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Compact Static Interferometer Instrument Studies for Greenhouse Gas Detection

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ABSTRACT

The detection and quantification of greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2) and methane (CH_4), is presently one of the main goals of remote sensing of atmospheric gasses on a global scale, for the strong impact these molecules have on climate change. Of particular urgency is the quantification of emissions from anthropogenic sources, a high-priority task addressed by the ESA Copernicus mission CO2M, which will provide global coverage detection of CO_2 and CH_4. The observation of CO2M, capable of quantifying emissions from the major sources, can be complemented by other observation systems addressing the smaller, and more numerous, sources. In this domain, static interferometers can offer several advantages.

This paper reports on the main results of two activities completed within the ESA Future Missions activities in the Earth Observation Program, for the development of small instruments based on static interferometer designs, for the detection of CO_2. The two studies, named Carbon-HIGS and Carbon-CGI, investigated two instruments operating in the SWIR and NIR bands, with a targeted precision of 2 ppm and an accuracy of 1 ppm for CO_2 atmospheric concentration, covering a relatively small swath of 50 km at a spatial sampling better than 300 m.

We summarize the general detection principles, the result of the design activities, and the estimated instrument performances. Both concepts are suitable candidates to work in conjunction with the Copernicus mission offering a *zoom-mode* observation, for quantification of medium-sized GHG sources and improved localization and understanding of anthropogenic emissions.

Keywords: static interferometer, carbon dioxide, methane, anthropogenic emissions

1. INTRODUCTION

The global detection from space of greenhouse gas (GHG) concentrations is of high scientific and political priority, to improve climate-change models and their predictions, as well as to define fact-informed emission reduction policies, and for the independent verification of their implementation, e.g. within the Paris Agreement. In this context, the main gas species of interest are carbon dioxide (CO_2) and methane (CH_4), for their strong impact on global warming.

Space-borne imaging spectrometers are widely used instruments for measuring both CO_2 and CH_4, in missions such as GOSAT (JAXA) and OCO-2 (NASA), as well as TANSAT (CNSA). While these missions are mainly dedicated to studying the global carbon cycle dominated by biogenic sources and sinks, the detection and

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quantification of emissions from anthropogenic sources is the goal of the ESA Copernicus mission CO2M[1] (and of the CO2Image mission,[2] DLR). The CO2M mission is supported by a suite of instruments, with an imaging spectrometer providing global measurements of CO_2 concentrations through observation in SWIR and NIR bands.

The nature of CO_2 is that of a well-mixed gas: the high concentrations found in the emission plumes decrease quickly with the distance from the source as the gas dilutes, with the consequence that only higher resolution images allow for the detection of smaller sources. The observations provided by CO2M will be available at a spatial resolution of 2 km: this enables the quantification of emissions from large sources (big power plants and cities, in the order of >10 Mt/year), which account for only a fraction of the anthropogenic CO_2 emissions. For reference, power plants emitting between 1 and 10 Mt/y of CO_2 account for 64% of the power plant emissions.[2]

The detection of mid-size sources (<10 Mt/year) requires a spatial resolution much better than 1 km while maintaining high precision. Such performance is difficult to achieve in conventional push-broom imaging spectrometers without resorting to large entrance pupils, impacting instrument size and incorporating technologically challenging optical components.

In this paper, we report on the results of two instrument studies completed within ESA's Earth Observation Programmes Directorate, Future Missions Department, for the development of small instruments based on static interferometers. Static interferometers are a class of instruments where the optical path difference (OPD) is determined by the optical design without the use of moving elements as e.g. in Fourier-transform spectrometers. The absence of mechanisms offers advantages with respect to compactness, reliability, and reduced complexity making static interferometers interesting options for applications on small satellites.

The two studies are named Carbon-HIGS (TNO and SRON, 2020) and Carbon-CGI (Thales Alenia Space, IRT and ACRI-ST, 2021), and both focused on the adaptation of pre-existing concepts for a compact CO_2 instrument in the SWIR band, complemented by measurements in the NIR region in the O_2 A-band for light path correction, and for estimation of water vapor content and aerosol.

Preliminary mission requirements were provided by ESA as reference performance for plume emission quantification. The radiometric requirements (precision and accuracy) are formulated in terms of the Level-2 product *dry air total column-averaged mole fraction* (XCO2), with the flow-down to Level-1 observation requirements to be established by the contractor. The preliminary mission requirements are summarized in Table 1.

Table 1. Preliminary mission requirements for the static interferometer instrument studies.

Requirement	Static interferometers	CO2M
Orbit	Sun-Synch. Mean Local Time 11:30, 730-810 km	
Spectral Bands	SWIR1 (1.6 µm), NIR (750-773 nm)	
Swath	>30 km (T), >50 km (G)	250 km
Swath access	de-pointing to acquire within CO2M swath	
Spatial sampling	60 m (G), 100 m (B), 300 m (T)	2000 m
Integrated Energy	70%	
Single sounding precision XCO_2	<2.0 ppm (T), <1.0 ppm (G)	<0.7 ppm$^{(*)}$
Single sounding accuracy XCO_2	<1.0 ppm	<0.5 ppm

T=threshold, B=baseline, G=goal; $^{(*)}$ on vegetation scene with SZA=50°.

The studies' tasks included the assessment of the instrument potential both as a self-standing observing system and as a support system for the CO2M mission. In the second case, addressed in this paper, the mission complexity is much reduced: high accuracy retrieval of XCO2 requires spatially and temporally co-located information on the other atmospheric contributors to the signal, including aerosols, clouds (cirrus), water vapor content, and surface pressure. The synergistic use with the CO2M mission, e.g. by flying in loose formation, ensures accurate co-located retrievals of the atmospheric composition at coarser resolution. In the following sections, we present the main results of the Carbon-HIGS and Carbon-CGI activities.

2. CARBON-HIGS

The Carbon-HIGS instrument design was developed by TNO, in collaboration with SRON for the simulation of the Level-2 performance. This instrument belongs to a family of trace gas sensors called HIGS[3] (Huibs Innovative Gas Sensor, patented[*]).

An HIGS sensor is an imager which performs the simultaneous acquisition of two co-registered images of a ground scene. Each of the images is obtained by introducing a fixed OPD values in the two interferometric propagation paths without physically splitting the beam. Such OPD determines a periodic spectral modulation of the throughput, as in a Fabry-Perot sensor, with the spectral positions of the maxima of the throughput for one channel correspond to the minima in the other channel, resulting in complementary spectral components acquired in the two images. The tuning of the throughput modulation allows to maximize the contrast between the two images for the specific trace-gas to be measured; this can be done by matching the periodic pattern of a gasses absorption lines of an absorption band, or by spectrally selecting full absorption bands. A spectral filter selects the spectral interval of interest to reduce out-of-band radiance. This detection principle has been proven with a breadboard for the detection of NO_2.[4]

In the HIGS instrument the retrieval of the trace-gas concentration is done by comparison of the intensities of the two images. Being an imager, the ground scene can be measured over an extended time in subsequent acquisitions and the signal averaged with time-delayed integration (TDI) approach, or in a step-and-stare configuration, to increase the measurement precision.

2.1 Instrument requirements

The consolidation of the instrument requirements was based on simulations performed by SRON for the impact of the instrument parameters on the Level-2 performance. The selection of the SWIR band for CO_2 detection was subject of a trade-off between three options, 1600-1615 nm (SWIR1), 2040-2085 nm (SWIR2 named "strong") and 1980-2090 nm (SWIR2 named "super-strong"). Preliminary instrument performance were calculated using interferometer design parameter adapted for the three wavelength ranges. The band selected for the CO_2 retrieval was the SWIR1 band; while it was determined SWIR2 has the potential to provide a better precision, SWIR1 was favored for the lower sensitivity to coarse aerosols and better scientific and technological maturity.

The use of additional bands was considered for the correction of biases introduced by aerosol and water vapor, and for the dry-air column estimate. For the correction of the water vapor content, the use an additional HIGS channel in the NIR band 705-752 nm was investigated and found to be a possible alternative to the use of data from other sources.

For the aerosol correction a multi-band retrieval was evaluated using NIR, SWIR1 and SWIR2 bands, which didn't result in a significant improvement for the retrieval accuracy. The chosen baseline solution is the use of data from CO2M: the coarser data resolution of 2 km for aerosol concentration is not considered critical as strong spatial variations are not expected. For the determination of the dry-air column, an additional HIGS channel has been investigated. Two NIR bands were considered, 765-771 nm and 740-790 nm. Both bands can measure O_2 with sufficient precision, but final accuracy is limited by the quantification of aerosol, hence the suggested baseline solution is to use surface pressure forecast to determine the dry-air column.

The consolidation of the instrument requirements also evaluated the impact of spatial resolution on the minimum detectable CO_2 flux. This was obtained by simulating point sources of different CO_2 emission intensities, and employing a gaussian plume model (a simplified assumption, but easily reproducible) with 5 m/s wind, and simulating instrument spatial resolution and noise. The analysis provided the minimum precision required in the XCO_2 value to retrieve the CO_2 flux with a 15% uncertainty. The results, summarized in Fig.1, show that for the 2 ppm (0.5%) precision and 300 m spatial sampling, sources down to 2.5Mt/yr can be measured.

[*]PCT/NL2015/050799 and PCT/NL2017/050866, further developed in cooperation with the University of Leiden PCT/NL2019/050267W

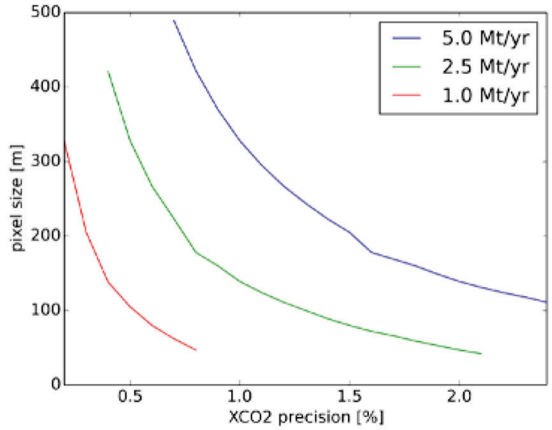

Figure 1. Relation between the minimum resolution (here pixel size) and XCO2 precision required to estimate with 15% uncertainty the flux of a point source. The different line indicate difference flux levels.

2.2 Instrument design

A concept of the Carbon-HIGS optical design is shown in Fig.2, and design parameters are summarized in Tab.2. Following a common reflective front telescope, a dichroic plate separates the SWIR1 and NIR bands in the CO_2 channel (bottom) and O_2 channel (right). In each of the two interferometers the incoming light passes first through a band-pass filter to reduce the out-of-band signal. In each channel, refractive optics is responsible for relaying the field stop to the detector.

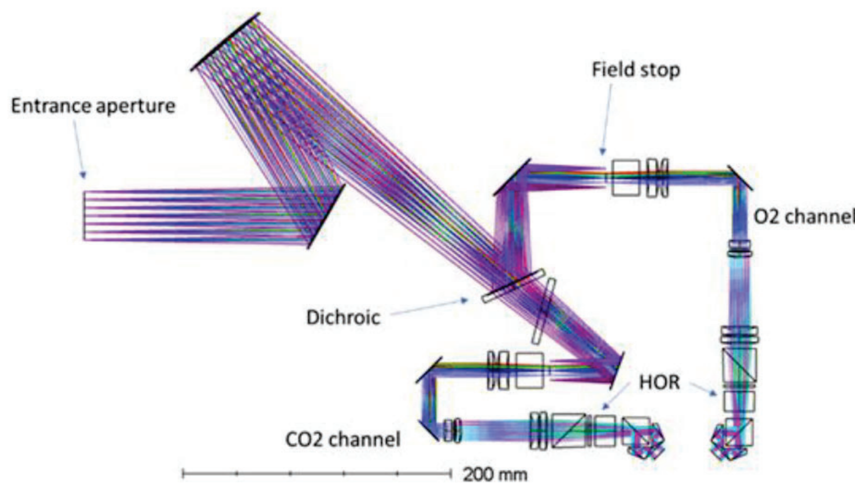

Figure 2. Concept optical design of the Carbon-HIGS instrument, comprehensive of the common front telescope and two HIGS interferometers.

The signal is split in the two interferometric paths using polarization: the incoming light is linearly polarized before passing through the High-Order-Retarder (HOR), based on a birefringent crystals with ordinary and extraordinary axis oriented at a 45° relative to the polarization direction of the incoming light[†]. The OPD introduced by the HOR is proportional to the difference between the ordinary and extraordinary refractive

[†]Patent registered PCT/NL2019/050267, international patent filed WO2019212354

indices: the small difference value determines a relatively thick crystal, making this specific design more suited for small OPD. Finally, a polarizing beam-splitter re-combines the two light-paths creating the two images.

The instrument employs for the CO_2 channel a single HgCdTe detector where both images can be located. The detector has a format of 512×640 pixels with a pitch of 15 µm. Alternative InGaAs detectors, with the same format and pixel size have been identified. Carbon-HIGS measurements are performed in a step-and-stare configuration, with pointing performed by satellite body pointing or via a scanning mirror, to allow an integration time as long as $\simeq$100 s and to achieve the required measurement precision.

Table 2. Instrument design parameter for the Carbon-HIGS instrument.

Instrument parameter	Value	Notes
Spatial sample size	$\simeq$ 200 m	Obtained with 3x3 binning
Field of View	$\geq$2.5°× 2.5°	$\geq$32 km (as CO2M auxiliary)
Effective Focal Length	180 mm	
Aperture diameter	36 mm	F#=5
Optical transmission	25%	inclusive of polarizer and band-pass filter
Band filter center tolerance	< 0.25 nm	
Band filter center stability	< 0.028 nm	
OPD tolerance	< 50 nm	
OPD stability	< 0.7 nm	

The thermal sensitivity analysis performed for the instrument showed that the estimated temperature stability of the polarization optics of ±1.4 K causes an OPD variations determining a bias of 5% (20 ppm) on the retrieved XCO2 concentration. This bias is large, but independent of Earth albedo and, therefore, it is constant over a scene and does not affecting the XCO2 plume anomaly seen by Carbon-HIGS.

A straylight analysis was performed for both ghosts and diffuse straylight components. The estimated bias introduced on XCO_2 is of 1% (4 ppm), for each component, when considering correction strategies. Since this bias depends on the scene structure, Additional work showed that a reduction of the sensitivity to straylight could be achieved if operating the instrument in the SWIR2 band. An additional mitigation is possible via the application of anti-reflection coating on the detector, for ghosts reduction. The inclusion of these design improvement are possible subject of a follow-up study.

2.3 Final considerations

The developed HIGS design for CO_2 measurements was shown to be able to measure point sources with the required precision of 2 ppm, at a spatial resolution of around 300m, with a relatively small aperture allowing a very compact optical design.

The study identified the sources of bias on the XCO_2 retrieval, related to both known atmospheric aspects like water vapor (measured with NIR channel), aerosol (auxiliary information from CO2M), and dry-air column estimation (using local forecast), as well as instrumental aspects like thermal stability and straylight. In general, it is highlighted that uncorrected biases might be acceptable if it does not interfere with the quantification of the XCO2 plume anomaly, i.e. when they are uniform over the scene. An evaluation of which biases are acceptable could be subject of a follow-up study. Straylight was found to be a critical performance, and mitigation strategies were proposed for a possible refinement of the design.

This study has demonstrated that a Carbon-HIGS instrument has the potential to extend the observation capabilities of the CO2M mission, by providing higher resolution imagery for XCO_2 while hosted on a small satellite flying in loose formation with the Copernicus mission. Possible subjects for a future activity are the consolidation of instrument design and performance, with the inclusion of Level-2 to Level-4 model errors to support an update of mission requirements.

3. CARBON-CGI

The Carbon-CGI acquisition and processing chain was designed by Thales Alenia Space and IRT, together with ACRI-ST for the radiative transfer modeling simulations and Level-2 performance. Carbon-CGI design is based on a technological development of IRT. The design resulting from the study is the optimized implementation of the Compact Gas Imager (CGI) concept, for the high-resolution detection of CO_2 and CH_4.[5]

The CGI instrument is a combination of an imager and a static interferometer: while imaging a scene CGI acquires partially scanned interferograms (PSI), i.e. interferograms measured only in a limited interval of OPD and in a spectral interval corresponding to the region where gas absorption lines are located. OPD interval and spectral band are instrument design parameters optimized to maximize the interferometric signal for the retrieval of atmospherical variables such as the concentration of a gas of interest.

The core of a CGI instrument is the fild widened interferometer component: a beam-splitter is complemented with specifically designed mirrors, positioned at a field stop of the instrument, which introduce, between the two interferometric paths, an OPD value that varies linearly along the direction parallel to flight velocity. The recombined signal is then relayed to the detector. Due to the positional dependence of the OPD value, the measured intensity shows a modulation in the along-track direction. An example of the result for a simulated single acquisition is shown in Fig.3.

With the orbital motion of the instrument, each on-ground sample is progressively imaged in subsequent rows of the detector, hence for different OPD values; the sequence of the intensities detected from a single on-ground sample represents the PSI associated with that specific location, and the full information for a 2D scene is named *image of PSI*. The PSI for one spatial sample is the sum of a constant intensity (baseline) and an oscillating intensity (modulation): both of them are used by the retrieval algorithm to produce images of atmospheric variables and then images of XCO_2 and XCH_4 (images of gas).

The Carbon-CGI instrument can measure PSI in different spectral bands on a single detector, with each band occupying a subset of the detector rows. One important aspect is the pointing stability during acquisition of interferograms, to ensure that subsequent acquisition can be attributed to a specific point on-ground allowing the reconstruction of the image of PSIs without radiometric errors introduced by misregistration.

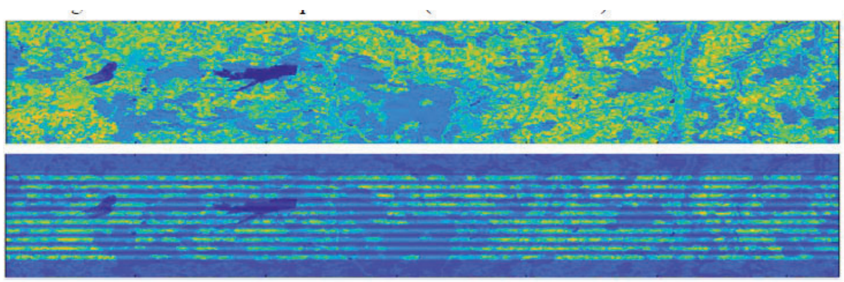

Figure 3. Example of classical image (top), and image detected by a CGI instrument, with modulation introduced by the variable OPD. Satellite velocity is in the vertical direction. The image is an albedo map at 760 nm from Sentinel-3 data.

3.1 Instrument requirements

The consolidation of the instrument requirement, in particular the trade-off on the PSI configuration, was based on simulation performed from ACRI-ST, with a radiative transfer model accepting as inputs spectral bands and OPD intervals, together with the relevant variables describing the atmospheric states, and calculating sounding precision and accuracy for XCO2 and XCH4. The trade-offs by assuming a specific detector format, and evaluated the optimal number of pixels allocated for each PSI, determining the sampling of the PSI fringes, together with instrument swath, and spatial sampling.

Two different instrument architectures were considered, with either one or two focal planes. The instrument employing a single focal plane included three spectral ranges, with one PSI in the NIR band (0,6-0,7 µm) for

O_2, and two PSIs in the SWIR1 band (1,6-1,7 µm) for CO_2 and CH_4. In this architecture the optimal operating point was found for a 200m sampling distance, providing a sounding precision for XCO_2 better than 1 ppm, and lower than 10 ppb for XCH_4.

In the two focal planes instrument, one detector was dedicated to the PSIs in the NIR (0,6-0,7 µm) and a PSI in the VIS band (0.4 µm) for the detection of NO_2, a gas that can be used as a proxy for the detection of CO_2 emissions. The second focal plane was dedicated to the SWIR bands, with two SWIR1 PSIs for CO_2 and CH_4 (1,6-1,7 µm), and an additional PSI in the SWIR2 band (2 µm) for CO_2. This additional SWIR2 band improves the sounding performance for XCO_2.

For the baseline design of the instrument, the configuration with two focal planes was chosen as it provides the best potential for XCO_2 performance, especially with low-albedo scenes, at the price of an increase in complexity which was considered modest. For this configuration, the optimal operating point was chosen with a 108 m sampling distance, with an estimated sounding precision for XCO_2 of 1.5 ppm, of 39 ppb or XCH_4, and of 5.5% for NO_2.

The forward model used in the retrieval of gas concentration values is a multi-band process, which as a result also provides the best estimates for some of the relevant atmospheric variables. This is the case for the water vapor content, since H_2O absorption lines are present in both the SWIR1 and SWIR2 bands for CO_2. For the dry-air column, the estimate obtained from the PSI in the NIR band, with an estimated surface pressure uncertainty in the order of 0.7 hPa.

For the aerosol bias correction the baseline approach, for the instrument as auxiliary of CO2M, is to use the coarser resolution data from the Copernicus mission, as strong spatial variations of aerosols are not expected, and can moreover be detected using high resolution image of XCO_2. For the Self-Standing instrument, in the first part of the study, another approach was considered, based on a machine learning algorithm and using information from the NIR and SWIR1 PSIs, in a configuration with a multi-views instrument.

The selection of the spatial sampling of $\simeq$ 108 m was also supported by flux inversion simulations, performed with a system developed in the context of TRACE (LSCE) to simulate the uncertainty in emission estimates as a function of the quality of the employed satellite imagery. In Carbon-CGI, TRACE was used to evaluate the fraction of point sources (e.g. power plants) and distributed sources (e.g. cities), using plumes simulations including turbulence effects, for a set of pre-defined surface and atmospheric conditions and different wind speeds. These analysis showed the potential to quantify with 20% uncertainty sources smaller with emission rates <1 Mt/y.

3.2 Instrument design

The instrument mechanical accommodation for the baseline design of Carbon-CGI is shown in Fig.4 with all the main sub-systems supported by an optical bench. The two very similar units visible contain the two interferometers and relay optics dedicated respectively to VIS-NIR and SWIR bands: these are here named extended focal planes (EFP).

The front optics of the instrument includes both a pointing mechanism, to allow observations within the CO2M swath of 250 km (see Tab.1), as well as a fast-steering mechanism of the Line-of-Sight Stabilisation System based on the ISABELA technology development; the latter is important to compensate pointing errors and control the pseudo-noise performance. The front optics also includes the dichroic plate used for the separation of VIS-NIR and SWIR bands: this is located after a common input objective.

The two EFP assemblies are similar, and both include refractive optics for the imaging of the scene on the field stop located at the mirrors of the interferometer, and an Offner telescope acting as relay optics to the detector. Band-pass filters are mounted just in front of the detector.

Carbon-CGI scenes are acquired continuously, for a dwell time in the order of few seconds for each spectral band, which enable achieving high sounding precision. The detector for the VIS-NIR bands is a Si-based sensor, while the baseline for the SWIR channel is a HgCdTe detector with a format of 1048×1280 pixels with a pitch of 20 µm, with possible alternatives identified during the study. The cryocooler and a radiator panel required to operate the SWIR detector are visible in Fig.4. Some design parameters are summarised in Tab.3.

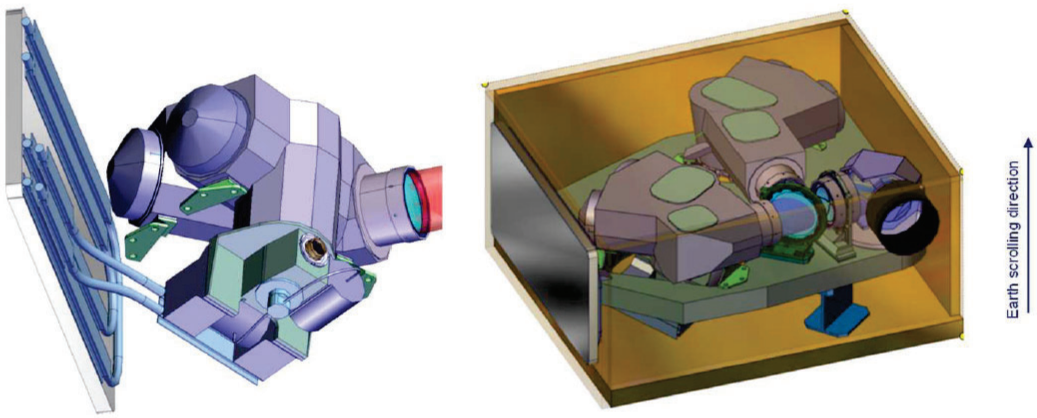

Figure 4. (Left) Bottom view of the EFP assembly for the SWIR channel, with the MCT detector unit visible at the bottom, connected to the radiator for the cryocooler. (Right) Top view of the Carbon-CGI payload, comprehensive of scanning mechanism (on the right) and two EFP assemblies for SWIR (leftmost) and VNIR (topmost).

Table 3. Instrument design parameter for the Carbon-CGI instrument.

Instrument parameter	Value	Notes
Spatial sampling	108 m	obtained with 2×2 binning
Field of View	4.9°× 3.9°	≃ 50 km
Effective Focal Length	300 mm	
Aperture diameter	80 mm	F#=3.6
Optical transmission	40%	

Straylight performance for the Carbon-CGI design was simulated with a ghost analysis performed in FRED. Ghosts were characterized for their spatial distribution, power, optical path, and impact on modulation. The results were used to calculate, via a Matlab model, the relevance of parasitic interferograms.[6] While the contribution of modulated straylight was found to be not significant, parasitic interferograms have an impact on sounding accuracy through non modulated ghosts (baseline). Stray-light analysis indicates that ghosts correction is necessary to achieve compliance with the sounding accuracy requirement (1 ppm for CO_2 and 10 ppb for CH_4). A second part of the straylight study has simulated the impact of both ghosts and scattering in the case of non-uniform (four-quadrant), that has determined a straylight level of around 4%. This result would meet the straylight specification for the CO2M instrument.

During the study, an additional tool was developed to calculate the pseudo-noise resulting from scene scrolling error during scene acquisition. The simulation encompasses the full processing chain, starting from the introduction of scene scrolling error generated by line of sight instability and effects of optical distortion and projection on curved Earth, and land topography. The simulated signal is processed by a correction algorithm, which resamples the acquired PSIs on a fixed grid (image of PSI), before retrieving the geophysical information (image of gas). This tool was used to estimate the impact on the line-of-sight stabilization system, and to determine the performance expected for different assumptions on the performance of the platform AOCS system.

3.3 Final considerations

The Carbon-CGI study has matured the design of an instrument capable of providing images of gas sampled on a 108 m grid over 50 km swath. The trade-offs performed within the study between complexity and performance have identified a pool of instrument configurations with a different number of subsystems (number of focal planes, detector models, pointing unit, AOCS), with associated options for classes of platforms, ranging from nano to micro satellite.

The baseline instrument configuration includes a VIS-NIR and a SWIR focal plane, and is able to provide sounding precision and accuracy both estimated as better than 1 ppm for XCO_2, with additional measurements of CH_4 with estimated precision of 30 ppb with an accuracy of 10 ppb. The instrument baseline has a dedicated spectral band for NO_2, a gas that is a proxy for CO_2 plumes identification. The baseline design also includes an existing technology for the line of sight stabilization, a key component of the design to reduces the impact of image scrolling and secure the mission performance, as resulting from simulations obtained with a dedicated tool. The validation of this technology by test is part of follow up activities to mature the Carbon-CGI technology, as identified by the long term implementation plan elaborated at the end of the study.

The development activities for Carbon-CGI have shown how this sensor has the potential as an auxiliary instrument for the CO2M mission, by providing high-resolution imagery for XCO_2 and XCH_4, and using CO2M measurements for atmospheric characterization. The instrument size with an instrument with the potential to be hosted on a small satellite flying in formation with the Copernicus mission.

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