Authors response to the editor

We thank the editor for his detailed and constructive review of our manuscript. We appreciate your time and the insightful feedback that will help significantly improve the quality and impact of our work. Below, we provide our point-by-point responses and outline how we have revised the manuscript accordingly.

Comments:

Section 3.1, line 90: I can hardly believe a Gaussian line shape is assumed for modelling the absorption lines, I guess you refer to the Voigt profile?

Section 3.1, line 90: You are correct, and as the reviewer also pointed out, the Voigt profile is used to model our spectral lines, while the Instrument Line Shape (ILS) is Gaussian. The simulated spectrum is therefore the result of a convolution between the Voigt profile and this Gaussian ILS.

Section 3.1, line 102: please rephrase: " …. while TCCON a-priori information is used for CO2 and H2O atmospheric profiles."

Response: We have rephrased this sentence as suggested.

Figure 2: The calculated H2O signatures seem undetectable in the measured spectrum - is the slant column used for the calculation not matched properly? In the figure description, please specify SZA of the observation and total integration time of the measurement shown.

Figure 2: We now specify the SZA and total integration time in the caption. We also investigated the apparent mismatch between the modeled and measured H_2O signatures, and the slant column has been corrected accordingly.

Section 3.2: in the opening section of this treatment, information needs to be given concerning which quantities are fitted in the retrieval (please add a table listing all components of the state vector): I guess in addition to the gas mixing ratios of CO2 and H2O, spectral shift (or scale) is fitted? Further fit variables are needed for describing the continuum background level. Is the solar spectral abscissa scale fitted (usually required in spectrally high-res measurements to compensate for residual LOS errors)?

Section 3.2, line 126: "the ith measurement" -> "the ith spectral channel in the measured spectrum"

Section 3.2: We have added a table in Section 3.2 listing all components of the state vector used in the retrieval. These include the gas volume mixing ratios of CO_2 and H_2O. As for the spectral shift and the solar spectral abscissa correction, these are handled during the preprocessing of the spectra. Prior to retrieval, a spectral alignment is applied by calibrating against a stable, unsaturated H_2O absorption line. A scaling factor α is derived from the observed and theoretical line positions to correct the solar spectral abscissa. This correction is performed during preprocessing and is not part of the state vector., but their effects are included via alignment steps prior to the inversion.

line 126: This expression has been corrected.

Section 3.3: unfortunately, the construction of the a-priori (see table 1) is so oversimplified that I doubt any useful conclusions can be drawn from the current information content analysis. If one wants to compare the expected performance of the presented LHR with existing FTIR setups in a sensible manner, the a-priori covariance matrix needs to be far more realistic. Moreover, the information content analysis needs to discuss explicitly the expected errors on column-averaged abundances, which are the products of current networks. Note that the current networks do not provide gas columns, but XGAS values, which are constructed with the help of co-observed O2 columns. Your claim "The LHR exhibits unique advantages … in retrieving gas columns with better vertical discretization [should be: resolution]. It is therefore a promising alternative instrument for local scale measurements or for satellite validation". This might be correct, but needs to be supported by the results of information content analysis. In the application context you refer to in the manuscript (especially satellite validation), high vertical resolution is mainly useful via improving the reconstruction of XGAS amounts over current techniques. (It needs to be kept in mind that the satellite also measures XGAS.)

Section 3.3 and Information Content Analysis: We acknowledge that the S_a matrices used were oversimplified; however, we would like to point out that this was done in the context of comparison with another previous study, which motivated the use of these simplified covariance matrices. We have now addressed this in greater detail and discuss it in the following section.

For achieving a meaningful comparison with current state-of-the-art, I would suggest to proceed in the following manner:

(1) construct sensible S_a matrices for CO2, H2O, and T. Note that the relevant variability here to be reported in S_a is the variability between the actual profile and the TCCON a-priori. This S_a matrix for CO2 can be constructed from aircore launches (the French community is quite active with this technique, so a sufficient amount of data should be available for constructing an S_a matrix). The equivalent matrices for H2O and T can be derived from meteorological soundings, ideally launches which were not used in the model

assimilation underlying TCCON a-prioris (perhaps H2O and T are by-products of aircore launches anyway?). When constructing the S_a matrices, it is crucially important to maintain the covariances, which inform about characteristic lengths of variability along the vertical. Only by maintaining the diagonal elements a meaningful S_a matrix is constructed.

(2) For the performance comparison with TCCON and COCCON for the XGAS values, the propagation of T errors into a O2 retrieval from the 1.26 um band needs to be included. This will alter (expectedly improve) the uncertainty budget for the target quantity XCO2, as this is calculated using the ratio of CO2 and O2 columns. This error compensation is lacking in the LHR approach. Moreover, note that SZA errors cancel out in this rationing approach, so in the discussion of model errors, the resulting error contribution for the LHR needs to be estimated (from the assumed SZA errors).

(3) A further important model parameter is the ground pressure. Ideally, it should be included in the error analysis, as the sensitivity of the LHR very likely differs from that of TCCON and COCCON due to the high spectral resolution and due to the fact, that there is no rationing over the O2 column. But if you clearly state in the text that you assume the availability of an ideal sensor, one might skip this item.

Using (1) and (2) and your error propagation equations, you can realistically establish the desired performance comparison between the LHR and current techniques. I would expect that the LHR is superior wrt the smoothing error, while the current networks might be more robust wrt the impact of model parameter errors (T and SZA). With respect to the smoothing error, it might be interesting for TCCON + COCCON to work out the smoothing error both for the operational setup (scaling retrieval) and a possible future data processing which performs a profile retrieval fit of CO2. The latter result would specifically reveal the improvement introduced by the high spectral resolution achieved by the LHR. If, however, you feel this is beyond the scope of your work, restrict the investigation to the operational setup.

(1) Construction of realistic prior covariance matrices (S_a):

- We constructed realistic S_a matrices for CO_2 and temperature using publicly available AirCore datasets, notably from the MAGIC campaign, covering the period from 2016 to 2023. For H_2O, we used data from the ERA5 reanalysis over the same period.
- In all cases, full covariance matrices were retained, including off-diagonal elements, to preserve the vertical correlation lengths. This approach ensures more realistic estimates of the smoothing error and enhances the accuracy of the vertical information content assessment. The diagonal covariance matrices are also kept as a comparison tool.

A short explanation of the method has been added to Section 4.1 of the manuscript.

(2) XGAS error propagation: temperature and SZA

We appreciate this important point regarding the propagation of temperature and SZA errors in a column-ratio retrieval framework. However, we respectfully note that in our current LHR configuration, we are not yet able to retrieve O_2 columns, as we lack a laser source covering the 1.26 µm O_2 absorption band. Procuring such a laser is a planned future upgrade to enable direct XCO2 retrieval via the CO_2/O_2 column ratio, consistent with the approach used in TCCON and COCCON. In the absence of an O_2 measurement, we do not currently compute XCO_2, and the uncertainty budget is expressed in terms of vertically integrated CO_2 profile uncertainty, rather than in terms of XCO_2. To clarify this and avoid confusion with standard total column quantities, we have revised our terminology throughout the manuscript. Specifically, we now refer to the 'total column uncertainty' as the 'integrated profile uncertainty' to clearly distinguish it from column-averaged quantities like XCO_2. We plan to quantify the error cancellation benefits once O_2 retrievals become available with the upgraded setup.

Regarding solar zenith angle errors, we agree that these can partially be cancelled when using a gas ratio approach. However, since our current implementation does not include such a ratio, we retain the SZA uncertainty contribution in the LHR error budget for completeness.

(3) Ground pressure as a model parameter

We agree that ground pressure is an important parameter, particularly given the high spectral resolution of the LHR and the absence of O_2-based column normalization as used in TCCON and COCCON. In our current setup, we use ground pressure measurements from a Vaisala PTU radiosonde with an accuracy of ±0.3 hPa. These values are used to overwrite the default ground pressure in the retrieval algorithm prior to inversion. Given the high accuracy of this input, and to keep the focus on dominant sources of uncertainty, we have not included ground pressure in the error analysis in this study. However, we acknowledge its potential impact and will consider its contribution explicitly in future studies.

Profile fit:

We agree that a comparison including the smoothing error from both the operational TCCON/COCCON scaling retrieval and a profile retrieval approach would be highly informative, particularly in demonstrating the benefits of the LHR's high spectral resolution. However, such a detailed comparison would require a significant expansion of the analysis, which we consider beyond the scope of the present work.

Nevertheless, we acknowledge the importance of this direction, and we are currently developing a full profile retrieval fit for CO_2 with the LHR. This will allow a more direct assessment of the smoothing error and will be the subject of a dedicated future study. For the current manuscript, we therefore restrict our analysis to the operational scaling retrieval approach.

In table 3, please add integration times, otherwise the comparison of SNR figures is not meaningful.

Table 3: Integration times have been added for all configurations to allow for meaningful SNR comparison.

In table 4, the column errors seem unrealistically large to me for all instruments. It therefore would be good to split the reported error into different contributions (spectral noise, model parameters, smoothing). This would make transparent which error source drives the total budget and would allow to explicitly verify at least the calculated noise error contribution, as this can be easily deduced from data retrieved from actual measurements.

Table 4: We now decompose total column errors (integrated profile uncertainty) into:

- Model parameter uncertainty (T, SZA),
- Smoothing error,
- Measurement error.

This helps clarify the dominant sources of uncertainty in each technique.

The treatment provided in section 4 needs to be refined. The authors claim that from this investigation, the preferred CO2 channels to be measured can be deduced, saving observation and data analysis time. This is in principle correct, but we need to realize that the presented LHR is operated as a ground-based solar absorption spectrometer. In this configuration, a model for the continuum background level needs to be included in the fit (because a solar reference measurement outside of the atmosphere is not doable). This in turn requires a sufficient number of background channels (spectral positions largely free of absorption) to be included both in the measurement and in the fit. The analysis, however, suggests using only channels with strong CO2 absorption, which seems unrealistic.

Response: We have revised this section to emphasize that realistic retrievals require not only strong CO_2 absorption channels, but also the identification of a set of informative channels that includes spectral regions free of absorption (i.e., baseline). The new analysis is calculated with a Jacobian that includes this baseline. Furthermore, we now present the top 100 channels ranked by information content, and importantly, we find that nearly 30% of these selected channels are located in baseline regions with little or no CO_2 absorption.