

Abstract

A commercial low-resolution (0.5 cm^{-1}) Fourier-Transform-Spectrometer (FTS) has been modified and is used for determining the total column XCO_2 of the atmosphere by analyzing direct solar radiation. The spectrometer has a small home-built solar tracker attached, so that it is a ready-to-use instrument. The results are validated with temporally coinciding on-site measurements taken with a high-resolution Total Carbon Column Observing Network (TCCON) FTIR-spectrometer. For the whole comparison period of 5 months (26 measurement days) an agreement with TCCON-results of $(0.12 \pm 0.08)\%$ is achieved. This makes the spectrometer a promising candidate for a low-cost addition to the TCCON core FTIR sites, especially suitable for locations with limited infrastructure. An impressive mechanical and thermal stability is proved, enabling the spectrometer for use in field campaigns and for the monitoring of local sources.

1 Introduction

Within the last several years, it has been recognized that a precise knowledge of the global abundances of greenhouse gases such as CO_2 , CO and CH_4 is required for understanding the mechanisms of the global carbon cycle and to determine its sources and sinks (Olsen and Randerson, 2004). To measure column averaged mole fractions of these gases, several satellite-borne instruments were developed such as SCIAMACY, GOSAT and OCO/OCO-2 (<http://oco.jpl.nasa.gov/news/>). The latter two missions are exclusively dedicated on measuring greenhouse gases and OCO-2 will presumably be launched in 2014. To support and validate these measurements great efforts have been undertaken to set up the Total Carbon Column Observation Network (TCCON). It consists of about 18 globally distributed, ground-based solar absorption Fourier transform spectrometers operating in the Near-Infrared (NIR) spectral region to measure the CO_2 -total column in the atmosphere. These high-resolution TCCON

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spectrometers achieve an unprecedented accuracy of 0.25 percent for the atmospheric XCO₂ content (Wunch et al., 2011). The XCO₂, which is the column-averaged dry-air mole fraction, is derived by ratioing the measured CO₂ and O₂ total columns by

$$XCO_2 = CO_{2,column} / O_{2,column} \cdot 0.2095 \quad (1)$$

This approach compensates for numerous systematic errors, such as a pointing offset or an erroneous surface pressure. To make the network results comparable to WMO (World Meteorological Organization) standards, the retrieved XCO₂ value is divided by a calibration factor of 0.989. This value was determined by comparisons with in situ profiles measured in the framework of aircraft campaigns (Wunch et al., 2010; Messerschmidt et al., 2011).

Despite its outstanding capabilities such as the precision and stability during normal operations, the IFS125HR-spectrometers from Bruker used by the TCCON also have their downsides. The IFS125HR is an expensive high-precision instrument, its large dimensions in the order of 1 × 1 × 3 m and the weight well beyond 100 kg makes it difficult to transport, and its operation requires a significant amount of infrastructure, such as a stable support platform, air conditioning and sufficiently large lab space. For regular maintenance such as realignment and for repairs, an experienced person has to access the instrument, which can be difficult and time-consuming. The IFS125HR is not a portable spectrometer, moving it to a new site requires time-consuming start-up procedures. These obstacles impede the scientifically important ground-based extension of atmospheric carbon column measurement on a global scale, e.g. in Africa and South America.

Some flexibility is gained by integrating the spectrometer into an overseas container including air-conditioners and solar-trackers (Geibel et al., 2010). But still, a truck and a forklift have to be available as the containers measure about 15 ft and weight several tons. For field campaigns and for operation in remote areas with low infrastructure (the power consumption of such a container is in the order of 5 kW), this approach is hardly manageable.

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To overcome these problems, the usage of smaller, cheaper and more easily transportable spectrometers were recently investigated towards the ability to measure XCO₂. Besides the ability to be used easily in field campaigns, assuming a sufficient compactness and mechanical stability, the spectrometers could even be sent back and serviced by the manufacturer or the staff of the home institution for repairs or realignments, reducing the costs and effort significantly. In addition, instruments with lower requirements to the ambient temperatures would simplify global deployments.

One alternative is the IFS125M-instrument, which is smaller and less sturdy than the IFS125HR, while offering comparable resolution. Due to its lightweight design, the stability of the instrumental line shape (ILS) is not at the level of the IFS125HR spectrometer, so that it is difficult to achieve the long-term-stability required by TCCON (V. Sherlock, NIWA, personal communication, 2012). In addition, it still has a length of about 2 m and requires on-site realignment by qualified personnel. The IFS125M spectrometer has been successfully operated on ships (Notholt et al., 2000).

In addition, several compact and medium to low-resolution instruments currently are under investigation, such as a grating spectrometer (about 0.16 cm⁻¹ resolution), a fiber Fabry-Perot interferometer (both setups presented in Kobayashi et al. (2010)), the IFS66 from Bruker (0.11 cm⁻¹) (Petri et al., 2012), a Nicolet Spectrometer from Thermo-Scientific (0.125 cm⁻¹) (Chen et al., 2012) and the IR-Cube from Bruker (0.5 cm⁻¹) (Jones et al., 2012).

In this work we demonstrate for the first time the suitability of a very compact setup, consisting of a modified commercial FTS with a resolution of 0.5 cm⁻¹ and a miniature solar tracker attached to it. We verify the long term stability, present the tracker setup and the modifications applied to the commercial spectrometer to achieve XCO₂ measurements with a precision 0.08 % over several months, validated with respect to a co-located TCCON spectrometer.

2 Instrumentation

Our aim was to investigate the capabilities of a compact and robust spectrometer, which is sufficiently small and light to be carried by one person, without compromising the ability to align, modify and check internal optical components due to the compactness. In addition we developed a small and transportable solar tracker which is directly attached to the spectrometer. This merged setup, which is displayed in Fig. 1, is ready to use for various kinds of environmental research measurements.

2.1 Home-built tracker

The target requirements for the tracker were to reach a high tracking precision with a compact and lightweight setup. We decided to realize an alt-azimuthal tracker, with 2 stepper-motor driven rotation stages. The complete tracker weights about 2 kg and has the dimensions $30 \times 20 \times 10$ cm. It supports a beam diameter of 50 mm, which actually is much wider than required for the purpose described in this paper, as only a beam diameter of 3 mm is used for the solar absorption measurements (see Sect. 2.2). However, this fact allows to apply the tracker for other kinds of observations (e.g. lunar, open path, emission measurements). We used 2 rotation stages with hollow axes from Standa (<http://www.standa.it>). They are driven by stepper-motors controlled by the "SMCI12" motor drivers from Nanotec (<http://www.nanotec.com>), allowing a microstep-size of 1/64th of a full step, which results in a theoretical 0.56 arc seconds resolution along both axes. The mirrors are elliptic glass plates with SiO₂ protected aluminum coating.

The tracker is controlled by our CamTracker approach, so the optical tracking feedback is derived from a camera recording the field stop of the spectrometer, leading to very consistent control of the spectrometer's line of sight. Technical details are given in Gisi et al. (2011). A camera-image of the illuminated aperture is shown in Fig. 3.

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2.2 The NIR-modified EM27 spectrometer

We decided to use the EM27™-spectrometer from Bruker. This spectrometer uses the RockSolid™ pendulum interferometer with 2 cube-corner mirrors and a CaF₂ beam-splitter, which offers very high stability with respect to thermal and mechanical disturbances. The interferometer supports a beam diameter of 40 mm. The pendulum is attached by springs, resulting in frictionless and wear-free movements. This principle results in even higher reliability of the interferometer in comparison to the 125HR setup. The latter suffers from wear due to use of friction bearings on the linearly moving retroreflector. This wear introduces a shear misalignment and requires regular realignment (Hase, 2012).

The EM27 achieves 1.8 cm optical path difference equivalent to 0.5 cm⁻¹ resolution. To realize this, the retroreflectors of the pendulum structure are moving by a geometric distance of 0.45 cm. The sampling of the interferogram is controlled by a standard, not frequency-stabilized HeNe-laser. The sealed spectrometer compartment contains a desiccant cartridge; the radiation enters through a wedged fused silica window. So the spectrometer withstands and can be operated in adverse environmental conditions, e.g. high relative humidity. It measures approximately 35 × 40 × 27 cm and weights 25 kg including our home-built tracker. Due to the current electronics, with a resolution of 0.5 cm⁻¹, the spectrometer is capable of recording single-sided interferograms only, however, an electronics update will overcome this limitation in the future. It is compact enough to be carried by one person, but still offers sufficient space inside for modifications and alignments of the light path, allowing us to test various setups.

A schematic drawing of the EM27 with modifications is presented in Fig. 2. The tracker, which was described in Sect. 2.1, leads the solar radiation into the EM27 spectrometer. We limit the beam to 25 mm free diameter by using a 750 nm long-pass-filter a few centimeters behind the entrance window in order to block unwanted radiation which would disturb the laser detectors of the interferometer.

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After the radiation has passed the interferometer, it is blocked by an aperture (which forms the aperture stop of the optical system) with a diameter of 3 mm. We inserted this aperture for controlling optical aberrations (to achieve a near-theoretical instrumental line shape, see Sect. 3.1) and for avoiding nonlinear detector response. The remaining part of the radiation is appropriate for recording solar absorption spectra. Finally the beam is focused on a field stop with 0.6 mm diameter by a 90 degrees off-axis paraboloid with an effective focal length of 101.6 mm. In combination, this results in a semi Field of View (FOV) of 2.96 mrad. The field stop is inclined versus the optical axis by a few degrees to avoid channeling. As partially illuminated detectors show unwanted non-linear and ILS-effects, a diffuser was placed between the field stop and the InGaAs-detector (size $1 \times 1 \text{ mm}^2$, spectral sensitivity $6000\text{--}9000 \text{ cm}^{-1}$). The detector signal is DC-coupled, allowing to correct for solar intensity variations due to thin clouds (Keppel-Aleks et al., 2007).

The image of the sun on the field stop is recorded by the camera which then is used as the optical feedback for the tracker (CamTracker), as described in (Gisi et al., 2011). This is a very precise method for controlling the actual line of sight of the spectrometer. Changes of the alignment of any mirror, e.g. during transportation, have no effect on the accuracy of the tracking and the resulting line of sight. An image of the sun on the aperture as it is recorded by the camera is shown in Fig. 3.

The tracker and the EM27-interferometer are connected to a controlling computer via a standard network cable. The USB cable of the camera uses a separate outlet of the housing of the spectrometer and is connected with a 15 m active USB extension cable to the computer.

The controlling computer is equipped with an Intel 3.2 Ghz processor, runs Windows 7, the operating-software for the spectrometer (Opus 7) and the CamTracker-program. It was located 1 floor below the terrace on which we placed the EM27 spectrometer.

3 Characteristics

3.1 Instrumental line shape

Any quantitative trace gas retrieval depends on a proper knowledge of the spectral degradation characteristics. For FTIR-spectrometers this instrumental line shape (ILS) is advantageously separated into one part which refers to the inherent self-apodization of an FTS with circular field stop, and therefore also exists for an ideally aligned spectrometer. This contribution can be calculated easily by the spectrometers field-of-view and the optical path difference of the interferometer. The second component of the ILS can be described by a complex modulation efficiency (represented by a modulation amplitude and a phase error, both functions of optical path difference) which result from misalignments and optical aberrations. These parameters have to be derived by experiment, e.g. by evaluating gas cell measurements (Hase et al., 1999).

A standard approach for the high-resolution FTIR-instruments is to use low-pressure gas cells. We checked the ILS of the EM27 by measuring the water vapor lines of about 2 m in ambient air using a collimated standard halogen bulb as light source. This minimalistic approach makes a gas cell obsolete and can easily be performed, e.g. during measurement campaigns. To analyze these results and to obtain the modulation efficiency and the phase error, we used the version 12 of the LINEFIT program (Hase et al., 1999). The required parameters for the correct interpretation of the spectrum are the ambient temperature, the total pressure and the partial water pressure (the latter is a by-product of the LINEFIT analysis).

We performed these measurements 2 times within the time series presented in this paper. On 8 February 2012 and 22 May 2012 the derived modulation efficiencies were 0.9954 and 0.9910 respectively. However, as the water vapor lines in HITRAN which we used contain inaccuracies, the absolute value for the derived modulation efficiency and the phase error depend on the selected spectral range. Therefore we can only conclude that the ILS of the EM27 is impressively stable, but the absolute calibration

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of the modulation efficiency requires further study of the H₂O line parameters in the 7000 cm⁻¹ spectral region.

For our system with a spectral resolution of 0.5 cm⁻¹ an increase of 1 % of the modulation efficiency results in an XCO₂ increase of 0.15 %. As in our time series the assumed modulation efficiency changed by less than 0.5 %, we used a constant ideal ILS in our retrievals. Note that no realignment of the spectrometer was performed over the whole period, although the spectrometer was transported frequently and was exposed to temperatures between -10 and +40 °C. We estimate that our knowledge of the absolute modulation efficiency is within 2 %, which implies that the systematic offset between the EM27 and 125HR XCO₂ timeseries should be below 0.3 %

3.2 Ghost to parent ratio

For the recording of NIR spectra in the 6000 to 9000 cm⁻¹ range, the IFG sampling has to be performed at each rising and falling zero crossing of the laser AC signal. This makes the IFG recording prone to alternating sampling errors, which generates artifacts (ghosts) in spectral domain, as described in detail by Messerschmidt et al. (2010). As this problem affected several TCCON measurement sites in the past, we decided to check the GPR (ghost-to-parent ratio) for our setup.

In contrast to the IFS125HR-spectrometers, it is not possible to readjust the GPR with the currently available EM27 electronics. The laser-detecting photo diodes, however, are the same as used in the latest 125HR version.

With our EM27 spectrometer we measured a GPR of 2×10^{-4} which is of the order of the current TCCON recommendations (1×10^{-4}). Hase recently suggested an IFG resampling scheme (F. Hase, personal communication, 2011) which could be applied to reduce the GPR further, but we refrained for performing any correction because the GPR is rather small.

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4 Measurements and analysis

4.1 Setup and operation of the spectrometers: EM27 and reference TCCON spectrometer

We operated the EM27 spectrometer on the roof-terrace of our office-building at 133 m a.s.l. with the coordinates 49.094° N and 8.4336° E. The testing period covered 26 measurement days from 3 February 2012 to 22 June 2012. For each day of operation, the spectrometer was moved from its storing place in the fourth floor to the terrace on floor 7, see Fig. 1. As we used a simple unsprung trolley for transportation, the spectrometer was subject to significant mechanical vibrations. When placing the spectrometer outside, we did not put much effort into a precise leveling or orientation. A coarse orientation relative to the wall of the building was sufficient to enable the CamTracker-program to detect the sun on the field plane and to center it to the field stop (see Fig. 3). During operation, the spectrometer experienced outside ambient conditions. Temperatures in February were as low as -10°C , in May the spectrometer was heated to temperatures above 40°C due to exposure to direct sunlight. We alternately recorded single-sided interferograms with 0.5 cm^{-1} and double-sided interferograms with 1 cm^{-1} resolution, with 10 averages each. The recording time for each of these measurements (being an average of 10 IFGs) was about 34 s. The applied scanner speed was 10 khz. For the further analysis in this work we only evaluated the 0.5 cm^{-1} resolution measurements, because a significant loss in contrast between the CO_2 lines and the adjacent continuum is observed when the resolution is reduced to 1.0 cm^{-1} , as can be seen in Fig. 4.

The TCCON-instrument in Karlsruhe located about 700 m north of our office building at 110 m a.s.l. at the coordinates 49.100° N and 8.4385° E provided the reference XCO_2 dataset. During each of the 26 EM27 measurement days, 125HR spectra were recorded in parallel.

In addition, various meteorological observations are available at the site. In our context, the records of ground-pressure and tall-tower temperatures at 100 and 200 m

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altitude are of relevance. These auxiliary data have been used for the analysis of the spectra (see Sect. 4.2).

4.2 Data processing and evaluation

The official analysis code for the TCCON network is GFIT. GFIT is maintained by G. Toon at the California Institute of Technology and used by the TCCON as a part of the software package GGG, which also includes preprocessing of the interferograms and post-processing of the resulting XCO₂. More details can be found in Wunch et al. (2011). However, we preferred to use our own calibration tools and retrieval code PROFFIT Version 9.6 for the EM27 study. Our setup is well established for work within the NDACC FTIR network and has been validated in various studies (Schneider et al., 2008, 2010; Sepúlveda et al., 2012). Therefore, we will first show that our setup well reproduces the official TCCON 125HR XCO₂ results for the high-resolution 125HR spectra. Next we analyze the EM27 spectra and resolution-reduced 125HR spectra with our retrieval setup. The resolution-reduced 125HR spectra have been included to discern instrumental effects from apparent XCO₂ changes when analyzing low resolution spectra.

We used the same O₂ line list and the same CO₂ and H₂O a-priori mixing-ratio profiles as used by the official TCCON analysis. For CO₂ we used the HITRAN08 lines with own line-mixing parameters which we derived from a code provided by J.-M. Hartmann (Lamouroux et al., 2010).

The pressure and temperature profiles for all PROFFIT evaluations were taken from local meteorological measurements (ground pressure and tall-tower temperatures at 100 and 200 m altitudes) and the Merra-modeldata “IAU3D assimilated state on pressure(inst3_3d_asm_CP)” (<http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldings.pl>). Besides other parameters, this provides the temperature and pressure on a 1.25 × 1.25 degrees grid, from 1000 to 0.1 hPa for 8 times per day. The pressure and temperature for each measurement was then interpolated temporally between these 8 times, and

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spatially inside the 3 dimensional model grid along the approximate path of the solar radiation.

No post-processing of the XCO₂ results has been performed within our analysis sequence apart from applying the TCCON calibration factor of 0.989 (Wunch et al., 2010) to all XCO₂ results. In accordance with previous studies (Petri et al., 2012) we find that reducing the spectral resolution significantly below the resolution applied by the TCCON network leads to a systematic increase of the retrieved O₂ and CO₂ columns. The study by Petri et al. (2012) was performed using GFIT, we observe similar - but not identical - changes with our independent analysis setup. Therefore we assume that this effect is partly introduced by deficiencies of the far-wing line shape model and partly stems from approximations of the line-by-line calculation of absorption cross-sections. Anyway, such a systematic offset can be removed by adjusting the XCO₂ calibration factor for a hypothetical EM27 network.

We processed and evaluated the data in 4 different ways which will later be denoted as “EM27”, “HR_High”, “HR_Reduced” and “GFIT”:

- “EM27”: PROFFIT-evaluated averages 10 IFG of EM27 with 0.5 wavenumber resolution. The IFGs were apodized by a Norton-Beer-Medium function.
- “HR_High”: PROFFIT-evaluated averages of 4 IFGs (2 forward, 2 backward) from TCCON-instrument with 0.014 wavenumber resolution.
- “HR_Reduced”: The initial measurements are the same as in “HR_High”, but the interferograms were truncated to 0.5 wavenumbers resolution and apodized by a Norton-Beer-Medium function. The retrieval scheme then was the same as described in “EM27”.
- “GFIT”: GFIT-evaluated averages of 2 forward or 2 backward interferograms of the TCCON-instrument with 0.014 wavenumbers resolution (forward and backward interferograms are analyzed separately). For the intercomparison in Sect. 5.3, these separate forward- and backward results are averaged, in contrast to the

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figures containing the gas columns and the XCO₂-values in the course of measurement days. In any presented data, we applied the IFG preprocessing routines from GGG, for XCO₂-values we also applied the standard postprocessing, including airmass-dependent corrections.

5 4.3 Spectral windows

In the official TCCON analysis, the CO₂ column is evaluated in the spectral ranges 6180–6260 and 6297–6382 cm⁻¹, for the O₂ analysis the range 7765–8005 cm⁻¹ is applied. For the PROFFIT analysis of the 125HR and EM27 spectra, we adopted the same O₂ window, but we merged the CO₂ windows into one broader region extending from 6173 to 6390 cm⁻¹.

An example of the spectral windows including the measurement, the fit and the residuum are presented in Fig. 5. For both windows the quality is very good and the standard deviation of the residuum is $1\sigma = 0.2\%$ for CO₂ and 0.17% for O₂. However, several peaks appear in the EM27 residuals (in the graph of the O₂ marked with arrows) which do not appear in the resolution-reduced 125HR spectra.

These residuals originate from the fact that the intensity and shape of the solar lines vary as function of the projected solar disc radius. Because the FOV of the EM27 instrument of 2.95 mrad (semi-FOV) is by a factor of about 3 greater compared to the one of the IFS125HR, which has a semi-FOV of 0.957 mrad, the EM27 observes a significantly larger fraction of the solar disc. An image of the solar disc superimposed to the field stop as recorded by the Camtracker is displayed in Fig. 3. The current NIR line list used by PROFFIT does not include parameters to describe the center-to-limb variability of the solar lines.

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5 Results

In this section, we evaluate the results for the EM27 in comparison to the 125HR reference. In Sects. 5.1 and 5.2 we provide an exemplary overview of the CO₂ and O₂ columns and the resulting intraday variability of XCO₂ during several sample days. In Sect. 5.3, a statistical analysis for the whole set of measurements is provided.

5.1 CO₂ and O₂-columns

Figures 6 and 7 collect the CO₂ and O₂ columns for the measurement days 21 February 2012 and 28 March 2012. In each graph, the ambient air temperature on the terrace is given for the beginning and the end of the EM27-measurements. In addition, the starting, the minimal and the last value for the solar zenith angle (SZA) of the measurements are displayed. The values in the areas with a gray background are not taken into account in the statistical analysis of Sect. 5.3. The shaded areas filter out SZAs beyond 70 degrees and measurements taken within the first 30 min after the start of measurements. We added the latter restriction as the EM27 requires some startup time before it operates in a stable manner. After moving it from the 20°C lab-environment to the outside temperature on the terrace, which was sometimes as low as -12°C, the HeNe reference laser tube temporarily undergoes fast temperature changes, thereby shifting the reference wavelength during a few scans.

Columns for O₂ recorded on 2 days are presented in Fig. 6. The data processing procedure for the 4 types of datapoints were described in Sect. 4. One observes a difference between the “HR_High” and the “HR_Reduced” columns, resulting from the reduction of the resolution. The “HR_Reduced” columns of O₂ are 0.4 % higher than the reference values. This systematic resolution-dependent difference was also observed before by Petri et al. (2012). Possible reasons for this discrepancy are discussed in Sect. 4.2. A closer inspection reveals that this is not a constant correction factor in case of the CO₂ column, but also a weaker air-mass-dependent contribution can be observed. The “HR_Reduced” CO₂ columns are 0.4 to 0.6 % higher than the reference

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values. This finding is not surprising for an effect probably induced by line-shape issues. Nevertheless, this is not an obstacle for a hypothetical EM27 network, but a matter of adjusting the analysis procedures, as the TCCON network also performs some air-mass dependent tuning in the course of the analysis of the 125HR spectra.

One would expect the EM27 O₂ and CO₂ columns to reproduce the “HR_Reduced” values. However, we observe values approximately 0.6 % lower. We are not sure about the origin of this offset, as the retrieval scheme (a-prioris, pressure and temperature profiles, used resolution,...) is exactly the same. As outlined in Sect. 3.1 the absolute ILS calibration of the EM27 might be slightly off, and the observed discrepancies are within the resulting error bar (moreover, the offset is nearly the same for CO₂ and O₂ columns as one would expect in this scenario). Therefore, we assume that the uncertainty of the ILS calibration is the leading effect. In addition, the deficiencies of the solar line model could trigger parts of the systematic offsets. The variation in the EM27-O₂-columns during the evaluated days is very low which proves the high stability of the EM27 spectrometer as well as the high performance of the CamTracker system. When comparing the “GFIT” and “HR_High” results generated with PROFFIT, one observes an air-mass dependent increase of the GFIT values. For this reason the TCCON applies an a posteriori airmass correction to the XCO₂-values. For the PROFFIT evaluated O₂ columns this effect is not evident, although the same line lists are used.

When compared to the intraday variability of the O₂ columns, the higher variability of the CO₂ columns is obvious. These enhancements are indicated by both the EM27 and the 125HR and are discussed in Sect. 5.3.

5.2 XCO₂

The XCO₂ values for 5 sample days are presented in Fig. 8. As described in Sect. 4.2, all datasets are calculated by Eq. (1) and include the WMO calibration factor of 0.989. In addition, the GFIT(TCCON) dataset contains a GFIT-specific post-correction, especially an air-mass dependent correction.

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Obviously the systematic differences between the 4 datasets cancel out very well so that they agree within about 1 ppm. The intra-day variability differs strongly between the measurement days. During some days the values vary very smoothly (e.g. 22 March 2012), others, such as the 28 March 2012, show several short-term increases. As these are observed both by the EM27 and the 125HR and the simultaneously recorded CamTracker images look unsuspectingly, we are confident that these enhancements reflect real increases in the atmospheric XCO₂. The measurement site is located in an urban area; it is surrounded by several coal- and gas power plants. The closest ones are in the town Karlsruhe (13 km to the South-West with 915 MW), in Mannheim (39 km to the North with 1675 MW) and in Heilbronn (57 km to the East with 950 WM). At the 28 March the wind came from the North, so we suspect the CO₂ increases to originate from the power plant in the city of Mannheim.

A slight air-mass dependent difference is visible between the 4 datasets. It is nearly negligible between the 2 low-resolution datasets and biggest between the “EM27” and the “HR_High”. However, it is worth to mention that these effects are below 0.25 % and could essentially be shifted into an air-mass-dependent post-correction.

5.3 Comparisons

To compare the XCO₂-results over the whole time series of 26 measurement days between February and May 2012, we calculated the daily means which are shown in Fig. 9.

As the error bars for the daily mean values mainly result from the intra-day variabilities, a more significant comparison can be done by calculating the differences between the “EM27” values and the three other data-types “GFIT”, “HR_High” and “HR_Reduced” (see Sect. 4.2). To reduce temporal variabilities, only data were taken into account, which were recorded at nearly the same time. In addition, as described above, only measurements were taken into account which had a corresponding SZA lower than 70° and were taken at least 30 min after the set-up of the instrument on the terrace. For one datapoint taken with the HR-instrument (duration 212 s, containing 2

forward and 2 backward IFGs), the data of 3 EM27 spectra (total duration 102 s; each spectrum containing 10 IFG) were averaged and used.

Following this procedure, the XCO_2 and the total O_2 -column values are investigated in the following. The O_2 -column values offer the advantage that there is no significant variability on short time scales which could superimpose the instrumental effects under investigation.

In Fig. 10 these O_2 -column differences are displayed, where the data is grouped in single days. This grouping is made only for graphical reasons and not for the following statistical values. For all simultaneously measured results in the whole time series, the differences in the O_2 -columns have the following values:

$$\begin{aligned} \text{EM27-GFIT:} \quad & (7 \pm 5) \times 10^{25} \text{ molec m}^{-2} \\ & \hat{=} (0.15 \pm 0.11) \% \end{aligned}$$

$$\begin{aligned} \text{EM27-HR.High:} \quad & (-7 \pm 4) \times 10^{25} \text{ molec m}^{-2} \\ & \hat{=} (-0.15 \pm 0.09) \% \end{aligned}$$

$$\begin{aligned} \text{EM27-HR.Reduced:} \quad & (-27 \pm 4) \times 10^{25} \text{ molec m}^{-2} \\ & \hat{=} (-0.59 \pm 0.09) \% \end{aligned}$$

The mean differences show significant offsets, as already discussed in Sect. 5.1. However, they compensate for the largest part when calculating the XCO_2 . The scatter around the mean systematic offset, the precision, is impressively good by values around 0.1 %, proving the high stability of the EM27 instrument.

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EM27. In total the intensity on the EM27-detector is a factor of about 150 smaller than on the HR-detector. However, the photon-noise part of the Signal-to-Noise (SNR) ratio of a FTIR-spectrum also is dependent on the resolution, or more precisely the number N of datapoints in the interferogram. This factor of $\sqrt{2/N}$ leads to a comparable SNR of the low-resolution measurements.

6 Conclusions

We presented the capabilities of retrieving atmospheric XCO₂ values with a NIR-modified version of the commercial EM27 FTIR spectrometer from Bruker, a low-resolution table-top FTS. We developed a small solar tracker with active control of the line-of-sight, which is attached to the spectrometer. The whole set-up is very portable.

To confirm the resulting data quality, we compared the EM27 results with simultaneously recorded measurements of the high-resolution TCCON FTIR spectrometer located in the vicinity of the test setup.

This intercomparison demonstrates for the first time the applicability of a well-characterized low-resolution FTS spectrometer for XCO₂ measurements. The precision of the EM27-values found in this investigation is well inside the current network-wide TCCON accuracy of 0.25%. The differences of temporally coinciding measurements for the retrieved XCO₂ were $(0.12 \pm 0.08)\%$ and $(0.20 \pm 0.09)\%$ when compared to high-resolution TCCON spectra, analyzed with the official GFIT and PROFFIT algorithm, respectively. The optical stability and the low influence of varying outside temperatures (-10°C to more than 40°C) are promising features of the EM27 spectrometer, so our study proves its high applicability especially for operation at remote sites and measurement campaigns.

Therefore, the EM27, with the modifications presented in this paper, seems a very promising candidate of an instrument supporting the core TCCON-stations for increasing the global representativeness of greenhouse gas measurements by the operation

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of EM27 spectrometers at places inaccessible with a TCCON spectrometer. Moreover, for the study of local emission sources as megacities, large power-plants, etc., several mobile EM27 units could be distributed.

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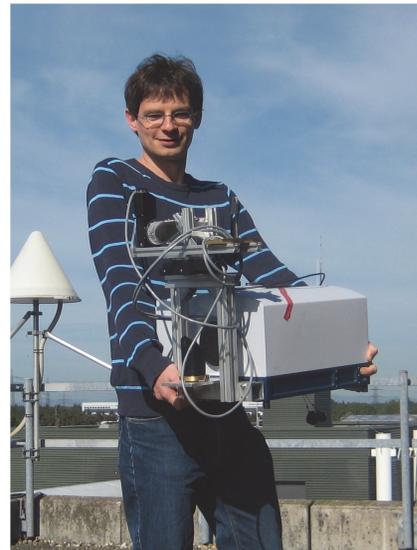
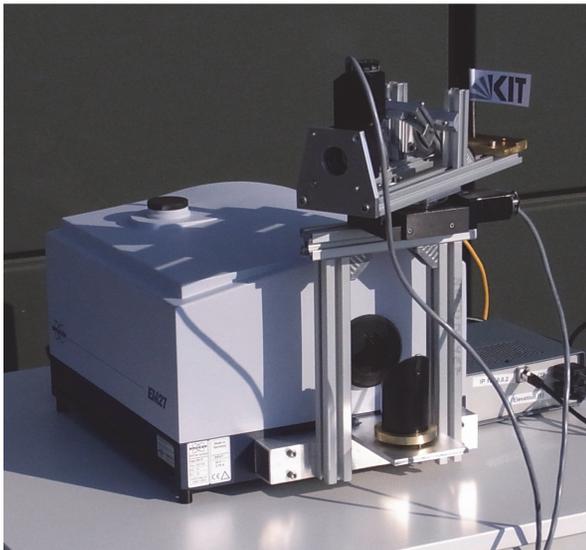


Fig. 1. The EM27-Spectrometer with the attached tracker. Right panel: transportation to the roof of the building where the measurements were made.

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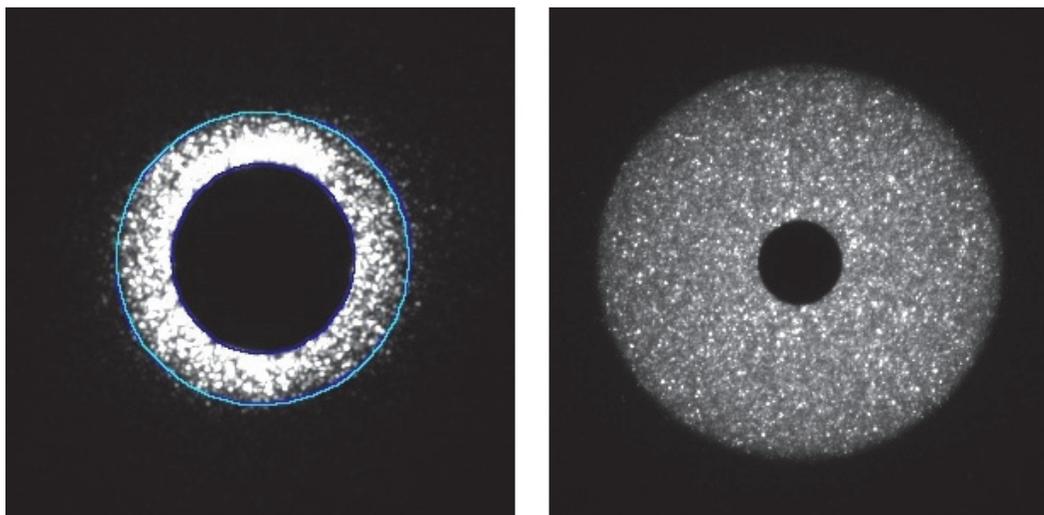


Fig. 3. Images of the solar image on the field stop of the EM27-spectrometer (left panel) and the IFS125HR in Karlsruhe (right panel) as recorded by CamTracker. The blue circles in the left image are the outlines, as they are detected and used by the CamTracker program for maintaining and correcting the precision of the tracking. The field-of-view differs between the EM27 and the IFS125HR.

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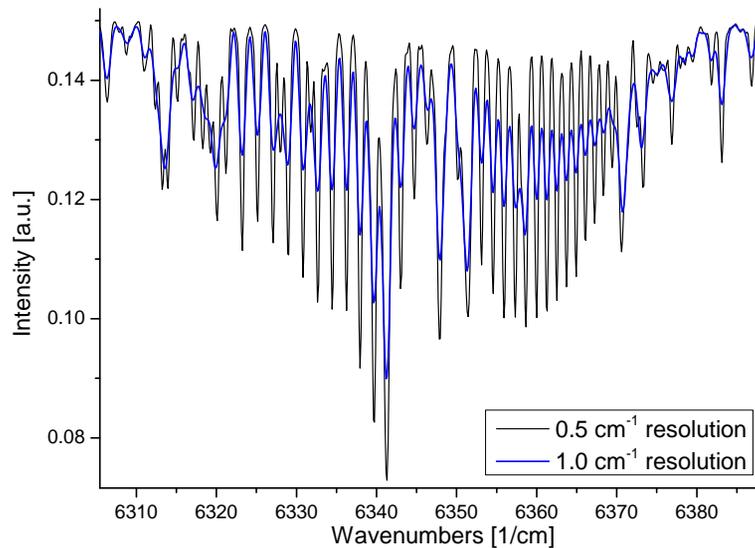


Fig. 4. A section of the CO₂ retrieval window with 0.5 and 1 wavenumbers resolution. As for the evaluation of the low-resolution spectra, a Norton-Beer apodization function was applied.

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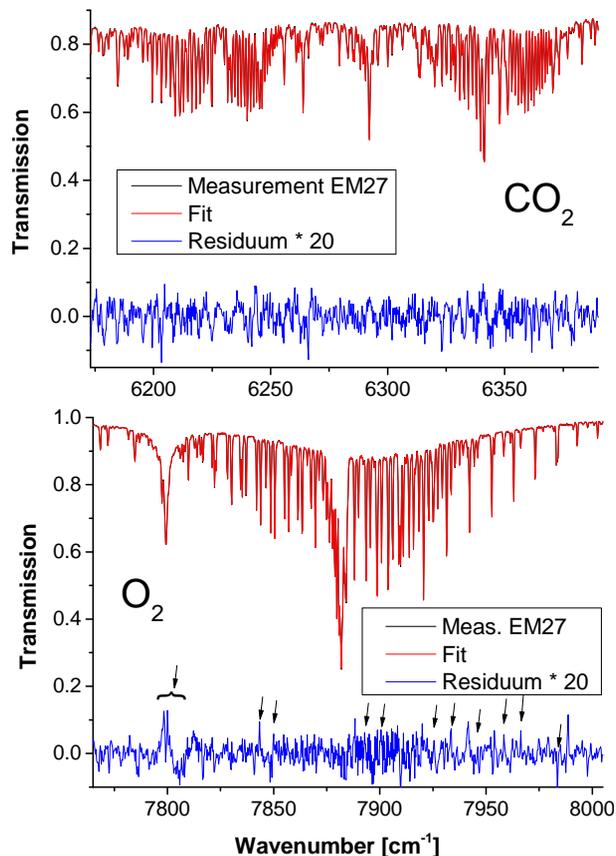


Fig. 5. Spectral windows used by PROFFIT to derive the CO₂ and O₂ columns. In the lower figure the systematically occurring residuals due to deficiencies of the solar line modeling are marked in the residuum.

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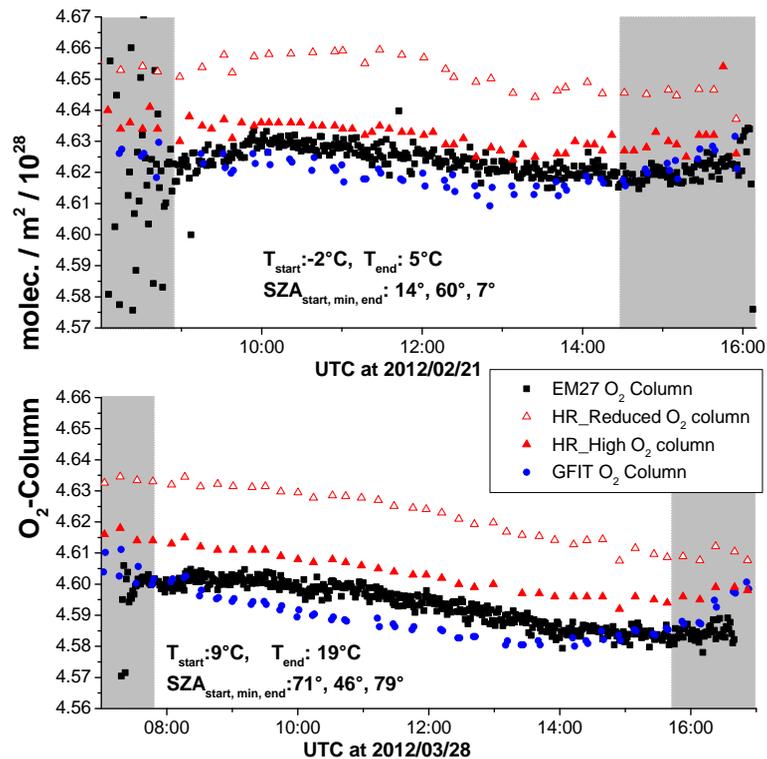


Fig. 6. O₂-columns for the four datasets for two sample days. The observed intraday variability is very low.

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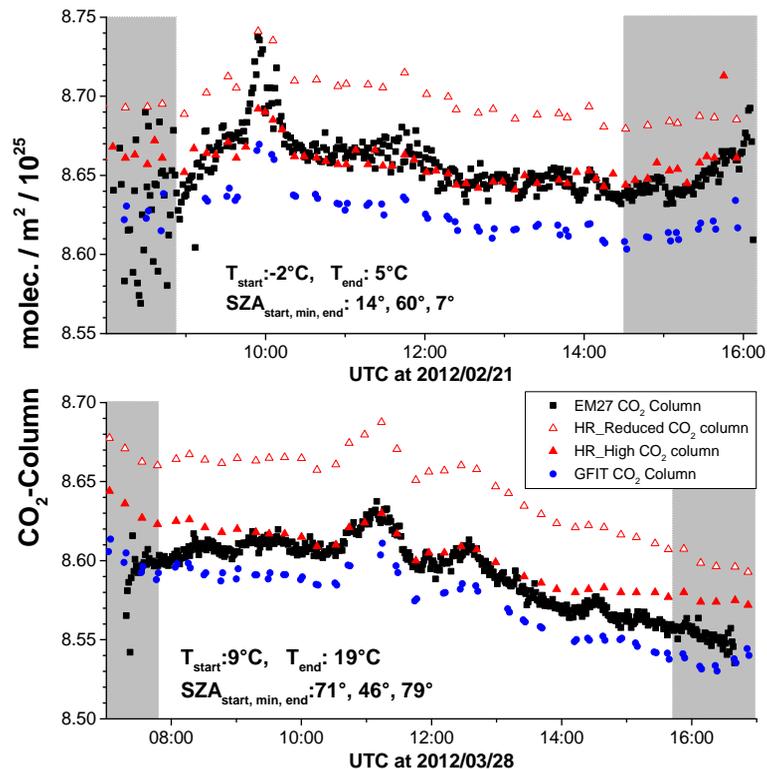


Fig. 7. CO₂-columns for 2 days. The systematic offsets of the 4 datasets is very similar to those in the O₂-columns.

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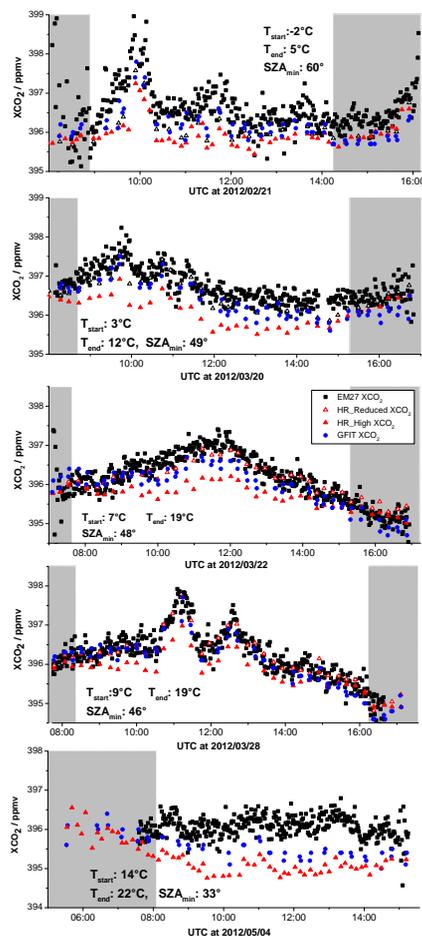


Fig. 8. Measurements of retrieved XCO₂ at 5 sample days.

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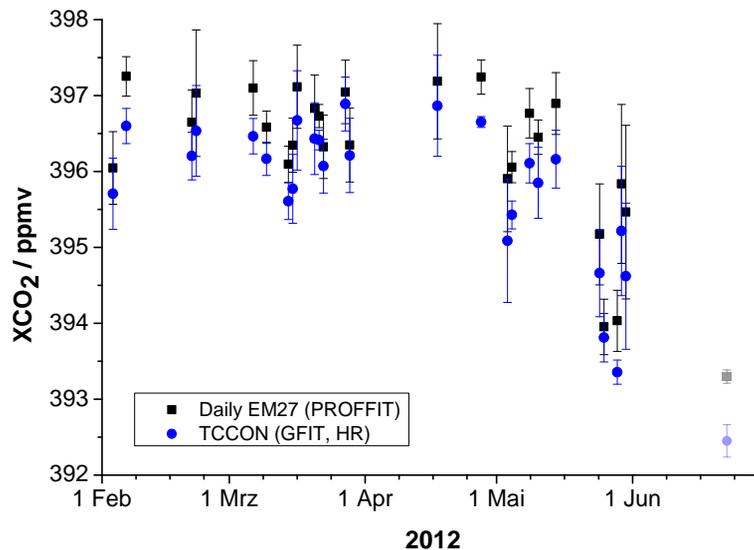


Fig. 9. Daily means of XCO₂ values of the EM27 and the TCCON instrument. The last day is preliminary only.

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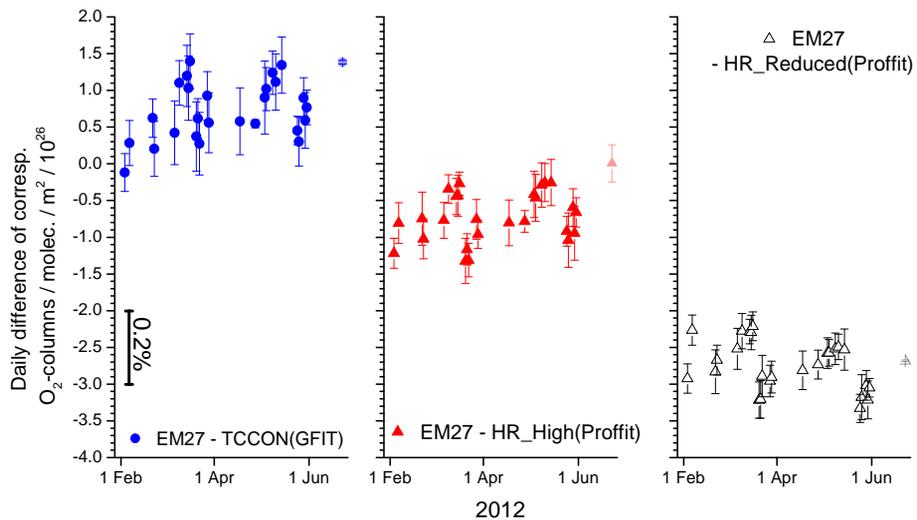


Fig. 10. Differences between the EM27-O₂ total columns and the 3 other datasets, grouped in single days. The last day is preliminary only and not taken into account in the statistical evaluation.

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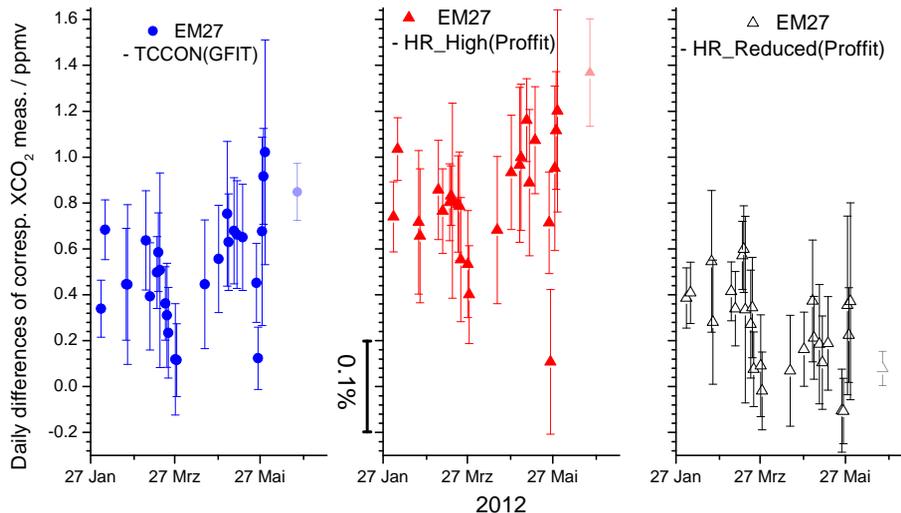


Fig. 11. XCO₂-values with the same data processing as for the O₂-columns in Fig. 10 for the 26 measurement days.

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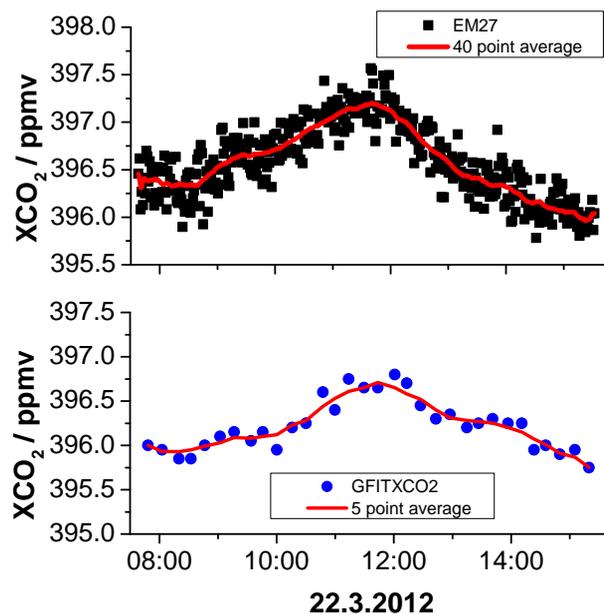


Fig. 12. Sample day to derive the XCO₂-noise of the EM27 and GFIT(TCCON) values. When taking into account the different recording durations, the noise level is comparable.

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