Strong spatial variability of NO_2 over polluted areas and within emission plumes observed by aircraft imaging DOAS

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1. Introduction

AirMAP: Airborne imaging DOAS Measurements of Atmospheric Pollution

Instrument developed at IUP Bremen in 2011

Flight campaigns in June 2011 (AWI Polar-5) and August 2013 (FU Berlin Cessna)

Objectives

- Tropospheric trace gas measurements at good spatial resolution and coverage
- NO_2 mapping, identification of pollution source regions and source strengths
- Detailed investigation of spatial variability of NO_2 column amounts

Advantages of IUP imaging DOAS instrument AirMAP

- High spatial resolution ~100 m (down to <30 m) at useful spatial coverage
- Many viewing directions observed at the same time within broad stripe below aircraft
- Full coverage with no data gaps independent of flight altitude

2011: AWI-Polar 5 (Basler BT-67 / DC3)
Owner/Operator: AWI Bremerhaven, Germany / Kenn Borek Air Ltd. Canada
Speed: typ. ~60 m/s
Operating height: 500–1500m

2013: FUB Cessna 207 Turbo (D-EAFU)
Owner/Operator: Free University of Berlin, Germany
Speed: typ. 50-60 m/s
Operating height: 800–1500m

2. Instrumental setup and viewing geometry

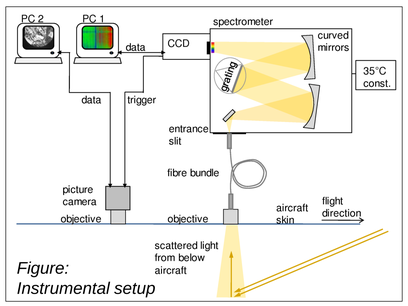


Figure: Instrumental setup

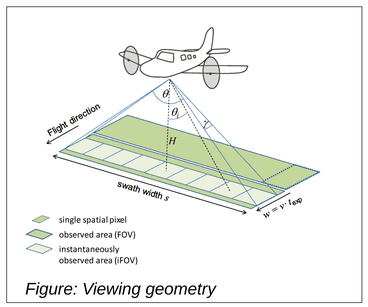


Figure: Viewing geometry

- Optics: Wide angle objective and sorted glass fibre bundle (35 fibres)
- Two nadir ports: spectrometer objective and picture camera
- Spectral window: 412 - 453nm; at 0.5-1.0nm resolution
- Detector: Frame transfer (FT) CCD detector, 512x512 pixels, 8.2x8.2 mm² chip size
- Field of view: ~48° across track (θ), ~1.5° along track (γ)
- Swath width: on the order of the flight altitude H
- Viewing directions: max. 35 individual LOS (line of sight)
- Averaging across track: combining fibres to typ. 9 LOS (θ_i)
- Exposure time t_{exp}: 0.5 s
- Flight speed: typ. 60 m/s
- Spatial resolution (for 9 combined viewing directions): <100m across track (at ~1km flight altitude), ~ 30 m along track
- Positioning information: GPS and gyrometer for correct geolocation

→ Gap-free measurements along and across flight direction

3. NO_2 vertical columns downwind of a power plant

Retrieval Method: DOAS

Differential **O**ptical **A**bsorption **S**pectroscopy
Fitting window: 425 – 450 nm
Reference: from rural scene nearby for each individual viewing direction

Power Plant

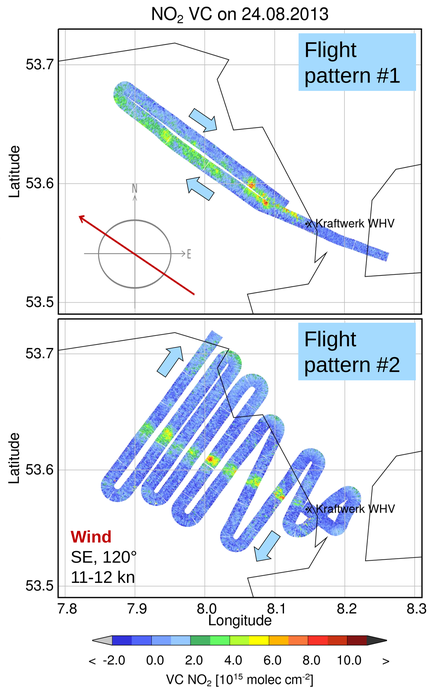
Location: Wilhelmshaven (53.57°N, 8.15°E)
Emission of NO_x/NO_2: ~2 kt/a (http://prtr.ec.europa.eu)

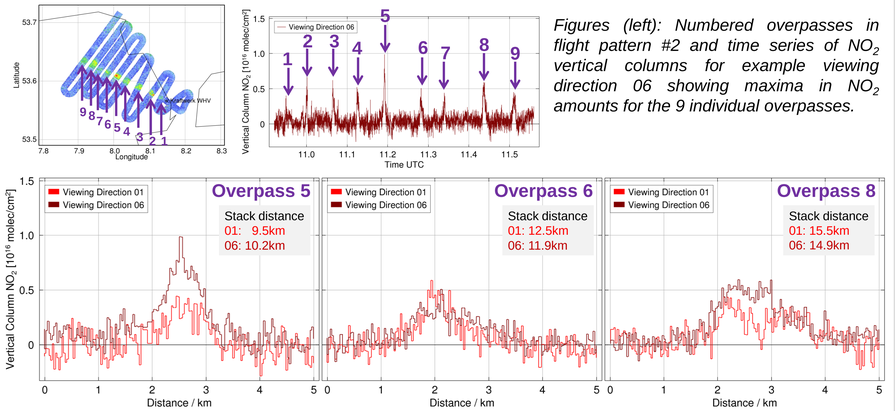
Observations of the NO_2 emission plume

NO is emitted from the power plant and is subsequently converted to NO_2.
Flight pattern #1: along the plume and back
Flight pattern #2: crossing the plume several times at different distances from the stack

Spatial distribution of NO_2 (Figures right)

- NO_2 enhancement downwind of the power plant stack clearly visible
- Localised NO_2 vertical column maxima reach up to $1{\cdot}10^{16}$ molec/cm²
- Distribution is strongly inhomogeneous and differs from a Gaussian plume (including bubble-like structures)





Figures (left): Numbered overpasses in flight pattern #2 and time series of NO_2 vertical columns for example viewing direction 06 showing maxima in NO_2 amounts for the 9 individual overpasses.

Figure (above): Plume cross sections of the NO_2 vertical column from flight pattern #2 for viewing directions 01 and 06, at three overpass locations, overpass 5 (left), 6 (middle) and 8 (right). The distance on the horizontal axis is the track length along flight direction, i.e. across the plume, with individual zero points for each overpass.

- Large differences in integral NO_2 amounts are observed between the viewing directions, i.e. for only slightly different distances from the exhaust stack (see insets in figures)
- With increasing distance from the stack (overpass 5 to 8), the plume slightly broadens
- Overpass 6 shows much less NO_2 than overpass 5, although further away from the stack, while generally, conversion from NO to NO_2 leads to an increase of NO_2 with time and distance
- Emission flux estimates calculated from these measurements are strongly variable (by factor 3)

4. NO_2 above inhabited and rural areas

Flight over parts of Berlin, 16.08.2013

- including inhabited and rural areas as well as a power plant and a three-leg motorway interchange

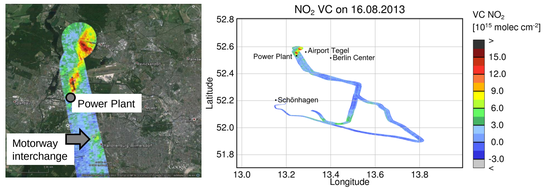


Figure: Strong variations of NO_2 amounts over Berlin and surroundings. Largest amounts are caused by power plant emissions, smaller scale NO_2 variations are also visible, e.g. around a motorway interchange and some industrial areas. NO_2 amounts in rural areas as well as above parts within Berlin City are substantially lower.

Flight over Northern Germany, 09.06.2011

- including cities and remote areas

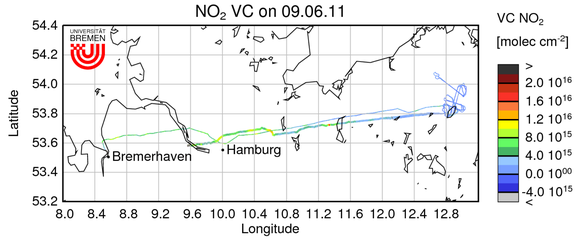


Figure: NO_2 amounts measured during a flight across Northern Germany with larger and strongly variable NO_2 amounts around $1{\cdot}10^{16}$ molec/cm² above and close to cites such as Hamburg, and consistently low values above remote, clean areas towards the East.

Flight detail for German motorway, 04.06.2011

- Flight along motorway A1 at high resolution with 35 LOS
- Each individual pixel size is 40m x 45m across x along track

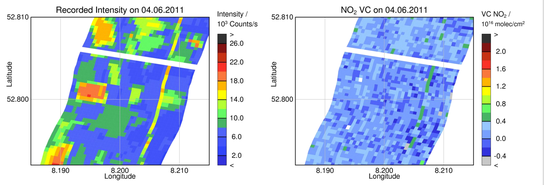


Figure: Measurement details from above motorway A1 showing the recorded intensity (left) and the NO_2 amount (right). The intensity is enhanced above the motorway and even more above bright fields west of the road. NO_2 amounts are slightly enhanced only above the motorway at $(5\pm2){\cdot}10^{15}$ molec/cm².

5. Summary & Outlook

- NO_2 vertical column amounts have been observed from aircraft above different regions, including power plants, cities, motorways as well as remote and unpolluted areas at good spatial resolution (down to 30-40m).
- Imaging capabilities of AirMAP allow detailed observations of small scale pollution sources and emission plumes.
- In all cases, strong spatial variability and gradients of NO_2 column amounts are observed.
- The spatial NO_2 distribution in power plant emission plumes is strongly non-uniform and variable.
- Instead of gradually increasing along the plume, NO_2 is often confined in bubble-like structures.
- The observations have implications for the importance of emission sources and downwind chemistry, because localised amounts of NO_2 lead to different effects than a smoothly averaged distribution.
- Possible reasons for non-uniform distributions and plume evolution include source variability, chemical transformations and local meteorology.
- Further analysis of the NO_2 variability and plume structures will include dynamics and plume chemistry.

Acknowledgements

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see also: www.iup.uni-bremen.de/doas

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