Review of "Potential CO_2 measurement capabilities of a transportable Near Infrared Laser Heterodyne Radiometer (LHR) (AMT-2025-250)"

The manuscript presents an innovative approach for measuring atmospheric CO_2 using a portable Laser Heterodyne Radiometer (LHR) operating in the near-infrared (NIR) region. This work is highly relevant to the scope of Atmospheric Measurement Techniques (AMT), and the manuscript provides a thorough description of the experimental setup, along with a theoretical framework for information content analysis. The authors apply this framework to quantify the Degrees of Freedom (DOF) of the LHR instrument and compare its performance against established systems such as the Total Carbon Column Observing Network (TCCON) and the COllaborative Carbon Column Observing Network (COCCON).

While the scientific content is of interest, the organization of the manuscript would benefit from improvement to enhance the logical flow and clarity for the reader. Several key concepts require more detailed explanation to ensure they are accessible to a broader audience. Below are some general comments that I believe would help strengthen the manuscript:

1. I suggest restructuring Section 3 to better reflect the logical progression of the work, which currently mixes theoretical background, instrument-specific inputs, and results into a single extended section. Reorganizing the content under a clearer functional structure:
— **Theory → Application → Results → Comparison** —would significantly improve clarity and readability. Specifically:

   Theory: Sections 3.1 and 3.2 present the forward model and the framework for information content analysis. These form the core theoretical basis of the study and could be grouped together under a dedicated section on theory.

   Application: Section 3.3 introduces the a priori information, measurement error covariance, and uncertainties in non-retrieved parameters as they pertain to the LHR. This section represents the application of the theoretical framework to the specific case of the LHR instrument and should be distinguished from the more abstract theory above.

   Results: Section 3.4, which applies the framework to retrieve CO_2 information content and uncertainty from LHR simulations, could be promoted to its own section—e.g., "Information Content and Uncertainty Estimation for the LHR". This would clearly signal the shift to presenting results derived from the defined retrieval setup.

   Comparison: Section 3.5, which compares the LHR with existing systems like TCCON and COCCON, should also be elevated to a standalone section, such as "Comparison with Existing Networks", to help readers easily locate this critical performance evaluation.

   The current placement of Sections 3.3.2 and 3.3.3 under the heading "A priori information" may be misleading. While Section 3.3.1 appropriately discusses the CO_2 profile and its covariance matrix as part of the a priori state vector, Section 3.3.2 refers to measurement error, and Section 3.3.3 introduces parameters such as temperature, humidity, and SZA as non-retrieved. However, in many retrieval frameworks, temperature and humidity profiles are typically treated as a priori inputs. Please clarify your definition of "a priori" to avoid confusion regarding the role of these parameters in the forward model versus the retrieval.

2. In the introduction (lines 30–36), I recommend expanding the description of the EM27/SUN spectrometer to improve clarity. For example, line 31 should clearly refer to it as the Bruker

EM27/SUN, and you can also include the spectral resolution for comparison against the earlier stated IFS125HR spectral resolution.

Additionally, the statement "the drawback of being portable is that the FTS reduces the spectral resolution" is somewhat misleading. The reduced resolution is not inherently due to portability but rather results from design trade-offs in optical path difference: smaller instruments have shorter maximum optical path lengths, which limits achievable resolution.

You could also expand on the consequences of lower spectral resolution. Specifically, lower resolution can limit the ability to resolve narrow absorption lines, potentially leading to increased interference from neighboring lines, reduced retrieval precision, and sensitivity to pressure broadening effects.

Moreover, there are published studies that directly compare the performance of the IFS125HR and the EM27/SUN, such as Herkommer et al. (2024) and Mostafavi Pak et al. (2023), which show that CO_2 retrievals from the EM27/SUN differ by only approximately 0.1%, which is quite impressive given its lower spectral resolution. This raises an important question for the present study: does the LHR system, with its much higher spectral resolution, offer a meaningful improvement over this offset?

3. In Section 3.1, where you describe the use of PTU Vaisala radiosondes and ancillary data from the TCCON database, I suggest adding more specific information to improve transparency and reproducibility.

   For the PTU Vaisala radiosonde, please include the typical accuracy specifications for temperature, pressure, and relative humidity. These values are likely used to define the uncertainties in your forward model or retrievals later in the analysis (e.g., Section 3.3.3), so it would be helpful to establish them clearly at this stage.

   Regarding the TCCON database, it would be beneficial to specify which TCCON station the ancillary CO_2 and H_2O data are derived from, especially considering the measurements are conducted in Dunkirk (51.035°N, 2.369°E). Are you using a nearby TCCON site (e.g., Orléans)? Additionally, please clarify what do you mean by ancillary data? Do you mean the a priori profiles?

4. In Section 3.5, you describe differences in averaging kernels between the LHR and existing FTS instruments (e.g., EM27/SUN and IFS125HR). To support this comparison more effectively, I recommend including a plot with the averaging kernels from those FTS instruments overlaid on top of the LHR kernel.

5. In Section 4, the term "channel selection" is used to describe the identification of individual absorption lines with the highest information content. However, in the TCCON and EM27/SUN communities, "channel" typically refers to detector channels (e.g., InGaAs vs. Si), rather than specific spectral lines or intervals within an absorption band. This difference in terminology may lead to confusion for readers familiar with those systems. To improve clarity, consider using more precise terms such as "line selection" or "micro-window selection", or alternatively, explicitly define your use of "channel" at the beginning of the section.

6. In the conclusion, you report a 2.74% error in total column CO_2 at 10° SZA. This level of uncertainty appears quite high, especially when compared to existing ground-based systems: TCCON reports an error budget of 0.16% for XCO_2, and the COCCON network shows an average offset of 0.1% relative to TCCON (e.g., Herkommer et al., 2024; Mostafavi Pak et al., 2023).

   Given that one of the key motivations stated in the introduction is that LHR's higher spectral resolution should improve retrieval quality, the reported uncertainty seems to contradict this expectation. It would be important to clarify how this instrument would compete with EM27/SUN in operational or satellite-validation contexts.

Minor corrections and comments:

- **Line 9:** Please be more specific, what type of sensitivity you are referring to. What kind of resolution is meant, spectral, temporal, vertical?
- **Line 16:** ... an extensive analysis...
- **Line 36:** "heterodyne spectro-radiometer" is not a method, maybe you mean measurement technique?
- **Line 52-71:** You seem to be switching from the present tense (Solar radiation is captured ...) to the past tense (The modulated radiation was split by ...). I recommend using the present tense throughout, since this is a description of the standard setup.
- **Line 121-122:** The variables A and S_x are introduced before they are defined in equations 3 and 5. Please consider restructuring the paragraphs accordingly.
- **Line 158:** "The a priori error covariance matrix S_a can be evaluated using in-situ data or climatology, but diagonal matrices are often used for space-based retrievals." The use of "but" in the sentence implies a contrast that does not really exist.
- **Line 163:** Define perr.
- **Line 198:** please be more specific what do you mean by Kernels. do you mean posterior(total), measured, etc?
- **Line 232:** The sentence "the total column uncertainty is calculated by adding up the concentration of each layer, adjusted by the dry air column (Figure 3)" is unclear and may be misleading. Summing layer concentrations gives the total column amount, but uncertainty in the total column requires proper error propagation.
- **Line 235:** the term OPD appears to be misused. If you are referring to the increased atmospheric path length at high solar zenith angles, "slant path" would be the correct terminology.
- **Line 251:** By green line and violet line, it seems like you are referring to Figure 3, please mention it.
- **Table 1:** I recommend adding a more comprehensive caption that explains what each state vector element refers to (e.g., whether CO_2 refers to a profile or total column scaling). Be more specific about what you mean by TCCON database.
- **Figure 2:** please clearly indicate which curve corresponds to the measured LHR spectrum and which one to the ARAHMIS simulation. In addition, could you clarify why CH_4 was not included in the forward model simulation shown? I would also recommend adding a residual plot (i.e., measured – modeled) below the main panel.
- **Table 2:** why is SZA = 10° used as the minimum value? At your measurement site in Dunkirk, the lowest achievable SZA is around 30° in summer. Using a range like 30°–80° would be more realistic and representative of actual observing conditions.
- **Table 3:** you present the full spectral ranges of the EM27/SUN and IFS125HR instruments. However, it would be more informative to also include the specific CO_2 micro-windows typically used for retrievals with these instruments. This would allow for a more direct and meaningful comparison with the spectral region covered by the LHR.
- **Figure 3:** The left panel displays numerous colored lines representing averaging kernels, but the caption and legend do not explain what these colors signify. Additionally, the right panel legend includes five color-coded components, but do they apply to the left panel? Please consider separating or clarifying the legends to avoid ambiguity. In addition, please explicitly state in the caption that the figure corresponds to a solar zenith angle (SZA) of 10°.