Airborne remote sensing in support of atmospheric satellite missions

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BIRA-IASB

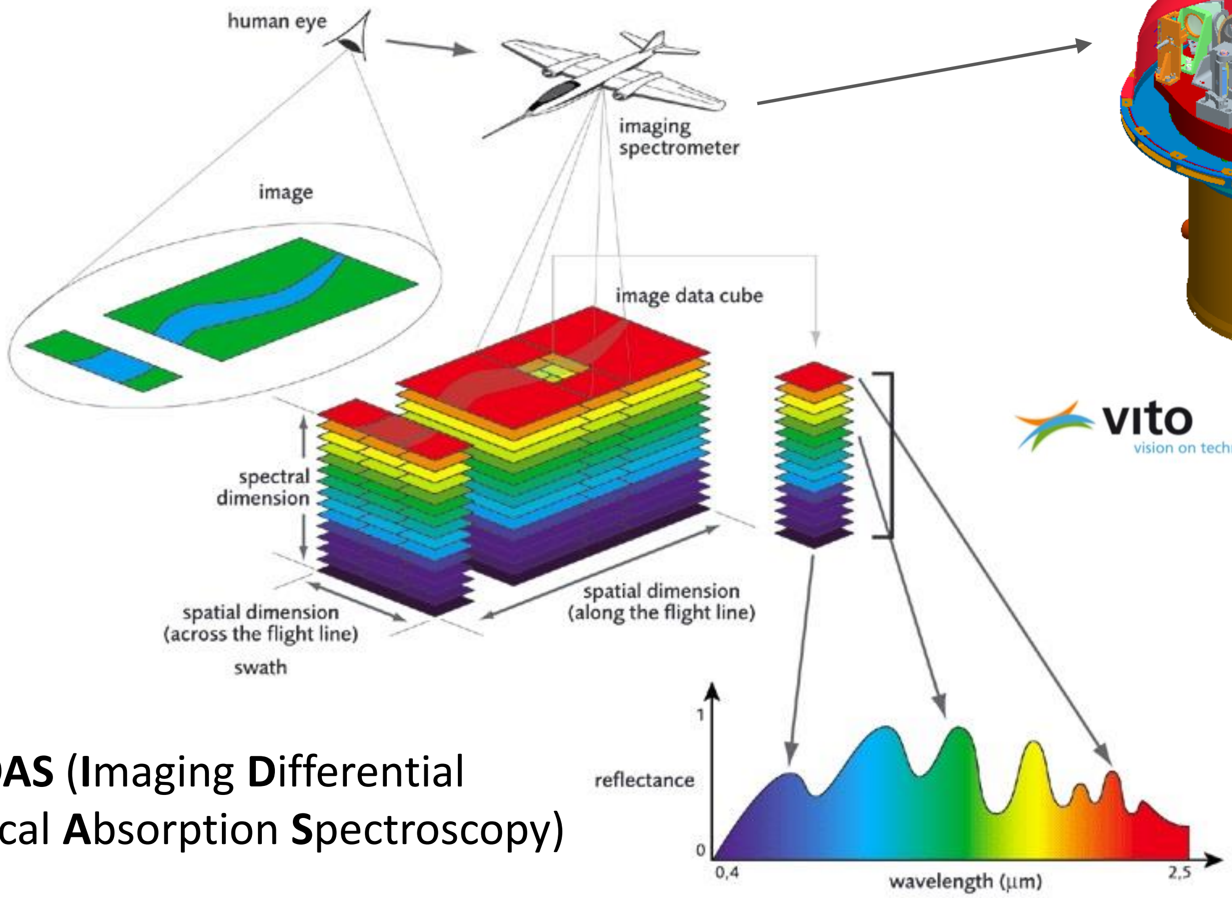
EUFAR Airborne Science Webinar, 15-06-2022

Outline

- **Introduction to airborne imaging**
  - Airborne Imaging Differential Optical Absorption Spectroscopy (**I-DOAS**)
  - Motivation
  - Key applications
- **Flight planning and survey strategies**
- **Airborne imaging systems**
- **Airborne imaging in support of atmospheric satellite missions**
  - Validation of satellite missions, dedicated to AQ and climate (ESA SVANTE/QA4EO project → S5P)
  - Support to future satellite mission design (ESA NITROCAM project → NITROSAT)
- **Conclusion & perspectives**

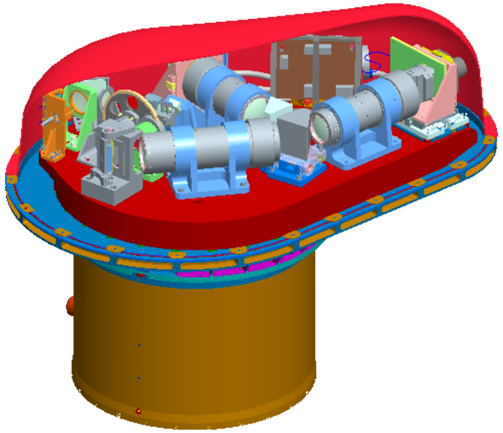
→ **Focus on hyperspectral imaging/mapping of UV-VIS products (mainly tropospheric NO_2)**

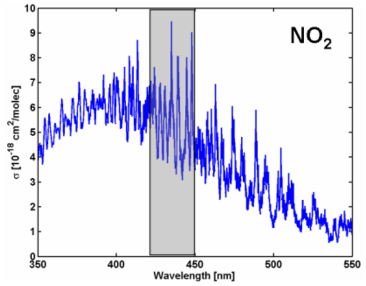
Airborne imaging spectroscopy



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

APEX

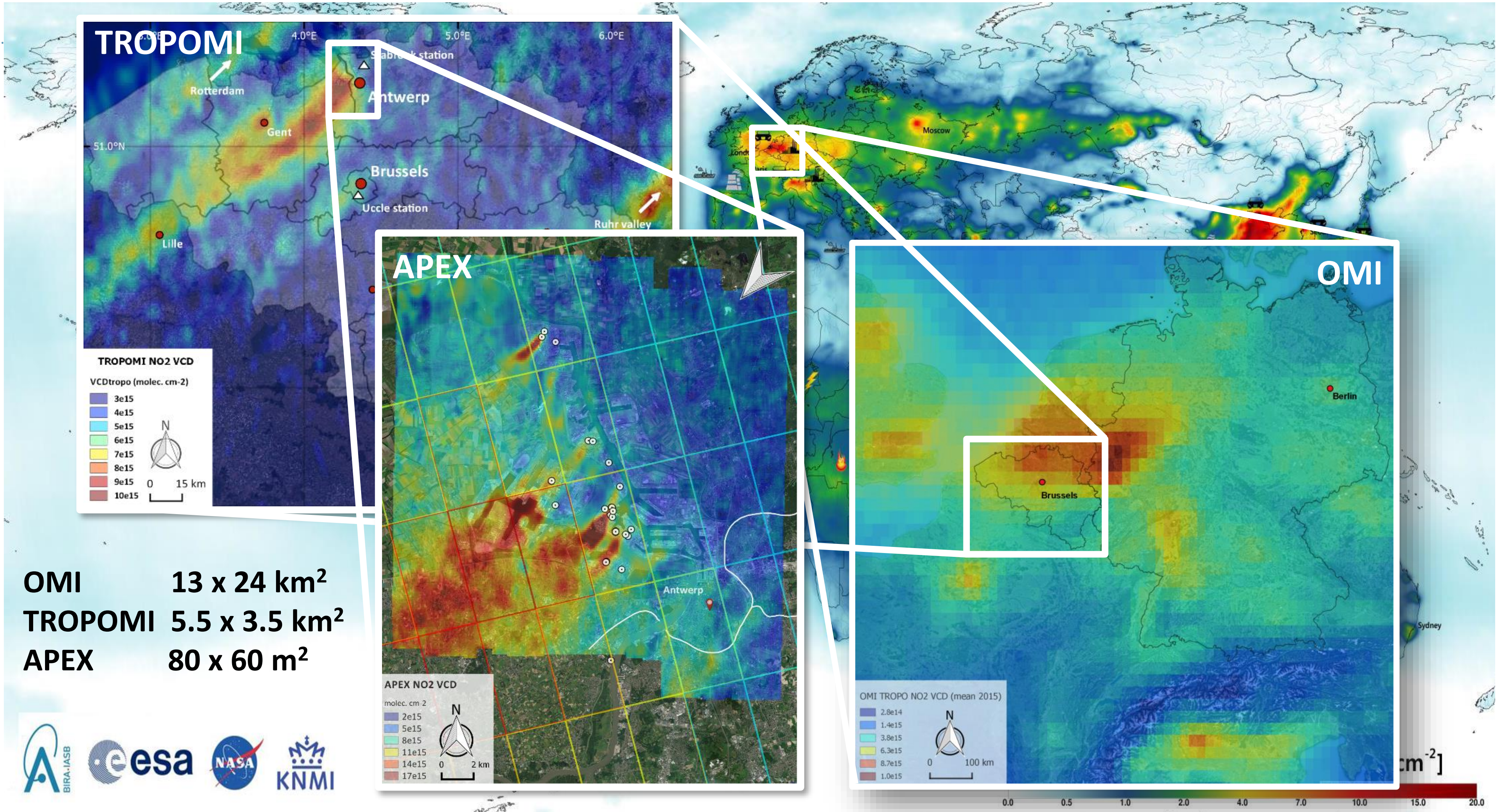




Spectral fit between ~400-500 nm for NO_2

Product: Slant column densities (SCD): integrated amount of molecules along the lightpath, expressed as molec. cm^{-2}

Motivation



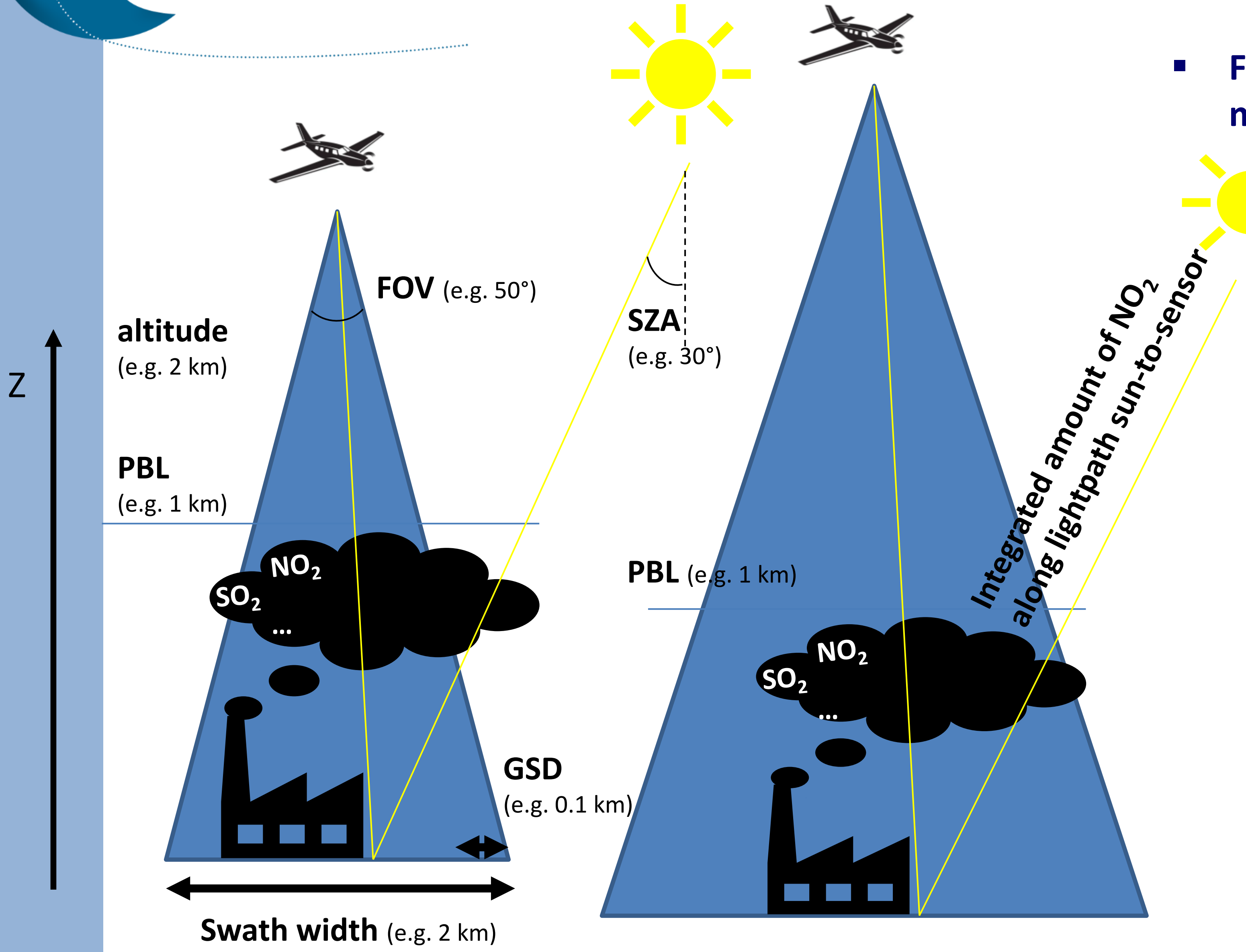
OMI 13×24 km^2
TROPOMI 5.5×3.5 km^2
APEX 80×60 m^2

Airborne sensors of great relevance for high resolution pollution mapping at scale of cities → complementary to spaceborne instruments

Motivation + 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
  - Top-down HR **source identification** and **emission rate estimation**
  - **Gapfiller** between spaceborne and ground-based observations
- **Trend monitoring**
- **Enforcement of (inter)national agreements and policymaking**, e.g. Paris Agreement (COP26, 2016), Green Deal, LEZ and ECA, etc.
- Chemistry transport **model input** or **validation** (BUMBA project)
- **Satellite validation +** study of satellite intra-pixel variability (SVANTE/QA4EO project)
- Support to future **satellite mission design** (NITROCAM project)
- …

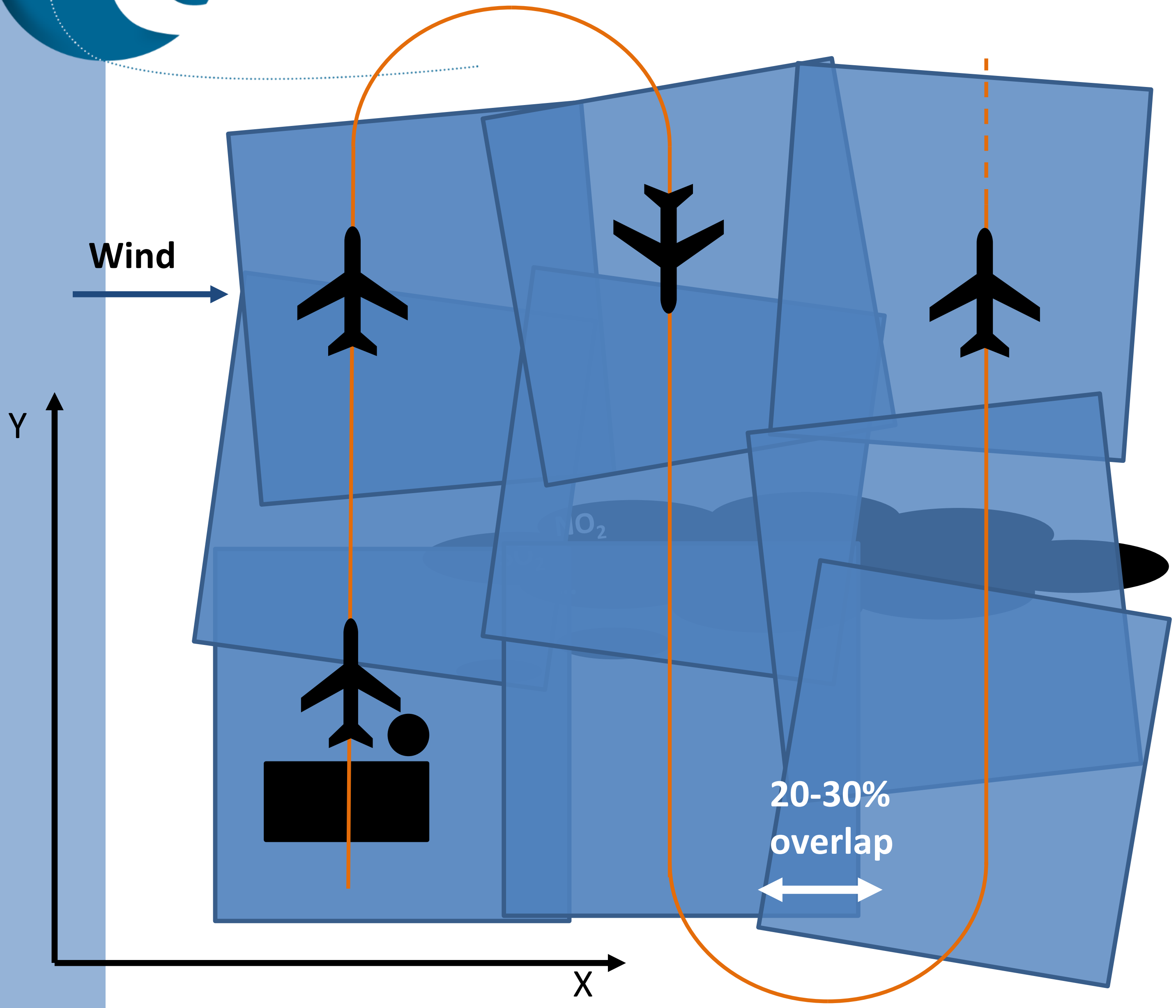
Flight planning for hyperspectral imaging



- **Flight planning requires much discussion and many trade-offs need to be taken into account:**
  - **Scientific properties**: *emission source location, air quality (quantify emission, identify source), satellite validation, etc.*
  - **Instrument properties**: *FOV, spectral and spatial resolution, SNR, detection limit, heat and/or pressure stabilization, etc.*
  - **Aircraft properties**: *speed, autonomy, max. altitude (pressurised?), amount of windows availabe, etc.*
  - **Flight approvals and ATC**: *restrictions in civil airspace due to airports, restrictions in military areas, last minute restrictions, etc.*
  - **Geo-physical properties**: *high sun (SZA), PBL height, clear-sky conditions, wind direction, temperature (related to thermal contrast), etc.*

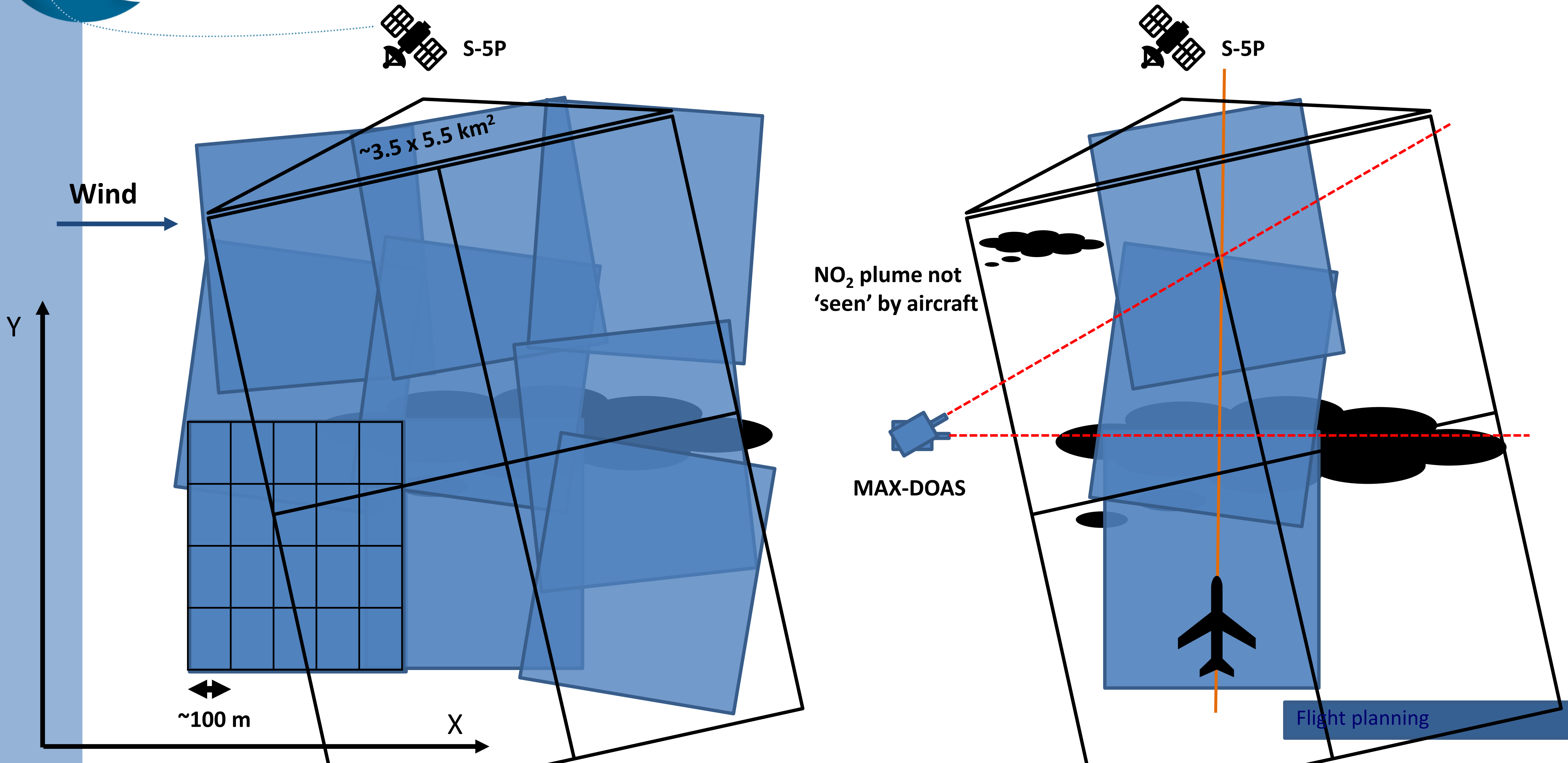
➡ **Each ‘choice’ is a compromise!**

Survey/mapping flight strategy



- Subsequent **overlapping (20-30%) flightlines** required for gapless mapping → compensating for roll, pitch and yaw
- Typically mapping time is **1.5-2 hours**, or 2.5-4 hours including ascend/descend
- Typically **area of 200-400 km^2** can be mapped (depends strongly on aircraft speed and FOV)
- Corresponding with **10-20 TROPOMI pixels**
- For satellite validation: mapping in close coincidence with overpass to reduce changes in NO_2 field (+/- 1 hour of overpass time)

Mapping vs transect flight for satellite validation



Centralised vs decentralised campaigns

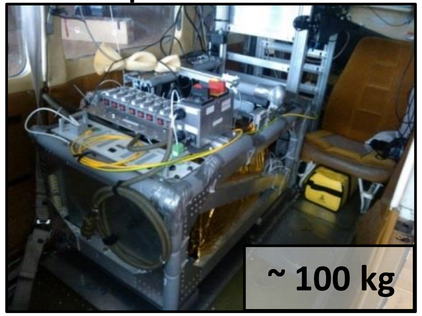
	Centralised campaigns	Decentralised/recurrent campaigns
Strengths	•Large number of teams and instruments •In-depth Cal/Val analysis •Intercomparison of instruments •Remote locations accessible •Exchange of knowledge	•Flexible •Cost-effective •Optimal distribution: latitude, species, pollution levels and sources, low vs high albedo, etc. •Recurrent (e.g. covering different seasons)
Weaknesses	•Requires much planning – more complex •Expensive •One shot/ Event-based (usually summer) •Requires strong local support	•Lack of routine (sensitive to errors) •No full instrument set up to intercompare •Reduced discussion between teams •Close to 'home base' of team or infrastructure
Examples	•AROMAT •AROMAPEX •NITROX •CINDI	•QA4EO •SVANTE •RAMOS •NITROCAM

UV-VIS hyperspectral imagers

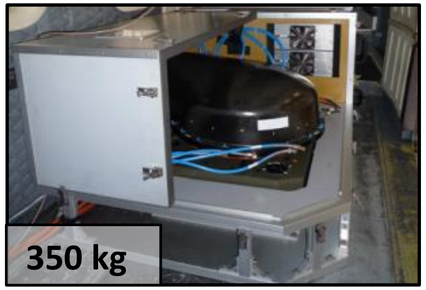
- Non-exhaustive list of deployed UV-VIS hyperspectral imagers

Instrument	Target (Tropo NO_2, HCHO, SO_2)	Reference
AirMAP	-Power plant (DE) -City of Bucharest + power plant (RO)	Schönhardt et al., 2015 Meier et al., 2017
APEX	-Zurich (city, airport, local harbour) (CH) -City of Brussels, Antwerp and Liège (BE) -TROPOMI validation (BE)	Popp et al, 2012 Tack et al., 2017 Tack et al., 2021
GCAS GeoTASO	-Houston city + harbour (refineries) (USA) -New York City and Long Island Sound (TROPOMI validation) (USA)	Nowlan et al., 2016 Nowlan et al., 2018 Judd et al., 2020
HAIDI	-Etna (IT) -Metropolitan area of Indianapolis (USA)	General et al., 2014
iDOAS	-Highveld Power plants (ZA)	Heue et al., 2008
SPECTROLITE (SBI)	-City of Berlin + power plant (DE)	Vlemmix et al., 2017 Tack et al., 2019
SWING	-City of Bucharest + power plant (RO)	Merlaud et al., 2018 Merlaud et al., 2020

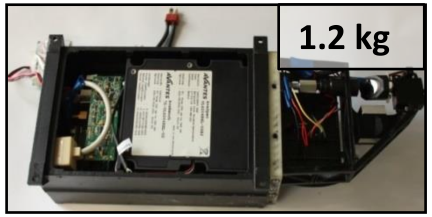
AirMap



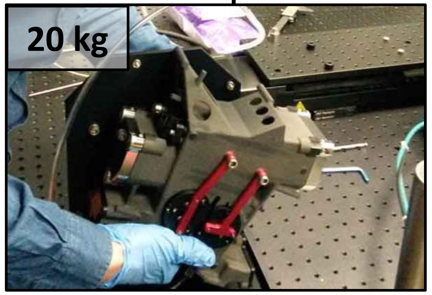
APEX



SWING

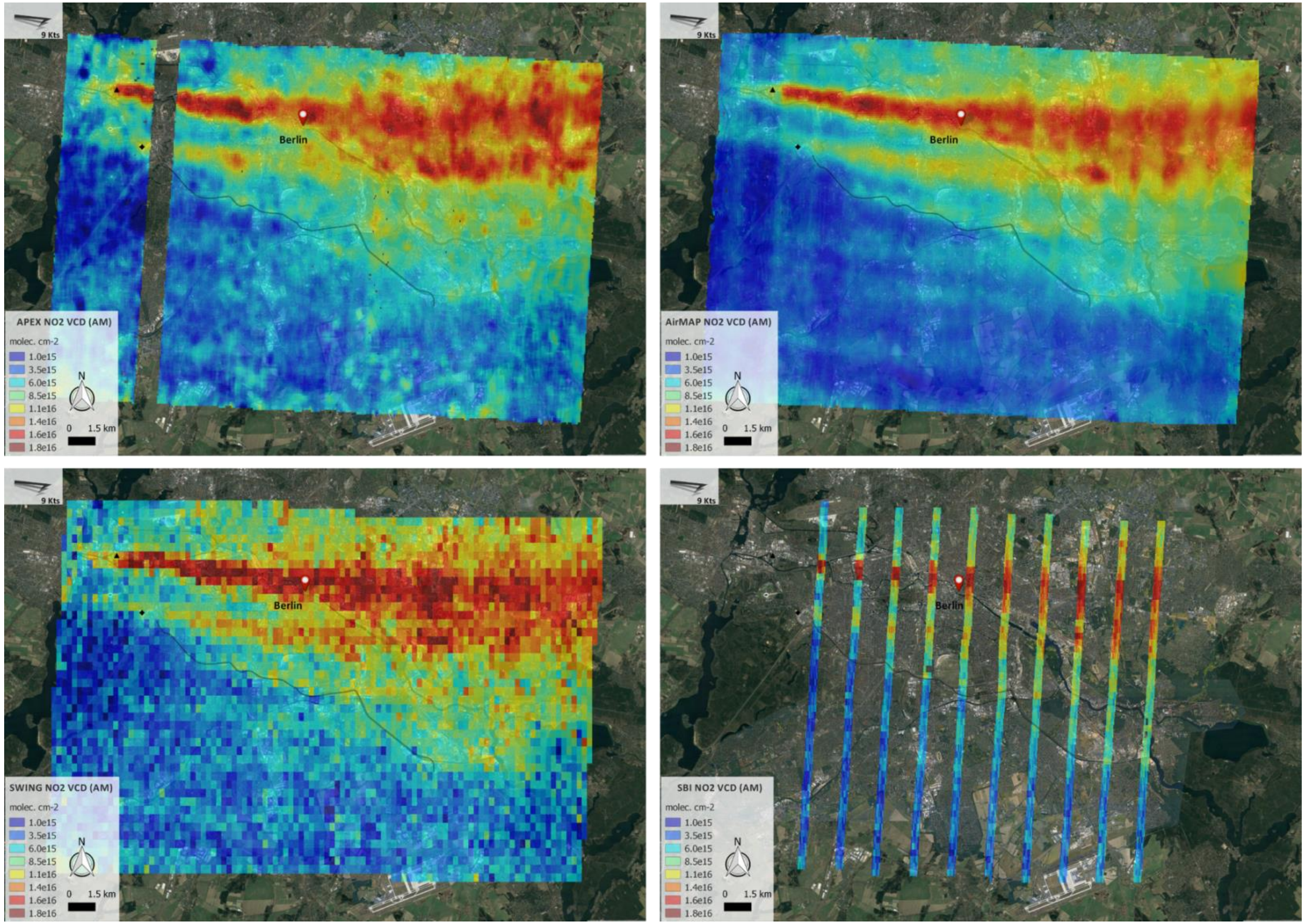


SpectroLite



UV-VIS hyperspectral imagers

NO_2 VCD over Berlin – 21/04/2016

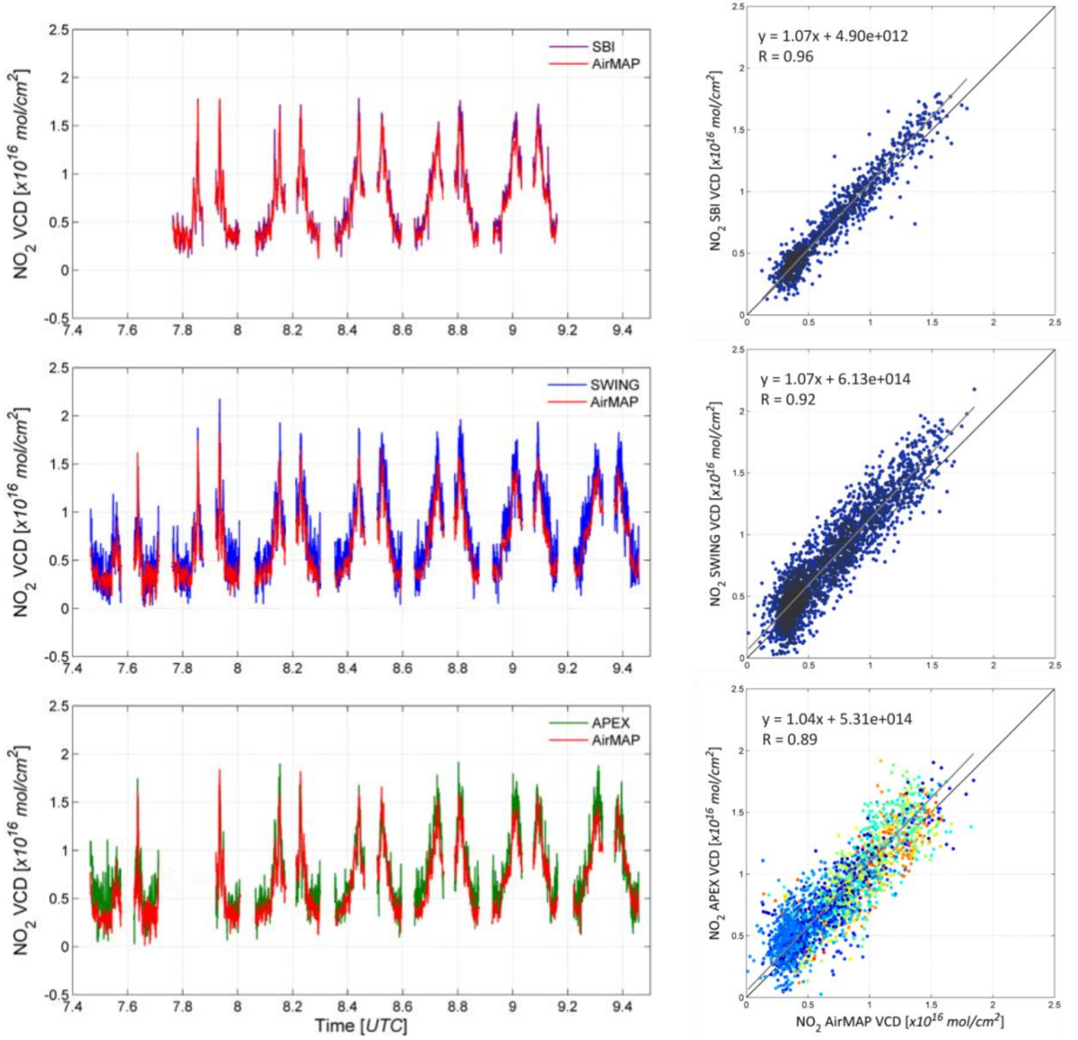


2016 AROMAPEX campaign over Berlin, Germany – mapping of NO_2 (Tack et al. 2019)

Reuter West CHP powerplant

1870 $t.yr^{-1}$ NOx (EEA, 2017)

UV-VIS hyperspectral imagers



2016 AROMAPEX campaign over Berlin, Germany – mapping of NO_2 (Tack et al. 2019)

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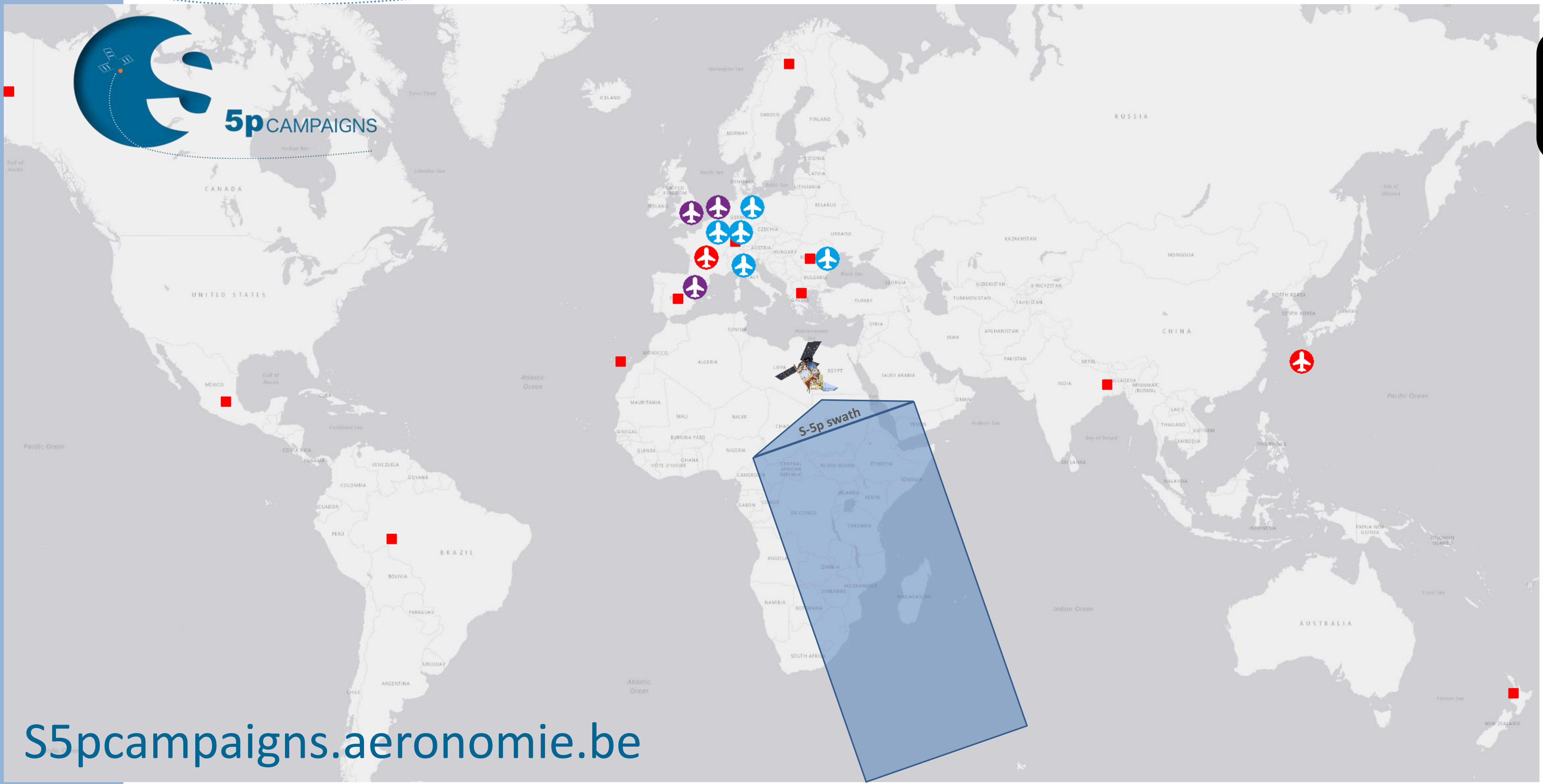
ESA SVANTE and QA4EO campaigns – S5P validation



S5PVAL-DE-RUHR
S5PVAL-DE-BERLIN
S5PVAL-RO
S5PVAL-BE
S5PVAL-TRANS

NO_2
SO_2
HCHO

NET-Sense

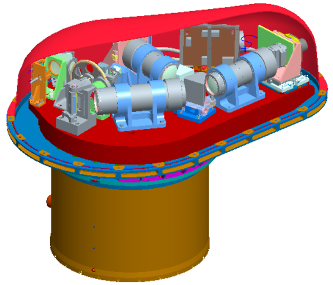
MAGIC
ACCLIP
S5PVAL-KOLKATA
COCCON

CO
CH_4

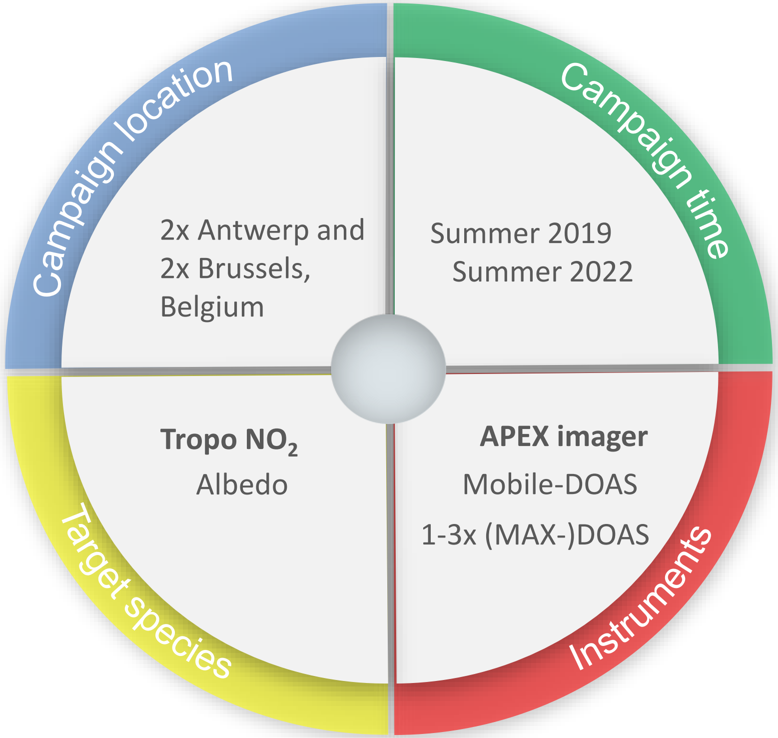
Legend
- Airborne UV-VIS
- Airborne IR
- Airborne UV-VIS & IR
- Ground-based IR

S5PVAL-BE

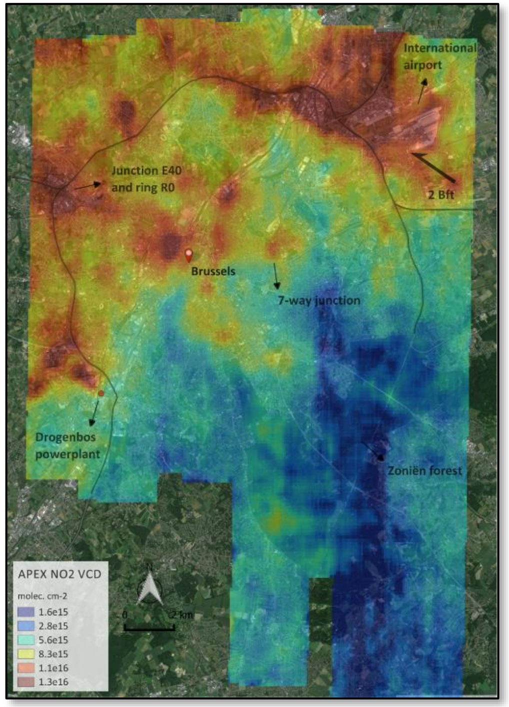
APEX

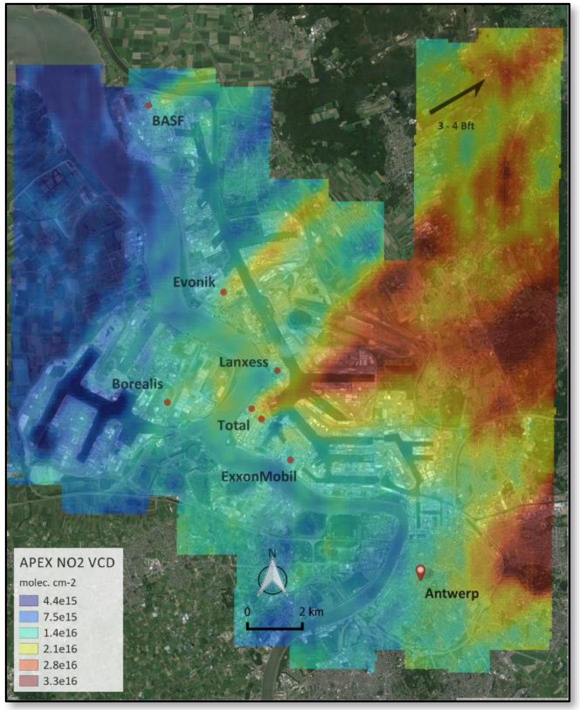


- Airborne mapping of tropospheric NO_2 with **APEX imager** (VIS - 80 m x 60 m)
- Antwerp one of largest petrochemical clusters in Europe + urban emissions
- 4th APEX flight campaign over these sites (BUMBA project) and 2nd for S-5p validation



BUMBA campaign (2015)





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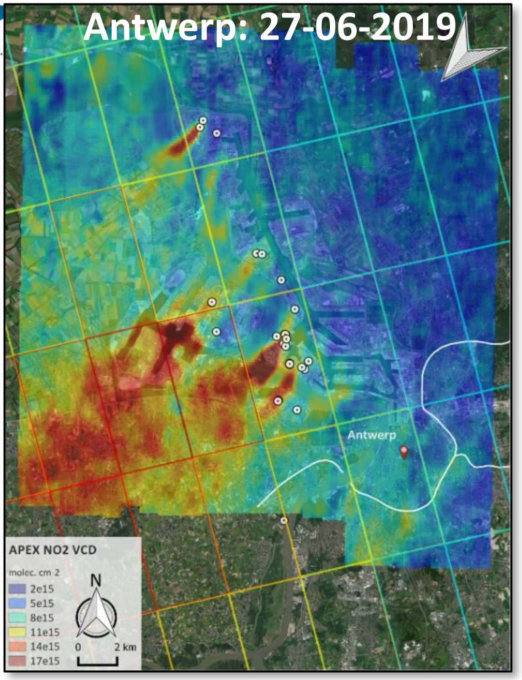
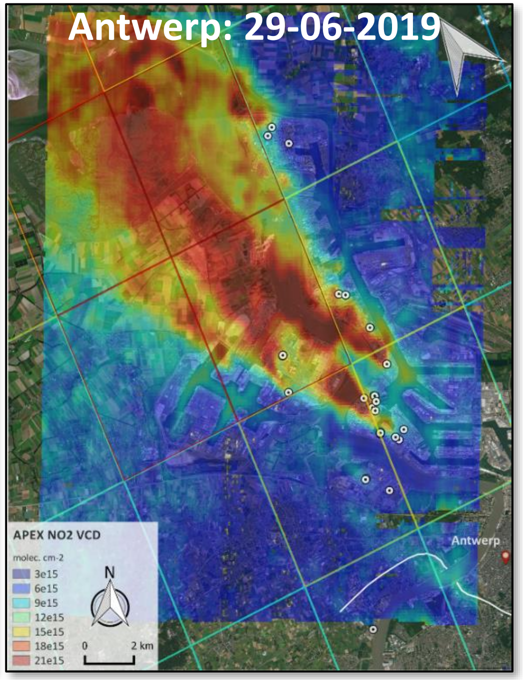
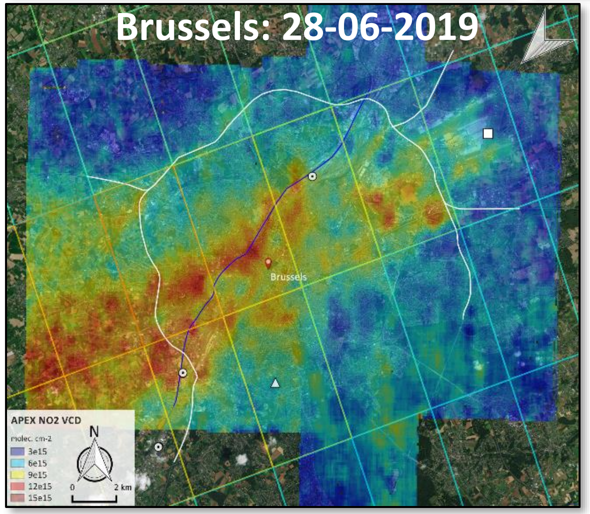
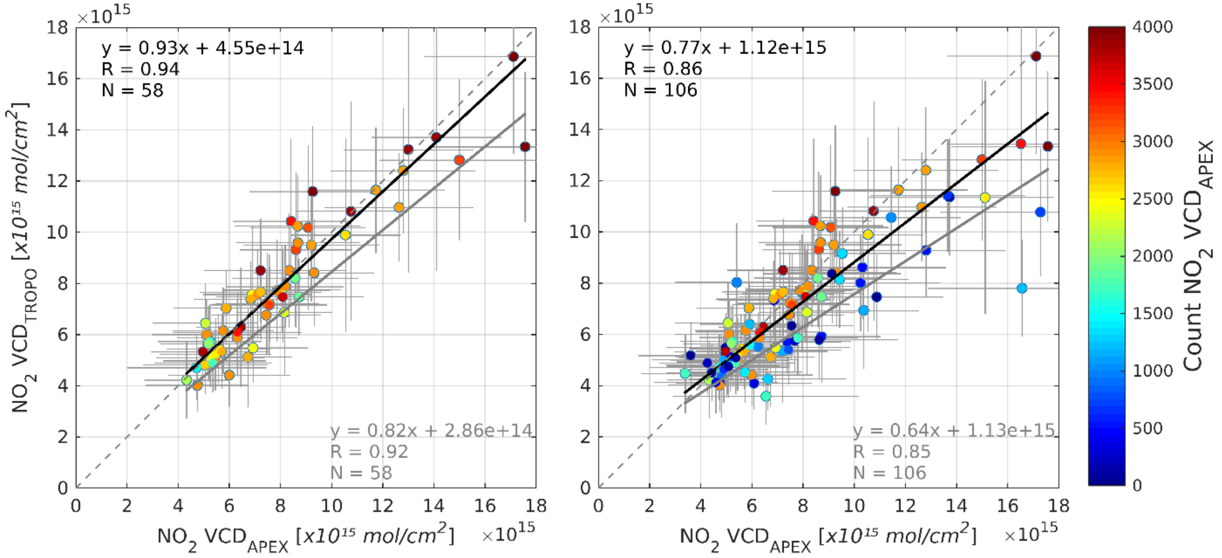
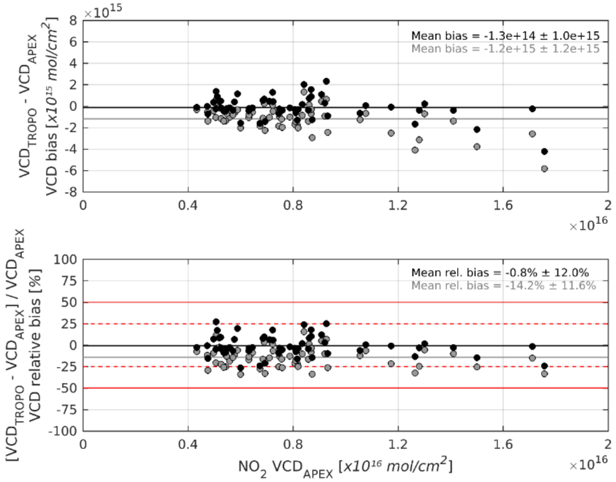
S5PVAL-BE - APEX NO_2 VCD retrievals





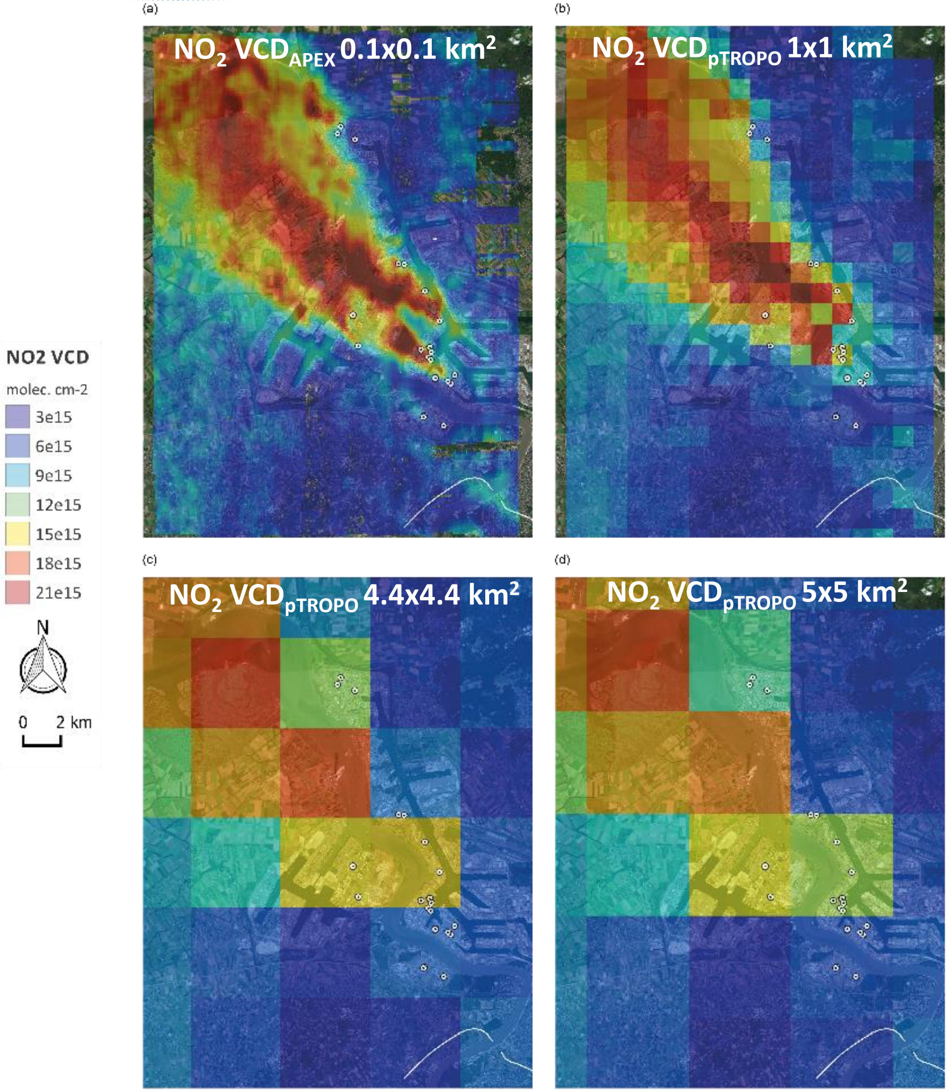




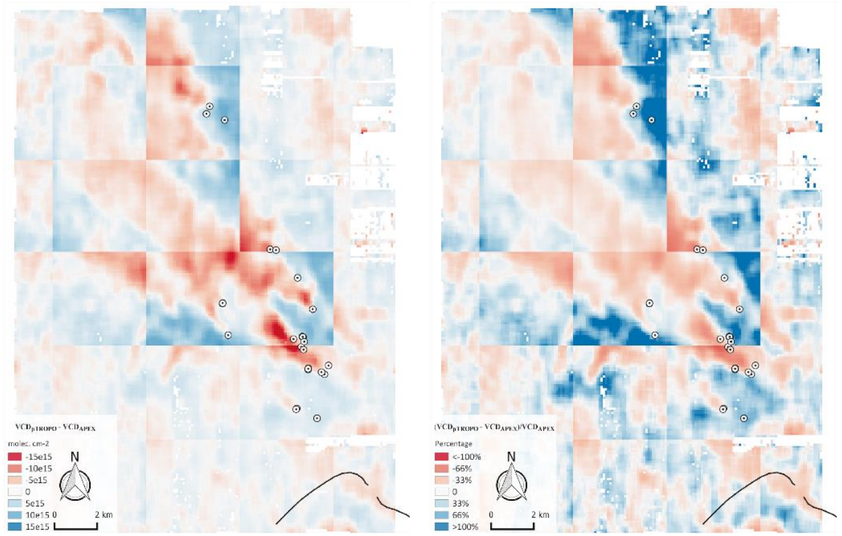


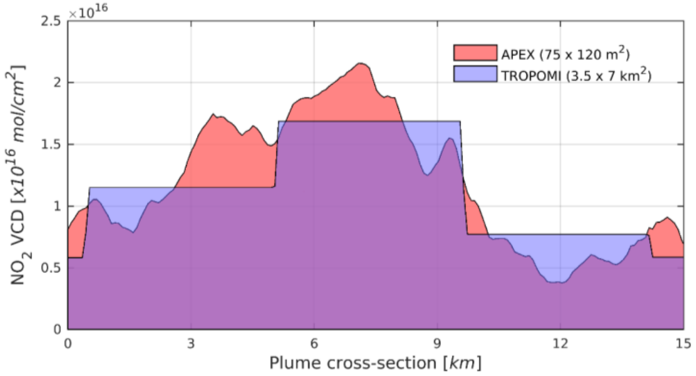
Scatterplots and linear regression analyses of co-located TROPOMI and averaged APEX NO_2 VCD retrievals for the data sets acquired on 26-29 June 2019 + **NO_2 VCD bias** ($VCD_{TROPO(-CRE)}$ – VCD_{APEX})

Full analysis available in AMT (Tack et al., 2021)



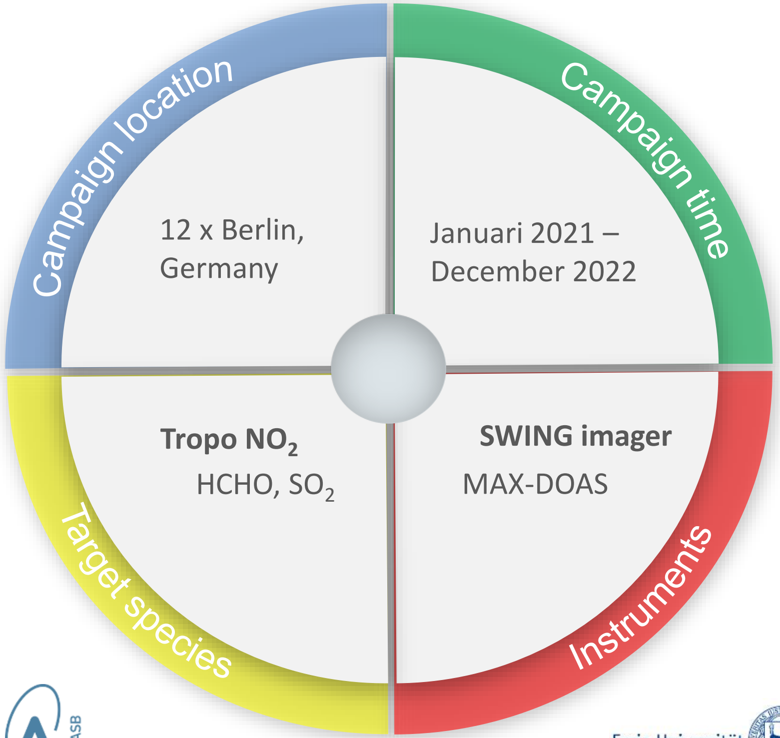
Satellite interpixel variability and signal smoothing can be studied based on high resolution airborne data → in the order of 1-2 x 10^{15} molec cm^{-2} on average, or **10% - 20%**, depending on the amount of heterogeneity in the NO_2 field and assuming a TROPOMI pixel size of 3.5 x 7 km^2

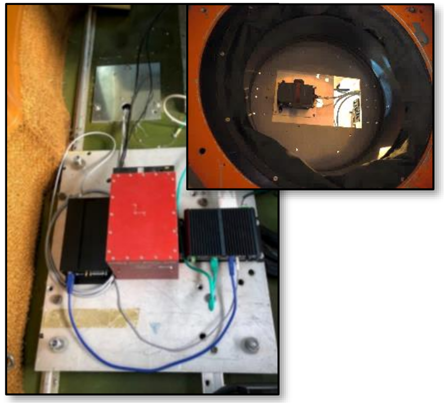


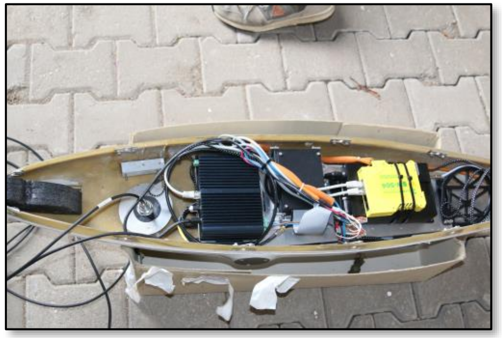


S5PVAL-DE-BERLIN

- **Recurrent** airborne mapping of tropo NO_2 over Berlin with **SWING imager** (UV-VIS – 160 x 160 m)
- 12 flights during one year over Berlin covering different conditions: pollution levels, meteorology, S-5p overpass angular dependence, etc.
- SWING+ from **FUB Cessna 207T** and SWINGPOD from **motorglider ASK16** (integrated April 2022)







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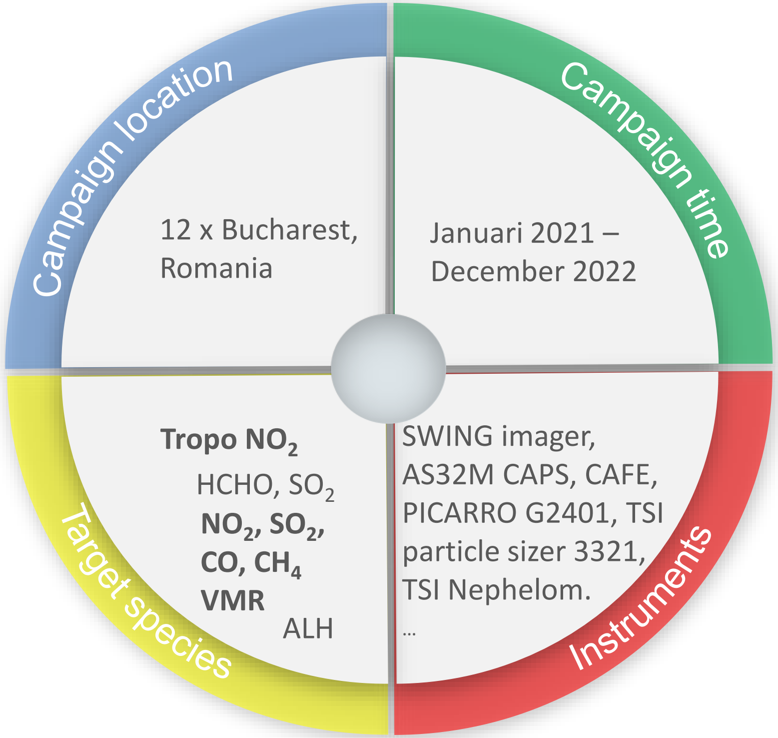
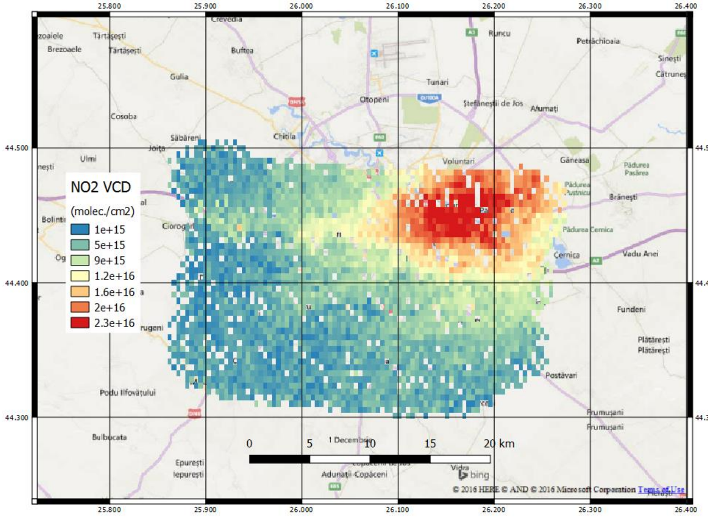
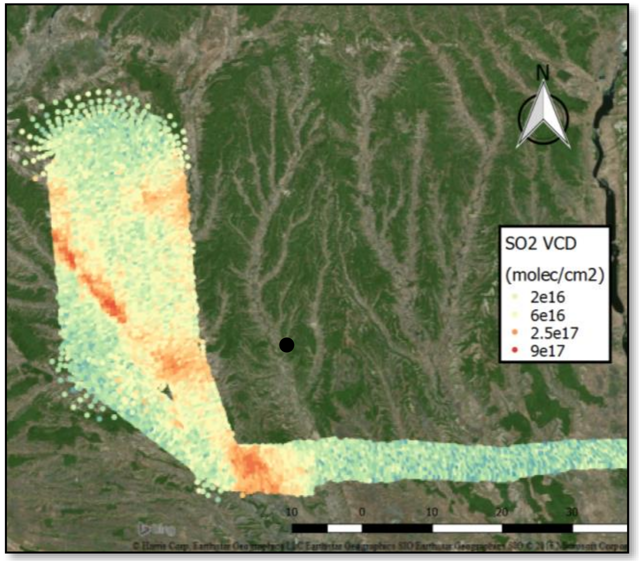
S5PVAL-RO

- **Recurrent** airborne mapping of tropo NO_2, SO_2, HCHO, with **SWING** imager, **and sounding** of NO_2, HCHO, CO, CH_4, aerosols over Bucharest (again major pollution hotspot) during 2 years
- Linked to ESA RAMOS project: development of Romanian atmospheric observation system



ESA AROMAT-I –II campaigns 2014 -2015

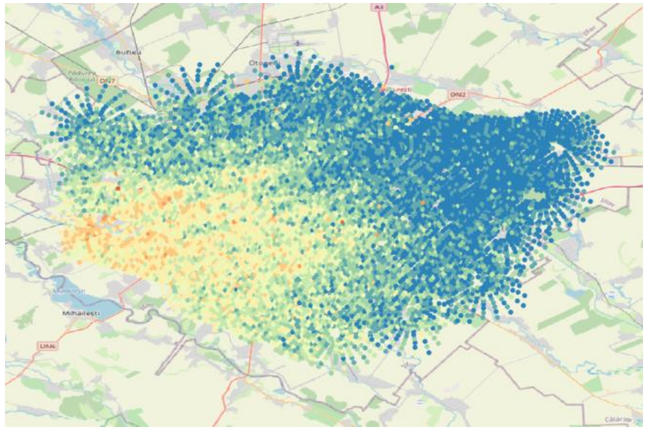




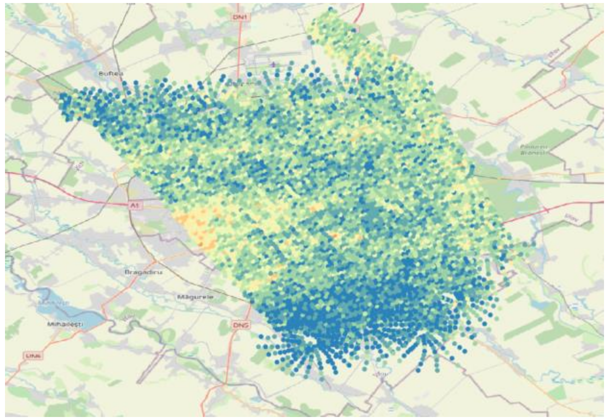
Preliminary quicklooks with fixed AMF

- -2.12 - 4.26
- 4.26 - 5.39
- 5.39 - 6.38
- 6.38 - 7.38
- 7.38 - 8.57
- 8.57 - 10.14
- 10.14 - 12.33
- 12.33 - 14.81
- 14.81 - 19.4
- 19.4 - 51.44

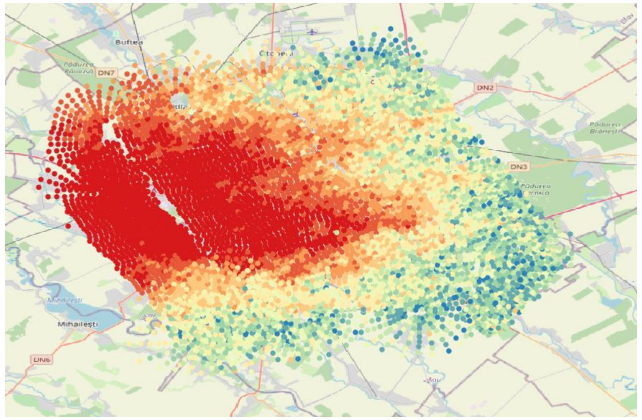
1 July 2021



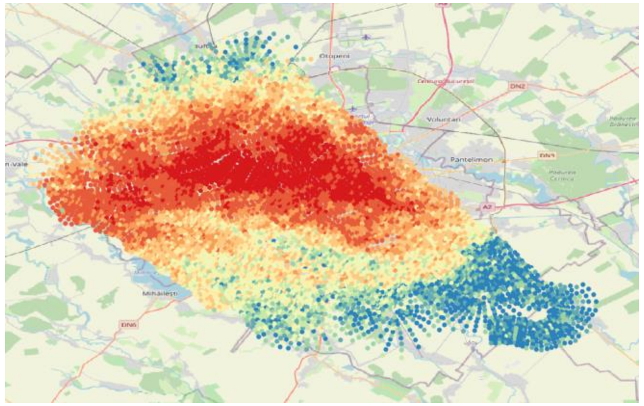
10 July 2021



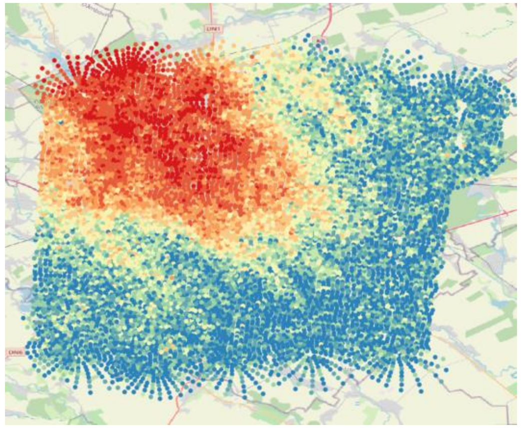
29 October 2021



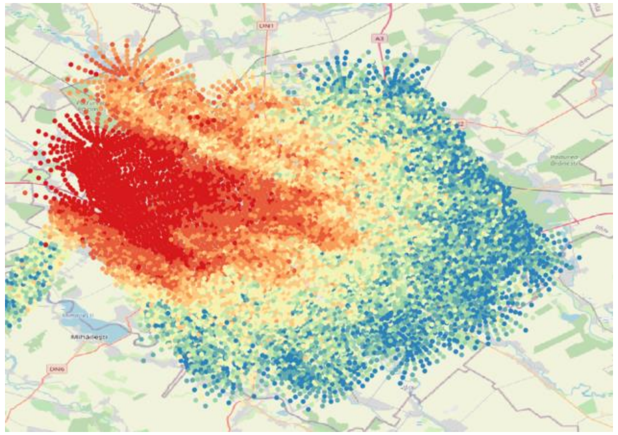
4 November 2021



5 November 2021

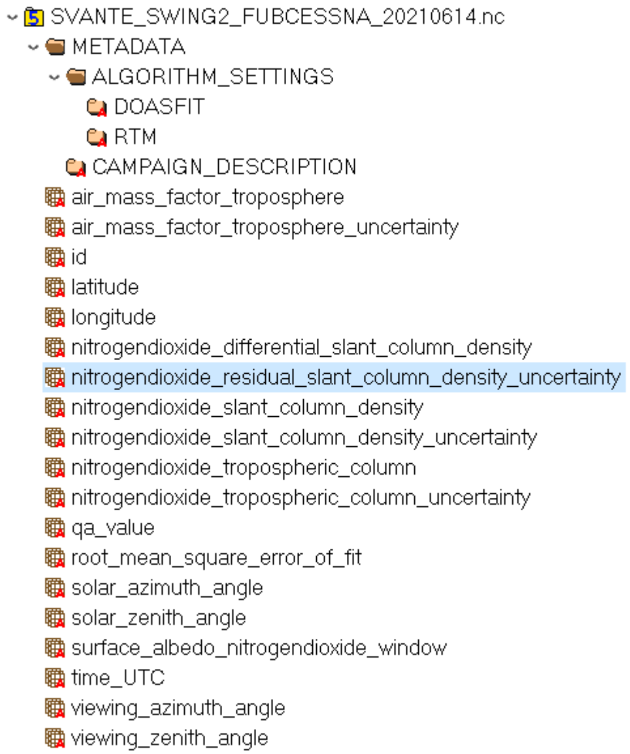


11 November 2021



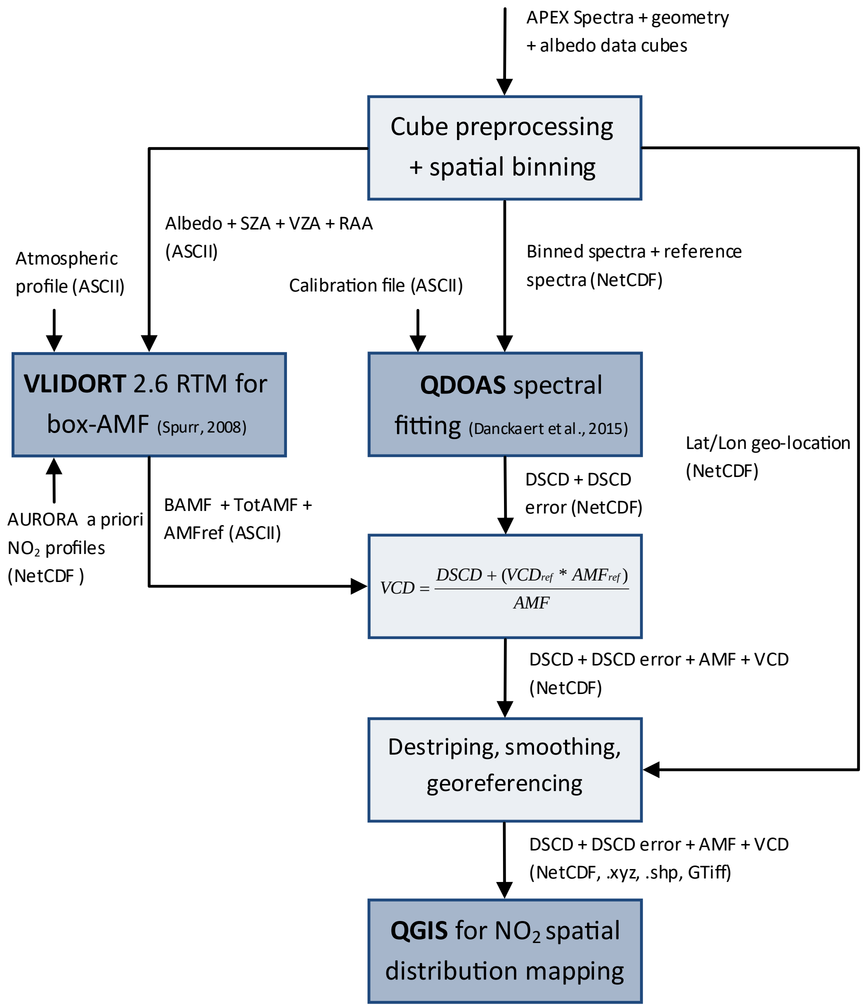
Airborne data format

- **NetCDF format (python script available to convert from own format and fill attributes)**
- **Following largely Climate and Forecast (CF) metadata conventions and TROPOMI L2 product definitions**
- **Global attributes**
  - Campaign description: ROI, date, aircraft, instrument, operator, etc.
  - Algorithm parameters – DOAS fit
  - Algorithm parameters – RTM
  - ERA-5 wind, PBL, Surface temperature (average and st. dev.)
  - → Fully traceable for user how data was processed
  - → Allows for different versions to exist next to each other



- **Data**
  - VCD + intermediate products such as AMF, (D)SCD
  - RTM input: albedo, RAA, VZA, SZA, etc.
  - Uncertainties on VCD, DSCD, SCDref and AMF
  - Lat, Lon, time for each pixel
  - → Similar to TROPOMI L2 data product
- **Can be used for all projects involving data from airborne imagers**

- **Central airborne data processor v1.1**
  - Key objectives
    - Collect data from different campaigns and different instruments
    - Avoid use of different a priori (albedo, NO_2 profile, aerosol scenario, SCD_{ref}) in processing of data from different campaigns/instruments
    - Process in a harmonized way in order to obtain independent reference data sets to compare with TROPOMI L2 products
  - 1) **Pre-processing and DOAS analysis (QDOAS)**
  - 2) **DSCD to VCD processing based on AMF computation (Lidort 2.6 RTM)**
    - Using same a priori (temperature correction, stratospheric correction, reference SCD, RTM parameters (vertical profile, albedo,…), etc.)
  - 3) **Intercomparison coinciding airborne-satellite data**
    - Using same gridding tools and spatial/temporal comparison with satellite data



ESA NITROCAM campaign in support of NITROSAT

NITROSAT

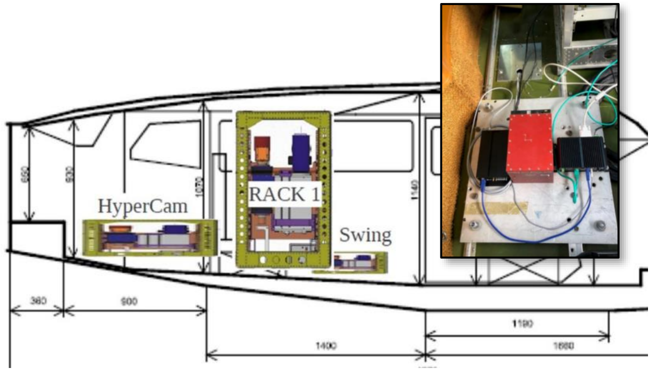
- NITROSAT is an **EE11 candidate** (potential launch 2032?)
- Satellite mission proposed to **simultaneously observe NO_2 (VIS) and NH_3 (TIR)** → Key reactive species of the global nitrogen cycle
- Globally at a **spatial resolution of at least 500 m** (current satellite missions, e.g. IASI, 12 km and S5P, 3.5x5.5 km^2)
- Main motivation:
  - NO_2 and NH_3 have a strong impact on human health, environment and climate
  - While NO_2 emissions are decreasing, NH_3 emissions are rising in Europe and developing countries

NITROCAM

- **ESA Airborne campaign** in support of the NITROSAT EE11 candidate (phase 0)
- BIRA (NO_2 retrievals, coordination), ULB (NH_3 retrievals), FUB (flight planning and instrument operations)
- Main objectives:
  - Simultaneous retrieval of NO_2 and NH_3 from various sources based on **airborne demonstrator**: agricultural, industrial, domestic, transportation
  - downsampling airborne to satellite resolution, study sensitivity + detection limit, emission rate retrieval, etc.

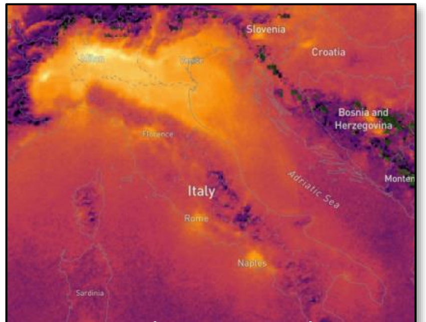
ESA NITROCAM campaign in support of NITROSAT

- **Airborne demonstrator: SWING (BIRA) and TELOPS Hyper-CAM LW (GFZ) in Cessna 207T (FUB)**

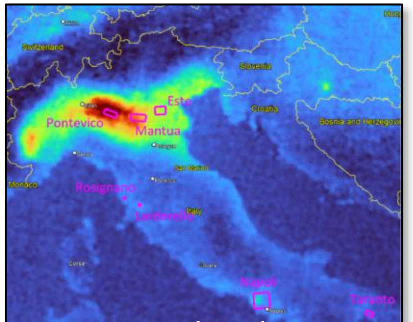


	SWING+	TELOPS Hyper-Cam LW
Wavelength range	280-550 nm	848-1288 cm^{-1}
Spectral resolution (FWHM)	0.7 nm	1.45 cm^{-1}
FOV across-track	100°	25.7° max
IFOV across track	3°	0.08°
Swath width	2900 m	1350 m
Ground speed	60 m/s	51 m/s
Exposure time	0.5 s	2.29 s
Spatial resolution	170 m	5 m
Weight	3 kg	140 kg
Size (LxWxH)	20 x 20 x 30 cm^3	100 x 60 x 50 cm^3
Scanning	Whiskbroom	Imaging Fourier interferometer
Target platform	UAV/aircraft	Aircraft

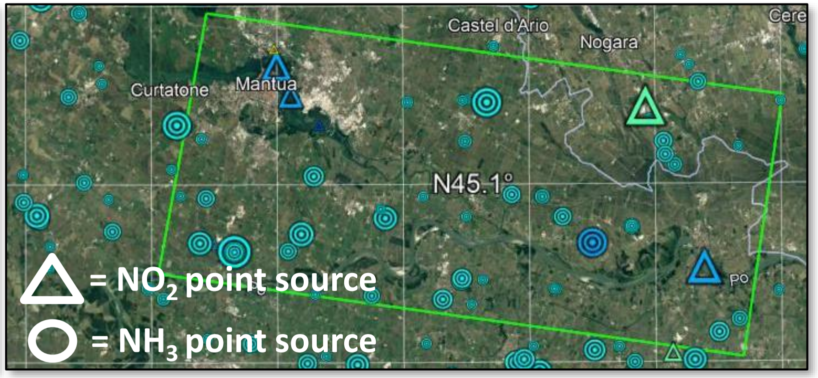
- **Airborne campaigns**
  - **Focusing on variety of sources** (agricultural, industrial, domestic, transportation)
  - **NITROCAM-DE**: 2021 – rural and urban/industrial sites close to **Berlin** (+ Bremen area in 2023?)
  - **NITROCAM-IT**: May-July 2022 – **Po Valley, Tuscany** – in collaboration with KCL, BAS, and NASA/JPL (HyTES)



NO_2 (TROPOMI)



NH_3 (IASI)

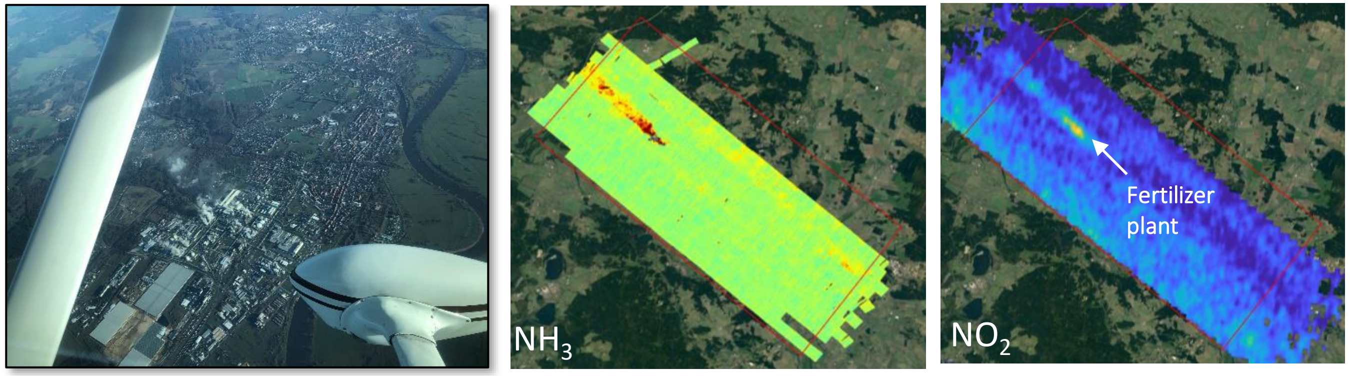



HyTES

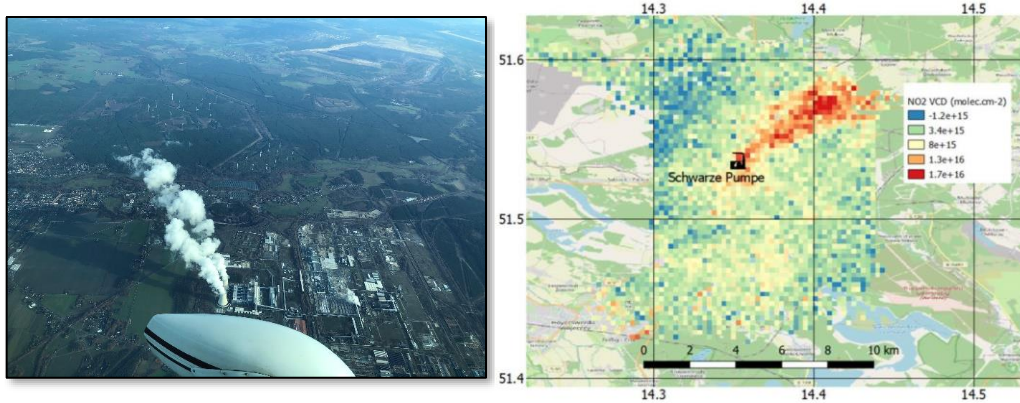

BAS Twin Otter

NITROCAM-DE

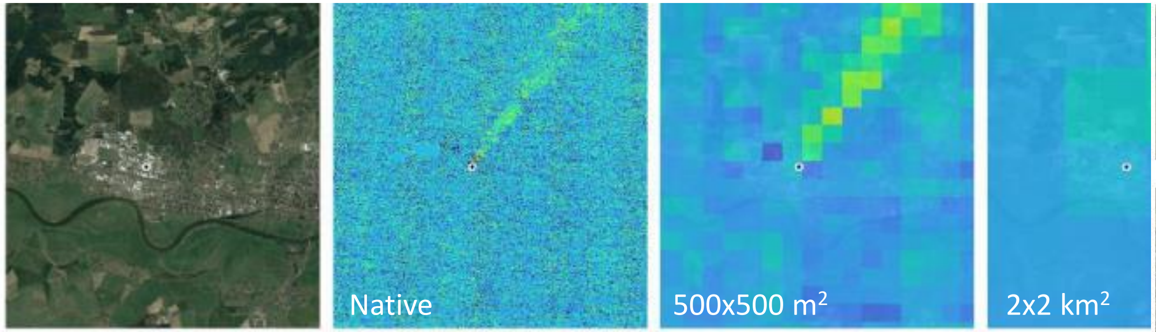
NH$_3$ and NO$_2$ over Piesteritz – 28/04/2021 – first simultaneous retrieval



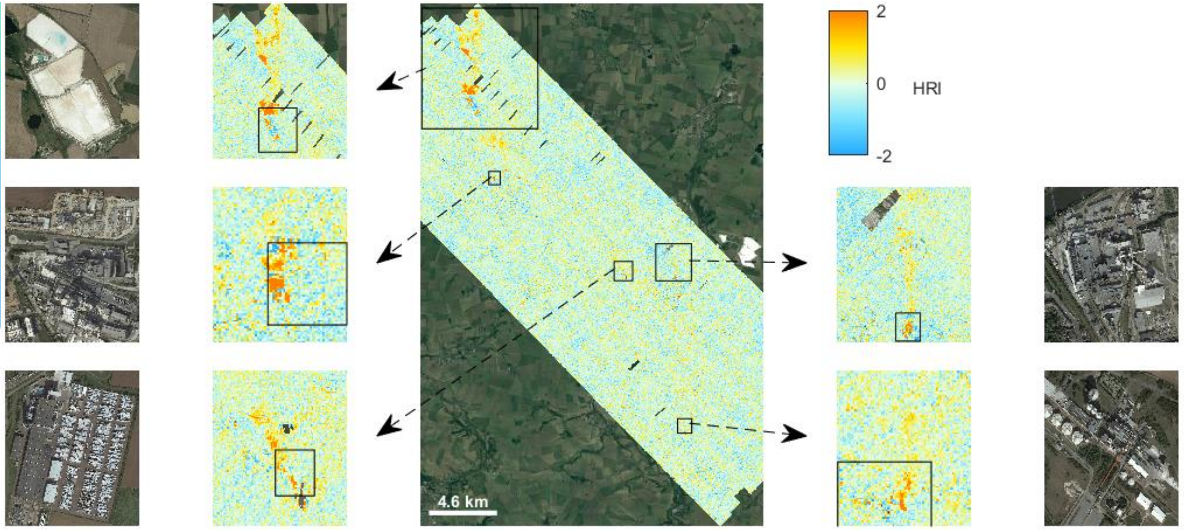
NO$_2$ over Schwarze Pumpe – 14/11/2020



NH$_3$ over Piesteritz – 08/10/2020 – downsampling to pseudo-satellite resolution



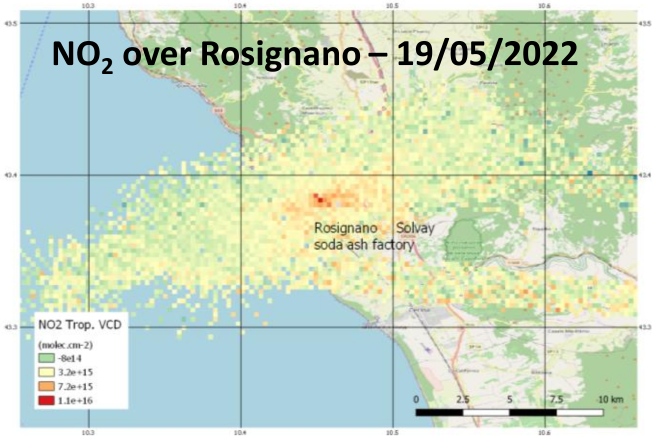
NH$_3$ over Stassfurt/Bernburg – 09/05/2021 – signal from many sources

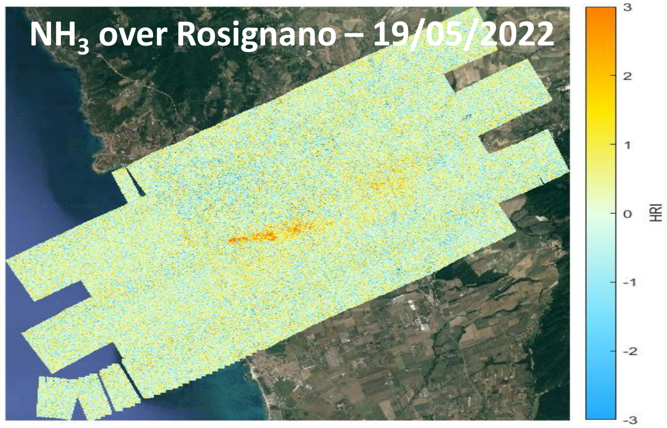


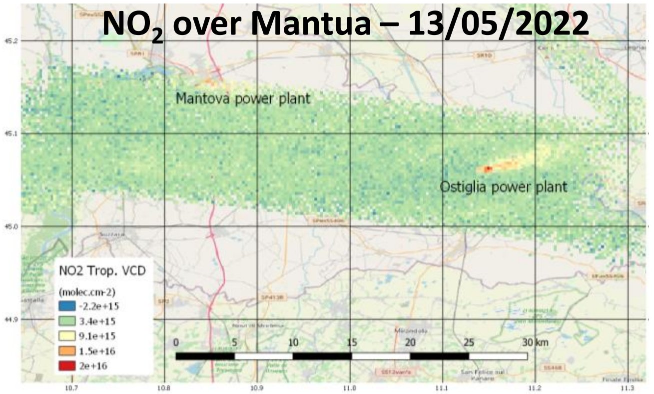
Contributions from Lieven Clarisse, Lara Noppen (ULB), Alexis Merlaud (BIRA), Thomas Ruhtz (FUB)

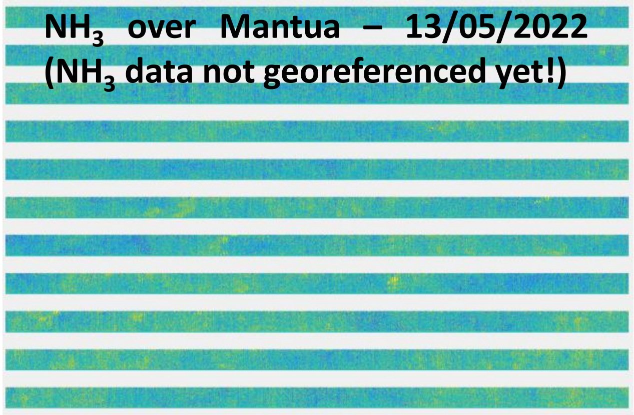
NITROCAM-IT

Preliminary quicklooks









Contributions from Lieven Clarisse, Lara Noppen (ULB), Alexis Merlaud (BIRA), Thomas Ruhtz (FUB)

Conclusion and perspectives

- **Several studies demonstrate that clear NO_2 (and NH_3) signals can be retrieved and individual NO_2 plumes can be identified and linked to their sources 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**
  - Local air quality studies → gap filler between satellites and ground-based networks
  - Input for emission inventories and CTMs
  - Trend monitoring and policymaking
  - Validation of satellite measurements and AQ models
  - Airborne precursor - support to future satellite mission design
- **But… Need for more best practice documents, joint standards, harmonization, protocols for data acquisition and processing → through EUFAR at European level?**

Conclusion and perspectives

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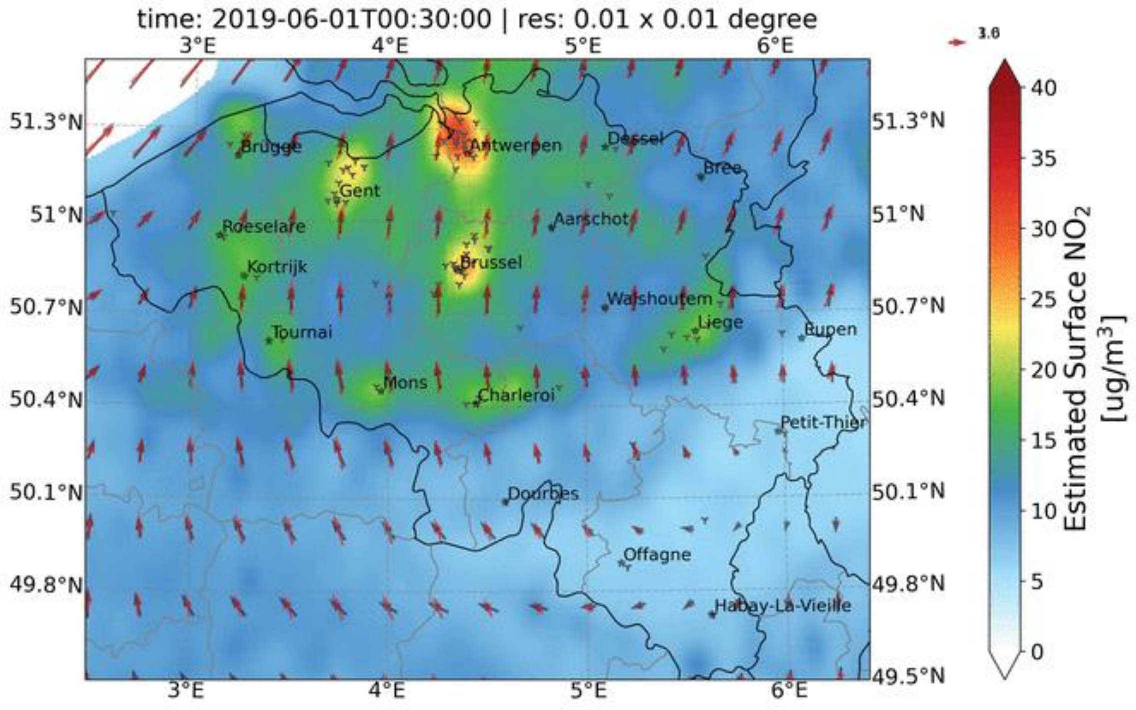

- **Needs and perspectives for air quality application**
  - Need for **high spatial and temporal resolution to monit** spatiotemporal variability

	✈	
Spatial resolution	•Spatial resolution (< 100 m²) close to the naturally smoothed signal of the dispersed NO_2 field	•Curren km² (S5
Temporal resolution	•Restricted to campaigns – need for more systematic flights for near-continuous monitoring	•Daily (•Hourly

  - Current airborne imaging systems as **precursors** for future (low-cost) stratospheric and spaceborne missions, complementing flagship missions like S5P, S5, S4, Nitrosat, etc
    - e.g. deploy on **HAPS/drone**s (20-30 km altitude) hovering over certain ROI or geostationary
    - e.g. deploy on large constellation of orbiting compact, **low-cost CubeSats** (400 km)

  - Need to convert retrieved atmospheric columns (VCD) to **surface concentrations** (VMR)

...Thank you!

uv-vis.aeronomie.be/airborne
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