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## *The CarbonSat candidate mission for imaging greenhouse gases from space: concepts and system requirements*

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## THE CARBONSAT CANDIDATE MISSION FOR IMAGING GREENHOUSE GASES FROM SPACE: CONCEPTS AND SYSTEM REQUIREMENTS

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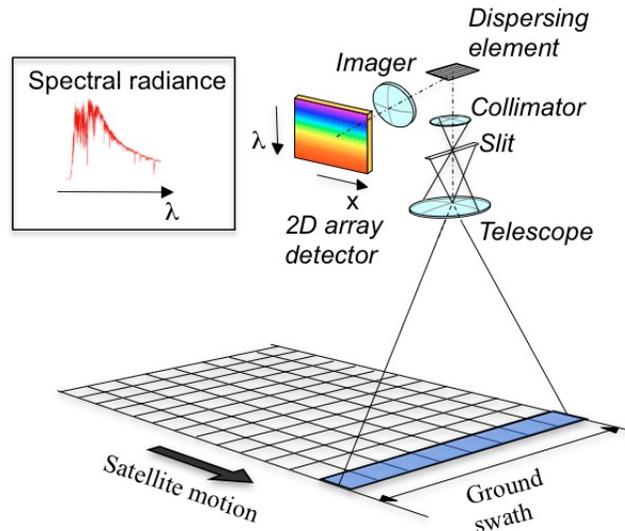
**CarbonSat is a candidate mission for ESA's Earth Explorer program, currently undergoing industrial feasibility studies. The primary mission objective is the identification and quantification of regional and local sources and sinks of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). The mission also aims at discriminating natural and anthropogenic fluxes. The space-borne instrument will quantify the spatial distribution of CO<sub>2</sub> and CH<sub>4</sub> by measuring dry air column-averaged mixing ratios with high precision and accuracy (0.5 ppm for CO<sub>2</sub> and 5 ppb for CH<sub>4</sub>). These products are inferred from spectrally resolved measurements of Earth reflectance in three spectral bands in the Near Infrared (747-773 nm) and Short Wave Infrared (1590-1675 nm and 1925-2095 nm), at high and medium spectral resolution (0.1nm, 0.3 nm, and 0.55 nm). Three spatially co-aligned push-broom imaging spectrometers with a swath width >180 km will acquire observations at a spatial resolution of 2 x 3 km<sup>2</sup>, reaching global coverage every 12 days above 40 degrees latitude (30 days at the equator). The targeted product accuracy translates into stringent radiometric, spectral and geometric requirements for the instrument. Because of the high sensitivity of the product retrieval to spurious spectral features of the instrument, special emphasis is placed on constraining relative spectral radiometric errors from polarisation sensitivity, diffuser speckles and stray light. A new requirement formulation targets to simultaneously constrain both the amplitude and the correlation of spectral features with the absorption structures of the targeted gases. The requirement performance analysis of the so-called effective spectral radiometric accuracy (ESRA) establishes a traceable link between instrumental artifacts and the impact on the level-2 products (column-averaged mixing ratios). This paper presents the derivation of system requirements from the demanding mission objectives and report preliminary results of the feasibility studies.**

### I. INTRODUCTION

The European Space Agency's Earth Explorers, as part of its Living Planet Programme, are research missions designed to address key scientific challenges while demonstrating breakthrough technology in observing techniques. In 2012, ESA selected two missions for feasibility studies carried out by industrial consortia: The FLuorescence EXplorer (FLEX) and the Carbon Monitoring Satellite (CarbonSat). This paper presents the concept and system requirements of the CarbonSat mission, which is designed to provide global measurements of greenhouse gas concentrations [1].

Carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) are the two most important greenhouse gases with the largest contribution to climate forcing. Ground-based in-situ measurements of CO<sub>2</sub> have been performed since the middle of the past century and indicate a steady increase of global CO<sub>2</sub> concentration. According to the International Panel on Climate Change (IPCC) it has risen by about 40 % since the beginning of industrialization [2]. CH<sub>4</sub> is an even more efficient greenhouse gas (per unit mass emitted), but has less climate impact than CO<sub>2</sub> due to lower emissions. However, the many natural and anthropogenic sources of this second most important greenhouse gas are poorly understood, and are a major focus of current research [3]. While local concentrations of both gases can be accurately measured with in-situ techniques, the identification of global, regional and local variability cannot be monitored on a global scale by ground-based techniques. As the carbon cycle is largely determined by the fluxes of greenhouse gases at various spatial scales, the lack of global observations result in large uncertainties, limiting the prediction capability of climate models.

The CarbonSat mission addresses the need for such observations by mapping CO<sub>2</sub> and CH<sub>4</sub> concentration at high spatial resolution and coverage. Dry air column-averaged mixing ratios of these gases, designated by XCO<sub>2</sub> and XCH<sub>4</sub>, respectively, are inferred from spectrally resolved measurements of top-of-atmosphere (TOA) reflectance. The measurement and retrieval technique are similar to those of the Orbiting Carbon Observatory (OCO-2), launched by NASA on July 2, 2014 [4]. However, CarbonSat is targeting significantly wider spatial coverage and broader spectral range, extending the range of retrieved products and exploring new retrieval schemes. With a swath width around 200 km complete global coverage will be achieved within three months at a spatial sampling of 2 km x 3 km. This unprecedented quantity of highly accurate XCO<sub>2</sub> and XCH<sub>4</sub> observations is expected to push the development of greenhouse flux inversion models beyond today's capabilities. Due to the imaging capability and high spatial resolution, it will be possible to disentangle natural and anthropogeneous sources and sinks of greenhouse gases.



**Fig. 1:** Principle of a push-broom imaging spectrometer. The entrance slit of the spectrometer is imaged onto the Earth surface, defining the swath width in across-track direction. The instrument spectrally disperses the slit image in along-track direction, which is sampled by the spacecraft motion during integration time. The products for each spatial sample are inferred from radiance spectra imaged onto the 2D array detector.

## II. MISSION CONCEPT

CarbonSat will perform simultaneous, spatially co-aligned space-borne observation of spectrally resolved Earth reflectance in three separated spectral bands: The Near Infrared band (NIR, 747-773 nm), the Short-Wave Infrared (SWIR)-1 band (1595-1675 nm), and the SWIR-2 band (1925-2095 nm). The instrument concept is based on three spatially co-aligned push-broom imaging spectrometers. Similar concepts have been chosen for a number of active or future missions atmospheric chemistry missions, like the Ozone Monitoring Instrument (OMI [5]) Sentinel-5 Precursor, Sentinel-4 and Sentinel-5 [6].

The measurement principle is depicted in Fig. 1: The nadir-pointing telescope of the instrument images the ground scene on the entrance slit of the spectrometer, projecting the slit onto the Earth surface perpendicular to the ground trajectory of the sub-satellite point (spacecraft motion vector). The projected slit length in across-track (ACT) direction defines the swath width of the instrument, which determines the spatial coverage of the mission. The slit width projection is the instantaneous footprint in along-track (ALT) direction, which is an important parameter determining the integrated energy within a spatial sample, and consequently spatial resolution. As the spacecraft moves along its orbit, the projected slit scans the Earth surface, while the diffraction grating disperses the slit image, which is focused onto the array detector by the spectrometer camera. At any instant, the detector pixels sample the image spatially in ACT and spectrally in ALT direction. The smear motion of the projected slit determines the spatial sampling in ALT direction during acquisition and the sampling distance is determined by the integration or dwell time.

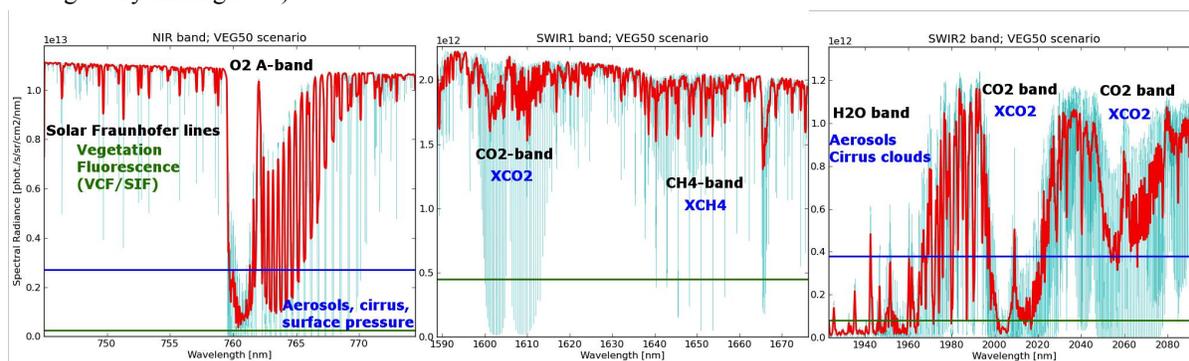
The instrument operates in three major observation modes: The nadir mode scanning the Earth as described above, the sun-glint mode in which the field-of-view is directed near the area of specular reflection over oceans, and the Sun calibration mode, in which observations of direct sunlight are performed. The number of electrons detected in the focal plane of the instrument is transformed via the radiometric calibration key data into spectral radiance  $L$  (for Earth observation in nadir and sun-glint mode), or Solar irradiance  $E$  (for Sun measurements). The latter are not only required for radiometric calibration of the Earth observation, but also for derivation of the quantity used in the retrieval of greenhouse gases, the Earth reflectance  $R$  which is defined as

$$R(\lambda) = \frac{\pi \cdot L(\lambda)}{E(\lambda) \cdot \cos(\theta)}, \quad (1)$$

with the solar zenith angle (SZA)  $\theta$  and sampled wavelength  $\lambda$ . In Fig. 2 top-of-atmosphere spectral radiance as simulated by a radiative transfer (RT) model is plotted for the three spectral bands measured by CarbonSat, both as monochromatic signal and at the required instrument resolution. The spectral signatures of the molecular species absorbing in these bands,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{O}_2$  and  $\text{H}_2\text{O}$  are clearly visible. Their depth and shape depends on the abundance of these molecules, as well as the effective (average) propagation path and the scattering conditions along it (in terms of aerosol and cloud cover). Each band contributes different pieces of information to the retrieval. The SWIR-1 band contains weak absorption features of  $\text{CO}_2$  and the distinct, sharp features of the  $\text{CH}_4$  molecule. The SWIR-2 band encompasses a very strong water vapour band, which is almost saturated under clear-sky conditions. It is utilized to detect cirrus clouds, which reflect part of the sunlight before it

reaches the humid troposphere, and therefore yield an unsaturated signal in the spectral region. The SWIR-2 also features two strong CO<sub>2</sub> bands in the center and long-wavelength end of the spectrum. The combination of weak, moderate and strong absorption bands in the two SWIR channels provides continuous sensitivity to CO<sub>2</sub> over a wide altitude range, all the way down to the troposphere.

The NIR band features the well-known oxygen A-band, as well as solar Fraunhofer lines in the continuum region around 750 nm. The latter contribute information on the fluorescence emission of plants underlying the atmospheric signal in measurements over vegetated areas [7]. The broadband vegetation fluorescence fills Fraunhofer lines, and their modulated depth is used to infer the intensity of this signal for correction, as well as a useful secondary product [8]. Since the well-mixed oxygen does not exhibit appreciable variation in concentration, the amount of absorption in the O<sub>2</sub> A-band only depends on the propagation path. The retrieval algorithm utilizes this to infer the effective average light path, which depends on the local topography (surface height) and scattering conditions (aerosols and cirrus cloud cover). This information is crucial for the interpretation of the retrieved greenhouse gas abundances (slant columns) in terms of concentration (column averaged dry mixing ratio).



**Fig. 2:** The three spectral bands measured by CarbonSat at monochromatic and instrument spectral resolution (0.1 nm for NIR, 0.3 nm for SWIR-1 and 0.55 nm for SWIR-2).

### III. SYSTEM REQUIREMENTS

In this section we briefly discuss the specific demands of the CarbonSat mission and their formulation in terms of system requirements. We restrict this discussion to the driving specifications regarding the geometrical, radiometric, spectral and polarisation performance of the instrument.

#### A. Geometrical Requirements - spatial coverage, resolution and co-registration

A key feature of the CarbonSat mission is a large swath width in combination with high spatial sampling and resolution. It targets a complete global coverage over land every three months, and every 12 days for latitudes higher/lower than +/- 40 degrees. CarbonSat will also cover the oceans, however in sun-glint mode and with reduced frequency and sampling w.r.t. land observations. Global ocean coverage will be achieved once per month with at least one measurement in every grid box of 1° in latitude by 5° in longitude. The coverage requirements translate into a minimum swath width of 180 km for a push-broom spectrometer on a spacecraft in a sun-synchronous orbit. The global coverage is combined with a high spatial resolution for an instrument recording continuous spectra at sub-nanometre resolution. The images will be sampled at 3 km in ACT and 2 km in ALT direction. Within such rectangular sample, the enclosed energy (fraction of photons coming from within the rectangle), referred to as System Integrated Energy (SIE), is required to be larger than 70% to ensure an appropriate assignment of the retrieved XCO<sub>2</sub> and XCH<sub>4</sub> to the spatial sample.

For an adequate interpretation of the retrieved products it is also essential that the photons detected in different spectral channels all originate from the same location on Earth within the limits defined by the co-registration requirements. Because of the impact of surface topography on the effective propagation path, the inter-band co-registration is two times stringent than for the Sentinel-4 and -5 missions: The maximum tolerable mis-registration between a spectral channel from the NIR and any channel of the two SWIR bands is specified to 15% of the ACT SSD, which corresponds to only 450 m on the ground. The requirement does not distinguish between inter- and intra-band co-registration, allowing industry to partition the budget between intra-band effects (like keystone distortion) and inter-band errors (like detector misalignment). The stringent co-registration requirements are driving the instrument design to high mechanical stability and low image distortion (keystone). It also favours concepts with a common entrance slit for the three spectrometers and the use of adaptive binning strategies, taking advantage of high ACT oversampling, made possible by large detector arrays, to co-align the ACT spatial samples.

*B. Radiometric Requirements - absolute and relative radiometric accuracies*

A fundamental specification for sizing an optical instrument is the required signal-to-noise (SNR) ratio, which is determined by retrieval simulation for various geophysical scenarios. Therefore it needs to be specified over the wide dynamic range of the instrument, ideally by equations yielding the required SNR as a function of input signal. The required SNR functions for CarbonSat are accounting for the detector technology to be used in the SWIR spectral region, which is based on Mercury-Cadmium-Telluride (MCT) CMOS devices. The noise characteristic of these detectors is typically dominated by read-out noise, resulting in increasingly linear noise dependence for decreasing incident intensity. This is incorporated in the requirement formulation specifying different SNR dependency for the dark and the bright regime of the dynamic range.

The absolute radiometric accuracy (ARA) required for CarbonSat is mainly driven by the necessity to determine the surface albedo of the measured spatial sample. In order to retrieve this important parameter the ARA of the measured reflectance has to be better than 2% for the NIR and 3% for both SWIR bands. It is pointed out that the radiometric system requirements are formulated in terms of reflectance, rather than spectral radiance. This has the advantage that any radiometric error, which are common in both the Earth radiance and Solar Irradiance cancel out in the ratio of Eq. 1. Still the level of absolute accuracy calls for an extensive, accurate on-ground calibration as well as regular and frequent in-flight calibration measurements. The required on-board calibration standard for reflectance is established by a Sun diffuser, which has been accurately characterized on ground in terms of the Bi-directional Reflectance Distribution Function (BRDF).

The relative radiometric accuracy, especially between spectral channels within an acquired radiance (resp. reflectance) spectrum is potentially more demanding than ARA. It is particularly critical as the retrieval products are retrieved from the shape and depth of their characteristic spectral signature. Any relative radiometric error altering these features, especially if spectrally correlated with the molecular absorption cross-section at instrument resolution will directly impact the retrieved XCO<sub>2</sub> and XCH<sub>4</sub>. Section IV is dedicated to this performance aspect and the requirements constraining it.

One particular source of relative spectral radiometric error is induced by the polarisation sensitivity of the instrument. It can be mitigated by means of a polarisation scrambler, as described in [9]. The sizing of such a device is a trade-off between the maximum tolerable polarisation sensitivity on one hand, and the detrimental impact on spatial resolution (SIE) and co-registration on the other.

*C. Spectral requirements - spectral channel knowledge, stability and ISRF*

The spectral requirements for CarbonSat are specified on the knowledge and in-flight stability of the spectral channel centres, which are the wavelengths, associated to the spectral pixels of the measured radiance and irradiance spectra. Those are in turn defined by the barycentre of the Instrument Spectral Response Function (ISRF), sometimes referred to as the instrument line shape (ILS). The ISRF is defined as the instrument response to a monochromatic stimulus and the spectral resolution is its Full Width at Half Maximum (FWHM).

In flight the ISRF will change due to thermo-mechanical stress and launch effects, but also because of non-homogeneous illumination of the entrance slit caused by radiometric contrasts in the ground scene (e.g. from cloud cover or albedo variations). Therefore CarbonSat requirements are applicable over specified non-uniform scenes. Taking all the above effects into account, the in-flight knowledge of the ISRF has to be better than 2% of its peak value over the entire shape (down to 1% of the peak). This demand can be addressed by a hardware solution implementing a slit-homogenizer (SH) instead of a conventional entrance slit. The approach to the mitigation of non-uniform scene effects for the CarbonSat mission is described in [10].

SNR @ Lref (dark reference radiance)	NIR: 150; SWIR-1: 160; SWIR-2: 130
Spectral resolution (3 times sampled)	NIR: 0.1 nm; SW1: 0.3 nm; SW2: 0.55 nm
Swath width (coverage)	Minimum 180 km; Breakthrough 240 km; Goal 500 km
Spatial sampling distance (SSD)	2 km (ALT) x 3 km (ACT)
Spatial co-registration	15% of ACT SSD (NIR-SWIR)
Integrated Energy	>70% within spatial sample
Absolute radiometric accuracy	NIR: 2%; SWIR: 3%
Relative radiometric accuracy	0.5% (spatial and spectral)
Effective spectral radiometric accuracy	0.05% (CO <sub>2</sub> ); 0.10 (CH <sub>4</sub> )
ISRF knowledge	1% on ground; 2% in flight
Spectral knowledge/stability	5%/25% of SSI
Polarization sensitivity	0.5% (all bands)

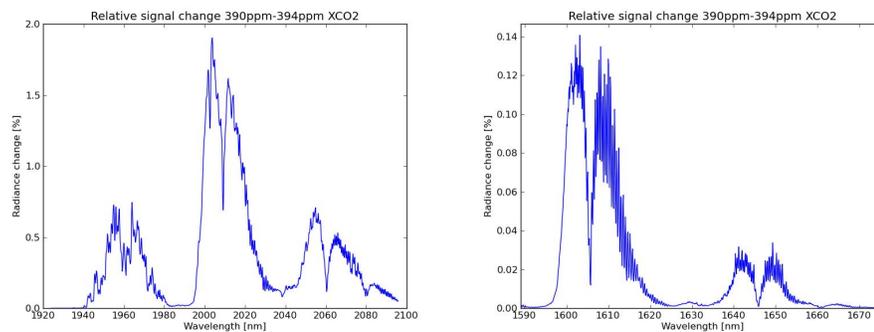
**Table 1:** Key system requirements for the CarbonSat mission

A SH device also mitigates variation in the spectral scale induced by non-uniform scenes, which makes it easier to comply to the spectral knowledge requirement, specified to of 5-6% of a spectral sampling interval (SSI, equivalent to the spectral bandwidth of a single spectral pixel). In previous missions similar accuracies have been achieved by applying spectral shift correction of the measured spectra performed on ground as part of the Level-1b processing. In order to ensure the performance of such correction schemes, it is necessary to impose requirements on in-flight spectral stability. This specification allows for a total amplitude of the spectral error up to 25% of the SSI and 10% after removal of the mean spectral error (additive shift) over the band.

The most driving system requirements of the CarbonSat mission are summarized in Tab. 1.

#### IV. CONSTRAINING RELATIVE SPECTRAL RADIOMETRIC ERRORS

The criticality of the relative radiometric accuracy of the spectrometric measurement is indicated in Section IIIB and is illustrated in Fig. 3. It shows the difference in spectral radiance for XCO<sub>2</sub> of 390 ppm and 394 ppm in the two SWIR bands at instrument resolution. This XCO<sub>2</sub> change is roughly corresponds to the single-measurement precision required for CarbonSat. In the SWIR-1 channel the two spectra differ by less than 0.2 % in the centre of the weak CO<sub>2</sub> absorption bands. In the SWIR-2 band the maximum signal difference around 2 % is observed only in the centre of the strong absorption feature near 2000 nm, where the centres of the CO<sub>2</sub> absorption lines are saturated. In the weaker absorption band at 2060 nm, the signal change is only around 0.7 %. These subtle spectral signal changes associated with variations of greenhouse gas concentrations highlight a priority for instrument design: The avoidance of any relative spectral errors, which could introduce spurious spectral features in the derived Earth reflectance. Potential error sources for this type of artefacts include stray light, diffuser speckles in the solar irradiance measurements, and polarisation features from the scrambler and subsequent optical components. The approach taken in the CarbonSat system studies is to constrain relative spectral radiometric errors by two dedicated requirements, which are described in the following subsections.



**Fig 3:** Relative signal change in the two SWIR bands for a difference of 4 ppm in XCO<sub>2</sub>.

##### A. Relative Spectral Radiometric Accuracy (RSRA)

The first requirement limiting spurious spectral features is the relative spectral radiometric accuracy (RSRA). It has been specified in previous instrumental studies [11], leading to extensive performance analysis. In CarbonSat a new definition of this figure of merit is used, which puts the maximum amplitude of the reflectance error within a spectral band in relation to the maximum signal in this band:

$$RSRA = \frac{\max_i(\Delta R_i) - \min_i(\Delta R_i)}{\max_i(R_i)}, \quad (2)$$

where  $R_i$  denotes the Earth reflectance signal detected in spectral channel  $i$ , and  $\Delta R_i$  its absolute error. RSRA is specified to 0.5% for each of the three spectral bands. It constrains the radiometric errors with low spectral frequency, like a smooth variation of the relative spectroscopic baselines (indicating zero and 100 % of absorption). However, it does not appropriately account for high-frequency radiometric errors in reflectance, as typically induced by the error mechanisms mentioned above. A requirement constraining such kind of error would have to account for the correlation of the reflectance error spectrum with the measured signal. The CarbonSat approach to such a specification is introduced in the subsequent section.

##### B. Effective Spectral Radiometric Accuracy (RSRA)

The second requirement constraining relative spectral radiometric errors aims at directly limiting their impact on the retrieval products of the mission. Systematic radiometric errors, which appear as spurious spectral features in the reflectance measurement induce biases in the retrievals of greenhouse gas concentrations. The severity of their impact strongly depends on the spectral structure of the reflectance error. The higher the

correlation with the spectral signature of the absorbing molecular species at instrument resolution (see Fig. 2), the larger is the expected error in the corresponding retrieved product.

A direct link between a radiometric error, including its spectral variation, and the impact on retrieval products is established via the Optimum Estimation algorithm used in the retrieval [12]. In an iterative retrieval scheme, corrections to the  $m$  estimated parameters  $P_m$  (such as e.g. the slant columns of the targeted molecular species) are related to the  $n$  differences between measured and modelled reflectance ( $\Delta R = R_{meas} - R_{mod}$ ) by the matrix equation:

$$\begin{pmatrix} \Delta P_1 \\ \Delta P_2 \\ \dots \\ \Delta P_m \end{pmatrix} = (K^T \cdot S_e \cdot K + S_a)^{-1} \cdot K^T \cdot \begin{pmatrix} \Delta R_1 \\ \Delta R_2 \\ \dots \\ \Delta R_n \end{pmatrix} \quad (3)$$

In this equation,  $K$  is the Jacobian matrix whose elements are the partial derivatives of the RT model w.r.t. the estimated parameters,  $S_e$  is the covariance matrix of the measurements and  $S_a$  the covariance a-priori knowledge of the estimated parameters. This equation can be used in the context of error mapping, in which the differences  $\Delta R_i$  with  $i=1, \dots, n$  are interpreted as radiometric errors, and the corrections to the parameters  $\Delta P_j$  as their corresponding impact on the retrieval product. We can therefore define the Gain matrix  $G$  for a subset of driving parameters (say the slant column of  $\text{CO}_2$  and  $\text{CH}_4$ ) by

$$G = (K^T \cdot S_e^{-1} \cdot K) \cdot K^T \quad (4)$$

where  $S_e$  is a diagonal matrix whose elements (variances) follow from the SNR requirement, and  $S_a$  has been neglected in order not to bias the gains by a-priori assumptions. The rows of this reduced gain matrix are the gain vectors, each corresponding to one retrieved quantity. The CarbonSat users provided them for the column-averaged mixing ratios (concentrations) of the two targeted greenhouse gases. For each of them, the Effective Spectral Radiometric Accuracy (ESRA) is then defined as the scalar product of the gain vector for  $\text{CO}_2$  and  $\text{CH}_4$ , respectively, and the reflectance error spectrum:

$$ESRA_{\text{CO}_2, \text{CH}_4} = \sum_i G_{\text{CO}_2, \text{CH}_4} \cdot \Delta R_i \quad (5)$$

This scalar product is defined for all spectral channels measured by CarbonSat, encompassing the entire spectral range of the instrument. However, it can of course be evaluated separately for the NIR, SWIR-1 and SWIR-2 bands to assess the criticality for each individual spectrometer w.r.t. a particular error source (like e.g. stray light). The gain vectors are plotted in Fig. 4 and can be interpreted as the weights of the individual reflectance measurements in the product retrieval. In the formulation chosen for the system requirement, the gain vectors for  $\text{XCO}_2$  and  $\text{XCH}_4$  are given in units of inverse reflection [sr], such that the two corresponding scalar products yield dimensionless ESRA values. The maximum ESRA limits specified for the two target species are directly linked to their tolerable systematic error in column-averaged dry mixing ratio. For  $\text{CO}_2$  the requirement of  $ESRA_{\text{CO}_2} < 0.05\%$ , corresponds to a systematic Level-2 error of 0.2 ppm. For the specified  $ESRA_{\text{CH}_4} < 0.10\%$  is equivalent to a maximum  $\text{XCH}_4$  error of 2.0 ppb. The approach to constrain relative spectral radiometric errors via gain vectors fully accounts for the correlation of radiometric errors with atmospheric absorption features.

### C. Application of ESRA to polarisation errors

As an example for the application of gain vectors to constrain the impact of relative radiometric errors, we demonstrate the analysis of polarisation errors in terms of the ESRA performance: The response of an instrument to polarized radiation can be completely described by its Mueller matrix (MM), which relates the Stokes vector of the incident radiation with the one of the detected light in the focal plane of the instrument. For our purpose, only the first line of the  $4 \times 4$  MM is relevant, as it maps the Stokes vector of the incident light into the detected intensity signal. Since circular polarisation by the atmosphere is negligible, only the first three elements  $M_{11}$ ,  $M_{12}$ , and  $M_{13}$  are determined utilizing optical design software. The first of these elements corresponds to the transmission of the instrument, and the other two describe the dependence of the detected intensity from linear polarisation in two mutually orthogonal directions. The MM elements relate to the radiometric error  $\Delta R_i$  in spectral channel  $i$  at wavelength  $\lambda_i$  induced by each of the two polarisation components as follows:

$$\Delta R(\lambda_i) = R(\lambda_i) \cdot DOP(\lambda_i) \cdot \left( \frac{M_{12}(\lambda_i)}{M_{11}(\lambda_i)} \cos(2\varphi) + \frac{M_{13}(\lambda_i)}{M_{11}(\lambda_i)} \sin(2\varphi) \right) \quad (6)$$

where  $\varphi$  denotes the polarisation angle of the incident light. The impact of this reflectance error spectrum on the retrieval could be evaluated in terms of ESRA for any given polarisation angle via Eq. (5). However, it can

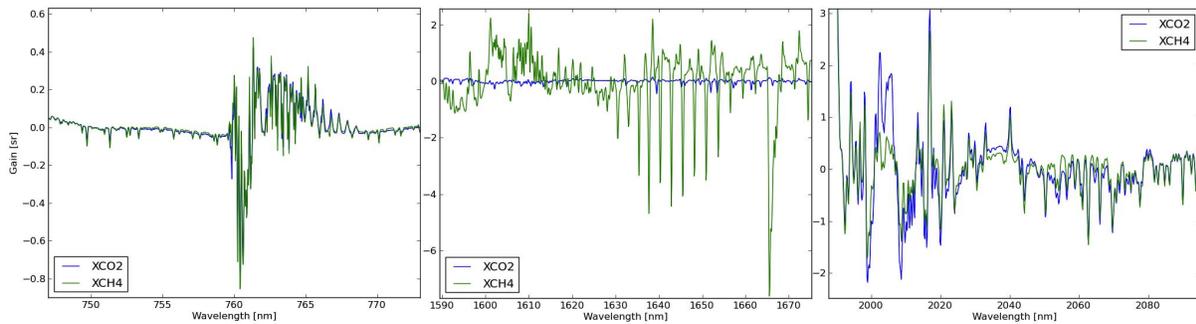
be shown that the worst-case ESRA value for the combined effect of the two polarisation components  $ESRA_{pol,tot}$  can be obtained from a separate evaluation, which is independent from  $\varphi$ :

$$ESRA_{M12} = \sum_i G_{CO2,i} \cdot R(\lambda_i) \cdot DOP(\lambda_i) \cdot \frac{M_{12}(\lambda_i)}{M_{11}(\lambda_i)}$$

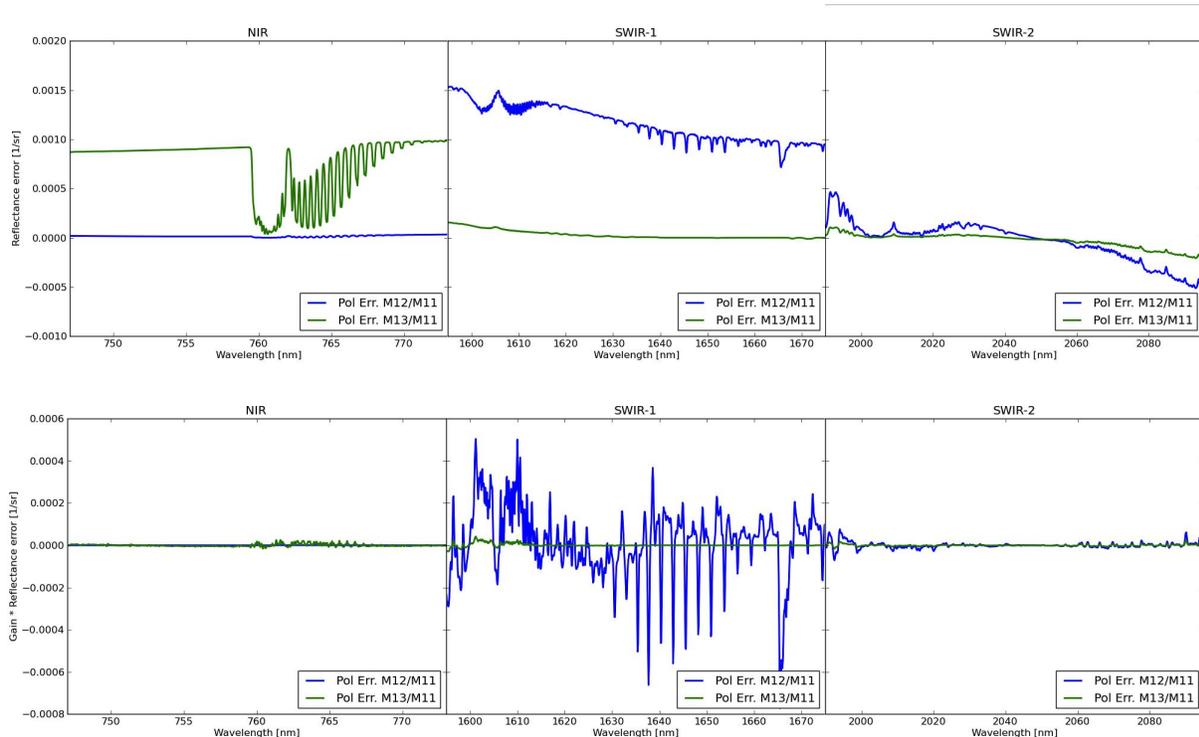
$$ESRA_{M13} = \sum_i G_{CH4,i} \cdot R(\lambda_i) \cdot DOP(\lambda_i) \cdot \frac{M_{13}(\lambda_i)}{M_{11}(\lambda_i)} \quad (7)$$

$$ESRA_{pol,tot} = \sqrt{ESRA_{M12}^2 + ESRA_{M13}^2}$$

The appearance of the Earth reflectance  $R(\lambda_i)$  as a factor in Eq. 6 and Eq. 7 implies that the radiometric error from polarisation is highly correlated with the measured Earth reflectance itself. This can also be seen in the upper panel of Fig. 5, where a simulated polarisation error spectrum for all bands is plotted. The MM underlying this calculation was taken from an instrument model of a spectrometer comparable to CarbonSat, which also complies with the PS limit of 0.5%. The absorption features of the Earth reflectance are superimposed on the smoothly varying radiometric error from the MM elements. The plot in the lower panel of Fig. 5 shows the elements of the scalar product for  $ESRA_{M12}$  defined in Eq. 7 and shows negative and positive contributions to the



**Fig. 4:** Gain vectors for  $XCO_2$  (blue) and  $XCH_4$  (green) in the three CarbonSat bands. Please note the different scale of the plots. It is evident that the information for  $CH_4$  retrieval comes almost entirely from the SWIR-1 band, while the SWIR-2 band contributes to both  $CO_2$  and  $CH_4$ .



**Fig. 5:** Product of  $CH_4$  gains and reflectance errors for all spectral channels, forming the summation elements of the ESRA scalar product. The sum of the plotted elements yields the ESRA value (in this case  $\sim 0.15\%$ ).

ESRA error. The negative and positive contributions compensate each other, but the large contribution of element  $M_{12}$  in this assumed MM would yield a significant non-compliance w.r.t. ESRA for  $\text{CH}_4$  (~0.15%). Such a result can be useful to further optimize the optical design w.r.t. the polarisation performance.

## V. CONCLUSIONS

We have presented the mission concept, scientific objectives and the system requirements of the CarbonSat mission. The demand for high-precision measurements of greenhouse gas concentrations at high spatial resolution and broad coverage translates into challenging geometrical, radiometric and spectral requirements, in some cases exceeding the stringency of those for comparable space-borne instruments. Emphasis is placed on constraining relative spectral radiometric errors, which are most critical when spectrally correlated with the molecular absorption cross sections. A new requirement was devised, which is based on gain vectors derived from the retrieval algorithm and relates radiometric errors with their impact on retrieved products. We demonstrated the application of the gain vector approach for constraining radiometric errors from polarisation sensitivity.

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## REFERENCES

- [1] H. Bovensmann, M. Buchwitz, J. P. Burrows, M. Reuter, T. Krings, K. Gerilowski, O. Schneising, J. Heymann, A. Tretner, and J. Erzinger, A remote sensing technique for global monitoring of power plant  $\text{CO}_2$  emissions from space and related applications, *Atmos. Meas. Tech.*, 3, 781-811, 2010.
- [2] T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.): "IPCC Summary for Policymakers". In: "Climate Change 2013: The Physical Science Basis", Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- [3] S. Kirschke, et al.: Three decades of global methane sources and sinks, *Nat. Geosci.*, 6, 813-823, doi:10.1038/ngeo1955, 2013.
- [4] D. Crisp, et al., The Orbiting Carbon Observatory (OCO) mission, *Adv. Space Res.*, 34, 700-709, 2004.
- [5] P. F. Levelt, E. Hilsenrath, G. W. Leppelmeier, G. H. J. van den Oord, P. K. Bhartia, J. Tamminen, J. F. de Haan, and J. P. Veefkind, Science objectives of the Ozone Monitoring Instrument", *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 5, pp. 1199-1208, May 2006.
- [6] P. Ingmann, B. Veihelmann, J. Langen, D. Lamarre, H. Stark, and G. Bazalgette Courrèges-Lacoste, "Requirements for the GMES Atmosphere Service and ESA's implementation concept: Sentinels-4/-5 and -5p", *Remote Sensing of Environment*, Vol. 120, 15 May 2012, pages 58-69
- [7] M. Buchwitz, M. Reuter, H. Bovensmann, D. Pillai, J. Heymann, O. Schneising, V. Rozanov, T. Krings, J. P. Burrows, H. Boesch, C. Gerbig, Y. Meijer, and A. Löscher, Carbon Monitoring Satellite (CarbonSat): Assessment of atmospheric  $\text{CO}_2$  and  $\text{CH}_4$  retrieval errors by error parameterization, *Atmos. Meas. Tech.*, 6, 3477-3500, 2013.
- [8] C. Frankenberg, O'Dell, C, Guanter, L., and McDuffie, J., Remote sensing of near-infrared chlorophyll fluorescence from space in scattering atmospheres: implications for its retrieval and interferences with atmospheric  $\text{CO}_2$  retrievals, *Atmos. Meas. Tech.*, 5, 2081-2094, 2012
- [9] J. Caron, J.-L. Bézy, G. Bazalgette Courreges-Lacoste, B. Sierk, R. Meynart, Polarization scramblers in Earth observing spectrometers: lessons learned from Sentinel-4 and 5 phases A/B1, Proceedings of the International Conference on Space Optics (ICSO), Ajaccio, Corse, France, Oct. 9-12, 2012, paper: ICSO-139, 2012.
- [10] J. Caron, B. Sierk, J.L. Bézy, A. Löscher, Y. Meijer, The CarbonSat candidate mission: Radiometric and spectral performances over spatially heterogeneous scenes, Proceedings of the International Conference on Space Optics (ICSO), Tenerife, Spain, 7-10 Oct. 2014, in print.
- [11] B. Sierk, J.-L. Bézy, J. Caron, R. Meynart, B. Veihelmann, and P. Ingmann, The GMES Sentinel-5 mission for operational atmospheric monitoring: Status and Developments, International Conference on Space Optics, Proceedings of the International Conference on Space Optics (ICSO), Ajaccio, Corse, France, Oct. 9-12, 2012, paper: ICSO-069, 2012.
- [12] C. D. Rodgers, *Inverse Methods for Atmospheric Sounding: Theory and Practice*. World Scientific, 2000.