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# Tropospheric trace gas mapping by airborne imaging DOAS

**Anja Schönhardt*, P. Altube, A. Richter, S. Krautwurst, K. Gerilowski, and J. P. Burrows**
**Institute of Environmental Physics, University of Bremen, Germany**
***Email: anja.schoenhardt@iup.physik.uni-bremen.de**

## Objectives

**Objectives**: Measurements of tropospheric trace gases

→ $NO_2$ pollution mapping, identification of source regions and source strengths, satellite data validation, investigation of sub-pixel variability.

**Advantages of aircraft measurements and imaging DOAS**

- Higher spatial resolution ~100 m (down to <30 m) than satellite observations at useful spatial coverage
- Several viewing directions are observed at the same time, i.e. a broad stripe below the aircraft
- Less data is lost as cp. to scanning instruments, adjacent regions are viewed simultaneously

**History of the IUP Bremen iDOAS instrument:** development in 2011; laboratory measurements for optical characterisation; first test flights conducted during a flight campaign in summer 2011

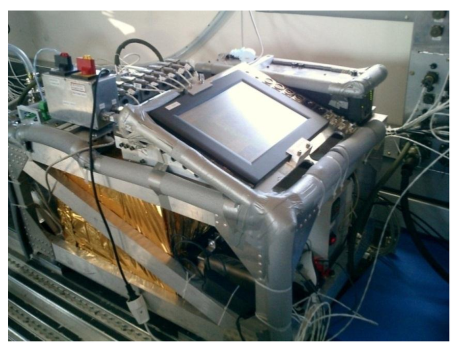
## iDOAS in the Polar-5 aircraft

**Polar-5**

Registration: C-GAWI, 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 |

*Polar-5 in Hangar at Bremerhaven Luneort airport*



*The IUP Bremen imaging DOAS instrument rack in the Polar-5 aircraft:*

## Instrumental setup and viewing geometry

**Technical information and special features**

- Wide angle objective and fibre bundle (35 fibres) as entrance optics
- Acton 300i imaging spectrometer, 600l/mm grating, blazed @500nm
- Spectral window 415 - 455nm; 0.7-1.0nm resolution
- Frame transfer (FT) CCD Detector, 512x512 pixels, 8.2x8.2 mm²

Instrumental setup allows gap-free measurements (due to FT CCD) and flexible positioning in aircraft (due to sorted fibre bundle).

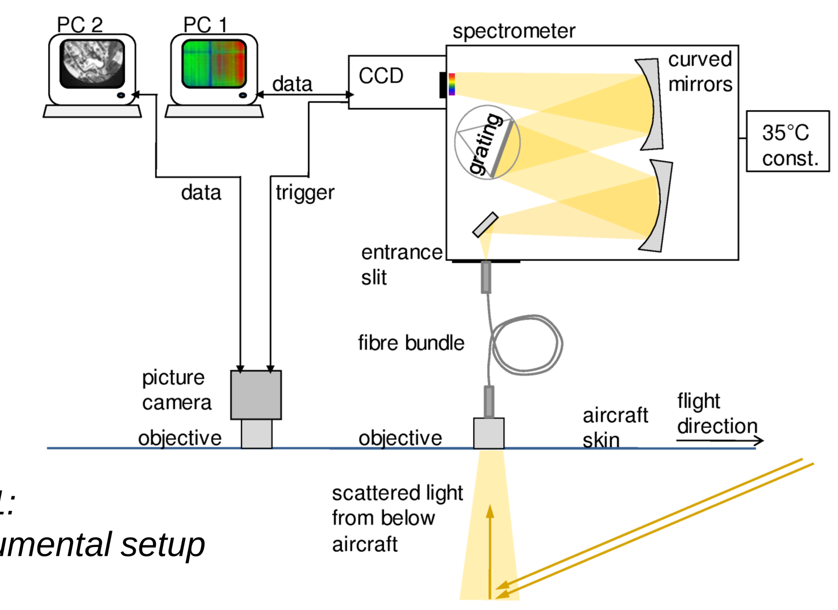



*Fig. 1: Instrumental setup*

**Observation and viewing geometry**

- Two nadir ports: spectrometer objective and picture camera
- Geolocation information: from GPS sensor and gyrometer
- Viewing directions: max. 35 LOS (line of sight) from 35 fibres
- LOS after averaging across track: fibres combined to 9 LOS ($\theta_i$)
- Field of view: ~48° across track ($\gamma$), ~3° along track ($\theta$)
- Swath width: on the order of flight altitude H
- Exposure time $t_{exp}$: typ. 0.5s
- Spatial resolution: ~100 m (at 1km flight altitude, 9 viewing directions, depending on flight altitude and required SNR)

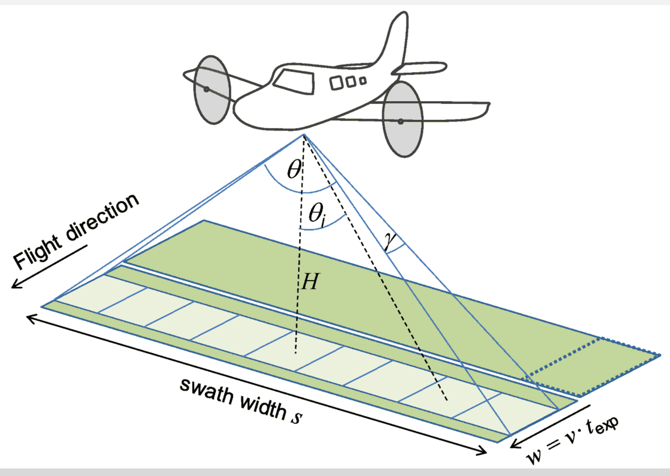
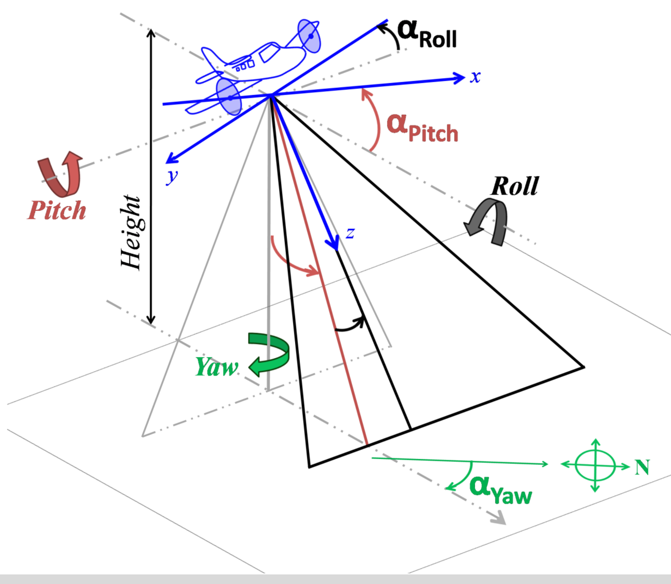



*Fig. 2: Sketch of the iDOAS viewing geometry*

**Computation of viewing geometry in flight**

- Calculation of correct ground geolocation is important
- Consideration of the aircraft angles (pitch, roll and yaw) is required in addition to GPS position
- Corner coordinates and pixel center for each LOS calculated for start and end of exposure to determine the pixel area
- The displacements of the ground pixel due to aircraft motions can be significant (depending on flight altitude)




**Displacements**
During straight tracks: few tens of metres
During turns: order of 500m, max. ~1km

*Fig. 3: Sketch of the aircraft angles affecting the observed area on the ground*

## $NO_2$ 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 (52° 17.2' N, 7° 44.8' E)
- Slant columns of $NO_2$ retrieved by Differential Optical Absorption Spectroscopy
- Large variation of $NO_2$ amounts across and along track are observed
- The $NO_2$ in the exhaust plume downwind of the power plant is clearly visible

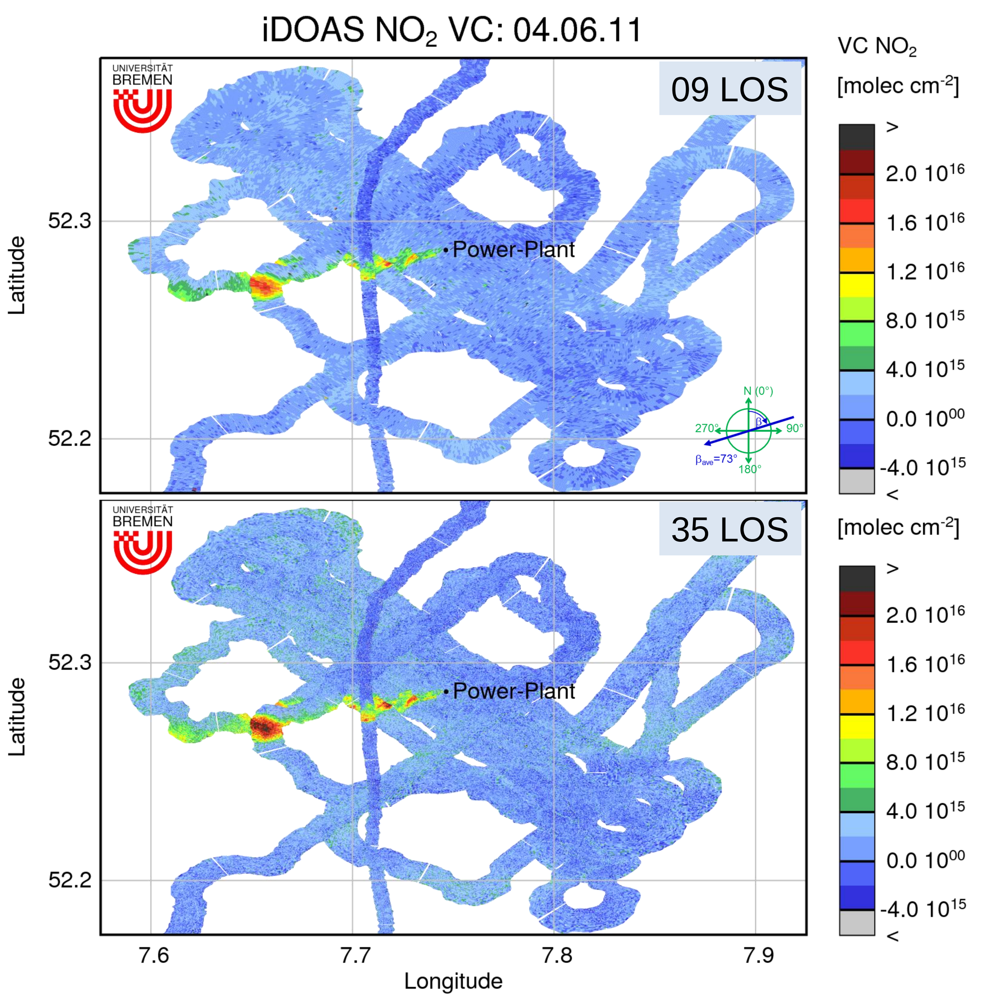



*Fig. 4: $NO_2$ amounts along the flight track retrieved from the flight on 04.06.2011. Downwind from the power plant of Ibbenbüren, strong enhancement of $NO_2$ is visible (average wind direction was about East North-East, see insert). Enhanced $NO_2$ is on the order of $10^{16}$ molec/cm². Top: Division 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 ~ 30m. Fine spatial variability of $NO_2$ amounts is resolved.*

**Retrieval Settings**

**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 $NO_2$**

Slant Column detection limit ~$10^{15}$ molec/cm²; optical density rms on the order of $10^{-3}$

**Air mass factors, AMF (SCIATRAN)**

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

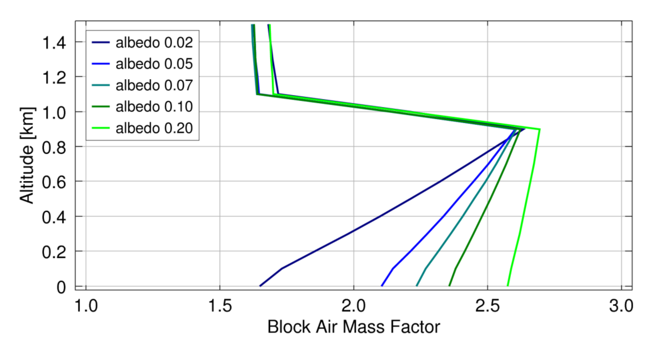



*Fig.5: Block AMF for different albedos at 40° SZA and a flight altitude of 1.1 km. AMF differences between box profile and elevated gaussian plume depend on altitude (example cases ~10% effect).*

**$NO_2$ emission flux calculations**

- based on Gaussian plume dispersion model
- mean wind speed & direction determined from $NO_2$ profile (Gaussian shape, cp. Fig.6) using COSMO-DE model wind data
- Flux calculations performed at different distances from 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 $\sigma_y$ and $\sigma_z$. 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 sum over the product of vertical columns ($VC$), wind speed and path length $dl$.

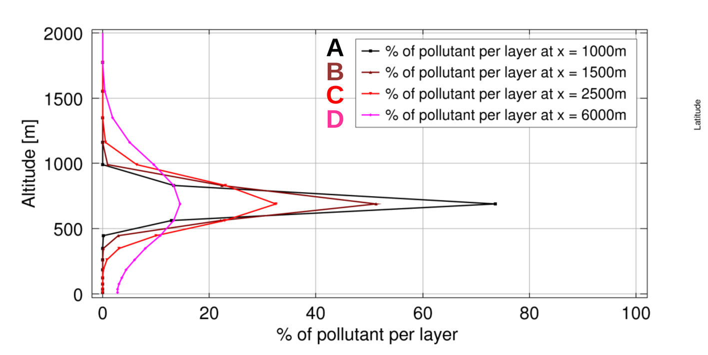
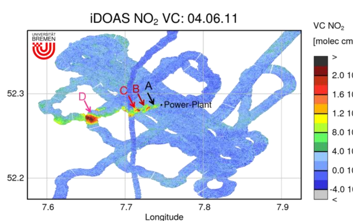



*Fig. 6: Relative $NO_2$ altitude distribution inside the plume at three different distances from the stack. The profiles are used to determine mean wind speed and direction.*



Estimated emissions of $NO_2$:
$E_{NO2}$ ~ 2100-2400 T/a
Emissions of $NO_x$
Using factor $NO/NO_2$ = ¼:
$E_{NOx}$ ~ 2635-3000 T/a
(good agreement with E-PRTR)

## $NO_2$ above inhabited and rural areas

**Flight on 09.06.2011**

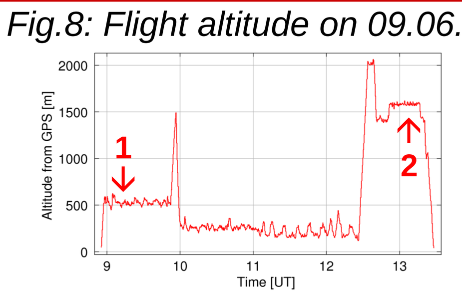

*Fig.7: $NO_2$ observations during two overflights over the city of Hamburg (same colour scale as Figs. 4 & 9.)*

**Hamburg:**

- $NO_2$ maxima ~1-2·$10^{16}$ molec/cm²
- Enhanced $NO_2$ above the city and close to the airport
- Strong spatial variability

**Rural areas:**
$NO_2$ overall much lower than closer to cities
Not all $NO_2$ enhancements can be assigned to local sources → transported $NO_2$ is observed.

*Fig.8: Flight altitude on 09.06.2011*



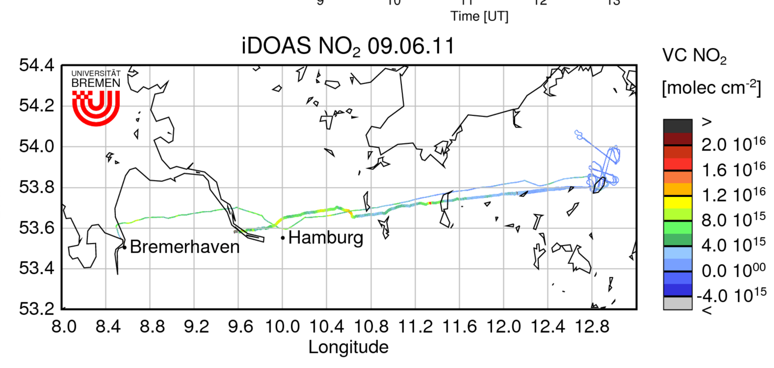




*Fig.9: $NO_2$ vertical columns observed on 09.06.2011*

## Summary and Outlook

**Summary**

- 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
- $NO_2$ emission fluxes are calculated for power plant point source
- Further observations: large spatial $NO_2$ variability, consistent low $NO_2$ above rural areas, transported $NO_2$

**Activities for the future**

- Air mass factor consideration will be improved in future analyses
- Further dedicated campaigns will be conducted

## Selected References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