Calibration and instrumental line shape characterization of a set of portable FTIR spectrometers for detecting greenhouse gas emissions

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Abstract. A comprehensive calibration procedure for mobile, low-resolution, solar-absorption FTIR spectrometers, used for greenhouse gases observations, is developed. These instruments commend themselves for campaign use and deployment at remote sites. The instrumental line shape (ILS) of each spectrometer has been thoroughly characterized by analyzing the shape of H\textsubscript{2}O signatures in open path spectra. A setup for the external source is suggested and the invariance of derived ILS parameters with regard to chosen path length is demonstrated. The instrumental line shape characteristics of all spectrometers were found to be close to nominal. Side-by-side solar observations before and after a campaign, which involved shipping of all spectrometers to a selected target site and back, are applied for verifying the temporal invariability of instrumental characteristics and for deriving intercalibration factors for XCO\textsubscript{2} and XCH\textsubscript{4}, which take into account residual differences of instrumental characteristics. An excellent level of agreement and stability was found between the different spectrometers: the uncorrected biases in XCO\textsubscript{2} and XCH\textsubscript{4} are smaller than 0.01 and 0.15 %, respectively, and the drifts are smaller than 0.005 and 0.035 %. As an additional sensitive demonstration of the instrumental performance we show the excellent agreement of ground pressure values obtained from the total column measurements of O\textsubscript{2} and barometric records. We find a calibration factor of 0.9700 for the spectroscopic measurements in comparison to the barometric records and a very small scatter between the individual spectrometers (0.02 %). As a final calibration step, using a co-located TCCON (Total Carbon Column Observation Network) spectrometer as a reference, a common scaling factor has been derived for the XCO\textsubscript{2} and XCH\textsubscript{4} products, which ensures that the records are traceable to the WMO in situ scale.

1 Introduction

The continuing increase of atmospheric greenhouse gas abundances is the major driver of anthropogenic global warming. Accurate measurements of the variable atmospheric concentrations are required for the quantification of sinks and sources of these gases (Olsen and Randerson, 2004). Recently great efforts have been undertaken to measure column-averaged dry air mole fractions of greenhouse gases with global coverage. Examples are satellite-borne instruments like SCIAMACHY (Frankenberg et al., 2006), GOSAT (Morino et al., 2011) or the recently launched OCO-2 sensor (Frankenberg et al., 2015). For the validation of OCO-2, a network of ground based high resolution Fourier-transform infrared (FTIR) spectrometers of the type 125HR from Bruker has been initiated by the California Institute of Technology: the Total Carbon Column Observation Network (TCCON). Currently, about 23 TCCON globally distributed stations measure the column-averaged abundances of greenhouse gases in the atmosphere, by recording solar absorption spectra in the near infrared (NIR) (Wunch et al., 2010). TCCON has been carefully calibrated against in situ aircraft measurements and sets the reference for remote-sensing measurements.
measurements of column-averaged greenhouse gas observations. However, it is difficult to use this technical approach for the observation of sources and sinks on a regional scale because the laboratory spectrometers applied for TCCON are not portable. Recently, KIT developed, in cooperation with Bruker, a portable low resolution FTIR spectrometer for the observation of greenhouse gases in the NIR and demonstrated the excellent stability of the device (Gisi et al., 2012). The spectrometer is now available from Bruker under the part name EM27/SUN. This lightweight device has low infrastructure demands so it can be operated on a campaign basis, at remote places and even on mobile platforms such as ships (Klappenbach et al., 2015). These features not only enable the EM27/SUN to contribute to the total column measurements of the TCCON in previously underrepresented regions, in particular it can be used to gain additional information about isolated sinks and sources of greenhouse gases. Boundary layer abundances of greenhouse gases influenced by emissions from cities have been observed since long using mass spectrometric (von der Weiden-Reimüller et al., 2014) or cavity ring down techniques, e.g., (Newman et al., 2013; Rella et al., 2013). The downside of this approach is the high sensitivity to local sources, which overemphasizes the near vicinity, and the sensitivity with respect to assumptions on vertical exchange of air masses.

An alternative approach is the application of ground based remote sensing application. This kind of method has been applied for the quantification of localized sources, e.g., refineries (Mellqvist et al., 2010), power plants (Utembe et al., 2014), and large cities (Wunch et al., 2009; Wong et al., 2015). Hase et al. (2015) demonstrate a sophisticated approach to measure the emissions of a major city: five EM27/SUN spectrometers were operated along the circumference of the Berlin metropolitan area. Over a period of 3 weeks, column averaged dry air mole fractions of XCH$_4$ and XCO$_2$ have been observed simultaneously at all stations. The emission of Berlin introduces an increase of downwind column averaged mole fractions in the sub percentage range. Therefore, high precision and stability of the instruments are a prerequisite of this approach. In this work, we develop a calibration scheme allowing for a reliable detection of small source signals from a differential analysis using data collected by several portable spectrometers. We hope that the proposed methods will contribute to the definition of a good practice for ensuring the reliability of data collected with portable, low-resolution FTIR spectrometers for campaigns as well as possible network applications. We constructed a suitable external radiation source and performed lab-air observations of water vapor signatures for the determination of instrumental line shape (ILS) characteristics. Moreover, we tested the spectrometers used in Berlin side by side for several days before and after the campaign, determined the level of instrumental stability and deduced calibration factors for XCH$_4$ and XCO$_2$ in order to assure that data measured by different spectrometers are compatible among each other and with TCCON measurements.

2 Instrumentation and spectrometer characteristics

2.1 EM 27 SUN spectrometer

For the acquisition of solar spectra we utilize the Bruker EM27/SUN, which was developed in collaboration with the KIT. A detailed description of the spectrometer can be found in Gisi et al. (2012), in the following only a short overview including changes from the original setup is given.

The EM27/SUN features a RockSolid™ pendulum interferometer with two cube corner mirrors and a CaF$_2$ beam splitter. This setup achieves high stability against thermal influences and vibrations. Gimbal-mounted retroreflectors move a geometrical distance of 0.45 cm leading to an optical path difference (OPD) of 1.8 cm which corresponds to a spectral resolution of 0.5 cm$^{-1}$. As a minor modification of the prototype spectrometer described by Gisi et al. (2012), the production device contains an off-axis mirror with a focal length of 127 mm for centering the solar beam on the detector. Together with the field stop (0.6 mm diameter) this leads to a semi field of view (FOV) of 2.36 mrad which results in an external FOV of about 56% of the apparent solar disc diameter. Measurements are recorded with an InGaAs detector operated at ambient temperature. Due to an electronics update it is now possible to record double-sided interferograms of 0.5 cm$^{-1}$ resolution. The detector is a photodiode type G12181-010K from Hamamatsu with a size of 1 mm × 1 mm and spectral coverage from 5000 to 11 000 cm$^{-1}$. In contrast to the detector used in the prototype that operated in the spectral region between 6000 and 9000 cm$^{-1}$, the wider spectral coverage allows the observation of CH$_4$. In addition, total columns of O$_2$, CO$_2$ and H$_2$O are derived from the recorded spectra. The detector signal is DC coupled and thereby supports the correction of variable atmospheric transmission (Keppel-Aleks et al., 2007).

2.2 Ghost to parent ratio

The EM 27 records spectra in the region from 100 to 15 798 cm$^{-1}$, so in order to satisfy the Nyquist theorem the sampling of the interferogram has to be performed at every zero crossing of the laser signal (HeNe laser, wavelength 633 nm). If the signal is not taken at exactly zero intensity, systematic sampling errors are introduced leading to artifacts in the measured spectrum (so-called sampling ghosts) (Messerschmidt et al., 2010; Dohe et al., 2013). The manufacturer has recently released an effective workaround for this problem which we adopted for our measurements. A temporal linear interpolation is applied for locating the downward zero crossings. This method suppresses the ghosts below the detection limit (< 5 × 10$^{-6}$). In addition, we tested
An external light source is required. The ILS is derived from few meters of lab air to avoid the need for a gas cell, only our proposed approach uses an open-path observation of a standard procedure to derive the ILS are gas cell measurements, EM27/SUN. Whereas for TCCON spectrometers the standard is of utmost importance to gain correct information from measurements because using wrong ILS values leads to systematic errors in the gas retrieval. The ILS can be divided into two parts. One part describes the modulation loss through inherent self-apodization of the spectrometer which is present also in an ideal instrument. This contribution can easily be calculated utilizing the OPD and FOV of the spectrometer. The other component of the ILS results from misalignments and optical aberrations of the spectrometer and can be characterized by a modulation efficiency amplitude and a phase error, both functions of the OPD (Hase et al., 1999). These parameters have to be deduced from lab measurements.

2.3 Instrumental line shape

Precise knowledge of a spectrometer’s instrumental line shape (ILS) is of utmost importance to gain correct information from measurements because using wrong ILS values leads to systematic errors in the gas retrieval. The ILS can be divided into two parts. One part describes the modulation loss through inherent self-apodization of the spectrometer which is present also in an ideal instrument. This contribution can easily be calculated utilizing the OPD and FOV of the spectrometer. The other component of the ILS results from misalignments and optical aberrations of the spectrometer and can be characterized by a modulation efficiency amplitude and a phase error, both functions of the OPD (Hase et al., 1999). These parameters have to be deduced from lab measurements.

Figure 1 shows a picture of our lamp system. We employ an Osram Halogen 50 W lamp as radiation source, together with a fast aspherical collimation lens of 2 inches diameter, as used in projection collimators. In order to avoid channeling we tilted the light bulb against the optical axis; to assure uniform illumination the glass surface of the bulb is roughened towards the lens with a piece of sandpaper. The system is mounted on a stable, height-adjustable tripod for the fine adjustment of the light beam. This setup for possible line shape errors and other kinds of out-of-band artifacts, but found no detrimental effects.

Figure 1. Setup of the lamp system. The bulb is tilted against the optical axis to avoid channeling. The lamp system is mounted on a height-adjustable tripod for the fine adjustment of the light beam.
Figure 2. Transmission spectrum of 4 m lab air (black curve) in the 7000–7400 cm\(^{-1}\) region. Overlying is the LINEFIT calculation (red curve), the residuum multiplied by a factor of 10 is shown in blue. For clarity reasons, an offset of —0.1 was added to the residuum.

Table 1. Compilation of ILS modulation efficiencies measured at maximum OPD = 1.8 cm. Measurements were performed in Karlsruhe in June and July 2014, in between the spectrometers were transported for campaign measurements by road thus experiencing a lot of mechanical impacts and vibrations.

<table>
<thead>
<tr>
<th>Instr.</th>
<th>3 Jun</th>
<th>15 Jul</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9979</td>
<td>0.9996</td>
</tr>
<tr>
<td>2</td>
<td>0.9914</td>
<td>0.9938</td>
</tr>
<tr>
<td>3</td>
<td>0.9971</td>
<td>0.9997</td>
</tr>
<tr>
<td>4</td>
<td>1.0010</td>
<td>1.0020</td>
</tr>
<tr>
<td>5</td>
<td>0.9959</td>
<td>0.9963</td>
</tr>
</tbody>
</table>

Figure 3. ILS results obtained with LINEFIT for two different ways of performing the analysis. The simple analysis assumes a uniform path between lamp and detector, whereas the more refined approach divides the observed absorption into one contribution from inside and one from outside the spectrometer. Results are in agreement within 0.15 %.
ported from Karlsruhe to Berlin by road, thus experiencing a lot of mechanical impacts and vibrations.

3 Measurement sites and data acquisition

In order to measure small differences upstream and downstream of a source, the instrument-to-instrument consistency is of utmost importance in avoiding bias between stations. For this purpose, calibration measurements were carried out.

3.1 Calibration measurements at KIT Campus North

The calibration measurements were performed before the Berlin campaign on 3 sunny days between 6 and 16 June 2014 and after the campaign on 3 consecutive days 16–18 July 2014 on top of our office building north of Karlsruhe, with an altitude of 133 m a.s.l., coordinates are 49.094° N and 8.434° E. The spectrometers were moved from the lab on the fourth floor to the roof terrace on the seventh floor thus being exposed to mechanical stress. Then they were coarsely oriented north, without effort for leveling. If further orientation was needed, we manually moved the spectrometer so that the solar beam was centered onto the entrance window. The CamTracker program was then able to track the sun. As we operated the EM27/SUN in summer, it was heated up to temperatures above 40°C. In order to protect the electronics from the heat, we built a sun cover for the EM27/SUN, which reduced the temperatures inside the spectrometer by about 10°C. We recorded double-sided interferograms with 0.5 cm⁻¹ resolution. With 10 scans and a scanner velocity of 10 kHz, one measurement takes about 58 s.

For precise time recording, we used a GPS receiver. Additionally, on-site pressure and temperature profiles are available from tall tower meteorological measurements (http://imkbemu.physik.uni-karlsruhe.de/~fzkmast/).

4 Data analysis

4.1 Data processing

In a first step, the recorded interferograms are Fourier transformed using the Norton–Beer medium apodization function. This apodization is useful for reducing sibolobs around the spectral lines, an undesired feature in unapodized low resolution spectra, which would complicate the further analysis. Furthermore, a DC-correction is performed. Together with a quality filter, which discards interferograms with intensity fluctuations above 10 % and intensities below 10 % of the maximal modulation amplitude, this is implemented in a Python tool. In this work, we analyzed spectra utilizing the PROFFIT Version 9.6. This code is in wide use and has been thoroughly tested in the past (e.g. Schneider and Hase, 2009; Schneider et al., 2010; Sepúlveda et al., 2012). Due to the low resolution of the EM27/SUN, we fitted the atmospheric spectra by scaling of a priori trace-gas profiles. As source of the a priori profiles, we utilized the WACCM ver. 6 climatology (http://www2.cesm.ucar.edu/working-groups/wawg).

For the retrieval we need accurate temperature and pressure profiles. In case of the Karlsruhe calibration experiments we use on-site data together with MERRA model data, which provides temperature and pressure data on a 1.25° × 1.25° grid from 1000 to 0.1 hPa 8 times a day.

Every retrieval depends on the choice of line lists for the solar lines and atmospheric gases absorption lines. We use the HITRAN 2008 line list in its original form for CH₄, the HITRAN 2008 line list with a line-mixing parameterization for CO₂ adopted from a code provided by Lamouroux et al. (2010) and the line list used by TCCON for O₂. For the H₂O line list we use the HITRAN 2009 line list with changes used by Wunch et al. (2010) and additional ad hoc adjustments where it seemed appropriate.

4.2 Spectral windows

For the evaluation of the O₂ gas column we use the 7765–8005 cm⁻¹ spectral region, which is also applied in the TCCON analysis (Wunch et al., 2010). For CO₂ we combine the spectral windows used by TCCON to one larger window ranging from 6173 to 6390 cm⁻¹. CH₄ is evaluated in the 5897–6145 cm⁻¹ spectral domain. For H₂O the 8353 to 8463 cm⁻¹ region is used. An example fit for the different spectral windows is shown in Fig. 4. The residual of the spectral fit for the water column retrieval is much bigger than for the other gases because of the difficulties in measuring H₂O line parameters. The standard deviation of the residual is σ = 0.2 % for CO₂ and CH₄, σ = 0.1 % for O₂ and σ = 0.5 % for H₂O.

5 Calibration measurement results

In this section we present results of the calibration measurements performed before and after the Berlin campaign. First we show the uncalibrated total columns followed by column-averaged DMF XGas of carbon dioxide and methane, where XGas is defined as

\[ X_{\text{Gas}} = \frac{X_{\text{Gas, Column}}}{O_{2, \text{Column}}} \cdot 0.2095. \] (1)

To make the measurements comparable to WMO scale, in TCCON the standard procedure is to divide the calculated DMFs by a calibration factor (Wunch et al., 2010). The application of this TCCON calibration factor is also an inherent part of our post processing. For XCO₂ the factor is 0.9898 whereas it is 0.9765 for XCH₄.

5.1 Total column amounts

In Fig. 5 are depicted the column values of the measured species of the different instruments. It is clear that the line-
shape of all the spectrometers is nearly identical. Data gaps appearing for all instruments were caused by passing clouds. In addition Instrument 4 suffered from a hardware problem on 13 June 2014 as well as on 2 days after the Berlin campaign and therefore was only partly able to perform measurements. The tracker of this instrument did not follow the sun anymore but moved to a random position during initialization. This was caused by a mechanical problem of the azimuthal tracker motor. Intraday changes of the O\textsubscript{2} column can be mostly attributed to pressure changes, which will be shown in Sect. 5.2. There are slight systematic offsets, strongest between Instrument 2 and Instrument 4 with a difference of 0.2\%. However, note that a similar offset is also observed in the CO\textsubscript{2} and CH\textsubscript{4} gas columns, as can be seen in Fig. 5, therefore the resulting effects on the target quantities XCO\textsubscript{2} and XCH\textsubscript{4} are much smaller.

For a better comparison an intercalibration factor between the instruments is established. This is done in the following way. We take the separate measurement days and divide the data into smaller bins of 15 min duration. Inside each bin all available values are averaged. This quantity is used as a reference value. For each individual station, the difference between each value and its bin reference is calculated. The squared sum of all these residuals sets the cost function contribution of the station. The total cost function is given by the sum of all station contributions. In an iterative procedure, the scaling factors for all stations are adjusted for minimizing the total cost function while the side constraint of an invariant average value of all scaling factors is respected. (We neglect the fact that the number of values per bin is slightly variable; in a more rigorous approach, an individual statistical weight of each bin could be taken into account when the associated contributions to the cost function is calculated.)
Table 2. Calibration factors for O$_2$ column for the different instruments. Measurements were performed in June and July 2014, in between the spectrometers were transported for campaign measurements. Instrument 1 has been scaled to one, which is an arbitrary choice.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
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<td>1.0020</td>
</tr>
<tr>
<td>5</td>
<td>1.0012</td>
<td>1.0011</td>
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</tbody>
</table>

In Table 2 the calibration factors for the O$_2$ column for the calibration measurements before and after the campaign are given. Differences before and after the campaign are very small, only 0.04 % for Instrument 2 and 4 and even less for the other instruments. This is surprisingly good because column values are sensitive to various potential error sources, including ILS errors, timing errors, tracking errors and nonlinearities.

5.2 O$_2$ column as an indicator of instrumental stability

The consistency between retrieved O$_2$ and measured surface pressure is a very sensitive test for the instrumental stability because, for the oxygen column, there is no compensation of possible instrumental problems which were discussed in the previous section. In order to compare the data set with barometer measurements recorded at the ground level of the Karlsruhe meteorological tall tower, we calculate the ground pressure from the measured O$_2$ and H$_2$O total columns:

\[
P_S = \left( \frac{O_2\text{Column}}{0.2095 \cdot \mu_{\text{H}_2\text{O}}} \right) \cdot \frac{\pi \cdot \mu_{\text{H}_2\text{O}}}{g \cdot \exp \left( \frac{\Delta h}{h_S} \right)}.
\]

$P_S$ is the surface pressure, $\pi$ the molecular mass of dry air, $\mu_{\text{H}_2\text{O}}$ the molecular mass of water, $g$ the gravity acceleration, $\Delta h$ the height difference between the Karlsruhe tall tower ground level and the Institute terrace where the EM27/SUN spectrometers were located and $h_S$ the scaling height. We find a systematic scaling factor of 0.9700 between these records and the barometric ground pressure. This factor was calculated with the method described in the previous section and is in good agreement with other observations (Hase et al., 2015 or Klappenbach et al., 2015). Its origin can mainly be attributed to oxygen line intensity errors (Washenfelder et al., 2006). The scatter between the different instruments is smaller than 0.02 %. In Fig. 6 we scaled the pressure values obtained from the total columns to the barometric data for better comparability. The record of the dry ground pressure is compatible with the retrieved water vapor and molecular oxygen column.

Figure 6. In situ pressure data from the Karlsruhe tall tower (http://imkemu.physik.uni-karlsruhe.de/~fzmast/) together with pressure data calculated from total column amounts of O$_2$ and H$_2$O. The column data is scaled with an in situ factor of 0.9700 for better comparability.

Table 3. Calibration factor for XCO$_2$ and XCH$_4$ for the different instruments. Measurements were performed in Karlsruhe June and July 2014, in between the spectrometers were transported for campaign measurements.

<table>
<thead>
<tr>
<th>Instr.</th>
<th>XCO$_2$ June</th>
<th>XCO$_2$ July</th>
<th>XCH$_4$ June</th>
<th>XCH$_4$ July</th>
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<td>0.99962</td>
<td>0.99892</td>
<td>0.99905</td>
</tr>
</tbody>
</table>

5.3 Column-averaged dry air mole fraction

Figure 7 shows the column-averaged DMF of CO$_2$, which was calculated using Eq. (1). In this representation systematic errors tend to cancel out, which leads to a high degree of reproducibility in the time series difference between the instruments. Until this point, no post calibration has been performed, only the individual ILS of each instrument has been taken into account.

Table 3 shows the intercalibration factor for XCO$_2$ and XCH$_4$ before and after the campaign. The method to derive the factors is the same that was used for the O$_2$ column calibration. For XCO$_2$ we obtain an agreement within the measured noise level. The difference is below 0.005 or 0.02 ppm for all instruments. This means we can apply a global intercalibration factor which is valid before and after the campaign. This is an important prerequisite for campaign measurements. For XCH$_4$ the agreement is slightly worse at 0.035 %, but still very good. In Fig. 8 the calibrated
Figure 7. Uncalibrated XCO$_2$ values for all instruments. Experiments and measurement days are the same as for O$_2$.

Figure 8. Calibrated XCH$_4$ values for all instruments. Experiments and measurement days are the same as for O$_2$.

XCH$_4$ time series for the calibration measurements is depicted. Note that one global intercalibration factor is applied for all measurement days.

The scatter is very low for both species. Variations during the day stem from real signals, for example the XCO$_2$ peaks on 16 July 2014 were also measured by a co-located TCCON instrument (see Fig. 9).

5.4 Solar zenith angle dependency

There is a slight solar zenith angle (SZA) dependency in the XCO$_2$ and XCH$_4$ data, which is hard to see in Figs. 7 and 8 because the SZA is small during a considerable fraction of the day in summer, and the temporal variability of the target gases is superimposed to the SZA dependence. In order to make the data traceable to the WMO reference scale, it is nevertheless important to correct for a systematic air-mass dependency originating from spectroscopic uncertainties and approximations by the radiative transfer model. For this we use a method similar to that implemented by Wunch et al. (2010) in TCCON. The correction formula is

$$X_{\text{Gas}} = X_{\text{Gas,unc}} \left\{ 1 + a \left[ \left( \frac{\theta + b}{90^\circ + b} \right)^2 - \left( \frac{45^\circ + b}{90^\circ + b} \right)^2 \right] \right\},$$

where $a$, $b$ are fit parameters, $\theta$ is the SZA, $X_{\text{Gas}}$ and $X_{\text{Gas,unc}}$ are the air-mass dependency corrected and uncorrected column-averaged DMF of the respective species. The choice of $45^\circ$ as the neutral angle is arbitrary and does not influence the fit results.

For the determination of the correction parameters we do not use our calibration measurement data recorded in Karlsruhe. The data set is not well suited for this task due to
the actual intraday variability which occurred. Instead we use parameters obtained from a comprehensive evaluation of EM27/SUN data from a ship cruise (Klappenbach et al., 2015). These data are not influenced by local source contributions and clearly show the SZA dependency in the XCO₂ and XCH₄ data. For these measurements the Ω₂ column-averaged mole fraction does not show a detectable SZA dependence for ZA < 80°; the SZA dependence is essentially generated by the CO₂ and CH₄ mole fractions in the numerator. The obtained parameters are a = 6.296 × 10⁻³, b = 1.291 for XCO₂ and a = 3.796 × 10⁻³, b = 16.04 for XCH₄. Using this correction we receive data traceable to in situ scale measurements, supported by the comparison with a colocated TCCON spectrometer. Figure 9 shows the air-mass dependency corrected XCO₂ values together with TCCON DMF for 16 July 2014. Additionally an in situ scaling was performed to match the EM27/SUN values to the TCCON instrument. This factor of 0.9951 was determined with the method described in Sect. 5.1. The EM27/Sun values match the TCCON values remarkably well. Note that due to the much lower spectral resolution of the EM27/SUN, the noise level of the resulting XCO₂ data is even smaller as compared to the data generated by the TCCON spectrometer. Again one global factor was found valid for the measurements before and after the campaign.

Figure 10 shows XCH₄ values for the same day. Similar to XCO₂ the values between EM27/SUN spectrometers and TCCON instrument differ slightly towards evening. For the in situ scaling factor we obtain 0.9951.

6 Conclusions

In this work we implemented an extensive calibration routine for mobile, low-resolution FTIR spectrometers. The instruments, used for greenhouse gases observations, are particularly suited for campaign use and for operation at remote places because of their compact design. A method for the accurate characterization of the instrumental line shape from open path measurements was presented. The ILS characteristics were found to be close to nominal for all spectrometers, the temporal variability is small. The drifts between the instruments, which were shipped for a campaign and back between the measurements, are smaller than 0.24 % modulation efficiency amplitude at maximum optical path difference. In order to verify the temporal invariability of the instrumental characteristics and to derive intercalibration factors for XCO₂ and XCH₄, side-by-side solar observations were carried out. The drifts are smaller than 0.005 and 0.035 %, respectively, the uncorrected biases are smaller than 0.01 and 0.15 %. As an additional sensitive test of the instrumental stability we show a comparison of ground pressure values obtained from barometric records and from the total column measurements of Ω₂. A scaling factor of 0.9700 was found between the different techniques. Scatter of the instruments is 0.02 %. Furthermore an empirical air-mass correction was applied to compensate for a spurious SZA dependency of the data. Finally, by a comparison with a colocated TCCON instrument, we derived a common calibration factor of 0.9951 ± 0.0001 valid for both XCO₂ and XCH₄ making the records traceable to the WMO in situ scale. Because of the high level of stability of the spectrometers demonstrated in this work, we are confident that our routine allows the unambiguous detection of XGas enhancements in the sub-ppm range for CO₂ and ppb range for CH₄. We conclude that this approach can be used for the detection of local sinks and sources of various kinds.
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