Airborne imaging DOAS measurements of NO$_2$ and SO$_2$ with the AirMAP instrument
A review of the AROMAT campaign activities

AO 28651

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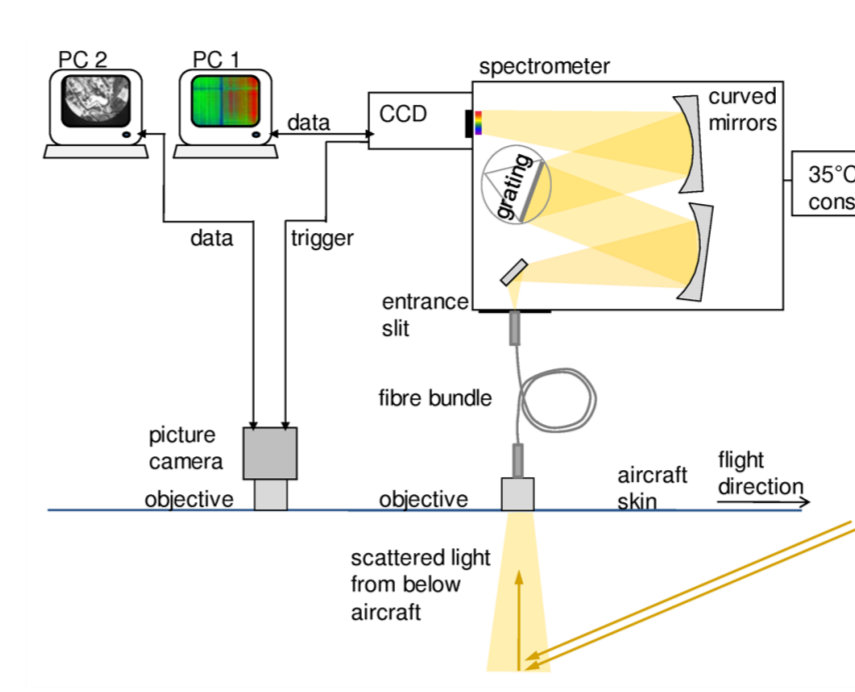
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1. Campaigns & target sites

1. NOSE (2013, non-ESA campaign)
   - Northern Germany => ship emissions
2. AROMAT (2014/ 2015)
   - Bucharest, Romania => urban NO$_2$
   - Berlin, Germany => urban NO$_2$
   - Turceni (power plant), Romania => NO$_2$ and SO$_2$
3. AROMAPEX (2016)
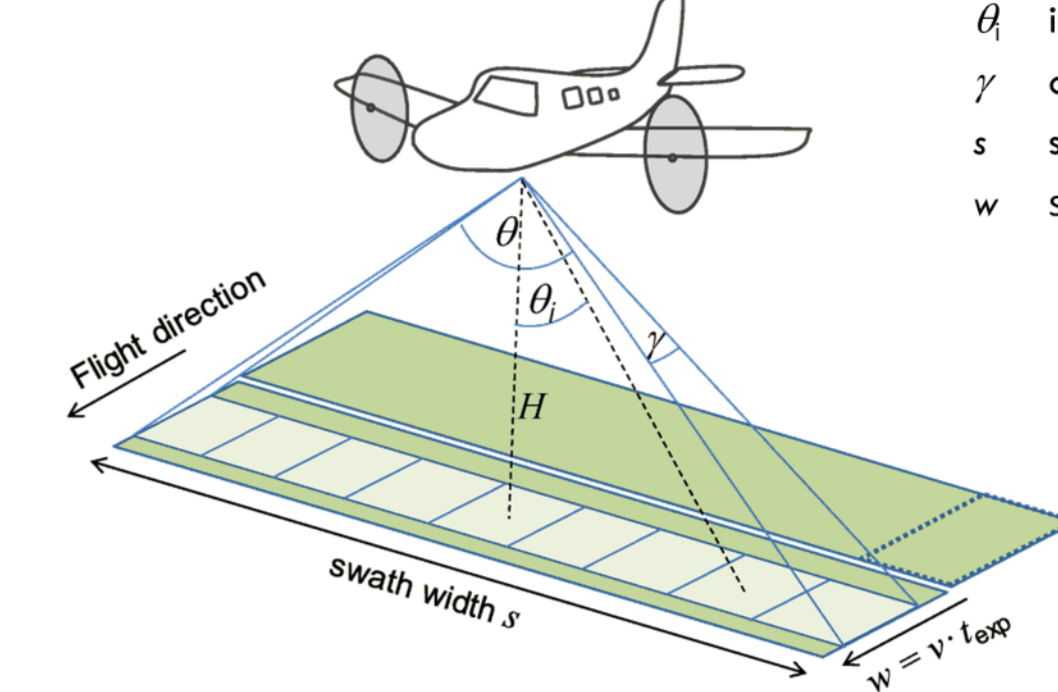   - Berlin => urban NO$_2$ & comparison airborne imagers
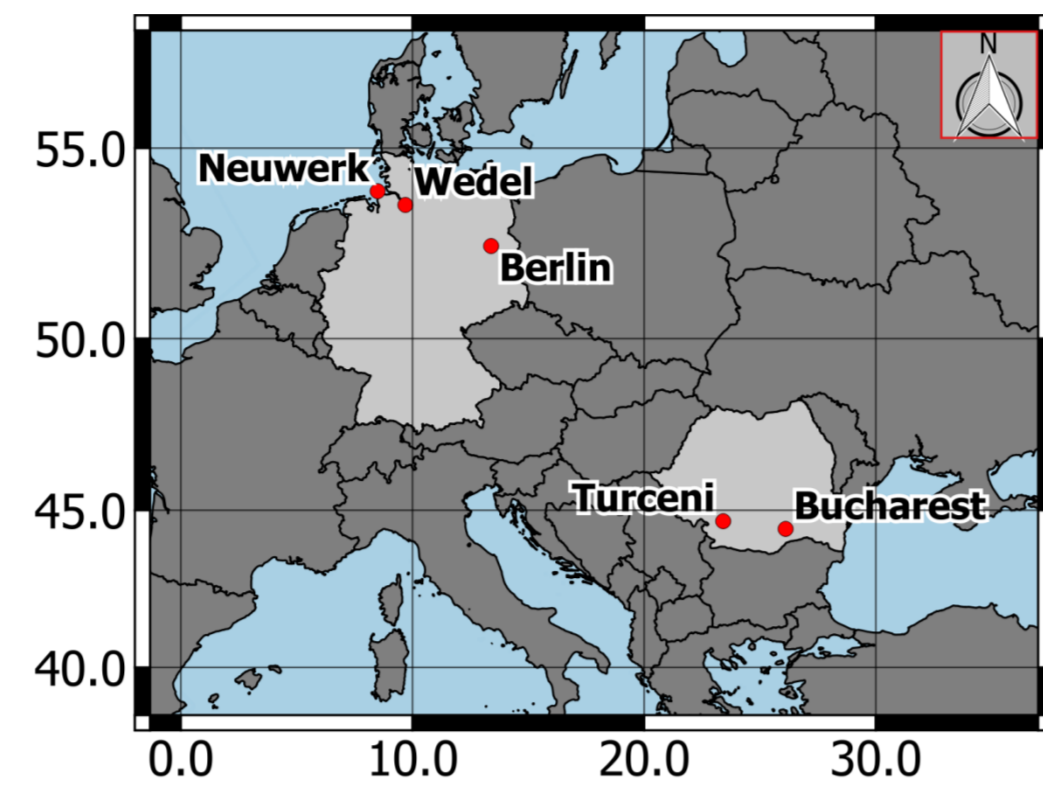
2. Instrumental setup

Instrumental setup

Viewing geometry

- θ opening angle/FOV across track ~ 52°
- θ_i individual viewing angle of direction i (max. 35)
- γ opening angle/FOV along track ~ 1.2°
- s side lengths of pixel across track
- w side length of pixel along track

- H flight altitude ~ 3400m
- V aircraft speed (typ. 60m/s)
- t_{exp} exposure time typ. 0.5s

$s = v \cdot t_{exp}$

For 35 individual viewing directions
Ground pixel size 90 x 30 m^2

- Scattered sunlight from below aircraft collected by entrance optics
- Fed into imaging spectrometer via sorted fibre bundle
- Dispersion at ruled grating
- Frame-Transfer CCD for fast measurements => no gaps

- Swath width about same as flight altitude
- Resolution along-track depends on aircraft velocity & exposure time
- For typical values during AROMAT this results in a spatial resolution of 30 x 90 m^2.

Photographs of AirMAP & platform:

Top left: Aircraft AirMAP was operated on (FUB Cessna 207 Turbo)

Bottom left: Nadir ports of entrance optics and scene camera

Right: Instrument rack carrying spectrometer, PCs, UPS etc.

3. Method

- DOAS retrieval
- Surface reflectance retrieval
  - Atmospheric correction
- Stratospheric correction
- Background correction
- Air Mass Factor Calculation (SCIATRAN)
 - 6D Look-Up Table
  - Including aerosols

Parameter	2013 / 2014 [nm]	2015 / 2016 [nm]
Spectral coverage	41	64
Fit window NO$_2$ (vis)	425 -- 450	438 -- 490
Fit window NO$_2$ (UV)	--	338 -- 366
Fit window SO$_2$ (UV)	--	307.5 -- 328

$$VCD^{trop} = \frac{dSCD + \left(AMF_0^{trop} \times VCD_0^{trop}\right) + \left(SCD_0^{strat} - SCD^{strat}\right)}{AMF^{trop}}$$

4. Shipping routes, Germany

2013-08-21
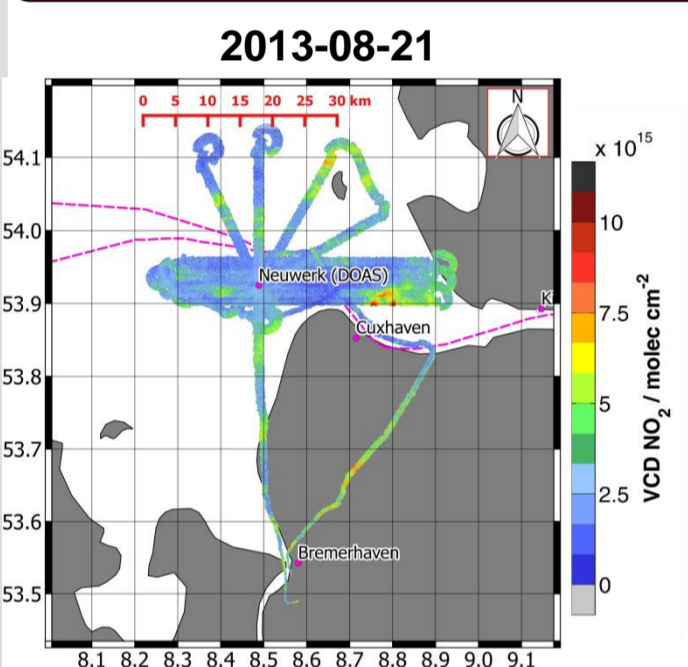
- Flight pattern in azimuth of MAX-DOAS on Neuwerk
- Additional mapping
- Detection of NO$_2$ above shipping lanes
- Spatially averaged values

2013-08-21 (ship lanes)
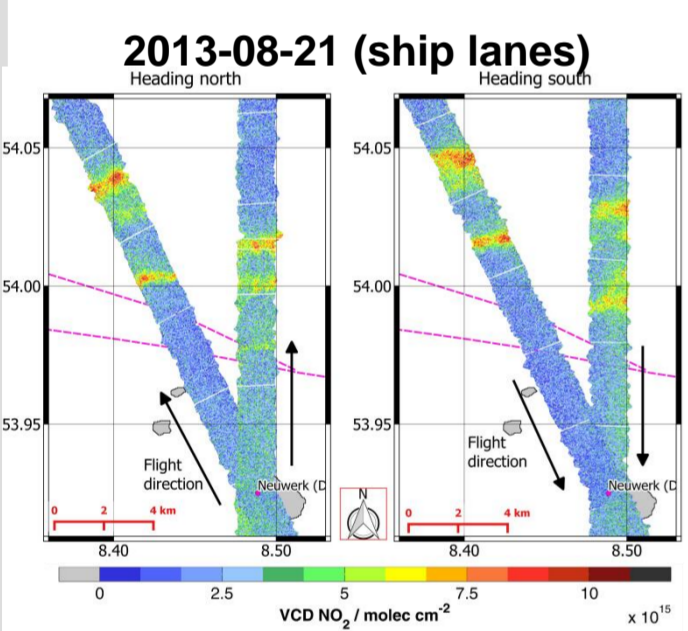
- Non gridded data reveals:
  - Spatial shift of NO$_2$
  - Broadening due to turbulent mixing
- Temporal offset
 - ~8 min (per azimuth)
  - ~18 min (between azimuths)

2013-08-21 (single ship)

AirMAP scene camera:
Cargo ship: 320 x 46 m^2
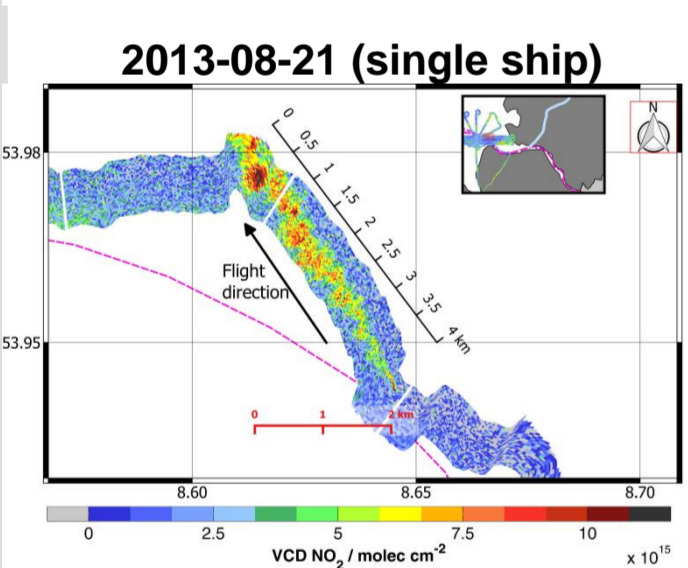
- Detection of individual NO$_2$ ship plumes
- Swath width ~800m
- NO to NO$_2$ conversion inside plume can be observed
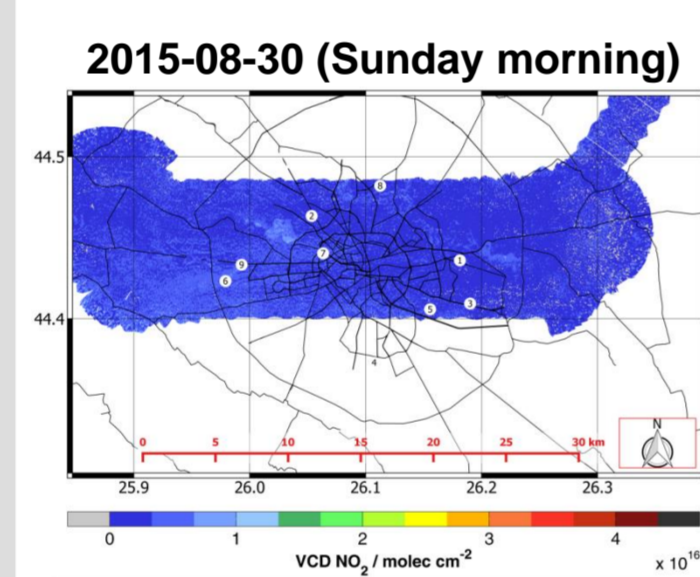- Non-uniform NO$_2$ distribution within plume

2013-08-22
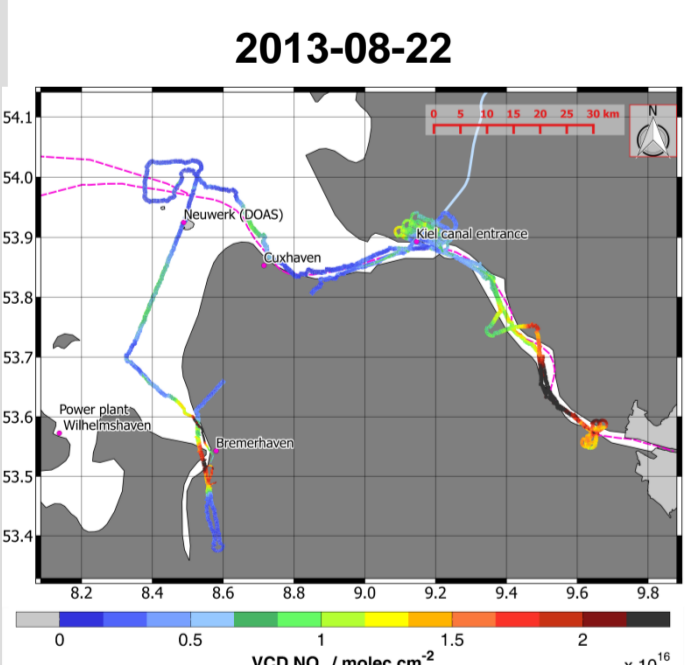
- Outflow of NO$_2$ from Hamburg & Bremerhaven
- Elevated NO$_2$ around entrance of Kiel canal
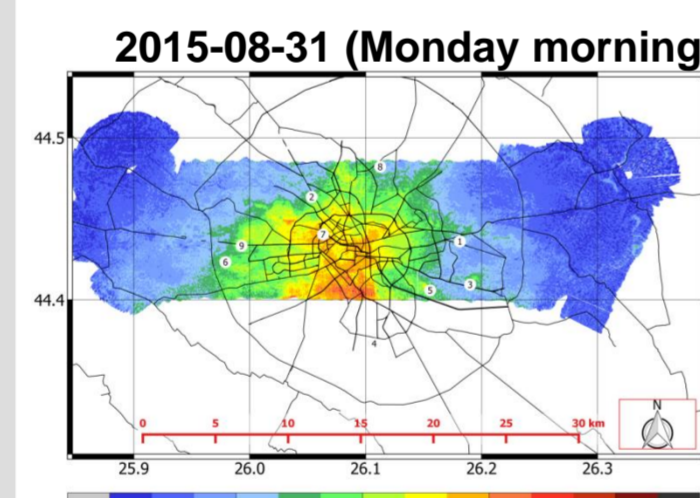- Several detections of individual ship plumes on river Elbe

5. Bucharest, Romania

2014-09-08 (Monday noon)
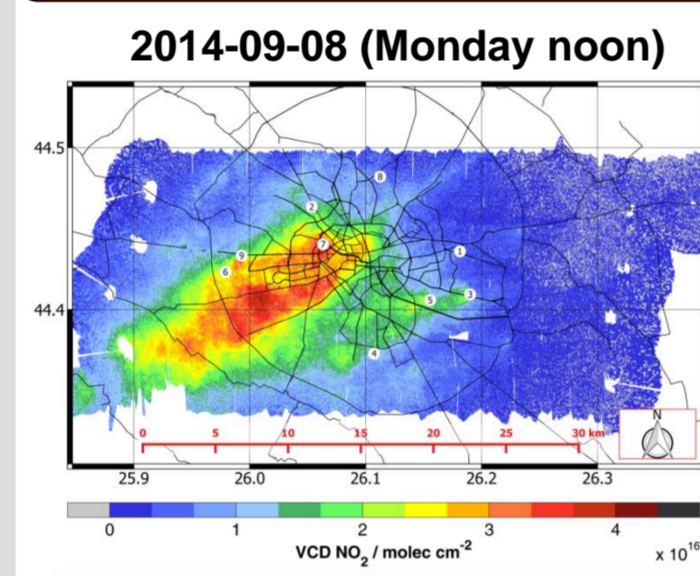
- Mapping of urban NO$_2$ distribution
- Large spatial gradients
- Industrial emitters identifiable

2015-08-30 (Sunday morning)

- Measurements on Sunday morning
- Rather low NO$_2$ levels
- Strong temporal variability (weekend / weekday)

Spatio-temporal variability of NO$_2$

2015-08-31 (Monday morning)

Individual overpasses
NO$_2$ VCD 150831 a t = 7.100 - 7.767 O1
NO$_2$ VCD 150831 a t = 7.767 - 8.383 O2
NO$_2$ VCD 150831 a t = 8.383 - 8.883 O3

- NO$_2$ levels on Monday ~ 4 times larger than on Sunday
- 3 overpasses above same area (24 x 7 km^2)
  - Temporal offset 40min
  - Spatial shift in distribution
  - Increase of NO$_2$ levels with time (~ 15% per 40 min)
    - Partly transport from south
- **Temporal coincidence important for validation!**

NO$_2$ VCD integrated across latitudes
Integrated NO$_2$ VCD (150831a)
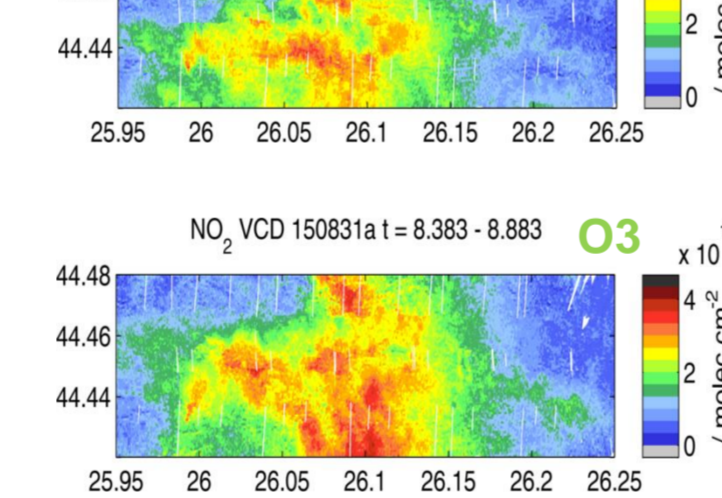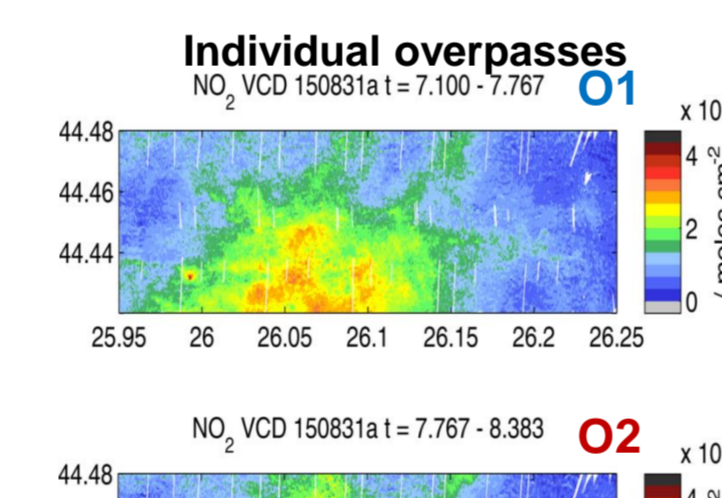
## 6. Turceni power plant, Romania

2014-09-11
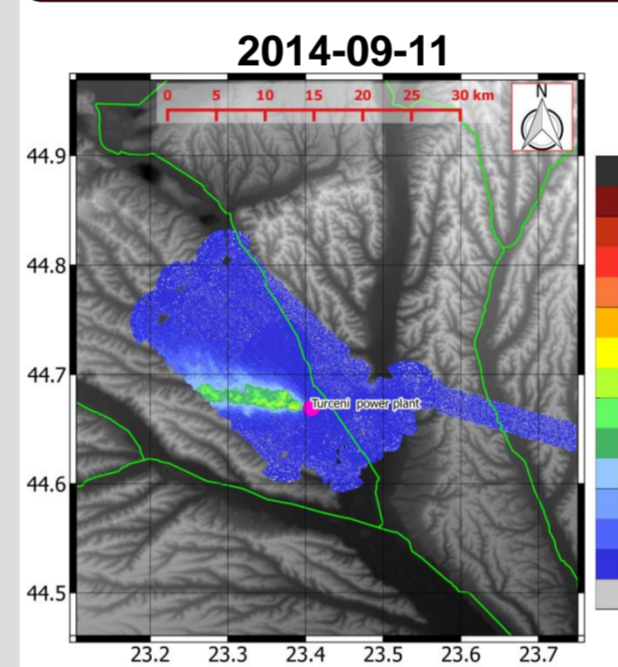
- Measurements in the visible spectral range (425– 450 nm)
- Good signal-to-noise
- Plume distribution influenced by topography
  - Large fraction of NO$_2$ close to surface

2015-08-28

2015-08-28
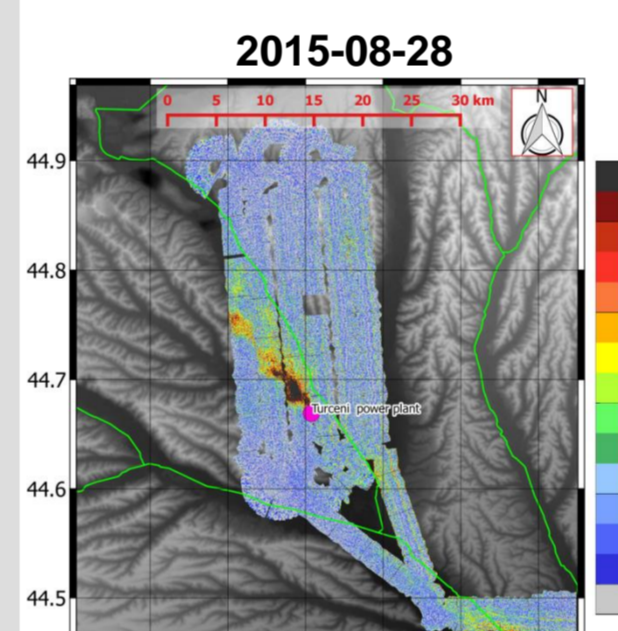
- Measurements in the UV spectral range
- Decreased SNR (vs. vis), but simultaneous SO$_2$ retrieval possible
  - NO$_2$ (338 – 366 nm)
  - SO$_2$ (307.5 – 328 nm)
- Similar spatial distribution for NO$_2$ & SO$_2$
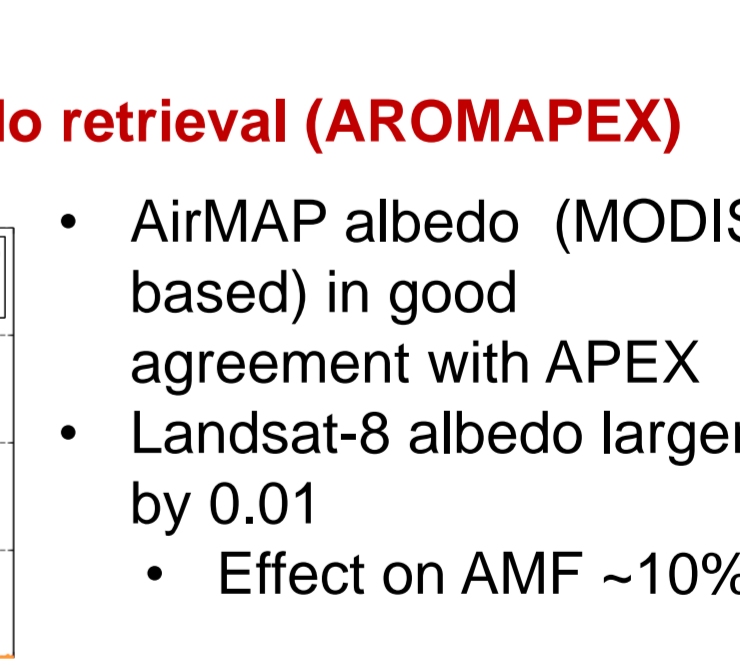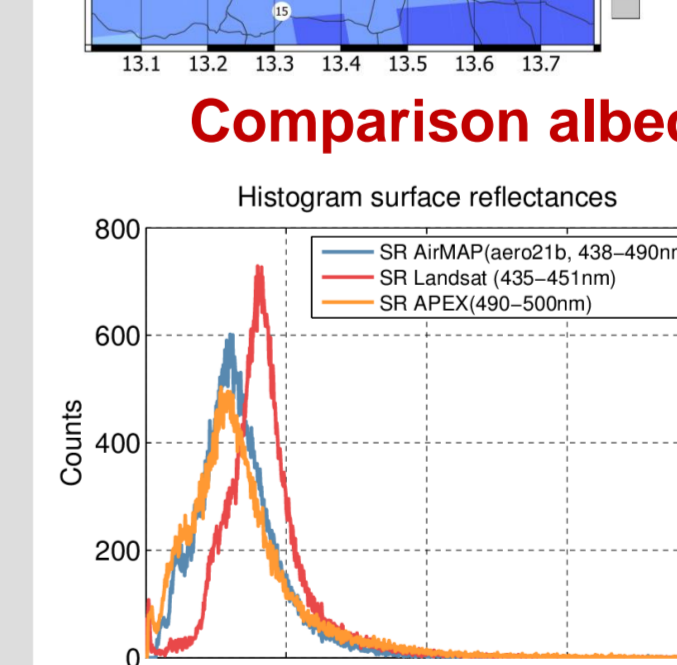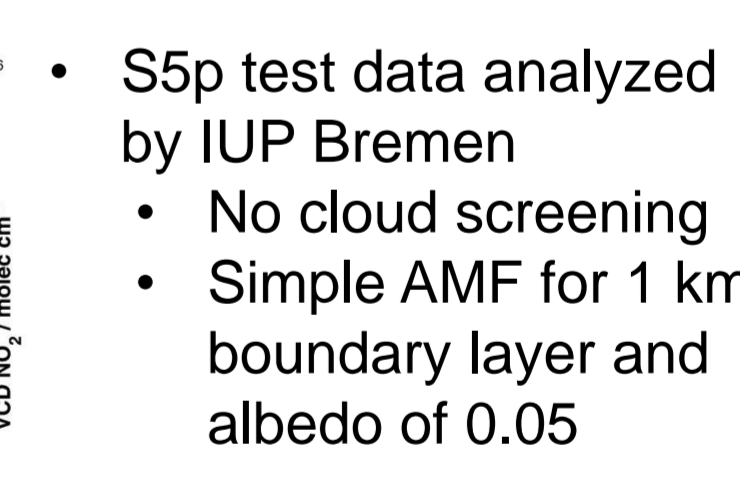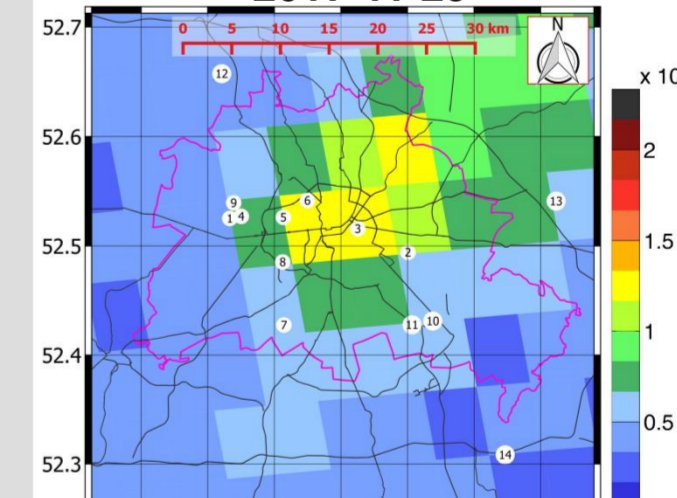- Also here: topography visible in trace gas distribution
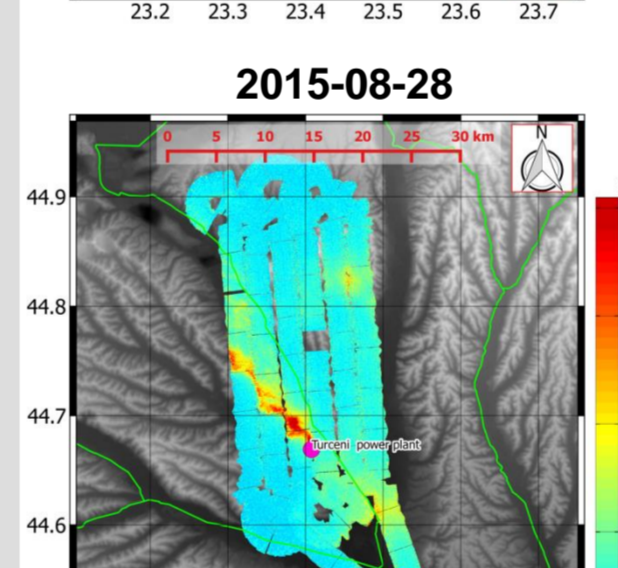
- **Will topography impact on S5p validation?**

Emission rate estimates

Emission rates NO$_2$, power plants
Emission rates SO$_2$, power plants
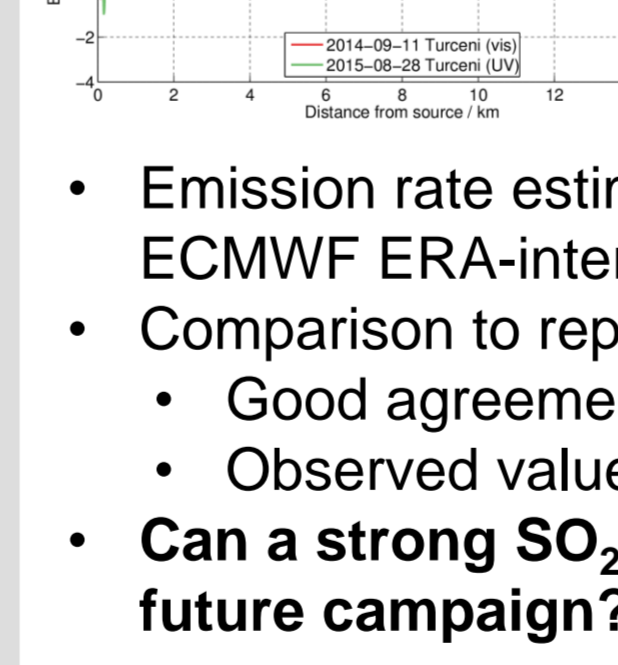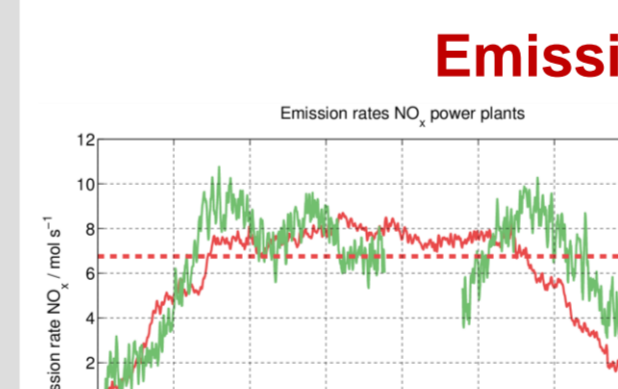
- Emission rate estimates based on wind data from ECMWF ERA-interim
- Comparison to reported values (E-PRTR)
  - Good agreement for NO$_x$
  - Observed values for SO$_2$ much larger (~9x)
- **Can a strong SO$_2$ signal be expected in a future campaign?**

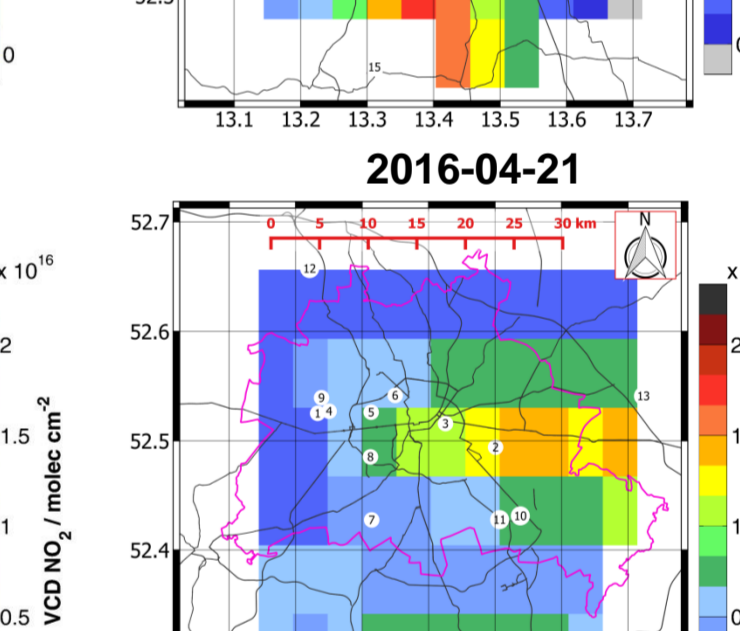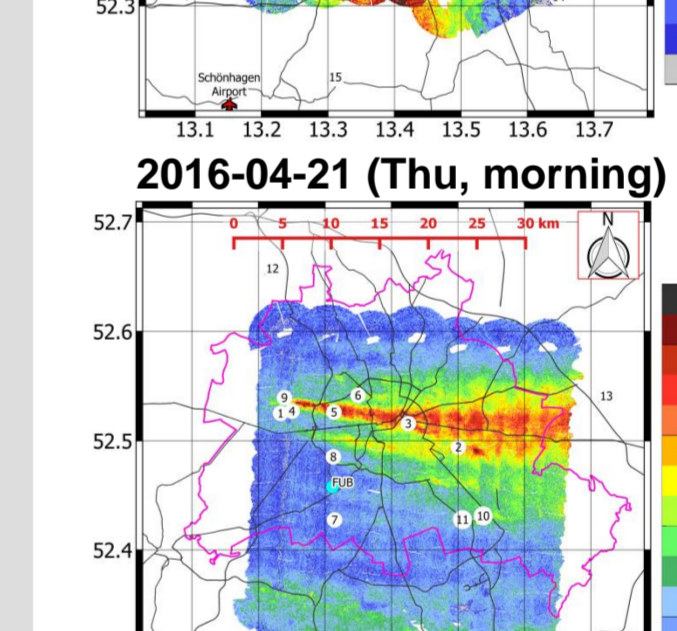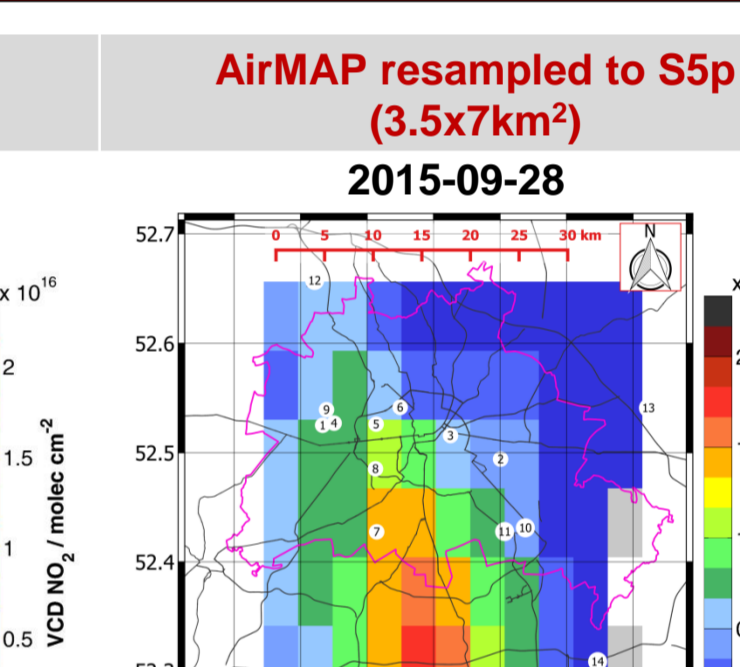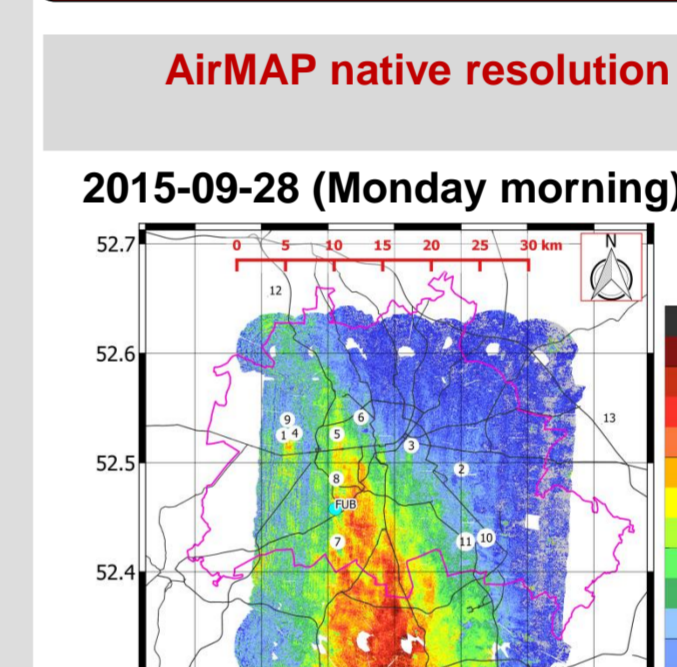## 7. Berlin, Germany

AirMAP native resolution	AirMAP resampled to S5p (3.5x7km2)
2015-09-28 (Monday morning)	**2015-09-28**
2016-04-21 (Thu, morning)	**2016-04-21**
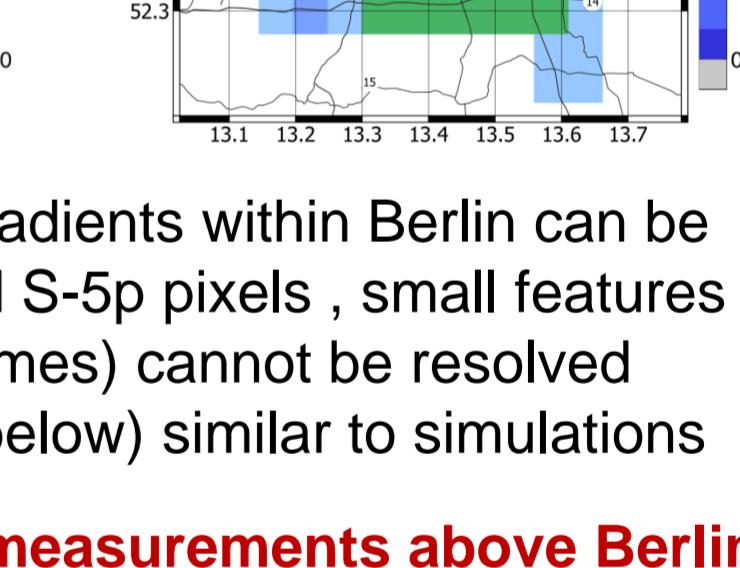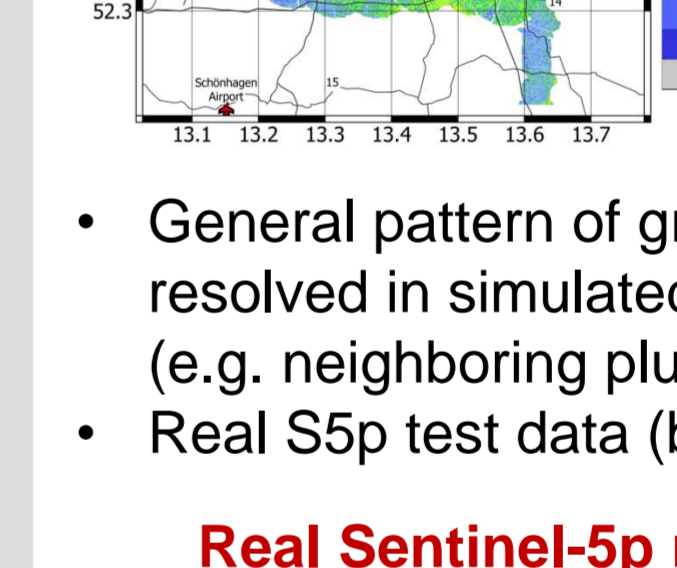
- General pattern of gradients within Berlin can be resolved in simulated S-5p pixels , small features (e.g. neighboring plumes) cannot be resolved
- Real S5p test data (below) similar to simulations

Real Sentinel-5p measurements above Berlin
2017-11-29

- S5p test data analyzed by IUP Bremen
  - No cloud screening
  - Simple AMF for 1 km boundary layer and albedo of 0.05

Comparison albedo retrieval (AROMAPEX)
Histogram surface reflectances
SR AirMAP(sen02Ib, 438-490nm)
SR Landsat (435-451nm)
SR APEX(490-500nm)

- AirMAP albedo (MODIS based) in good agreement with APEX
- Landsat-8 albedo larger by 0.01
  - Effect on AMF ~10%

Selected references

- Schönhardt, A., Altube, P., Gerilowski, K., Krautwurst, S., Hartmann, J., Meier, A. C., Richter, A. and Burrows, J. P.: A wide field-of-view imaging DOAS instrument for two-dimensional trace gas mapping from aircraft, Atmos. Meas. Tech., 8(12), 5113–5131, doi:10.5194/amt-8-5113-2015, 2015.

- Meier, A. C., Schönhardt, A., Bösch, T., Richter, A., Seyler, A., Ruhtz, T., Constantin, D.-E., Shaiganfar, R., Wagner, T., Merlaud, A., Van Roozendael, M., Belegante, L., Nicolae, D., Georgescu, L. and Burrows, J. P.: High-resolution airborne imaging DOAS measurements of NO$_2$ above Bucharest during AROMAT, Atmos. Meas. Tech., 10(5), 1831–1857, doi:10.5194/amt-10-1831-2017, 2017.

- AROMAT special issue in AMT: https://www.atmos-meas-tech.net/special_issue868.html

Acknowledgements

8. Summary & Outlook

- Successful deployment of AirMAP on many flights and targets (ships, power plants, cities)
- AirMAP measurements superior tool for Sentinel-5p validation
  - Coverage of 30x40 km^2 in ~2 hours at spatial resolution better than 100 m
  - Full coverage of several S5p pixels close to satellite overpass
  - Important to capture and characterize natural spatio-temporal variability
  - Data products:
    - NO$_2$ VCD (& SO$_2$ VCD)
    - Surface reflectance

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