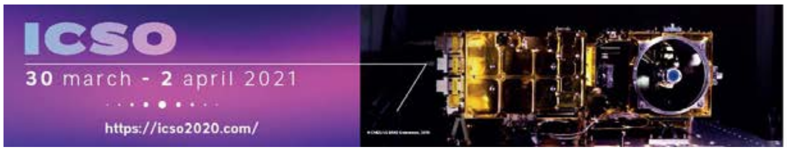
International Conference on Space Optics—ICSO 2020

Virtual Conference

30 March–2 April 2021

Edited by Bruno Cugny, Zoran Sodnik, and Nikos Karafolas



ICSO 2020
INTERNATIONAL CONFERENCE
ON SPACE OPTICS
VIRTUAL

CarbonHIGS

icso proceedings

International Conference on Space Optics — ICSO 2020, edited by Bruno Cugny, Zoran Sodnik,
Nikos Karafolas, Proc. of SPIE Vol. 11852, 118520D · © 2021 ESA and CNES
CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2599154

CarbonHIGS

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ABSTRACT

CarbonHIGS is a 2D imager designed to measure the enhancement of CO_2 concentration in emission plumes from power plants. The origin of HIGS, and the physics of the working principle will be explained. Two possible implementations of HIGS will be presented, i.e. one that uses power splitting while the other one uses polarization splitting. The characteristics of these implementations will be discussed. In the final part of this paper the preliminary design of the CarbonHIGS system will be shown.

Keywords: Imager, Remote sensing, Interferometer, Carbon dioxide

1. INTRODUCTION

The onset for the HIGS idea was brought about by the ever increasing requirements for the spectrometers in Earth observation satellites [1]. The spectral resolution requirements were getting more stringent as well as those for the spatial resolution. The amount of light captured per detector pixel will thereby reduce strongly, requiring a larger instrument to meet the SNR requirement. Since this will ultimately lead to large and costly instruments, we considered alternative approaches to space-borne observations for atmospheric chemistry and climate applications. Owing to the knowledge built up using spectrometers, the HIGS concepts could be developed.

The name HIGS is an acronym that stands for Huib's Innovative Gas Sensor. The HIGS idea was conceived in the year 2013 around the time the HIGGS boson was first measured, and it was selected as name for this instrument concept to honour the inventor Huib Visser. HIGS can most easily be described as a static FTS (Fourier Transform Spectrometer), however, while a standard FTS is used to measure a spectrum, HIGS makes use of the knowledge about the spectrum thus enabling a new measurement method. The name CarbonHIGS will be used in the following in case we discuss the CO_2 measuring unit. For general discussions on the presented measuring method the name HIGS will be used, since HIGS is not limited to the detection of CO_2. In 2017 result on a breadboard version of HIGS, operating in the visible wavelength range was published [2]. That breadboard was designed to detect NO_2 in the atmosphere.

The past two decades have seen an impressive evolution of space-borne instruments for atmospheric chemistry applications (SCIAMACHY, GOME, GOME-2, OMI, TropOmi, and TropOMI/Sentinel-5p). The instrument concept has evolved from scanning to push-broom imaging, enabled by the advent of large image detectors in the near- and short-wave infrared spectral regions. More recently, the concept of push-broom imaging spectrometers has been applied to measuring greenhouse gases carbon dioxide (CO2) and methane (CH4) by JAXA's GOSAT and NASA's OCO-2 missions, as well as the Chinese TANSAT mission. While these missions, as well as the CNES' future MicroCarb mission, are mainly dedicated to studying the global carbon cycle, which is dominated by biogenic sources and sinks, imaging of emission plumes from anthropogenic CO2 sources, such as power plants, has been demonstrated by [3]. Due to its nature as a well-mixed gas, the enhanced concentration of CO_2 in emission plumes quickly decreases with distance from the source. Therefore, spatial resolution is of paramount importance for imaging anthropogenic CO_2 plumes. Detection and quantification of mid-size point sources (power pants) and cities will require spatial resolution below one kilometre, while still maintaining high

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precision. Such high resolution is difficult to obtain from conventional push-broom imaging spectrometers based on diffraction grating technology. This is because the dispersion of light for measuring an extended spectral band at high spectral resolution necessitates a large entrance pupil size to reach the required signal-to-noise ratio (SNR) of the measured radiance. This in turn leads to impractically large instruments and unfeasible grating sizes.

2. GOAL OF CarbonHIGS

ESA has funded a study at TNO with a budget to investigate the possibilities of CarbonHIGS to measure CO_2 concentration levels in emission plumes from e.g. power plants. A key requirement in this study is that the instrument should have a spatial resolution better than 300 m, and an accuracy for measuring the concentration of CO_2 of 1 to 2 ppm. The Field of View (FoV) should be 30 $\times$ 30 km. The science analysis in the frame of the CarbonHIGS study concluded that this accuracy level allows to quantify the flux of power plants with emissions higher than 2.5 (2 ppm) - 1 (1 ppm) $MtCO_2$/year to an accuracy of 15%..

The possibilities for a CarbonHIGS based system have to be investigated to either fly together with another instrument in a so called zoom-mode, or as a stand-alone mission. In case CarbonHIGS flies in formation with a companion instrument, e.g. a push-broom imaging spectrometer like Copernicus CO2M, it is expected that all corrections for e.g. water vapour and aerosols are derived from the co-located measurements of the companion instruments. A stand alone version of CarbonHIGS, on the other hand, would require additional units or other 2D imagers to provide those corrections. An instrument with a shared telescope that measures both water vapour and CO_2 has conceptually been designed.

3. HIGS EXPLAINED

The idea of HIGS is based on the fact that many gases in the Earth's atmosphere show a characteristic absorption structure. As an example the absorption coefficient for CO_2 is shown in Fig.1. This regular absorption feature shows a strong resemblance with the transmission of an interferometer having a optical path difference (OPD) between its two arms. This OPD creates a wavelength dependent throughput where the two interferometer outputs are of course mutually out of phase. If the OPD is matched to the spectral density of the absorption features, a highly selective and sensitive detector can be created. In this way one output of the interferometer will have the spectral throughput corresponding to the absorption features, while the other output receives light of the wavelengths that are not, or at least not so strongly, absorbed. The bandwidth of light reaching the detector is limited by a band-filter. The HIGS instrument records two images, the outputs of the interferometer, pertaining to one ground scene. The difference in intensity of those two images is a direct measure for the concentration of the gas being measured.

3.1 Modes of operation

Looking at Fig.1 two HIGS implementation modes become apparent. The first is the Line-mode. In this mode a large OPD value is implemented such that a fast oscillating throughput function is obtained that matches the line structure in the absorption features. The second mode of operation is the Lobe-mode, in which a smaller OPD is created such that the oscillating throughput matches the envelope of the absorption features.

3.1.1 Line mode

As stated above, in the Line mode the OPD value is tuned such that the transmission function equals the spectral density of the absorption features. In this mode the HIGS instrument is optimally sensitive for the gas to which the OPD is matched, and shows limited sensitivity for other absorption features in the spectral range being measured.

A drawback of the Line mode is that a large OPD values is often required in order to arrive at a high spectral density. In the implementation section, Sec.4, the two basic interferometer types will be explained with their limitations on OPD values. The overlap of the OPD filter and the absorption features is often only good over a limited wavelength range. This wavelength range has to be selected by the band filter in the system, resulting in less photons as compared to the Lobe mode, that can lead to a decreased sensitivity.

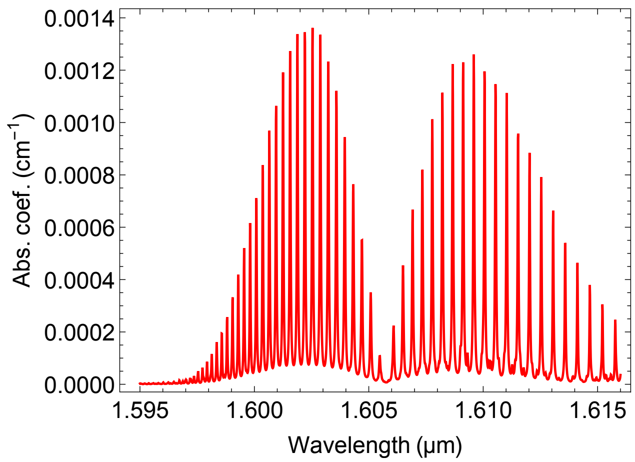


Figure 1. Absorption coefficient of CO_2 showing two lobes, each consisting of many absorption lines.

In Fig.2 a possible Line mode OPD is shown. The lines being measured are in the shorter wavelength lobe as shown in Fig.1. The required OPD is about 8 mm.

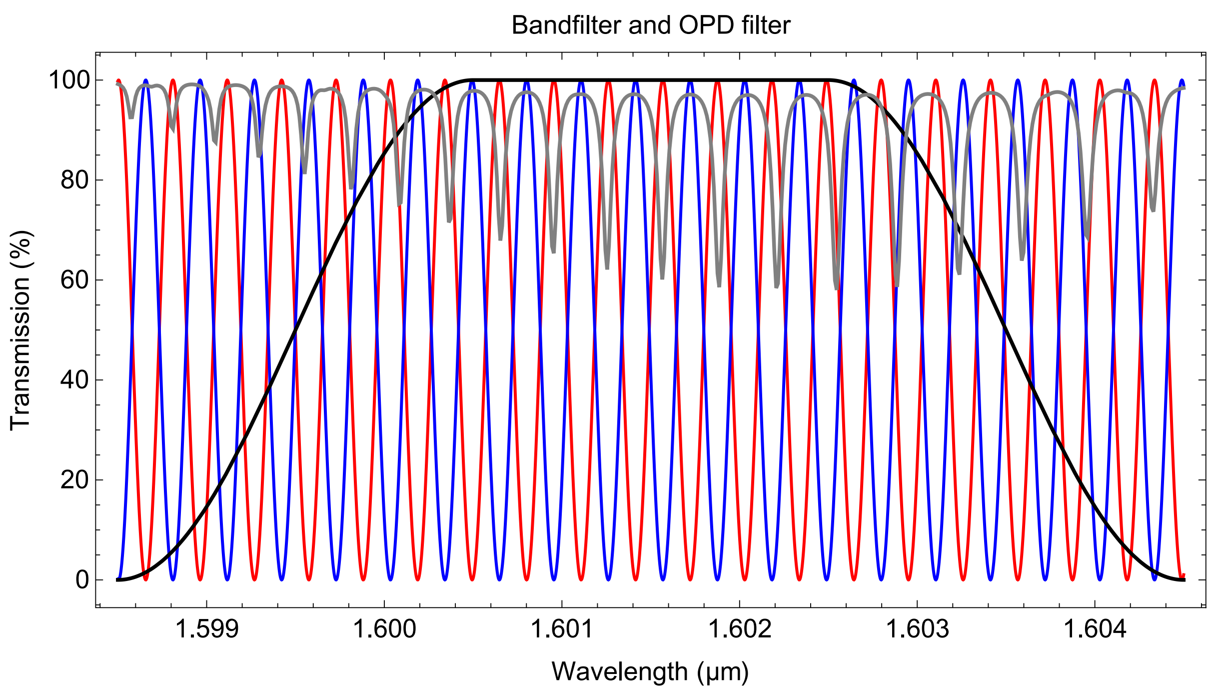


Figure 2. Filter functions for the Line mode. In red and blue the OPD functions and in black the band-filter. In grey the CO_2 spectrum is shown.

3.1.2 Lobe mode

Figure 3 shows the filter functions for the Lobe mode. In the Lobe mode a smaller OPD value is required since the spectral density is far lower than in the Line mode: an OPD value of about 0.37 mm was used. The drawback of the Lobe mode is that it is less selective than the Line mode. The Lobe mode can be more sensitive for the gas being measured and the signal levels are higher than in the Line mode owing to the wider spectral range being measured.

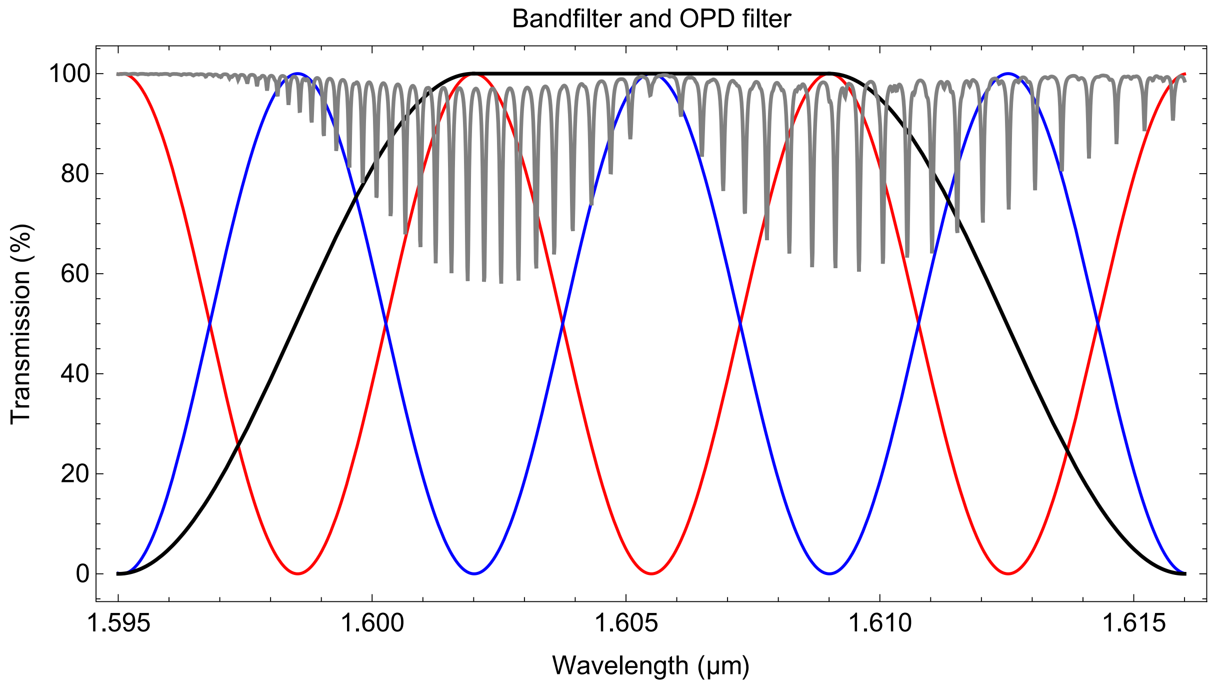
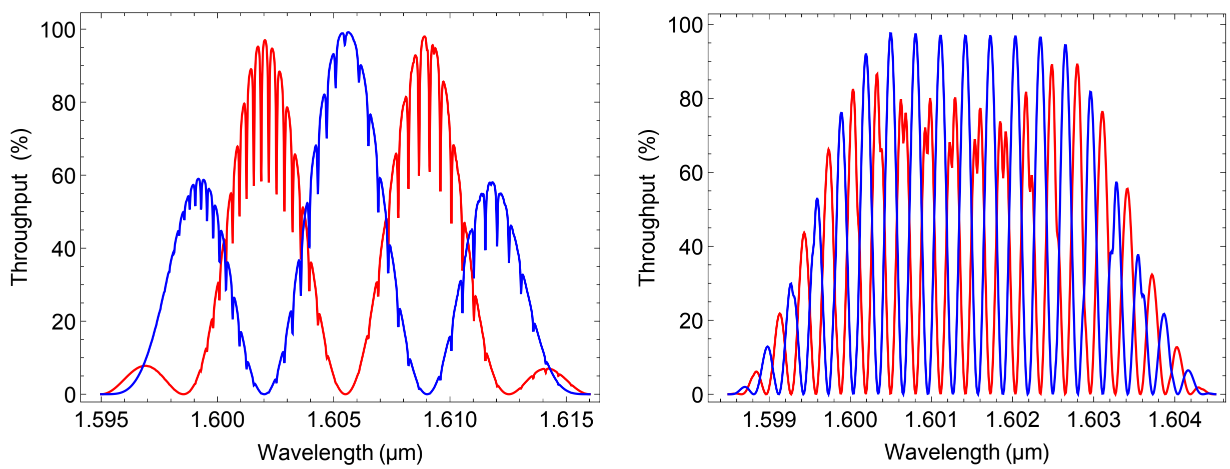


Figure 3. Filter functions for the Lobe mode. In red and blue the OPD functions and in black the band-filter. In grey the CO_2 spectrum is shown.

3.2 Detection limit



Lobe Line

Figure 4. In Red and Blue the in- and out-of-phase signals are shown for the two presented modes

In order to get a value for how sensitive a given HIGS configuration is for measuring a certain gas, the first steps of the data analysis are discussed. The throughput spectra have to be integrated over the spectral range as defined by the band filter. A scaled version of the signal to be integrated in case of CO_2 measurements is shown in Fig.4, both for the Line and Lobe mode. The signal per detector pixel can be described by

$$S_{in} = \int_{\lambda_{min}}^{\lambda_{max}} I(\lambda) \left[\frac{1}{2} + \frac{1}{2}\cos\left(\frac{\text{OPD}}{\lambda}2\pi\right)\right] \partial\lambda \quad (1)$$

$$S_{out} = \int_{\lambda_{min}}^{\lambda_{max}} I(\lambda) \left[\frac{1}{2} - \frac{1}{2}\cos\left(\frac{\text{OPD}}{\lambda}2\pi\right)\right] \partial\lambda \quad (2)$$

where $I(\lambda)$ stands for the Earth radiance (expressed in $ph/cm^2.sr.s.nm$) multiplied by the etendue ($cm^2.sr$), the efficiency of the optical system and detector, and the integration time. The integration interval λ_{min} to λ_{max} is defined via the band-filter. The subscripts *in* and *out* stand for in-phase and out-of-phase, respectively, i.e. the two images as recorded in the HIGS system.

The difference signal

$$\Delta S = S_{in} - S_{out} \quad (3)$$

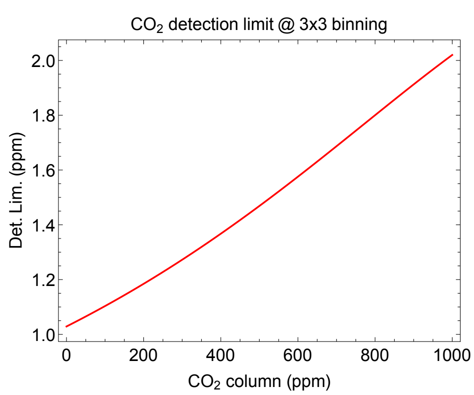
is a measure for the concentration of the gas being measured. The noise, or inaccuracy in determining this difference signal is equal to

$$\text{Noise} = \sqrt{S_{in} + S_{out}} \quad (4)$$

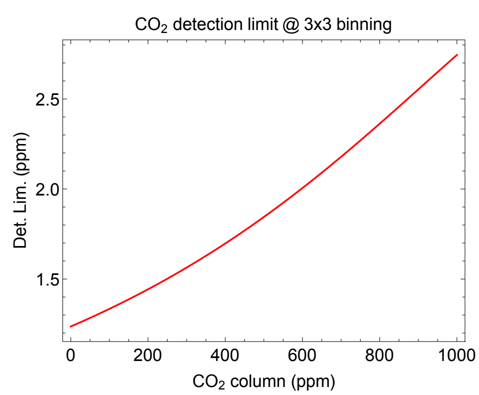
Signal noise is for HIGS often allowed owing to the high signal levels, therefor other noise sources are omitted here. Since the ΔS can become zero for certain concentration levels depending on spectral width of the band-filter, the ratio between ΔS and the Noise cannot be used to specify the Signal to Noise ratio. It is better to determine what concentration change can be measured with an SNR of unity. To determine this value the slope of ΔS as a function of concentration has to be determined, the $\Delta S'$. The detection limit DL (at unit SNR), expressed in ppm, is found by

$$DL = \frac{\text{Noise}}{\Delta S'} \quad (5)$$

For this analysis the Earth albedo is assumed to be known. The detection limit for the CarbonHIGS unit operating in Lobe mode (lhs), and Line mode (rhs) are shown in Fig.5. For the shown detection limit a 3×3 binning is taken into account as well as an f/5 beam towards the detector. To arrive at the detection limits, an integration times of about, or even exceeding 60 s is required. A scanning mirror to freeze the scene enables these integration times.



Lobe



Line

Figure 5. Detection limit for measuring CO_2, for the two presented modes.

4. IMPLEMENTATIONS

The HIGS system is an interferometer with an OPD between its two arms. A sketch of a HIGS based system is shown in Fig.6. The light path from the entrance aperture, through the telescope and band filter, into the interferometer can be seen. The interferometer has two outputs that can be guided to a single detector, or each to its own detector. In an interferometer the light is split into two arms. The light propagates through these two arms, after which the light recombines. Splitting can be done in two ways, power- or polarization splitting, see Fig.7. A power splitting interferometer that is best suited for HIGS is the Mach-Zehnder, based on the accessible two output ports that are mutually in anti-phase. The OPD creating element for a Mach-Zehnder is a planar piece of glass with the proper thickness to create the desired spectral throughput function.

For a polarization splitting interferometer the most stable version is the one where the beams propagate common path. This can be achieved via birefringent crystals where the splitting of the polarized input is into the Ordinary- and Extraordinary beams in the crystals. The incoming light needs to be linearly polarized and the optical axis of the crystal has to be placed under 45 degrees with the polarization direction. A polarizing beam splitting cube in the light path after passage thought the birefringent crystal combines the two modes and creates the two images as required for the HIGS concept. The OPD for birefringent crystal is the thickness of the crystal multiplied by the difference between the ordinary and extraordinary refractive indices. Since this difference is often very small this automatically results in thick crystal. Due to this a birefringent based HIGS cannot be used in case a large OPD value is required.

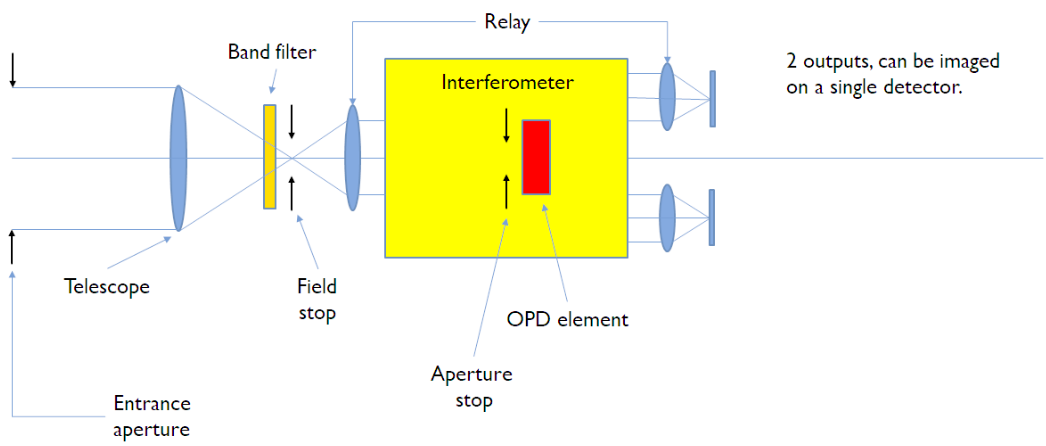


Figure 6. Sketch of HIGS system.

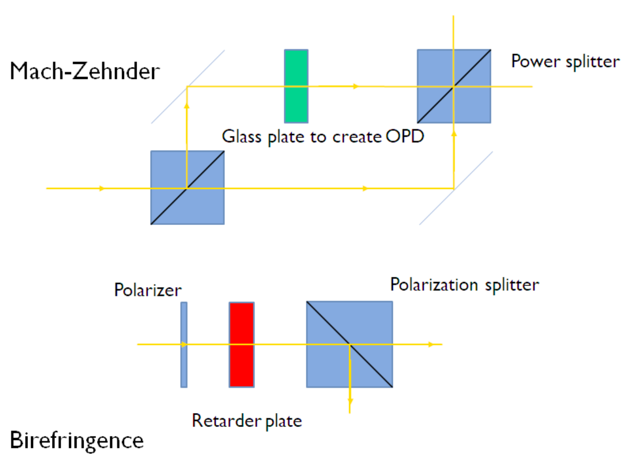


Figure 7. Layout of the interferometers in Fig.6. Top: the power splitter based Mach-Zehnder, and bottom: the polarization based interferometer.

5. DISCUSSION AND CONCLUSIONS

The HIGS concepts has been explained and two modes of measuring have been presented, the Line- and Lobe-mode. Due to the fact that the Line-mode for many gasses will require a large OPD value, i.e. exceeding 1 mm, the Mach-Zehnder based HIGS is often most suited for that mode. The Lobe-mode, owing to the widely spaced spectral fringes, requires a low OPD value and can make use of the polarization based interferometer. This system is inherently stable owing to the common path propagation through the interferometer. Although the Lobe-mode will have a higher SNR than the Line-mode, owing to the larger spectral range, this does not automatically lead to a higher sensitivity for the gas being measured. This sensitivity is determined by the difference signal between the two images and is found to be higher for the Line-mode in certain situations. It should be noted that the Line-mode will have lower sensitivity to other gasses, e.g. in the case of measuring CO_2, water vapour and aerosols.

The schematically presented system will have a detection limit of down to 1 ppm of CO_2, for a ground pixel of 200×200 m, which makes it an ideal system to fly along a larger instrument and to operate in so-called zoom-mode. A scan mirror will allow the system to measure for a longer time at one place, thereby obtaining the indicated low detection limit. The larger instrument, although having a coarser ground sampling, can be used for some of the required corrections. For the corrections that need to be recorded using the same ground sampling, an additional HIGS or other 2D imager needs to be integrated in the same satellite. Ideas for a completely stand-alone mission have been developed and will be presented in the future.

In the course of 2021 the ESA study will be completed. At that time the sensitivity to stray-light and ghosting will be known, and a full tolerance analysis will have been made. A follow-up paper will be issued in which all these results will be presented.

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