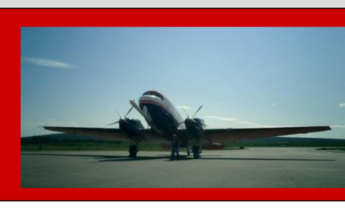
High resolution measurements of NO_2 by aircraft imaging DOAS



DOAS-WS
August 2013
Boulder, CO

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1. Introduction

Objectives of aircraft imaging DOAS measurements:

- Retrieval of tropospheric trace gases, here nitrogen dioxide NO_2
- Mapping of NO_2 pollution sources, identification of source regions and strengths
- Satellite data validation, investigation of sub-pixel variability

Positive aspects of aircraft measurements and imaging DOAS

- High spatial resolution ~100 m (down to ~30 m) at useful spatial coverage
- Several viewing directions across track are observed simultaneously
- No data gaps occur along track

The iDOAS instrument in the Polar-5 aircraft

Aircraft Type:	Basler BT-67 / DC3
Length/Height/Span:	21 m / 5.2 m / 29 m
Speed & Altitude:	50-105 m/s; 100-19000 ft
Owner & Operator:	AWI, Germany; Kenn Borek Air Ltd. Canada

Photographs: (top) iDOAS installed in the Polar-5 aircraft (bottom) Polar-5 in the hangar at Bremerhaven regional airport

2. Instrumental setup and viewing geometry

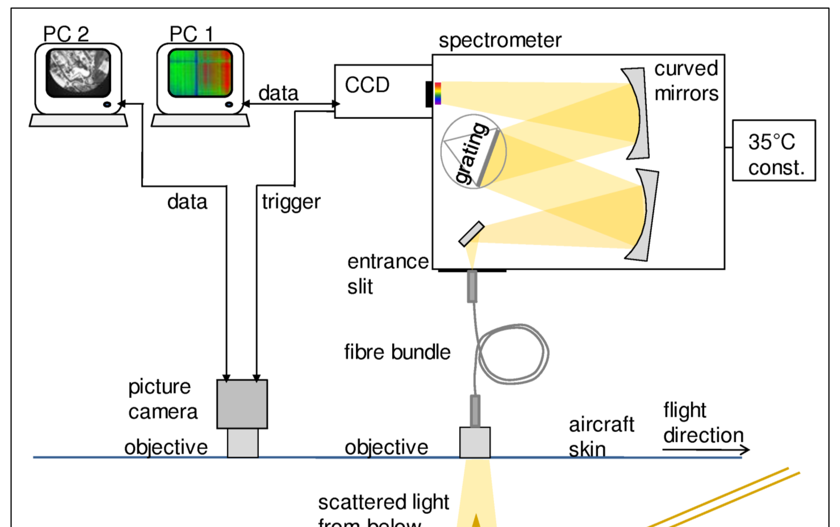


Fig. 1: Instrumental setup

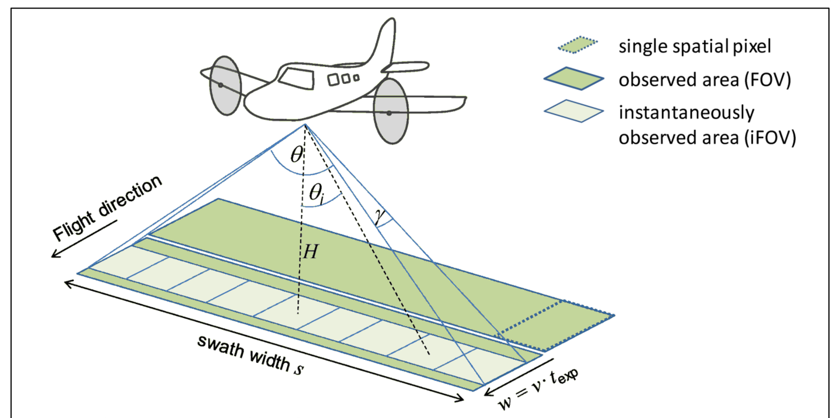


Fig. 2: The iDOAS viewing geometry

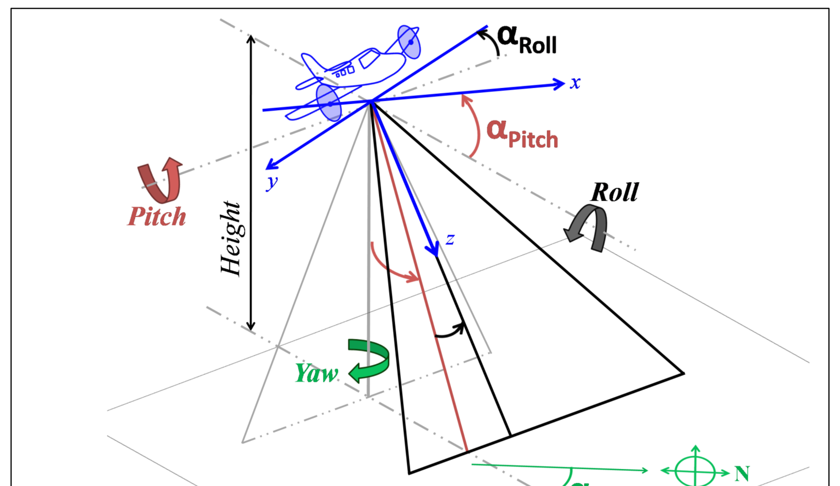


Fig. 3: How the aircraft angles affect the ground pixel location

Technical information

- Wide angle objective and fibre bundle (35 fibres) as entrance optics
- Acton 300i imaging spectrometer
- Grating 600l/mm, blazed @500nm
- Spectral window 412 - 453nm
- Spectral resolution 0.7 - 1.0nm
- Frame transfer (FT) CCD Detector, 512x512 pixels, 8.2x8.2 mm²

→Gap-free measurements (due to FT CCD) and flexible positioning in aircraft (due to sorted fibre bundle)

Viewing geometry

- 2 nadir ports: spectrometer & camera
- Geolocation: from GPS & gyrometer
- Viewing directions: max. 35 (typ. 9) lines of sight, (LOS, θ_i) from 35 fibres
- Field of view: ~48° across track (θ)
- Swath width: ~order of flight altitude H
- Exposure time t_{exp}: typ. 0.5s
- Spatial resolution: 30m … 100m

Computation of ground pixel location

- Consideration of the aircraft angles (pitch, roll and yaw) is required in addition to GPS position for correct determination of the geolocation
- Displacements of the ground pixel due to aircraft motions can be significant

3. Imaging quality and NO_2 retrieval quality

Demonstration of imaging quality

The imaging quality is investigated by the recorded intensity on the spectrometer CCD image. Differently bright ground scenes are distinguished.

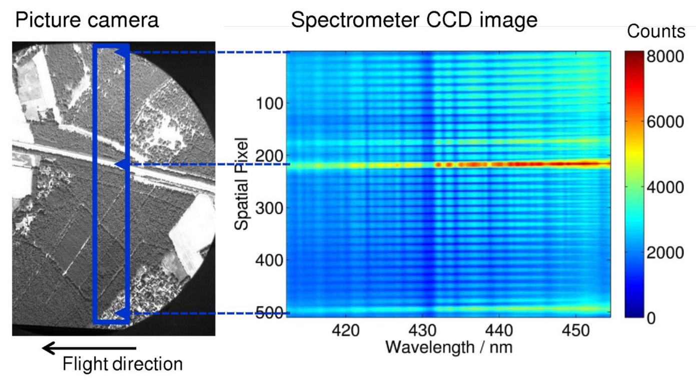


Fig. 4: The blue box (left) marks the field of view of the spectrometer. Bright scenes such as roads are identified by higher intensity in single glass fibres, i.e. single LOS, on the CCD (right).

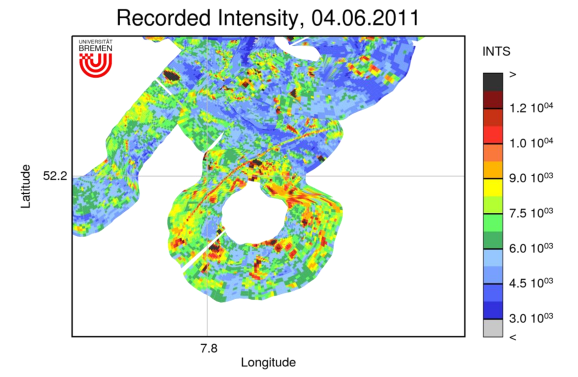


Fig. 5: Taking into account the aircraft angles (Fig. 3), imaging is also successful during tight curves, and streets are mapped continuously and in the correct location.

Retrieval Settings for NO_2 columns

Fitting window: 425 – 450 nm

Trace gases:

NO_2 (293K), O_3 (241K), O_4 (296K), H_2O (HITRAN)

Atmospheric effects:

Ring (SCIATRAN calculated), intensity offset

Polynomial: quadratic

Reference I_0: rural scene from same LOS

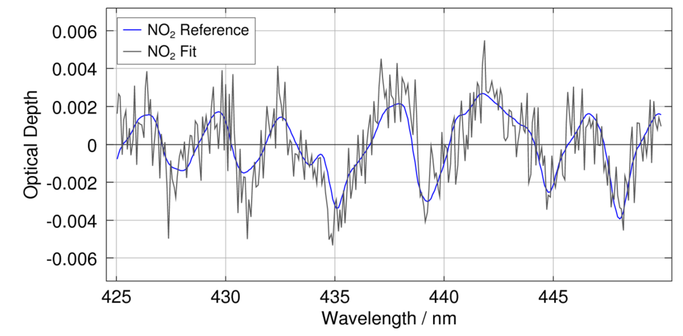
Slit function: individual for each LOS

Detection Limit for NO_2

NO_2 detection limit on the order of $3\cdot10^{15}$ molec/cm²

Optical density RMS: on the order of 10^{-3} for a single measurement of 0.5s and an individual LOS.

Fig. 6: Example retrieval result from 04.06.11 at 10:11:47 UT for the central viewing direction from division into 9 LOS. The scaled NO_2 cross section (blue) and the NO_2 fit (black) are shown.



Example retrieval result:

Slant Column: $SC(NO_2) = (4.0\pm0.1) \times 10^{16}$ molecules/cm²

Vertical Column: $VC(NO_2) = (1.8\pm0.1) \times 10^{16}$ molecules/cm²

Residual RMS: $RMS_{res} = 1.5 \times 10^{-3}$ (optical depth)

The stated error here is the fitting uncertainty.

Detection limit using $2 \times RMS_{res}$ as criterion:

$VC_{lim} = 3.6 \times 10^{15}$ molec/cm²

(for SZA = 40°, 5% ground reflectance, 1km NO_2 box profile)

4. NO_2 vertical columns and emission flux calculations above a power plant

NO_2 retrieval above a power plant

- Black coal power plant (848 MW) at Ibbenbüren, Germany (52°17'N, 7°45'E)
- Slant columns of NO_2 retrieved by Differential Optical Absorption Spectroscopy
- Large variability of NO_2 amounts across and along track is observed
- The NO_2 in the exhaust plume downwind of the power plant is clearly visible
- Transects through the plume are used for emission flux estimations
- High resolution results with 35 LOS are consistent with the 9 LOS results

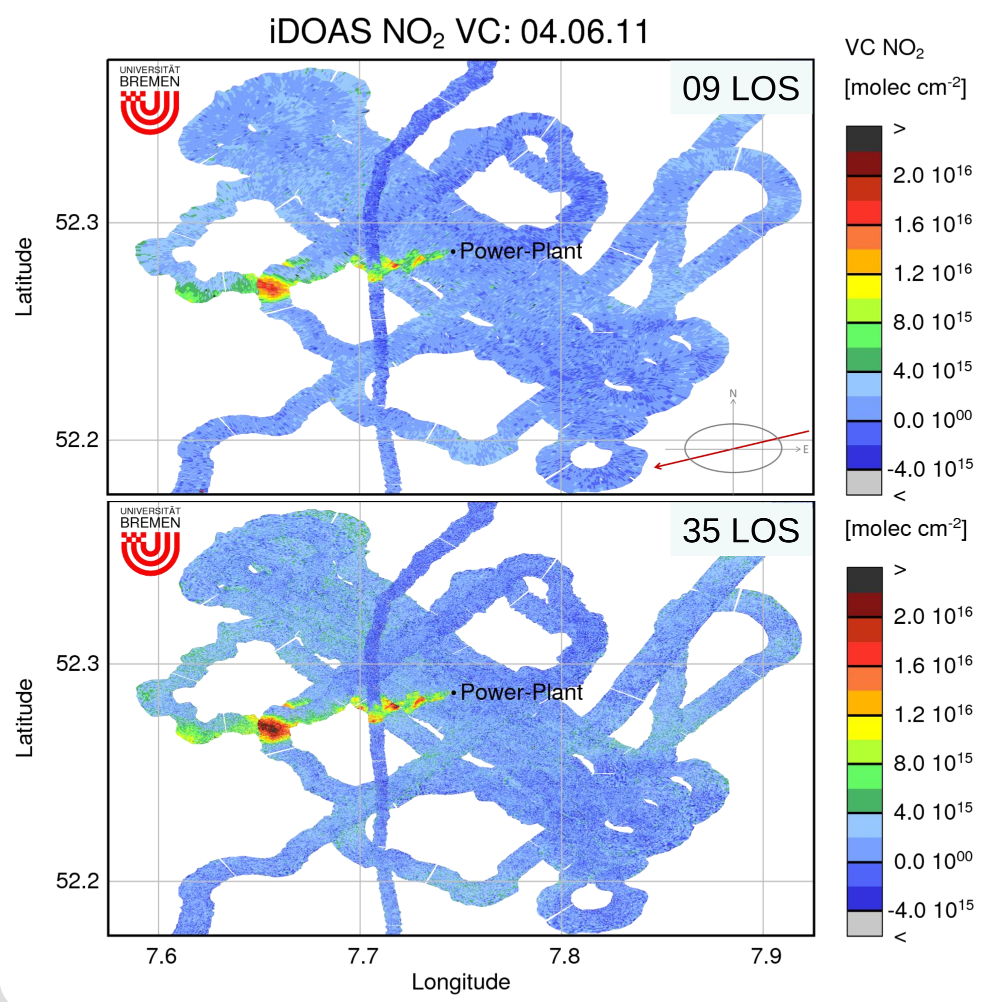


Fig. 7: NO_2 vertical column amounts along the flight track retrieved from the flight on 04.06.2011. Downwind from the power plant of Ibbenbüren, strong enhancement of NO_2 is visible. Average wind direction was about East North-East, see inset. Enhanced NO_2 is on the order of 10^{16} molec/cm² with maxima > $2\cdot10^{16}$ molec/cm². Top: Division of the field of view into 9 lines of sight (LOS) allowing spatial resolution of ~100m. Bottom: Consistent result for full spatial resolution of 35 LOS with ground pixel side length on the order of around 30m. Fine spatial variability of NO_2 amounts is resolved.

Air mass factors,

AMF (SCIATRAN calculations)

Rayleigh atmosphere, 1 km NO_2 box profile, 5% albedo, SZA and LOS dependence.

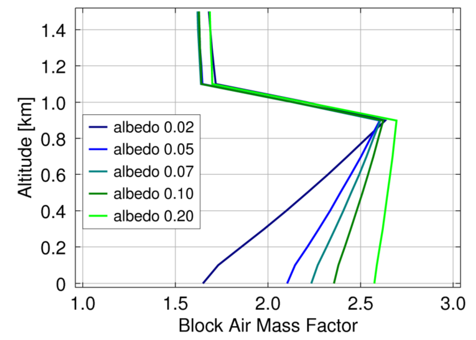
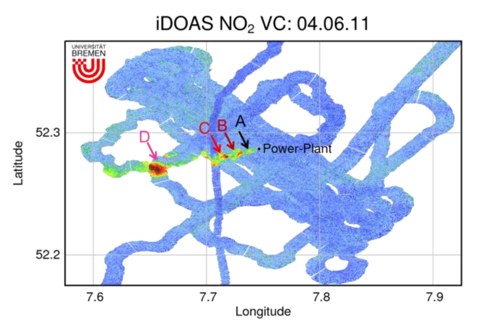


Fig.8: Block AMF for different albedos at 40° SZA and 1.1km flight altitude. AMF differences between box profile and elevated Gaussian plume: ~10%.

Fig. 9: Transect positions through exhaust plume at different distances from the stack around 10:00 UT used for emission calculations:



NO_2 emission flux calculations

- Based on Gaussian plume dispersion model
- Mean wind speed & direction determined using COSMO-DE model wind data and weighting by NO_2 profile (Gaussian shape, cp. Fig.10)
- Flux calculations are performed at different distances from the stack

$$c(x,y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

Eq. 1: Gaussian distribution of concentration c

Dispersion of concentration c across plume (y) and over altitude (z) is taken into account, with source strength Q, wind speed u and spread σ_y and σ_z. Along the wind direction x only advection is considered.

$$Q \cong \int_L VC\cdot\vec{u}\cdot d\vec{l} \approx \sum_i VC_i\cdot\vec{u}\cdot d\vec{l}_i$$

Eq. 2: Derived using Gaussian divergence theorem

Approximation of source strength is achieved via discrete summation over the product of vertical columns (VC), wind speed and path length dl.

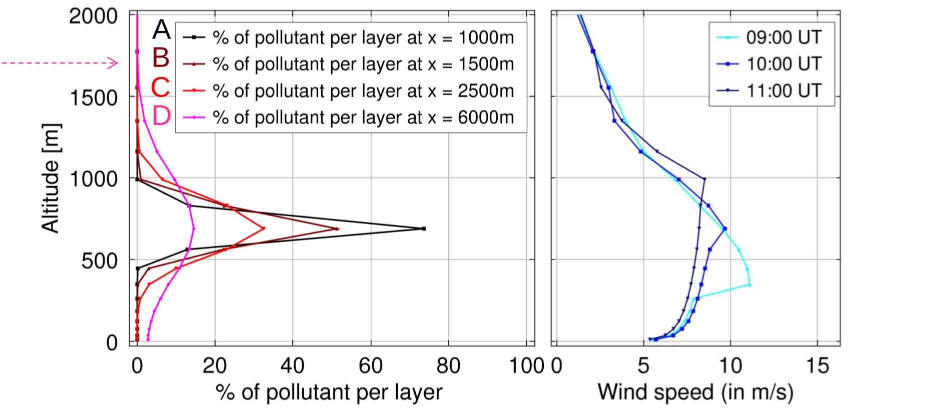


Fig. 10: Relative NO_2 altitude distribution inside the plume at four different distances from the stack (left) and wind speeds from the COSMO-DE model (right). NO_2 profiles are used as weighting factors to determine mean wind speed and direction.

→ Estimated NO_2 emissions: $Q_{NO2} \approx$ 2100-2400 T/a

→ Emissions of NO_x (using $NO/NO_2 \approx$ ¼) : $Q_{NOx} \approx$ 2600-3000 T/a

→ Results are in agreement with E-PRTR* (1910-3280 T/a in different years)

*European Pollutant Release and Transfer Register

5. Summary & Outlook

Summary

- The imaging DOAS instrument shows good imaging quality and good performance for NO_2 measurements
- Aircraft pitch, roll and yaw angles are fully taken into account for correct ground geolocation
- NO_2 column amounts have been retrieved, pollution sources are observed (power plant, cities, etc)
- For typical situations (geometry, albedo, SZA), spatial resolution of 30 m (along and across track) is achieved
- Further findings: Large spatial NO_2 variability and consistent NO_2 retrieval results for different LOS divisions
- NO_2 emission fluxes are calculated for a power plant point source in agreement with emission reports

Activities for the future

- Air mass factor consideration will be refined in future analyses
- Further dedicated campaigns will be conducted with the imaging DOAS instrument above pollution sources

Acknowledgements

The presented work is financially supported by the University of Bremen. Campaign support from AWI Bremerhaven, Martin Gehrmann and Franziska Nehring, is gratefully acknowledged. Thank you to the aircraft crew from Kenn Boreck, Canada. COSMO-DE model data is provided by the German weather service DWD. Radiative transfer calculations are performed with the IUP Bremen SCIATRAN model, thanks to V. Rozanov.

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