Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2016-142-AC1, 2016

Atmospheric Measurement Techniques Discussions

Interactive comment on "Thermal infrared laser heterodyne spectro-radiometry for solar occultation atmospheric CO_2 measurements" *by* Alex Hoffmann et al.

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Received and published: 11 August 2016

Dear Dr Feist,

We thank you for your comments and your insightful contribution as a TCCON PI to the discussion on our manuscript related to the LHR instrument development. It is particularly useful to have views from an operational (user) and community perspective.

As a preliminary word of caution, we would like to re-emphasize that it is by no means our intention to suggest that LHR instruments should replace well-established FTIR instrumentation as part of TCCON. Commercial FTIR with its associated experimental protocols, data analysis and traceability developed in the context of TCCON benefit

from a high level of maturity. For this reason, we believe TCCON remains the established benchmark against which it makes sense to evaluate the performance of the LHR during its instrumental development phase. We do emphasize that our retrievals are preliminary and require more analysis and developments (p. 17 l. 27). As with the instrumental development, our data processing maturity is not yet on a par with that of TCCON, which has benefited from a decade of international development (e.g. Yang et al., 2002, doi: 10.1029/2001GL014537). However, we do see interesting potential in thermal infrared LHR systems based on the initial demonstration we presented in the manuscript. This appears to us to be complementary to TCCON, offering potentially light-weight and compact instruments, which may offer interesting trade-offs as far as deployment is concerned (high density, rapid and temporary deployment, remote autonomous operation for instance). It is also worth keeping in mind that the experimental approach to trace gas sensing focused upon in our manuscript is, of course, generic. Hence, LHR can be used for different targeted gases and applications. The stringent requirements within the context of CO2 monitoring provide an excellent opportunity to demonstrate the research instrument capabilities.

Specific replies to your comments follow hereafter.

Comment 1 on XCO2

It is correct that we do not observe O2 and hence air mass. We agree that the implications in terms of accuracy ought to be analysed and quantified. Our initial retrieval efforts rely on auxiliary input data (ultimately from ECMWF analyses, where we intend to use near real time products) for air pressure and temperature profiles, and a surface-level pressure for the dry air column estimation. The current scope of the manuscript focuses on instrumental error propagation. Follow-up studies on detailed error and bias analysis propagating down to XCO2 are planned for the next phase of our endeavour, as emphasized in our conclusions and elsewhere. We do welcome contributions and collaborations for improving our retrieval efforts.

Comment 2 on TCCON network density and running costs

Thank you for sharing your TCCON cost analysis. This is very enlightening, especially since we are in the process of developing one of our Bruker IFS125 FTIR's towards TCCON status at our Harwell site. We propose to change p. 3 l. 19 from '[. . .] and the subsequent running costs prevent the network from reaching a high density.' to '[. . .] and the subsequent running costs are high.', which should be factually correct. From our interactions with various funding bodies, and prospective users, we gathered that even an up-front investment of 10-15% of the total cost is still worth taking into consideration. In a very pertinent manner, you mention that the basic cost model for running a remote site would only change substantially for a lightweight, autonomous (and solar-powered) instrument. That is precisely what we aim to work towards with the LHR. The current prototype described in this manuscript is built on an optical table and uses cryogenic cooling for the heterodyne mixer/detector (the QCL is TEC- and water-cooled). We have already demonstrated in the laboratory cryogenic-free operation with a test system about the size of a shoe box. Forthcoming development iterations are planned to be heavily integrated and ruggedized (see p. 20 l. 10). As you mentioned, the use of a TEC-cooled detector is documented in the manuscript (p. 17 l. 18).

Comment 3 on the degrees of freedom (DFS)

We have consistently derived DFS (trace of the AK matrix for all retrieval products combined) values of that order for our simulations, the inputs to which are outlined in the text. A new simulation with the latest iteration of our retrieval algorithm and with high-density optimized grids for CO2 and H2O, produces a DFS of 8.4 (of which $\sim$1 is due to the a0 baseline coefficient, $\sim$2.8 relates to H2O and $\sim$4.6 to CO2). Yes, the OSS currently assumes 'idealized conditions', in terms of perfectly known temperature, pressure and potential interfering species profiles, a 1D atmosphere, an instrument working at the shot-noise limit, and no forward model error in the retrieval. The instrument noise is assumed Gaussian (p. 7 l. 23), and a rudimentary Shapiro-Wilk normality statistical test is performed during measurement pre-processing to check whether the Gaussian

noise hypothesis must not be rejected. This feature has not yet been fully tested, and has not been mentioned in the manuscript, but preliminary trials seem to imply that Gaussian noise is a mostly valid assumption. The instrument line shape is taken into account and, unlike for other type of spectrometers, can be precisely measured in the electronic domain and is very stable, which is one of the advantages of LHR (p. 7 l. 20, p. 15 l. 16). Indeed, a change of airmass over the 90s measurement is not considered for the purpose of this instrument development manuscript, as this would be part of follow on work related to more advanced data processing and analysis. The manuscript concludes with section 5.2 on a first retrieval of real measurements with real noise (Fig. 9). The DFS for a sample measurement therein is 7.6 (of which 3 are due to the baseline coefficients). For our first retrieval showed in this manuscript, a priori are almost not constrained. The a priori error in Connor et al. (2015) is not specified, it may also account for the difference you raised. The DFS of $\sim$3 by Connor et al. seems to relate to the DFS of CO2 only. Though retrieval performed on CO2 only would need to be performed to estimate an exact figure, the partial DFS for CO2 in Fig. 9 (i.e. the trace of sub-matrix A) amount to $\sim$2.5. Lastly, we would welcome independent cross-checking of our results, e.g. with a different retrieval model, should that be desirable. Sample data or code can be made available upon request.

Comment 4 on the passive solar tracker

We agree and are aware that the tracking system currently implemented for the instrument demonstration is not as accurate as the camera-based tracking recommended for TCCON operation sites. We do mention that '[. . .] better pointing accuracy may eventually be required, especially at low elevation. This, in turn, is likely to be best achievable with a complementary active feedback mechanism.' (p. 12 l. 6.) We have been considering options such as the Sun disc imaging technique described by Gisi et al., 2011 (referenced) for future iterations (the camera-tracking you mentioned). Alternatively, commercial solutions based around this CamTRACKER concept may also be available, and could easily be interfaced to the LHR. The detailed quantification of pointing accuracies is outside the scope of this work. Again, this relates to forth-coming instrument bias analysis and full error budget. Once pointing errors propagation down to XCO2 have been quantified and compared to other error sources, we aim to ensure the optimum cost/performance trade-off for the pointing system. Since we are not observing solar lines, the measurements are insensitive to the Doppler shift error related to tracker pointing inaccuracies and solar rotation. Ultimately, we believe that it is of the utmost importance to know accurately where we are pointing (providing we remain within the solar disk), rather than pointing to a specific line of sight. The bias and error budget analysis work planned as a next step will provide further quantitative insight.

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-142, 2016.