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ESA FRM4GHG V2.0

LHR instrumental improvements

Technical note – Deliverable D1.2

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1. Introduction

This document briefly summarises modifications made to the LHR instrument as part of the FRM4GHGv2 project. Together with the retrieval improvements described in [1], the outcomes of these improvements are evaluated as part of a 3 month joint measurement campaign with the reference Harwell TCCON observatory [2].

2. Hardware upgrades

2.1. Solar disk imager

The instrument uses a solar disk imager to control the Sun Tracker. Previously a monochrome CMOS camera (Thorlabs DCC1545M) was used. This was upgraded to a hyperspectral sensor (Ximea MQ022HG-IM-SM4x4-REDNIR). The hyperspectral sensor has 2048 x 1088 pixels and sixteen different spectral channels, resulting in a 517 x 272 pixel image of the solar disk for each of the sixteen spectral channels ranging from 600 nm to 860 nm. As a result, the solar disk imager now produces hyperspectral data in addition to providing feedback for the instrument pointing. We intend to use these data to carry out air mass correction from the oxygen bands, to produce a water vapour and aerosol product.

In addition, the optical assembly used to image the solar disk onto sensor was upgraded from a fixed one-lens system to a two-lens system with adjustable focus. The new camera assembly is shown in Figure 2.1. The new focus optics increased the effective focal length from 100 mm to 376 mm, producing an image almost four times larger on the sensor. The increased image size enabled greater pointing precision. By using two lenses, an effective focal length of 376 mm was achievable within a total length of 140 mm. Image aberrations have also been reduced.

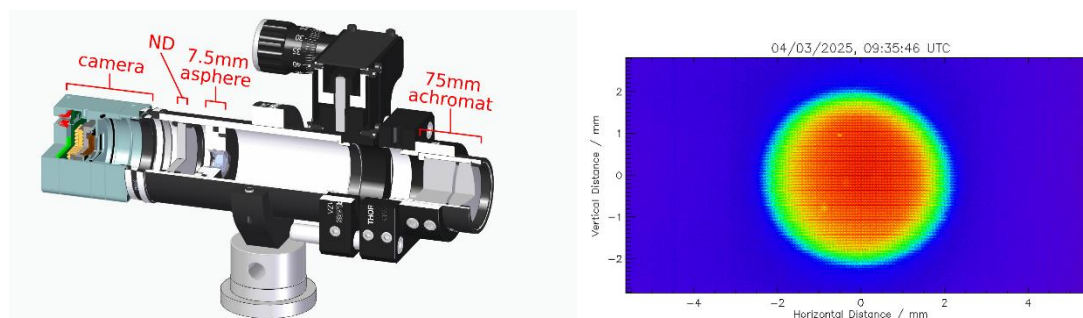


Figure 2.1: Left, CAD model of upgraded solar camera. Right, example of hyperspectral image of the sun disk captured by the system.

2.2. Solar bandpass filters

Optical bandpass filters were added to the instrument to minimise the intensity of out-of-band solar radiation reaching the photomixer, which otherwise would introduce an artificial heterodyne signal.

Two bandpass filters were installed, one for each laser wavelength, along with a mechanism to switch between the two filters. A 10.53 μm bandpass filters with 200 nm fullwidth at half maximum (Northumbria Optical Coatings NC-0412) was used for the CO_2 channel and an 8.00 μm bandpass filters with 500 nm fullwidth at half maximum (Thorlabs FB8000-500) was used for the CH_4 channel. A dual position slider (Thorlabs ELL6) was installed to switch between the two filters.

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To accommodate the bandpass filters within the instrument the bandpass filter slider was packaged together with the shutter slider which blocks all solar radiation. The new combined bandpass filter and shutter module is shown in Figure 2.2. A PCB breakout board to control up to three sliders with one D-sub 9 cable was designed, manufactured and installed.

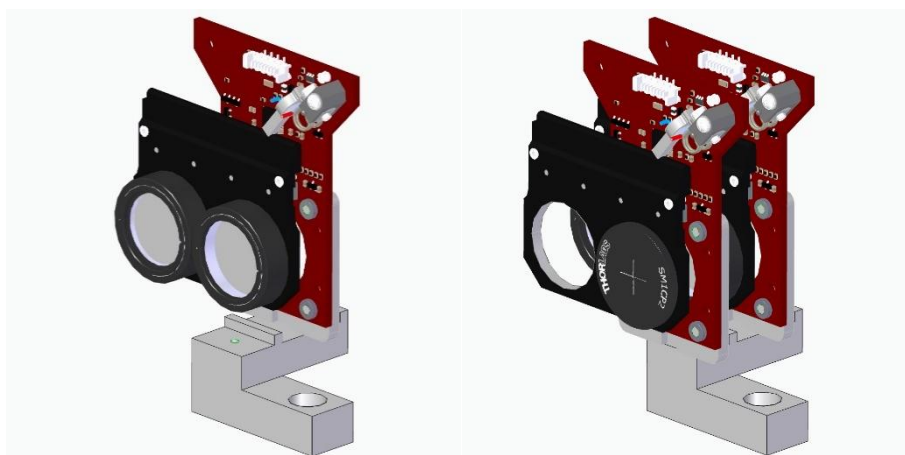


Figure 2.2: Left, CAD model of partially assembly of sliders showing the two optical bandpass filters. Right, CAD model of full assembly with shutter and bandpass filter sliders.

2.3. Optical isolators

Previously each laser had a wire grid polariser to control the laser power but shared a common quarter wave plate. The polarisation control was upgraded so each laser had a separate wire grid polariser and quarter wave plate. This enhanced polarisation control allows the variation in laser intensity due to etalon fringes to be suppressed for both lasers, thereby reducing the effective noise of the instrument.

The wire grid polariser and quarter waveplate were integrated into a single package for each instrument, with the waveplate held at a 10° angle relative to the polariser to reduce etalons between these two optical components. This package is shown in Figure 2.3.



Figure 2.3: CAD model of the new optical isolator used for both lasers.

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2.4. Water chiller

The old water chiller was upgraded from an Oasis 160 chiller to a Lauda L100. This increases to ambient temperature operating range from 10 – 40 C to 4 – 80 C, but decreases the cooling capacity from 160 W to 120 W.

2.5. Thermal stabilisation

The thermal stability of the instrument was upgraded using water cooling and thermal insulation.

Thermal heat exchangers, or cold plates, were installed on the bottom of the aluminium optical breadboard. The chilled water returning from the laser modules was passed through the cold plates, keeping the breadboard at a temperature close to the water chiller temperature. A new floor, suspended from the breadboard, was added to the instrument such that the cold plates did not directly contact the surrounding environment.

Expanded polystyrene cladding was added to the four walls and roof of the instrument, increasing its thermal insulation. This makes the instrument less susceptible to temperature fluctuations when the conditions of the deployment location (temperature, incident sunlight, wind, etc) change.

These two modifications increased the temperature stability of the instrument. Drifts in the instrument temperature was identified in FRMGHv1 to bias atmospheric retrievals.

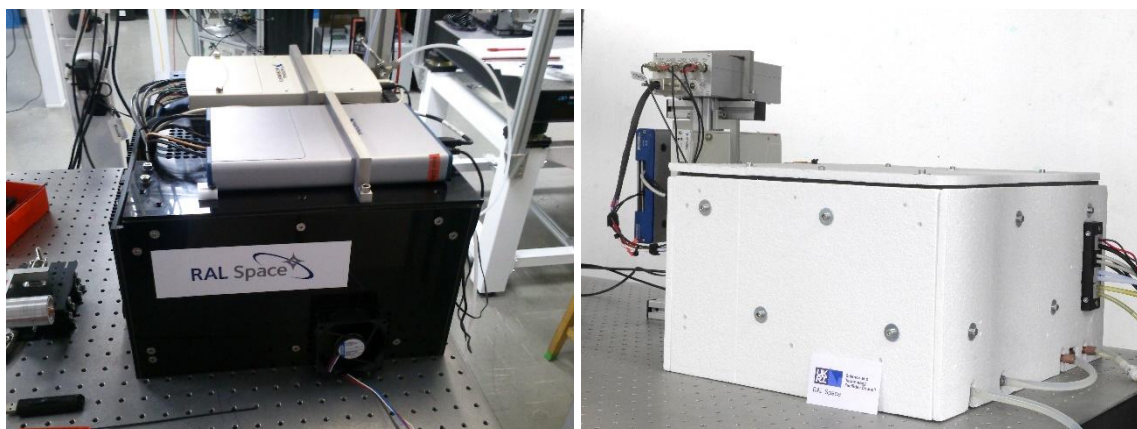


Figure 2.4: Left, original LHR configuration with DAQs on lid. Right, new LHR configuration with DAQs on nearby stand and expanded polystyrene cladding.

2.6. Thermometry

Thermistors were added to the instrument to monitor the temperature of the optical breadboard and the cold plates.

2.7. Detection chain

A low-noise amplifier was added to the detection chain after the lowpass filter and before the Schottky diode. The purpose of the amplifier is to increase the signal prior to the lock in amplifier which was observed to sometimes pickup electric interference. The electrical isolation of the instrument has since been improved, so the effectiveness of the low-noise amplifier should be reviewed.

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2.8. Power distribution

A small PCB board was designed, manufactured and installed to deliver power to modules that draw little current and require 12, 9 or 5 V. The PCB board is powered by a 12 V input and uses a 9-volt and 5-volt regulator (Figure 2.5). This power distribution unit reduces the number of external power supplies needed and reduces the number of ground loops. It has the added benefit of eliminating the need for multiple switch-mode power supplies, which are typically inject noise into the instrument.

Instruments powered by the power distribution PCB include the etalon flip mirror, the laser flip mirror, the bandpass filter slider and the shutter slider.

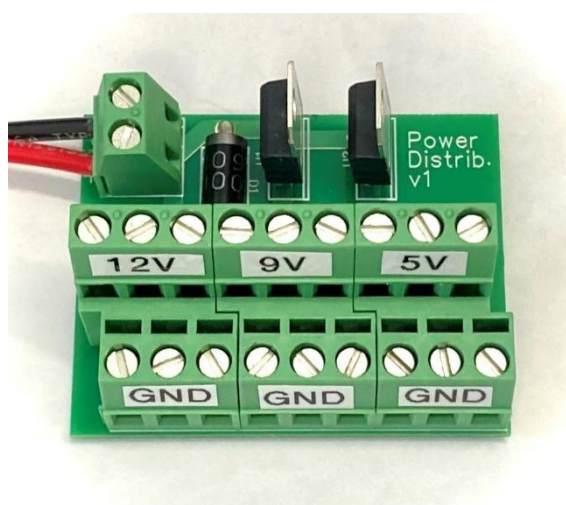


Figure 2.5: picture of low-current power distribution PCB.

2.9. Cable routing

The two NI-DAQs were removed from the lid of the LHR and placed on a stand made of extruded aluminium located next to the LHR. The lock in amplifier was also removed from inside the LHR and placed on the stand. This reduces the heat load of the LHR and makes optical alignment easier.

Upon moving the NI-DAQs and lock-in amplifier, all cabling was replaced with cables of suitable length to reduce excess cabling inside the instrument. Where possible, cables were routed along the optical breadboard and held in place with clips. This significantly reduces the clutter within the instrument and should reduce triboelectric noise (Figure 2.6).

In addition, a bracket was 3D-printed to mount the two flip mirror controllers in a compact manner.

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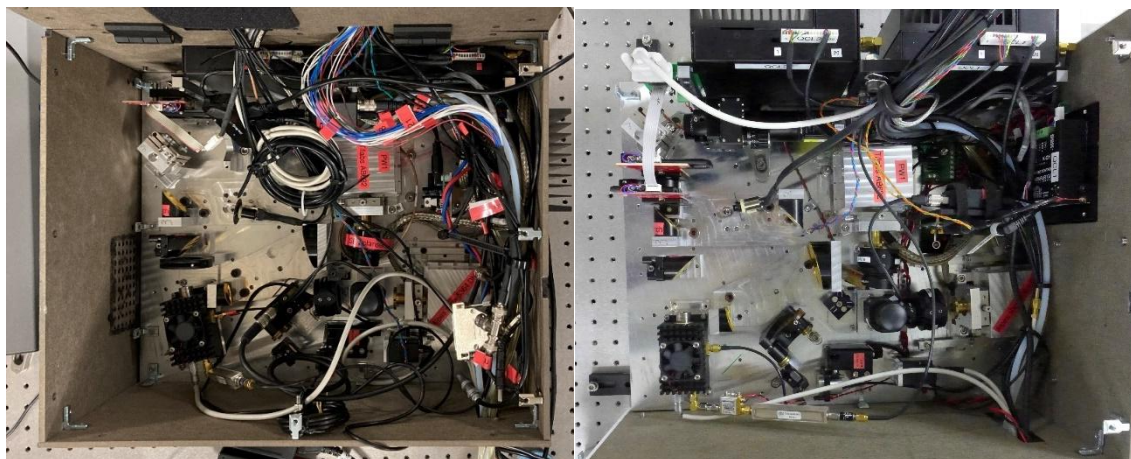


Figure 2.6: Left, top view of LHR showing old cable routing (May 2023). Left, top view of LHR showing new cable routing (July 2024).

2.10. Reduce noise interference

The electrical ground network was rationalised to reduce the number of ground loops. Optical isolators were added to the USB cables that interface with the two DAQs, the solar camera, solar tracker stepper motor controller and the water chiller. Optical isolation of the control inputs of the laser drivers was enabled. The photomixer, laser drivers, TECs, flip mirrors and sliders were all powered from floating linear power supplies. The effect of this isolation is to reduce the number of ground loops hence reduces instrument noise via electrical interference.

In addition, an error in the cabling of the etalon detector was corrected to enable a differential readout of detector, greatly reducing the noise and drift in this signal.

2.11. Optical mounts

A spacer and retaining ring were added to the dichroic mirror mount to centre the dichroic within the mount and reduce distortion of the input solar radiation induced by a distorted dichroic. This makes instrument alignment easier and improves the solar image quality.

New optic mounts were manufactured for the shutter and optical bandpass filter sliders.

Rails were manufactured to allow the CO₂ laser to be moved to a new position to accommodate the new optical isolator assemblies.

2.12. Realignment

A full realignment of the instrument was performed. The collimation lenses of the laser modules were adjusted to achieve a symmetric, collimated beam. The positions of the laser modules were changed to accommodate the optical isolators and the change in beam pointing they induce. The CO₂ laser now protrudes from the optical breadboard, so hole was made in the instrument wall and a cover affixed to ensure the instrument is still protected from the environment.

Through-holes in the optical breadboard were tapped to allow the new polarisation assemblies, slider assemblies, flip-mirror controllers and solar imager to be fixed in their new positions. Figure 2.7 shows a CAD image of the updated instrument with the optical beampaths highlighted.

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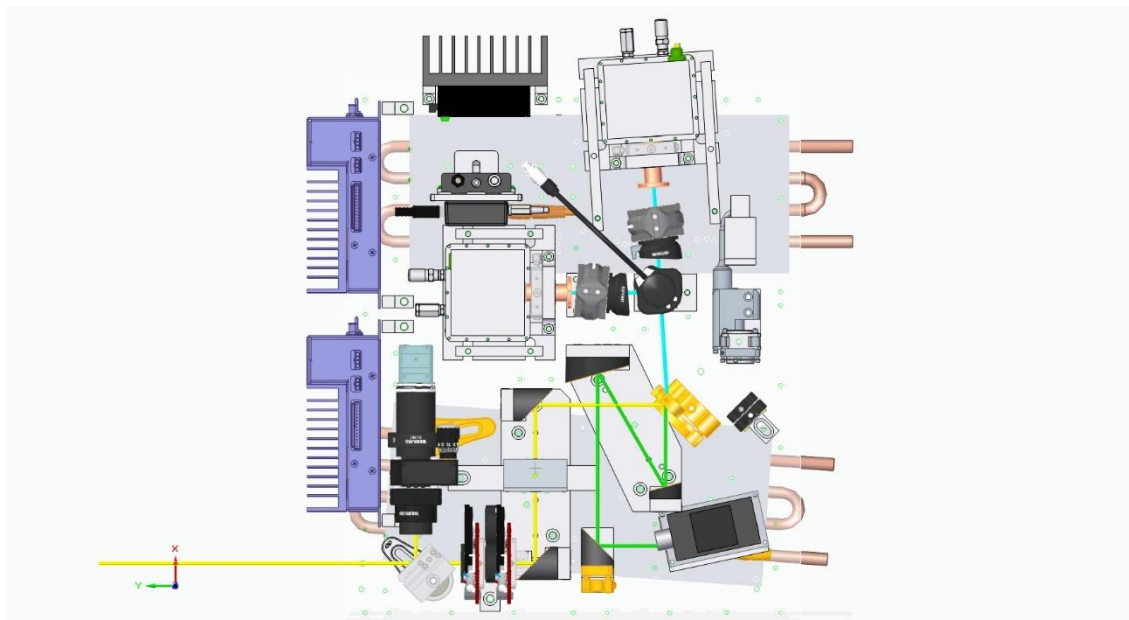


Figure 2.7: Top view of the updated LHR CAD schematic showing path of light fields. The yellow ray represents input solar radiation, the cyan ray represents laser light, and the green ray represent overlapped solar and laser radiation.

3. Software upgrades

In addition to the hardware updates, instrument software updates were also implemented as part of the overhaul.

3.1. Hyperspectral camera

The solar tracking software was modified to read the data format from the new hyperspectral camera, as well as modify the settings of the camera. The solar tracking software was also modified so that multiple solar images are averaged during a laser sweep and the resulting image is saved synchronously with the LHR data.

3.2. Auto exposure

An optional feature was added to the solar tracking software, where the exposure time of the sensor is automatically adjusted to yield a correctly exposed solar disk image.

3.3. Chopper feedback

The control of the chopper frequency was upgraded from an open-loop control system to a closed-loop control system. Now, the user specifies a target chopper frequency, and a software implemented PID controller adjusts the chopper control voltage to achieve the target.

3.4. Chiller interface

Control of the water chiller was incorporated into the software, allowing the chiller setpoint to be set and for the chiller to be turned on and off remotely. In addition, the software was upgraded to shut down the lasers if a fault (high temperature, low flow rate, etc) was detected by the chiller.

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3.5. NetCDF structure

The structures and format of the output data files were updated. Three separate NetCDF files are generated which cover each of the three sub-instruments. These are the laser heterodyne radiometer (LHR) itself which generates atmospheric spectra using heterodyne measurements of incoming solar radiation, the hyperspectral solar disk imager (HSDI) which generates spectral images of the solar disk, and the solar tracker (ST) which couples solar radiation into the LHR and HSDI. Figures 3.1 and 3.2 show the new data structure for the three files.

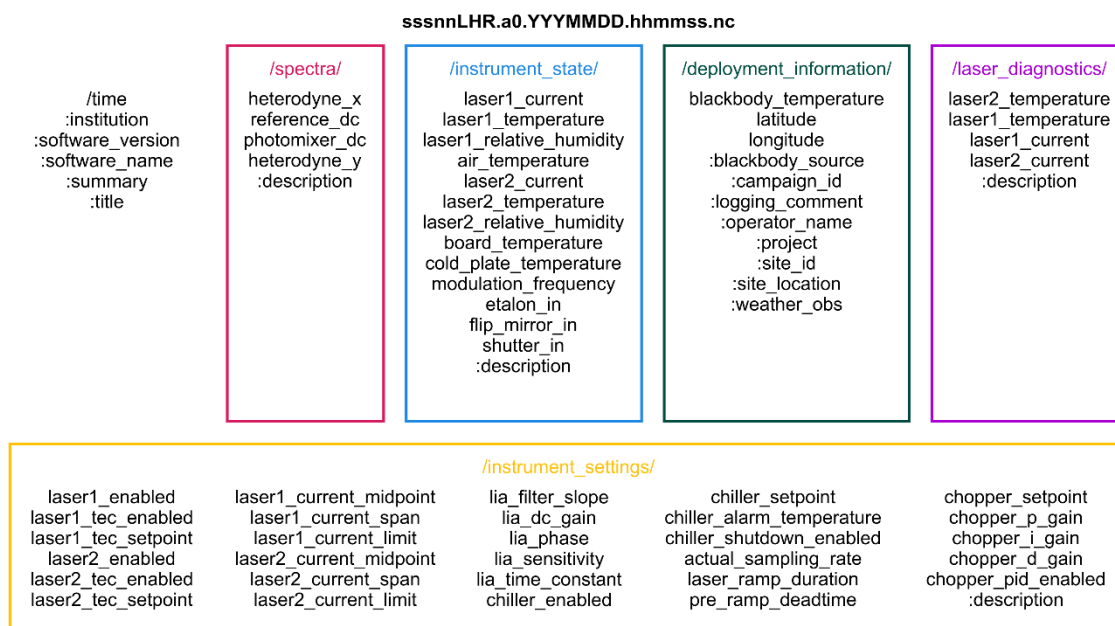
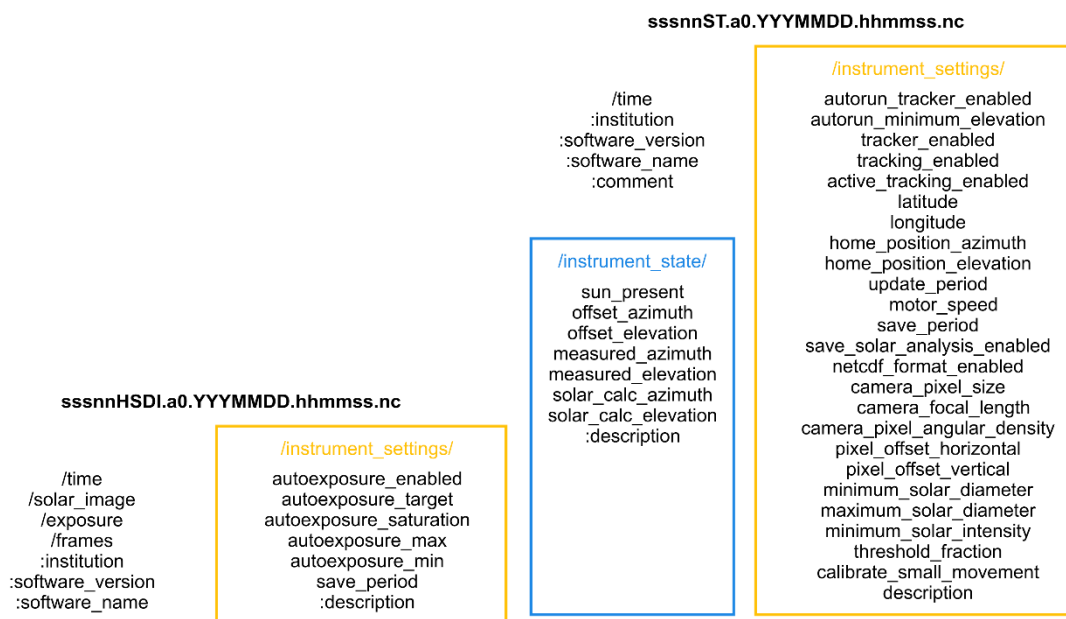


Figure 3.1. Structure of the updated NetCDF file for the LHR data.



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Figure 3.2. Structure of the updated NetCDF files for the HSDI imager (left) and for the solar tracker (right).

4. Evaluation deployment

4.1. Settings

In order to evaluate the updated LHR instrument, it was installed within the instrumentation clamshell dome of the Harwell TCCON observatory located on the roof of our laboratory [2]. The arrangement is shown in Figure 4.1. The left-hand side photograph shows the dome fully open. The central structure is the TCCON sun tracker. The LHR location materialized by the green rectangle, and its dedicated 25 mm aperture solar tracker is indicated within the yellow rectangle.



Figure 4.1: Photographs of the LHR and its dedicated solar tracker installed in the Harwell Observatory clamshell dome.

The timeline of the deployment was:

19/07/2024	- Instrument installed in roof observatory
19/07/2024 to 08/08/2024	- Instrument optimisation and characterisation
09/08/2024 to 17/09/2024	- Measurement Campaign (16 days recorded)
19/09/2024 to 13/12/2024	- Noise reduction updates
08/01/2025 to 07/04/2025	- Instrument optimisation and characterisation
07/04/2025 to 10/07/2025	- Measurement campaign.

During the 3 months measurement campaign, the LHR was operated manually, meaning that it was operated during business hours, and reliant on staff intervention for switch on and off. Over the 3 months period, 33 days of data could be recorded.

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4.2. Sun pointing performance

The solar tracker developed for the LHR uses a similar approach to the Harwell TCCON [2]. The main difference is that it is shrunk in size and uses 25 mm aperture mirrors. The feedback camera also acquires hyperspectral information of the atmospheric transmission in the visible (600-860 nm) hyperspectral imaging camera (see section 2.1). Figure 4.2 shows a photograph of the heliostat installed in the dome (left-hand side) and a screenshot of the LabVIEW user interface (right-hand side).

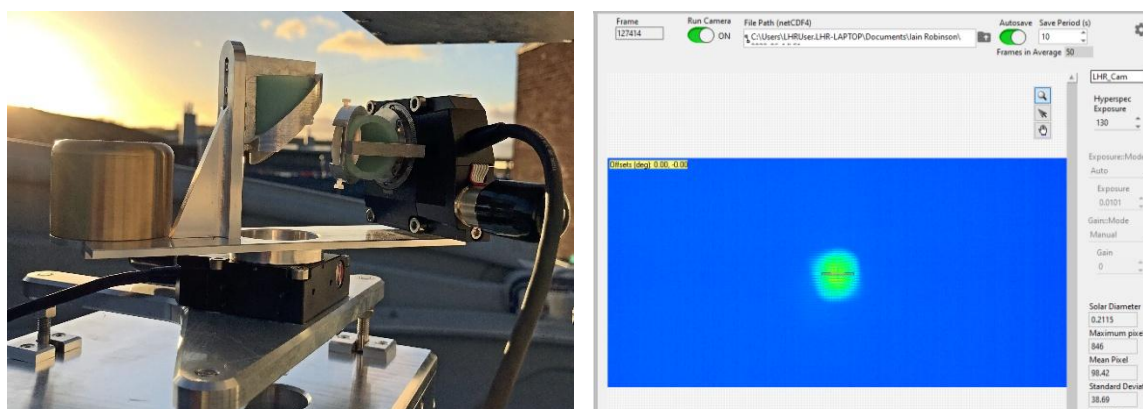


Figure 4.2. Left, photograph of the miniature solar tracker developed for LHR (mirrors are 25 mm aperture). Right, screenshot of the LabVIEW user interface for the tracker.

To assess the solar tracker performance, the tracker data over the course of a single clear day (11th April 2025) is considered. The solar tracker pointing elevation and azimuth angular positions are updated after each image to re-centre the solar image on the hyperspectral imager. The update period was 1 second. Figure 4.3 shows the pointing coordinates over a day – the time axis is relative to local noon. The top panel of each column shows the calculated and measured azimuth (elevation) angles while the second panel shows the difference between these values. This panel shows the tracker initially correcting immediately after switch-on and then maintaining a smooth variation over time. The third panel shows a 2-hour period in which the difference in angular position has been detrended (using a 4th order polynomial). The azimuth axis shows a periodic oscillation (10-15 minute period) while the elevation axis is smoother. Two small periods of instability are seen at times around -2.5 hours in both channels. These are due to attenuation of the solar intensity due to light clouds. Even under unfavourable conditions, the tracker is still capable of tracking to less than 1 milliradian.

The bottom panels show the histograms of the detrended data (in units of microradians). A Gaussian fit to the distributions shows standard deviations of < 100 μ rad for both axes. This performance is comparable with the results of the RAL TCCON system operated using the same tracker software.

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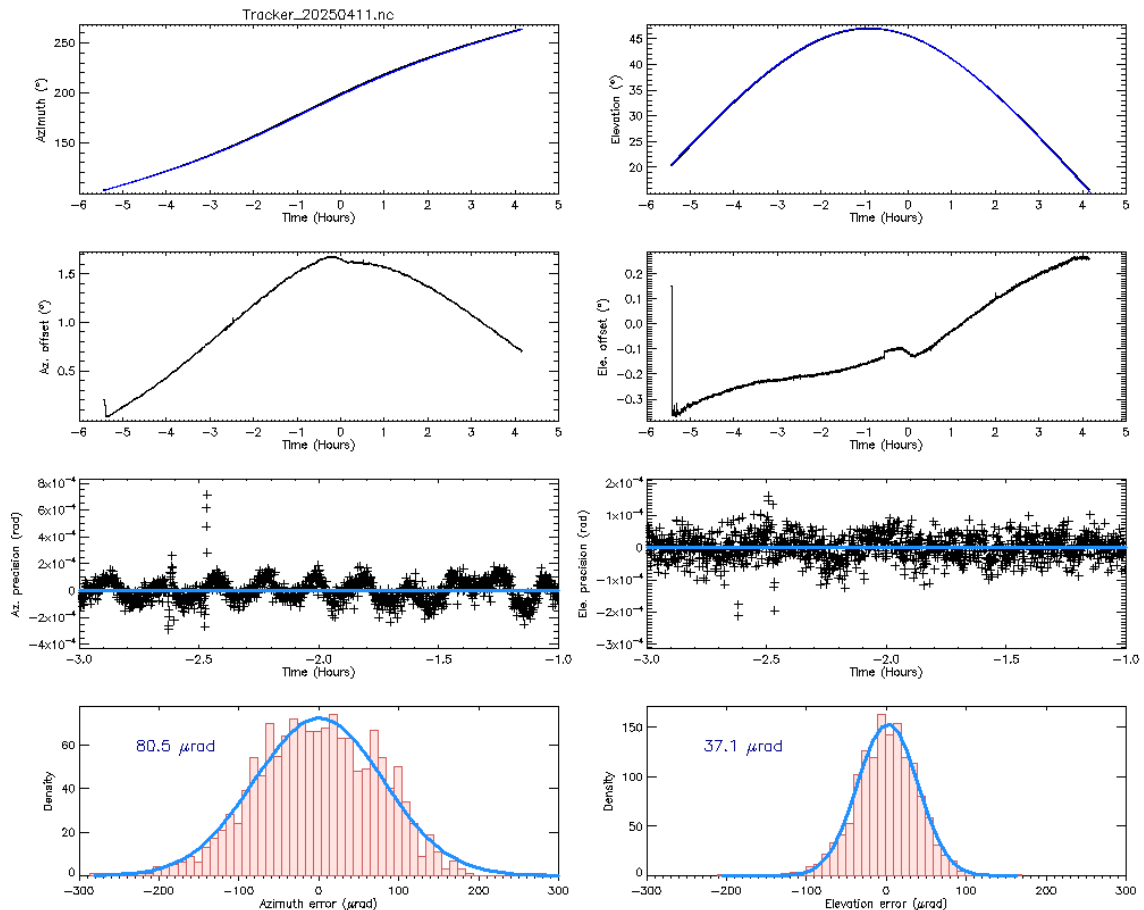


Figure 4.3. Estimation of the sun tracker precision for a single day (11/04/2025). The first (second) column corresponds to the azimuth (elevation) coordinate. From top to bottom, the plots represent (1) the actual and calculated angular coordinates of the sun center, (2) the residuals between the actual and calculated angular coordinates, (3) the residuals further detrended by a 4th order polynomial over a 2 hour period, and (4) the histograms of the residuals with a fitted Gaussian distribution and standard deviation.

4.3. Environmental stability

The outcomes from the upgrades to the thermal management of the LHR described in section 2.5 have been tested. The left hand panel of Figure 4.4 shows a comparison of the internal instrument temperature versus time before and after the upgrade, measured in laboratory conditions. The upgraded instrument temperature remains within 0.5 K over 5 hours of operation. In comparison, operation prior to the upgrades showed a constantly increasing temperature over time due to heat build up.

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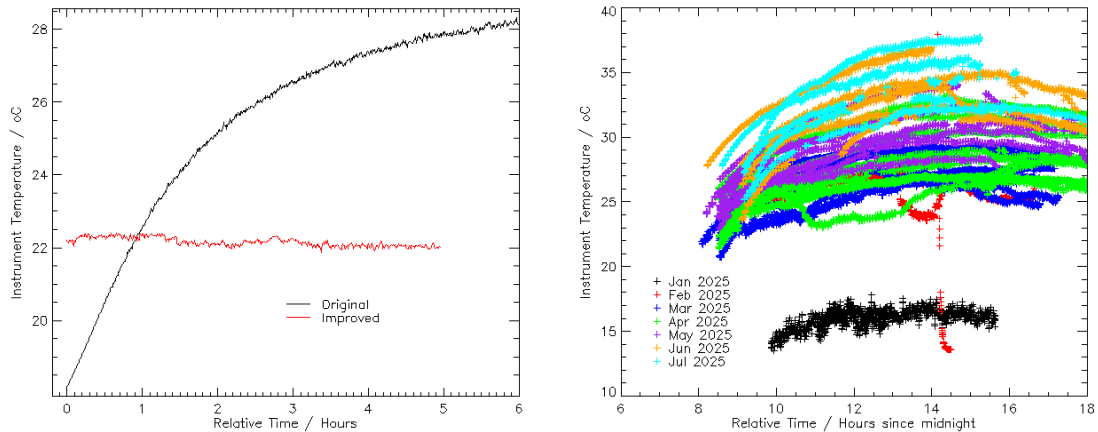


Figure 4.4. Temperature of the LHR instrument over time. Left, direct comparison of instrument internal temperature for operation within an air-conditioned laboratory environment. Right, instrument temperature for all measurements taken during the 2025 installation and campaign as a function of relative time since midnight.

The right-hand panel of Figure 4.4 shows the internal instrument temperature in real deployment conditions, once installed within the outside dome and fully exposed to the ambient conditions. The plot shows all temperature data measured from January 2025 through to July 2025 as a function of relative time. Clear evidence of a diurnal pattern can be seen with the temperature rising and falling over the day. Additionally, there is an increase in maximum temperature over the installation and measurement period. Figure 4.5 shows a comparison of the temperature rise of the instrument over the course of a day for the original LHR (red) and the updated one (black). The improvement in temperature management is very significant as the red trace was recorded in an air-conditioned lab, whereas the black one is for the LHR installed outside and exposed to direct sunlight.

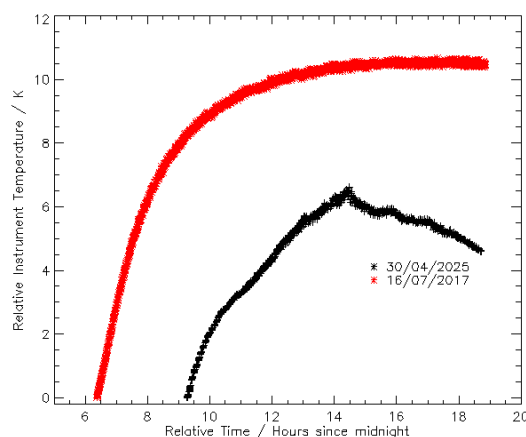


Figure 4.5. Comparison of relative change in instrument temperature as a function of time. The red trace shows the original (FRM4GHGv1) instrument operated in an air-conditioned environment while the black trace shows the upgraded instrument operated in the uncontrolled environment of the Harwell observation dome. The

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relative temperature is calculated using the instrument temperature immediately after switch-on.

4.4. Campaign data analysis

The L0 dataset produced over the 3.5 months campaign was processed using the retrieval scheme fully described in [1].

Methodology

Data from a full sunny day (28/04/2025), was used to study the best averaging strategy. The LHR is configured to record an individual spectral micro-window in 10 seconds. For each measurement cycle, it acquires 12 CO₂ spectra, then switches laser to record 12 CH₄ spectra. Comparison runs were made to compare averaging L1 (calibrated spectra) or L2 data (columns). The latter was found to give better results, at the cost of increased processing time, because it reduces impact of slowly varying drifts occurring for L1 data.

We also conducted a comparison study on the width of the selected spectral micro-window. The CO₂ window was found to be very sensitive to the laser power modulation (through the spectral baseline). It was found that reducing this window to focus only on the CO₂ transition (952.55 – 953.2 cm⁻¹ spectral range) produced improved outputs. As a results, H₂O column data is now solely determined from the CH₄ micro-window.

Compared to [1], a-priori climatology has been updated to the latest GEOS-IT profiles, reference to the precise location of the instrument, as established for the Harwell TCCON site [2]. The profiles come in eight files per day with each file covering a 3-hour period. The prior profile for each measurement is interpolated to the exact measurement time from all available files for the day.

Pressure and temperature information at the first mirror level is also now included, obtained from the local meteorological station described in [2], to constrain the ground level of the a-priori profile.

In addition to the dry mole fraction columns and their associated errors, the processor outputs information content, the fits' final χ^2 and spectral residuals.

Single day processing

The output from a single day processing (28/04/2025), following the input choices mentioned above, is hereby reported. The CO₂ and CH₄ micro-windows are processed independently.

Figure 4.6 shows the retrieved CO₂ dry mole fraction column and the corresponding retrieval error for the CO₂ micro-window. The L2 data sampling is about 5 measurements per min. The average retrieval 1-sigma error is 1.35 ppm, whilst the random scatter (1 standard deviation) on the retrieved column is 3.66 ppm.

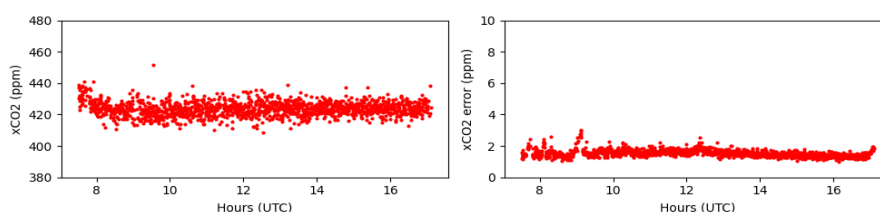


Figure 4.6. Retrieved CO₂ dry mole fraction columns (left) and associated errors (right) for a full day of measurements on 28 Apr. 2025.

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Figure 4.7 shows the corresponding Shannon information content of the measurement which is stable to 15 over most of the day. The right-hand side of the Figure shows the reduced χ^2 . The values are consistent with the slight random noise underestimation on the retrieval error. It also shows strong correlation with the solar zenith angle.

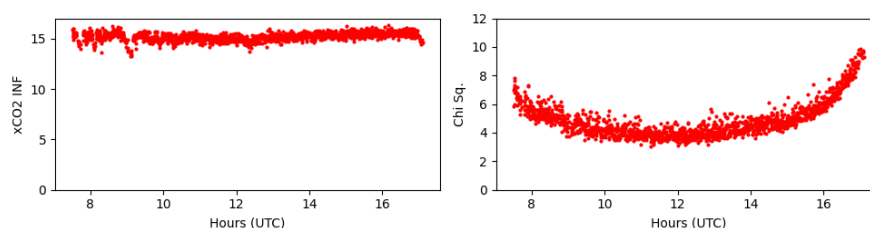


Figure 4.7. Retrieved CO₂ associated Shannon information content and reduced χ^2 from the spectral fits.

Figure 4.8 shows an example of a single CO₂ micro-window trace in which the measured data (L1c, blue trace) is compared with the retrieved data (Rt, red trace). The bottom panel shows the residual between measured and retrieved traces. The right-hand side plot shows the evolution of the residual over the course of the day indicating a fairly stable residual with a systematic slight model error in the vicinity of the line peak, suspected to originate from a slight frequency calibration mismatch.

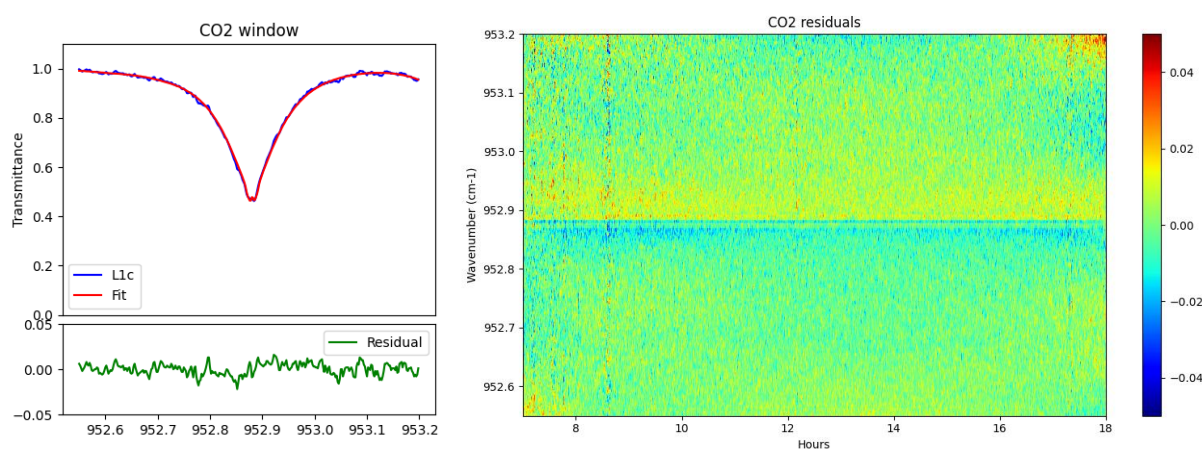


Figure 4.8. Single transmittance window fit and associated residual (left) and fitting spectral residuals for the CO₂ micro-window with respect to time on 28/04/2025.

Figures 4.9 to 4.11 show similar results for the CH₄ micro-window which also contains information about water vapour. The retrieval 1-sigma error for CH₄ and H₂O is on average 0.016 ppm and 25.0 ppm respectively, whilst the random scatter on the retrieved column is 0.101 ppm for CH₄ and 105.7 ppm for H₂O.

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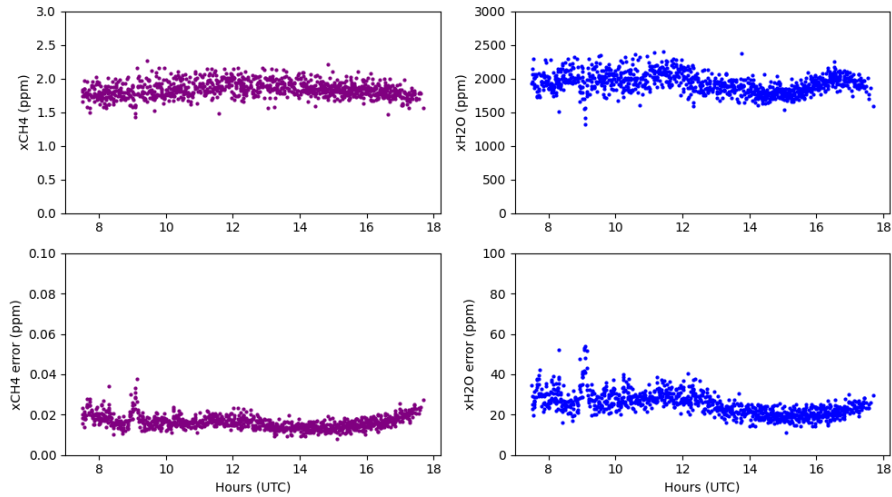


Figure 4.9. Retrieved CH₄ (left) and H₂O (right) dry mole fraction columns (top) and associated errors (bottom) for a full day of measurements on 28 Apr. 2025.

The Shannon information content (Figure 4.10) is around 12 and 11 for CH₄ and H₂O respectively. The reduced χ^2 varies greatly showing, and when greater than 10 is considered as non-convergent by the retrieval software. Currently, at the high frequency end of the CH₄ line, the instrument noise is very significant (low LO power), as seen in the residual of Figure 4.11 for a single measurement (left panel). The mismatch with the modelled line is consistent throughout the daily record.

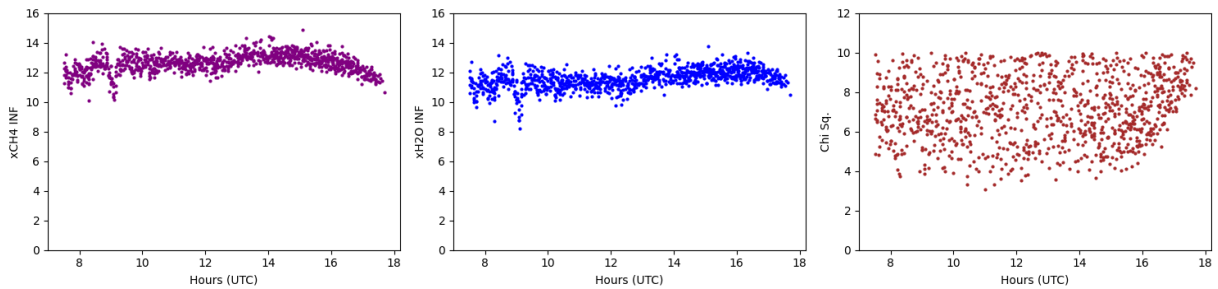


Figure 4.10. Retrieved CH₄ (left) and H₂O (middle) associated information content and reduced χ^2 (right).

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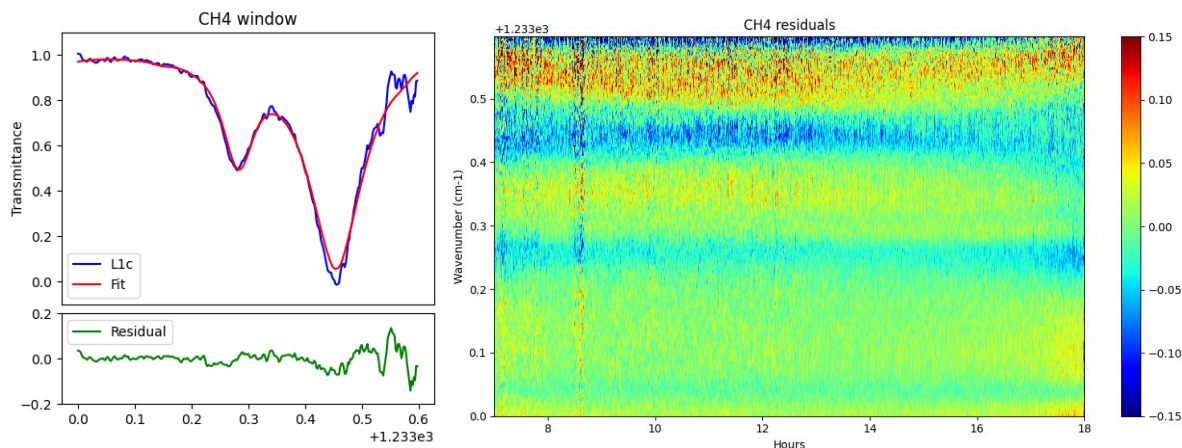
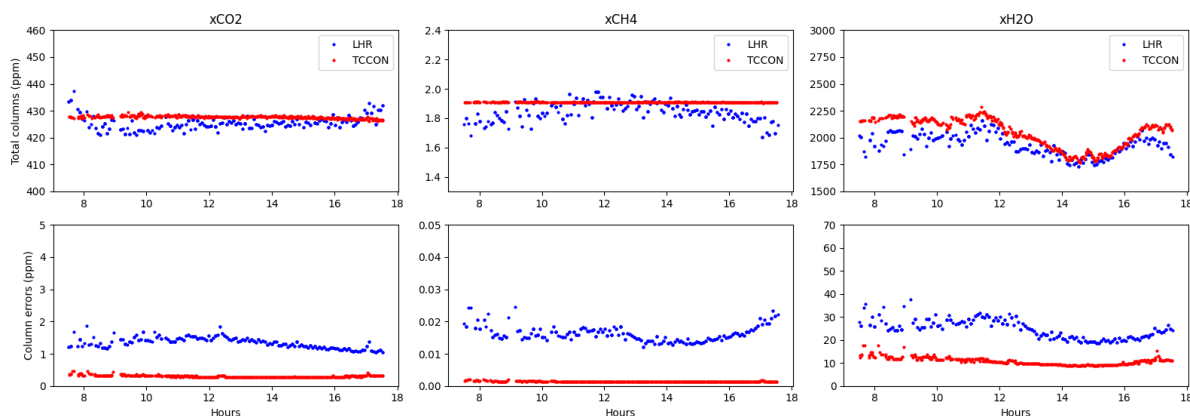


Figure 4.11. Single transmittance, fit and associated residual (left) and fitting spectral residuals for the CH₄ micro-window (right), with the H₂O line at 1233.286 cm⁻¹ and the CH₄ line at 1233.455 cm⁻¹.

Single day – column averaging and comparison with Harwell TCCON

For comparison between the LHR and the Harwell TCCON column measurements, the LHR dataset (which has a higher sampling rate) were averaged over each measurement cycle (duration ~2.5 min) and matched within 1 minute to the sampling resolution of the TCCON series.

Figure 4.12 shows the diurnal variability of X_{CO₂}, X_{CH₄} and X_{H₂O} from the LHR on 28/04/2025, and corresponding TCCON values as reference. Differences between the LHR data and TCCON one are further illustrated in Figure 4.13. Compared to TCCON, the LHR X_{CO₂} appears underestimated, with some artefactual structures at the beginning and end of the diurnal record. Some remaining effects from instrument temperature correlation are strongly suspected, particularly for the warm-up period. The X_{CH₄} data are not affected by the temperature because the late day decrease does not correlate at all with instrument temperature. Instead, it shows a strong solar zenith angle (SZA) dependence linked to changes in the airmass with SZA. The accuracy of the CH₄ spectroscopic data is a potential source of this error. The integrated line strength of the absorption line is reported as having an uncertainty of >20% in HITRAN 2016. In contrast, the CO₂ line has a reported uncertainty of 1-2%.



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Figure 4.12. Averaged LHR (blue) and Harwell TCCON (red) measurements on 28 Apr. 2025 for X_{CO_2} (left), X_{CH_4} (middle) and X_{H_2O} (right) and associated column errors (bottom panels).

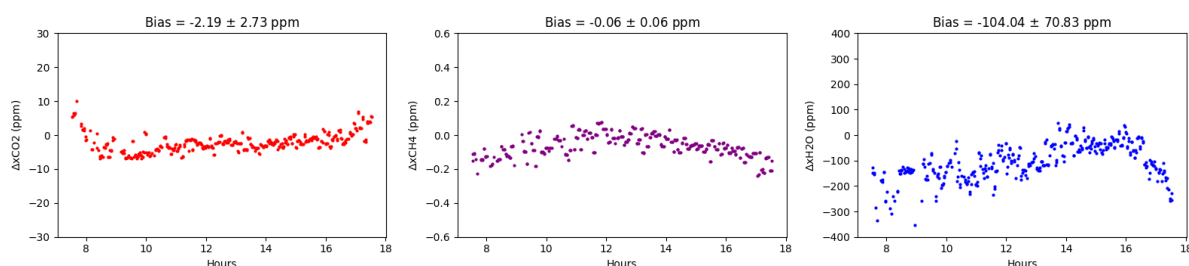


Figure 4.13. Difference of L2 averaged LHR X_{CO_2} (red), X_{CH_4} (purple) and X_{H_2O} (blue) with respect to TCCON on 28 Apr. 2025.

Figure 4.14 shows the retrieved total column values plotted against the measured instrument temperature. For X_{CO_2} , there is a period of instability at lower temperatures ($< 28^{\circ}C$) before the values settle to a flat value. The X_{CH_4} does not show the lower temperature dependence. There appears to be a slight dependence on temperature – however, since the instrument temperature does follow a diurnal pattern (see Figure 4.4) this correlation may be coincidental.

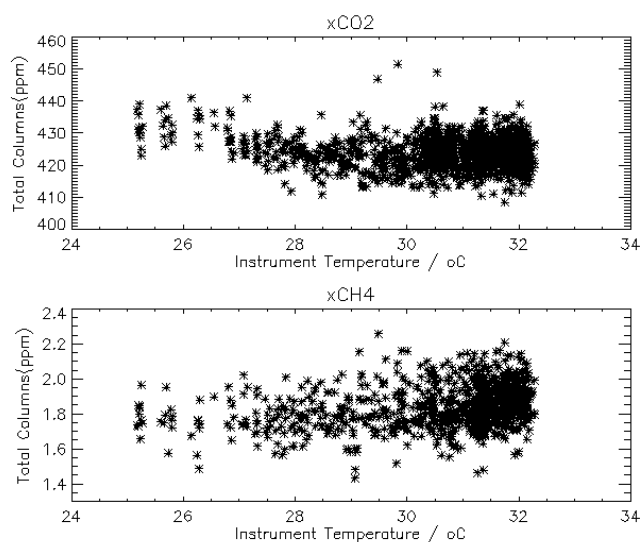


Figure 4.14. Correlation of LHR X_{CO_2} total column against instrument temperature on 28 Apr. 2025.

Compared to previously reported data [3], an improvement in bias (difference between the daily average LHR value and the corresponding TCCON reference one) and diurnal scatter (span between the minimum and maximum reported value) is very significant for the X_{CO_2} product. In contrast, the improvement for X_{CH_4} is marginal, if any observed, which would be consistent with an airmass dependence rather than instrumental varying biases. Table 4.1 summarizes the bias and scatter values for the Sodankylä campaign (2017-2020) as broadly taken from [3], and shows the same metrics for the 28 April 2025.

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Product	2017 - 2019 (SOD)	28/04/2025 (HW)
X _{CO2} (ppm) bias	~ -20 in 2017 ~ -25 in 2018 ~ 5 in 2019	-2
X _{CO2} (ppm) scatter	~ ± 15 in 2017 ~ ± 45 in 2018 ~ ± 30 in 2019	± 9
X _{CH4} (ppm) bias	~ +0.05 in 2018 ~ +0.05 in 2019	-0.06
X _{CH4} (ppm) scatter	~ ± 0.07 in 2018 ~ ± 0.10 in 2019	~ ± 0.10

Table 4.1. Comparison of bias and diurnal scatter between LHR and TCCON for CO₂ and CH₄. The two-letter abbreviation next to each date denotes the measurement location, SOD for Sodankylä (FI) and HW for Harwell (UK).

The correlations between LHR and Harwell TCCON for 28/04/2025 are shown in Figure 4.15. The small correlations of X_{CO2} and X_{CH4} are owed to the diurnal dependencies on instrument temperature and SZA respectively, as explained above. The best correlations are identified during the local noon (13:00 UTC), when the sun is at its lowest SZA. Airmass dependence has not been addressed for the current dataset yet.

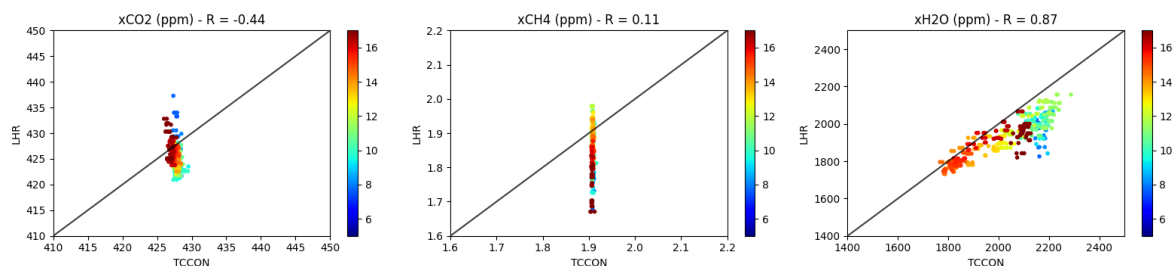


Figure 4.15. Correlations of L2 averaged LHR X_{CO2} (left), X_{CH4} (middle) and X_{H2O} (right) with respect to TCCON on 28 Apr. 2025. Colour-scale denotes the hour of the day.

Timeseries and comparison with Harwell TCCON

The retrieved product time series for the >3 months have been processed under the same condition as the single day case. Figure 4.16 shows the LHR X_{CO2} evolution during the reporting period with the corresponding TCCON data as reference. LHR appears to consistently underestimate X_{CO2} and the diurnal drifts also remain consistent. From end of June to mid-July, LHR X_{CO2} shows more instabilities, correlated to UK heatwave periods with instrument temperature in the 35 degree range (see Figure 4.4 for increased instrument temperature during June and July 2025). The averaged bias of LHR X_{CO2} compared to TCCON is -4.04 ppm. The diurnal artefactual variation is observed on all the dataset. Whilst significantly improved, the X_{CO2} artefactual diurnal variation remains and will need to be studied in more details.

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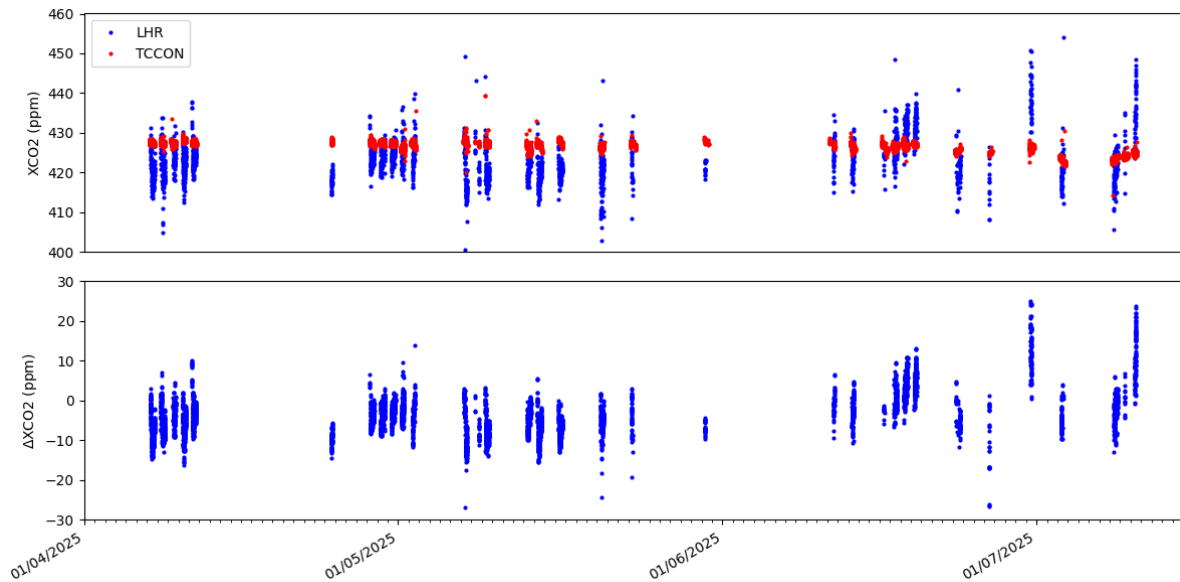


Figure 4.16. LHR (blue) and Harwell TCCON (red) X_{CO_2} measurements for the duration of the current campaign (top) and column differences between LHR and TCCON for matched measurements (bottom).

Similarly, Figure 4.17 shows the LHR X_{CH_4} variability over the campaign period with TCCON as reference. The LHR underestimation is consistent throughout the whole period owing to the SZA diurnal variation, which also remain consistent. The X_{CH_4} measurements don't appear to be strongly affected by the heatwave period, suggesting the temperature variation effect relates to the laser sources (as the detection chain is identical to both micro-windows). The averaged bias of LHR against TCCON is -0.1 ppm. For the same data but limiting the observation times around local noon (Figure 4.17b) in an attempt to ignore the SZA diurnal variation, the bias drops to -0.067 ppm. It also reveals that the high temperature owing to UK heat waves at the end of June and during July did affect the X_{CH_4} measurements.

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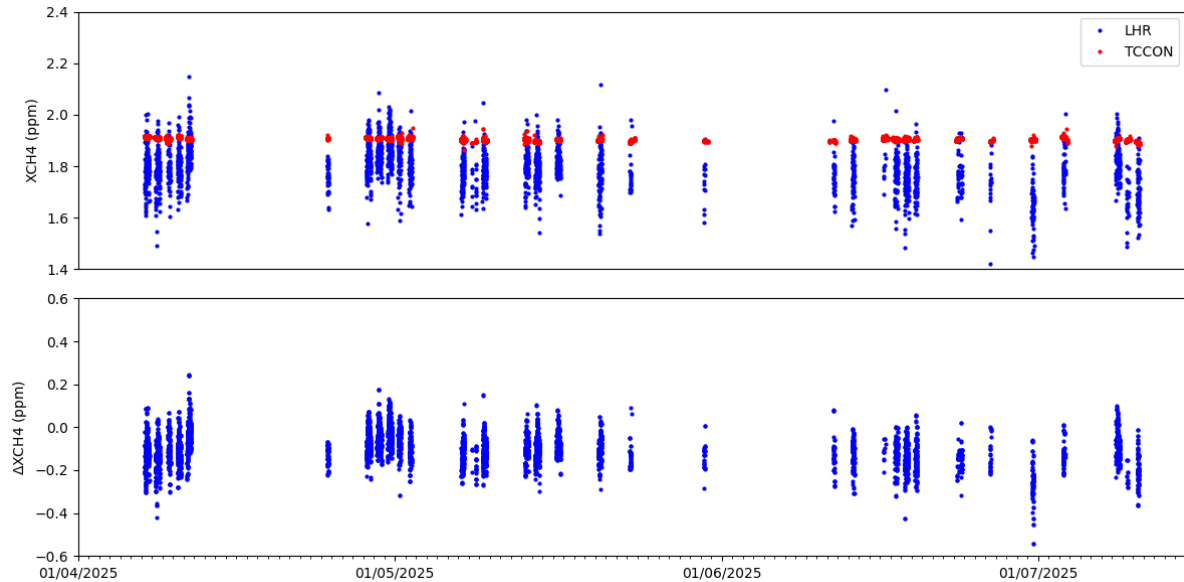


Figure 4.17. LHR (blue) and Harwell TCCON (red) X_{CH_4} measurements for the duration of the current campaign (top) and column differences between LHR and TCCON for matched measurements (bottom).

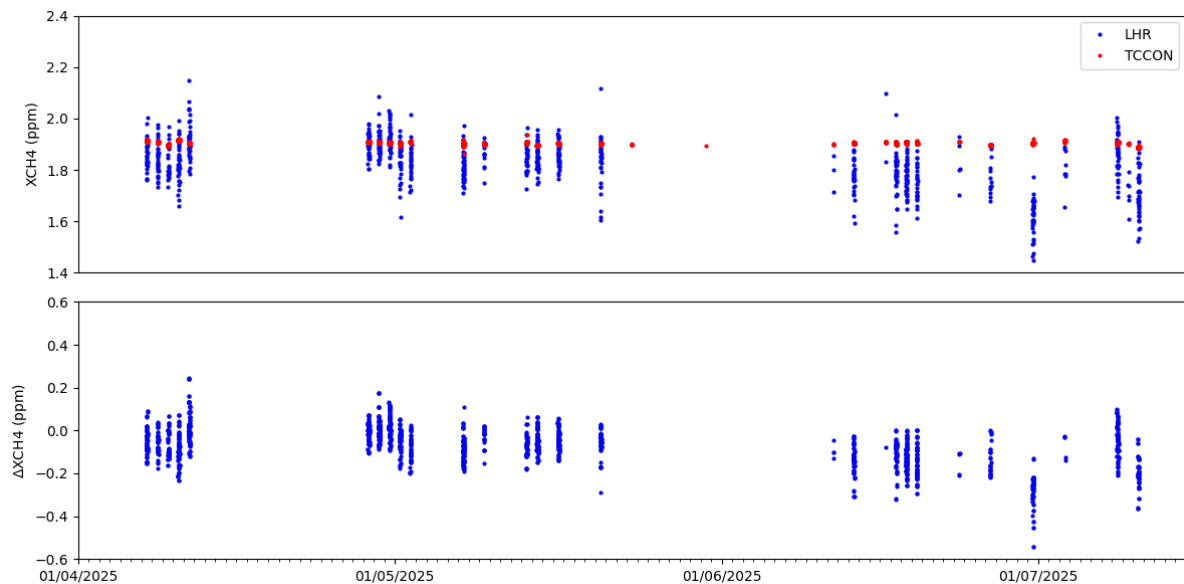


Figure 4.17b. As Figure 4.17, but for measurements around the local noon (11:00 to 13:00).

The LHR X_{H_2O} shows similar underestimation with respect to TCCON, as shown in Figure 4.18. However, it captures well the H_2O day-to-day variability over the period. The reported bias compared to TCCON is -160 ppm.

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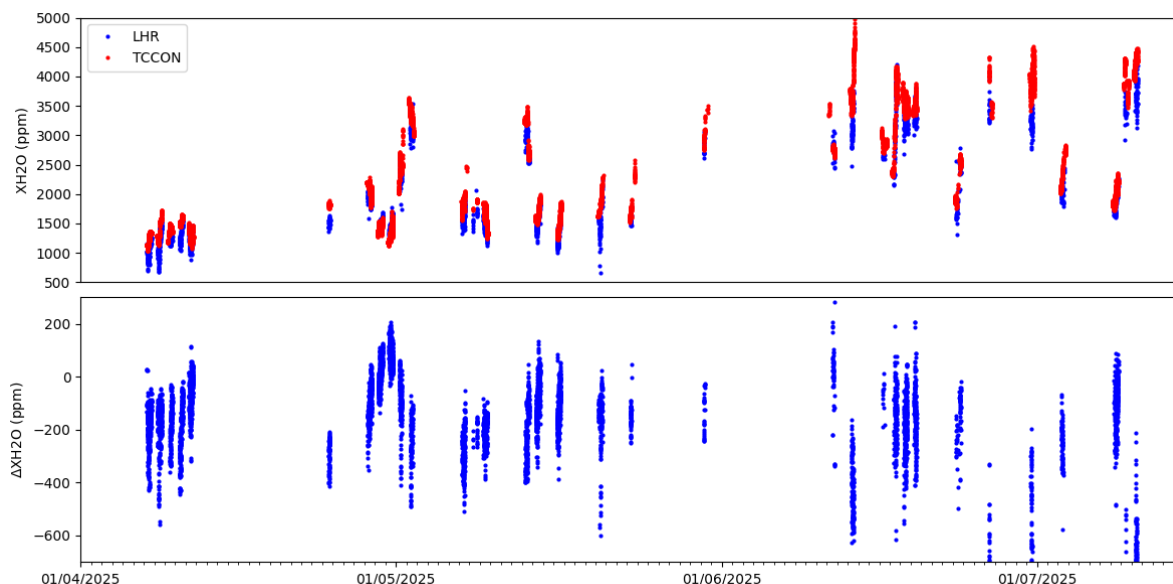


Figure 4.18. LHR (blue) and Harwell TCCON (red) X_{H_2O} measurements for the duration of the current campaign (top) and column differences between LHR and TCCON for matched measurements (bottom).

Figure 4.19 shows the correlation between LHR and TCCON for X_{CO_2} , X_{CH_4} and X_{H_2O} . The results mirror the reported correlations for single day data and reflect the dependencies discussed above.

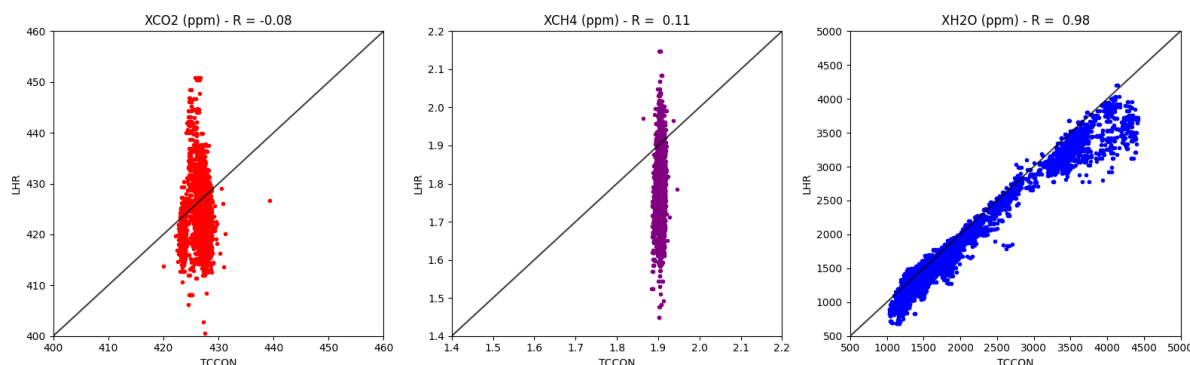


Figure 4.19. Correlations of LHR X_{CO_2} (left), X_{CH_4} (middle) and X_{H_2O} (right) with respect to TCCON for the duration of the campaign (07/04/2025 – 10/07/2025).

5. Conclusion and next steps

The instrumental LHR upgrades together with new Level 1 and Level 2 processors have led to the first production of a >3 months dataset recorded in conjunction to the Harwell TCCON. This very first run shows promising results as the X_{CO_2} product has been greatly improved compared to the case of the Sodankylä campaign. The systematic bias has been reduced by one order of magnitude (from -20 ppm to -2 ppm), and the artefactual diurnal amplitude from >+/-30 ppm to +/-9 ppm, this without any correction of any sort so far. The artefactual diurnal amplitude remains an issue that requires more investigation to be understood.

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Some clear differences were observed between X_{CO_2} and X_{CH_4} . Their artefactual diurnal variations were found to be of different origin. Unlike that of X_{CO_2} , the X_{CH_4} one appears strongly correlated to the solar zenith angle variation. Besides, we haven't seen any significant improvements from the instrumental update and from the new data processor. We would need to wait for the integration of the O_2 band product from the hyperspectral imager to investigate the relationship with the airmass variation, and a possible correction strategy.

In terms of next steps:

- The dataset presented here is a very first run. Few analyses have been conducted. We will study the dataset further to attempt to identify sources of biases, and explore further retrieval strategies, as well as possible post-retrieval corrections such as removing temperature correlations and airmass dependencies.
- The presented data comparison between LHR and TCCON includes instrument and retrieval. We plan to process the TCCON data using the MORSE-GB retrieval so that only the instrumental effects are considered. This will help identifying biases originating from instrument, and those from the retrieval software.
- The hyperspectral imager has not yet been finalized as issues with the dichroic splitter were identified (image degradation introduced by the optical component). We need to complete installation and integrated to the retrieval to carry out O_2 airmass correction.
- The new retrieval software is very flexible and has been developed with the capability to retrieve profile information from either only LHR data, or through sequential optimum estimation using both the NIR TCCON data and the TIR LHR data. Implementing the dual instrument profile retrievals is the medium-term goal.

6. Reference

- [1] FRM4GHG2.0 Deliverable D2.2 – October 2024 – Technical note on LHR data retrieval.
- [2] Weidmann, D., Brownsword, R. & Doniki, S. The Harwell TCCON observatory. Geosci. Instrumentation, Methods Data Syst. 14, 113–129 (2025) - <https://doi.org/10.5194/gi-14-113-2025>.
- [3] Sha, M. K., De Mazière, M., Notholt, J., Blumenstock, T., Bogaert, P., Cardoen, P., Chen, H., Desmet, F., García, O., Griffith, D. W. T., Hase, F., Heikkinen, P., Herkommer, B., Hermans, C., Jones, N., Kivi, R., Kumps, N., Langerock, B., Macleod, N. A., Zhou, M. (2024). Fiducial Reference Measurement for Greenhouse Gases (FRM4GHG). Remote Sensing, 16(18), 3525. <https://doi.org/10.3390/rs16183525>