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

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1. Background

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

CO2Image is a satellite demonstration mission, now in Phase B, to be launched in 2026 by the German Aerospace Center (DLR).

Instrument: COSIS (CO2 Sensing Imaging Spectrometer)

Next generation imaging spectrometer for measuring atmospheric column concentrations of carbon dioxide (CO2). CO2Image will enable quantification of point source CO2 emission rates of less than 1 MtCO2/a.

Presentation of the process to find the best SWIR spectrometer design for COSIS:

Different possible spectrometer concepts will be presented and evaluated w.r.t. their compatibility with the requirements. The focus is on reflective spectrometer designs and the use of free form optical surfaces.

2. Team

DLR German Aerospace Center,
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Institute of Atmospheric Physics, Earth Observation Center, Münchener Str. 20, 82234 Weßling,
https://www.dlr.de/pa/en/desktopdefault.aspx/

Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str.7, 07745 Jena,
https://www.iof.fraunhofer.de/en.html

Institute of Environmental Physics, University of Heidelberg, Im Neuenheimer Feld 229
https://www.iup.uni-heidelberg.de/en

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4. COSIS instrument design based on mission requirements

The 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:

Parameter	Value
F# of optics	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** **carbon dioxide: 1.925 – 2.085 µm** **methane: 2.305 – 2.385 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
System MTF @ Nyquist frequency	15%...25%
Spectral FWHM	**1.5 nm**
Pixel Pitch	20 x 20 µm²
Frame Rate	11 Hz
Mass	85 kg

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5. DESIS – DLR heritage on MUSES platform on ISS

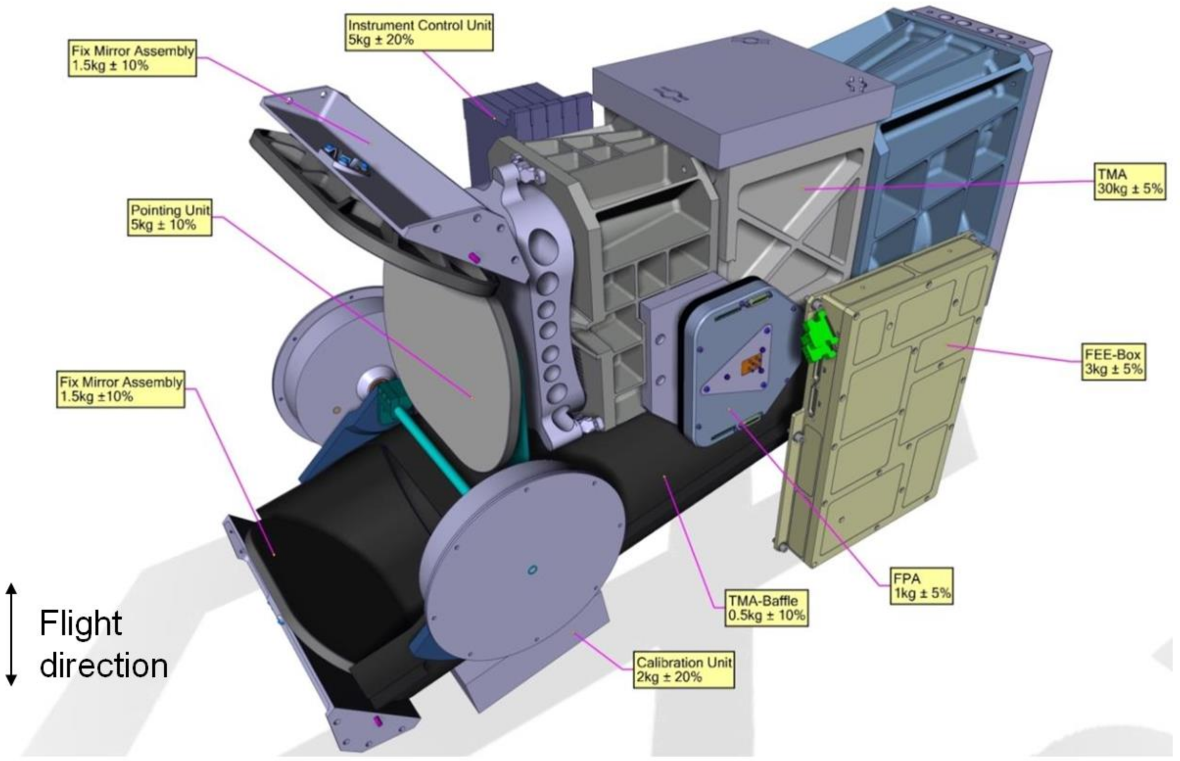
https://www.dlr.de/os/en/desktopdefault.aspx/tabid-12933/ https://www.tbe.com/what-we-do/markets/geospatial-solutions/desis

- DESIS – DLR Earth Sensing Imaging Spectrometer
- Hyperspectral VIS/NIR Imaging System 0.4-1 µm
- 235 spectral channels
- 30 m GSD
- 2.5 nm spectral sampling distance
- Spectral FWHM of 3.5 nm

- Operated at ISS in collaboration between Teledyne Brown Engineering (TBE) and DLR

- All-reflective Offner spectrometer design with Three Mirror Anastigmate (TMA) of **DESIS has been taken as initial starting optics design for COSIS.**

DESIS Design



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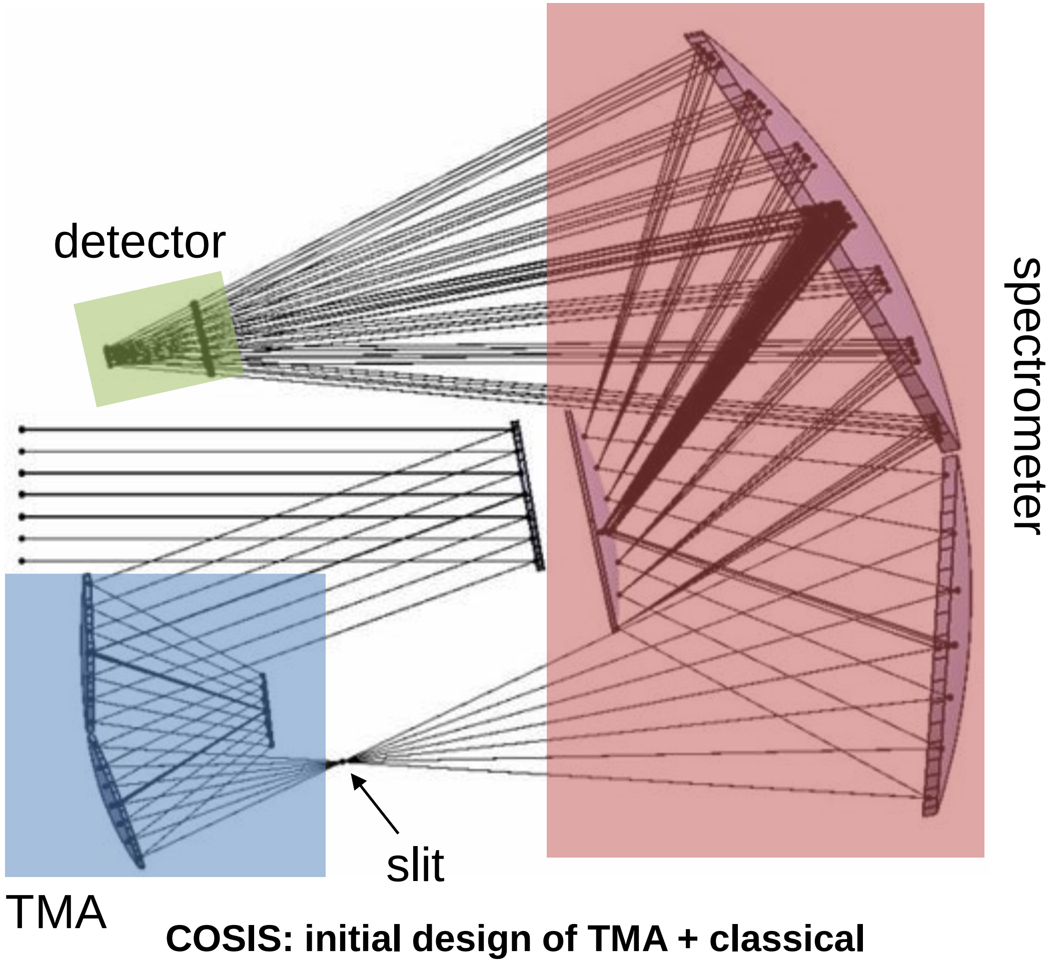
6.1 Initial design: TMA + classical Offner type spectrometer

- Front optics as Three Mirror Anastigmat (TMA) in blue
- Initial Offner type spectrometer in red
- Detector (with dewar) in green
- **Advantage:** fair optical performance, drops down at the edges of the slit
- **Disadvantage:** Challenging dimensions - the overall optics length: about 1m
- **Disadvantage:** Challenging grating technology – grating would be a convex curved surface of more than 200 mm diameter
- **Classical Offner type spectrometer has been rejected.**



COSIS: initial design of TMA + classical Offner type specrtrometer

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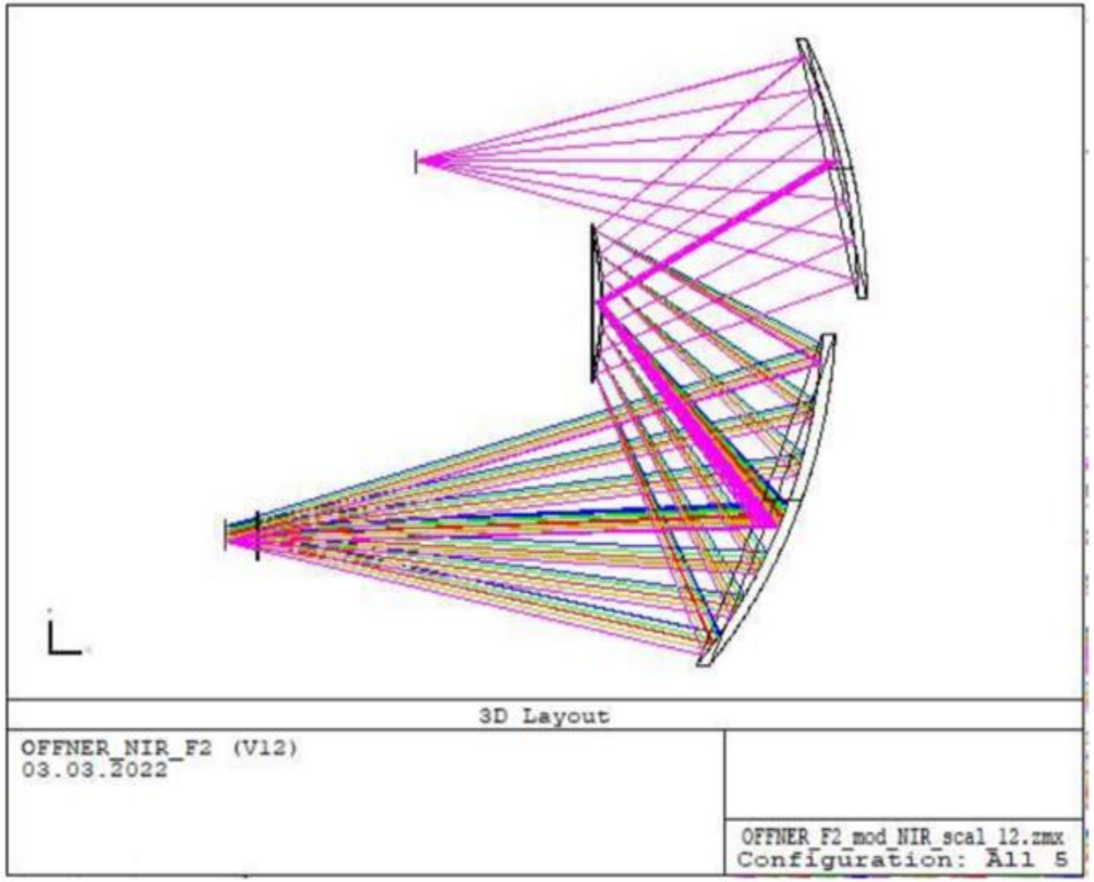
6.2 Offner spectrometer modifications

- Offner-Chrisp modification allows different raddii and distances at input and output side of the spectrometer.

- **Advantage:** Compact (smaller) design with more homogeneous, excellent MTF over field and spectrum.
- **Advantage:** Convex grating (diameter 138 mm) would based on diamond turned technique with an expected efficiency of about 60%.

- **Disadvantage:** Inadequate geometry situation for placing the detector led to discard this option.

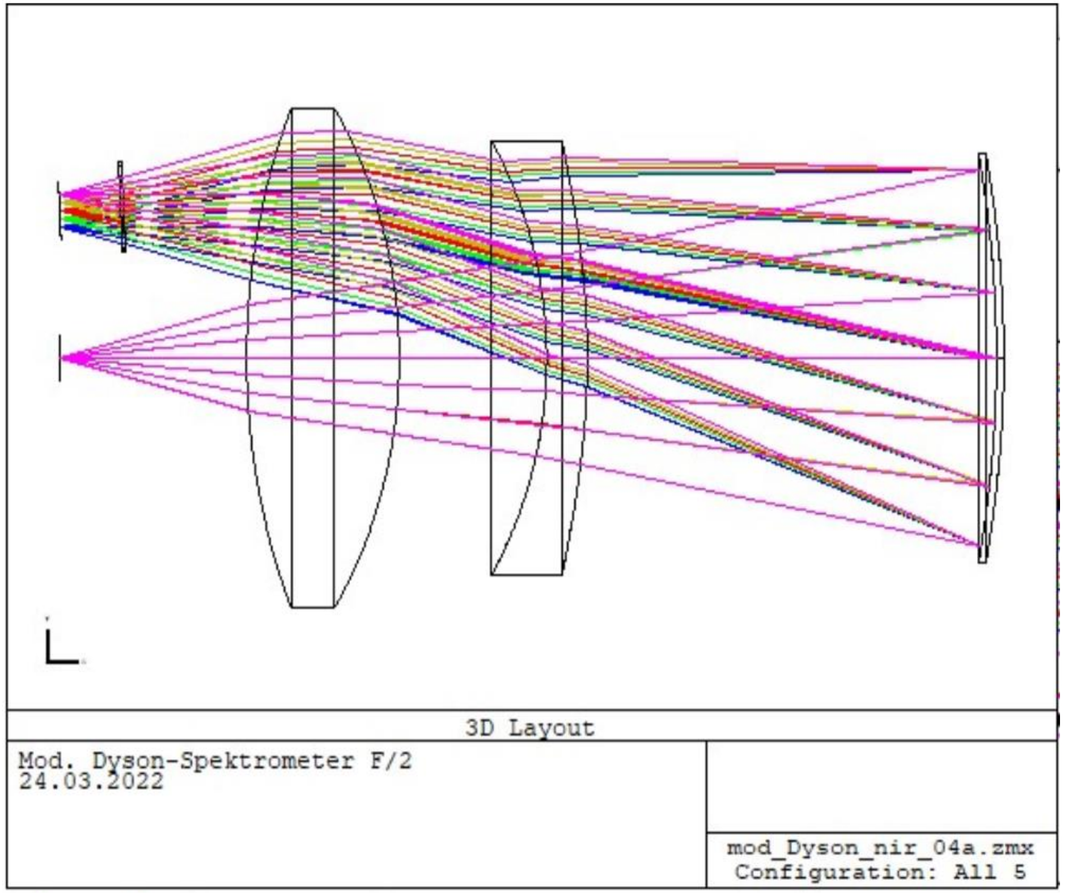


Offner-Chrisp spectrometer lay-out. The grating diameter is 138 mm. Free form parts of the mirrors surface provide excellent performance over the slit and wavelengths

6.3 Dyson spectrometers

- Dyson spectrometer: refractive alternative using a grating on a large, concave mirror in combination with a (double) lens of similar size based on synthetic fused silica
- **Advantage:** Excellent performance in the centre wavelengths dropping slightly towards the upper and lower extremes
- **Disadvantage:** Typical lens diameters of 200 mm with masses of 4.1 and 1.7 kg, respectively
- **Disadvantage:** Manufacturing of the concave grating of this size with diamond processing is much more demanding compared to turning for convex gratings regarding tool control.
- **Disadvantage:** Material mix results in strong sensitivity to temperature changes

- **Dyson spectrometer has been rejected.**



Dyson spectrometer lay-out.
The option with 2 lenses reduces mass but requires aspherical geometry.

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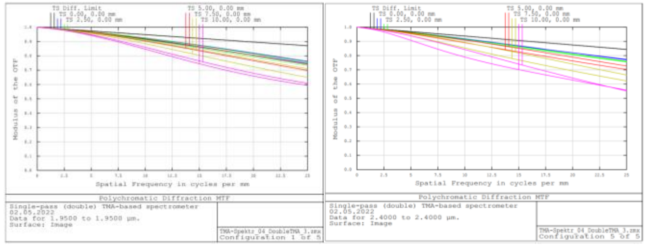
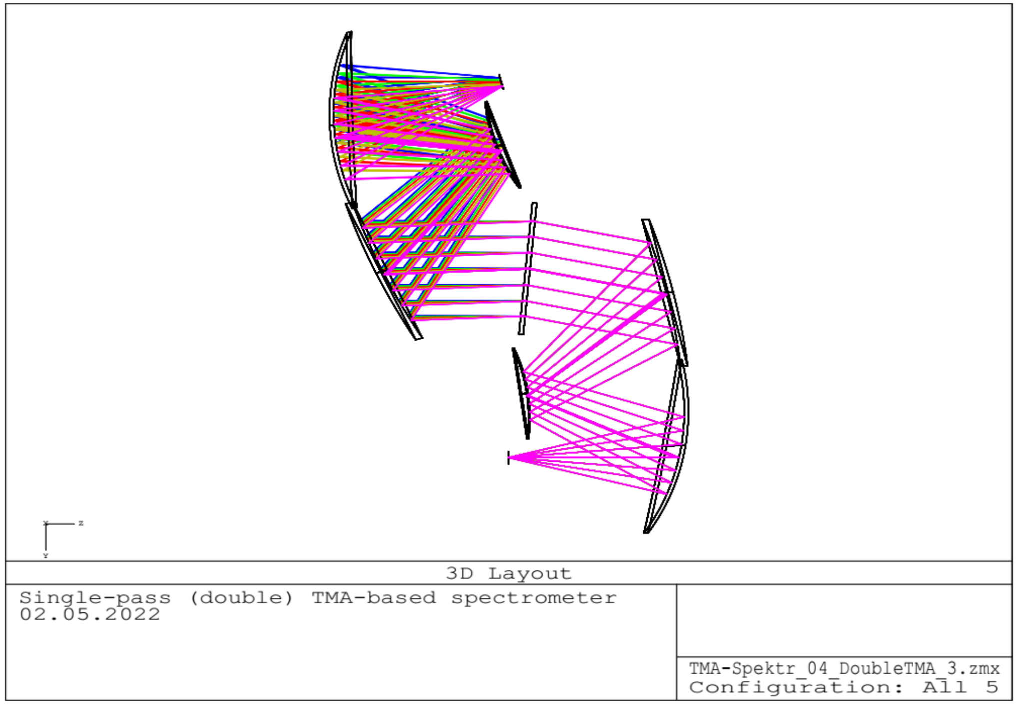
6.4 TMA-based spectrometers

- Double TMA spectrometer in single-path configuration: The TMA design is identical for both, the grating diameter is about 200 mm.
- The double TMA spectrometer shows a similar well MTF performance compared to the Offner-Chrisp.

- **Advantage:** Transmissive planar grating in Littrow configuration with efficiency better than 80% - able for manufacturing on e.g. e-beam lithography or holography manufacturing techniques
- **Advantage:** Test of system performance can be organized sequentially with TMA alignment and focusing without the grating installed before



MTF of the TMA-based spectrometer in single-path @ 1.95 µm (left) and @ 2.4 µm (right)



TMA-based spectrometer in single-path configuration lay-out.
The TMA design is identical for both, the grating diameter is about 200 mm.

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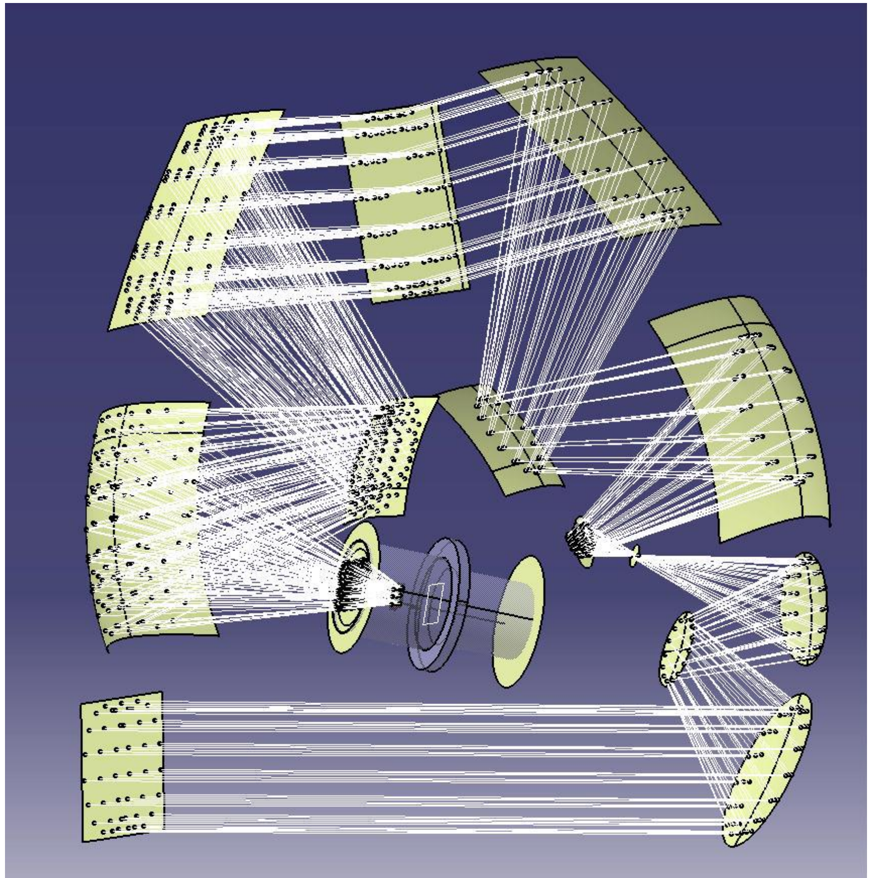
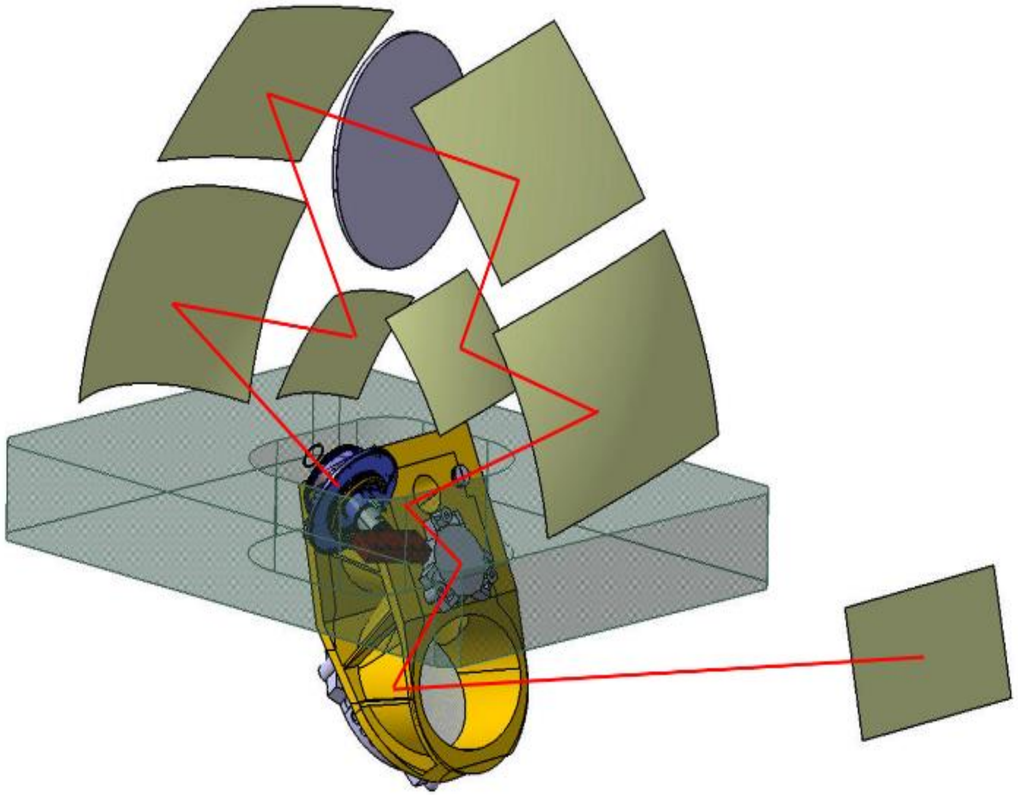
6.4 TMA-based spectrometers II

Final: The folded double TMA spectrometer combined with the front optics TMA (3 TMAs in total) have been decided for the COSIS optics baseline design.



Assembly on platform: Spectrometer in folded configuration using 3 TMAs. The entrance is located underneath the platform together with the dewar containing the detector.
The grating is assessible from top.



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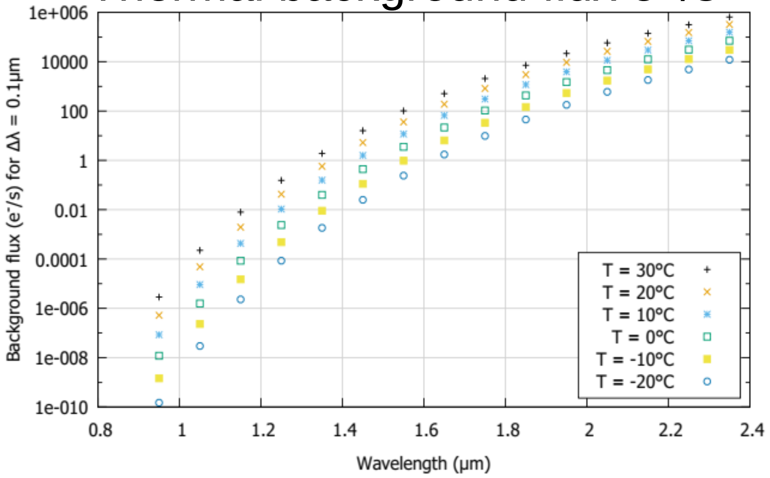
6.5 Thermal background

Thermal background flux e- /s

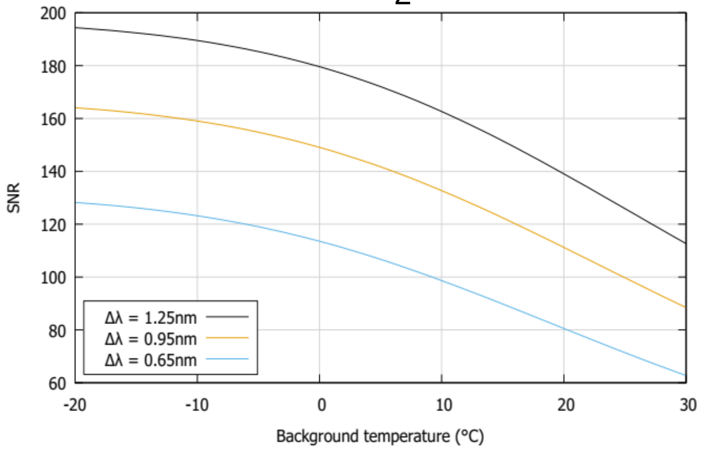


Parameter	Value
Pixel pitch	$p = 20\,\mu\mathrm{m}$
Integration time	$t_{\mathrm{int}} = 100\,\mathrm{ms}$
Dark current	$d = 7500\,\mathrm{e}^-/\mathrm{s}$
Readout noise	$r = 100\,\mathrm{e}^-$
Quantization noise	$q = 4\,\mathrm{e}^-$
Optics f-number	$F_\# = 2$
Background f-number	$f_\# = 1.1$
Quantum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

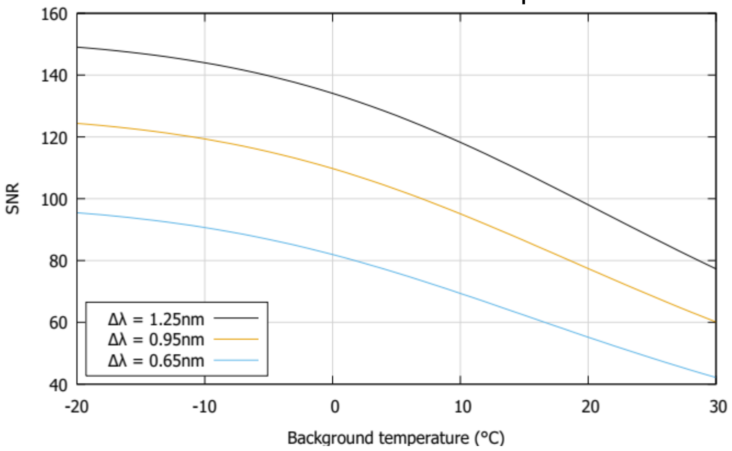
$$n_b = \frac{\pi}{4f_\#^2} p^2 \cdot \mathrm{QE} \cdot t_{\mathrm{int}} \int_{\lambda_1}^{\lambda_2} B_T(\lambda) \frac{\lambda}{hc} d\lambda$$

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.

SNR: CO_2



SNR: CH_4



Signal to noise ratio SNR for the CO2 reference radiance L=1.3x10^{12} ph/s/sr/cm²/nm (left) and the CH4 reference radiance L=8.5x10^{11} ph/s/sr/cm²/nm (right) for different spectral sampling distances as a function of temperature.

Preliminary analysis requires an operational range of -30 to -10°C .

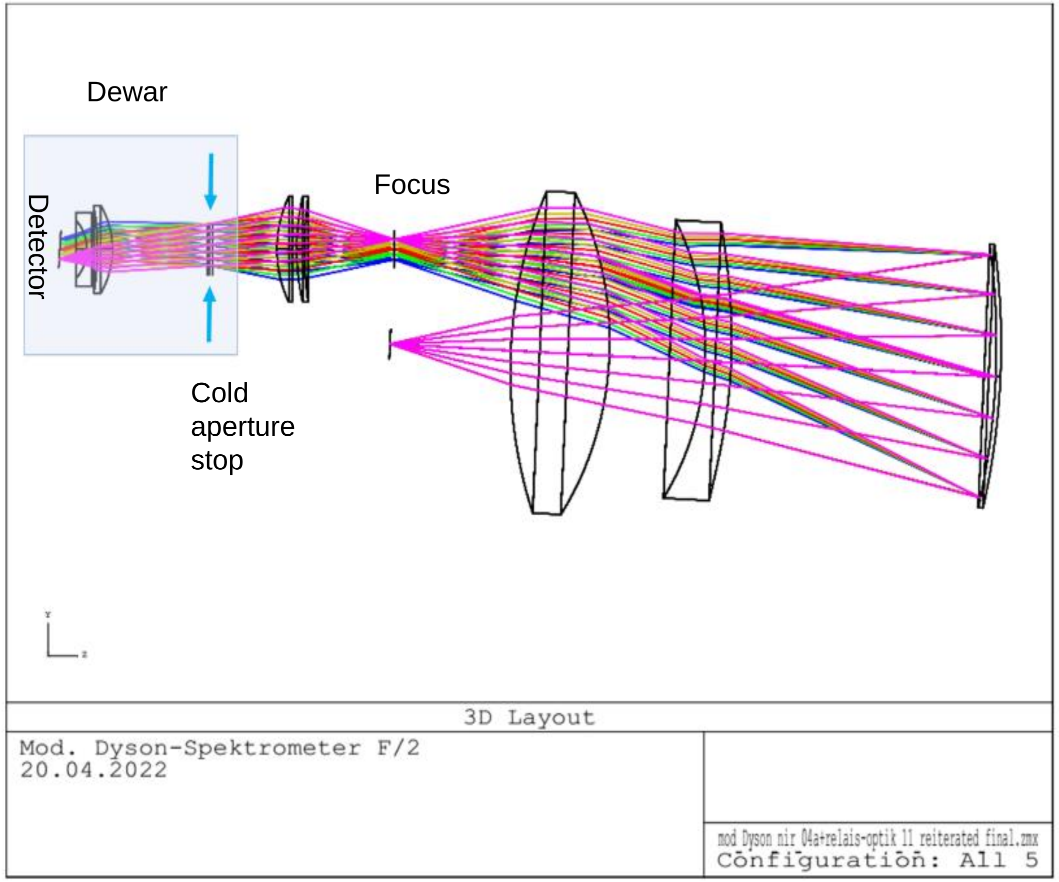
6.6 Re-imaging versus optics cooling

- Implementation of a cold shield in front of the detector to reduce the thermal background which acts as a cold aperture stop of the optics

- **Advantage:** keep thermal background of the instrument rear area out of detector, testing @ ambient possible
- **Disadvantages:**
    - Re-imager parts inside the dewar – highly complicate
    - Thermal background from slit cannot eliminated
    - Reduced radiometric throughput

- Re-imaging is perfect for standard imaging telescopes (with high F/#) – but less effective for COSIS.

- **Conclusion: cooling the complete optics is preferred**



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

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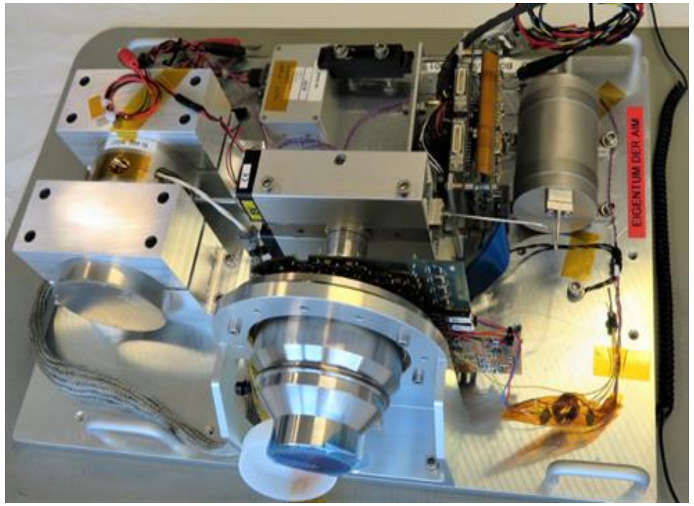
7. Detector system

- AIM (https://www.aim-ir.com/en/home.html) HgCdTe 1280 x 1024 pixels AGD system
- Dewar, cooled down to 150 K nominally with a pulse- tube split stirling cooling system
- High reliability and flight heritage.
- Lifetime is optimized by reduced mechanics-wear in the helium chain and balanced compressor operation by magnetic bearings for lowest possible vibration.



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

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 On request also available with extension to VIS-SWIR and/or 2.5 µm (0.4) < 0.8 – 2.3 < (2.5) µm	50 % QE
Dark current	< 0,3 nA/cm²	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 MeVcm²/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

8. Summary

- **The double TMA-based 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. It has been identified as the optics best solution for the CO2Image mission.**

- The Offner spectrometer is a well understood solution with certain risks in the mirror size and the grating performance.

- The Dyson re-presenting the refractive design option is not providing significant size reduction and is due to the most challenging grating technology of less significance.