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, 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., 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 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 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 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 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 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

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 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 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

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 – 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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References

Babel, W., Lüers, J., Hübner, J., Rebmann, C., Wichura, B., Thomas, C. K., Serafimovich, A., and Foken, T.: Long-term carbon and water vapour fluxes, in: Energy and Matter Fluxes of a Spruce Forest Ecosystem, Ecological Studies, Vol. 229, edited by: Foken, T., Springer, Cham, 73-96, doi: 10.1007/978-3-319-49389-3_4, 2017.

Baldocchi, D.: 'Breathing' of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems, Australian Journal of Botany, 56, 1-26, doi: 10.1071/BT07151, 2008.

Baldocchi, D., Ryu, Y., and Keenan, T.: Terrestrial Carbon Cycle Variability [version 1; referees: 2 approved], F1000Research, 5(F1000 Faculty Rev), 2371, doi: 10.12688/f1000research.8962.1, 2016.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B. D., and Munger, J. W.: Post-field data quality control, in: Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, edited by: Lee, X., Massman, W. J., and Law, B., Kluwer, Dordrecht, 181-208, 2004.

Foken, T., Leuning, R., Oncley, S. P., Mauder, M., and Aubinet, M.: Corrections and data quality in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by: Aubinet, M., Vesala, T., and Papale, D., Springer, Dordrecht, Heidelberg, London, New York, 85-131, doi: 10.1007/978-94-007-2351-1_4, 2012.

Foken, T.: What can we learn for a better understanding of the turbulent exchange processes at FLUXNET sites, in: Energy and Matter Fluxes of a Spruce Forest Ecosystem, Ecological Series, Vol. 229, edited by: Foken, T., Springer, Cham, 461-475, doi: 10.1007/978-3-319-49389-3_19, 2017.

Fratini, G., and Mauder, M.: Towards a consistent eddy-covariance processing: an intercomparison of EddyPro and TK3, Atmos. Meas. Techn., 7, 2273-2281, doi: 10.5194/amt-7-2273-2014, 2014.

Ifeachor, E. C., and Jervis, B. W.: Digital Signal Processing - A Practical Approach, Addison-Wesley Publishing Company, Wokingham, 968 pp., 2002.

Keenan, T. F., Hollinger, D. Y., Bohrer, G., Dragoni, D., Munger, J. W., Schmid, H. P., and Richardson, A. D.: Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise, Nature, 499, 324-327, doi: 10.1038/nature12291, 2013.

Keenan, T. F., Gray, J., Friedl, M. A., Toomey, M., Bohrer, G., Hollinger, D. Y., Munger, J. W., O/'Keefe, J., Schmid, H. P., Wing, I. S., Yang, B., and Richardson, A. D.: Net carbon uptake has increased through warming-induced changes in temperate forest phenology, Nature Clim. Change, 4, 598-604, doi: 10.1038/nclimate2253, 2014.

Kutsch, W. L., and Kolari, P.: Data quality and the role of nutrients in forest carbon-use efficiency, Nature Clim. Change, 5, 959-960, doi: 10.1038/nclimate2793, 2015.

Mauder, M., Foken, T., Clement, R., Elbers, J., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O.: Quality control of CarboEurope flux data - Part 2: Inter-comparison of eddy-covariance software, Biogeoscience, 5, 451-462, doi: 10.5194/bg-5-451-2008, 2008.

Mauder, M., and Foken, T.: Eddy-Covariance software TK3, Zenodo, 10.5281/zenodo.20349 doi: 10.5281/zenodo.20349, 2015.

Moffat, A. M., Papale, D., Reichstein, M., Barr, A. G., Beckstein, C., Braswell, B. H., Churkina, G., Desai, A., Falge, E., Gove, J. H., Heimann, M., Hollinger, D. Y., Hui, D., Jarvis, A. J., Kattge, J., Noormets, A., Richardson, A. D., and Stauch, V. J.: Comprehensive comparison of gap filling techniques for eddy covariance net carbon fluxes, Agric. For. Meteorol., 47, 209-232, doi: 10.1016/j.agrformet.2007.08.011, 2007.

Moncrieff, J. B., Massheder, J. M., DeBruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Søgaard, H., and Verhoef, A.: A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide, J. Hydrol., 188-189, 589-611, doi:10.1016/S0022-1694(96)03194-0, 1997.

Oechel, W. C., Laskowski, C. A., Burba, G., Gioli, B., and Kalhori, A. A. M.: Annual patterns and budget of CO2 flux in an Arctic tussock tundra ecosystem, J. Geophys. Res.: Biogeosci., 119, 2013JG002431, doi: 10.1002/2013JG002431, 2014.

Siebicke, L., Hunner, M., and Foken, T.: Aspects of CO2-advection measurements, Theor. Appl. Climat., 109, 109-131, doi: DOI 10.1007/s00704-011-0552-3, 2012.

Vickers, D., and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, J. Atm. Oceanic Techn., 14, 512-526, doi: 10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2, 1997.

Wilczak, J. M., Oncley, S. P., and Stage, S. A.: Sonic anemometer tilt correction algorithms, Boundary-Layer Meteorol., 99, 127-150, doi: 10.1023/A:1018966204465, 2001.

Williams, C. A., Reichstein, M., Buchmann, N., Baldocchi, D. D., Beer, C., Schwalm, C., Wohlfahrt, G., Hasler, N., Bernhofer, C., Foken, T., Papale, D., Schymanski, S., and Schaefer, K.: Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers Water Resources Res., 48, W06523, doi: doi:10.1029/2011WR011586 2012.

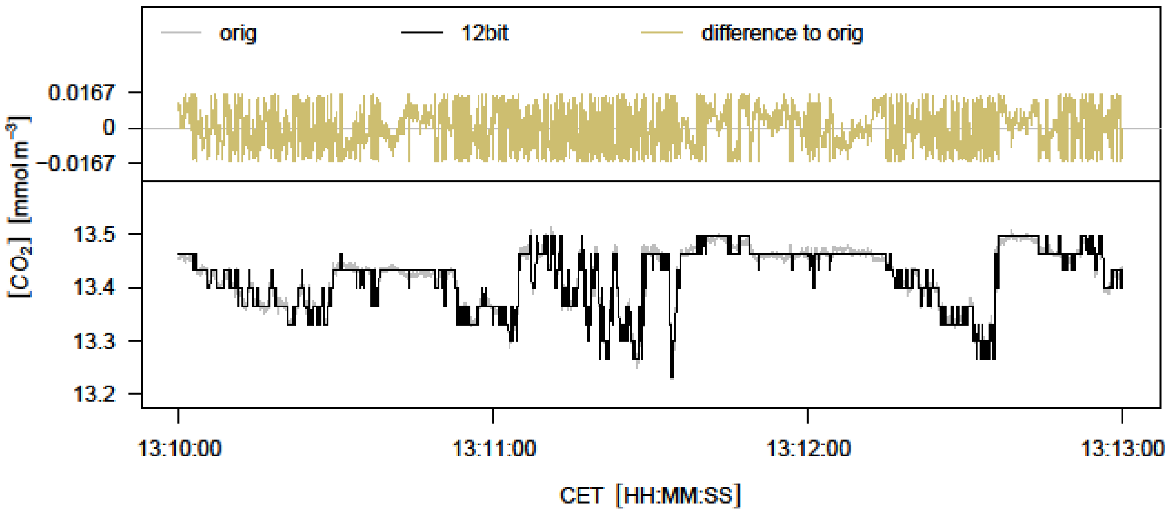

Figure 1: Carbon dioxide concentration on 02 August 2012 measured with LiCor 7500 (orig.) and reduced to 12-bit resolution. In the upper panel the difference between both signals is shown and in the lower panel both signals show the typical ramp structures above the spruce forest.

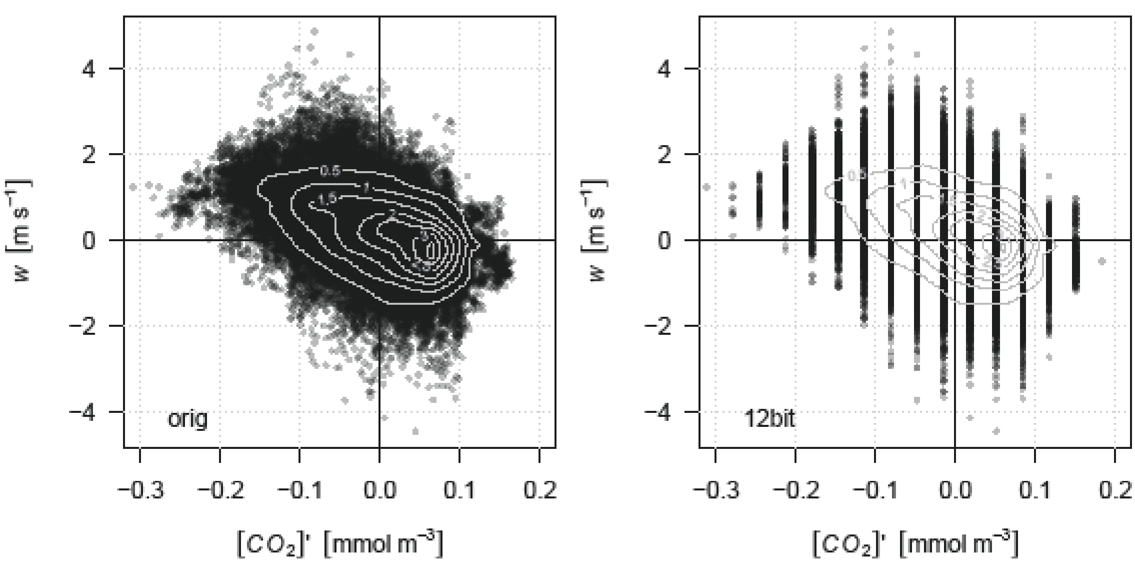

Figure 2: Quadrant (hole) analysis of all data points (20 Hz sampling rate) of the vertical wind velocity and the carbon dioxide concentration for one hour (summer at noon) with 16-bit-digatalization (left) and reduced to 12-bit-digitalization (right). A normalized density distribution in form of isopleths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

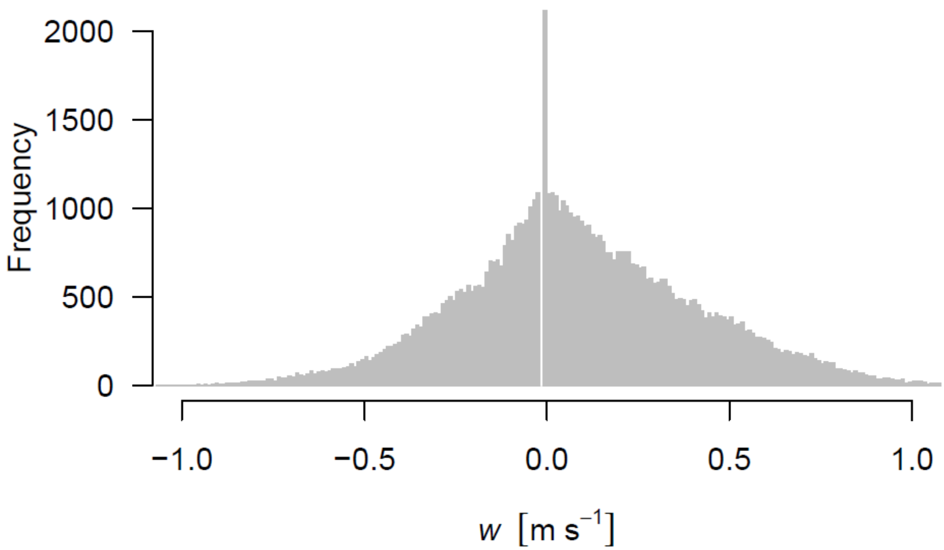

Figure 3: Probability density plot of the vertical wind velocity for one hour (summer at noon) with the manipulated instrumental error of the R2 sonic anemometer.

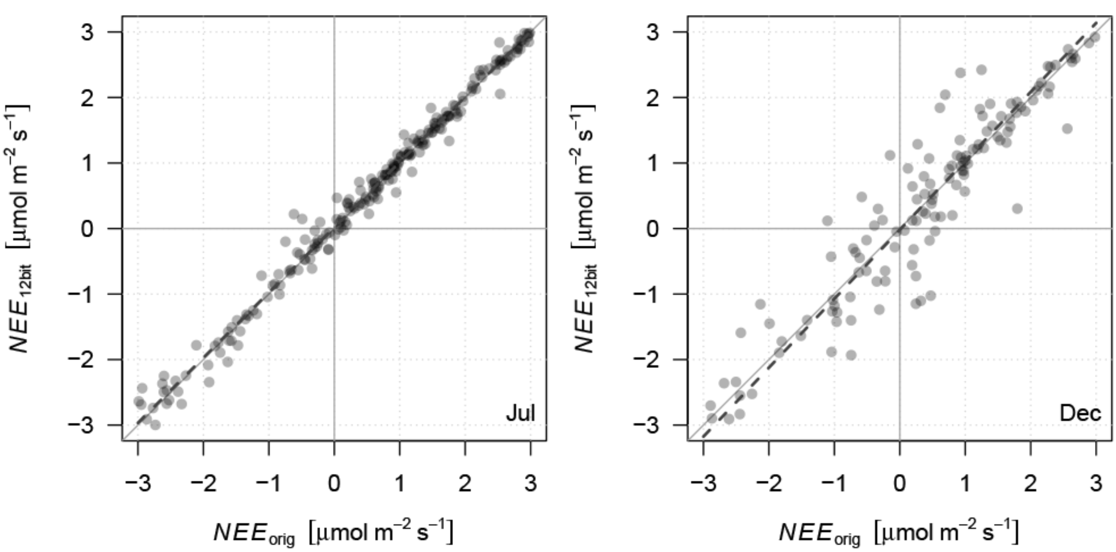

Figure 4: Comparison of the original NEE measurements at Waldstein-Weidenbrunnen site in 2012 (original 16-bit-digitalization) with calculations using data with 12-bit resolution for the gas analyser in summer (July, left, $NEE_{12bit} = 0.995\ NEE_{org} \pm 0.000$ mmol m^{-2} s^{-1}, $R^2 = 0.99$, $N = 219$) 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.

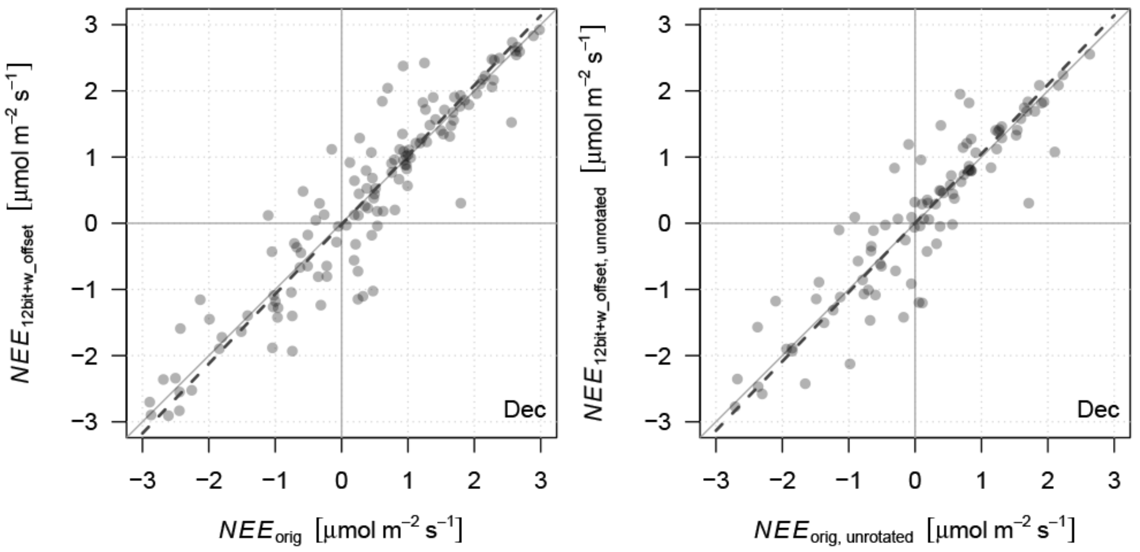

Figure 5: Comparison of the original NEE measurements at Waldstein-Weidenbrunnen site of December 2012 (original 16-bit-digitalization) with synthetic data with 12-bit-digitalization for the gas analyser and the instrument error (*w*-offset) of the sonic anemometer R2. In the left figure the data were rotated (compare with Fig. 4 right, $NEE_{12bit\_w\_offset}$ = 1.052 NEE_{org} ± 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 $NEE_{org\_unrotated}$ ± 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 calculation

	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}

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}		