# CO2Image: the design of an imaging spectrometer for CO2 point source quantification

David Krutz, Ingo Walter, Ilse Sebastian, Carsten Paproth[a], Thomas Peschel, Christoph Damm,
Stefan Risse, Henrik von Lukowicz[b], Anke Roiger[c], Andre Butz[d], Claas Köhler[e]

German Aerospace Center, [a]Institute of Optical Sensor Systems, Rutherfordstr. 2, 12489 Berlin,
[c]Institute of Atmospheric Physics, [e]Earth Observation Center, Münchener Str. 20, 82234 Weßling,
[b]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str.7, 07745
Jena, [d]Institute of Environmental Physics, University of Heidelberg, Im Neuenheimer Feld 229

## ABSTRACT

CO2Image is a satellite demonstration mission, now in Phase B, to be launched in 2026 by the German Aerospace Center (DLR). The satellite will carry a next generation imaging spectrometer for measuring atmospheric column concentrations of Carbon Dioxide (CO2). The instrument concept reconciles compact design with fine ground resolution (50-100 m) with decent spectral resolution (1.0-1.3 nm) in the shortwave infrared spectral range (2000 nm). Thus, CO2Image will enable quantification of point source CO2 emission rates of less than 1 MtCO2/a. This will complement global monitoring missions such as CO2M, which are less sensitive to point sources due to their coarser ground resolution and hyperspectral imagers, which suffer from spectroscopic interference errors that limit the quantification.

**Keywords:** Carbon dioxide, Short wave infrared, Imaging spectrometer

## 1. INTRODUCTION

The CO2Image mission, currently in Phase B, complements current and planned Copernicus missions such as Sentinel-5p [1] and CO2M [2]. Current instruments typically have a spatial resolution of a few kilometers and are able to measure greenhouse gas concentrations in the Earth's atmosphere with high precision and broad spatial coverage. CO2Image, under lead of the Institute of Atmospheric Physics in co-operation with the University of Heidelberg, will work in concert with these missions, acting as a sort of magnifying glass – to precisely measure emissions of the greenhouse gases carbon dioxide and methane from sources like power plants, industrial facilities and coal mines which global survey missions cannot resolve. This is accomplished through a novel instrument development with a comparatively high spatial resolution of 50 meters under responsibility of the Institute of Optical Sensor Systems together with the Fraunhofer Institute of Applied Optics and Precision Engineering. The instrument, called COSIS, is scheduled for launch in 2026 as the mission's main payload. The Earth Observation Center is in charge of processing the scientific data and calibrating the instrument.

Currently, about 30% of fossil $CO_2$ emissions are released from such point sources, primarily from coal-fired power plants, but also from industrial facilities. Figure 1 shows the spatial distribution of these emissions, as well as their magnitude. Based on the measurement capabilities of the currently planned satellite missions about a quarter of these point-source emissions will be detectable from space. In contrast, the technique demonstrated by CO2Image would be able to measure about 90% of these emissions [3].

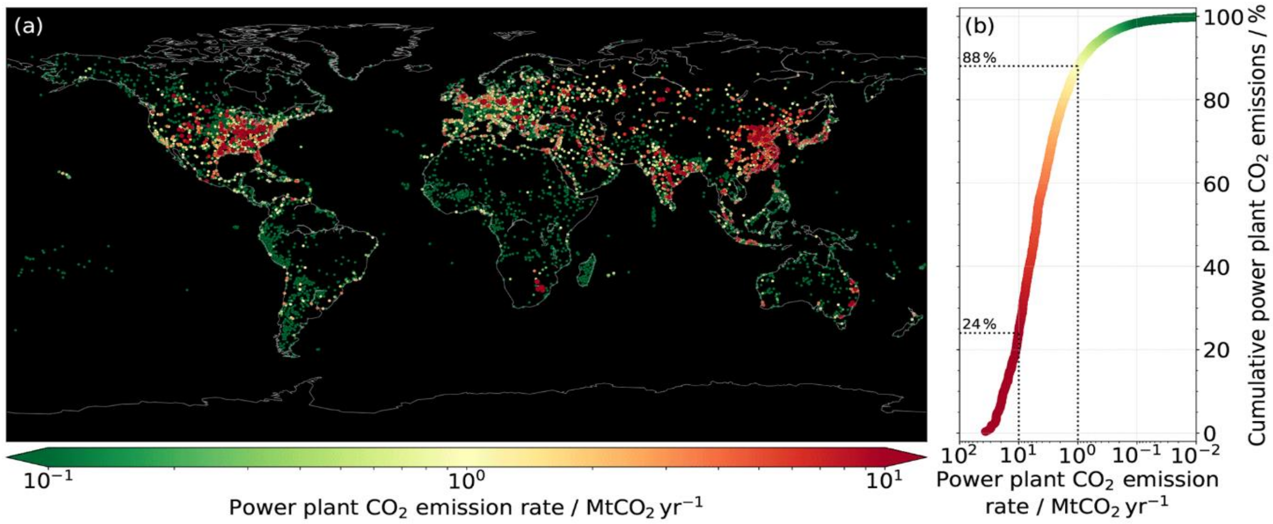


Fig 1, left: Geographic distribution of estimated annual CO2 emissions from power plants worldwide (CARMA database). Right: The cumulative distribution of the same CO2 emissions. About 64% of these emissions come from medium-sized power plants with emissions of 1-10 MtCO2 per year (images from [3])

## 2. COSIS INSTRUMENT DESIGN

### 2.1. Requirements and pre-conditions

The primary payload of the CO2 Image mission consists of COSIS (CO2 Sensing Imaging Spectrometer) which is under detailed design study right now. Base is a technical parameter set answering the requirements for the verification of $CO_2$ and $CH_4$ emissions on a point source scale from a LEO orbit (575 km) according to table 1.

| Parameter | Value |
|---|---|
| F# | 2.0 |
| Focal length | 230 mm |
| Field of view | +/- 2.5° |
| Instantaneous field of view | +/- 0.0025° |
| Ground sampling distance | 50 m |
| Swath | 50 km |
| Spectral range | 1.9 … 2.4 µm |
| Spectral channels | 693 |
| Spectral sampling distance | 0.65 nm |
| Signal-to-Noise Ratio (@ 2.0um with 1.0E+12 photons/s/sr/cm^2/nm) | 100 |
| Radiometric linearity | > 98% |
| Radiometric resolution | 12 bit |
| MTF | 15%...25% |
| FWHM | 1.5 nm |
| Pixel Pitch | 20 x 20 µm² |
| Frame Rate | 11 Hz |
| Mass | 85 kg |

Table 1. COSIS instrument requirements

Due to the extremely small sampling distance required an excellent radiometric performance is the main development goal. As a consequence, a high numerical aperture according to F#2 is mandatory combined with sufficient pixel size at detector level. Furthermore, it was decided to cover the spectrum with a single focal plane although the science would require a range between 1.925 and 2.085 nm for carbon dioxide and 2.305 and 2.385 µm for methane detections leaving a gap of about 200 nm not used.

### 2.2. Instrument heritage and archetype

An important technology background for the COSIS development is the DESIS instrument [4,5,6] providing hyperspectral imaging with 30 m ground resolution in 235 bands of 2.5 nm spectral sampling in the range of 400 to 1000 nm. This system according to Figure 3 is operational since 2018 as an external payload aboard the International Space Station.

Fig. 2 Astronaut A. Gerst handling the DESIS container for ISS external operation

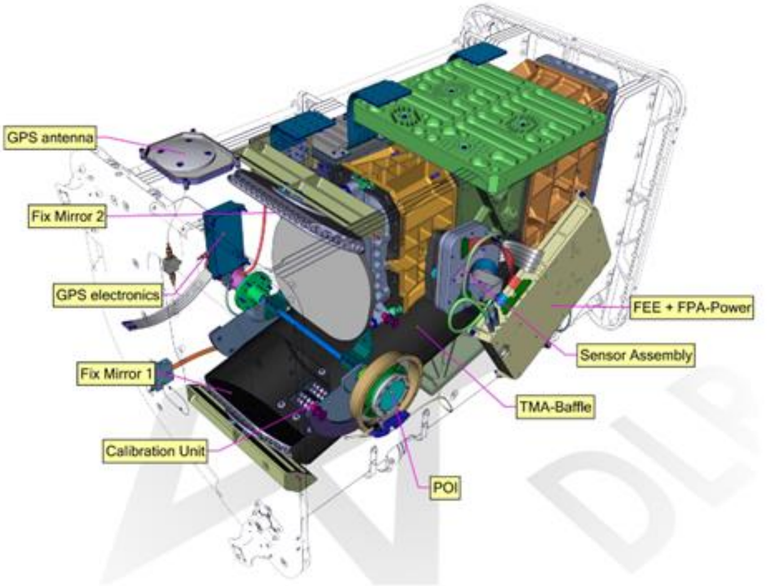


Fig. 3 DESIS instrument adapted to the base plate (green) completed by pointing and calibration device, sensor electronics and attitude control components

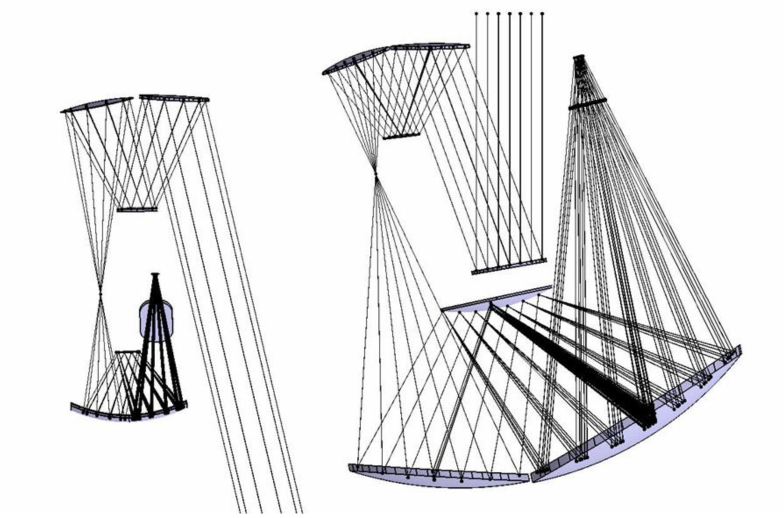
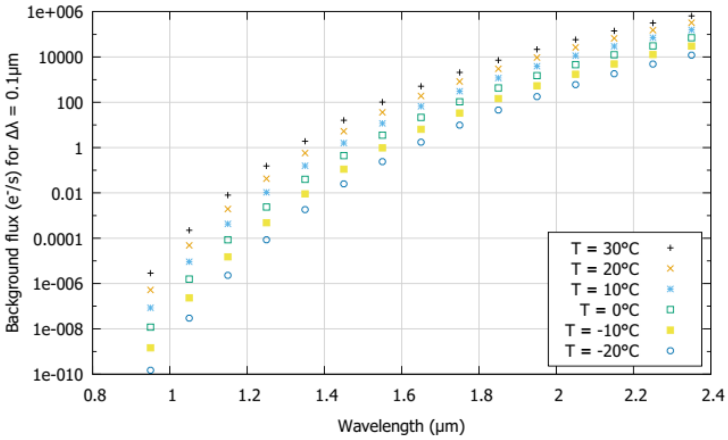


Fig. 4 DESIS optics design (left, [7]) for VISNIR imaging at 30 m ground sampling distance (GSD), 3.5 nm spectral sampling transformed into COSIS optics (right) of the same principle for SWIR imaging at 50 m GSD, 0.5 nm spectral sampling. The sizes are of the same scale for comparison: COSIS largest mirror is of 450 mm diameter, the overall optics length is about 1 m

### 2.3. Initial design and performance

The heritage of the DESIS system was taken as the starting point. It is basically an all-reflective Offner spectrometer using the 1st order of diffraction at a slit illuminated by a Three Mirror Anastigmate (TMA) as front optics. The same principle was used according to Figure 4 for a COSIS baseline system. Driven by the spectral resolution the Offner is growing significantly and mirrors and grating reaching technology challenging dimensions. However, this design was used for early radiometric analysis work resulting in the following general statements:

- The thermal background is a substantial noise contribution (see Fig. 5)
- The system can cope with the SNR requirements (see Fig. 6)



| Parameter | Value |
|---|---|
| Pixel pitch | $p = 20\,\mu\mathrm{m}$ |
| Integration time | $t_{\mathrm{int}} = 100\,\mathrm{ms}$ |
| Dark current | $d = 7500\,\mathrm{e}^-/\mathrm{s}$ |
| Readout noise | $r = 100\,\mathrm{e}^-$ |
| Quantization noise | $q = 4\,\mathrm{e}^-$ |
| Optics f-number | $F_\# = 2$ |
| Background f-number | $f_\# = 1.1$ |
| Quantum efficiency | $\mathrm{QE} = 0.75$ |
| Optical efficiency | $\mathrm{OE} = 0.5$ |
| Start wavelength | $\lambda_1 = 0.9\,\mu\mathrm{m}$ |
| End wavelength | $\lambda_2 = 2.4\,\mu\mathrm{m}$ |

$$n_b = \frac{\pi}{4 f_\#^2} p^2 \cdot \mathrm{QE} \cdot t_{\mathrm{int}} \int_{\lambda_1}^{\lambda_2} B_T(\lambda) \frac{\lambda}{hc} d\lambda$$

Fig. 5 Thermal background flux ($n_b$ = number of background electrons) with the parameters applied as a function of the operational wavelength depending on the system temperature. While irrelevant in the VISNIR the region above 2µm is affected.

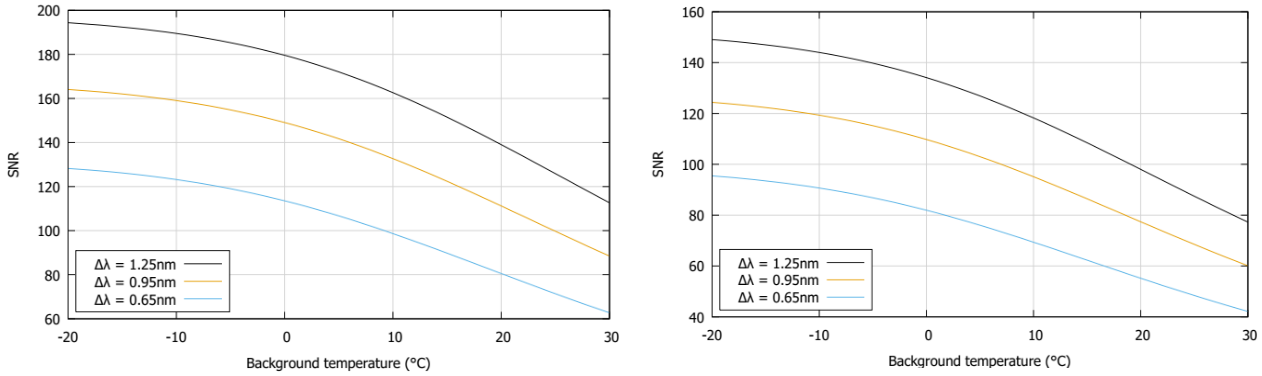


Fig. 6 Signal to noise ratio SNR for the CO2 reference radiance L=1.3x$10^{12}$ ph/s/sr/cm$^2$/nm (left) and the CH4 reference radiance L=8.5x$10^{11}$ ph/s/sr/cm$^2$/nm (right) for different spectral sampling distances as a function of temperature.

Because of this the optics design needs to be optimized regarding the thermal background by cooling or cold apertures implementation. Secondly the optics aperture size needs to be kept with no option of reduction for sufficient SNR performance. Consequently, several optic design alternatives have been considered for improvements and to study the opportunities for technical realisation in reasonable cost and time frames.

### 2.4. Offner modifications

Leaving the symmetry principle of the classical Offner a modification to Offner-Chrisp allows for different radii and distances at input and output sides for the spectrometer. This results in a more compact design with homogeneous MTF over field and spectrum. The convex grating is based on diamond turned technique with an expected efficiency of about 60%. However, tool parameters have significant influence on this efficiency causing a need for qualified bread board manufacturing.

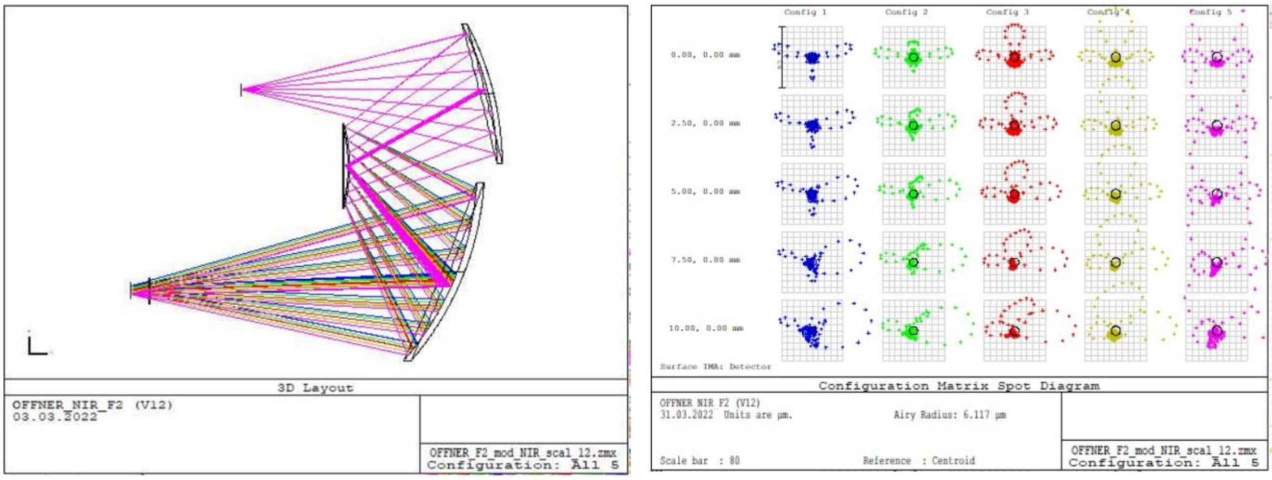


Fig. 7 Offner-Chrisp spectrometer lay-out and spot images. The grating diameter is 138 mm. Free form parts of the mirrors surface provide excellent performance over the slit and wave lengths

Using the -1$^{st}$ diffraction order with the output close to the input side of the spectrometer leads to the Littrow-configuration resulting in a very compact lay-out. For F#2 the MTF reached was by far not sufficient which together with the inadequate geometry situation for placing the detector led to discard this option.

### 2.5. TMA-based spectrometers

These spectrometers using TMA to collimate the radiation from the slit and to focus the diffracted light onto the detector.

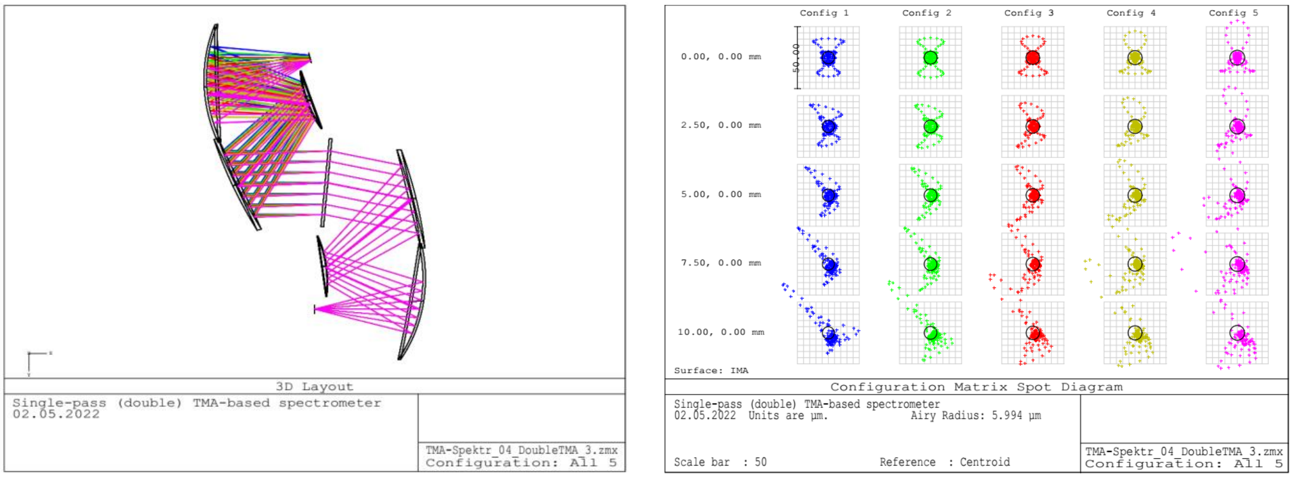


Fig. 8 TMA spectrometer in single-path configuration lay-out and spot images. The TMA design is identical for both, the grating diameter is about 200 mm.

The grating has fully planar geometry while being transmittive for individual paths with 2 TMA (single-pass design) and reflective for the double-pass option using the same TMA in two-way manner. Although being compact the ladder has the similar difficulty with the vicinity of slit position and the image plane as the Littrow and therefor a low potential of using.

Showing a similar well MTF performance compared to the Offner-Crisp the advantage of the single-pass TMA design is the high grating transmission performance which is expected to be better than 80% based on e.g. e-beam lithography or holography manufacturing techniques. Furthermore, system performance testing can be organized sequentially with TMA alignment and focusing without the grating installed before full spectral performance verification.

The configuration shown has a potential of getting more compact by turning the two TMA's at the grating plane into a 3D folded configuration as shown in Figure 9. A third TMA is added as the entrance telescope combining at least 3 components of similar size and technology.

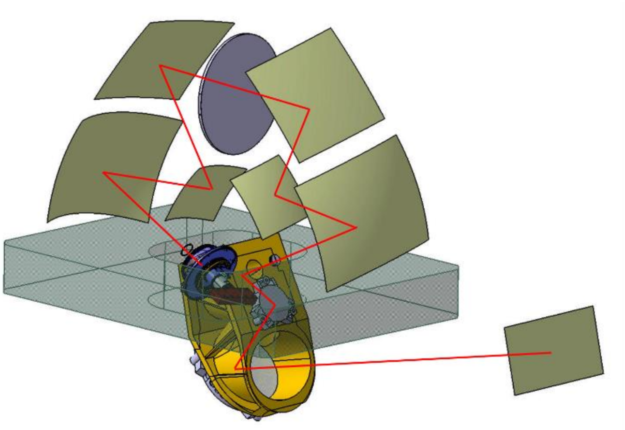


Fig. 9, right   Spectrometer in folded configuration using 3 TMA. The entrance is located underneath the platform together with the dewar containing the detector. The grating is assessible from top.

### 2.6. Dyson spectrometers

In order to consider refractive alternatives also the Dyson spectrometer using a grating on a large, concave mirror in combination with a lens of similar size. Since in the basic form slit and image plane are located directly at the lens entrance surface the output spectrum is barely accessible by the detector and the design must be modified in order to get access to the image.

An optimized variant with a double lens system including a rotationally symmetric asphere is shown in Figure 10. providing excellent performance in the centre wavelengths dropping slightly towards the upper and lower extremes. The typical lens diameter shown is 200 mm with masses of 4.1 and 1.7 kg respectively based on synthetic fused silica as the material.

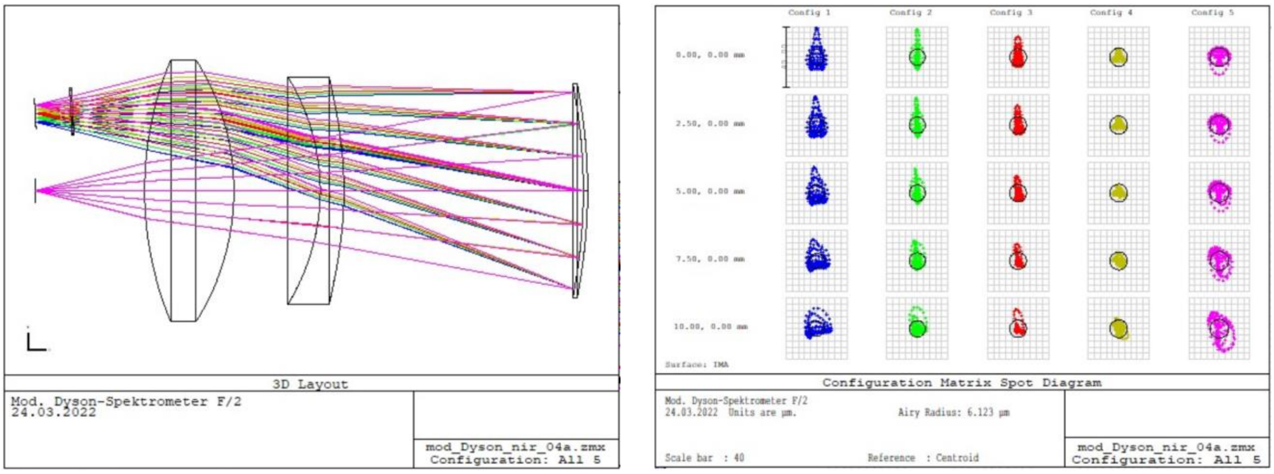


Fig. 10   Dyson spectrometer lay-out and spot images. The option with 2 lenses reduces mass but requires aspherical geometry.

A major challenge of the Dyson is the manufacturing of the concave grating of this size while diamond processing is much more demanding compared to turning for convex gratings regarding tool control.

Due to the material mix of the applied materials the sensitivity to temperature changes of the lens-based system is higher, in this case requiring an optics thermal stabilization of about 10K.

### 2.7. Entrance optics implementation

Combining the entrance TMA with the spectrometer completes the system. To cope with the components size avoiding collisions fold options needs to be considered. The fold mirrors are also suitable for spectral cut-on filter implementation. For system alignment aspects the slit assembly is physically added to the TMA. This is shown in Figure 11 for the Dyson design but relevant for all other options.

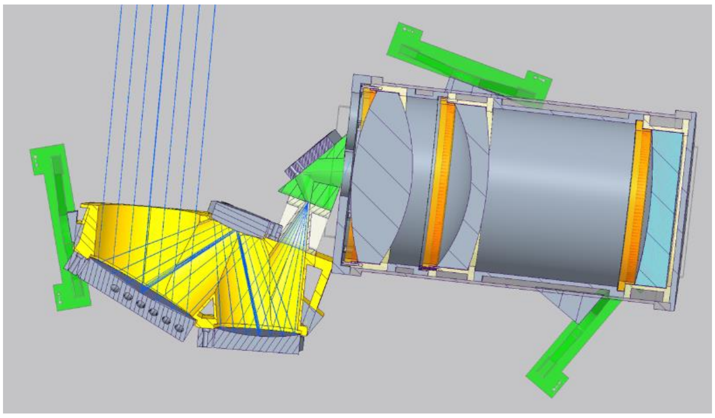


Fig. 11 Dyson spectrometer equipped with the entrance TMA via a fold mirror.

### 2.8. Re-imaging versus optics cooling

One of appropriate ways to reduce the thermal background in IR-systems is the implementation of the cold shield installed in front of the detector in such a way that it acts as a cold aperture stop of the optics. Driven by the aperture size required a re-imaging system needs to be considered for that purpose. Secondly the problem with the geometry limits for the focal plane gets solved also.

A full refractive solution is shown for the Dyson in Figure 12 which can be adapted to the reflective options the same way in principal.

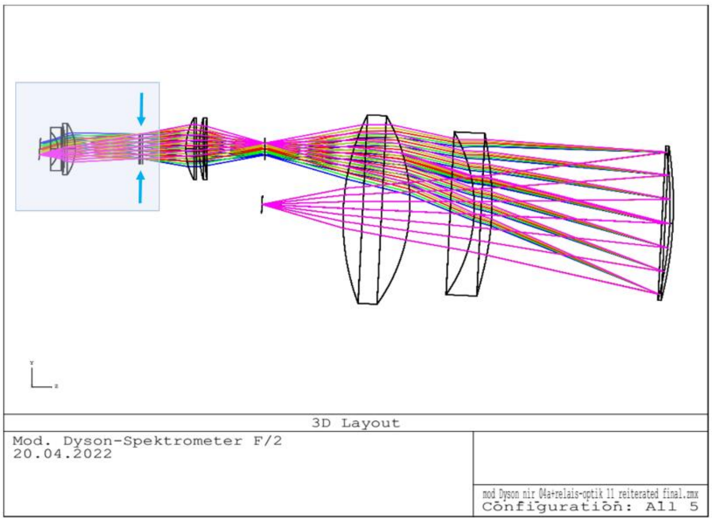


Fig. 12 Re-imaging telescope added to the entrance of the Dyson spectrometer. The cold stop is identified with the arrows inside the dewar.

Despite the effort of the additional optics there are several draw backs to be mentioned:

- Re-imager optics parts inside the dewar complicating its design substantially
- Thermal background signal from the slit cannot be eliminated
- The overall radiometric throughput is reduced by additional transmissive losses

Considering this the re-imaging is perfect for standard imaging telescopes but less effective for COSIS. Here the best solution is to adapt the detectors cold shield inside the dewar to the F# beam and keep all relevant optic elements cold enough. Basically, this is the last optics element in front of the detector with cooled-down surrounding or baffle es well as the slit unit cooled. Preliminary analysis requires an operational range of -30 to -10°C for those. The option of cooling the optics is also raising the question if the detector needs to be installed in a dewar or the full optics-detector system will be operated at cryogenic temperatures. With respect to ground testing efforts the dewar is the by far the preferred option.

### 2.9. Detector system

Early definition of the sensor system for the project is crucial for the instrument design and its development approach. For the spectral range to be covered by COSIS in principle several detector materials could be considered. With respect to availability of high-performance framing detectors only HgCdTe and spectral extended InGaAs are realistic to be used. At least a project dedicated selection defined AIM's 1280 x 1024 pixels AGD MCT system as the baseline.

According to Figure 13 the detector is situated in a dewar, cooled down to 150 K nominally with a pulse- tube split stirling cooling system behind. Although of significant size this technology is of high reliability and flight heritage. The lifetime is optimized by reduced mechanics-wear in the helium chain and balanced compressor operation with the help of magnetic bearings for lowest possible vibration.

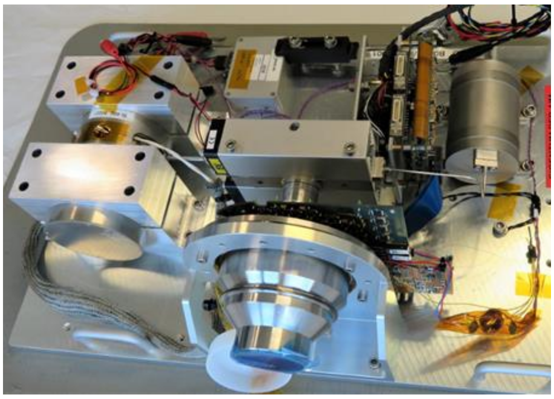
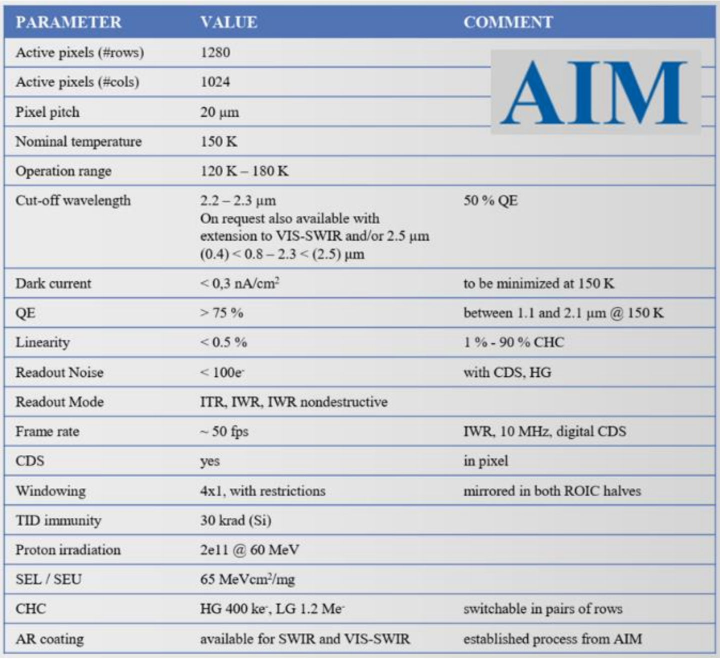


Fig. 13 SWIR sensor engineering model: dewar in the centre with ADC and Cooler Electronics, Stirling compressor on the left, Pulse tube volume on the right side

Table 2 AIM SCD detector parameter set



| PARAMETER | VALUE | COMMENT |
|---|---|---|
| Active pixels (#rows) | 1280 | |
| Active pixels (#cols) | 1024 | |
| Pixel pitch | 20 µm | |
| Nominal temperature | 150 K | |
| Operation range | 120 K – 180 K | |
| Cut-off wavelength | 2.2 – 2.3 µm<br>On request also available with extension to VIS-SWIR and/or 2.5 µm<br>(0.4) < 0.8 – 2.3 < (2.5) µm | 50 % QE |
| Dark current | < 0,3 nA/cm$^2$ | to be minimized at 150 K |
| QE | > 75 % | between 1.1 and 2.1 µm @ 150 K |
| Linearity | < 0.5 % | 1 % - 90 % CHC |
| Readout Noise | < 100e$^-$ | with CDS, HG |
| Readout Mode | ITR, IWR, IWR nondestructive | |
| Frame rate | ~ 50 fps | IWR, 10 MHz, digital CDS |
| CDS | yes | in pixel |
| Windowing | 4x1, with restrictions | mirrored in both ROIC halves |
| TID immunity | 30 krad (Si) | |
| Proton irradiation | 2e11 @ 60 MeV | |
| SEL / SEU | 65 MeVcm$^2$/mg | |
| CHC | HG 400 ke$^-$, LG 1.2 Me$^-$ | switchable in pairs of rows |
| AR coating | available for SWIR and VIS-SWIR | established process from AIM |

## 3. SUMMARY

For the COSIS instrument as the main payload of the CO2 mission the baseline design with rich heritage from space operational systems has been established. While the detector system is in prototype operation already for proving the relevant system parameters for the optics several trades are going on.

Here the focus is now on reaching the next step for the best performance option paired with achievable technology effort reducing the risk of the mission. Therefor the Offner spectrometer is a well understood solution with certain risks in the mirror size and the grating performance. The TMA spectrometer in single path configuration relaxes the components sizes, simplifies the diversity of optics and provides the best radiometric performance by high grating efficiency. This consistently all-reflective design shall be combined with appropriate thermal design for cooling the optics. The Dyson representing the refractive design option is not providing significant size reduction and is due to the most challenging grating technology of less significance. Radiometric throughput and thermal design issues are less advantageous also.

After the optics decision the design is going to be more detailed. Here also the in-flight calibration system will be worked out. Conceptual it will be a U-sphere device in combination with a beam shaping fold mirror in front of the system aperture providing SWIR flat field imaging. The mirror is default in open position and sequentially flipped into the optical path for closing the aperture for dark and calibration measurements.

## REFERENCES

[1] M. Reuter, et al.: Towards monitoring localized CO2 emissions from space: co-located regional CO2 and NO2 enhancements observed by the OCO-2 and S5P satellites, Atmos. Chem. Phys., 19, 9371–9383, https://doi.org/10.5194/acp-19-9371-2019, 2019. a, b

[2] ESA: Copernicus CO2 Monitoring Mission Requirements Document, available at: https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v2.0_Issued20190927.pdf (last access: 12 November 2019), EOP-SM/3088/YM-ym, 2019. a

[3] J. Strandgren et al, “Towards spaceborne monitoring of localized CO2 emissions: an instrument concept and first performance assessment”, Atmos. Meas. Tech., 13, 2887–2904, https://doi.org/10.5194/amt-13-2887-2020, 2020.

[4] D. Krutz et al., “The instrument design of the DLR Earth Sensing Imaging Spectrometer (DESIS)”, Journal of Photogrammetry & Remote Sensing, Feb 2019

[5] A. Eckardt et al., "DESIS (DLR Earth Sensing Imaging Spectrometer for the ISS-MUSES platform)," 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2015, pp. 1457-1459, doi: 10.1109/IGARSS.2015.7326053.

[6] G. Kerr et al., "The hyperspectral sensor DESIS on MUSES: Processing and applications," 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2016, pp. 268-271, doi: 10.1109/IGARSS.2016.7729061.

[7] T.Peschel et al., “Design of an imaging spectrometer for Earth observation using freeform mirrors” International Conference on Space Optics ISCO, Biarritz, France, Oct 2016