Technical Note: Possible errors in flux measurements due to limited digitalization by Thomas Foken et al.

Anonymous Referee #1

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I am missing a detailed description of all the steps of A/D and D/A conversions from the measured signal to the final data storage on the data acquisition system. These steps and their individual resolution in signal amplitude depend highly on the devices (gas analyser and sonic anemometer and also data storage device) being used. Not only today but also several years ago various combinations of instruments have been used which should be accounted for in this paper. The influence of the selected range of a measured gas concentration which is being converted to a specific voltage output of the gas analyser should also be considered in more detail.

Answer to reviewer #1

Thank you very much for your comment. We presume your assumption was that different sensors and combination of sensors were available to investigate the influence of the digitalization error on carbon flux measurements. For this case a list of different sensor combinations and technical parameters would be necessary. But our paper is addressed only to the first carbon flux measurements in networks like AMERIFLUX or EUROFLUX in the middle of the 1990s. At this time several institutional developments of sensors to measure the carbon dioxide concentration with a high resolution in time (10-20 Hz) were available and are listed in Foken et al. (1995). But these sensors never were used in these networks. Only the Li-Cor 6262 closed path IR gas analyzer was applied with a 12-bit digitalizaton. This sensor combination was replaced at the beginning of the 2000s by open and closed path sensors with 16-bit digitalization. For this new generation of sensors the physical resolution of the sensor (the same for all sonic anemometers) was the limiting factor, but not the digitalization. Hence the focus on the effects of digitalization on the first generation of sensors. We will follow the reviewer and add some relevant parameters of the Li-Cor 6262 sensor in the paper and we will add the reference Moncrieff et al. (1997) where this system is partly described. See also answer to reviewer #2.

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This technical note aims to quantify the effect some of commonly encountered errors on raw eddy-covariance data have on fluxes estimation. In particular, the authors focus their attention on digitalization errors affecting data from gas-analyzers and R2 and R3 sonic anemometers. Having compared original NEE estimates with those obtained after being contaminated by simulated errors, the authors conclude that the flux bias is negligible.

The paper is well structured and addresses important issues in long term analyses of eddy-covariance (EC) data. In principle, I agree with the authors findings, however:

a) the authors should explain in more detail the simulation design, highlighting drawbacks and advantages of their choices.

b) I would suggest to use data sampled in more than one site in order to achieve robust estimates. Further, in the comparison of NEE estimates, I suggest i) to use an error-in-variables model and ii) to interpret results on the basis of confidence intervals rather than on point estimates.

c) considerations about consequences errors can have on other methods involved in EC data processing need to be discussed. If bias introduced by digitalization errors on flux estimates is negligible, what are advantages of using error free data? I would invite the authors to discuss about the effects they could have on other procedures (eg on uncertainty quantification at half-hourly time scale, on spectral correction factor estimates).

d) In Section 3.1, the authors affirm that "From a theoretical point of view the digitalization error should only impact small magnitude fluxes". I'd suggest to provide more details about this statement.

Answer to reviewer #2

Thank you very much for the helpful comments and that you agreed with our conclusion that the digitalization error of the sensor configuration used in the 1990s years for carbon flux measurements is negligible. This finding enables ecosystem trend analyses of carbon fluxes including data from the 1990s, which are not affected by the limited digitalization in a significant fashion . Our answers to the specific comments are (we changed the order):

d) Fluxes of water vapour and carbon dioxide are small if the fluctuations of the vertical wind velocity or those of the trace gas concentration or both are small. This follows from the eddy-covariance theory (see e.g. Foken et al. 2012a); the flux (covariance) is a non-normalized correlation coefficient. Data with low wind fluctuations will not be used because of gap filling or/and data quality criteria based upon flow statistics such as friction velocity or non-dimensional flow statistics (Goulden et al. 1996, Foken and Wichura 1996, and all follow up papers). If the fluctuations of the concentration are too low and on the order of the resolution of the digitalization procedure (see Table 1) the signal is constant or changes only by a few digits and is therefore affected by the digitalization error. We will include this explanation in the paper. If the fluctuation is much larger than the digitalization step, the fluxes are not affected as shown in the paper.

b) From the statement in Section 3.1 and the explanation d) follows that the fluxes of other measurement sites are only affected for low fluxes (no turbulence, transition time, partly at night). These fluxes are mostly not affected by the ecosystem or with other words: The finding, that only low

fluxes may be affected by low resolution digitalization can be generalized to other sites. The abundance of such situations differs among sites, but from the error magnitude in our analysis it is very unlikely, that other sites were significantly affected by the digitalization problem. On the other hand, most of these small fluxes are gap-filled and high-resolution raw-data data were rarely archived in the 1990s. Therefore only a simulation of the digitalization problem with recently collected data at sufficient resolution is a viable way of investigating this effect (see a). For these reasons and because of other error sources result in much larger uncertainties (see c) we conclude that our conclusion would not change.

c) The focus of our paper was only the digitalization error that was not yet discussed in the literature. For other errors there are many papers with exact error bands available, also from the first author (Foken et al. 2012a,b, Foken 2017 and many references within these publications). The magnitude of most flux corrections scale with the magnitude of the computed flux and hence in case of the flux error resulting from digitalization the correction is very small. The spike test of the original data is not relevant because the digitalization error does not generate spikes. Only the ogive test – made with the original date – may be affected. However, the correction is within the error band for low fluxes (Charuchittipan et al. 2014). This test is not applied in standard flux calculations.

a) We used the standard eddy covariance processing software (see description in paper). The only modifications we administered was i) converting the 16-bit-data into data with 12-bit-digitalization by applying bin-averages according to the 12 bit resolution specified in Table 1 and ii) modifiying the sonic anemometer data to reproduce the digitalization error mimicking the error observed for the R2/R3 data. Therefore the 12-bit-calculations were not done with the original data but with data where we artificially introduced these errors, which we call here simulation. We will change the wording for a better understanding.

We have made some small language editions.

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Technical Note: Possible errors in flux measurements due to limited digitalization

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Abstract. Recently reported trends of carbon dioxide uptake poses the question if trends may be the result of the limited digitalization of gas analysers and sonic anemometers used in the 1990s. Modifying a 12-bit digitalization and the instrument error reported for the R2 and R3 sonic anemometers found elsewhere, the influence of these deficits in comparison to the now commonly used 16-bit digitalization were quantified. Both issues have an effect only on trace gas fluxes of small magnitude,
15 mainly for the carbon dioxide rather than for the water vapour fluxes. The influence on the annual net ecosystem exchange is negligible, because other errors resulting from e.g. gap filling routines are much larger.

1 Introduction

Nowadays, data sets of FLUXNET sites are available and many papers have been published which analyse and compare these data and link them to ecosystems, phenology, regions, and climate (Baldocchi, 2008; Williams et al., 2012; Keenan et al.,
20 2013; Keenan et al., 2014; Kutsch and Kolari, 2015; Baldocchi et al., 2016; Babel et al., 2017). Among the factors with a possible influence on the resulting budgets is the quantification (digitalization) error (Ifeachor and Jervis, 2002), arising from the use of a limited 12-bit-digitalization of turbulence data about 15–20 years ago (Vickers and Mahrt, 1997). This error could introduce trends (Foken, 2017) and has, up to now, not been investigated thoroughly. The influence of the digitalization error on flux calculations is the topic of this short note. An effect similar to the effect of the digitalization error could have been
25 caused by the instrument error reported for the formerly used R2 and R3 sonic anemometers before the year 2003 (Foken et al., 2004, found by Chr. Thomas, University of Bayreuth, 2002). The problem was identified when applying these sonic anemometers for a relaxed eddy accumulation (REA) system, where the vertical wind velocity near 0.00 m s⁻¹ must be accurately measured. The problem was reported to the manufacturer (now: Gill Instruments Ltd, Lymington, UK) and the firmware was updated. For this study a data set output with 16-bit-digitalization will be compared to the same data modified
30 into a 12-bit-digitalization.

2 Material and Methods

2.1 Data sets for the analysis

The data used for this study are from the FLUXNET site (DE-Bay) Waldstein-Weidenbrunnen (50°08'31" N, 11°52'01" E, 775 m a.s.l.), which is located in the Fichtelgebirge Mountains in the northeast of Bavaria (Germany), where Norway spruce (*Picea abies*) forest dominates. Measurements of energy and carbon dioxide fluxes started in 1996 on the top of a 32 m high walk-up scaffold tower. Possibly affected time series are the measurements made with the R2 and R3 sonic anemometer from 1997 to 2006 and the LiCor 6262 gas analyser (LI-COR Inc., Lincoln, NE, USA) from 1997 to 2002. The complete data set was analysed by Babel et al. (2017).

The instrumentation of not only the Waldstein-Weidenbrunnen site, but all FLUXNET sites, has changed dramatically, occurring mainly at the beginning of the 2000s. At this time, the first commercial open-path instruments for carbon dioxide and water vapour concentration measurements became available. Before 2000 only the LiCor 6262 closed-path instruments mainly in combination with R2 and later R3 sonic anemometers (Moncrieff et al., 1997) were used, which had only a 12-bit signal digitalization, while later devices offered 16-bit or more. The root mean square noise (possible resolution) of the carbon dioxide channel of LiCor 6262 is about 0.2 ppm and the digitalization step for 12-bit digitalization is much larger with 0.73 ppm (see Table 1). In contrast, for the LiCor 7500 instrument used later the root mean square noise is about 0.1 ppm, which is much larger than the digitalization step of the 16-bit digitalization of 0.046 ppm (s. Table 1) and therefore the digitalization has no influence on the data since the beginning of the 2000s.

One year of measurements collected during 2012 from the METEK sonic anemometer USA-1 (METEK GmbH Elmshorn, Germany) und the LiCor 7500 gas analyser were used for this study. Turbulent fluxes of carbon dioxide and water vapour were calculated using the internationally-compared software package TK2/TK3 (Mauder et al., 2008; Fratini and Mauder, 2014; Mauder and Foken, 2015). All necessary corrections and quality checks were done in accordance with micrometeorological standards (Foken et al., 2012). Coordinate rotation was carried out using the planar-fit method (Wilczak et al., 2001) for each separate month, based on an analysis by Siebicke et al. (2012). The net ecosystem exchange (NEE) is defined as the sum of the vertical eddy-covariance carbon dioxide flux and the change in storage of the air column below the sensor.

2.2 12-bit-digitalization

The effect of limited amplitude resolution of fluxes of small magnitude was already discussed by Vickers and Mahrt (1997) and is illustrated in a time series of the carbon dioxide concentration in Fig. 1.

The typical characteristics of 12-bit- and 16-bit-digitalization are shown in Table 1. The problem is more significant for carbon dioxide than for water vapour because the carbon dioxide fluctuations are much smaller in relation to measurement range than

those of water vapour. Furthermore, under stable stratification the carbon dioxide concentration can be 3- to 4-times higher than the mean concentration and the measurement range must be extended. The output resolution of all sonic anemometers is currently at least 0.01 m s^{-1} and is not affected by any digitalization error. A quadrant (hole) analysis of all data points (20 Hz sampling rate) for one hour of the vertical wind velocity and the carbon dioxide concentration is shown in Fig. 2. The included

5   density distributions show only small differences between the 12-bit and 16-bit digitalizations and are not significantly affected by the binned concentration data, which explains the small impact of the digitalization error on the computed flux.

2.3 Instrument error of R2 and R3 sonic anemometer

The R2 and R3 sonic anemometers had, up to 2003, instrument error (Foken et al., 2004) such that the R2 did not output vertical wind velocities of w = –0.01 m s^{-1}, but added these values to the digitalization step 0.00 m s^{-1} (Fig. 3). For R3 there

10   was a similar pattern every 0.07 m s^{-1} for negative w-values and every 0.14 m s^{-1} for positive w-values.

3 Results and discussion

3.1 Effect of 12-bit-digitalization

From a theoretical point of view the digitalization error should only impact small magnitude fluxes, mainly in winter due to small magnitude of perturbations. If the fluctuations are on the order of the digitalization step the signal becomes constant or

15   changes are limited to a few decimal places only. In Fig. 4 only fluxes smaller than |0.003 mmol m^{-2} s^{-1}| are shown. In summer, even for small net fluxes, the amplitude of the fluctuations is high and no effect on the fluxes can be seen. In winter the data are much more scattered and the respiration fluxes may be overestimated by approximately 5 %. Similar effects on cumulative fluxes could also be shown for incorrectly applied correction under these conditions (Oechel et al., 2014).

3.2 Effect of instrumental errors of the sonic anemometers R2 and R3

20   The original data of the vertical wind velocity were replaced by data simulating the error of the R2 sonic anemometer. The simulated errors had no significant impact on the results (Fig. 5 left, compare with Fig. 4 right). To isolate the effect of the coordinate rotation from that instrument error on to the fluxes the analysis was repeated with unrotated data in which the digitalization step 0.00 m s^{-1} bin was empty. As shown in Fig. 5 right, the effect of the sampling error of R2 is negligible, even for low fluxes and vertical wind velocities in the relevant range. Identical results were obtained when simulating the R3 sonic

25   anemometer error (produced before 2003).

3.3 Influence on longer time series

To investigate the influence of digitalization errors on annual sums of the NEE the data of 2012 were analysed and the results are shown in Table 2. The time series was not gap filled, therefore respiration date are partly missing and NEE is larger than

3

==expected biological sink. The simulated 12-bit-digitalization error has== no significant impact on ==the== annual carbon budget, except for reduction of the respiration for fluxes smaller |0.003 mmol m^{-2} s^{-1}| in winter (DJF). The simulated R2-error has no influence on the results.

4 Conclusions

5   Since long time-series for carbon fluxes bare high relevance for ecosystem behaviour, investigations of older data sets should be undertaken with care due to possible artefacts resulting from changes in instrumentation and data handling. The present study showed that the effect of a limited 12-bit-digitalization of the gas analyser LiCor 6262 and an instrumental error of the sonic anemometers R2 and R3 showed no significant impact on summer flux estimates and for annual budgets. Only selected data of low magnitude fluxes show increased scatter and differences of approximately 5 % due to the digitalization error –

10   mainly in wintertime. The effect of the R2 and R3 instrument error was negligible. Low fluxes and fluxes in wintertime are often discarded from quality routines and gap filled. ==Because of general low winter-time fluxes across ecosystems, the findings can be universally applied to carbon flux measurement sites.== In comparison, errors resulting from the gap filling [Moffat, 2007 #1505] are much larger than the errors reported here.

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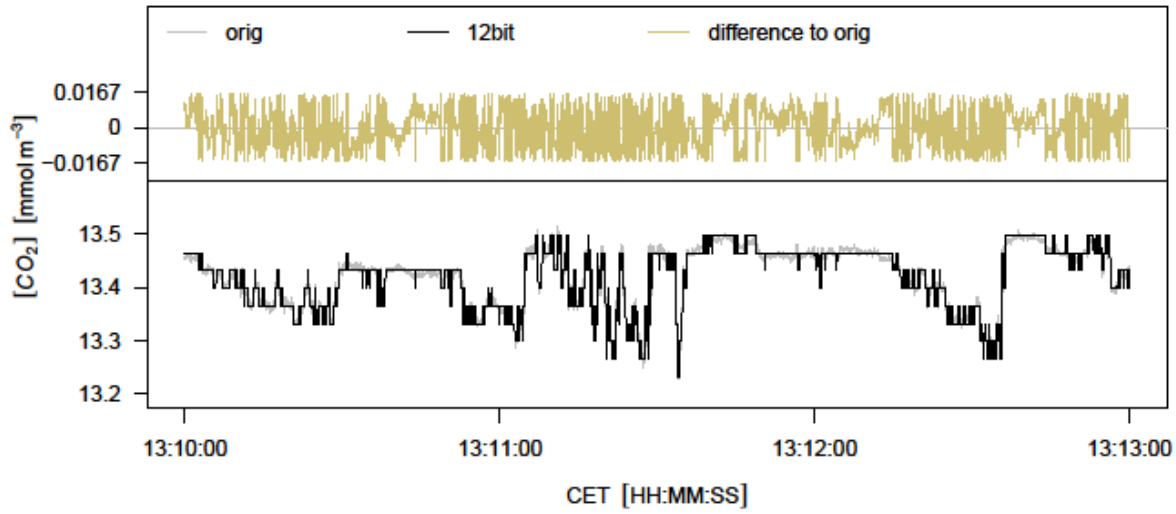
Figure 1: Carbon dioxide concentration on 02 August 2012 measured with LiCor 7500 (orig.) and reduced to 12-bit resolution. In the upper panel the difference between both signals is shown and in the lower panel both signals show the typical ramp structures above the spruce forest.
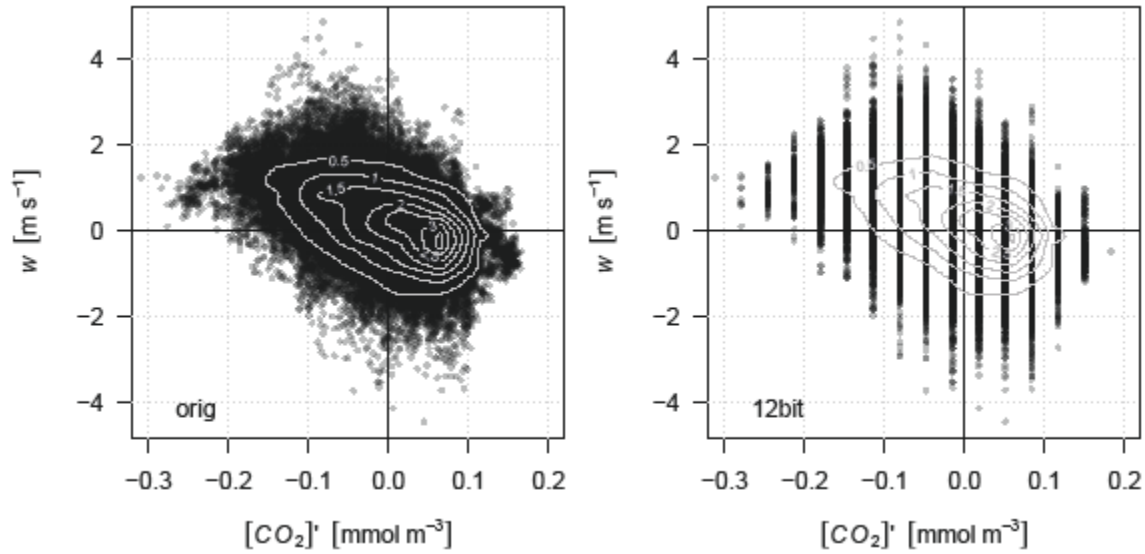

Figure 2: Quadrant (hole) analysis of all data points (20 Hz sampling rate) of the vertical wind velocity and the carbon dioxide concentration for one hour (summer at noon) with 16-bit-digatalization (left) and reduced to 12-bit-digitalization (right). A normalized density distribution in form of isopleths is included in both figures.
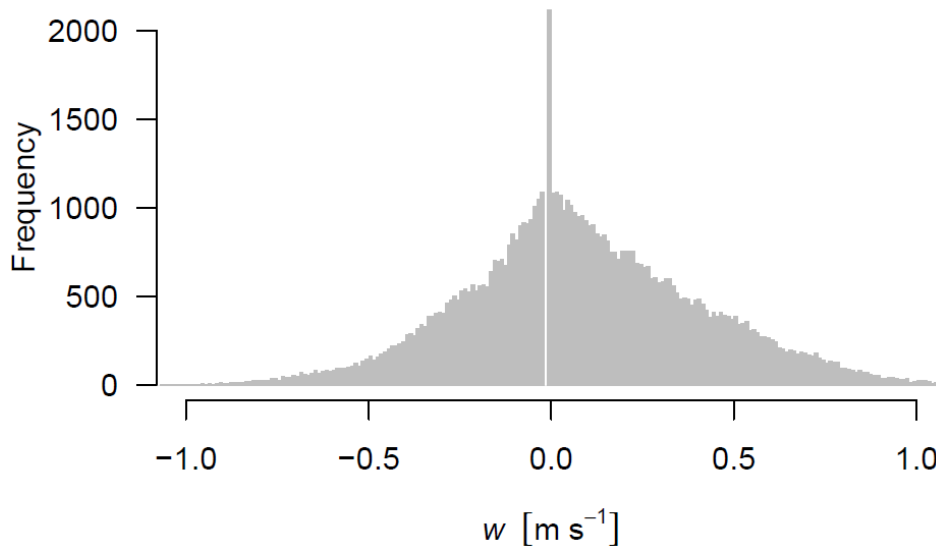
Figure 3: Probability density plot of the vertical wind velocity for one hour (summer at noon) with the manipulated instrumental error of the R2 sonic anemometer.
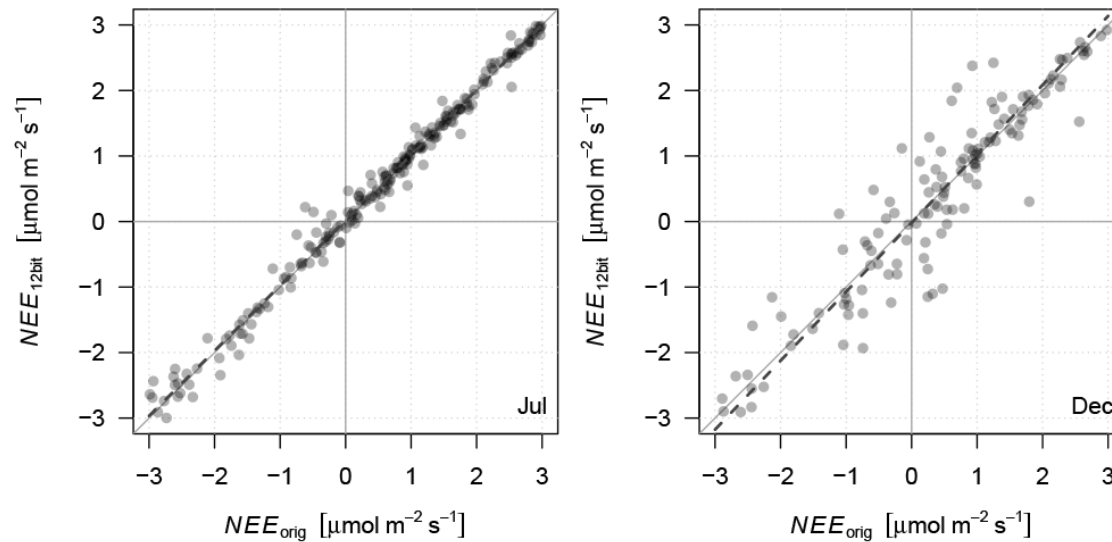

Figure 4: Comparison of the original NEE measurements at Waldstein-Weidenbrunnen site in 2012 (original 16-bit-digitalization) with calculations using data with 12-bit resolution for the gas analyser in summer (July, left, $NEE_{12bit} = 0.995\ NEE_{org} \pm 0.000$ mmol $m^{-2}\ s^{-1}, R^2 = 0.99, N = 219$) and winter (December, right, $NEE_{12bit} = 1.052\ NEE_{org} \pm 0.000$ mmol $m^{-2}\ s^{-1}, R^2 = 0.87, N = 129$). Only data smaller than $|0.003$ mmol $m^{-2}\ s^{-1}|$ are shown.
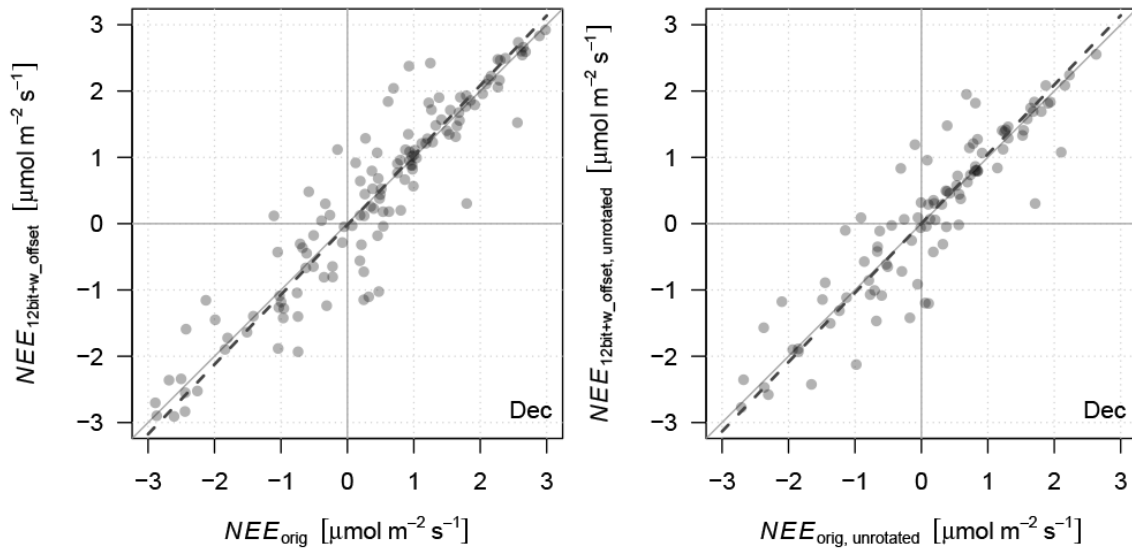
Figure 5: Comparison of the original NEE measurements at Waldstein-Weidenbrunnen site of December 2012 (original 16-bit-digitalization) with synthetic data with 12-bit-digitalization for the gas analyser and the instrument error (*w*-offset) of the sonic anemometer R2. In the left figure the data were rotated (compare with Fig. 4 right, $NEE_{12bit\_w\_offset} = 1.052\ NEE_{org} \pm 0.000$ mmol m^{-2} s^{-1}, $R^2 = 0.87$, $N = 129$) and in the right figure were not ($NEE_{12bit\_w\_offset\_unrotated} = 1.045\ NEE_{org\_unrotated} \pm 0.000$ mmol m^{-2} s^{-1}, $R^2 = 0.83$, $N = 97$). Only data smaller than |0.003 mmol m^{-2} s^{-1}| are shown.

Table 1: Characteristic resolutions for water vapour and carbon dioxide concentrations with 12-bit- and 16-bit-digitalization, italic data were used for the <mark>calculation</mark>

	12-bit-digitalization	16-bit-digitalization
Sampling points within the measurement range	$2^{12} = 4{,}096$	$2^{16} = 65{,}536$
Measurement range for water vapour	0 – 75 ppth or about 0 – 3250 mmol m^{-3}	
Measurement range for carbon dioxide	0 –3,000 ppm or about 0 – 130 mmol m^{-3}	
Digitalization step for water vapour	0.018 ppth or *0.8 mmol m^{-3}*	0.0011 ppth or 0.05 mmol m^{-3}
Digitalization step for carbon dioxide	0.73 ppm or *0.033 mmol m^{-3}*	0.046 ppm or 0.002 mmol m^{-3}

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Table 2: Annual sum of NEE with 12-bit- and 16-bit-digitalization and with and without R2 instrumental error (the data were not gap filled, therefore the sum is larger than usual, relevant differences italic)

Data selection	12-bit- digitalization	16-bit-digitalization	Number of (30 minute) data points
All data, without R2 error	-799.73 g C m^{-2}	- 798.27 g C m^{-2}	8419 of 17520
All data, with R2 error	-799.71 g C m^{-2}		
Only data < |0.003 mmol m^{-2} s^{-1}|, without R2 error	33.663 g C m^{-2}	33.145 g C m^{-2}	2678 of 17520
Only data < |0.003 mmol m^{-2} s^{-1}|, with R2 error	33.660 g C m^{-2}		
Only data < |0.003 mmol m^{-2} s^{-1}|, without R2 error (only winter, DJF)	*1.328 g C m^{-2}*	*1.150 g C m^{-2}*	284 of 4320
Only data < |0.003 mmol m^{-2} s^{-1}|, with R2 error (only winter, DJF)	1.328 g C m^{-2}		

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