Author comment: We would like to thank reviewer #2 for the positive assessment of our manuscript and the very constructive comments. We followed them as described in detail below. In the following, the reviewer's comments will be in normal typeface, our responses in italic and bold typeface.

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Referee comment: General impression:

The authors present a new method to derive two dimensional NO2 distribution maps based on the data of the APEX imaging spectrometer. The data are very interesting and demonstrate very well the possibilities offered by this instrument. However, up to now the APEX instrument is not that well known in the context of the DOAS retrievals and trace gas distribution measurements, therefore it would be good to give some more details on the description of the instrument although this is clearly not the focus of the paper. The APEX spectra were originally not intended to be used for DOAS analysis. Therefore the spectral sampling interval and the spectral resolution are not ideal for DOAS retrieval, with a spectral resolution of roughly 1.3 pixels the DOAS retrieval is at high risk of under sampling. This seems to be either unclear to the authors (hard to believe) or they knew about the problem and solved it. However this point is completely ignored in the discussion of the data and the retrieval. Please add short paragraph on this topic.

Answer: We will provide some additional information about the instrument and the flight campaign in different sections in the revised version of the manuscript (c.f. also answers to the next Referee comments below for more details).

We agree with Referee #2 that the spectral characteristics of the instrument are far from ideal for DOAS retrieval of NO2. The theoretical spectral undersampling from the pre-flight specifications is around 1.3-1.5. However, the QDOAS spectral calibration suggested that the in-flight FWHM is about twice as large as specified during the ground calibration so that the spectral resolution increases to more than 2.6 pixels which reduces problems associated with spectral undersampling. For the sake of verification, we also tested integrating an undersampling cross section in the DOAS retrieval without any sizeable improvement of the fit quality.

We'll add a sentence discussing this point in Sec. 3.1. as follows:

"It is noteworthy that this increase in FWHM on the other hand reduces problems associated with spectral undersampling expected for the better spectral resolution defined in the pre-flight specification."

Please also note that we erroneously provided preliminary and outdated FWHM values (page 2453 and line 2). The values from the latest calibration of the unbinned configuration at the CHB before the overflights (2009) revealed a FWHM between 1.00 (at 420 nm) and 1.95 (at 520

nm). With regard to our fitting interval, the SSI and FWHM are 1.00 and 1.45 (at 470 nm) and 1.31 and 1.81 (at 510 nm), respectively. This is corrected in the revised manuscript.

Referee comment: Specific comments

2.2 Test side and data

Referee comment P2453 L13 Is there any reference concerning the APEX acceptance flight campaign. Please give some details on the campaign, e.g. used aeroplane, flight altitude,. . . In the current version of this sections it seems this campaign should be known to everyone and the APEX is flying by itself.

Answer:

We extend the first paragraph of section 2.2 as follows:

"APEX acceptance flight activities took place in Belgium and Switzerland in June/July 2010 using a Dornier DO-228 aircraft operated by the German Aerospace Center (DLR) (Jehle et al. 2010). Image data were collected in more than 42 flight hours for a variety of studies of the land-surface and the atmosphere and six of these image data sets, acquired in unbinned mode over Zurich, Switzerland, on Saturday 26 June under cloud free conditions (c.f. Fig. 1) were used in this study. Three of them were flown around 10:00 local time (08:00 UTC) and three in the late afternoon around 17:30 local time (15:30 UTC) at a cruise level of 5400m above sea level (asl) and a flight heading of 45° and 225°, respectively."

Referee comment P2453 L15-20 The instrument was operated with a fixed integration time, is it possible to adapt the integration time? Why was this integration time used? The spectra in figure 2 look quite dark for large parts of the spectrum. For future mission I suggest sacrificing parts of the spectrum (with wavelength higher than 700 nm) and getting better spectra in the interesting interval.

Answer:

We add the following in sec 2.2 of the revised manuscript:

"The data integration time of the APEX can be adjusted. The definition of an adequate integration time for the unbinned mode is, however, critical because the incoming radiation in the unbinned bands is comparatively small. An integration time of 57ms was found to be a reasonable compromise between radiometric performance and the resulting pixel size of 2.5m across-track and approximately 6m along-track, respectively. This setting, in particular, ensures a sufficient signal stability in these spectral bands (i.e., the visible part from 370-500nm) and avoids signal saturation in other parts of the sampled spectrum (e.g., near infrared (NIR) from 700nm onwards)."

And the following in the conclusions of the revised manuscript:

"Based on the findings of this study, an adjustment of the APEX data acquisition mode is proposed for NO_2 retrieval applications to optimize SNR in the VIS spectral region, e.g., by increasing the data integration time. Enhanced pixel sizes along-track as a consequence of longer integration times were found to be less critical for this application. On the other hand a longer integration time will potentially lead to signal saturation in the NIR spectral region which may cause problems for the detector read-out and the smearing correction. Specific NIR filters might be used to compensate this effect."

3.1 DOAS analysis

Referee comment P2456 L5-12 The section concerning the reference spectra is unclear, please try to explain differently. According to the figures you used one reference per over flight. Did you try to use one for all 3 flights? Does this help to reduce the difference between individual over flights. See also general comment concerning under sampling.

Answer: We use one reference spectrum per flight column. In other words, for each of the six over-flights, we obtained 50 reference spectra from the areas highlighted in Fig. 7.We found that individual reference spectra for each column leads to better NO_2 fits because this minimizes spectral differences between the reference and measured spectrum, e.g. due to spectral smile. We clarified these sentences as follows:

"Reference spectra were selected for each individual column (along-track) of each overflight separately. This results in 50 different reference spectra per overflight and allows minimizing errors in the DOAS analysis caused by spectral miss-calibration (e.g. spectral smile) and optical imaging imperfections. Based on visual inspection, areas in the individual overflights were determined which are assumed to only contain a background abundance of NO_2 (pollution free), c.f. in the forested and elevated area to the south of the city (c.f. Fig. 7a). The reference spectr obtained in the highlighted areas span over ten rows (across-track) and were additionally averaged in the columnar direction to increase the SNR."

4.1 SCD analysis

Referee comment P2460 L15 The authors seem to expect the dSCD to resemble a Gaussian distribution. Why should that be the case for the NO2 dSCD over Zurich or any other city?

Answer: We agree with Referee #2 that a Gaussian distribution is not to be expected and therefore removed this sentence.

4.2 NO2 spatial distribution

Referee comment P2462 L5 Without going into details of the model, but does this model have a weekly cycle included? So it should be possible to retrieve a typical Saturday NO2 distribution.

Answer: This simple model uses annual wind statistics to calculate a representative dispersion and therefore only provides annual mean NO_2 concentrations at the surface. Therefore, it is also not possible to compare the APEX NO_2 VCD to a typical Saturday situation.

4.3 examples of source identification

Referee comment P2464 L27,28 There was northerly wind on this day, hence the planes most probably came in from the south and took of towards the north. Does this affect your data? Please zoom in a bit more on the waste incinerator. The background NO2 is quite high and the variability also, so the plume is hard to detect in the picture (11d-e). Did you try to estimate the source strength? This should not change during the course of the day, hence morning and afternoon flights should be comparable.

Answer: According to the detailed monthly noise bulletin for June 2010 published by the airport authorities, planes took-off towards the south (http://www.flughafen-zuerich.ch/Portaldata/2/Resources/documents_unternehmen/umwelt_und_laerm/laermbulletin/1006_Laermbulletin_Juni.pdf) in the morning of 26 June 2010. Aircrafts usually emit more NOx during take-off than during landing/approaching/taxiing which might be reflected in the retrieved NO_2 distribution which reveals higher NO_2 VCD at the end of the runway used for take-off during that day. We will add the following sentence in the revised manuscript (sec 4.3.):

"Aircraft took-off towards the south on 26 June 2010 (c.f. http://www.flughafen-zuerich.ch/Portaldata/2/Resources/documents_unternehmen/umwelt_und_laerm/laermbulletin/1006_Laermbulletin_Juni.pdf). The enhanced NO_2 VCD at the end of the north-south runway thus likely reflects the increased NO_X emissions by aircraft during take-off."

The white and red area corresponds to the (already slightly diluted) plume of the waste incinerator. We will point this out more clearly in the corresponding figure caption. We have made no attempts to estimate the source strength of the waste incinerator. The main reason for this is the unknown and strongly varying wind speed at the time of the morning overpass which makes it very difficult to characterize the flow speed and dispersion of the plume required for flux estimates. Unfortunately, no obvious plume is detectable in the afternoon data which is likely due to strong dilution as a result of the much larger wind speed in the afternoon.

4.4 Comparison to ground based measurements

Referee comment P 2465 L 25 To calculate the AMF the authors assumed a certain NO2 profile, thereby the VCD might be used to calculate the ground based concentration, however this would not change the regression as the it adds a constant factor on the VCDs. On the other hand it should at least be in a similar range.

Answer: We considered this point the "other way round": we can use the assumed a priori NO2 profile to calculate an "in situ NO2 VCD" which allows comparing two identical quantities:

in situ VCD = a priori VCD * NO2 surf meas/NO2 surf model

Where "a priori VCD" is the total of the sub-columns from the a priori from the ground to the flight altitude, "NO2 surf meas" the concentration measured at the ground and "NO2 surf model" the concentration of the lowest model layer. In the revised manuscript, we will replace and discuss Fig. 12 with the new scatter plot shown below (Fig. 1).

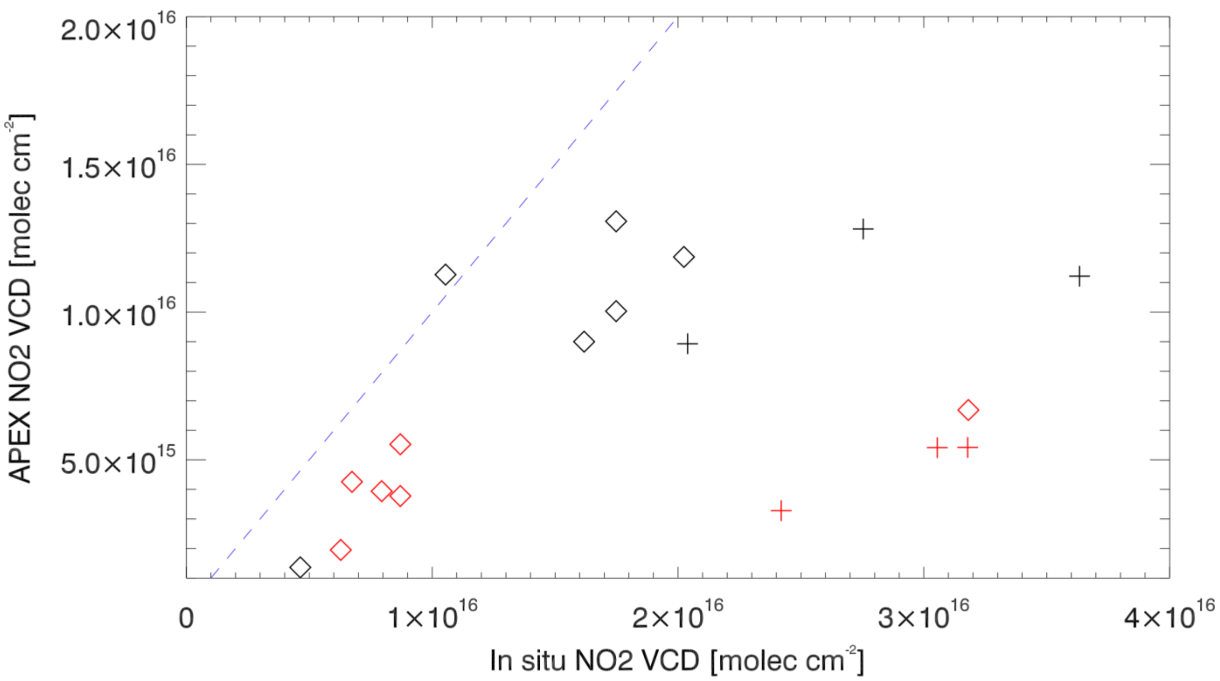

Figure 1: Scatter plot between in situ derived NO_2 VCD and APEX retrieved NO_2 VCD for the morning (black symbols) and afternoon (red symbols) overpasses. Crosses denote in situ sites next to a road. The 1:1 line is plotted as the dotted blue line.

We change Sec 4.4. as follows:

"4.4 Comparison to ground-based measurements

The APEX derived NO2 VCD are subsequently compared to the ground-based in-situ measurements. Such a comparison is not straightforward since APEX NO2 VCD is a columnar product (in molec cm−2) while the in-situ measurements represent a trace gas concentration at a single point (in µgm−3). Therefore, we convert the in situ measured concentrations to an "in situ VCD" assuming that the a priori NO2 profile correctly described the true NO2 profile:

in situ VCD = a priori VCD * NO2 surf meas/NO2 surf a priori

Where "a priori VCD" is the total of the sub-columns of the a priori NO2 profile from the ground to the flight altitude, "NO2 surf meas" the concentration measured at the ground and "NO2 surf a priori" the concentration of the a priori profile in the lowest layer.

The comparison is shown in Fig. XX where the APEX retrieved NO2 VCD are plotted as a function of the in-situ derived VCD at the eight NABEL and Ostluft sites. The Pearson correlation coefficient for the morning and afternoon results separately are almost identical (R =0.61) suggesting that the variability between the in situ sites corresponds to some extent to the spatial pattern observed by APEX. When disregarding the match-ups corresponding to the in situ sites located at kerbsides (cross symbols) a rather good agreement is found and the APEX derived NO_2 VCD are in a similar range as the in situ VCD, and the morning and afternoon results fit well. However, almost all match-ups are located below the 1:1 line suggesting that the a priori NO_2 profile is not perfectly suitable to convert the in situ measurements to a columnar quantity. This is particularly true for the sites Opfikon, Stampfenbach, and Schimmelstrasse located directly at a road where the true atmospheric NO_2 profile is probably much more strongly peaked at the surface than the a priori profile leading to a strong overestimation of the NO2 VCD constructed from the in situ data . This further underlines the need for accurate vertical profile information, e.g. by flying vertical NO_2 and aerosol profiles with complementary in situ instrumentation."

The correlation coefficients described here will also be adjusted in the abstract and the conclusions of the revised manuscipt.

Figures

Referee comment Figures 9 and 10 Both figures show time series of some independent measurements. However two different time scales are used, this is a bit inconvenient for the readers.

Answer: In order to show the trend of the meteorological variables (wind speed and direction) during that day, we also plotted the night time data in Fig. 10 to point out the rather calm conditions previous to the first flights. The two time slots of the overflights are plotted in these two figures for the reader's convenience.

Referee comment Figure 11 Zoom in a bit more in the pictures d) and e).

Answer: We will make sure that the figure will be displayed sufficiently large in the final version.

References:

Jehle, M., Hueni, A., Damm, A., D' Odorico, P., Kneubühler, M., Schläpfer, D., and Schaepman, M. E.: APEX – current status, performance and product generation. Proc. IEEE Sensors 2010 Conference,Waikoloa, Hawaii (USA),1–4 November 2010, 553-537, doi: 10.1109/ICSENS.2010.5690122, 2010.