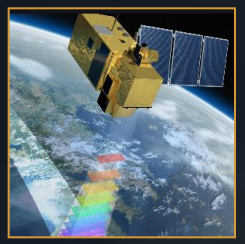
BUMBA – Belgian Urban NO_2 Monitoring based on APEX Remote Sensing



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BIRA·IASB aeronomie·be

BUMBAir.be

BELSPO BEODAY 2.0, 13-11-2018

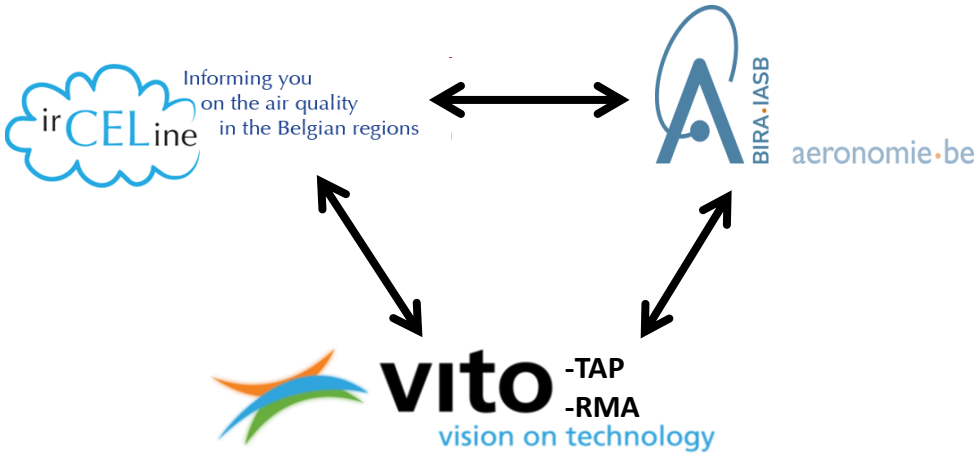
Outline

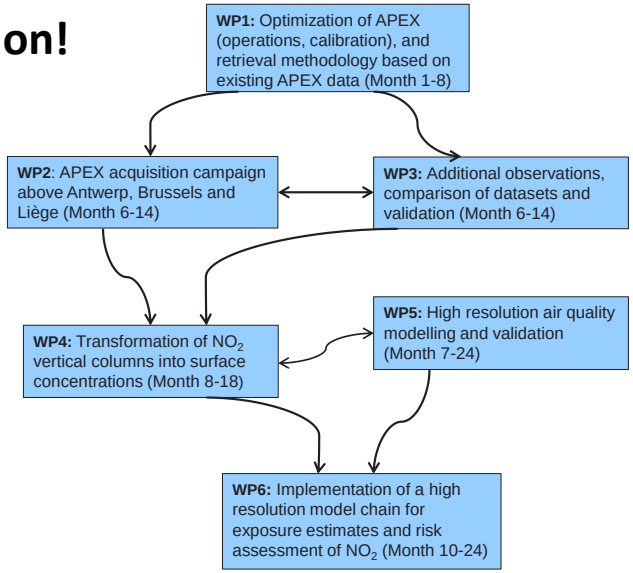
- Introduction
  - Belgian Urban NO_2 Monitoring Based on APEX hyperspectral data (**BUMBA**)
  - Airborne imaging spectroscopy (**DOAS**)
- NO_2 Remote sensing (**APEX**)
  - Data acquisition: campaign overview
  - Data analysis: NO_2 VCD maps
- NO_2 Modeling (**RIO-IFDM**)
  - Development of near real-time model chain: hourly NO_2 maps at 25x25 m^2
  - Validation: constrain model output based on APEX data
  - NO_2 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 NO_2 field at high spatial resolution and development of NO_2 retrieval scheme
  - Validation and improvement of the recently developed RIO-IFDM high resolution air quality model
  - Development of near real-time (hourly) model chain: NO_2 exposure maps

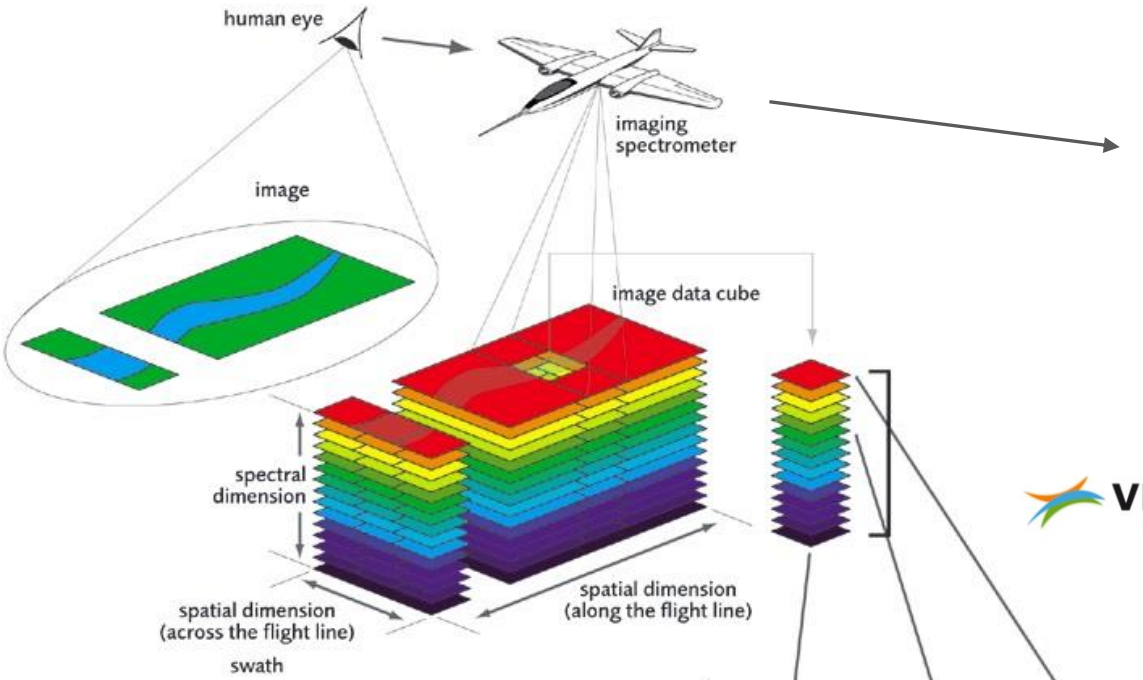
NO_2: key pollutant and proxy for air quality/pollution!

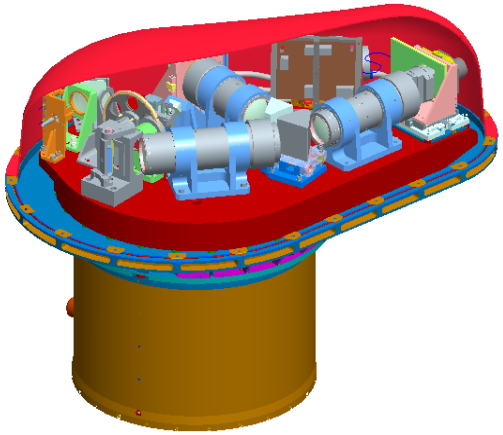




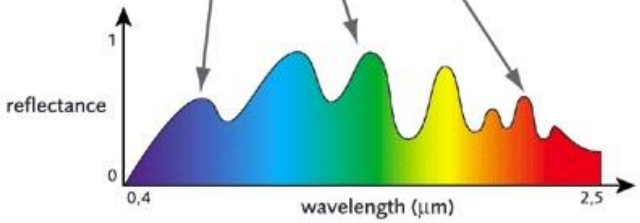
Airborne (APEX) imaging spectroscopy

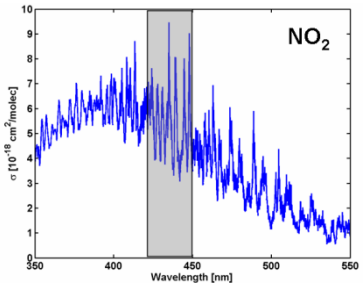
APEX





DOAS (**D**ifferential **O**ptical **A**bsorption **S**pectroscopy)





Product: Vertical column densities (VCD): integrated amount of molecules along the vertical, expressed as molec. cm^{-2}

BUMBA & AROMAPEX campaigns 2015 - 2016

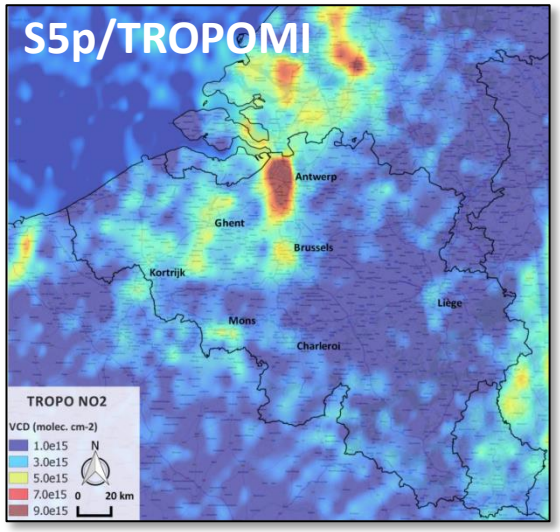
	BUMBA				AROMAPEX	
	Brussels	Antwerp	Liège	Antwerp	Berlin AM	Berlin PM
Date	30-06-2015	15-04-2015	15-04-2015	19-07-2016	21-04-2016	21-04-2016
Flight time LT (UTC + 2)	14:43 - 16:04	10:06 - 11:30	11:55 - 12:18	15:33 - 18:03	09:34 - 12:01	14:24 - 16:39
# flightlines	8	9	3	14	15	14
Flight pattern (Heading °)	0 - 180	0 - 180	40 - 220	0 - 180	0 - 180	0 - 180
SZA (°)	29.7 - 38.6	60.4 - 49.6	46.0 - 44.1	36.7 - 57.3	58.3 - 42.4	43.3 - 58.7
Average wind direction (°)	125	235	240	-	276	285
Average wind speed (Bft)	2	3	3	-	3	4
Temperature (°C)	27.2	18.7	20.8	-	10	14
PBL height (m)	1200	450	700	-	525	1075
Lat (°N) / Long (°E)	50.8 / 4.4	51.2 / 4.4	50.6 / 5.6	51.2 / 4.4	52.28 / 13.18	52.28 / 13.18
Terrain altitude (m ASL)	76	10	66	10	70	70
Total population	1.175.173	513.570	195.968	513.570	3.500.000	3.500.000
Population density (#/km²)	6751	2496	2828	2496	3994	3994

BUMBAir.be

belspo

Ground-based campaign

- Mobile-DOAS
- (Mini-) MAX-DOAS
- CAPS in-situ analyzer
- Ceilometer, CIMEL, …



A•ROMAT

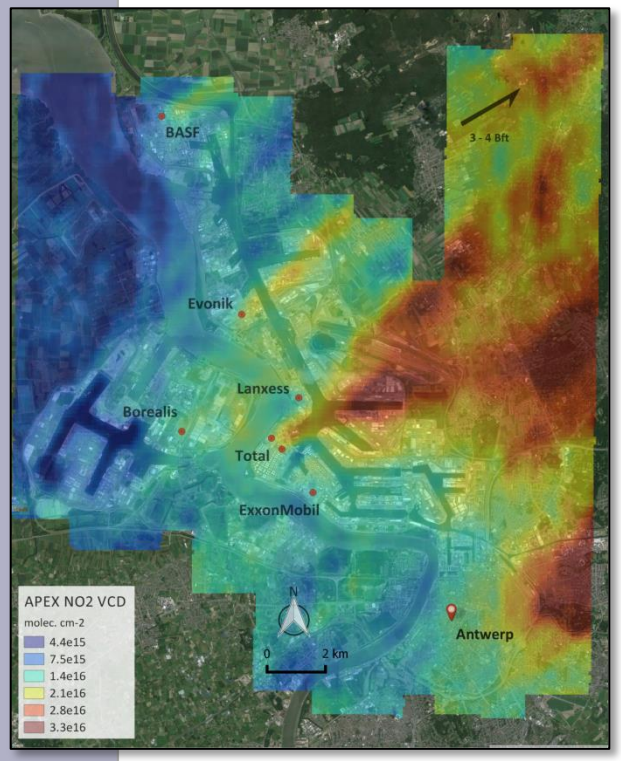
EUFAR European Facility For Airborne Research

esa

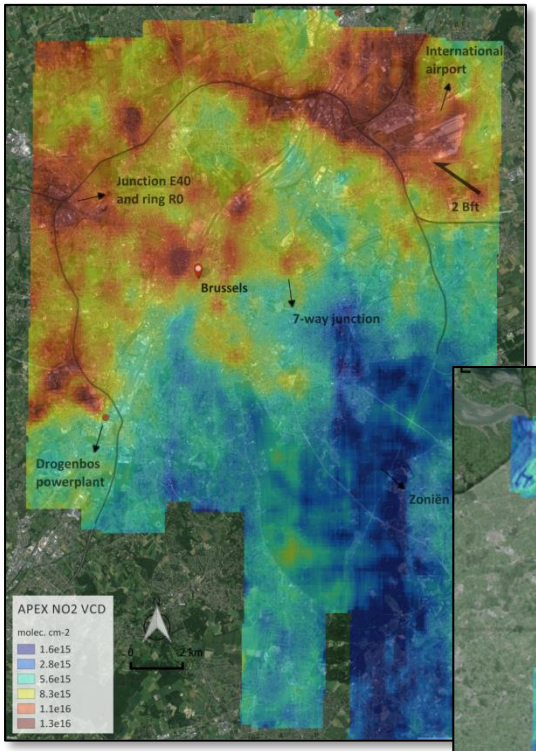
APEX NO_2 VCD maps (BUMBA 2015)

(Tack et al., 2017 in AMT)

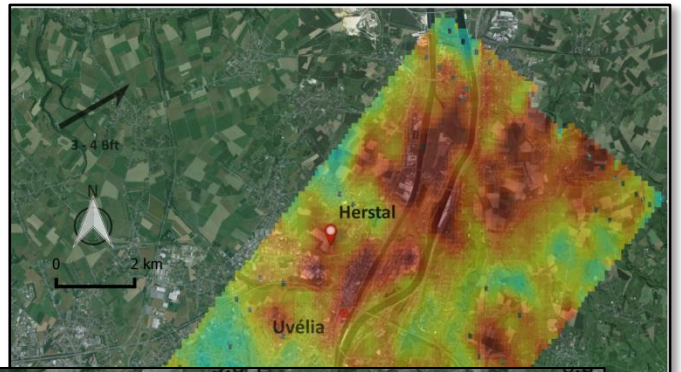
Antwerp: 15-04-2015

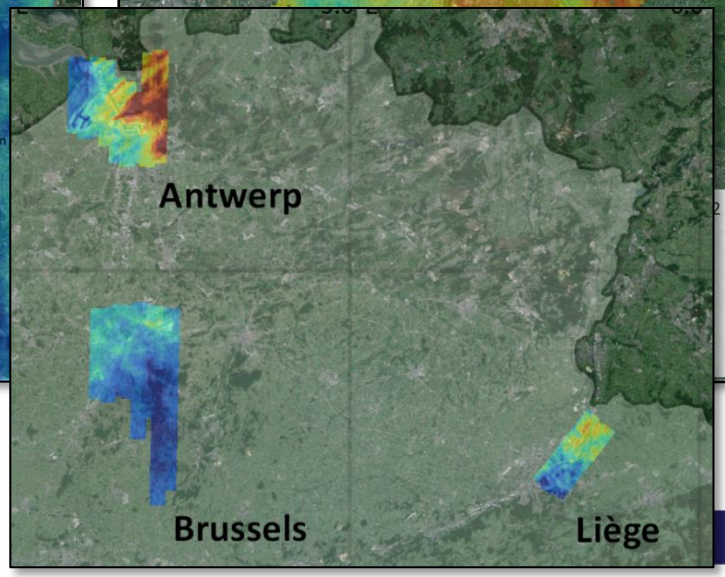


Brussels: 30-06-2015

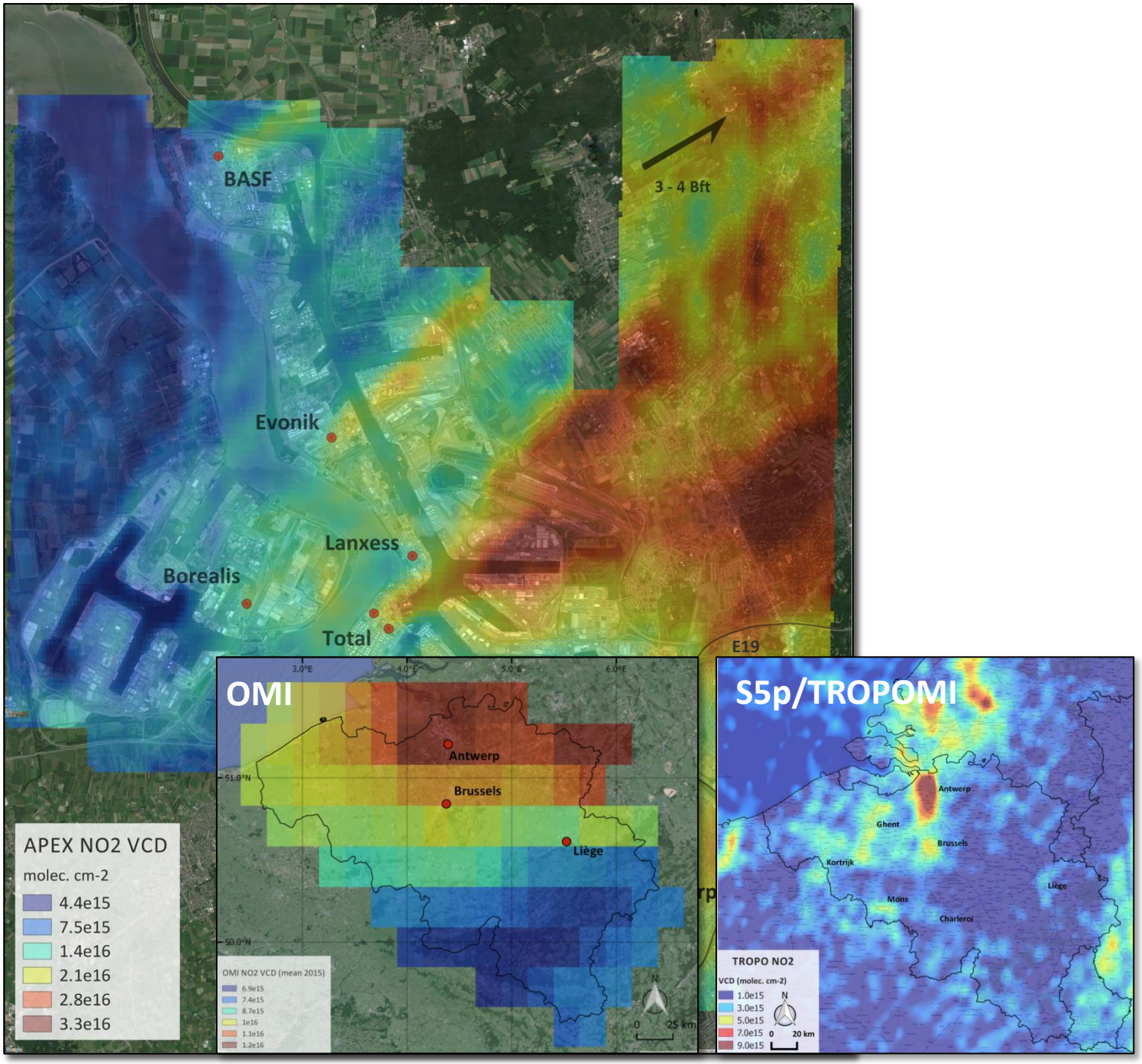


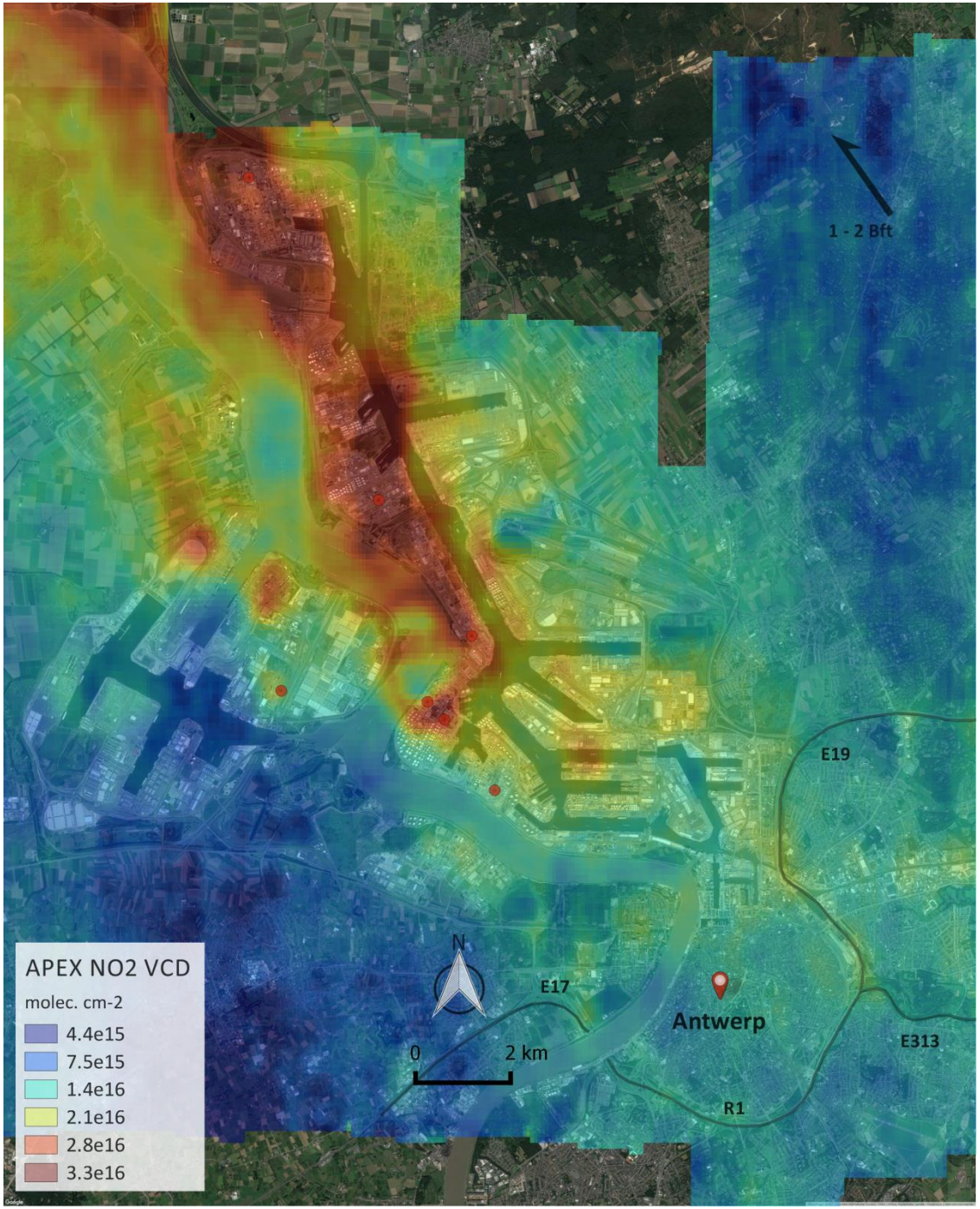
Liège: 15-04-2015

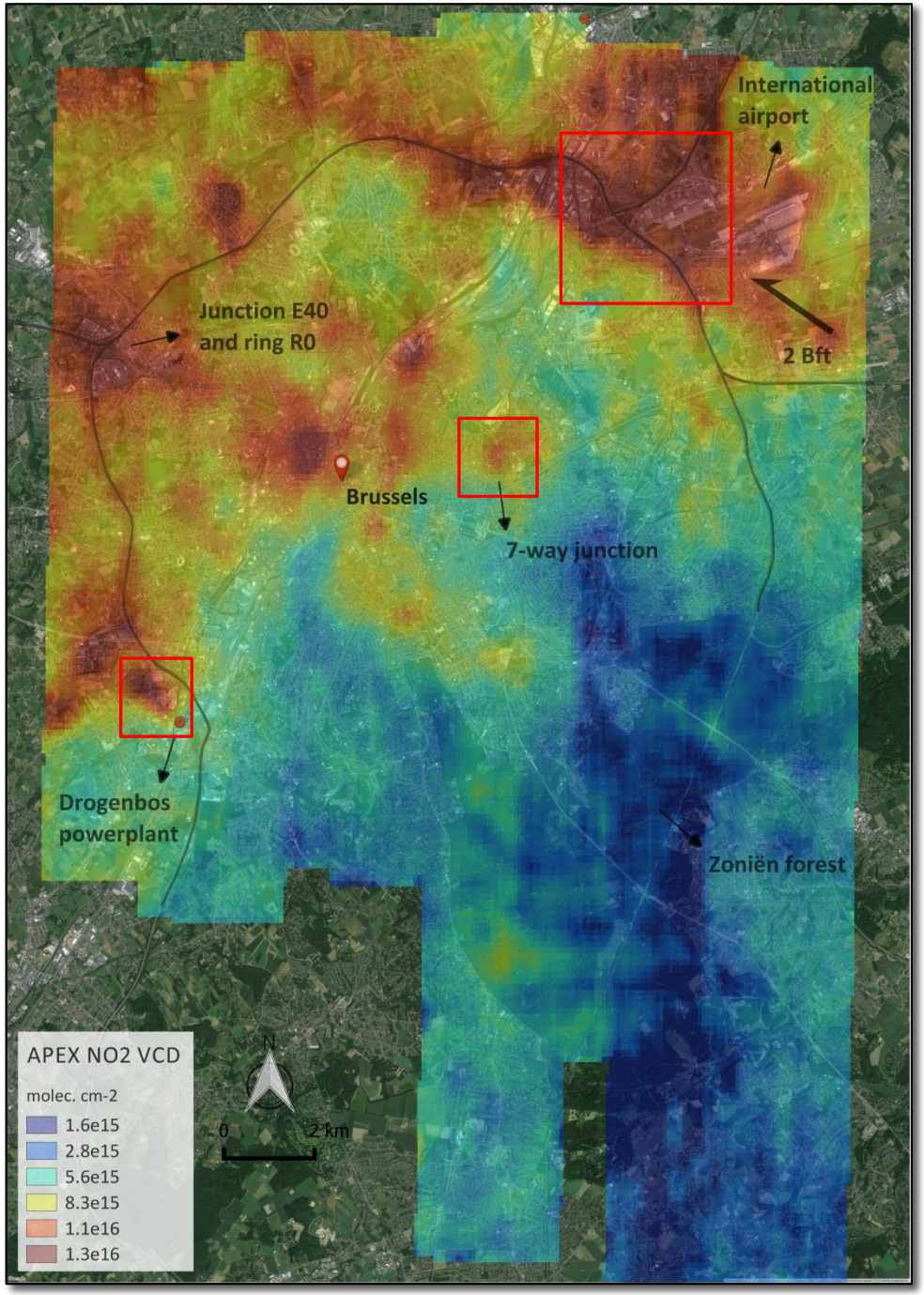


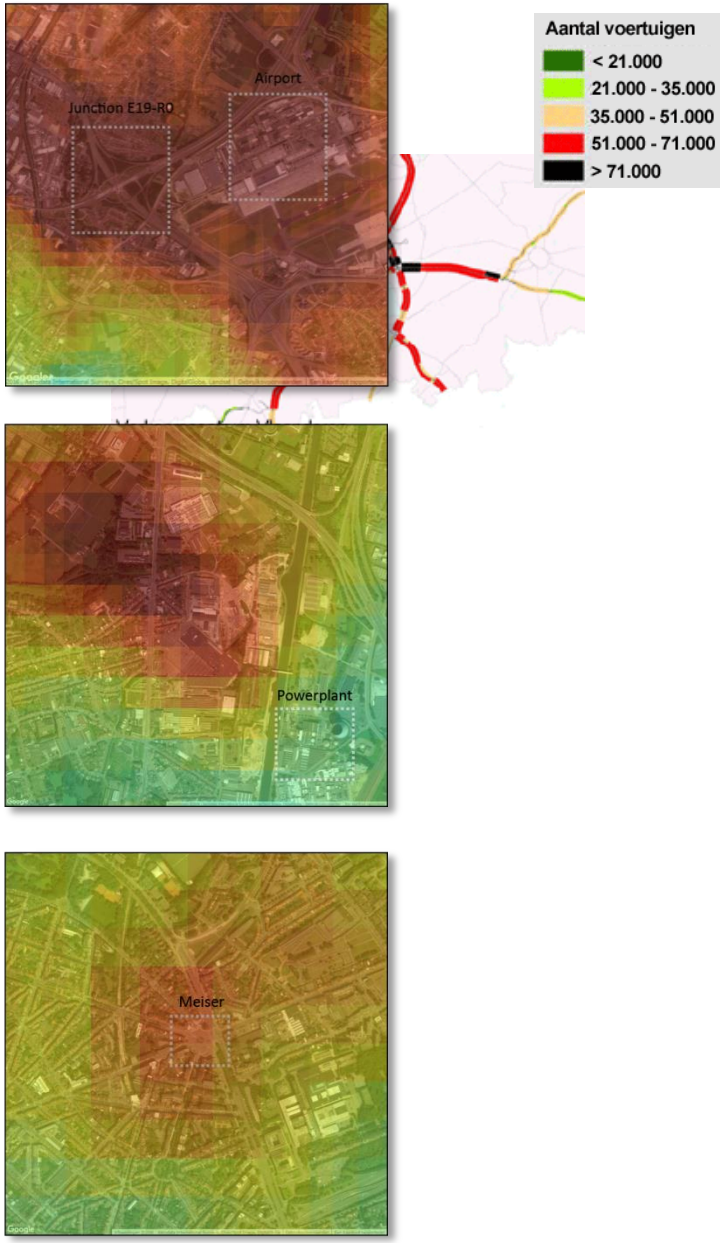


Note: color scales optimized for each flight


BASF
3 - 4 Bft
Evonik
Lanxess
Borealis
Total
E19
APEX NO2 VCD
molec. cm-2
4.4e15
7.5e15
1.4e16
2.1e16
2.8e16
3.3e16
OMI
Antwerp
Brussels
Liège
OMI NO2 VCD (mean 2015)
6.9e15
7.4e15
8.7e15
1e16
1.1e16
1.2e16
0
25 km
S5p/TROPOMI
Antwerp
Ghent
Brussels
Kortrijk
Liège
Mons
Charleroi
TROPO NO2
VCD (molec. cm-2)
1.0e15
3.0e15
5.0e15
7.0e15
9.0e15
0
20 km

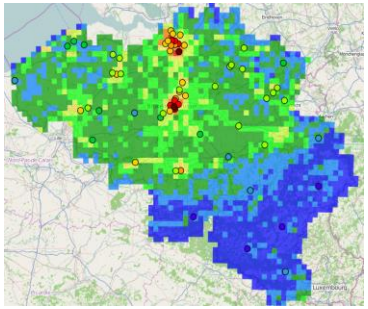

1 - 2 Bft
E19
E17
Antwerp
E313
R1
N
0
2 km
APEX NO2 VCD
molec. cm-2
4.4e15
7.5e15
1.4e16
2.1e16
2.8e16
3.3e16


International airport
Junction E40 and ring R0
2 Bft
Brussels
7-way junction
Drogenbos powerplant
Zoniën forest
APEX NO2 VCD
molec. cm-2
1.6e15
2.8e15
5.6e15
8.3e15
1.1e16
1.3e16
N
0
2 km


Junction E19-R0
Airport
Powerplant
Meiser
Aantal voertuigen
< 21.000
21.000 - 35.000
35.000 - 51.000
51.000 - 71.000
> 71.000

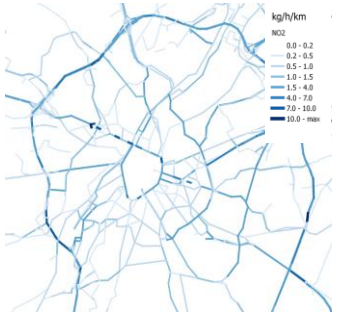
High resolution air quality model: RIO-IFDM

RIO interpolation tool + bi-gaussian dispersion model IFDM



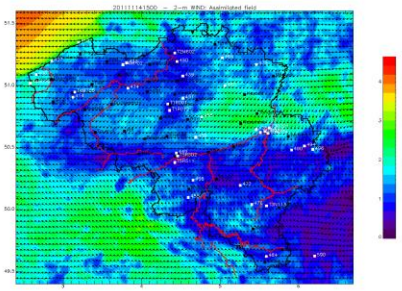
RIO interpolation (4x4 km^2):
-Based on Telemetric AQ monitoring network (85 Belgian stations)

+



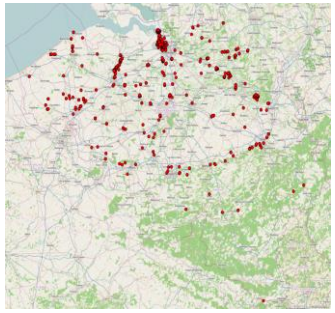
Line source emissions, e.g. traffic

+

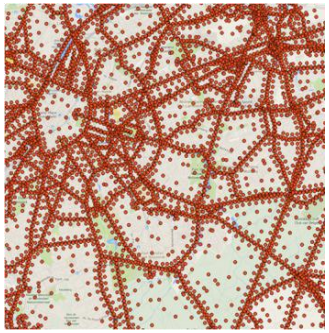


Assimilated meteo

+

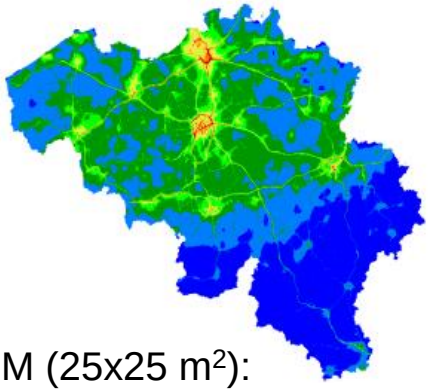


Point source emissions, e.g. industry



Grid of receptor points

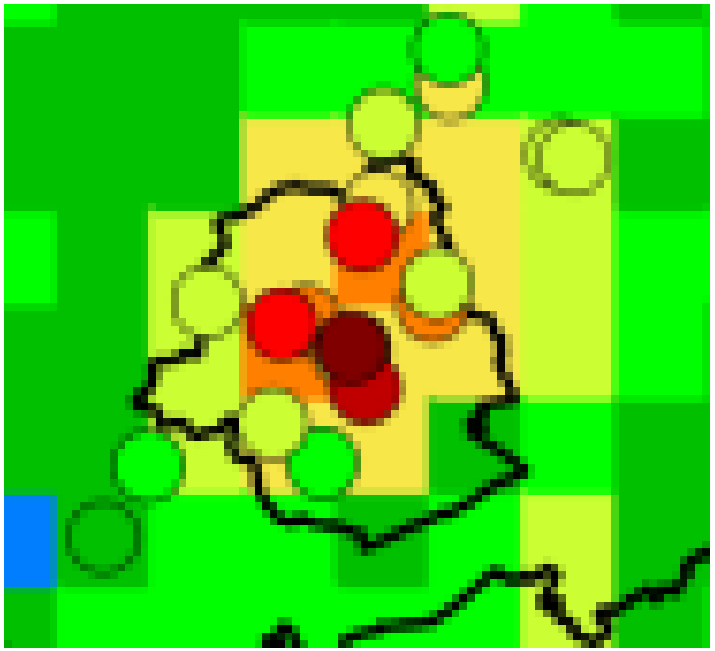
IFDM



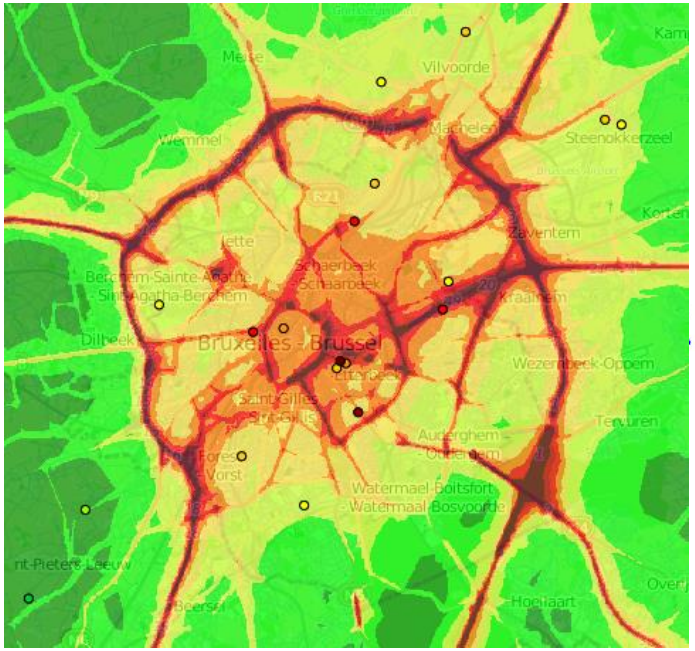
RIO-IFDM (25x25 m^2):
-Annual mean concentrations
(EU *ATMOSYS project)*
-Hourly mean concentration + Model validation
(BUMBA project)

High resolution air quality model: RIO-IFDM

4 x 4 km² RIO



25 x 25 m² RIO-IFDM



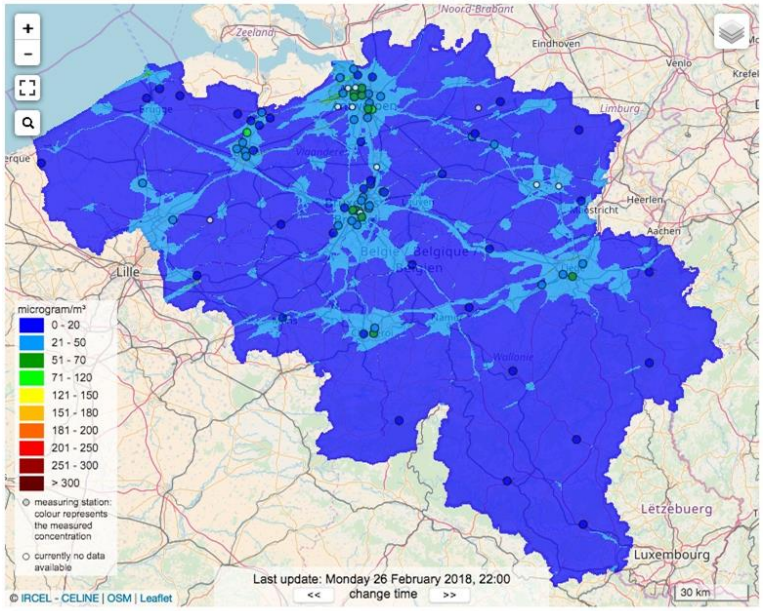
RIO-IFDM validation

- **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
    - ...

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 NO_2 and also O_3, PM_{10}, $PM_{2.5}$, BC (not validated)
  - Population exposure (based on Census data 2011)
  - Further development: app for personalised AQ data, e.g. healthiest route
  - http://geo.irceline.be/www/no2_hmean_rioifdm_EN.html

Modelled hourly NO2 concentrations in Belgium



Population Exposure Nitrogen Dioxide (NO_2)

concentration class	percentage inhabitants	cumulative percentage inhabitants
0 - 20	52.3	100
21 - 50	47.2	47.7
51 - 70	0.4	0.4

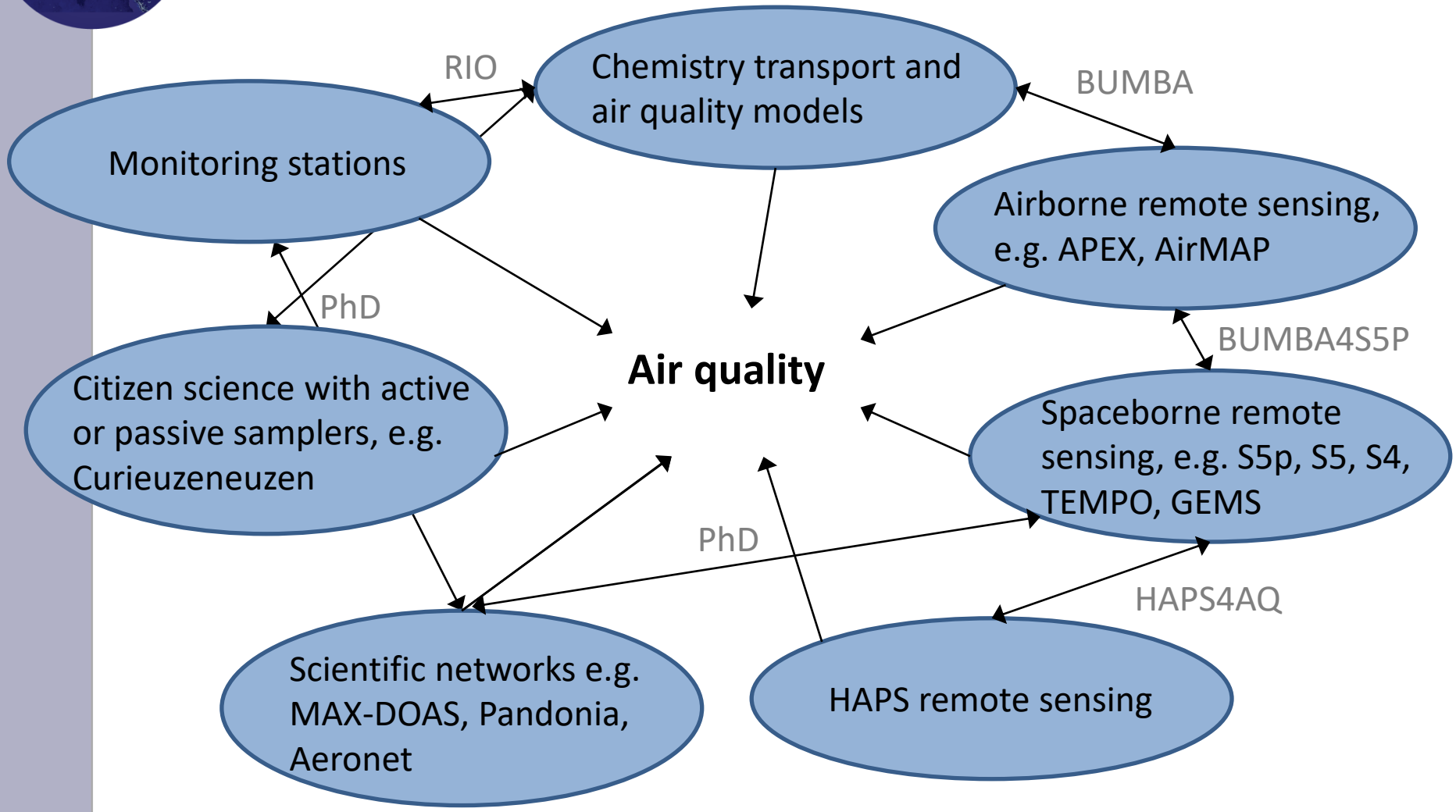
Conclusion

- Demonstrated that clear NO_2 signals can be retrieved and individual NO_2 plumes can be identified over urban/industrialised areas based on APEX spectra
  - High spatial resolution (60 x 80 m^2)
  - High spatial coverage (350 km^2 within 90 minutes)
  - NO_2 VCD error approximately 20%

- High potential for
  - Better understanding of urban NO_2 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

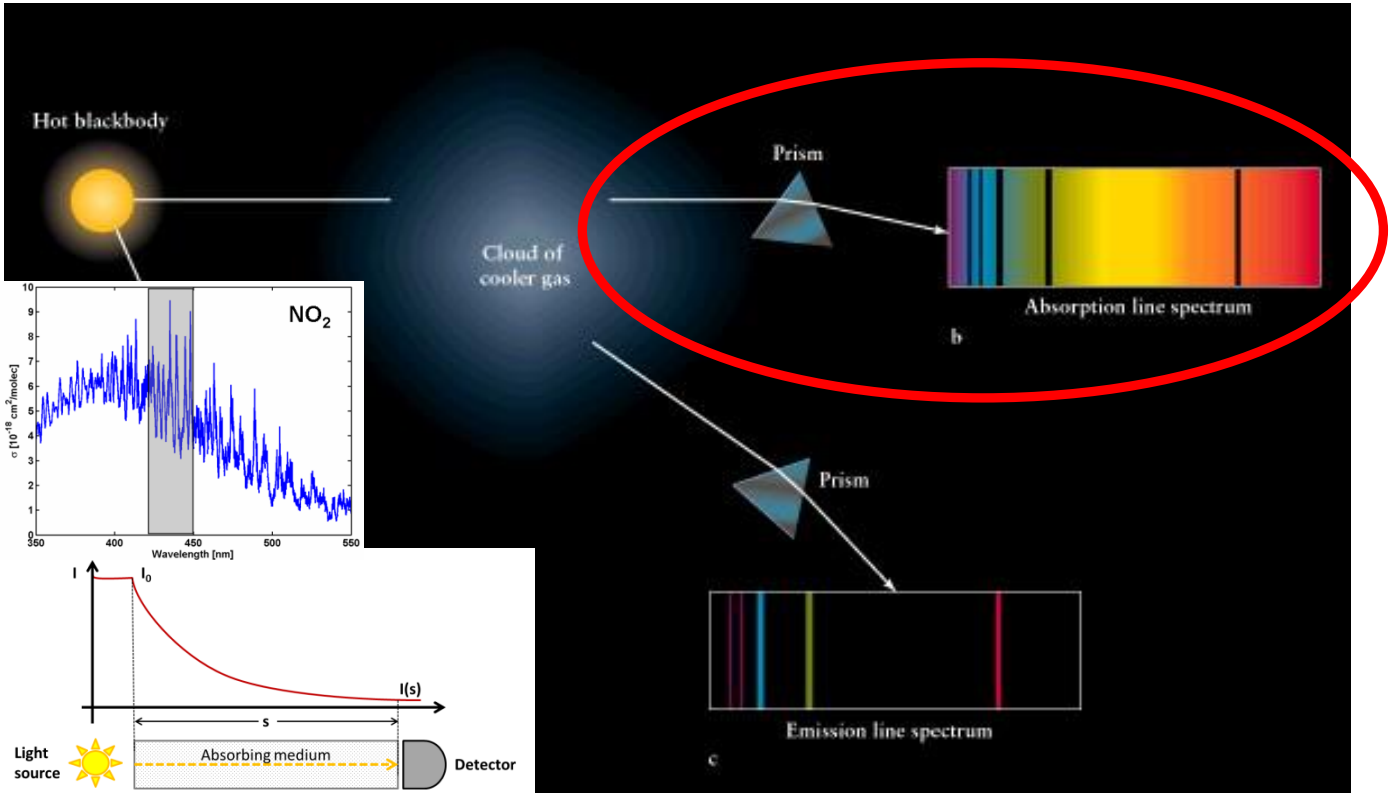
Perspectives



...Thank you!

http://uv-vis.aeronomie.be/airborne/bumba.php
http://www.bumbair.be
http://geo.irceline.be/www/no2_hmean_rioifdm_EN.html

DOAS for trace gas retrieval



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
  - O_3, HCHO, CHOCHO, BrO… but airborne has focus on **NO_2 and SO_2**
  - DOAS equation based on **Lambert-Beer's law**:

$$\ln \frac{I_o(\lambda)}{I(\lambda)} = Q_{(a)}(\lambda) + \sum_i \sigma_i(\lambda) SCD_i$$

- **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)	
Spatial CCD	1000 detectors
FOV (across-track)	28°
Swath width	3000 m
IFOV (across-track)	0.028°
Spatial resolution (across-track)	3 m (binned 60 m)
Spatial resolution (along-track)	4 m (binned 80 m)
Other	
Plane speed	72 mps
Integration time	58 ms
APEX total mass	354 kg
Radiometric calibration	yes

Spectral performance for NO_2 calibration window	
Spectral interval	370 - 600 nm
NO_2 fitting interval	470 - 510 nm
Spectral detectors	249 (unbinned mode)
Nominal FWHM	1.5 nm
In-flight FWHM	> 2.8 and < 3.3 nm
Nominal spectral shift from CW	< 0.2 nm
In-flight spectral shift from CW	> 0.05 and < 0.8 nm
Spectral sampling interval (SSI)	0.9 nm
Sampling rate	3.1 to 3.6 pixels per FWHM

Dornier DO-228, operated by DLR

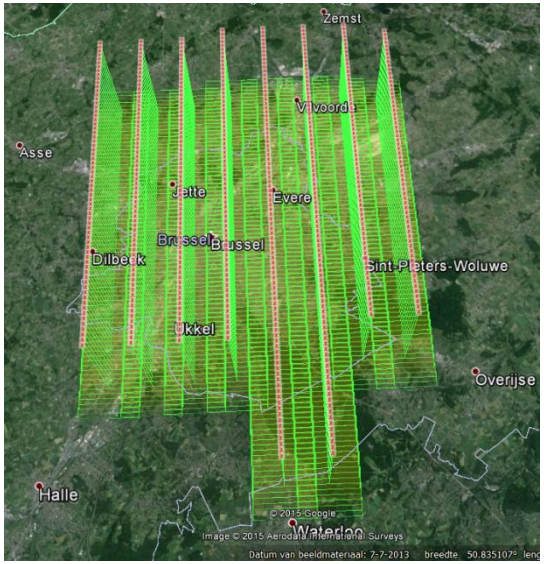
vito vision on technology

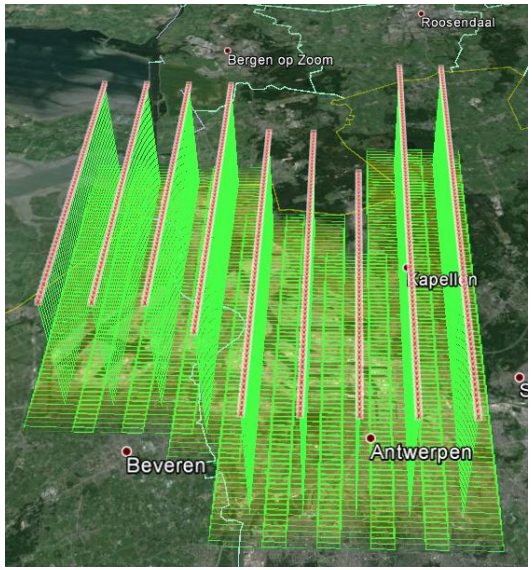
RSL measurements | products | policy

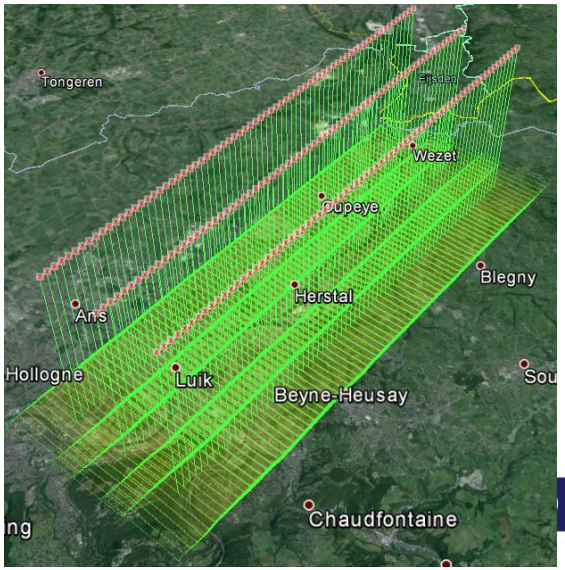
esa

VITO-TAP flight planning

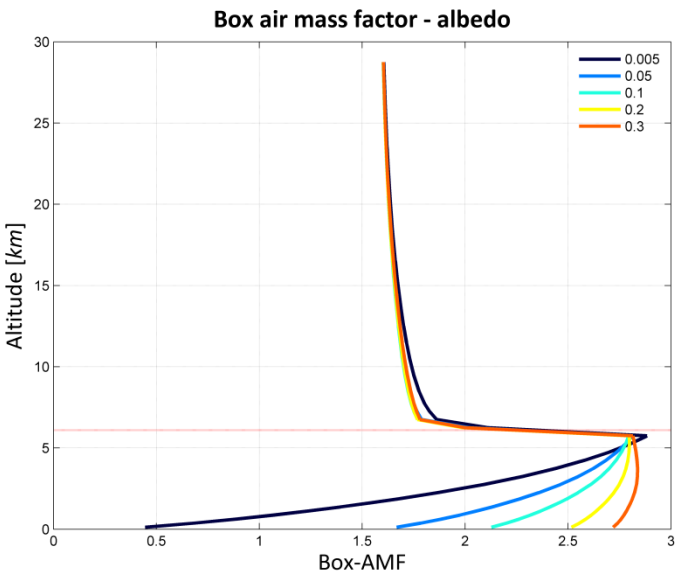
- Flight plan
  - Altitude: 20000ft. (6096 m)
  - Length of one flightline (FL): 16-22 km
  - Overlapping flightlines
  - Integration time: 58ms (typical for **unbinned** mode)
  - Extended FLs for “clean” reference spectra and more FLs downwind
  - Time of flight close to local noon or smallest SZA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



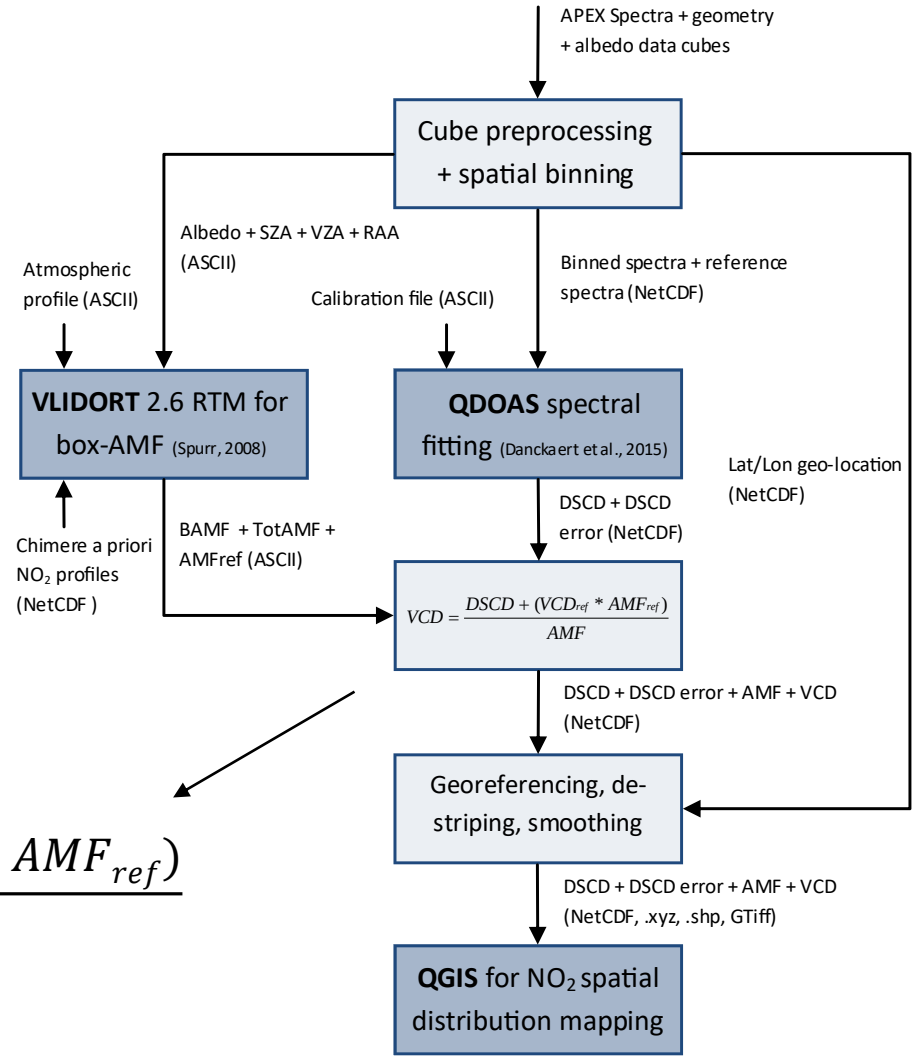




APEX NO_2 VCD retrieval algorithm



pixel size of 60 by 80 m² instead of 3 by 4

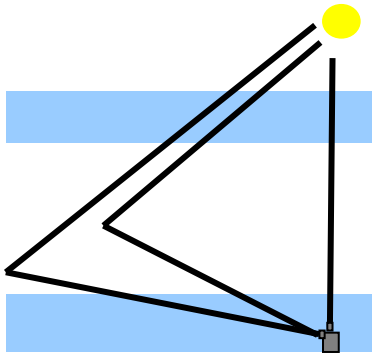


$$VCD_i = \frac{DSCD_i + (VCD_{ref} * AMF_{ref})}{AMF_i}$$

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

Multi-AXis DOAS

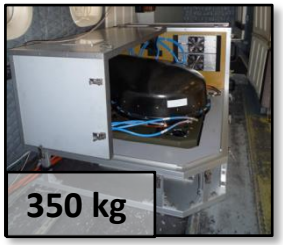


AROMAPEX campaign 2016 (Berlin)

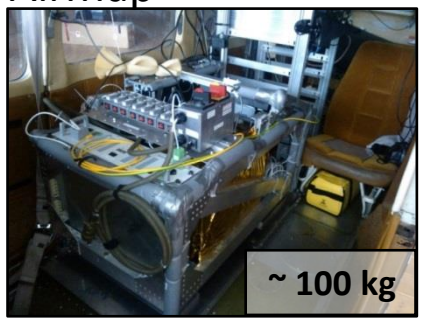
(Tack et al., 2018 in AMTD)

- 4 imaging sensors simultaneously operated
  - APEX (VITO/BIRA) } DLR Dornier (6 km AGL)
  - AirMAP (IUP Bremen/FU Berlin)
  - SWING (BIRA)
  - SpectroLite (TNO/TU Delft/KNMI) } FUB Cessna (3 km AGL)

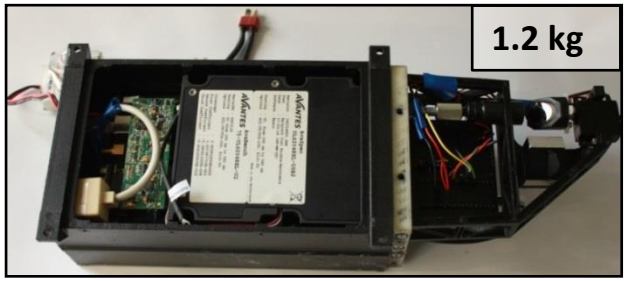
APEX



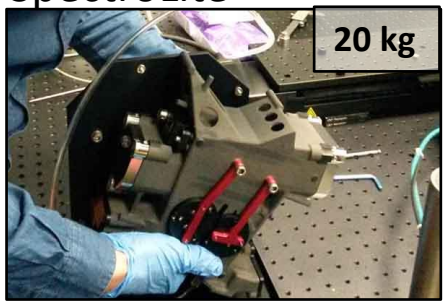
AirMap



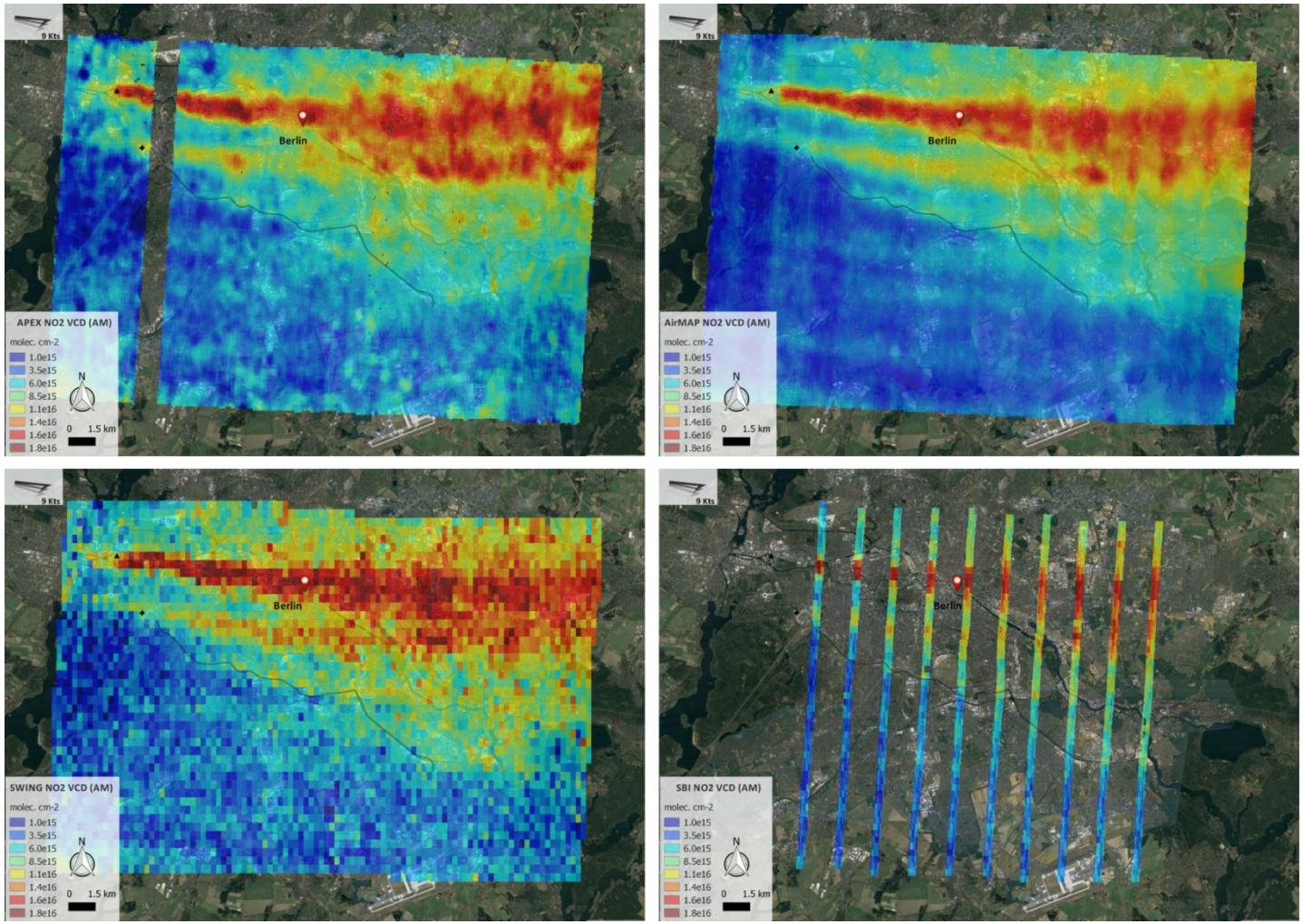
SWING



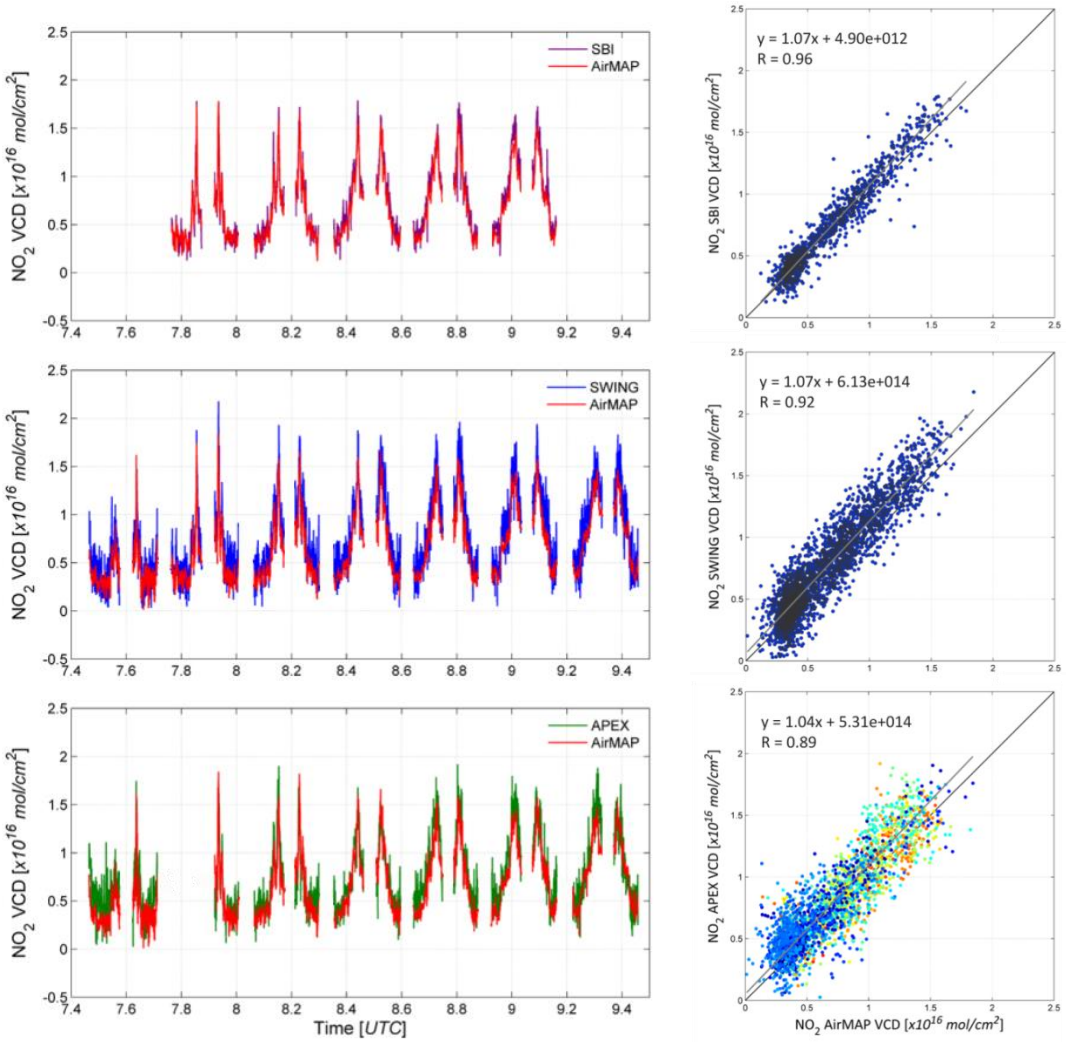
SpectroLite



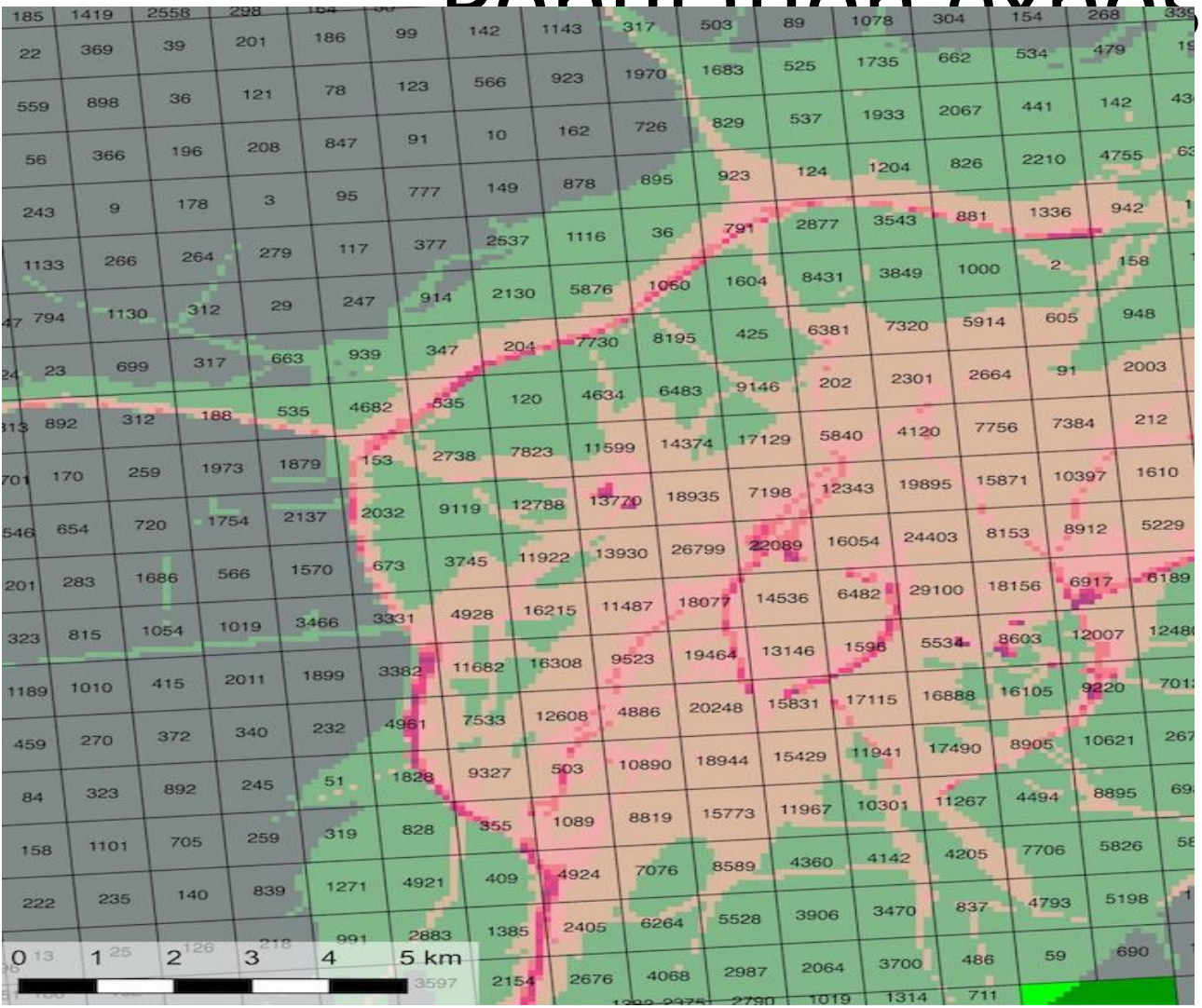
AROMAPEX campaign 2016 (Berlin)



AROMAPEX campaign 2016 (Berlin)



Population exposure



- the best population data set for the whole of Belgium: data from Census 2011 (Geostat – a Eurostat project)
http://census2011.fgov.be/idk/idk4_nl.html

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

- exposure calculated every hour for BC, NO2, O3, PM10 & PM2.5

http://www.irceline.be/air/pop_exp_bc.php
http://www.irceline.be/air/pop_exp_no2.php
http://www.irceline.be/air/pop_exp_o3.php
http://www.irceline.be/air/pop_exp_pm10.php
http://www.irceline.be/air/pop_exp_pm25.php

Variations in NO_2 surface concentrations on 15 April, 2015 in Antwerp between 9 and 11 a.m. (UTC)