BUMBA – Belgian Urban NO$_2$ Monitoring based on APEX Remote Sensing

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Introduction

• Belgian Urban NO₂ Monitoring Based on APEX hyperspectral data (BUMBA)
• Airborne imaging spectroscopy (DOAS)

NO₂ Remote sensing (APEX)

• Data acquisition: campaign overview
• Data analysis: NO₂ VCD maps

NO₂ Modeling (RIO-IFDM)

• Development of near real-time model chain: hourly NO₂ maps at 25x25 m²
• Validation: constrain model output based on APEX data
• NO₂ population exposure

Conclusion & perspectives
BUMBA objectives

- **BUMBA: BELSPO STEREO III project (01/2015 – 02/2018)**
  - Assessment of the operational/technical capabilities of APEX to map the urban NO₂ field at high spatial resolution and development of NO₂ retrieval scheme
  - Validation and improvement of the recently developed RIO-IFDM high resolution air quality model
  - Development of near real-time (hourly) model chain: NO₂ exposure maps

**NO₂: key pollutant and proxy for air quality/pollution!**
Airborne (APEX) imaging spectroscopy

DOAS (Differential Optical Absorption Spectroscopy)

**Product:** Vertical column densities (VCD): integrated amount of molecules along the vertical, expressed as molec. cm$^{-2}$
BUMBA & AROMAPEX campaigns 2015 - 2016

**BUMBA**

<table>
<thead>
<tr>
<th>Date</th>
<th>Brussels</th>
<th>Antwerp</th>
<th>Liège</th>
<th>Antwerp</th>
</tr>
</thead>
<tbody>
<tr>
<td># flightlines</td>
<td>8</td>
<td>9</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Flight pattern (Heading °)</td>
<td>0 - 180</td>
<td>0 - 180</td>
<td>40 - 220</td>
<td>0 - 180</td>
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<tr>
<td>SZA (°)</td>
<td>29.7 - 38.6</td>
<td>60.4 - 49.6</td>
<td>46.0 - 44.1</td>
<td>36.7 - 57.3</td>
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<tr>
<td>Average wind direction (°)</td>
<td>125</td>
<td>235</td>
<td>240</td>
<td>-</td>
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<td>Average wind speed (Bft)</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>27.2</td>
<td>18.7</td>
<td>20.8</td>
<td>-</td>
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<tr>
<td>PBL height (m)</td>
<td>1200</td>
<td>450</td>
<td>700</td>
<td>-</td>
</tr>
<tr>
<td>Lat (°N) / Long (°E)</td>
<td>50.8 / 4.4</td>
<td>51.2 / 4.4</td>
<td>50.6 / 5.6</td>
<td>51.2 / 4.4</td>
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<tr>
<td>Terrain altitude (m ASL)</td>
<td>76</td>
<td>10</td>
<td>66</td>
<td>10</td>
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<tr>
<td>Total population</td>
<td>1.175.173</td>
<td>513.570</td>
<td>195.968</td>
<td>513.570</td>
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<tr>
<td>Population density (#/km²)</td>
<td>6751</td>
<td>2496</td>
<td>2828</td>
<td>2496</td>
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</table>

**AROMAPEX**

<table>
<thead>
<tr>
<th>Date</th>
<th>Berlin AM</th>
<th>Berlin PM</th>
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<tbody>
<tr>
<td>Date</td>
<td>21-04-2016</td>
<td>21-04-2016</td>
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<tr>
<td>Flight time LT (UTC + 2)</td>
<td>09:34 - 12:01</td>
<td>14:24 - 16:39</td>
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<tr>
<td># flightlines</td>
<td>15</td>
<td>14</td>
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<tr>
<td>Flight pattern (Heading °)</td>
<td>0 - 180</td>
<td>0 - 180</td>
</tr>
<tr>
<td>SZA (°)</td>
<td>58.3 - 42.4</td>
<td>43.3 - 58.7</td>
</tr>
<tr>
<td>Average wind direction (°)</td>
<td>276</td>
<td>285</td>
</tr>
<tr>
<td>Average wind speed (Bft)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>PBL height (m)</td>
<td>525</td>
<td>1075</td>
</tr>
<tr>
<td>Lat (°N) / Long (°E)</td>
<td>52.28 / 13.18</td>
<td>52.28 / 13.18</td>
</tr>
<tr>
<td>Terrain altitude (m ASL)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Total population</td>
<td>3.500.000</td>
<td>3.500.000</td>
</tr>
<tr>
<td>Population density (#/km²)</td>
<td>3994</td>
<td>3994</td>
</tr>
</tbody>
</table>

Ground-based campaign
- Mobile-DOAS
- (Mini-) MAX-DOAS
- CAPS in-situ analyzer
- Ceilometer, CIMEL, ...

![S5p/TROPOMI](image)
APEX NO$_2$ VCD maps (BUMBA 2015)

(Tack et al., 2017 in AMT)

Antwerp: 15-04-2015

Brussels: 30-06-2015

Liège: 15-04-2015

Note: color scales optimized for each flight
High resolution air quality model: RIO-IFDM

RIO interpolation tool + bi-gaussian dispersion model IFDM

RIO interpolation (4x4 km²):
- Based on Telemetric AQ monitoring network (85 Belgian stations)

Line source emissions, e.g. traffic

Assimilated meteo

Point source emissions, e.g. industry

Grid of receptor points

RIO-IFDM (25x25 m²):
- Annual mean concentrations (EU ATMOSYS project)
- Hourly mean concentration + Model validation (BUMBA project)

NO₂ modeling
High resolution air quality model: RIO-IFDM

4 x 4 km² RIO

25 x 25 m² RIO-IFDM

NO₂ modeling
RIO-IFDM validation

- Conversion of APEX VCD columns to surface concentrations based on 3D CTM (AURORA, CHIMERE)

RIO-IFDM quantitative validation

- Constrain model parameters/output based on APEX remote sensing data
- Are the spatial patterns consistent?
  - Yes : OK 😊
  - No: improve receptor points grid, assess sensitivity of input data (meteo, emissions), improve simplified model chemistry, etc.

- Complexities
  - Instantaneous measurements vs hourly averages
  - Changing atmospheric conditions, e.g. impact of PBL height on dispersion
  - Use of emission time factors in model
  - Decreased sensitivity to the surface for spaceborne/airborne remote sensing
  - Vertical profiles only available at coarse resolution
  - Errors/uncertainties in both RS data and model
  - ...

NO₂ modeling
RIO-IFDM near real-time chain

- Implementation of near real-time processing chain and web map service (WMS)
  - Processing time reduced from 3 h to 23 min (parallelisation of source code)
  - Hourly maps available for NO₂ and also O₃, PM₁₀, PM₂.₅, BC (not validated)
  - Population exposure (based on Census data 2011)
  - Further development: app for personalised AQ data, e.g. healthiest route
### Conclusion

- Demonstrated that clear NO₂ signals can be retrieved and individual NO₂ plumes can be identified over urban/industrialised areas based on APEX spectra
  - High spatial resolution (60 x 80 m²)
  - High spatial coverage (350 km² within 90 minutes)
  - NO₂ VCD error approximately 20%

- High potential for
  - Better understanding of urban NO₂ field → gap filler between spaceborne and ground-based
  - Completing emission inventories by identification of sources → BUMBA commercial track
  - Validation of satellite measurements and AQ models + support to satellite mission design

- Improvement of RIO-IFDM model and implementation of near-real time model chain: inform people (hourly) on exposure to air pollution
Perspectives

Monitoring stations

Citizen science with active or passive samplers, e.g. Curieuzeuzen

Scientific networks e.g. MAX-DOAS, Pandonia, Aeronet

Chemistry transport and air quality models

Airborne remote sensing, e.g. APEX, AirMAP

Spaceborne remote sensing, e.g. S5p, S5, S4, TEMPO, GEMS

HAPS remote sensing

Conclusion and perspectives
Thank you!

http://www.bumbair.be
http://geo.irceline.be/www/no2_hmean_rioifdm_EN.html
**Product**: Vertical column densities (VCD): integrated amount of molecules along the vertical, expressed as molec. cm\(^{-2}\)
DOAS for trace gas retrieval

- Trace gas retrieval based on spectral analysis of scattered sunlight
- **DOAS remote sensing** (indirect!) technique
  - **Differential Optical Absorption Spectroscopy**
  - Works in UV-Visible region
  - O₃, HCHO, CHOCHO, BrO... but airborne has focus on NO₂ and SO₂
  - DOAS equation based on **Lambert-Beer’s law**:

\[
\ln \frac{I_o(\lambda)}{I(\lambda)} = Q_{(a)}(\lambda) + \sum_i \sigma_i(\lambda) \Delta C D_i
\]

- **Differential slant column (DSCD)** as direct output: integrated amount of molecules along the observed light path relative to the same quantity in a reference spectrum
### Airborne Prism Experiment sensor (APEX)

#### Spatial performance (at 6000 m AGL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial CCD</td>
<td>1000 detectors</td>
</tr>
<tr>
<td>FOV (across-track)</td>
<td>28°</td>
</tr>
<tr>
<td>Swath width</td>
<td>3000 m</td>
</tr>
<tr>
<td>IFOV (across-track)</td>
<td>0.028°</td>
</tr>
<tr>
<td>Spatial resolution (across-track)</td>
<td>3 m (binned 60 m)</td>
</tr>
<tr>
<td>Spatial resolution (along-track)</td>
<td>4 m (binned 80 m)</td>
</tr>
</tbody>
</table>

#### Other

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Plane speed</td>
<td>72 mps</td>
</tr>
<tr>
<td>Integration time</td>
<td>58 ms</td>
</tr>
<tr>
<td>APEX total mass</td>
<td>354 kg</td>
</tr>
<tr>
<td>Radiometric calibration</td>
<td>yes</td>
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</tbody>
</table>

#### Spectral performance for NO₂ calibration window

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Spectral interval</td>
<td>370 - 600 nm</td>
</tr>
<tr>
<td>NO₂ fitting interval</td>
<td>470 - 510 nm</td>
</tr>
<tr>
<td>Spectral detectors</td>
<td>249 (unbinned mode)</td>
</tr>
<tr>
<td>Nominal FWHM</td>
<td>1.5 nm</td>
</tr>
<tr>
<td>In-flight FWHM</td>
<td>&gt; 2.8 and &lt; 3.3 nm</td>
</tr>
<tr>
<td>Nominal spectral shift from CW</td>
<td>&lt; 0.2 nm</td>
</tr>
<tr>
<td>In-flight spectral shift from CW</td>
<td>&gt; 0.05 and &lt; 0.8 nm</td>
</tr>
<tr>
<td>Spectral sampling interval (SSI)</td>
<td>0.9 nm</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>3.1 to 3.6 pixels per FWHM</td>
</tr>
</tbody>
</table>
Flight plan

- Altitude: 20000ft. (6096 m)
- Length of one flightline (FL): 16-22 km
- Overlapping flightlines
- Integration time: 58ms (typical for **unbinned** mode)
- Extended FLs for “clean” reference spectra and more FLs downwind
- Time of flight close to local noon or smallest SZA
- Mandatory condition: clear sky
APEX NO₂ VCD retrieval algorithm

\[ VCD_i = \frac{DSCD_i + (VCD_{ref} \times AMF_{ref})}{AMF_i} \]

pixel size of 60 by 80 m² instead of 3 by 4
NO$_2$ VCD to surface concentration

- **Car-DOAS + CAPS AS32M NO$_2$ in-situ analyser**
  - Perform simultaneous observations of VCDs and surface concentrations

- **MAX-DOAS (Ukkel)**
  - Scanning horizontally and vertically -> 3D NO$_2$ distribution
  - Comparison of MAX-DOAS with monitoring stations (PhD E. Dimitropoulou)

- On the wishlist: Set up of DOAS at each monitoring station
AROMAPEX campaign 2016 (Berlin)

(Tack et al., 2018 in AMTD)

4 imaging sensors simultaneously operated

- APEX (VITO/BIRA)
- AirMAP (IUP Bremen/FU Berlin)
- SWING (BIRA)
- SpectroLite (TNO/TU Delft/KNMI)

APEX (VITO/BIRA) DLR Dornier (6 km AGL)

AirMAP (IUP Bremen/FU Berlin)

SWING (BIRA) FUB Cessna (3 km AGL)

SpectroLite (TNO/TU Delft/KNMI)

- APEX
  - 350 kg
- AirMAP
  - 100 kg
- SWING
  - 1.2 kg
- SpectroLite
  - 20 kg

NO₂ remote sensing
AROMAPEX campaign 2016 (Berlin)

NO$_2$ remote sensing
AROMAPEX campaign 2016 (Berlin)

NO$_2$ remote sensing
Population exposure

- The best population data set for the whole of Belgium: data from Census 2011 (Geostat – a Eurostat project)

- Bin RIO-IFDM to Geostat grid (mean concentration per grid cell)

- Exposure calculated every hour for BC, NO2, O3, PM10 & PM2.5
Variations in NO$_2$ surface concentrations on 15 April, 2015 in Antwerp between 9 and 11 a.m. (UTC)