Airborne Remote Sensing of Atmospheric Composition

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BIRA·IASB

aeronomie·be

GTEO « air-atmosphere », 27-11-2020

Outline

- **Introduction**
  - Airborne Imaging Differential Optical Absorption Spectroscopy (**I-DOAS**)
  - Motivation
  - Key applications

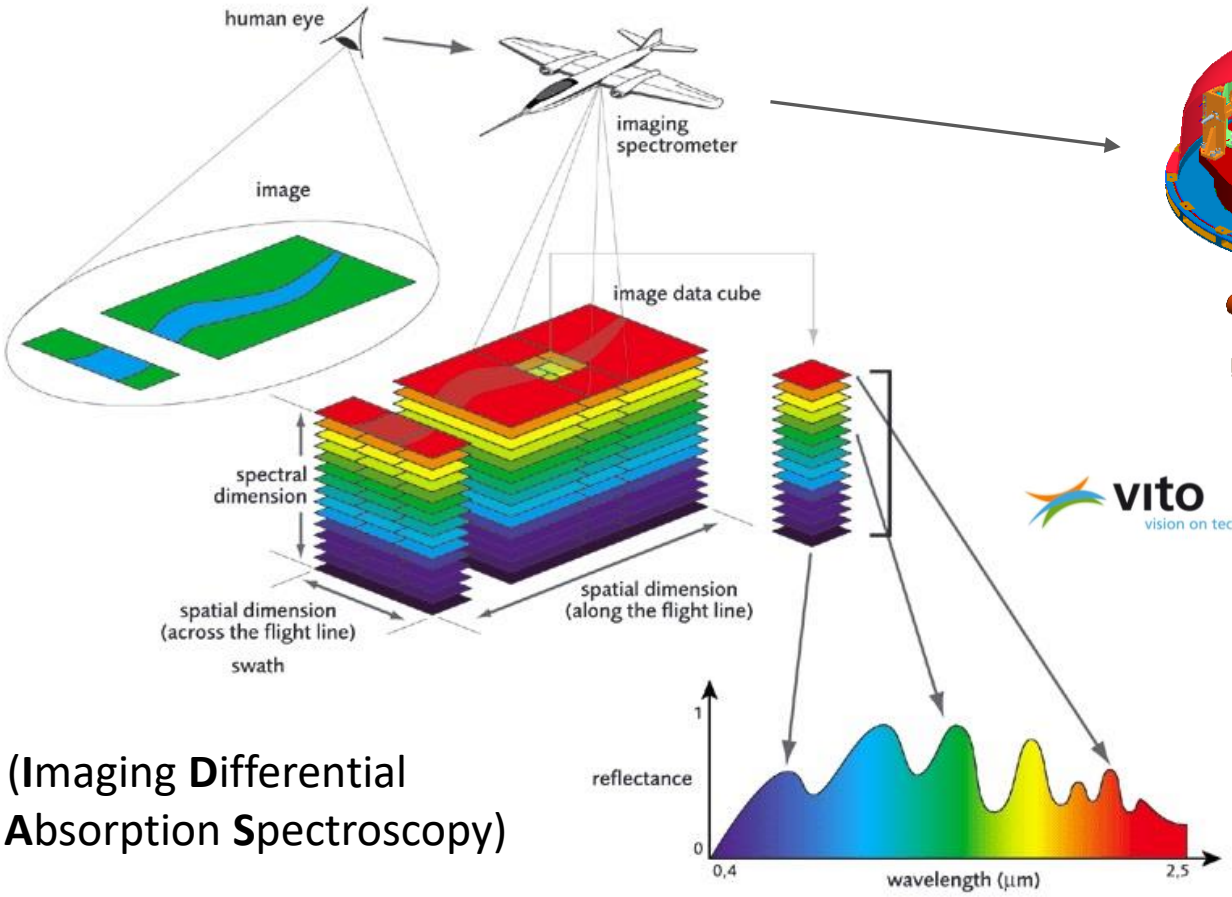
- **Airborne Remote Sensing of Atmospheric Composition**
  - Air quality monitoring & CTM validation → BELSPO **BUMBA project** (2015-2018)
  - Instrument testing and cal/val strategies → ESA **AROMAPEX project** (2013-2016)
  - S-5p/TROPOMI validation → ESA **S5PVAL-BE project** (2019-2021)

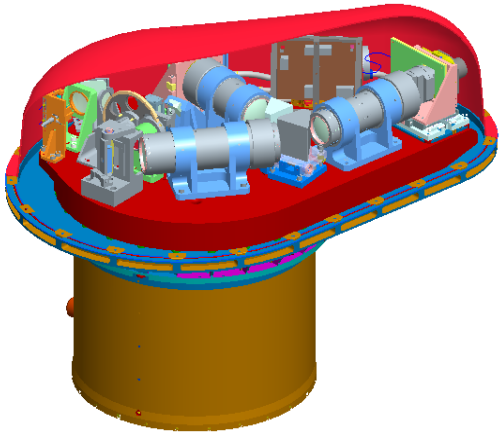
- **Conclusion & perspectives**

→ **Focus on tropospheric NO_2 and APEX hyperspectral imager**

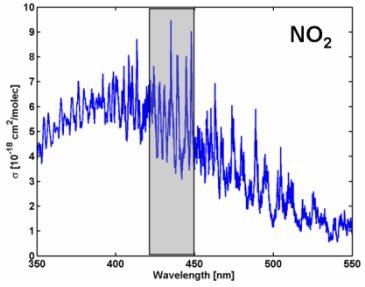
Airborne (APEX) imaging spectroscopy

APEX





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



Spectral fit between ~400-500 nm for NO_2

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

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

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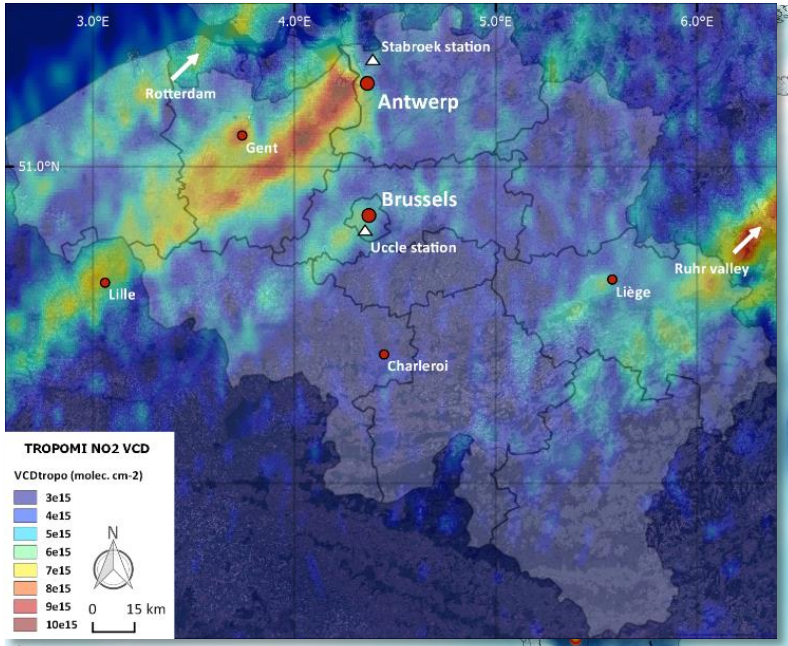
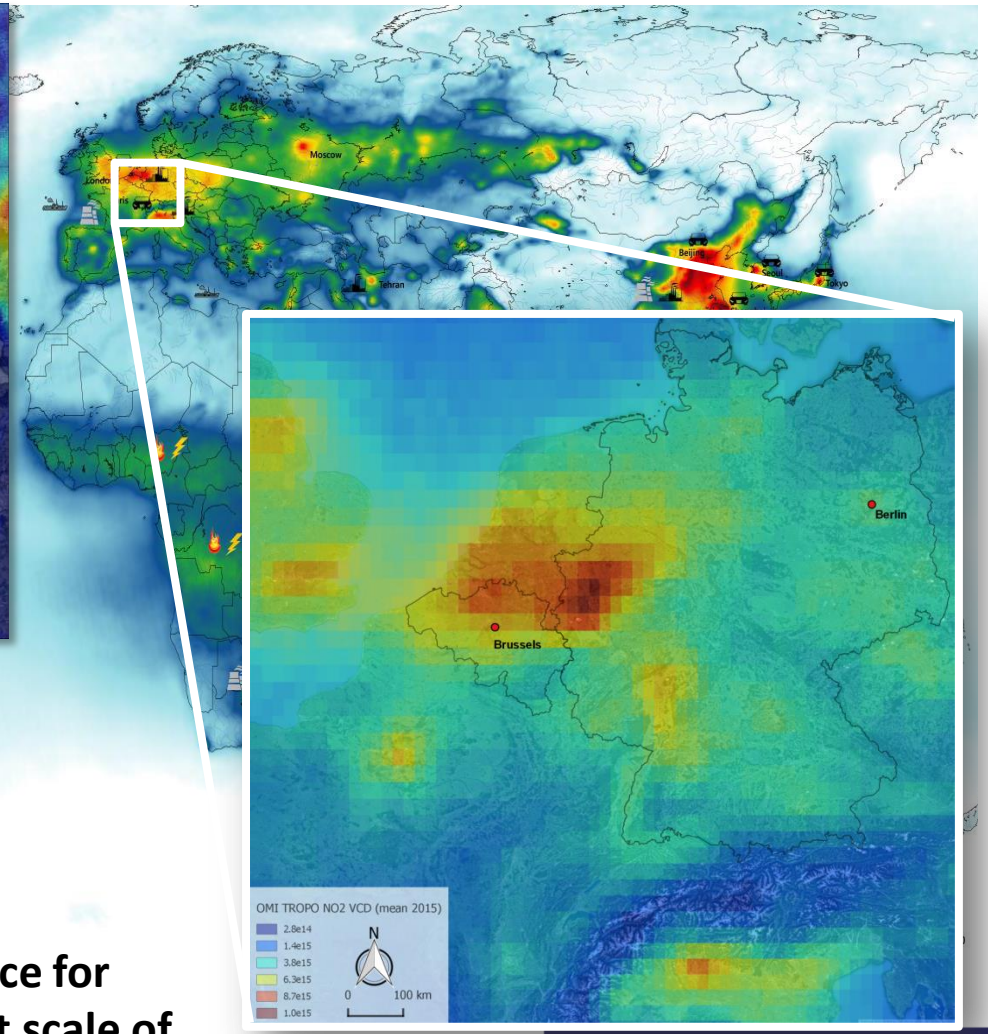
RSL measurements | products | policy

esa

Motivation





OMI 13 x 24 km^2
TROPOMI 7 x 3.5 km^2
APEX 80 x 60 m^2

Airborne sensors of great relevance for high resolution NO_2 monitoring at scale of cities → complementary to spaceborne

Key applications

- **Air quality monitoring** (BUMBA and AROMAPEX project)
  - Mapping of the spatial distribution of pollutants (e.g. NO_2, SO_2, HCHO) at high resolution (~100 m) over cities/industrialised areas
  - Gapfiller between spaceborne and ground-based observations
- Top-down HR **source identification** and **emission estimates**
- **Trend monitoring** and enforcement of (inter)national agreements, e.g. LEZ and ECA
- Chemistry transport **model validation** (BUMBA project)
- **Satellite validation** (S5PVAL-BE project)
- Support to **satellite mission design** (NITRO-CAM project)

BUMBA project 2015-2018 (Belgium)

- **BUMBA**: Belgian Urban NO_2 Monitoring Based on APEX remote sensing
- **Objectives**: 1) Air quality monitoring, 2) AQ/CTM model validation
- Published in Tack et al., 2017 in AMT

	Brussels	Antwerp	Liège	Antwerp	Liège
Date	30-06-2015	15-04-2015	15-04-2015	19-07-2016	29-06-2018
Flight time LT (UTC + 2)	14:43 - 16:04	10:06 - 11:30	11:55 - 12:18	15:33 - 18:03	10:18 - 10:40
# flightlines	8	9	3	14	4
Flight pattern (Heading °)	0 - 180	0 - 180	40 - 220	0 - 180	40 -220
SZA (°)	29.7 - 38.6	60.4 - 49.6	46.0 - 44.1	36.7 - 57.3	-
Average wind direction (°)	125	235	240	-	-
Average wind speed (Bft)	2	3	3	-	-
Temperature (°C)	27.2	18.7	20.8	-	-
PBL height (m)	1200	450	700	-	700
Lat (°N) / Long (°E)	50.8 / 4.4	51.2 / 4.4	50.6 / 5.6	51.2 / 4.4	50.6 / 5.6
Terrain altitude (m ASL)	76	10	66	10	66
Total population	1.175.173	513.570	195.968	513.570	195.968
Population density (#/km^2)	6751	2496	2828	2496	2828

BUMBAir.be

belspo

Ground-based campaign

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

irCELine Informing you on the air quality in the Belgian regions

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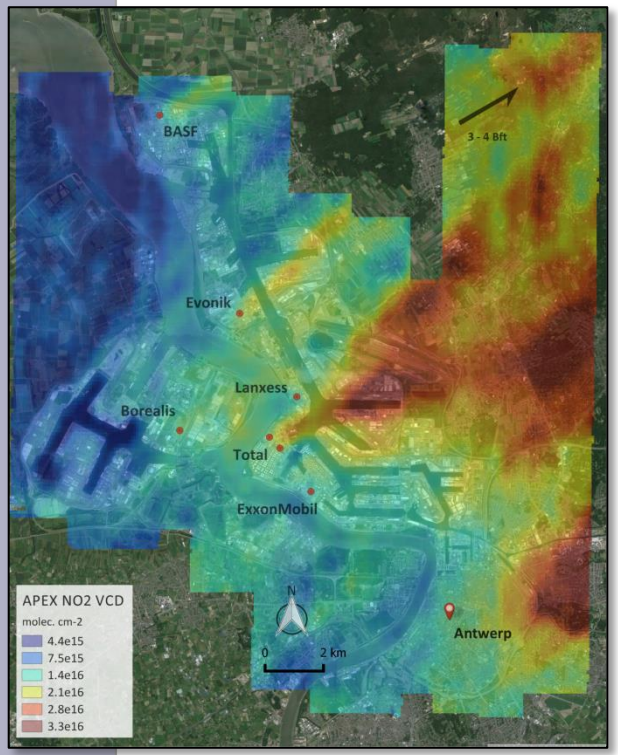
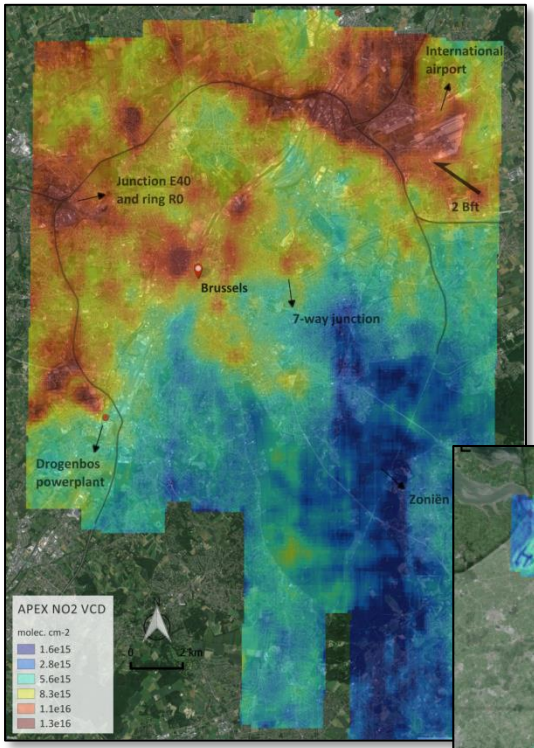
APEX NO_2 VCD retrievals (BUMBA)

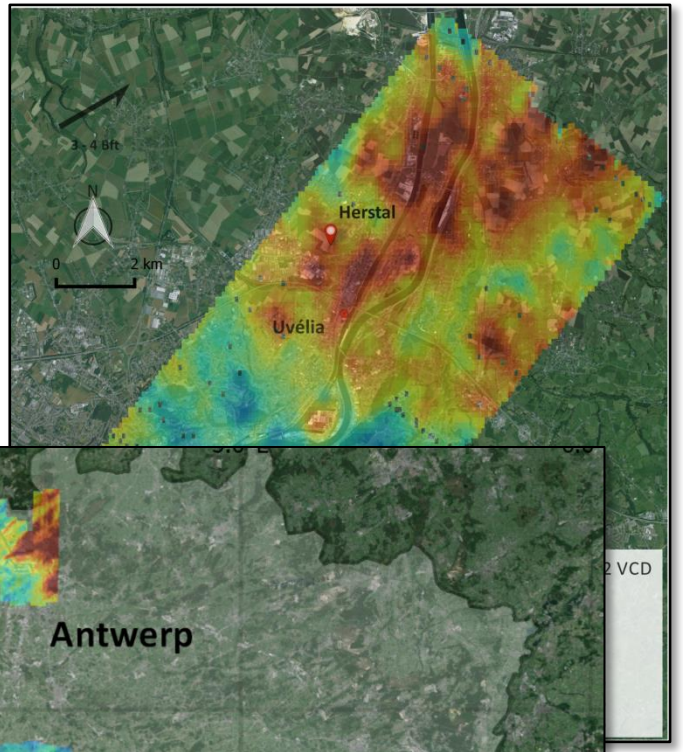
Antwerp: 15-04-2015

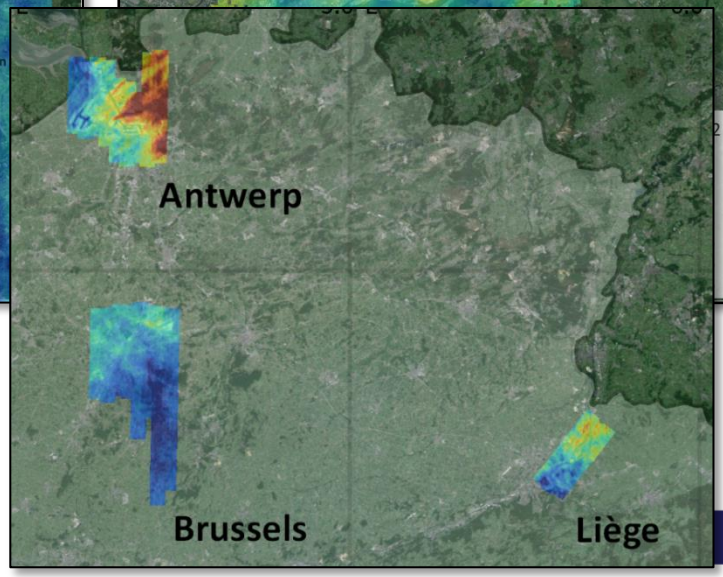


Brussels: 30-06-2015

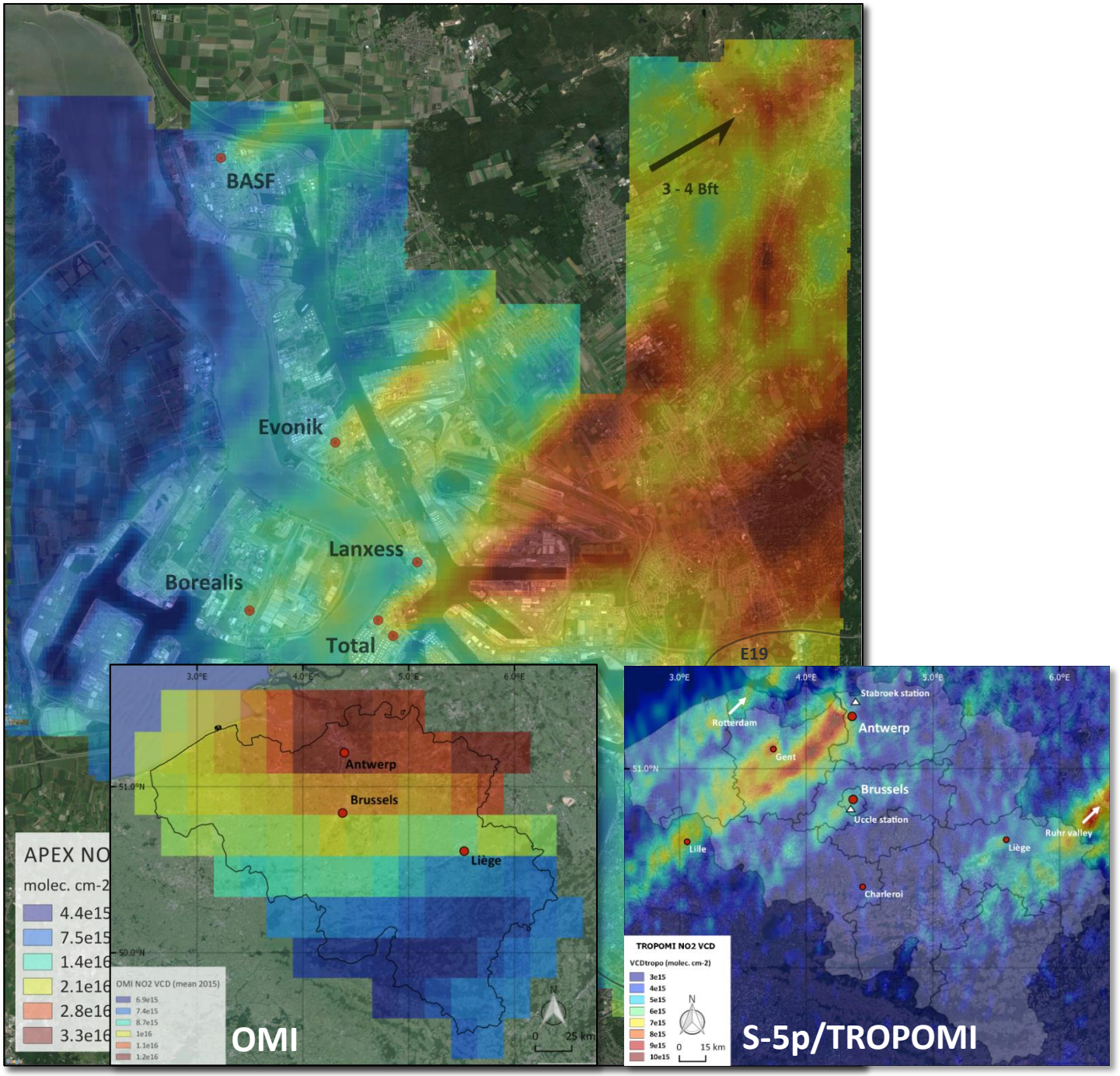


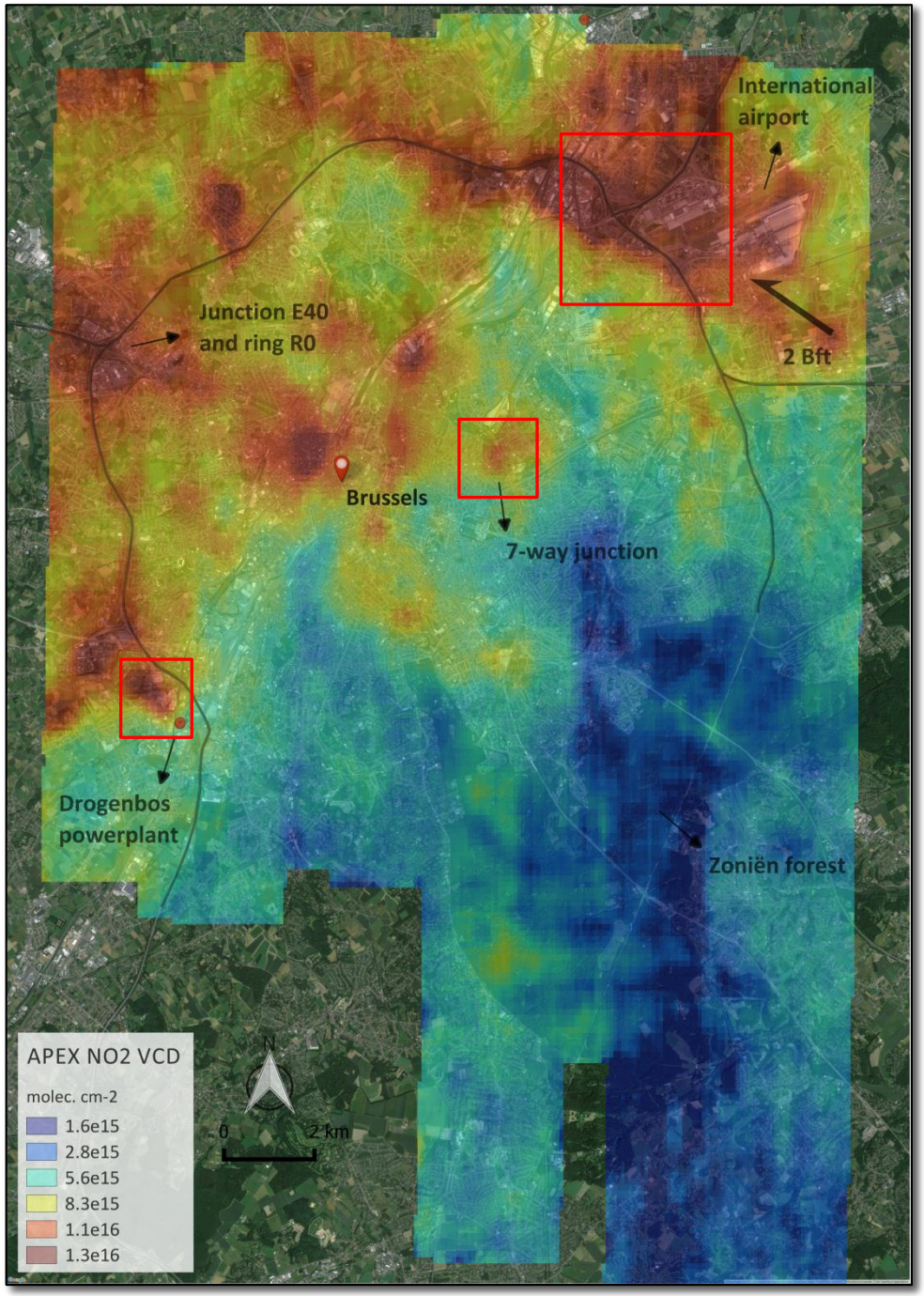
Liège: 15-04-2015

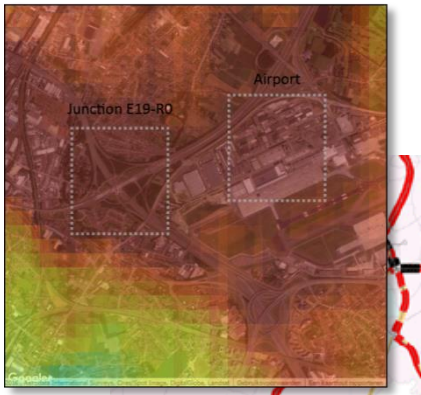


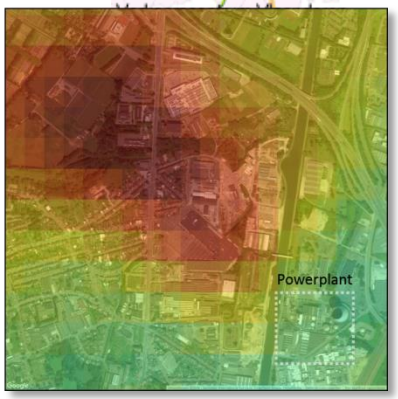


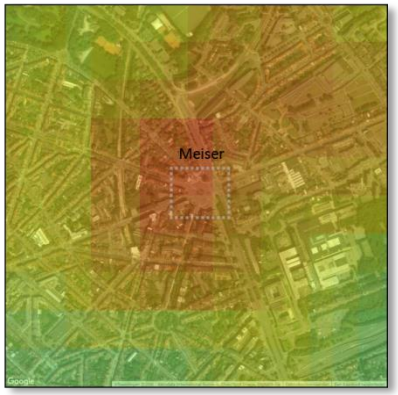
Note: color scales optimized for each flight

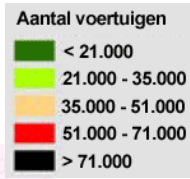

BASF
3 - 4 Bft
Evonik
Lanxess
Borealis
Total
E19
APEX NO
molec. cm-2
4.4e15
7.5e15
1.4e16
2.1e16
2.8e16
3.3e16
3.0°E
4.0°E
5.0°E
6.0°E
51.0°N
50.0°N
Antwerp
Brussels
Liège
OMI NO2 VCD (mean 2015)
6.9e15
7.4e15
8.7e15
1e16
1.1e16
1.2e16
N
0
25 km
OMI
Stabroek station
Rotterdam
Antwerp
Gent
Brussels
Uccle station
Ruhr valley
Lille
Liège
Charleroi
TROPOMI NO2 VCD
VCDtropo (molec. cm-2)
3e15
4e15
5e15
6e15
7e15
8e15
9e15
10e15
0
15 km
S-5p/TROPOMI


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

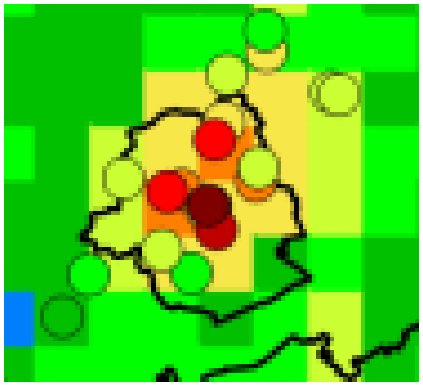

Aantal voertuigen
< 21.000
21.000 - 35.000
35.000 - 51.000
51.000 - 71.000
> 71.000

HR air quality model validation (BUMBA)

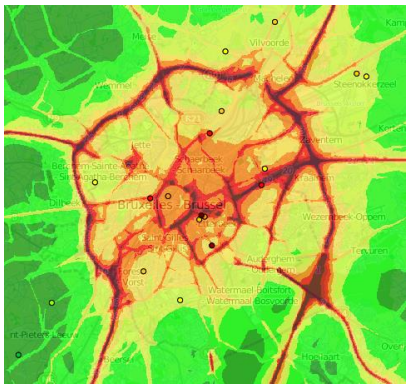
- Conversion of **APEX VCD columns to surface concentrations** based on 3D CTM (AURORA, CHIMERE)
- **RIO-IFDM quantitative validation**
  - Constrain model parameters/output based on APEX remote sensing data
  - Are the spatial patterns consistent ?
    - Yes : OK ☺
    - No: improve receptor points grid, assess sensitivity of input data (meteo, emissions), improve simplified model chemistry, etc.

RIO-IFDM (25x25 m²):
-Hourly mean NO_2, O_3, PM_{10}, $PM_{2.5}$

4 x 4 km² RIO



25 x 25 m² RIO-IFDM



http://geo.irceline.be/www/no2_hmean_rioifdm_EN.html

AROMAPEX project 2016 (Berlin, DE)

- **AROMAPEX** is an ESA **AROMAT** activity: Airborne Romanian Measurements of Aerosols and Trace gases (2013 -2016)
- **Objectives**: 1) Air quality monitoring, 2) Instrument testing, 3) cal/val strategies
- Published in Tack et al., 2019 in AMT

Berlin AM	Berlin PM
21-04-2016	21-04-2016
09:34 - 12:01	14:24 - 16:39
15	14
0 - 180	0 - 180
58.3 - 42.4	43.3 - 58.7
276	285
3	4
10	14
525	1075
52.28 / 13.18	52.28 / 13.18
70	70
3.500.000	3.500.000
3994	3994

Ground-based campaign

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

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat

Freie Universität Berlin

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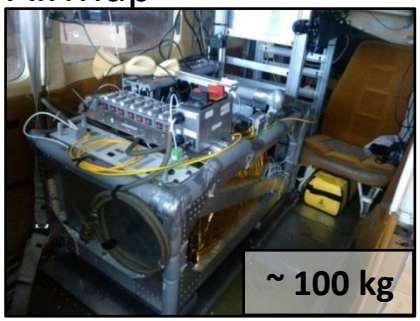
AROMAPEX project 2016 (Berlin, DE)

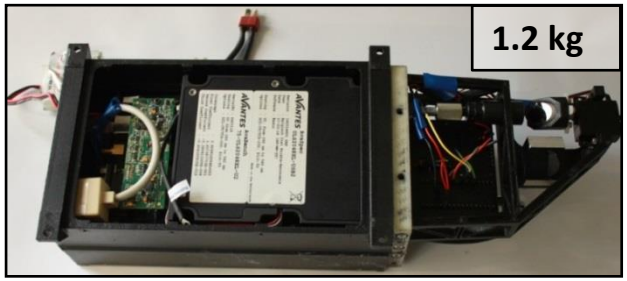
- **4 imaging sensors simultaneously operated**
  - **APEX** (VITO/BIRA) } DLR Dornier (6 km AGL)
  - **AirMAP** (IUP Bremen/FU Berlin)
  - **SWING** (BIRA)
  - **SpectroLite** (TNO/TU Delft/KNMI) } FUB Cessna (3 km AGL)

APEX

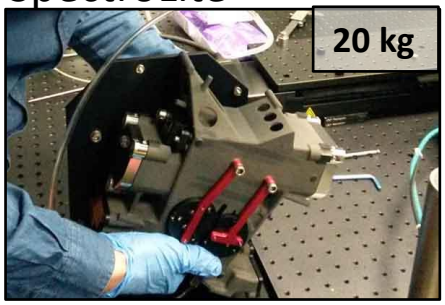
AirMap



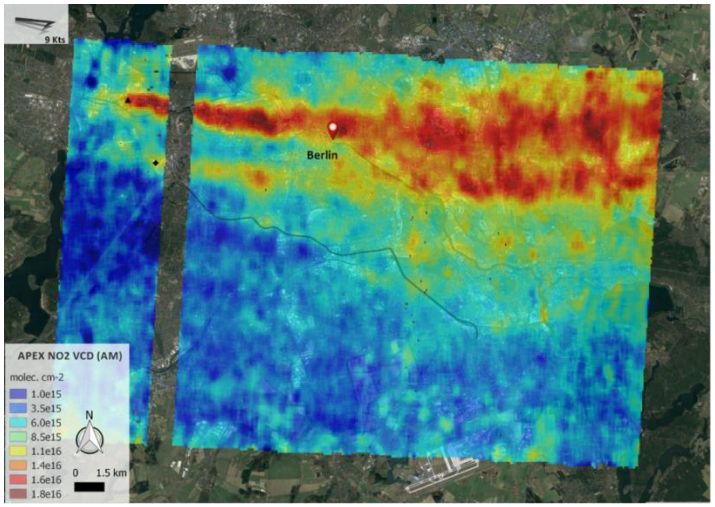
SWING

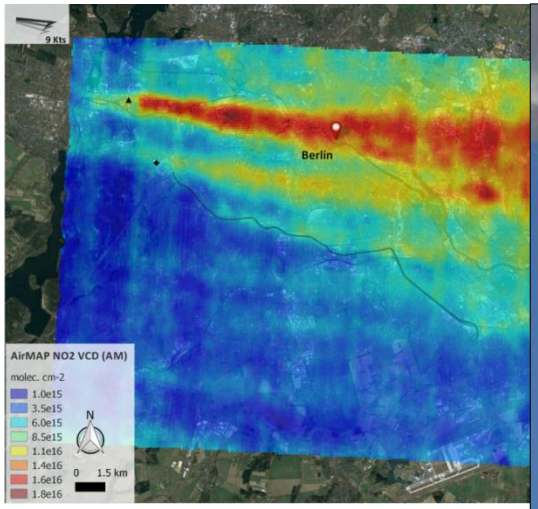


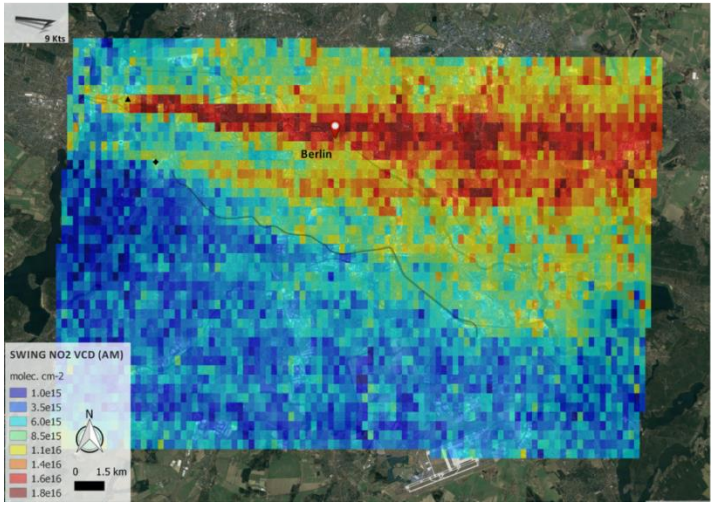
SpectroLite

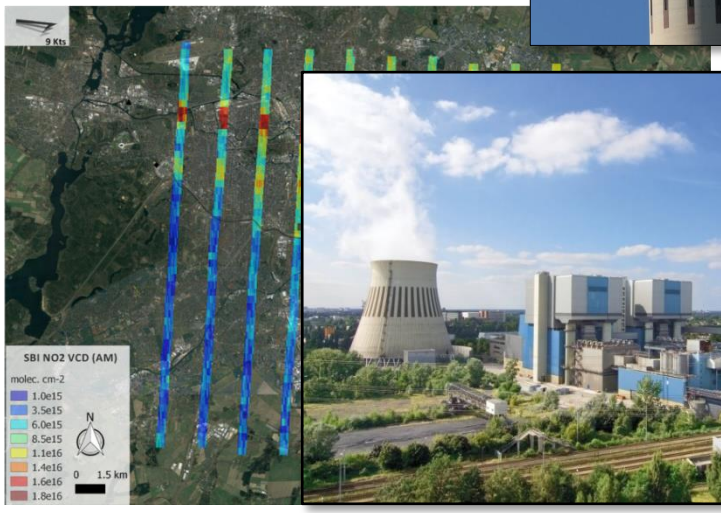


APEX NO_2 VCD retrievals (AROMAPEX)

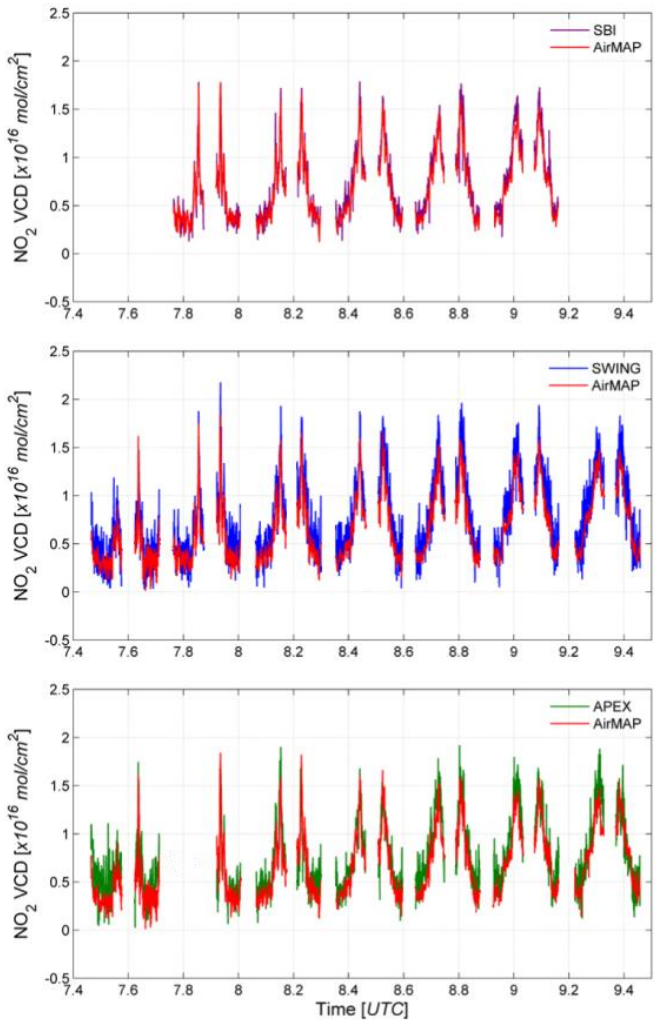


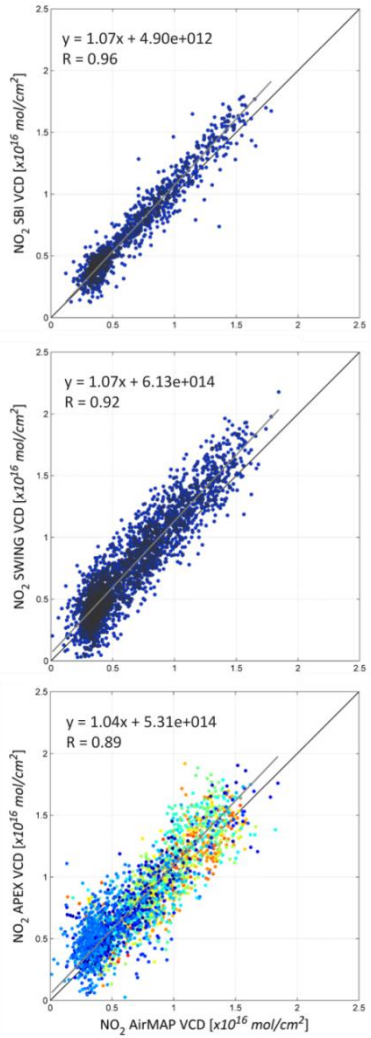






APEX NO_2 VCD retrievals (AROMAPEX)





S5PVAL-BE project 2019-2021 (Belgium)

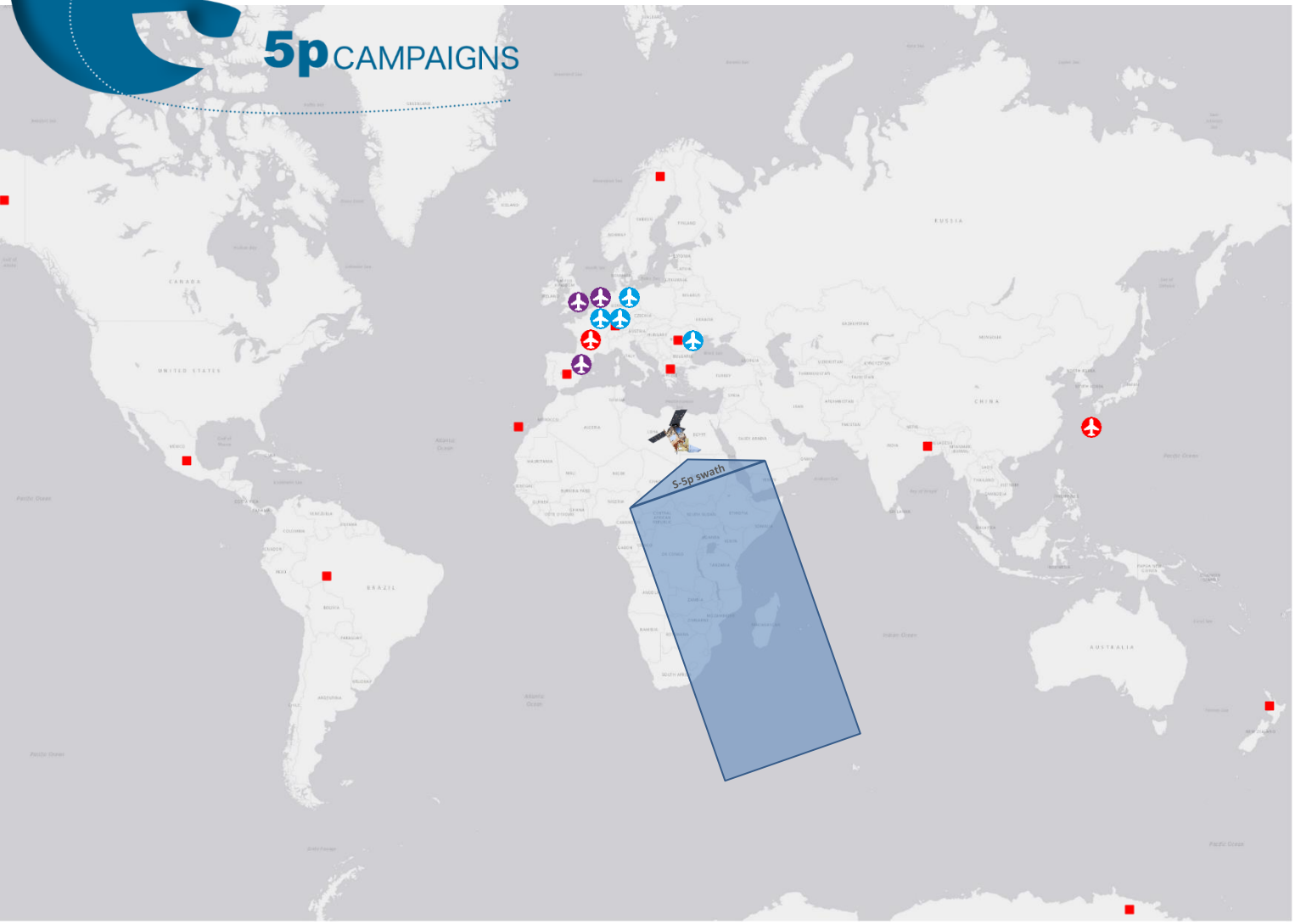
- **S5PVAL-BE**: Sentinel-5 precursor validation - Belgium
- **Objectives**: 1) S-5p NO_2 product validation, 2) Air quality monitoring
- Published in Tack et al., 2020 in AMTD

	Brussels	Antwerp	Brussels	Antwerp
Date	26-06-2019	27-06-2019	28-06-2019	29-06-2019
Flight time LT (UTC+2)	14:07 - 15:44	13:37 - 15:23	13:52 - 15:26	13:00 - 14:34
TROPOMI overpass LT (UTC+2)	13:16 (orbit 08811) 14:56 (orbit 08812)	14:37 (orbit 08826)	14:19 (orbit 08840)	14:00 (orbit 08854) 15:41 (orbit 08855)
# flight lines	12	11	12	11
Flight pattern (Heading)	0°, 180°	0°, 180°	0°, 180°	0°, 180°
SZA	28° - 36°	28° - 34°	28° - 34°	29° - 30°
Average wind direction	4°	36°	49°	143°
Average wind speed	3.7 m s^{-1}	3.7 m s^{-1}	2.6 m s^{-1}	2.6 m s^{-1}
Average temperature	26° C	23° C	24° C	30° C
Average PBL height	684 m	888 m	798 m	No Data

Ground-based campaign

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

5p CAMPAIGNS



S5PVAL-DE-RUHR
S5PVAL-DE-BERLIN
S5PVAL-RO
S5PVAL-BE
NET-Sense
MAGIC
ACCLIP
S5PVAL-KOLKATA
COCCON

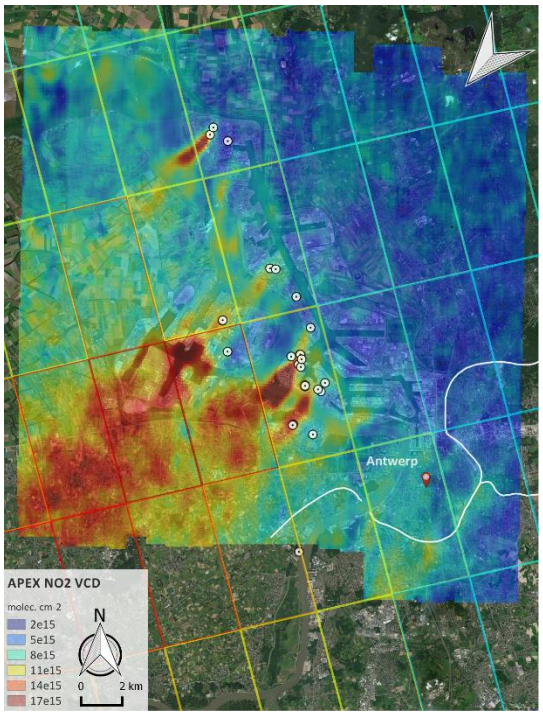
NO_2
SO_2
HCH
O
CO
CH_4

Legend

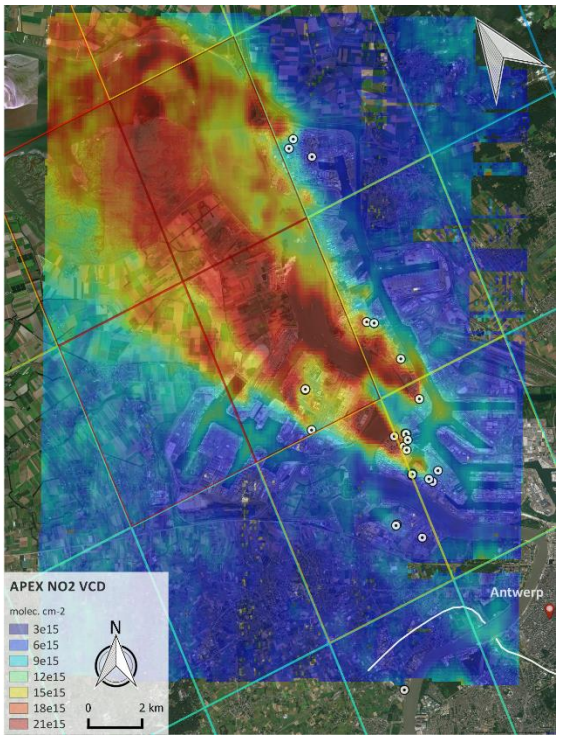
- Airborne UV-VIS
- Airborne IR
- Airborne UV-VIS & IR
- Ground-based IR

APEX NO_2 VCD retrievals (S5PVAL-BE)

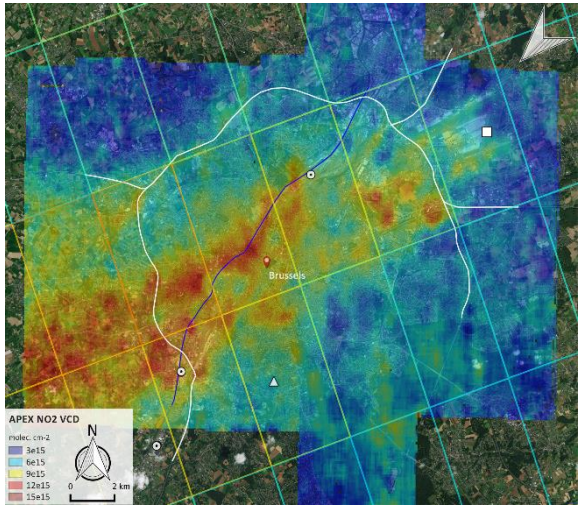
Antwerp: 27-06-2019



Antwerp: 29-06-2019

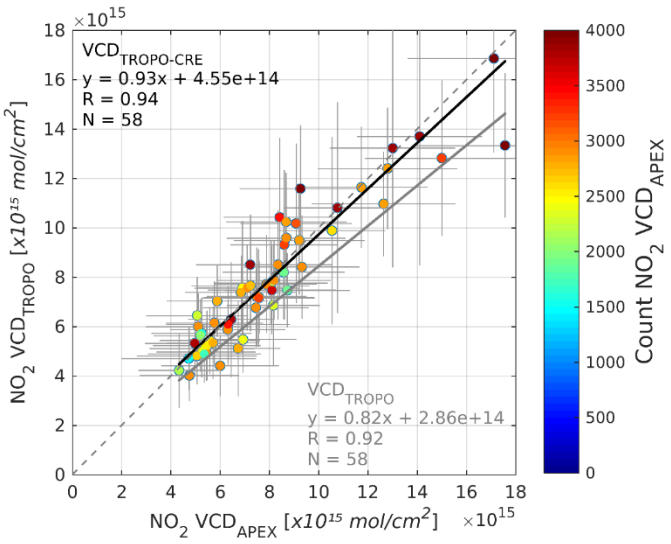


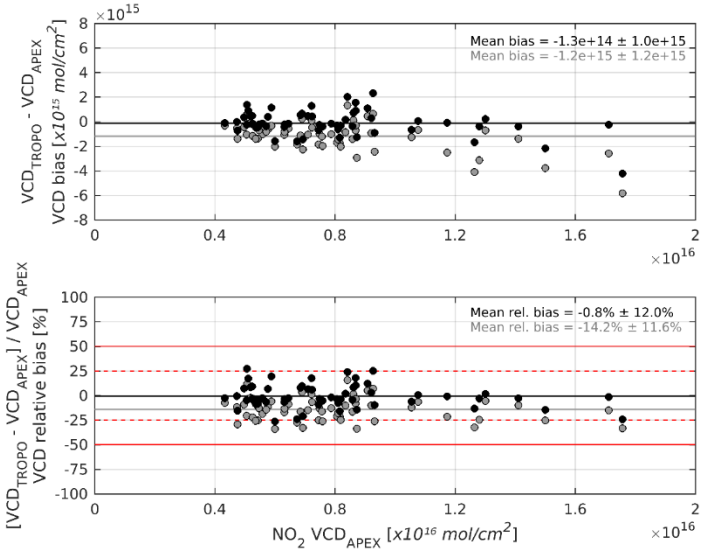
Brussels: 28-06-2019



APEX NO_2 VCD retrievals (S5PVAL-BE)

Scatterplots and linear regression analyses of co-located TROPOMI and averaged APEX NO_2 VCD retrievals for the data sets acquired on 26-29 June 2019 + **NO_2 VCD bias** ($VCD_{TROPO(-CRE)} - VCD_{APEX}$)





Conclusion and perspectives

- Demonstrated that clear NO_2 signals can be retrieved and individual NO_2 plumes can be identified over urban/industrialised areas based on airborne imaging data
  - High spatial resolution (~100 m^2)
  - High spatial coverage (350 km^2 within 90 minutes)
  - NO_2 VCD error approximately 20%

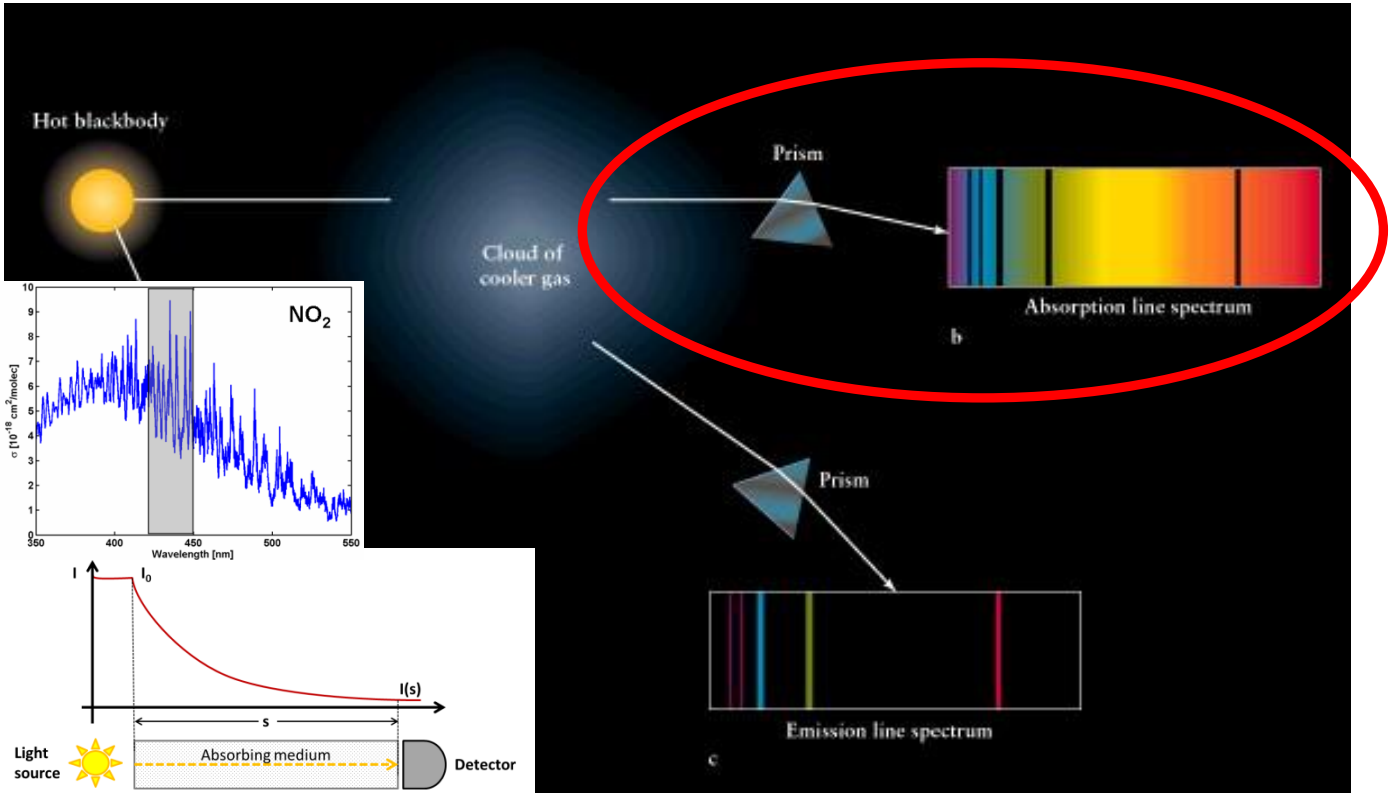
- High potential for
  - Better understanding of urban pollution → gap filler between spaceborne and ground-based
  - Completing emission inventories + trend monitoring
  - Validation of satellite measurements and AQ models + support to satellite mission design

- Perspectives
  - Need for recurrent/systematic flights for continuous monitoring → Now restricted to campaigns
  - Deployment in developing countries → Emission inventories are lacking or not well updated
  - Operations from HAPS and drones (ESA HAPS programme)

©ESA


...Thank you!
uv-vis.aeronomie.be/airborne
S5pcampaigns.aeronomie.be

DOAS for trace gas retrieval



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

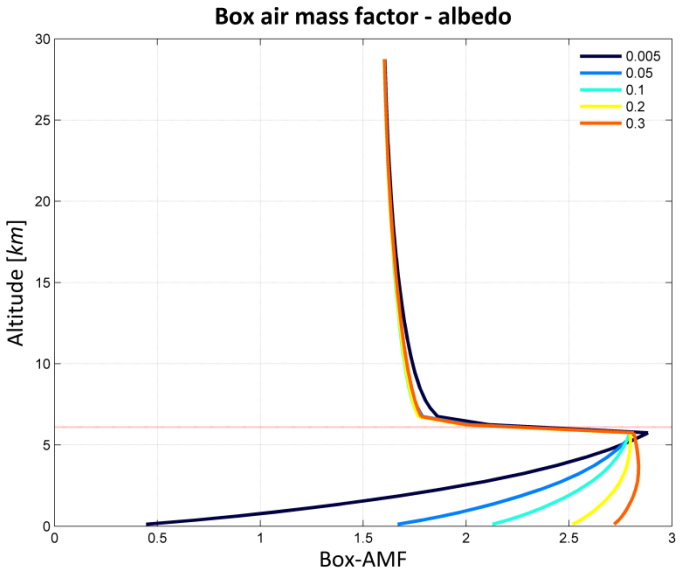
DOAS for trace gas retrieval

- 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**:

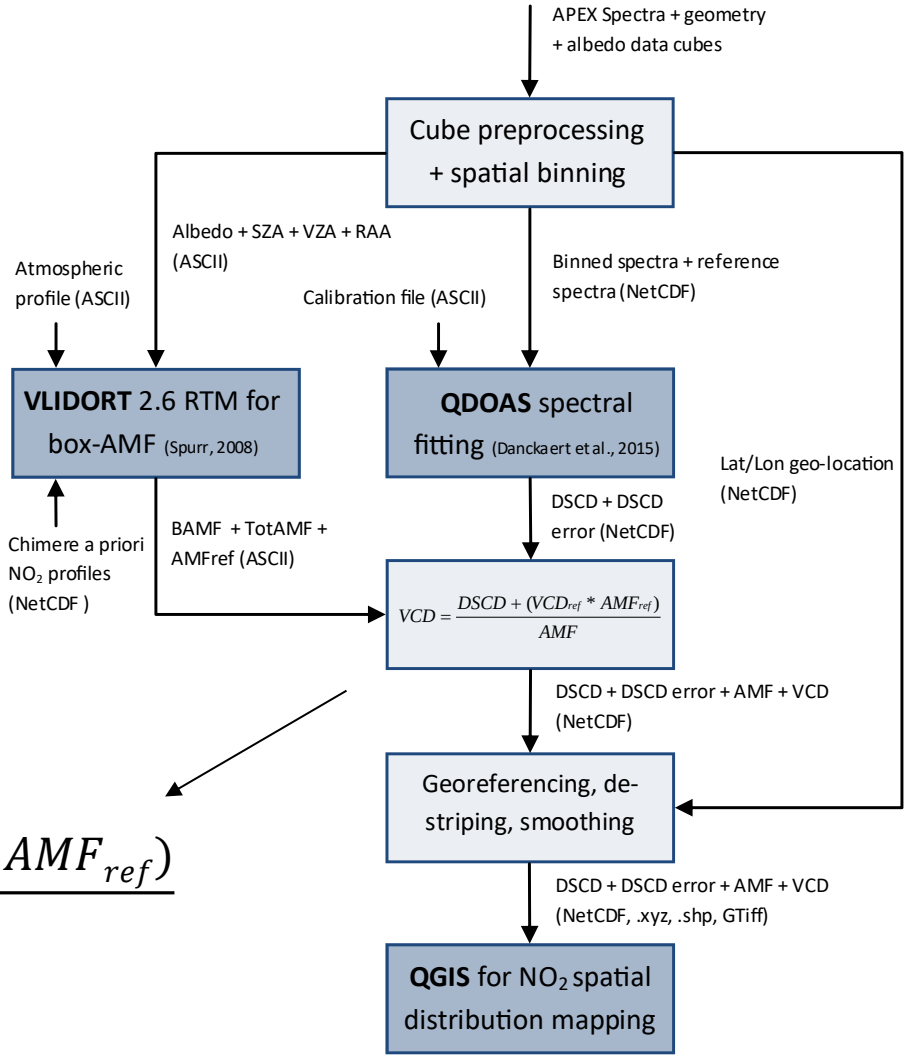
$$\ln \frac{I_o(\lambda)}{I(\lambda)} = Q_{(a)}(\lambda) + \sum_i \sigma_i(\lambda) SCD_i$$

  - **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

APEX NO_2 VCD retrieval algorithm



pixel size of 60 by 80 m^2 instead of 3 by 4



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

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