Authors' response to referee comment by F.-M. Bréon: MAMAP – a new spectrometer system for column-averaged methane and carbon dioxide observations from aircraft: retrieval algorithm and first inversions for point source emission rates

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The referee had some very helpful major and a few minor comments and raised interesting questions. We discuss all comments in detail below and incorporated the recommendations to improve our paper.

Referee: *One of the approach used to invert the emission fits the column measurements to a Gaussian shape as described in eq 13. The inversion has therefore one free parameter (the emission rate) but the width of the plume has to be fixed according to strong hypothesis on the atmosphere stability. I wonder why the authors did not rather made an inversion with 2 free parameters, i.e. the "a" parameter of eq 15 in addition to the emission. There is certainly enough independent observations to invert two free parameters, and this would avoid a strong hypothesis in the retrieval.*

Authors: Having only one free linear parameter was initially the most simple inversion scheme. As the referee suggests, we now included also the stability parameter a as a free parameter to be retrieved from the data in addition to the emission rate. This requires an iterative inversion approach since the equation to be solved is not linear any more. Inverting also for the stability leads to a significant improvement especially for Schwarze Pumpe which suffered from nonstationary wind conditions (see Table 10 below).

Referee: *I am rather surprised by the modeled vertical distribution of the CO2 plume (eq 26). There are two terms. One with a maximum concentration at stack height (OK, fair enough) and another below the ground but another with a maximum below the surface. What is the purpose of the second term ? In addition, is there any evidence that the plume vertical distribution has such shape. Because the effective wind speed is directly affected by the vertical distribution, this has some consequences.*

Authors: For the vertical distribution like the horizontal distribution, we assume a Gaussian plume dispersion. The second term of the equation accounts for the "reflection" of the plume from the ground since CO_2 is not expected to be absorbed on the time scales of interest here. This is a fairly standard method in stack gas dispersion modelling (compare e.g. http://www.air-dispersion.com/gaussian.html). For clarification, we will cite an according textbook (Beychok, 2005).

Referee: *I already posted a comment on the computation of the averaged wind speed. I give it again here: The wind speed is an essential parameter to infer the emission from the column concentration. Indeed, the column con-*

centration is inversely proportional to the wind speed (see eq 13). From the wind speed vertical profile (in fact, two layers with different wind speeds), the authors compute an averaged value Ua, weighted by the fraction of the emission in each of two layers (w1 and w2). Ua = w1 U1 + w2 U2 I argue that, as the vertical column is proportional to the inverse of the wind speed, the averaged wind speed should be computed as 1/Ua = w1/U1 + w2/U2 This has large consequences; In the case of Janschwalde, the values are w1=56%, w2=44%, U1=3.6; U2=6.5 Which leads to averaged wind speeds of either 4.88 (authors method), or 4.48 (present) In the case of Schwarze, w1=55%, w2=45%, U1=2.5; U2=5.6 Which leads to averaged wind speeds of either 3.9 (authors method), or 3.33 (present) Thus, it seems that the effective wind speed is overestimated by about 10%, with an equivalent impact on the power plant emission estimate.

Authors: The referee is right that the weighted harmonic mean is the more appropriate method to obtain an average wind speed in the present case. This has been changed accordingly in the revised version of the paper. The final results (including also the modification due to the simultaneous retrieval of the stability parameter) can be seen in Table 10 below.

Referee: *Atmospheric stability : There is a discussion at page 2232 that leads the authors to assume that the atmosphere can be classified as very unstable. I disagree with the authors has, during early mornings, the night inversion is usually still presents and provides some stability to the atmosphere. In addition, the sun energy inputs is much smaller than at midday which therefore limits the surface heating. I believe that the authors try to justify here their choice of a rather wide plume (observations) which can only be reproduced by the Gaussian model with a very unstable parameter. This is, I believe, another argument to keep the plume width (i.e. a) as a free parameter in the inversion.*

Authors: Our explanation was not very precise but we believe that with respect to the flue gas the atmosphere is essentially unstable. This can partly be attributed to the higher temperature of the exhaust fumes compared to the atmosphere and is further supported by the fact that turbulences were present at 1.0 km altitude as was stated in the manuscript. Eventually, this is now also confirmed by the retrieval of the stability parameter. We will change the respective paragraph as follows:
"The measurements over the two power plants were performed in summer in the morning under almost cloud free conditions and hence strong solar insulation. Additionally, the flue gas containing the CO_2 is considerably warmer than the surrounding air masses leading to observed turbulences in up to 1.0 km altitude. Consequently for the inversion, the a priori atmospheric stability was set to very unstable (Stability class A), i.e. $a = 213.0$ with an uncertainty of $\pm$100.0."

Referee: *In addition to Figure 3, it would be most useful to show a cross-section (along black lines) of the measurements and models. I understand the model would be a Gaussian shape along the flight track and would like to see how the measurements get distributed. Please add a figure.*

Authors: The mentioned figures have been produced for both power plants (see below) and will be appended to the revised version of the manuscript. They show a rather good agreement between model and data, confirming a good fit quality.

Referee: *I am rather surprised that the authors estimate the uncertainty on the wind speed based on its reported bias. I am aware of many variables which are known with essentialy no biases but rather large uncertainties (ie uncertainties much larger than biases). Please justify the choice.*

Authors: The difficulty with the wind uncertainty is that the error estimate we would need is not available as such. That would be the error between model and data at the respective location for the respective time. However, in the meantime we collaborated with the DWD (German Weather Service) to obtain an estimate for bias and root mean square error (rmse) for the morning of July 27 compared to the Lindenberg observatory wind profiler data which is close to the power plant sites. The rmse error turned out to be $\approx 0.9\, ms^{-1}$ while the bias is close to zero. We now used this rmse error for the error estimation (see Table 12 below).

Referee: *The section on aerosol impact on the measurement (p 2237-2238) is rather long and could be very much reduced.*

Authors: We skipped the 2nd to 4th paragraph to shorten the respective chapter.

Referee: *Other minor comments (mostly typos) are given below. I strongly recommend that the author use a spelling/grammar corrector. In fact, they should have done so before submission... Abstract : "reliable estimates" should be more quantitative P2211, L28: sampling, not samling P2213,L18: Description of instrument FOV is not clear P2218, L11: topographic P2220, L8 to the fact that... (no comma) P2224, L17: "decent" does not seem appropriate here P2229, L4: inhomogeneity P2236, L22: sophisticated*

Authors: The revised manuscript has been checked with a spell checker and the typos have been corrected. Additionally, it has been proof read by two native speakers. In the abstract we state now:
"Both methods – the Gaussian plume model fit and the Gaussian integral method – are capable of delivering estimates for strong point source emission rates that are within ±10% of the reported values, given appropriate flight patterns and detailed knowledge of wind conditions."
Regarding the field of view (FOV) description: The instantaneous FOV is $1.34° \times 0.02°$, so the along track dimension of the resulting FOV is determined by ground speed and exposure time, i.e. the distance which is covered during the time of exposure by the instantaneous FOV. For the revised manuscript, we will modify the corresponding paragraph as follows:
"The instantaneous field of view (IFOV) of the SWIR spectrometer is about $1.34° \times 0.02°$ (cross track × along track). For an exposure time of $\sim 0.6\,s$, a typical aircraft altitude of about $1.25\,km$ and $200\,km\,h^{-1}$ ground speed, this

results in a ground pixel size of about 29 m × 33 m, where the along track extension is primarily determined by ground speed and exposure time."

References

Beychok, M. R.: Fundamentals of Stack Gas Dispersion, Milton R. Beychok, 4th edn., 2005.

Table 10. Emission rate results for the power plants Jänschwalde and Schwarze Pumpe using the Gaussian plume model and the Gaussian integral inversion methods. For the Gaussian plume model, the result for the retrieved stability parameter a and the statistical errors according to Eq. (21) are also given.

	Reported emissions	Plume Inversion				Integral Inversion	
Power plant	[$Mt\,CO_2\,yr^{-1}$]	absolute [$Mt\,CO_2\,yr^{-1}$]	relative to reported [−]	# pixels used for inversion	stability parameter [-]	absolute [$Mt\,CO_2\,yr^{-1}$]	relative to reported [−]
Jänschwalde	24.125	26.131 ±1.838	1.083 ±7.03%	174	327.4 ±10.2%	24.066	0.998
Schwarze Pumpe	13.035	11.865 ±1.473	0.910 ±12.41%	209	357.3 ±13.6%	11.748	0.901

Table 12. Overall uncertainty on the final emission rate estimates for the power plants Jänschwalde (JW) and Schwarze Pumpe (SP). Note that Schwarze Pumpe has a higher assumed uncertainty on the wind direction (±10°) due to nonstationary conditions.

	Uncertainty on emission rate [%]			
	Plume Inversion		Gaussian integral	
Parameter	JW	SP	JW	SP
Statistical error	7.0	12.4	*	*
Wind speed ($\pm0.9\,m\,s^{-1}$)	20.0	27.3	20.0	27.3
Wind direction ($\pm5°$ resp. $\pm10°$)	5.3	4.7	9.1	4.8
Aerosol	0.4	*	0.3	*
Conversion factor k	1.3	*	0.9	*
Flight pattern (can be accounted for)	–	–	−17.7	−3.1

* according values not determined

– parameter not important for method

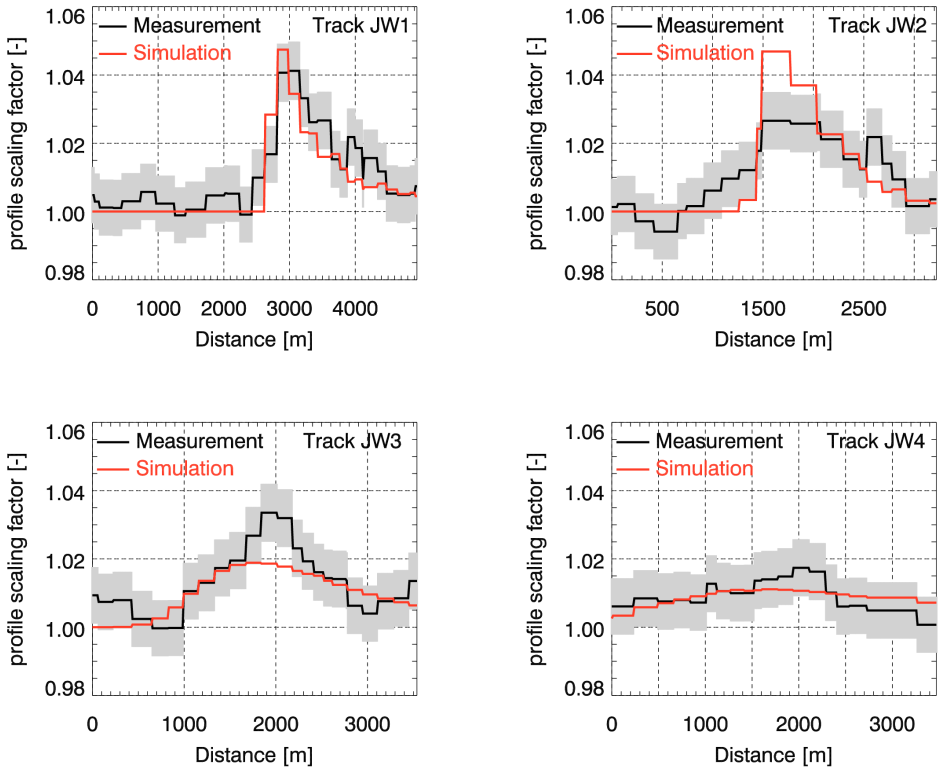

Figure 1: The figure shows model data (red) computed from the inversion result for the Gaussian plume model and measurements (black) in case of Jänschwalde power plant along horizontal cross sections through the CO_2 plume. Statistical errors are shown in grey.

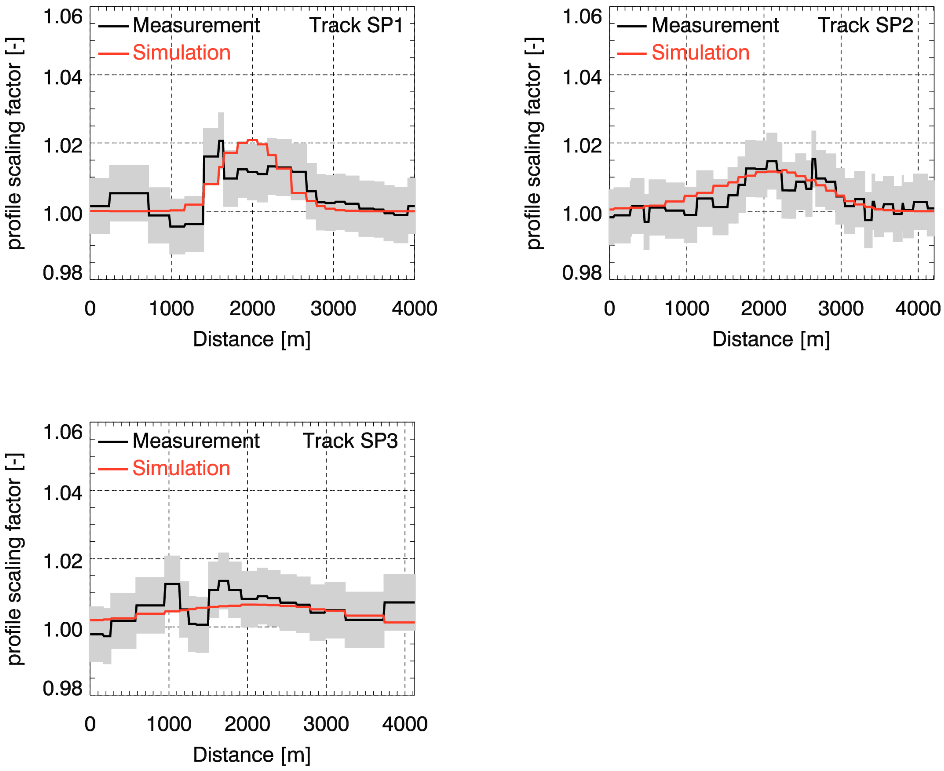

Figure 2: The figure shows model data (red) computed from the Gaussian plume inversion and measurements (black) in case of Schwarze Pumpe power plant along horizontal cross sections through the CO_2 plume. Statistical errors are shown in grey.