

Preliminary results from the Lauder site of the Total Carbon Column Observing Network TCCON

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Abstract

We give a brief description of the Total Carbon Column Observing Network (TCCON), a new network of ground-based Fourier Transform spectrometers (FTS) dedicated to measurement of greenhouse gas absorption (CO_2 , CO , N_2O , CH_4) in the near infrared. We present preliminary retrievals of CO_2 total column densities from the TCCON site in Lauder, New Zealand between July 2004 – when routine measurements began – and April 2005, and compare these retrievals with in-situ CO_2 measurements from the monitoring station at Baring Head, New Zealand. A discussion of how we plan to compare the ground-based FTS retrievals with in-situ surface observations and greenhouse gas retrievals from satellite radiances follows.

Introduction

The strengths of the sources and sinks of greenhouse gases such as CO_2 and CH_4 are currently inferred from in-situ measurements made at a network of ground-based monitoring stations. However inverse modelling based on this data set has serious limitations because of the sparsity of the network, and because errors in model predictions of advective transport and mixing are aliased into flux estimates (Heimann and Kaminski, 1999).

Accordingly, a number of extensions to the ground and space-based trace gas observing system are currently being planned and implemented (e.g. the North American Carbon Program, the CarboEurope Integrated Project, current operational satellite instruments SCIAMACHY, MOPITT, AIRS, IASI, and planned dedicated satellite missions OCO and GOSAT).

Ground-based measurements of trace gas column densities are an important component of these new observing systems. Accurate ground-based measurements of column densities provide useful constraints in inverse modelling, particularly when coupled with simultaneous, co-located in-situ surface measurements, and they are vital to validation of measurements of trace gas column densities from space.

In this paper we give an overview of the TCCON network (including preliminary results from the Lauder site) and briefly describe how we plan to make best use of FTS measurement information content in comparisons with in-situ measurements and retrievals from satellite radiances.

Overview of the TCCON network

TCCON is a global network of ground-based Fourier Transform spectrometers which acquire near infrared solar absorption spectra in the 4000–14000 cm^{-1} interval at 0.02 cm^{-1} resolution. Spectra are analysed to retrieve CO_2 , CO, CH_4 , N_2O , HF and O_2 column densities and column average mixing ratios (denoted X_Y). FTS measurements will be complemented with simultaneous in-situ surface measurements of all target trace gas concentrations (CO_2 , CO, CH_4 , N_2O) wherever possible. The five confirmed and three proposed TCCON sites are tabulated in Table 1.

Column-integrated trace gas measurements are less sensitive to local sources and sinks and seasonal and diurnal rectifier effects than in-situ surface measurements. However, if the TCCON network CO_2 measurements are to provide useful additional constraints for the global carbon budget – both directly, and through validation of satellite column measurements – they must achieve a precision of 0.1% and an accuracy of 0.3%. Accurate solar tracking, surface pressure measurements, spectroscopy and retrieval algorithms are all key factors in achieving these error targets.

At each TCCON site the solar tracker and interferogram acquisition are coupled to a GPS timing system and tracker pointing accuracy (± 0.4 mrad, 10% of the solar radius) will be monitored using spectral characteristics of the observed solar spectrum (Doppler shift and strength of line absorption). The FTS measurement is complemented with accurate measurements of surface pressure (± 0.1 hPa, ~ 10 minute frequency), and the FTS instrument line shape (ILS) is routinely monitored using an HCl cell.

Currently retrievals are performed using a maximum likelihood profile scaling algorithm GFIT developed by G. Toon. In this method the total column density is retrieved assuming the relative *a priori* distribution of the absorber in the vertical is specified correctly, thus reducing the problem to the retrieval of a single profile scale factor. Alternative, and in principle optimal, methods to estimate the total column density by integration of full profile retrievals are being developed by B. Connor in the framework of the OCO mission.

While profile scaling is clearly a suboptimal retrieval of the total column for cases where the vertical profile of absorber number density is not known perfectly, this method is believed to be less sensitive to forward model errors (e.g. specification of the ILS, spectroscopic parameters and/or atmospheric temperature) than methods based on full profile retrieval. Research is currently being undertaken in the TCCON program to characterise the impact of forward model error on retrieval accuracy for profile scaling and profile retrieval algorithms (Connor et al., 2004).

Finally, independent estimates of O_2 column densities (derived from measurements of surface pressure and estimates of water vapour column density) are compared with O_2 column densities retrieved from O_2 1.27 micron and A-band spectra to provide an end-to-end characterisation of measurement and retrieval accuracy, and hence provide an internal network standard.

Note: we refer hereinafter to the ratio of retrieved and independently estimated O_2 column densities as the O_2 profile scale factor. Similarly, column average volume mixing ratios X_{CO_2} are derived by dividing retrieved CO_2 column density by corresponding independent estimates of the dry air column density.

Table 1: Geographical location of confirmed and proposed TCCON sites. Sites denoted with a † will have continuous in-situ surface measurement capability for all target trace gases (CO₂, CO, CH₄, N₂O). Park Falls has continuous in-situ CO₂ measurement capability and weekly surface flask sampling of all target trace gases. Arrival Heights has monthly surface flask sampling of all target trace gases.

Confirmed sites		Lat.	Long.	Proposed sites		Lat.	Long.
Park Falls	WI USA	45.9N	-90.3E	Billings	OK USA	36.6N	-97.5E
Lauder†	New Zealand	45.0S	169.7E	Arrival Heights	Antarctica	77.8S	166.8E
Darwin†	NT Australia	12.5S	130.9E	Wollongong†	NSW Australia	34.4S	150.9E
Bremen	Germany	53.1N	8.8E				
Ny Alesund	Spitzbergen	78.9N	11.8E				

Preliminary results from the Lauder site

Near infrared spectra have been acquired routinely at the Lauder site since July 2004. Results from preliminary analysis of this data are described here.

1.27 micron band retrievals of O₂ column densities

O₂ profile scale factors derived from Lauder spectra are illustrated in Figure 1. Profile scale factors should be unity at all zenith angles. The non-unity, zenith angle dependent character of retrievals is attributed to spectroscopic uncertainties and should be corrected with improved band strength and spectroscopic parameter estimates (magnetic dipole linewidths and their temperature dependence, parameterisation of collision-induced continuum absorption).

At a given solar zenith angle retrieval precision is of the order of 0.002 (0.2%), compared with the target precision of 0.001 (0.1%). Efforts to identify the sources of retrieval error and improve retrieval precision are ongoing. Our current focus is the characterisation of solar tracker pointing accuracy, the effects of errors in the specification of ILS in general (particularly phase errors), the effect of variations in source intensity during interferogram acquisition in particular, and the effect of errors in the atmospheric temperature profile assumed in retrievals.

A preliminary and encouraging measure of accuracy is given by the comparison of the quadratic regression relations derived from Lauder and Park Falls retrievals, which agree to within 0.1–0.3%.

Timeseries of 1.6 micron band CO₂ retrievals

Column average CO₂ volume mixing ratios X_{CO₂} derived from Lauder spectra are illustrated in Figure 2. The mean mixing ratio for the timeseries is 376.2 ± 0.7 ppmv (0.2%). The standard deviation of diurnal variations range from 0.1 to 1.0 ppmv and the day-to-day variation is of the order of 0.5 ppmv.

Comparison with preliminary Baring Head baseline data

In-situ surface CO₂ concentrations measured in southerly wind conditions at the trace gas monitoring station at Baring Head, New Zealand (41.4S, 174.9E) between January 2004 and April 2005 are also

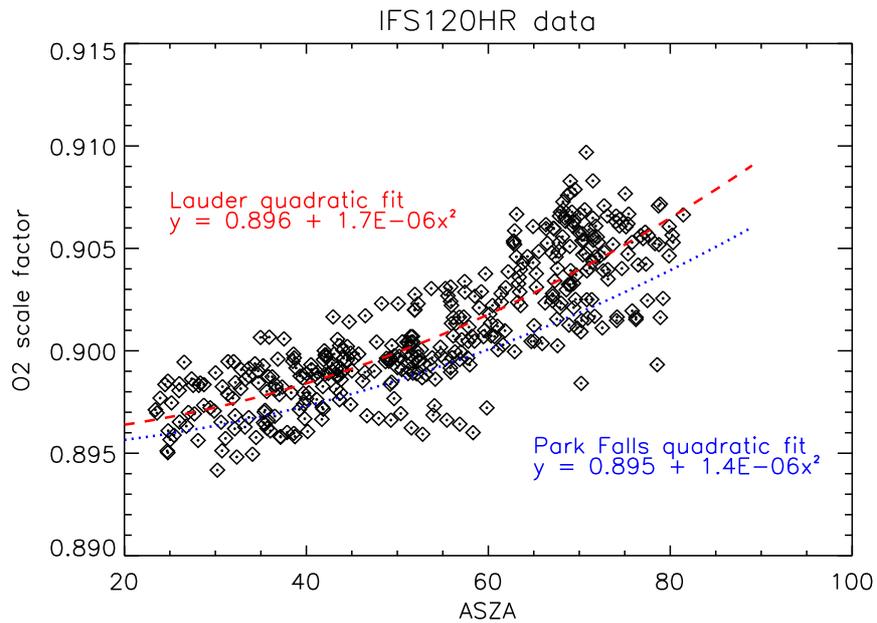


Fig. 1: O₂ profile scale factors retrieved from the 1.27 micron band as a function of solar zenith angle. Scale factors should be unity at all zenith angles. A regression fit of retrieved scale factors as a quadratic function of solar zenith angle is illustrated for Lauder retrievals in red. An equivalent analysis of scale factors retrieved from Park Falls data is illustrated in blue.

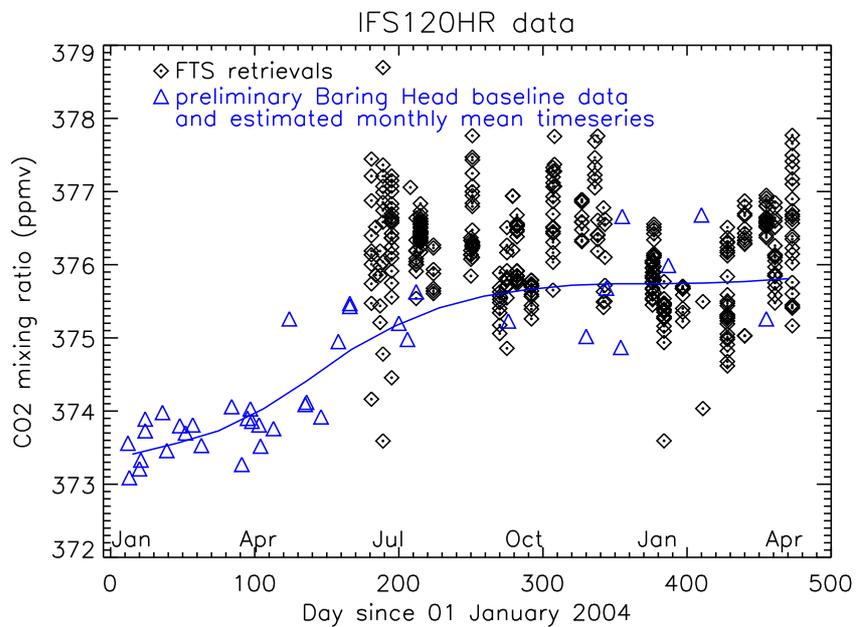


Fig. 2: CO₂ column average volume mixing ratios derived from 1.6 micron band CO₂ retrievals since routine measurements began at Lauder (July 2004). In-situ CO₂ measurements from the surface monitoring network site at Baring Head are illustrated for comparison.

illustrated in Figure 2. Direct comparison of surface volume mixing ratio and FTS X_{CO_2} is justified, at least to first order, because i) the surface measurements (by the nature of their sampling) are representative of Southern Hemisphere background CO_2 concentrations and ii) the tropospheric CO_2 volume mixing ratio is nearly constant with height in the Southern Hemisphere (Olsen and Randerson, 2004).

The two sets of measurements are generally in good agreement, and notably show no marked temporal (seasonal) variation in column average or surface in-situ CO_2 concentrations over the period of the FTS measurements (July 2004 – April 2005). This is because the secular increase and seasonal draw-down of atmospheric CO_2 are of similar magnitude in the Southern Hemisphere during this period of the year (e.g. see Figure 4 of Brailsford et al., 2005).

The FTS estimates of X_{CO_2} are on average 0.1% (0.4 ppmv) higher than the surface measurements, which may be due to spectroscopic band strength errors. This difference between surface and column average volume mixing ratios could however be a result of the enhancement of CO_2 concentrations (of the order of 1%) in the mid and upper troposphere in Southern Hemisphere midlatitudes due to poleward transport of CO_2 enriched tropical air in the upper troposphere and oceanic uptake in the southern midlatitudes (Olsen and Randerson, 2004).

Diurnal variations

A significant component of the diurnal variation of the FTS X_{CO_2} is associated with a monotonic decrease in X_{CO_2} of the order of 1 ppmv over the course of the day (not shown). This decrease is significantly larger than the range of decreases (0–0.6 ppmv) in X_{CO_2} due to plant photosynthesis predicted by modelling studies (Olsen and Randerson, 2004). The FTS retrievals may overestimate the diurnal cycle of X_{CO_2} due to solar zenith angle dependent retrieval averaging kernels (see Figure 3) and/or coherent diurnal variation in the errors in the atmospheric temperature profile assumed in retrievals. These effects will be quantified in the near future.

There is also evidence that line width errors introduce solar zenith angle dependent CO_2 retrieval errors of the type illustrated in Figure 1 for oxygen profile scale factor retrievals. These spectroscopic errors will also contribute to observed diurnal variability in retrieved X_{CO_2} .

Day-to-day variability

The day-to-day variability observed in the Lauder time series (of the order of 0.5 ppmv) is much higher than expected based on model predictions of the spatial gradients of CO_2 column densities in the Southern Hemisphere (Olsen and Randerson, 2004). This may be due to aliasing of the diurnal variation of X_{CO_2} retrievals (be it real or a retrieval artifact) because the FTS temporal sampling of the diurnal cycle differs from day to day (and measurements on a given day are often clustered either in the morning, or in the afternoon).

CO_2 retrievals from AIRS (and TOVS) could provide very useful, complementary information on the spatial homogeneity of CO_2 concentrations in the mid and upper troposphere of the Southern Hemisphere, and guide further FTS retrieval error diagnostics and retrieval validation. We hope to make a

preliminary comparison of retrievals from the Lauder ground-based FTS and the AIRS instrument on the EOS-AQUA platform in the coming year.

Correlation of O₂ and CO₂ retrievals

The mean quadratic solar zenith angle dependence illustrated in Figure 1 has been subtracted from retrieved O₂ scale factors, and the resulting residuals have been plotted against retrieved X_{CO₂}. These plots (not shown) indicate that O₂ scale factor residuals and X_{CO₂} are correlated ($r=0.5$), suggesting some of the variability in the O₂ and CO₂ retrievals is due to common retrieval errors. In this case O₂ column densities could be used to derive and hence improve the precision of X_{CO₂} estimates once issues with the spectroscopy of the 1.27 micron O₂ band have been resolved (and if common sources of error cannot be otherwise mitigated).

Profile retrieval and applications

As discussed in the introduction, in principle profile retrieval has several advantages over profile scaling algorithms. Firstly, as illustrated in Figure 3, profile retrieval algorithms are capable of providing nearly ideal, solar zenith angle independent total column averaging kernels, thus reducing the smoothing error contribution to the retrieval error budget substantially, and secondly, it extracts some information on absorber distribution in the vertical (typically 3–4 degrees of freedom for signal for CO₂ retrievals). However, as noted previously, profile retrieval is potentially more sensitive to forward model errors and careful study is needed to determine the most appropriate retrieval algorithm in practice.

Comparison of FTS, in-situ and satellite measurements

Planned comparison of ground based FTS and satellite measurements and retrievals will take retrieval errors and averaging kernels into account explicitly, following the work of Rodgers and Connor (2003). One way of doing this is to apply satellite retrieval averaging kernels to ground based FTS profile retrievals.

Theoretical FTS partial column averaging kernels for CO₂ retrievals are illustrated in Figure 4, and suggest several further possibilities: corresponding boundary layer and free troposphere partial column profile retrievals should improve comparisons with in-situ surface measurements and provide a potential link between surface and satellite measurements.

Conclusions

Preliminary results from the Lauder TCCON site are encouraging: Lauder O₂ and CO₂ retrievals have a precision of 0.2% and O₂ retrievals are in good agreement with data from the Park Falls site.

Work is ongoing to identify the sources of observed variability and improve the precision and accuracy of retrievals to attain the TCCON error targets (0.1% precision, 0.3% accuracy). This work includes monitoring and improving solar tracker accuracy, characterising the effects of ILS errors (phase errors)

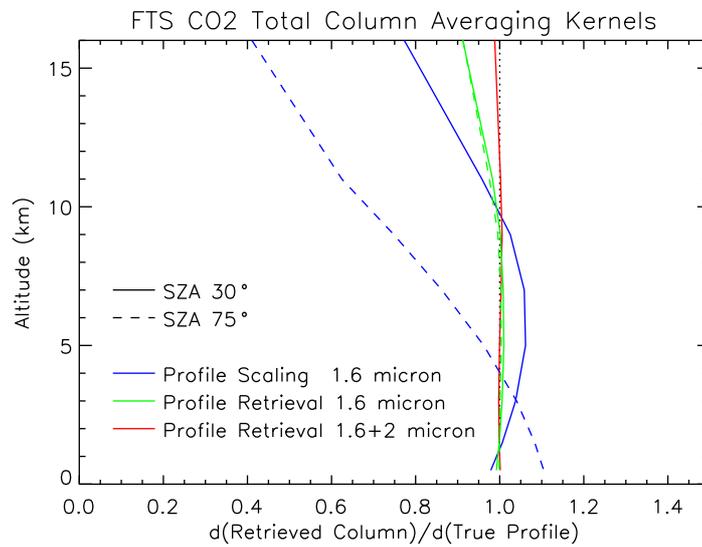


Fig. 3: FTS CO₂ total column averaging kernels for profile retrieval and profile scaling algorithms and solar zenith angles of 30 and 75 degrees. The ideal column averaging kernel is unity at all levels.

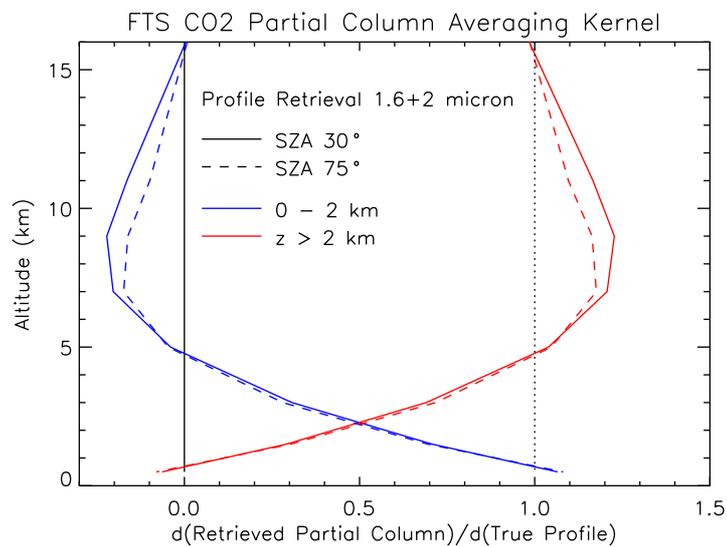


Fig. 4: FTS CO₂ partial column averaging kernels for profile retrieval integration from 0–2 km (boundary layer) and for z > 2 km (free troposphere) and solar zenith angles of 30 and 75 degrees.

and variations in source intensity during interferogram acquisition on retrieval accuracy, quantifying possible sources of bias in retrieved diurnal variation of X_{CO_2} (averaging kernels, temperature dependence), improving near infrared spectroscopic parameterisations (O_2 and CO_2 linewidths and band strengths and parameterisation of collision-induced continuum absorption), and the development and comparison of profile scaling and profile retrieval algorithms (with due consideration of the impact of forward model errors).

Comparison with independent measurements of CO_2 , while not trivial, will be an important component of FTS retrieval validation. Initial comparisons of FTS retrievals with in-situ surface measurements from the Baring Head monitoring station show good agreement between the measured CO_2 concentrations and their temporal variation. We will continue to compare FTS retrievals with surface in-situ measurements of CO_2 from Baring Head and the Lauder site, and we will extend these comparisons to attempt to take the very different measurement sampling characteristics into account explicitly (e.g. estimate biases, compare partial column retrievals).

CO_2 retrievals from satellite thermal infrared radiances will potentially provide useful additional information on CO_2 concentrations in the mid and upper troposphere, and their spatio-temporal variability, and we intend to compare of retrievals from the Lauder ground-based FTS and EOS-AQUA AIRS spectra in the coming year.

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