av}/8$: I1, I2, I3 and I4. The differences I2-I1 and I4-I3 give the derivatives of the interferogram, thus reduce the effect of background and offset slow variations. Processing I2-I1 and I4-I3 allows to double the number of samples, then to increase the stability and the performance of the resampling algorithm with respect to noise.

SIFTI's schematic

Erreur ! Source du renvoi introuvable. illustrates the orientation of the mirrors in the interferometer, and the splitting of the beam between bands.

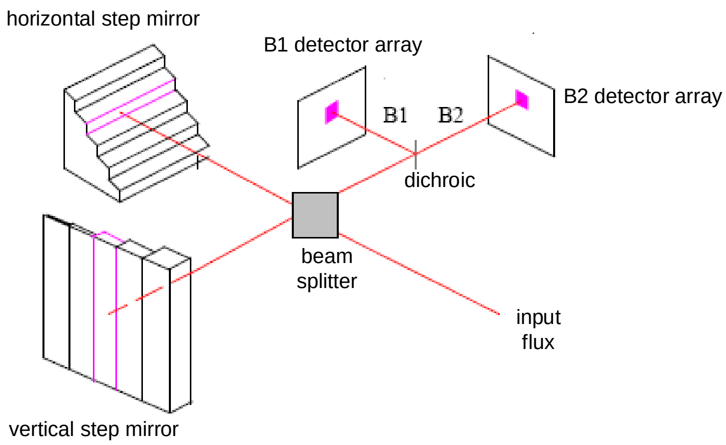

Figure 10: orientation of mirrors in the interferometer

The general layout of the instrument is given by Figure 11:

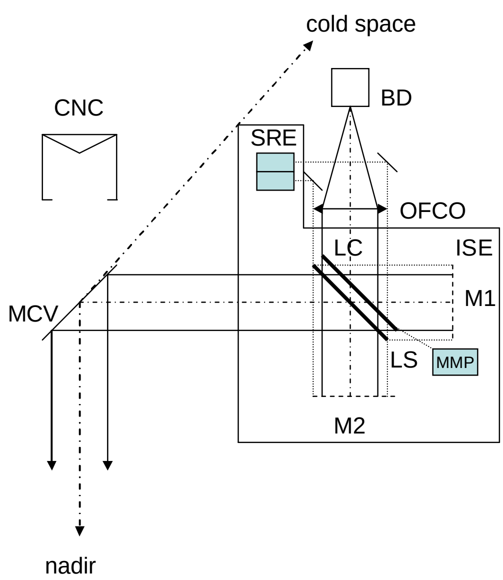

Figure 11 : Functional layout of SIFTI

In Figure 11, one can see the following sub-systems:

- MCV = Scanning mirror: insures the cover of the swath and the view on calibration targets;
- CNC = Calibration black body: provides the knowledge of BBB(σ, T_{BB});
- Mi = (facet) mirrors (× 2): form the 32×32 OPDs;
- LS = Beam splitter; separates the incident beam into 2 equal parts and recombines them;
- LC = compensating plate: equalizes the depth of glass crossed by light in the two harms of the interferometer. It may be translated closed to M1;
- SRE = sampling reference subsystem: based on a very stable laser, provides the accurate knowledge of each OPD for each interferogram;
- MMP = phase modulation subsystem. May be based on piezo actuators. May act on the compensator or on one mirror;
- ISE = interferometer;
- OFCO = focusing optics: focuses the image of the earth onto the entrance of the detector box;
- BD = detector box: transfers the optical signal into an electrical current; defines a cold pupilla; images the facets onto the detectors; defines the field of view; separates the two (or three) spectral bands; passively cools down the optics, and actively the detectors. The architecture of the BD is of the same kind as for IASI, as depicted in Figure 9. It includes the narrow optical filters that have a width of 363 nm, 89 nm and 16 nm in B1, B2 and B3 respectively.

Instrument specifications

The mission objectives and rationale of the instrument specifications have been previously exposed by Hébert et al (2006). The requirements at the mission level and at the instrument level are summarized in Table 2.

Table 2: SIFTI mission requirements (spectra) and instrument specification (interferogram)

<table>
<tr><th>Species</th><th>Spectral range</th><th>Total SNR in spectra</th><th>NEDT (mK)</th><th>$\delta\sigma$ unapodized (cm^{-1})</th><th>max OPD (cm)</th><th>SNR in 2 × 1000 points interferograms</th></tr>
<tr><td>O_3</td><td>[1030 – 1070 cm^{-1}]
(9.71 – 9.35 µm)</td><td>650</td><td>80</td><td>0.0625
(R = 8500)</td><td>8</td><td>11000</td></tr>
<tr><td rowspan="2">CO</td><td>[2140 – 2180 cm^{-1}]
(4.67 – 4.59 µm)</td><td>200</td><td>120</td><td>0.0625
(R = 17000)</td><td>8</td><td>4500</td></tr>
<tr><td rowspan="2">[4270 – 4300 cm^{-1}]
(2.34 -2.32 µm)</td><td rowspan="2">90 (TBC)</td><td rowspan="2">TBD</td><td rowspan="2">0.075
(R = 29000)</td><td rowspan="2">8</td><td rowspan="2">TBD</td></tr>
<tr><td>CH_4</td></tr>
</table>

The unapodized spectral resolution is specified at 0.0625 cm^{-1} in the 3 bands. For a Michelson interferometer, this implies a maximum Optical Path Difference of 8 cm. The figure for the sampling step of spectra is the same.

The requirements for the noise in the spectra might be the most stringent. The Signal to Noise Ratio must be as high as 650 in B1 and 200 in B2, with a surface temperature of 280 K, seen through the pseudo-transmission of Figure 2. In terms of NEDT, this is equivalent to 80 mK and 120 mK RMS, respectively, at 280 K. Special care was taken to specify non white noise, i.e. noises whose intensity depends on the wavenumber, and correlated noise, i.e. noise that is no independent from a channel to another. A specific process was proposed by CNES to evaluate an "equivalent white noise", based on the transformation of the noise covariance matrix.

At the level of interferograms, the radiometric requirement leads to a very high Signal to Noise Ratio. The transfer of SNR from interferogram to spectrum is proportional to the square root of the number of samples. As the later is around one thousand, doubled thanks to the Phase Modulation Mechanism, this yield to the need of a SNR of more than 11000 in B1 band, and 4500 in B2 band. This covers only the instrumental noise. These figures must be added to the pseudo-noises, like those due to the instability of Line Of Sight, in order to reach the global requirement of SNR in the spectrum, recalled in Table 2.

The swath of SIFTI must be ± 50° with respect to na dir, which leads to a width of 1700 km on ground.

The spatial sampling on ground aims to be 50 km at nadir, and the spatial resolution, i.e. the diameter of the pixel on ground, will be 10 km at nadir. The goal is to obtain at least 25 measurement points in the ±850 km with respect to nadir swath.

The CLIM imager will give information about the cloud cover in the sounder pixel, in order to make the declouding process possible, and the geolocation too.

The first instrumental option is a third spectral band B3 = [4270 – 4300 cm-1] (2.3 µm) that is used to force the CO column amount by daytime, in terms of reflected / backscattered solar flux, in the profile retrieval process, and then enhances the accuracy of the later. This band can be implemented either in TROPOMI or in SIFTI. Further studies will assess the best compromise.

The second option deals with the agile pointing scan, as symbolized in Figure 12.

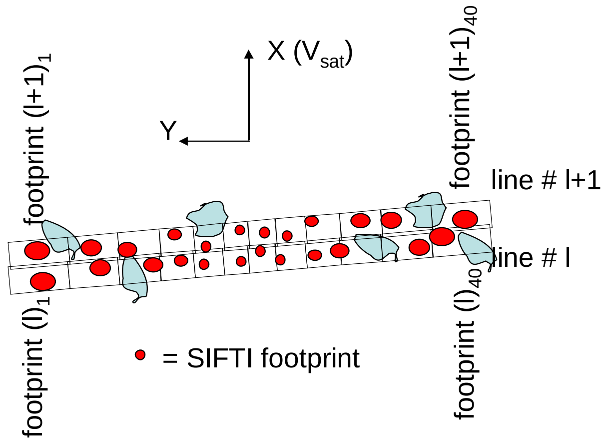

Figure 12: schematic of the agile pointing along two successive swaths

Conclusion

We have presented a new kind of interferometer, that can provide high quality data on the atmosphere for an air quality mission. The SIFTI instrument must be associated to few others to constitute a complete payload dedicated to this mission. The technology of static Fourier transform interferometry presents several advantages, and makes it possible to embark on board a small satellite. Thus the objective of a low cost mission for science research can be reached.

The on-going industrial phase A study, the development of an infrared breadboard, and the performance models are the means to define a global preliminary design of SIFTI, in a first step, then to build the performance budgets, mass and volume of SIFTI, and eventually to establish its feasibility and design.

Although the specified performances are high, specially the spectral resolution and the radiometric noise, the principle of static interferometry allows to obtain a robust, optimized and simplified on-board hardware. Its advantages have been reviewed: the Phase Modulation Mechanism is more simple than in a classical scanning mechanism, with a stroke of few tenths of µm, against at least 4 cm; the interferometer is less sensitive to multiplicative noises, as the signal of each sample is averaged during the integrating time; the data rate is basically limited to the minimum amount, as the interferograms are "undersampled". All this makes SIFTI well adapted to its mission.

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