

**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.

# A method to correct sampling ghosts in historic near-infrared Fourier Transform Spectrometer (FTS) measurements

S. Dohe<sup>1</sup>, V. Sherlock<sup>2</sup>, F. Hase<sup>1</sup>, M. Gisi<sup>1</sup>, J. Robinson<sup>2</sup>, E. Sepúlveda<sup>3,4</sup>,  
M. Schneider<sup>1,4</sup>, and T. Blumenstock<sup>1</sup>

<sup>1</sup>Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (IMK-ASF), Karlsruhe, Germany

<sup>2</sup>National Institute of Water and Atmospheric Research, Lauder, New Zealand

<sup>3</sup>La Laguna University, Tenerife, Spain

<sup>4</sup>Izaña Atmospheric Research Center, Agencia Estatal de Meteorología (AEMET), Santa Cruz de Tenerife, Spain

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Correspondence to: S. Dohe (susanne.dohe@kit.edu)

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Abstract

The Total Carbon Column Observing Network (TCCON) has been established to provide ground-based remote sensing measurements of the column-average dry air mole fractions of key greenhouse gases. To ensure the network wide consistency, biases between Fourier Transform spectrometers at different sites have to be well controlled. In this study we investigate a fundamental correction scheme for errors in the sampling of the interferogram. This is a two-step procedure in which the laser sampling error (LSE) is quantified using a subset of suitable interferograms and then used to resample all the interferograms in the timeseries. Timeseries of measurements acquired at the TCCON sites Izaña and Lauder are used to demonstrate the method. At both sites the sampling error histories show changes in LSE due to instrument interventions. Estimated LSE are in good agreement with sampling errors inferred from lamp measurements of the ghost to parent ratio (Lauder). The LSE introduce retrieval biases which are minimised when the interferograms are resampled. The original timeseries of  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  at both sites show discrepancies of 0.2–0.5 % due to changes in the LSE associated with instrument interventions or changes in the measurement sample rate. After resampling discrepancies are reduced to 0.1 % at Lauder and 0.2 % at Izaña. In the latter case, coincident changes in interferometer alignment may also contribute to the residual difference.

## 1 Introduction

Accurate prediction of future atmospheric composition and resultant radiative forcing requires a better understanding of the spatial distribution and temporal variability of the surface sources and sinks of carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ) and other greenhouse gases (GHG). To date top-down trace gas surface flux inversions have been constrained by surface in situ measurements. Although the in situ measurements have high precision and absolute accuracy ( $\sim 0.1\%$ , WMO, 2011), the network has

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## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

inhomogeneous spatial coverage, with few or no observing stations in many regions of importance to the global carbon cycle. Furthermore, errors in modelled atmospheric transport can introduce significant errors in the surface flux estimates. Remote sensing measurements of the integrated abundance of trace gases through the atmosphere (column measurements) are less sensitive to redistribution of the trace gas due to vertical mixing. They have the potential to provide useful complementary information to constrain surface flux inversions – with quasi-global coverage in the case of satellite measurements – provided they are sufficiently precise and accurate.

The Total Carbon Column Observing Network (TCCON, Wunch et al., 2011, <https://tcon-wiki.caltech.edu>) has been established to provide ground-based remote sensing measurements of the column-averaged dry air mole fraction (DMF) of CO<sub>2</sub> and other GHG for satellite validation and carbon cycle research. It currently comprises 17 sites worldwide which routinely acquire high resolution near infrared (NIR) direct solar absorption spectra using Fourier Transform Spectrometers (FTS). Spectra are analysed using a standard algorithm to retrieve total column abundances of target GHG and O<sub>2</sub>, and derive the GHG column-averaged DMFs. Biases between FTS instruments at different sites have to be well controlled to ensure the network-wide consistency of the measurements. The target inter-site comparability for TCCON using the O<sub>2</sub> internal network standard is 0.1 %.

In the following we are concerned with an error source which is of special relevance for NIR FTS measurements, namely errors in the sampling of the interferogram. As a result of the missampling, a fraction of the input spectral signal is assigned to an incorrect frequency, generating a ghost spectrum, which can overlap with and perturb the original spectrum, leading to errors in retrieved column abundances.

Messerschmidt et al. (2010) showed that the interferogram sampling in earlier versions of the Bruker 125HR laser sampling board does not control ghost amplitudes in the NIR to the level of accuracy required for TCCON work. Typical magnitudes of the errors in X<sub>CO<sub>2</sub></sub> and O<sub>2</sub> column retrievals encountered in practice are 0.1–0.5 % (0.3–2 ppm) (Messerschmidt et al., 2010, 2011), which compromise network measurement

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

comparability for carbon cycle research and satellite validation applications. The FTS manufacturer Bruker subsequently developed an improved laser sampling unit which offers the accuracy required by TCCON, and which has now been installed in all TCCON spectrometers. However, the post-correction of historic TCCON measurements still remains a particular problem, because the sampling error varies from instrument to instrument and is also expected to change through time (e.g. on instrument intervention or change in measurement sample rate) at any given site.

Messerschmidt et al. (2010) proposed an empirical ghost correction scheme which reposes on (1) the determination of the ghost-to-parent ratio (GPR) using narrowband lamp spectra and (2) an empirical determination of the variation of the column-average DMF  $X_Y$  of the target gas  $Y$  as a function of the GPR. However, there are several reasons the scheme described by Messerschmidt et al. (2010) cannot be applied satisfactorily in practice to historical TCCON timeseries. Firstly, the retrieval bias depends on the sign and magnitude of the sampling error, but only the latter can be determined from the lamp GPR measurement. Secondly, a site-independent relationship between  $X_Y$  and GPR cannot generally be assumed, due to differences in the instrument spectral response and/or differences in the absorber line-of-sight abundances (which impact both the magnitude of the aliased ghost signatures and the retrieval sensitivity to these artifacts). Thirdly, no TCCON site has a set of narrowband filter lamp spectra acquired through time which would enable changes in the sampling error on instrument intervention to be adequately characterised (even if the sign of the sampling error and the retrieval sensitivity could be adequately determined/modelled).

In this work we introduce a fundamental ghost correction scheme for historic measurements. The method consists of two steps: in the first step the degree of missampling is determined from a subset of suitable interferograms. This assumes the kind of missampling under consideration here is a slowly-varying function of instrumental status (unless an intervention on the spectrometer is performed), so a subset of interferograms can be used to reconstruct the full history of laser sampling errors (LSE). In the second step, all interferograms of the timeseries are resampled and retransformed

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and the corrected spectra are reanalysed. We demonstrate the proposed method using timeseries of measurements acquired at the TCCON sites in Izaña and Lauder. The following section describes the instrumentation at both sites and the data analysis within TCCON. Section 3 deals with the theory of ghosts and explains the strategy of ghost-correction of historic measurements in detail. The results are presented in Sect. 4 while Sect. 5 summarizes and concludes the study.

## 2 Instrumentation and data analysis

### 2.1 TCCON data acquisition

NIR measurements at both case study sites are undertaken in accordance with the TCCON data protocol ([https://tccon-wiki.caltech.edu/Network\\_Policy/Data\\_Protocol](https://tccon-wiki.caltech.edu/Network_Policy/Data_Protocol)). NIR solar absorption spectra are measured with a Bruker 125HR Fourier Transform Spectrometer (FTS) using a DC-enabled room temperature InGaAs detector with a resolution of  $0.02 \text{ cm}^{-1}$  (maximum optical path difference 45 cm) and high folding limit of  $15\,798 \text{ cm}^{-1}$ .

Since the work of Messerschmidt et al. (2010) there have been several versions of the Bruker 125HR laser sampling unit. Their laser sampling error characteristics are summarised here briefly for reference. Prior to board version ECL03 the LSE could not be minimised and was a function of sample rate (scanner velocity). At version ECL03 a potentiometer was introduced enabling the LSE to be minimised for a given sample rate (sampling errors at other sample rates remained significant). Version ECL04 of the laser board and improved linearity of the v02 laser diodes have reduced the magnitude of the LSE. The LSE is still manually minimised via a potentiometer adjustment, but once minimised is independent of sample rate for practical purposes. The ECL05 board has a modification to further minimise any temperature dependence of the LSE. The ECL04/05 boards and v02 laser diodes were distributed by Bruker to TCCON partners in 2010.

## 2.2 Case study sites

### 2.2.1 Izaña

The Izaña Atmospheric Research Center is a subtropical high mountain observatory on Tenerife (28.3° N, 16.5° W, Canary Islands, Spain) located at 2370 m altitude over a temperature inversion layer, acting as a natural barrier for local pollution. The site provides an extensive measurement program, which includes both in situ and ground based FTS measurements. The latter were started in the late 1990s in collaboration between the Meteorological State Agency of Spain (AEMET) and the Karlsruhe Institute of Technology (KIT). The FTS program is involved in two global networks: for measurements in the mid-infrared (MIR) region it has contributed to the Network for the Detection of Atmospheric Composition Change (NDACC, <http://www.ndacc.org>) since 1999 and from 2007 also to TCCON (<http://www.tcon.caltech.edu>) for NIR measurements.

The Izaña TCCON measurements are acquired with the Bruker 125HR spectrometer, which had the original ECL02 laser board at installation (January 2005). In June 2008 the instrument was realigned and the measurement mode was changed from AC to AC + DC. The electrical low-pass-filter was changed in March 2009. In November 2009 the laser board was replaced by an ECL03 board (LSE was minimised at 40 kHz) and an optical long-pass filter was installed. After some problems due to loss of power and very cold temperatures inside the container (January–March 2010) and the change of the electrical low-pass-filter (May 2010) the new ECL04 laser board and v02 diodes, provided by Bruker, were installed in November 2010 and the LSE was eliminated for all practical purposes in routine TCCON measurements. The interferometer was also realigned at this time. All Izaña measurements are acquired with a 40 kHz sample rate.

Interferograms are recorded via the Optics User Software (OPUS) version 6.5 (provided by Bruker). Calibrated spectra are generated with calibration tools (M. Gisi, M. Schneider, F. Hase), which rely on OPUS macro functionalities and in-house

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



external routines (e.g. DC correction, calculation of SZA, etc.). To evaluate the impact of sampling errors for Izaña within this study, we applied the PROFFIT analysis software (Hase et al., 2004). We have performed extensive comparisons and find excellent agreement between the standard TCCON retrieval software (GGG) (Wunch et al., 2011) and the PROFFIT algorithm for the primary post-processed TCCON parameter  $X_{\text{CO}_2}$  (0.05–0.1 %) (Dohe et al., 2012). For 40–60° zenith angle range typically used for  $X_{\text{air}}$  comparisons in this paper, GGG and PROFFIT agree to 0.3–0.5 %.

### 2.2.2 Lauder

Lauder is located in a sparsely populated rural environment on the South Island of New Zealand (45.0° S, 169.7° E) 370 m a.s.l. (above sea level). It is a long established atmospheric monitoring station with a MIR FTS measurement program which has contributed to the NDACC since 1990 (Griffith et al., 2003) and NIR FTS measurements within the TCCON since 2004.

The Lauder TCCON measurements from 2004–2010 were acquired with an older 120HR spectrometer. In August 2009 a 125HR spectrometer was installed at the site and commissioned over the following six months. The LSE characterisation in this paper is restricted to the 125HR timeseries.

At installation the Lauder 125HR spectrometer had an ECL03 laser board and the LSE was minimised at 20 kHz. At the time, the sample rate dependence of the LSE minimisation for the ECL03 boards was not fully appreciated. The early operational data (November 2009–January 2010) were acquired with a 10 kHz sample rate and require ghost correction. From February 2010 to January 2011 routine measurements were acquired with a 20 kHz sample rate and LSEs are small. In January 2011 the replacement laser board (ECL05) and diodes provided by Bruker were installed and the LSE reminimised for the 20 kHz sample rate used in routine measurements.

In addition to routine solar measurements, a number of experimental data sets were acquired on the Lauder 125HR, which can be used to validate the resampling algorithm. These experiments are (1) solar measurements cycling through the 10, 20 and







We will use the variable  $X_{\text{air}}$  to characterise the contribution of  $\text{O}_2$  retrieval errors in a way that is readily understood.  $X_{\text{air}}$  is the column average dry air mole fraction of dry air,

$$X_{\text{air}} = 0.2095 \frac{C_{\text{air}}(C_{\text{H}_2\text{O}}, P_s)}{C_{\text{O}_2}}, \quad (2)$$

where the dry air column abundance in the numerator is derived from an independent co-located measurement of surface pressure ( $P_s$ ), corrected for the  $\text{H}_2\text{O}$  column overburden. In the absence of any systematic errors, the expected value of  $X_{\text{air}}$  is 1, and the relative error in  $X_Y$  due to  $\text{O}_2$  retrieval errors is calculated/given by  $X_{\text{air}} - 1$ .

In the presence of LSE, the records of retrieved  $\text{O}_2$  columns are biased, whereas the independent measurement of  $P_s$  remains unaffected. Punctual changes in the LSE on instrument intervention introduce discontinuities in the  $X_{\text{air}}$  timeseries. Other measurement and retrieval error sources (timing and pointing errors, instrument line shape (ILS) and spectroscopic errors) can introduce changes in  $X_{\text{air}}$ , so  $X_{\text{air}}$  can only be exploited to characterise the LSE history if these other factors are controlled well enough. Significant effort has been invested at both sites to ensure this is the case, including the development of the camera controlled high precision solar tracker system, CamTracker (Gisi et al., 2011) used at Izaña and regular monitoring of the ILS by LINEFIT analysis of low pressure HCl, HBr, and  $\text{N}_2\text{O}$  cell spectra (Hase et al., 1999). Solar zenith angle ranges are restricted in some analyses to prevent changes in  $X_{\text{air}}$  of instrumental origin from being masked by airmass-dependent retrieval biases due to spectroscopic errors.

### 3 Periodic sampling errors and sampling ghosts

#### 3.1 Theory of ghost formation

Interferograms recorded with FTS need to be sampled very accurately as a function of Optical Path Difference (OPD) to avoid artificial spectral lines (ghosts) after Fourier

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Transformation (FT). To ensure this precise sampling, a frequency-stabilized, single-mode HeNe reference laser is fed into the spectrometer. The zero crossings of the lasers interferogram serve as reference for the sampling of the infrared signal. However, the original measurement signal of the reference laser is actually a cosine-shaped oscillation between a low and a high intensity level. If the construction of the mean intensity level is erroneous, a sampling error pattern of alternating narrow and wide distances will result (see Fig. 1).

Following Guelachvili (1981), the spectrum of a monochromatic light derived from an interferogram with periodic sampling error  $\epsilon$  of frequency  $\beta$ ,

$$\epsilon = \epsilon_0 \sin(2\pi\beta x) \quad (3)$$

is given by:

$$B(\sigma) = J_0(2\pi\sigma_0\epsilon_0) \int_0^{x_m} \sin(2\pi\sigma_0 x) \sin(2\pi\sigma x) dx + \sum_{k=1}^{\infty} J_k(2\pi\sigma_0\epsilon_0) \int_0^{x_m} [\sin(2\pi(\sigma_0 + k\beta)x) + (-1)^k \sin(2\pi(\sigma_0 - k\beta)x)] \sin(2\pi\sigma x) dx, \quad (4)$$

where  $x$  is the OPD,  $\sigma_0$  is the frequency of the incident light and  $J_k$  are Bessel's function for integer  $k = 1, 2, \dots, n$ . The  $k = 0$  term describes the incident radiation modified by the instrument response function for finite maximum optical path difference  $x_m$ . If  $\epsilon_0 \neq 0$  the intensity of the parent line is scaled by the factor  $J_0(2\pi\sigma_0\epsilon_0)$  which is less than one. Similar features with intensities proportional to  $J_1(2\pi\sigma_0\epsilon_0)$ ,  $J_2(2\pi\sigma_0\epsilon_0)$ ,  $\dots$ ,  $J_n(2\pi\sigma_0\epsilon_0)$  appear at  $\sigma_0 \pm \beta$ ,  $\pm 2\beta$ ,  $\dots$ ,  $\pm n\beta$ .

$\beta$  depends on the sampling rate per laser wavelength, which is determined by the high folding limit (HFL) for the measurements. In the case of TCCON measurements, the HFL is set to  $15798 \text{ cm}^{-1}$  and the laser interferogram is sampled on every zero crossing. Thus  $\beta = 15798 \text{ cm}^{-1}$  and ghosts occurring at  $\sigma_0 \pm 15798 \text{ cm}^{-1}$  are both aliased to  $15798 - \sigma_0 \text{ cm}^{-1}$ . Note FTS measurements in the MIR as acquired by the NDACC are not affected by this problem. In this spectral region a high folding limit of

7899 cm<sup>-1</sup> or less is applied. The sampling is performed only at each rising zero crossing of the laser interferogram and an error in the evaluation of the mean laser intensity level does not generate an alternating sampling pattern.

In summary, a periodic sampling error leads to distortions of the true spectrum. Line strengths are modified and the baseline (zero level) of the spectrum is falsified by the folded ghost alias of the true spectrum. These distortions can and do lead to significant retrieval biases in the case of TCCON measurements. They must be corrected at the source, by resampling the interferograms.

## 3.2 Quantification of the sampling error

### 3.2.1 Interferogram resampling

In the interferogram resampling method we seek to determine the sampling shift which minimises the magnitude of the signal intensity in selected, fully absorbed regions of the solar spectrum. In this study we use the 7290–7360 cm<sup>-1</sup> interval shown in Fig. 2. It is essentially opaque for slant H<sub>2</sub>O column abundance of > 5 × 10<sup>22</sup> molecules cm<sup>-2</sup> (generally satisfied at large solar zenith angles) and the associated aliased ghost interval at 8440–8510 cm<sup>-1</sup> has appreciable signal levels. Izaña is unique among the TCCON sites due to its high altitude, and often the 7290–7360 cm<sup>-1</sup> microwindow is not saturated. An additional microwindow (10 900–11 300 cm<sup>-1</sup>) was therefore used to determine the LSE timeseries at Izaña.

The sampling error is determined using the low resolution double-sided interferogram portion of the high-resolution interferogram. A set of probable sampling errors Δx<sub>*i*</sub> is defined. For each Δx<sub>*i*</sub> the odd sample points of the interferogram are shifted and the interferogram (*I*(*x*)) is interpolated to the shifted sample locations assuming

$$I(x + \Delta x) \simeq I(x) + \frac{\partial I}{\partial x} \Delta x. \quad (5)$$

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The derivative of the interferogram with respect to the sampling position  $x$  is estimated by determining the local slope of the interferogram at each odd sample location using a sinc interpolation. We then take the FT of the resampled interferogram and evaluate the mean absolute signal intensity ( $\sum |B(\sigma)|$ ) in the selected spectral window (7290–7360  $\text{cm}^{-1}$ ). The signal intensity is tabulated as a function of  $\Delta x$ , and the shift which minimises the mean absolute signal intensity is the LSE used subsequently to correct the full interferogram. The procedure is performed separately for the forward and reverse scans to allow for differences in magnitude as well as in sign between LSE of the two scan directions. Example output from a resampling test for the (7290–7360  $\text{cm}^{-1}$ ) is shown in Fig. 3. Here and throughout the paper the sampling error is expressed as a fraction of the sampling interval.

As noted above, the interferogram sampling points are classified into even and odd points. The phase of the laser interferogram changes by  $\pi$  with a one point indexing shift, and the inferred LSE is of opposite sign. The classification or indexing used to derive the LSE must therefore be consistent with the indexing used when applying the LSE to correct interferograms. Although the laser fringe counting of the Bruker spectrometer is performed in quadrature and therefore assures that the sampling number of a physical point is conserved, this assignment is lost during re-initialization of the scanner or if the spectrometer is switched off. On the other hand, the true physical location of the infrared beam zero path difference (ZPD) constructive interference maxima (centrebust peak) and the phase of the laser interferogram are expected to remain constant through scanner re-initialization etc. For this reason, it is preferable for our purpose to reference the sample indexing to the centerburst peak position. The centerburst of a real interferogram is not perfectly symmetric. The shapes of forward and backward centerbursts differ due to small time delays between IR and laser signal processing chains which depend on scanner speed, optical bandpass and electrical filter settings. So it can happen that the even/odd referencing differs for forward and reverse scans and may switch upon instrumental intervention.

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

In its current implementation the resampling LSE estimate is based on the minimisation of the mean absolute signal intensity in an opaque section of the atmospheric spectrum. This assumes that detector nonlinearity is negligible or has been corrected by means of the common DC-correction prior to the LSE estimation procedure (Keppel-Aleks et al., 2007).

The current implementation also assumes that the LSE determined at the position around the interferogram centerbursts are representative for the whole high-resolution interferogram. This is probably not fully verified, so some high-resolution artifacts of the original ghosts might survive. However, it would be difficult to characterise these tiny artifacts and to use them for an improved correction scheme (in which the LSE would become a function of optical path difference), because the offset introduced by the ghosts is significantly lower than the noise level of the high-resolution spectrum.

One known source of short term variability in the LSE is not addressed by the current implementation of the resampling methodology. The LSE can vary significantly at very low pressure ( $< 0.5$  hPa) due to heating of the electronic components of the laser board (Ralf Sussman, Markus Rettinger, Axel Keens, pers. comm.). In this case, the LSE must to be determined at higher temporal resolution if possible. Where this is not possible, affected historical data should not be retained for TCCON analysis, or should be flagged as ghost affected. The temperature dependence of the LSE in the ECL04 board is negligible because the LSE itself is acceptably small. DC power dissipation has been minimised in the ECL05 board, thus minimising the temperature dependence of the residual LSE.

### 3.2.2 Derivation of the LSE timeseries

In order to establish a timeseries of LSE estimates for a given site we assume the LSE is stable or slowly varying on timescales of days to weeks, but allow for possible, discontinuous changes in the LSE during instrument intervention (depending on the nature of the intervention).

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Interferograms are selected which were acquired in cloud-free conditions at large solar zenith angles to ensure the optical opacity of the 7290–7360 cm<sup>-1</sup> microwindow. All selected interferograms acquired on the same day are coadded, and the LSE is determined using the resampling algorithm on the coadded interferogram.

Selection criteria for the Lauder timeseries analysis are: solar zenith angles in the range 60–75°, line-of-site (LOS) H<sub>2</sub>O column abundance of > 5 × 10<sup>22</sup> molecules cm<sup>-2</sup> and coadd sample size ≥ 10. The resulting timeseries comprises 240 days over two years.

In the case of Izaña 28 days with clear sky conditions were selected. For every day, measurements with large SZA were coadded (coadd sample size ≥ 4 interferograms). In the case of only few measurements with large SZA on a single day, measurements of several days were coadded and the same LSE value is reported for each of these days.

### 3.3 Correction of the sampling error

The LSE timeseries is evaluated to define the most suitable temporal description of the LSE to apply to all measurements acquired at the given site. Typically this will be a piecewise linear function with a constant LSE for stable periods between instrument interventions. Each full resolution interferogram is corrected based on the LSE estimate for the given day. The odd sample points of the full resolution interferogram are shifted and the interferogram  $I(x)$  is interpolated to the shifted sample locations as previously (Eq. 5). The resampled interferogram is transformed (FT) and retrievals are performed for the resultant, ghost-corrected spectrum.

### Lamp LSE estimates

Bandpass-limited lamp spectra were acquired at Lauder using two optical filters, referred to hereafter as the NDACC and TCCON filters, to determine the GPR following Messerschmidt et al. (2010). The NDACC filter spans a 100 cm<sup>-1</sup> interval centred

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



on  $4150\text{ cm}^{-1}$ , with ghost alias at  $11\,598.0\text{--}11\,698.0\text{ cm}^{-1}$ . The TCCON filter spans a  $200\text{ cm}^{-1}$  interval centred on  $5790\text{ cm}^{-1}$  with ghost alias at  $9908.0\text{--}10\,108.0\text{ cm}^{-1}$ . The GPR is calculated by the ratio of the signal intensities at the parent and ghost frequencies integrated across the filter bandpass. The GPR is frequency dependent and is related to the LSE by a factor  $\gamma = (\pi\sigma\Delta)^{-1}$ , where  $\sigma$  is the optical filter bandpass centre frequency, and  $\Delta$  is the sampling interval (Learner et al., 1996).

The resampling algorithm was also applied to the lamp spectra. In this case, the magnitude of the signal intensity is minimised for the ghost alias wavenumber interval of the respective filter.

## 4 Results

### 4.1 LSE timeseries

#### 4.1.1 Lauder 125HR timeseries

The LSE timeseries derived from solar interferograms for the Lauder 125HR is illustrated in Fig. 4. Corresponding LSE estimates determined from analysis of Tungsten lamp spectra acquired with narrow bandpass optical filters are illustrated in Fig. 5. A comparison of lamp and solar LSE and GPR estimates is given in Table 1.

Consider first the resampling results derived from solar data acquired with the original ECL03 laser board and v01 diodes (dates prior to January 2011). The LSE estimates for forward and reverse scans are comparable in magnitude but opposite in sign. The corresponding retrieval biases (Sect. 4.2) are independent of scan direction, indicating this is a result of the sample point indexing definition (specifically, forward and reverse scan peak positions differ by one point).

The LSE for the ECL03 board are sample rate dependent, as expected. The LSE is minimum for the 20 kHz data, because the sampling error was minimised for this sample rate. Stepwise changes in the 20 kHz LSE are evident for the early instrument



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



interventions and a drift (or possibly a further stepwise change) is apparent during the period July 2010–January 2011. The magnitude of the 10 kHz LSE derived from solar measurements appears fairly stable through time. There is a slight increase in the LSE following the instrument intervention in December 2009. The magnitude of LSE is greatest at 40 kHz and the sign of the LSE for a given scan direction has opposite sign to that at 10 and 20 kHz. This sign change is not an indexing artifact and is discussed further in Sect. 4.2.1.

Lamp LSE estimates derived with NDACC and TCCON filters are in excellent agreement with one another and with the LSE inferred from the GPR estimate proposed by Messerschmidt et al. (2010). The scan direction and sample rate dependence of the signs of the LSE determined from lamp measurements with the NDACC optical filter are consistent with those determined from the solar measurements up to a global sign change of  $-1$  (which is attributed to differences in determining the ZPD index for the wider lamp interferogram centreburst). The sign of the LSE determined using the TCCON filter is more difficult to interpret, but once differences in ZPD indexing for different scan directions and sample rates are taken into account (see the caption of Table 1 for details), the sample rate dependence of the sign of the LSE is consistent with that inferred from solar data and lamp measurements with the NDACC filter.

There is good qualitative agreement between the magnitude of ECL03 lamp and solar LSE estimates at the three sample rates. Solar and lamp estimates at 10 kHz are in excellent agreement, however there are differences of up to 0.0007 and 0.0012 in the lamp and solar LSE estimates for the 20 and 40 kHz data respectively. The reason for this is not understood, but is not believed to be due to detector nonlinearity. Lamp LSE estimates suggest a slight increase in the magnitude of the LSE between July and October 2010 at 10 and 20 kHz sample rates. Unfortunately, the very limited number of lamp measurements precludes any real validation of the LSE tendency observed in the 20 kHz solar LSE timeseries between July 2010 and January 2011.

We turn now to the LSE estimates for the ECL05 laser board and v02 diodes, (post January 2011). The contrast between the magnitude and sample rate dependence of







## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



between March 2009 and May 2010. This might be due to changes of the electrical low-pass-filter settings in this period but has to be investigated further. Note in the KIT interferogram pre-processing the forward and reverse scans are coadded to generate one spectrum per forward/reverse pair, so the reduction in the discrepancy between forward and reverse scans on resampling has not been characterised explicitly.

The  $X_{\text{CO}_2}$  timeseries shows a reduction of  $X_{\text{CO}_2}$  for resampled measurements. As mentioned before, most of this difference is due to changes in the  $\text{O}_2$  retrieval. For measurements at the beginning of the timeseries in 2008, the difference between retrievals from uncorrected and resampled spectra is about 0.2%. Smaller differences (0.03%) are found in the period before the laser board exchange in 2010.

### 4.2.3 Retrieval sensitivities inferred from the resampled timeseries

At Lauder retrieval differences for  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  are only weakly dependent on airmass for zenith angles less than  $80^\circ$ .  $X_{\text{air}}$  retrieval biases vary by 0.0005 (increasing with solar zenith angle) for zenith angles between  $20$  and  $80^\circ$ .  $X_{\text{CO}_2}$  varies by 0.05 ppm over the same range of zenith angles. There is evidence of more marked differences (0.001–0.002) in  $X_{\text{air}}$  at high zenith angles, but the impact in  $X_{\text{CO}_2}$  remains small. No marked temporal signatures (other than that associated with the changes in the LSE estimates applied in resampling) were evident in the timeseries of retrieval differences, although admittedly the sequence only spans a year and is generally very sparsely sampled.

To first order the retrieval sensitivity for the Lauder 125HR  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  measurements can therefore each be characterised by a single number. We estimate an  $X_{\text{air}}$  bias of 0.0012 and  $X_{\text{CO}_2}$  bias of 0.36 ppm per 0.001 LSE for LSE in the range 0–0.004. We infer the error due to the discrepancy in lamp and solar LSE estimates is small for the Lauder 125HR data (0.1%), but this is still significant compared to the TCCON inter-station comparability target (0.1%).

For Izaña the bias of  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  per LSE with the 40 kHz sample rate is estimated assuming an effective LSE equal to the mean LSE of the forward and reverse scans.

The bias of  $X_{\text{air}}$  per 0.001 LSE is about 0.0003, whereas a  $X_{\text{CO}_2}$  bias of 0.11 ppm per 0.001 LSE is determined for  $|\text{LSE}|$  in the range of 0.001–0.01.

These retrieval sensitivities inferred from the resampled timeseries at Lauder and Izaña can be compared with sensitivities of 0.00085 and 0.28 ppm per 0.001 LSE for  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  derived from a reanalysis of the Messerschmidt et al. (2010) data sets (Sherlock et al., 2011). The retrieval sensitivity to LSE inferred from the three data sets differ significantly: by a factor  $\sim 1.3$ –4. Taken at face value, this result implies a site independent relationship between  $X_{\gamma}$  and the LSE (a key assumption of the empirical correction proposed by Messerschmidt et al. (2010)) cannot generally be assumed. Such a discrepancy could be due to differences in the instrument spectral response and/or differences in the line-of-sight abundances of the target gases and interfering absorbers (particularly  $\text{H}_2\text{O}$ ), which depend on site altitude and environmental conditions. Given the magnitude of the discrepancy, this merits some further study.

## 5 Conclusions

We have described and demonstrated a two-step procedure which enables the LSE history to be characterised through time and which enables sampling errors to be corrected at the source, by resampling the interferograms.

LSE estimates derived using the resampling method are in good agreement with sampling errors inferred from lamp GPR measurements at Lauder. The maximum difference observed for the 20 kHz sample rate is 0.0007 implying a limit to correction accuracy of 0.08 %. The corresponding limit inferred for the 40 kHz sample rate is slightly higher, at 0.14 %.

Sampling histories at Lauder and Izaña show clear changes in LSE due to instrument interventions and changes in the measurement sample rate. Similar histories are to be expected at other TCCON sites. Resulting retrieval biases are in the range of 0.2–0.5 %, and are time and site dependent. After resampling, discrepancies in the retrieved  $X_{\text{air}}$  and  $X_{\text{CO}_2}$  due to instrument interventions and changes in the measurement sample

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



rate are reduced to 0.1 % at Lauder and 0.2 % at Izaña. In the latter case coincident changes in interferometer alignment may also contribute to the residual difference.

These errors could not have been adequately corrected for using the empirical method proposed by Messerschmidt et al. (2010), first and foremost because no suitable timeseries of lamp GPR characterisations exist for these or other TCCON sites. Inferred retrieval sensitivities to LSE also differ by a factor of 1.3–4, indicating a site independent relationship between  $X_{\gamma}$  and the LSE cannot generally be assumed.

Although not shown explicitly here, laser sampling errors affect the estimated DMF of other TCCON target gases ( $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{CO}$ ) in a similar manner. This is because the bias in  $X_{\gamma}$  for these gases is primarily driven by the bias in the  $\text{O}_2$ , as it is for  $X_{\text{CO}_2}$ .

In the next step, corrections must be determined and applied to historical data at all TCCON sites. This should improve the inter-station comparability of the TCCO network, and this will be characterised using the  $\text{O}_2$  internal network standard.

*Acknowledgements.* We thank Axel Keens of Bruker Optik GmbH for many useful discussions through the course of this work. From 2004 to 2011 the Lauder TCCON programme was funded by the New Zealand Foundation of Research Science and Technology contracts CO1X0204, CO1X0703 and CO1X0406. Since 2011 the programme has been funded by NIWA's Atmosphere Research Programme 3 (2011/13 Statement of Corporate Intent). E. Sepúlveda is funded by a pre-doctoral fellowship from the Spanish Ministry of Education. We thank the Goddard Space Flight Center for providing the temperature and pressure profiles of the National Centers for Environmental Prediction via the automailer system. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of the Karlsruhe Institute of Technology.

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**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## References

- Dohe, S., Hase, F., Gisi, M., and Blumenstock, T.: Progress on GFIT/PROFFIT intercomparison, Presentation at the 2012 TCCON Meeting, Wengen, Switzerland, 2012. 3551
- Gisi, M., Hase, F., Dohe, S., and Blumenstock, T.: Camtracker: a new camera controlled high precision solar tracker system for FTIR-spectrometers, *Atmos. Meas. Tech.*, 4, 47–54, doi:10.5194/amt-4-47-2011, 2011. 3553
- Griffith, D., Jones, N., McNamara, B., Paton-Walsh, C., Bell, W., and Bernardo, C.: Intercomparison of ground-based solar FTIR measurements of atmospheric gases at Lauder, New Zealand, *J. Atmos. Ocean. Tech.*, 20, 1138–1153, 2003. 3551
- Guelachvili, G.: *Spectrometric Techniques*, chap. 1. Distortions in Fourier spectra and diagnosis, Academic Press, 1–61, 1981. 3554
- Hase, F., Blumenstock, T., and Paton-Walsh, C.: Analysis of the instrumental line shape of high-resolution Fourier Transform IR spectrometers with gas cell measurements and new retrieval software, *Appl. Optics*, 38, 3417–3422, 1999. 3553
- Hase, F., Hannigan, J., Coffey, M., Goldman, A., Hopfner, M., Jones, N., Rinsland, C., and Wood, S.: Intercomparison of retrieval codes used for the analysis of high-resolution, ground-based FTIR measurements, *J. Quant. Spectrosc. Ra.*, 87, 25–52, doi:10.1016/j.jqsrt.2003.12.008, 2004. 3551
- Keppel-Aleks, G., Toon, G., Wennberg, P., and Deutscher, N.: Reducing the impact of source brightness fluctuations on spectra obtained by Fourier-transform spectrometry, *Appl. Optics*, 46, 4774–4779, 2007. 3557
- Learner, R., Thorne, A., and Brault, J.: Ghosts and artifacts in Fourier-Transform spectrometry, *Appl. Optics*, 35, 2947–2954, 1996. 3559
- Messerschmidt, J., Macatangay, R., Notholt, J., Petri, C., Warneke, T., and Weinzierl, C.: Side by side measurements of CO<sub>2</sub> by ground-based Fourier transform spectrometry (FTS), *Tellus B*, 62, 749–758, doi:10.1111/j.1600-0889.2010.00491.x, 2010. 3547, 3548, 3549, 3552, 3558, 3560, 3565, 3566
- Messerschmidt, J., Geibel, M. C., Blumenstock, T., Chen, H., Deutscher, N. M., Engel, A., Feist, D. G., Gerbig, C., Gisi, M., Hase, F., Katrynski, K., Kolle, O., Lavrič, J. V., Notholt, J., Palm, M., Ramonet, M., Rettinger, M., Schmidt, M., Sussmann, R., Toon, G. C., Truong, F., Warneke, T., Wennberg, P. O., Wunch, D., and Xueref-Remy, I.: Calibration of TCCON column-averaged

AMTD

6, 3545–3579, 2013

### A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



CO<sub>2</sub>: the first aircraft campaign over European TCCON sites, Atmos. Chem. Phys., 11, 10765–10777, doi:10.5194/acp-11-10765-2011, 2011. 3547

Sherlock, V., Messerschmidt, J., and Hase, F.: Ghost working group update 17 January 2011, Internal TCCON technical report, available on request, 2011. 3565

5 WMO: Global Atmosphere Watch, GAW Report No. 194, WMO TD No. 1553, 15th WMO/IAEA Meeting of Experts on Carbon Dioxide, 7–10 September 2009, Jena, Germany, 330 pp., 2011. 3546

10 Wunch, D., Toon, G., Blavier, J.-F., Notholt, R. W. J., Connor, B., Griffith, D., Sherlock, V., and Wennberg, P.: The Total Carbon Column Observing Network, Philos. T. Roy. Soc. A, 369, 2087–2112, doi:10.1098/rsta.2010.0240, 2011. 3547, 3551

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

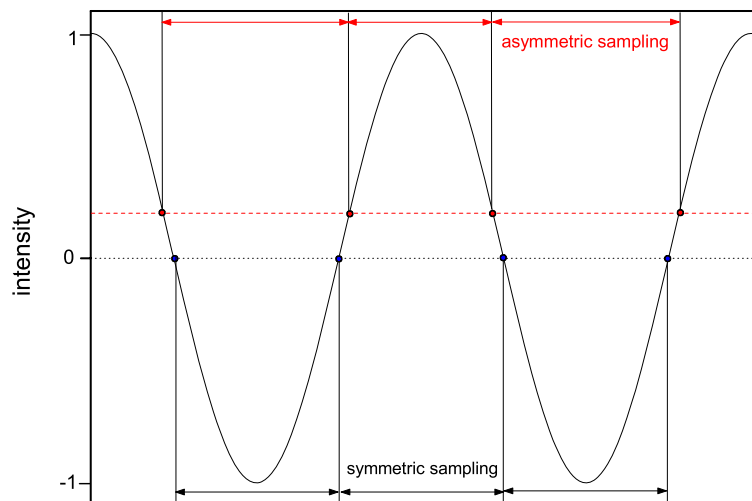
**Table 1.** LSE characterisations for the Lauder 125HR with the ECL03 laser board. In general there is good agreement between the magnitude of the LSE inferred by the resampling algorithm and GPR estimates, and between solar and lamp measurements. The parity of the peak position assumed in the TCCON filter LSE estimates is the same for forward and reverse scans for all sample rates except 10 kHz. The sign of the LSE estimates with and asterisk have been multiplied by  $-1$  to enable a self-consistent analysis of the ensemble of TCCON filter LSE estimates. The parity of the NDACC filter peak position is opposite for forward and reverse scans, hence the sign difference between tabulated LSE for NDACC and TCCON forward scans.

Vel (kHz)	Date	Lamp				Solar	
		GPR NDACC	$\gamma \times$ GPR NDACC	resample LSE		Date	LSE
				NDACC	TCCON		
10	19 Jul 2010	0.0008	0.002	-0.0020(f) 0.0020(r)		4 Aug 2010	0.0025(f) -0.0026(r)
20		0.00005	0.000125	0.0001(f) 0.0001(r)			0.0006(f) -0.0008(r)
40		0.00239	0.006	0.0060(f) -0.0056(r)			
10	8 Oct 2010	0.0009	0.0022	-0.0022(f) 0.0024(r)		2 Oct 2010	0.0025(f) -0.0027(r)
20		0.00015	0.0004	-0.0002(f) 0.0004(r)			0.0009(f) -0.0011(r)
40		0.0021	0.00525	0.0053(f) -0.0050(r)			-0.0041(f) 0.0038(r)
10	18 Jan 2011	0.0010	0.0025	-0.0023(f) 0.0023(r)	0.0022(f) *0.0023(r)	9 Jan 2011	0.0009(f) -0.0009(r)
20		0.0002	0.0005	-0.0004(f) 0.0005(r)	0.0004(f) 0.0005(r)		
40		0.0020	0.0050	0.0049(f) -0.0046(r)	-0.0050(f) -0.0047(r)		
10	19 Jan 2011	0.0009	0.0023	-0.0022(f) 0.0024(r)	0.0022(f) *0.0024(r)	13 Jan 2011	0.0004(f) -0.0009(r)
20		0.0002	0.0005	-0.0004(f) 0.0005(r)	0.0003(f) 0.0004(r)		
40		0.0020	0.0050	0.0050(f) -0.0047(r)	-0.0050(f) -0.0047(r)		



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 1.** An interferogram of the reference laser. The zero crossings are taken as reference for the measurement-sampling which is ideally symmetric (black arrows). Due to an erroneous determination of the mean intensity level, a zero offset occurs, which gives rise to an asymmetric sampling (red arrows). As a consequence phase ghosts arise, which are added to the spectrum.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

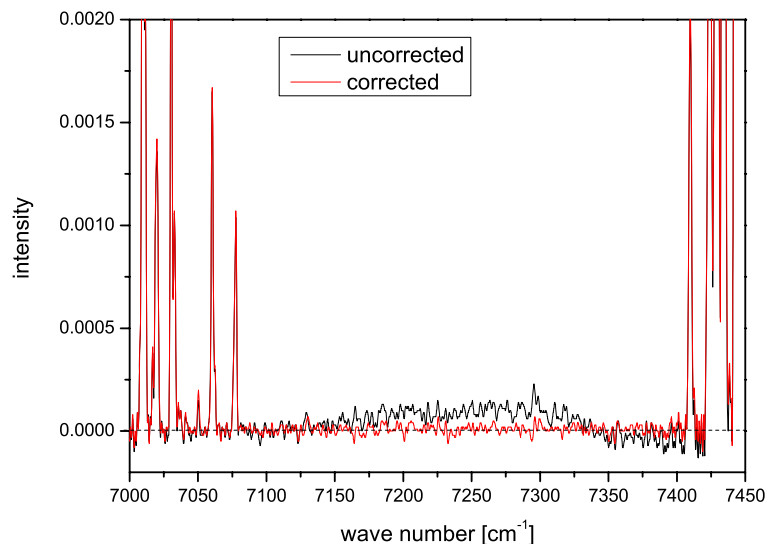
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.

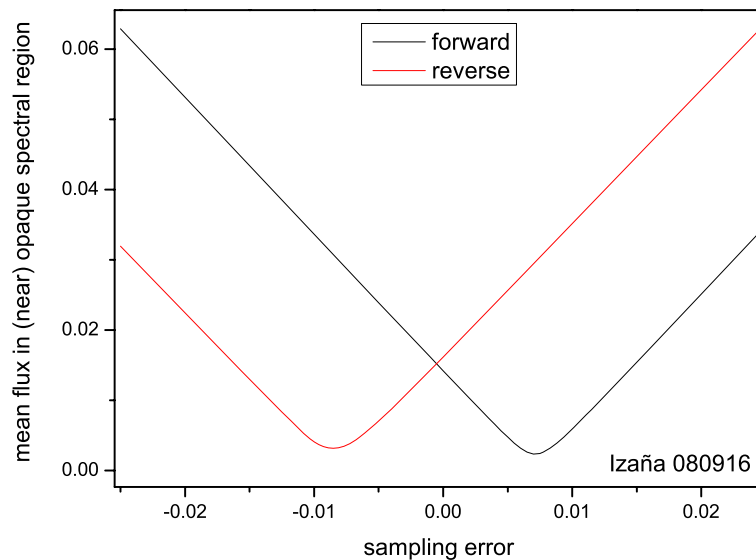


**Fig. 2.** The opaque region of the solar spectrum between 7290 and 7360  $\text{cm}^{-1}$  used in the resampling analysis. The mean intensity in the modulus spectrum is reduced when the ghost correction is applied (black: uncorrected, red: corrected).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.

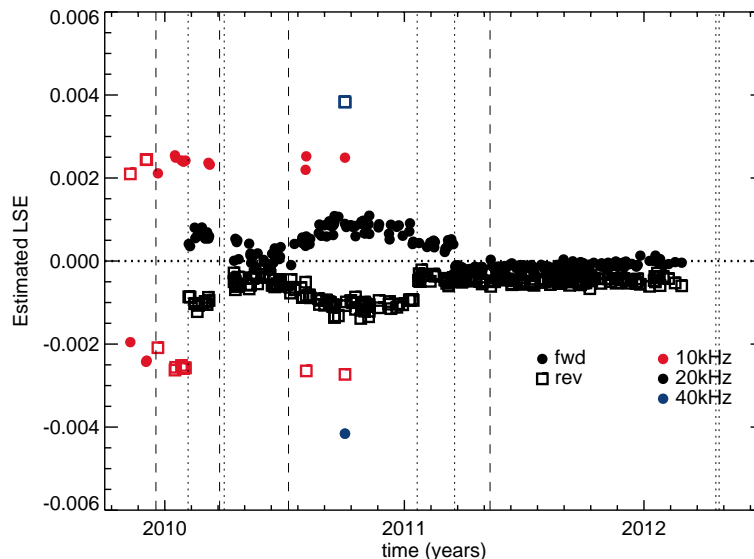


**Fig. 3.** The mean flux in the (near) opaque spectral region for the spectral window  $7290\text{--}7360\text{ cm}^{-1}$  as a function of LSE. The scanner velocity of  $v = 40\text{ kHz}$  introduces a significant mis-sampling for forward and reverse scans.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 4.** Lauder 125HR LSE timeseries determined from resampling analysis of solar interferograms using the  $7290\text{--}7360\text{ cm}^{-1}$  interval. Instrument changes relevant to the LSE and/or its determination are shown with dashed lines: change from 10 to 20 kHz sample rate for routine acquisition (February 2010); increased phase resolution (April 2010); laser board and diodes exchange (January 2011); reminimisation of laser sampling error at 20kHz after beamsplitter exchange (March 2011). Instrument realignments are shown with dotted lines.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

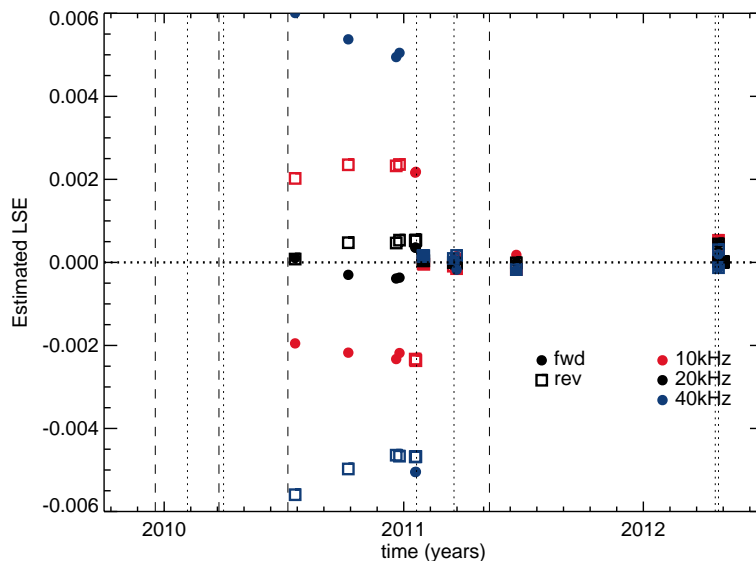
Printer-friendly Version

Interactive Discussion



## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 5.** Lauder 125HR LSE timeseries determined from analysis of Tungsten lamp spectra acquired with narrow bandpass optical filters (NDACC, TCCON) since July 2010. The lamp sequences acquired in January 2011 have been artificially reshuffled for clarity: estimates acquired with the NDACC HF filter appear plotted just prior to 1 January 2011, followed by two realisations with the TCCON filter. The TCCON filter has been used exclusively to monitor the LSE monitoring following the laser board exchange board exchange (20 January 2011). Instrument changes are shown with vertical lines (refer to the caption of Fig. 4 for details).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

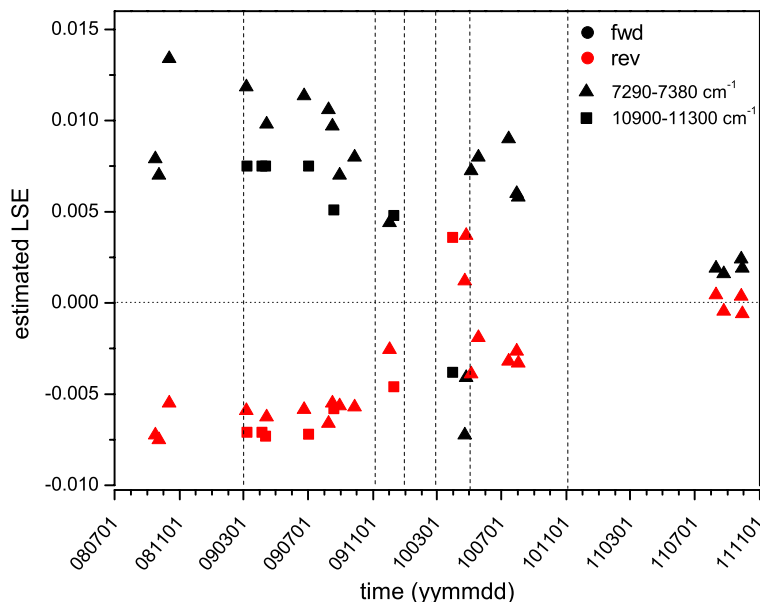
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 6.** Izaña LSE timeseries from 2008–2011 analysed using the regions  $7290\text{--}7360\text{ cm}^{-1}$  and  $10\,900\text{--}11\,300\text{ cm}^{-1}$ . The LSE which minimises the mean intensity is determined by a polynomial fit around the minimum of a curve like those shown in Fig. 3. Forward (black) and reverse scans (red) vary in magnitude and sign. The beginning of new sub-periods with different LSE due to instrumental interventions or breakdowns are indicated with vertical dashed lines: Electrical low-pass-filter change (March 2009), laser board exchange and red-filter installation (November/December 2009), loss of power and very cold temperatures (January–March 2010), electrical low-pass-filter change (May 2010), installation of ECL04 laser board and v02 diodes (November 2010).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

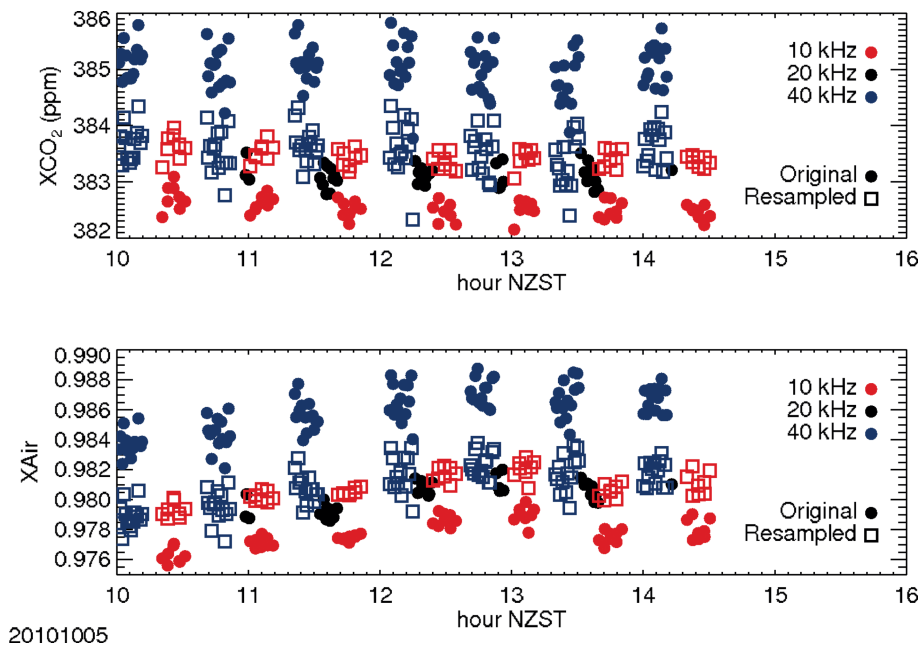
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 7.** Cycling sample rate experiments undertaken on the Lauder 125HR with the ECL03 version of the laser board on 5 October 2010. Retrievals from original IFGs are illustrated with circles for three sample rates 10 kHz (red), 20 kHz (black) and 40 kHz (blue) showing a marked sample rate dependence. Retrievals from resampled interferograms are shown in squares. Resampling reduces discrepancies between the sample rates to  $\sim 0.1\%$ .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

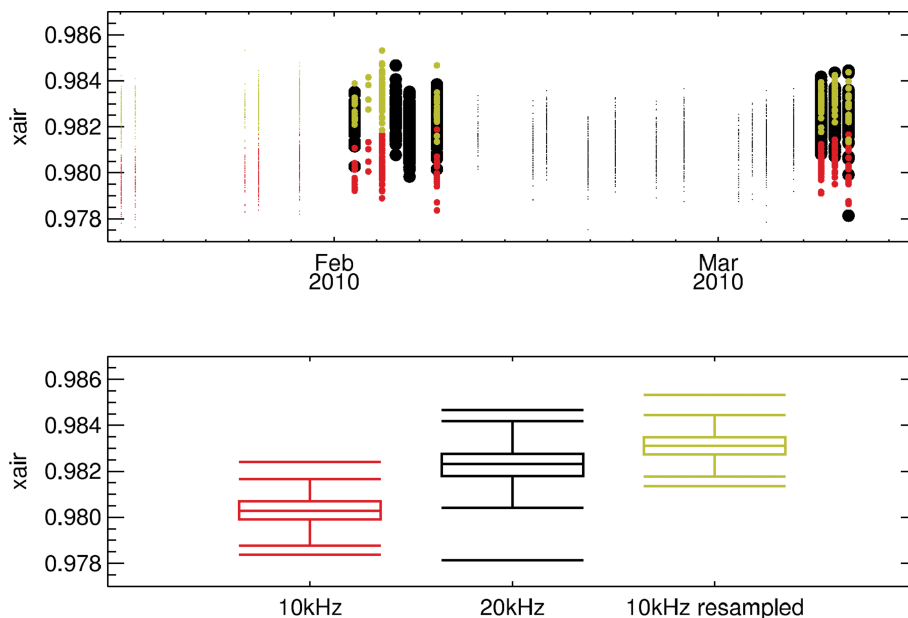
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## A method to correct sampling ghosts in historic near-infrared FTS measurements

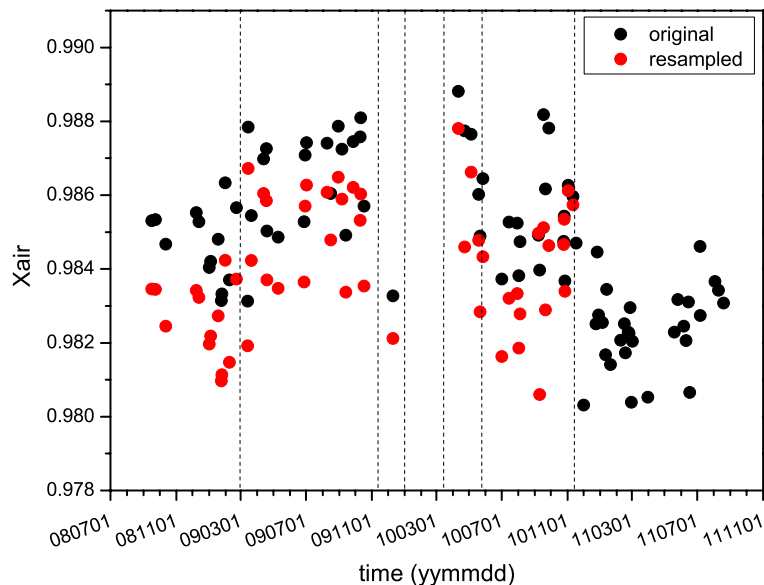
S. Dohe et al.



**Fig. 8.** Upper panel: Lauder 125HR  $X_{\text{air}}$  retrievals from original 10 and 20 kHz data acquired between 18 January and 18 March 2010 at solar zenith angles of 40–60° (red and black points respectively), and the corresponding resampled 10 kHz retrievals (yellow points). Lower panel: box and whisker plots of the  $X_{\text{air}}$  data for the periods shown with large symbols in the upper panel.

## A method to correct sampling ghosts in historic near-infrared FTS measurements

S. Dohe et al.



**Fig. 9.** Izaña 125HR timeseries of daily mean  $X_{\text{air}}$  from 2008 to 2011 for original and re-sampled measurements. The beginning of new sub-periods with different  $X_{\text{air}}$  due to instrumental interventions or breakdowns are indicated with vertical dashed lines: Electrical low-pass-filter change (March 2009), laser board exchange and red-filter installation (November/December 2009), loss of power and very cold temperatures (January–March 2010), electrical low-pass-filter change (May 2010), installation of ECL04 laser board and v02 diodes (November 2010). Resampling reduces the discrepancy to  $\sim 0.2\%$ .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

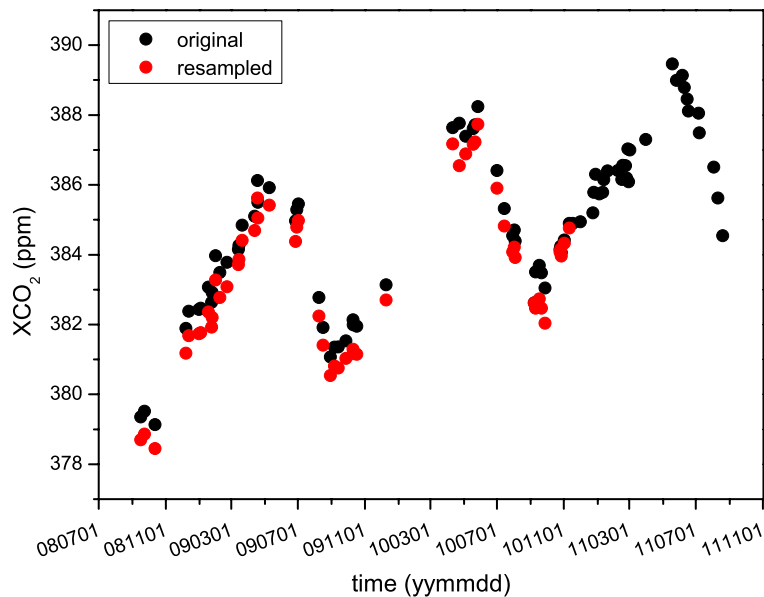
Printer-friendly Version

Interactive Discussion



**A method to correct sampling ghosts in historic near-infrared FTS measurements**

S. Dohe et al.



**Fig. 10.** Izaña 125HR timeseries of daily mean  $X_{\text{CO}_2}$  from 2008 to 2011 for original and re-sampled measurements. The plot indicates a reduction of  $X_{\text{CO}_2}$  for resampled measurements, which is mostly due to changes in the  $\text{O}_2$  retrieval.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)