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# Assessment of the TROPOMI tropospheric $NO_2$ product based on recurrent airborne campaigns

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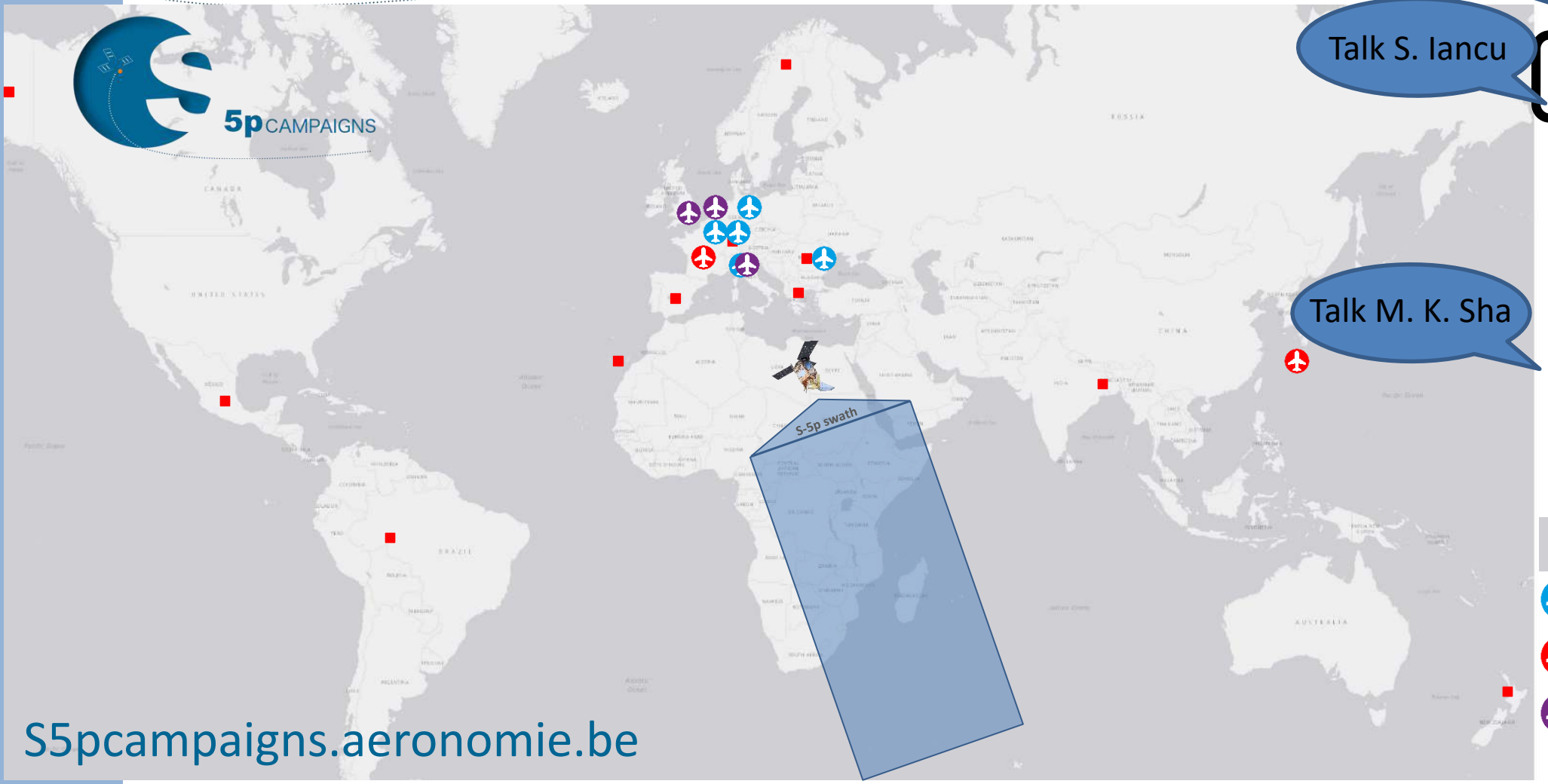
BIRA-IASB

S5PVT meeting, Taormina, 11-10-2022

# Outline

- **Broader context: S5P campaigns**
  - S5P campaigns: SVANTE project and QA4EO project
- **SVANTE airborne data format + central processor v1.1**
- **Recurrent airborne campaigns over Berlin and Bucharest**
- **S5P $NO_2$ validation - Preliminary results**
- **Conclusion and perspectives**

# ESA SVANTE and QA4EO campaigns – S5P validation




Talk K. Lange

Talk S. Iancu

Talk M. K. Sha

S5PVAL-DE-RUHR
S5PVAL-DE-BERLIN
S5PVAL-RO
S5PVAL-BE
S5PVAL-TRANS
NITROX
MAGIC
ACCLIP
S5PVAL-KOLKATA
COCCON

$NO_2$
$SO_2$
HCHO
CO
$CH_4$

Legend

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

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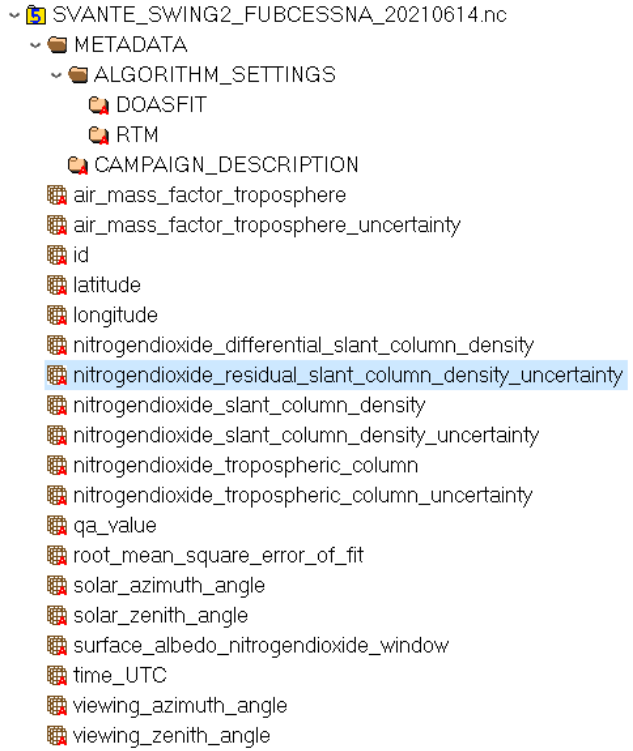
# SVANTE airborne data format

- **NetCDF format (python script 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 + reference spectrum
  - 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 $NO_2$ product
- **Data format can be used for all projects involving airborne imaging data, e.g. future S4/S5 cal/val**



# SVANTE central processing

- **Central airborne data processor v1.1**
  - Key objectives
    - Collect and process data from different campaigns and different imaging instruments
    - **Consistent** a priori assumptions (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) **Step 1: DOAS spectral fitting, georeferencing and pre-processing**
  - 2) **Step 2: DSCD to VCD processing**
    - SCD stratospheric and temperature correction
    - $AMF_{tropo}$ - LIDORT 2.6 RTM based on MODIS MCD43A3 albedo, TM5 a priori $NO_2$ profile, sun/viewing geometry, etc.
  - 3) **Step 3: harmonized gridding tools and spatiotemporal comparison tools with satellite**
  - Airborne format and code is well-documented (can be used in other projects and for S-4/S-5 cal/val)
  - Improvements/changes regarding format will be implemented in v1.2 (similar to satellite data processors)

# S5PVAL-DE-BERLIN and S5PVAL-RO

- **Recurrent** airborne mapping of tropo $NO_2$ over **Berlin** + **Bucharest** with **SWING imager**
- 12 flights during one year **covering different conditions**: pollution levels, meteorology and geo-physical parameters, S-5p overpass angular dependence, etc.
- SWING+ (UV-VIS – 0,7 nm – 170 x 170 m) operated from **INCAS BN-2** (RAMOS), **FUB Cessna 207T, FUB motorglider ASK16** (integrated April 2022)
- Spatiotemporal coïncidence with TROPOMI overpass

**SWING+ specifications (at 3 km a.g.l.)**

| | SWING+ |
|---|---|
| Wavelength range | 280-550 nm |
| Spectral resolution (FWHM) | 0.7 nm |
| FOV across-track | 100° |
| IFOV across track | 3° |
| Swath width | 2900 m |
| Ground speed | 60 m/s |
| Exposure time | 0.5 s |
| Spatial resolution | 170 m |
| Weight | 3 kg |
| Size (LxWxH) | 20 x 20 x 30 $cm^3$ |
| Scanning | Whiskbroom |
| Target platform | UAV/aircraft |

**SWING+ on INCAS BN-2**

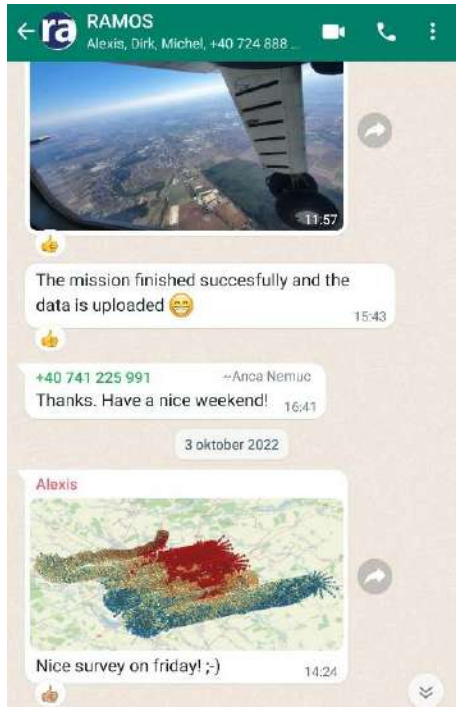

**SWING+ on FUB Cessna 207T**

**SWINGPOD on FUB ASK16 glider (integrated since April 2022)**

# Intercomparison with TROPOMI

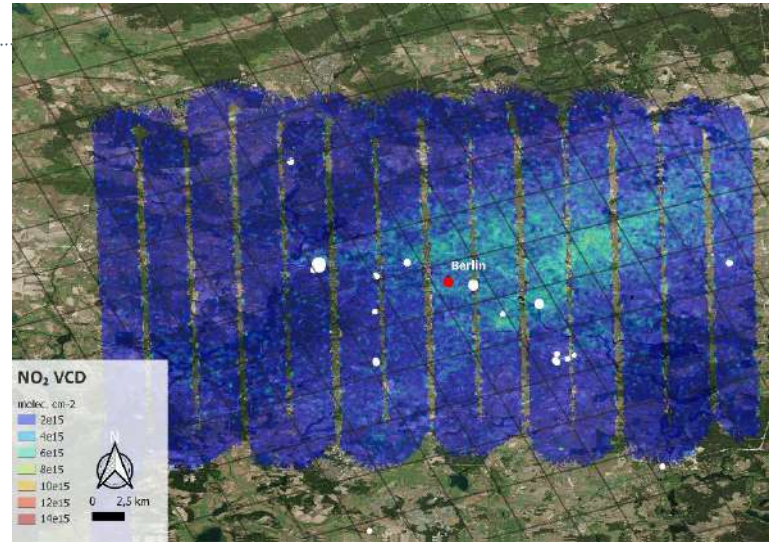
- **Averaging airborne pixels (~ 0.17 x 0.17 km$^2$) within each TROPOMI pixel (~3.5 x 5.5 km$^2$)**

| | SWING-TROPOMI intercomparison |
|---|---|
| **Constraints** | |
| -Data quality | -TROPOMI **QA value >= 0.75**<br>-SWING slant error <= 3 x detection limit (~7e15 molec. cm$^{-2}$) |
| -Spatial | TROPOMI pixel **covered at least 50%** by airborne data |
| -Temporal | **ΔT < 1 hour** (difference between airborne vs spaceborne overpass) |
| -Weather | Clear-sky conditions |
| **Flights** | |
| -Bucharest | ~20 flights since 01/07/2021 |
| -Berlin (Cessna 207 T) | 6 flights since 14/06/2021 |
| -Berlin (Glider ASK 16) | 7 (test) flights since 06/04/2022 |
| -Next slides | 4 flights over Berlin + 4 flights over Bucharest are analysed, mostly in autumn conditions |
| **TROPOMI products** | Comparisons with **OFFL**, **PAL**, **OFFL-CAMS** and **PAL-CAMS** |
| **TROPOMI versions** | -01/01/2021 → 01/07/2021: **TROPOMI $NO_2$ v1.4**<br>-01/07/2021 → 15/11/2021: **TROPOMI $NO_2$ v2.2**<br>-15/11/2021 → 17/07/2022: **TROPOMI $NO_2$ v2.3** |

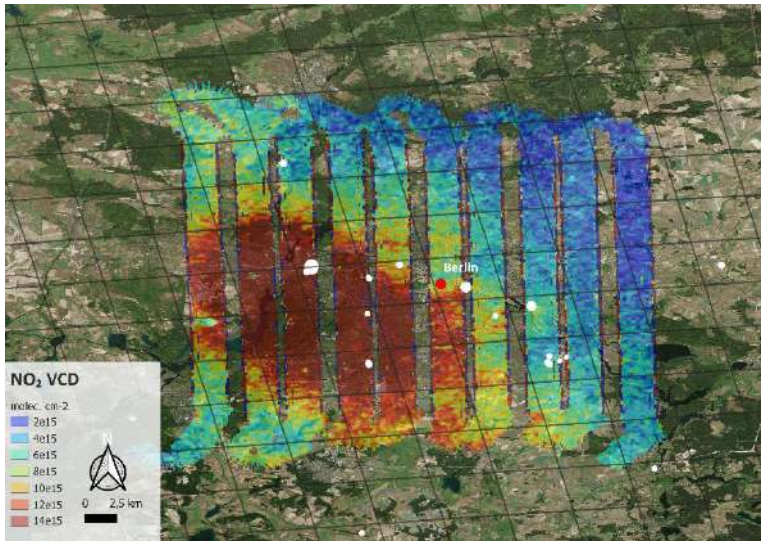


# Preliminary results ($NO_2$ VCD maps) – Berlin, DE

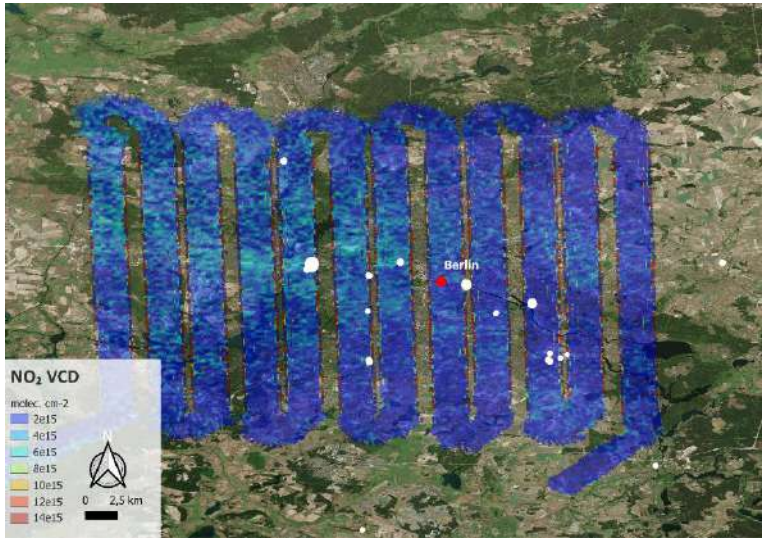
**14-06-2021 (Monday)**



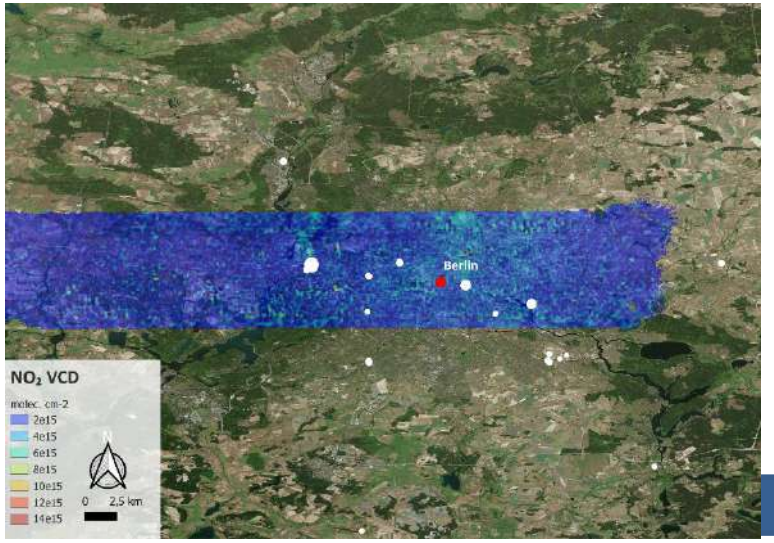

**07-10-2021 (Thursday)**




**09-10-2021 (Saturday)**

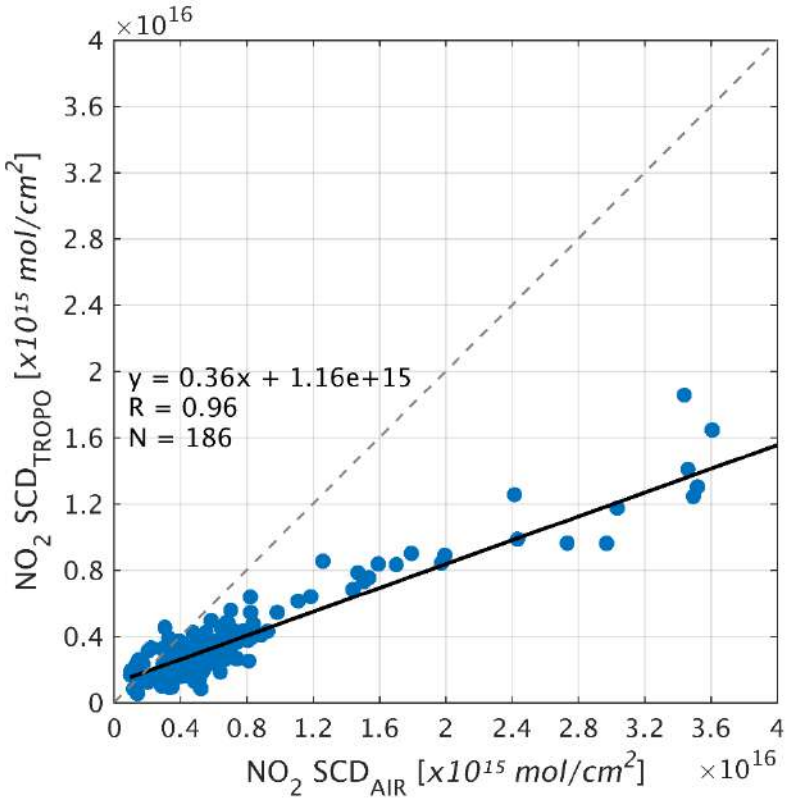



**24-10-2021 (Sunday)**

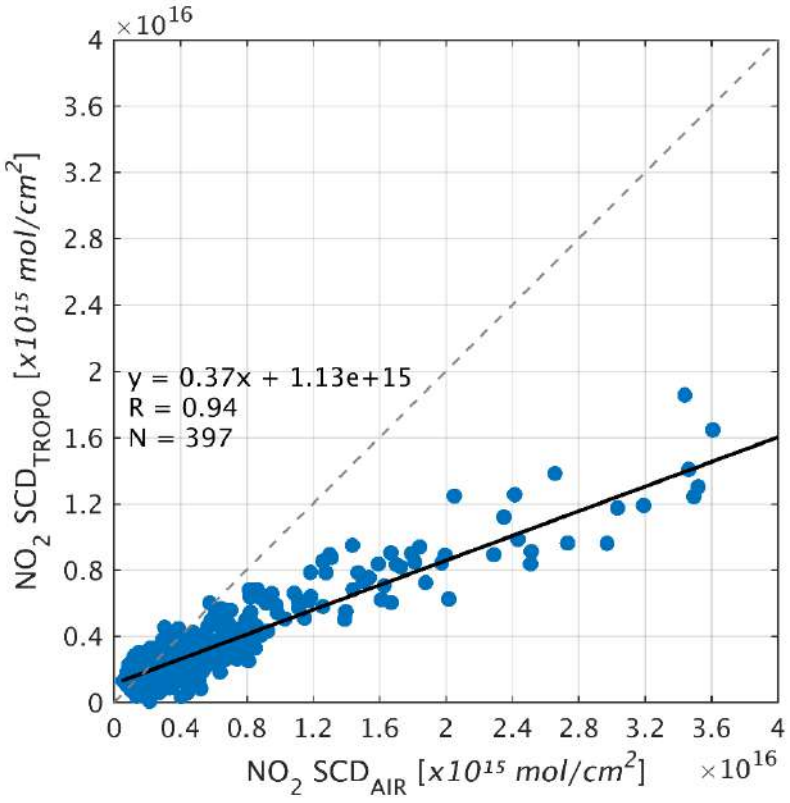


# Preliminary results (SCD) – Berlin, DE

**Ensemble 4 flights (OFFL v2.2 - 50% overlap - <=1 hour)**

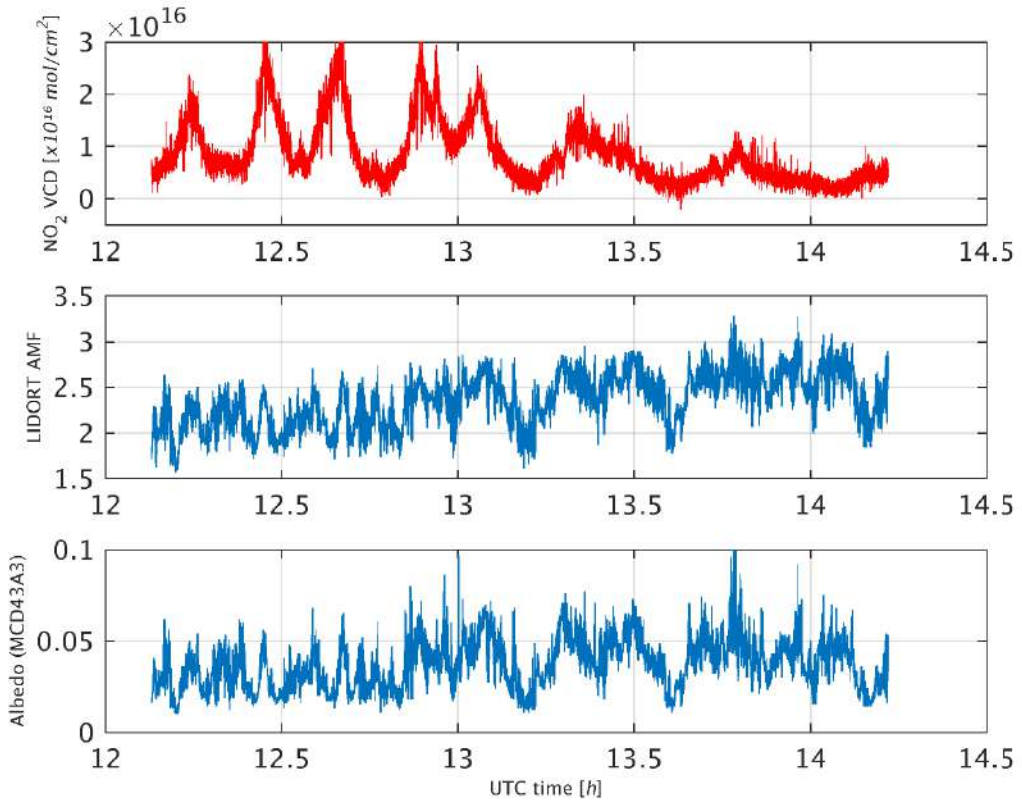



**Ensemble 4 flights (OFFL v2.2 – no spatiotemp. constraints)**



# Preliminary results (VCD) – Berlin, DE

**07-10-2021**

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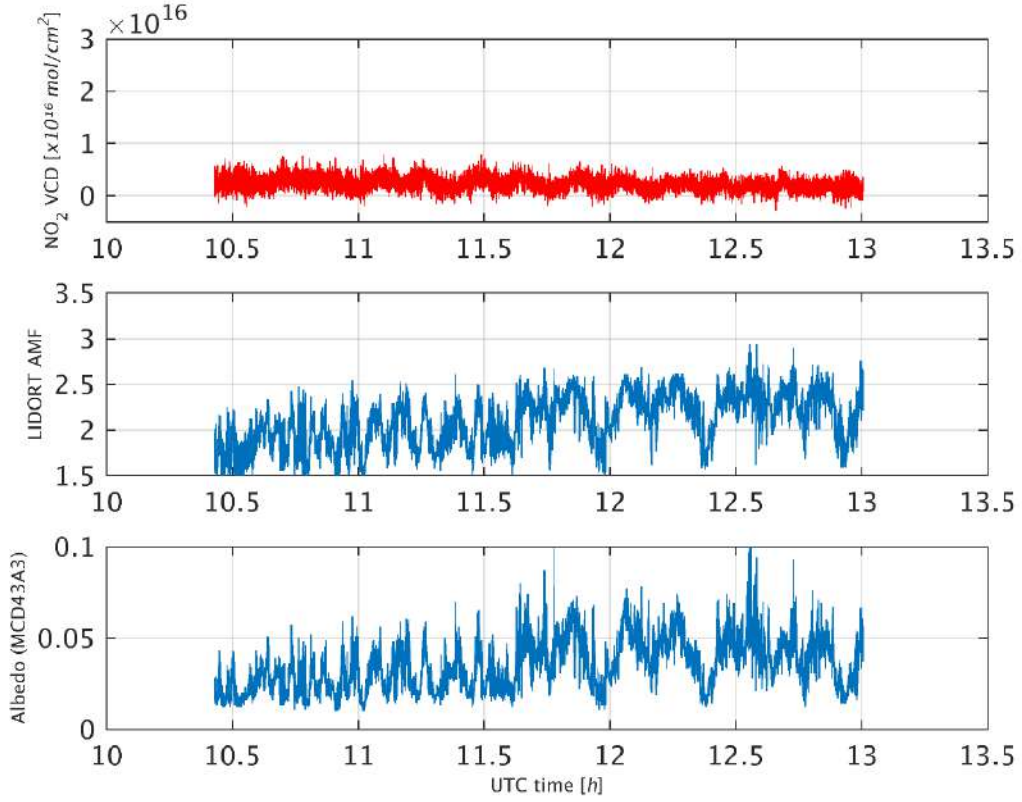
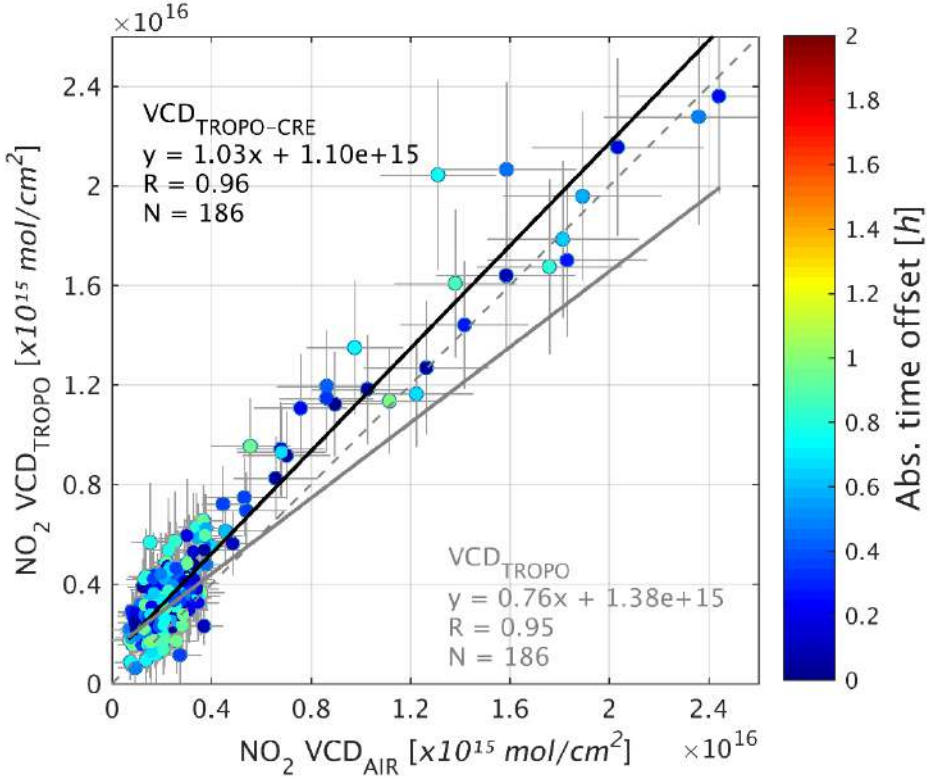
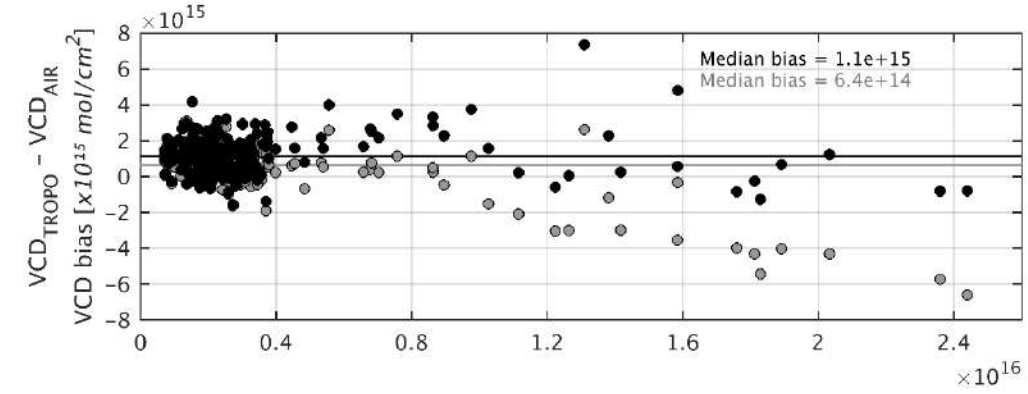
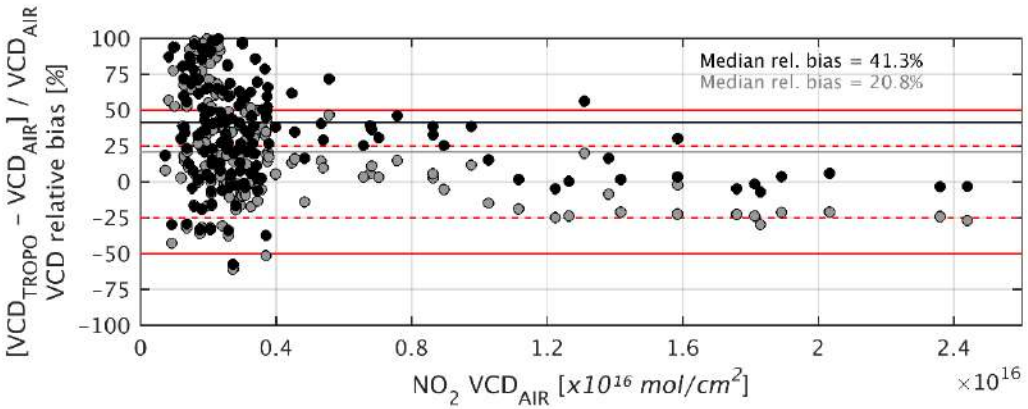


# Preliminary results (S5P $NO_2$ validation) – Berlin

**Ensemble 4 flights (OFFL(-CAMS) v2.2 - 50% overlap - <=1 hour)**



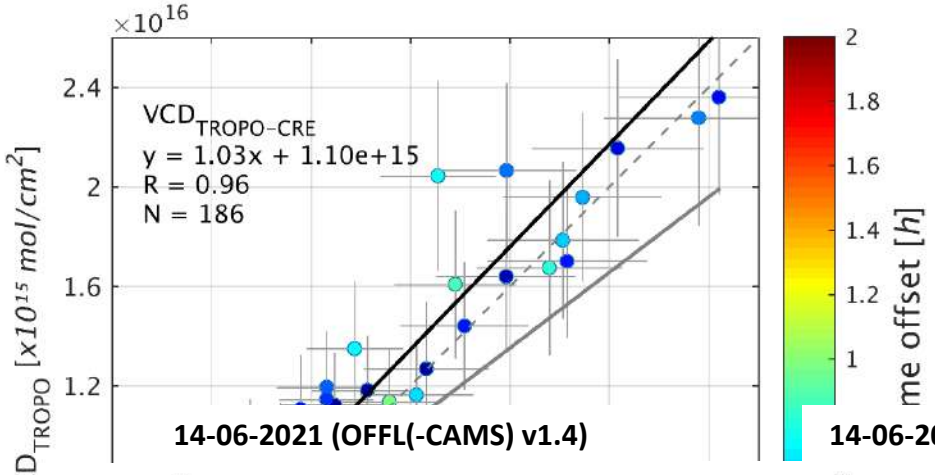

**Error bars**

$$\sigma_{VCD_{TROPOi}} = \sqrt{\left(\frac{\sigma_{SCD_{TROPOi}}}{AMF_{TROPOi}}\right)^2 + \left(\frac{\sigma_{SCD_{TROPOi}^{strato}}}{AMF_{TROPOi}}\right)^2 + \left(\frac{SCD_{TROPOi} - SCD_{TROPOi}^{strato}}{AMF_{TROPOi}^2} \cdot \sigma_{AMF_{TROPOi}}\right)^2}$$

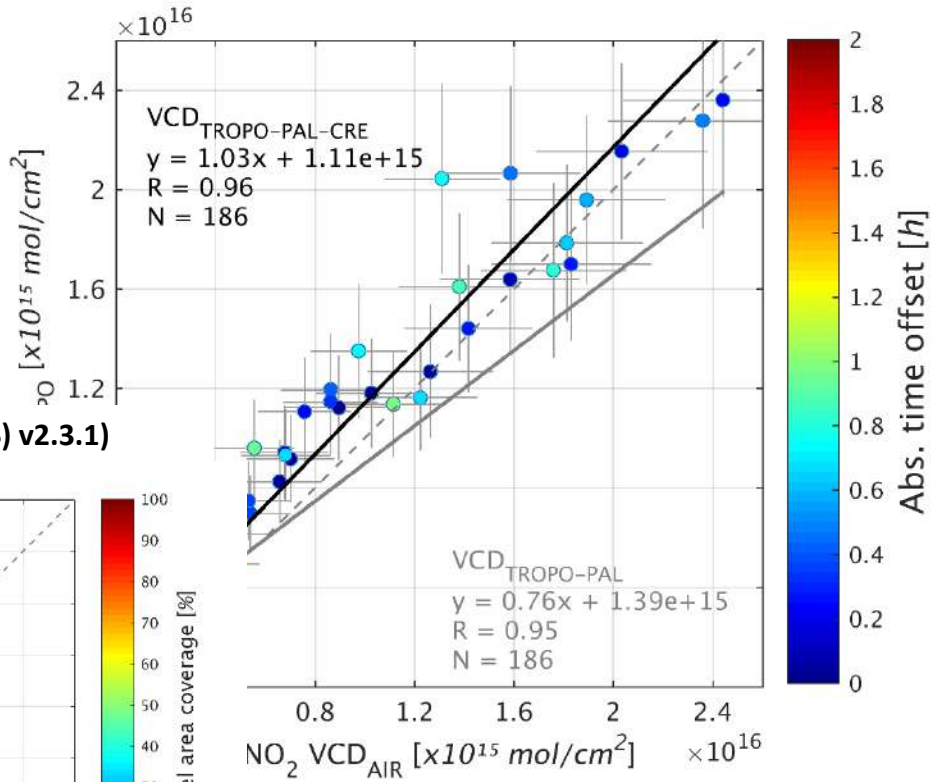
$$\sigma_{VCD_{APEXi}} = \sqrt{\left(\frac{\sigma_{DSCD_{APEXi}}}{AMF_{APEXi}}\right)^2 + \left(\frac{\sigma_{SCD_{ref}}}{AMF_{APEXi}}\right)^2 + \left(\frac{SCD_{APEXi}}{AMF_{APEXi}^2} \cdot \sigma_{AMF_{APEXi}}\right)^2}.$$

# Preliminary results (S5P $NO_2$ validation) – Berlin

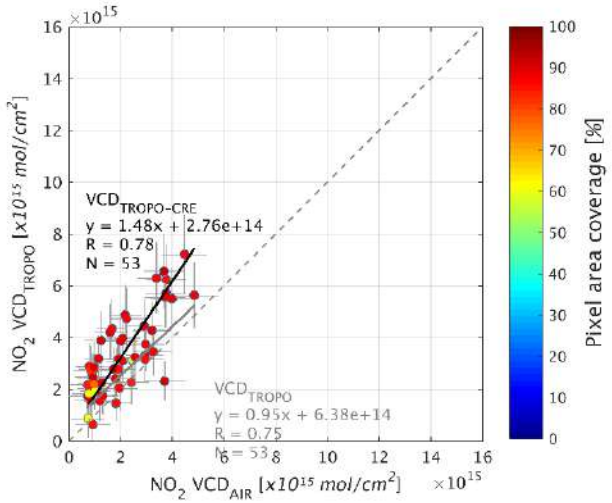
**Ensemble 4 flights (OFFL(-CAMS) v2.2 - 50% overlap - <=1 hour)**



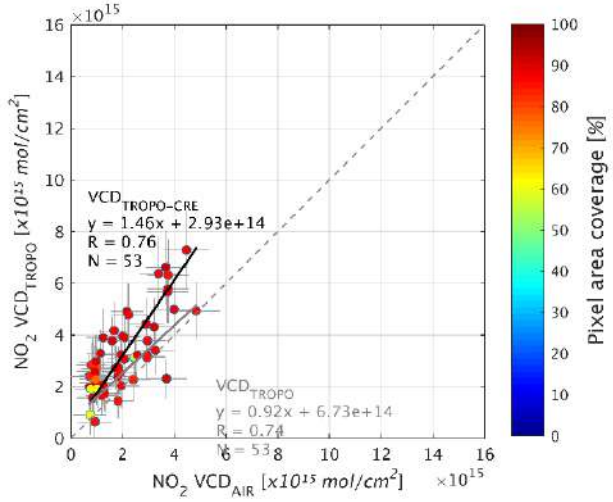

**Ensemble 4 flights (PAL(-CAMS) v2.3.1 - 50% overlap - <=1 hour)**




**14-06-2021 (OFFL(-CAMS) v1.4)**

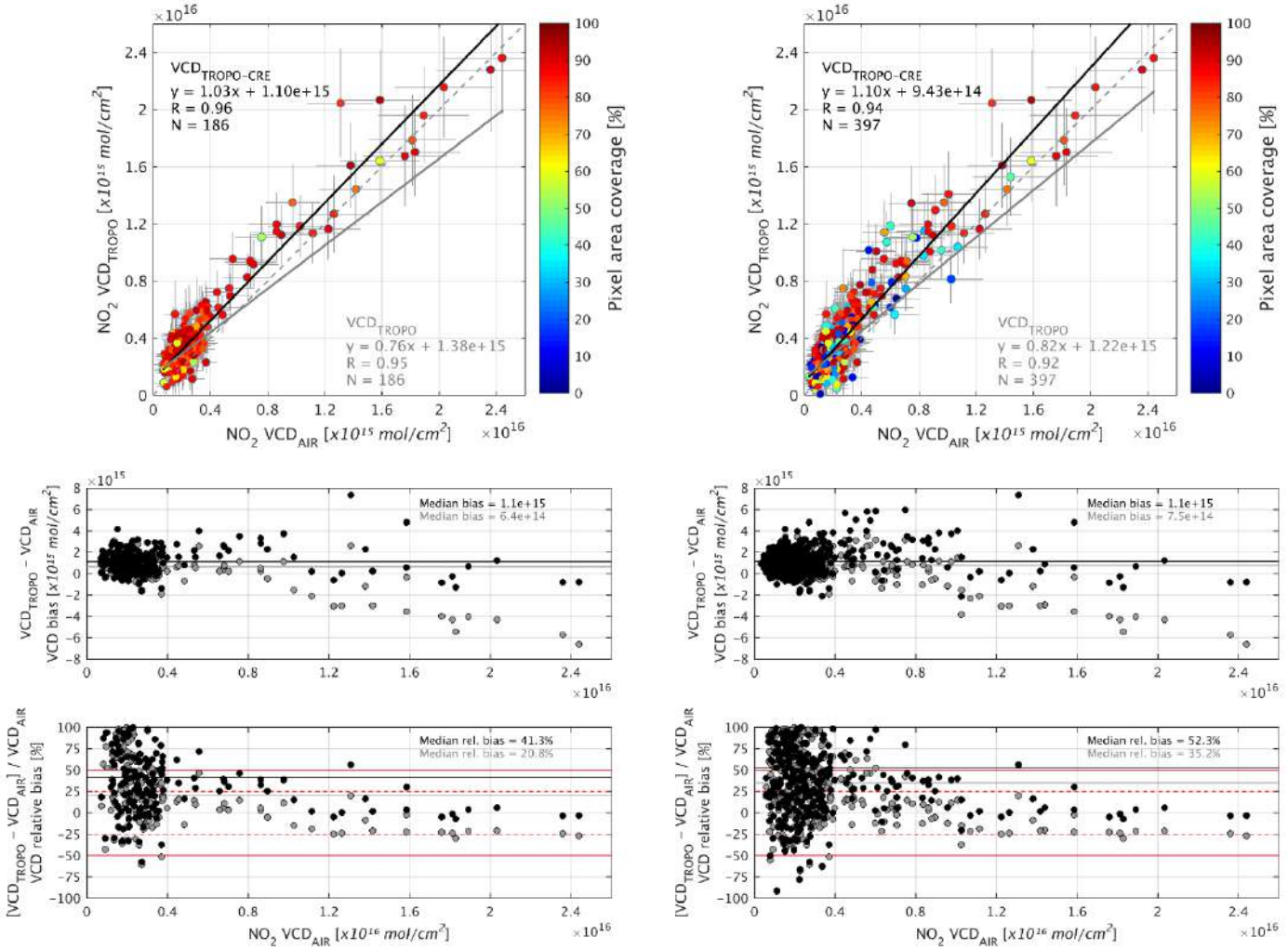



**14-06-2021 (PAL(-CAMS) v2.3.1)**



# Preliminary results (S5P $NO_2$ validation) – Berlin

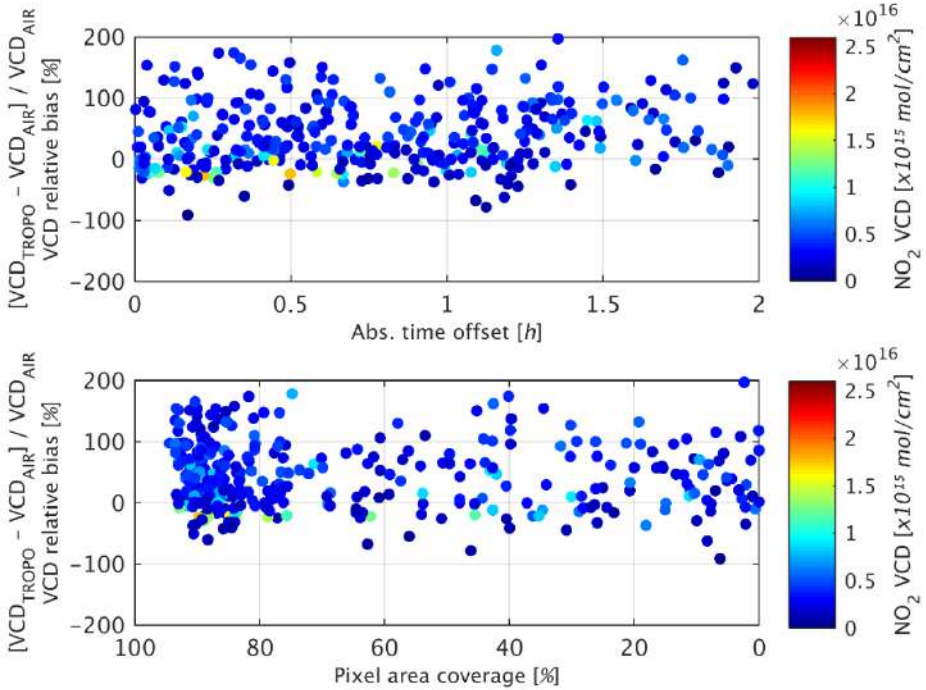
**Ensemble 4 flights**
**(OFFL(-CAMS) v2.2 - 50% overlap - <=1 hour)**




**Ensemble 4 flights**
**(OFFL(-CAMS) v2.2 - No spatiotemp. constraints)**

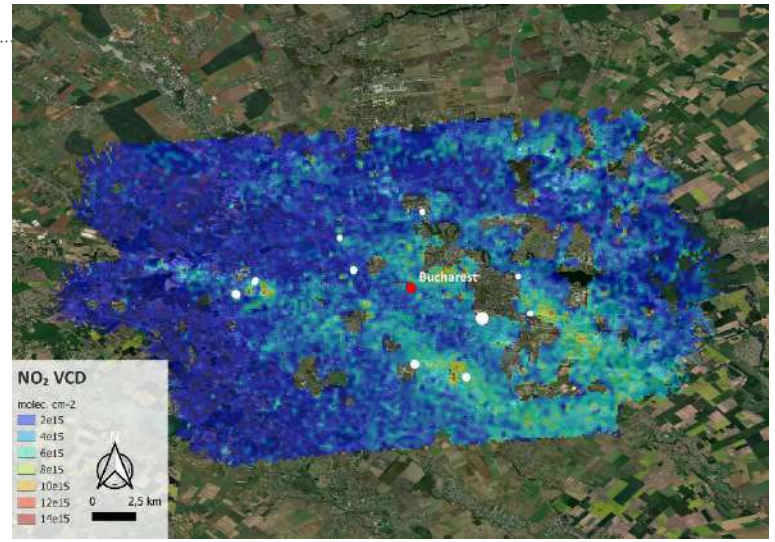



**Ensemble 4 flights – Impact spatiotemporal variability**

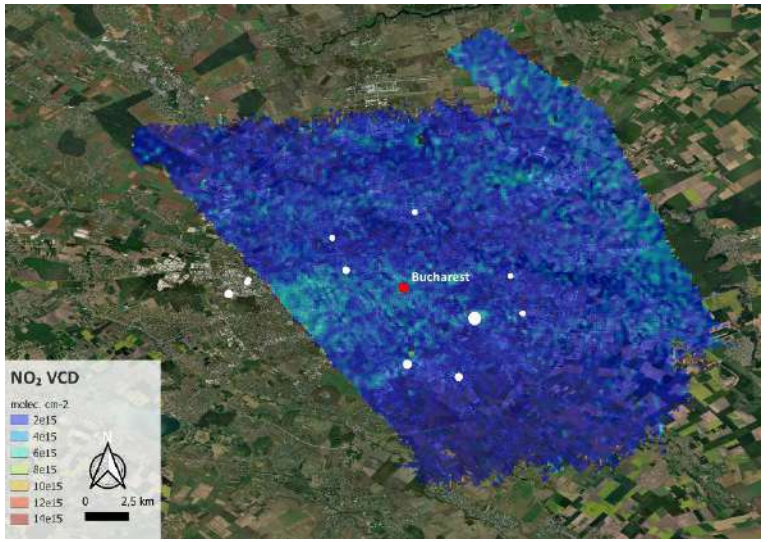


# Preliminary results ($NO_2$ VCD maps) – Bucharest, RO

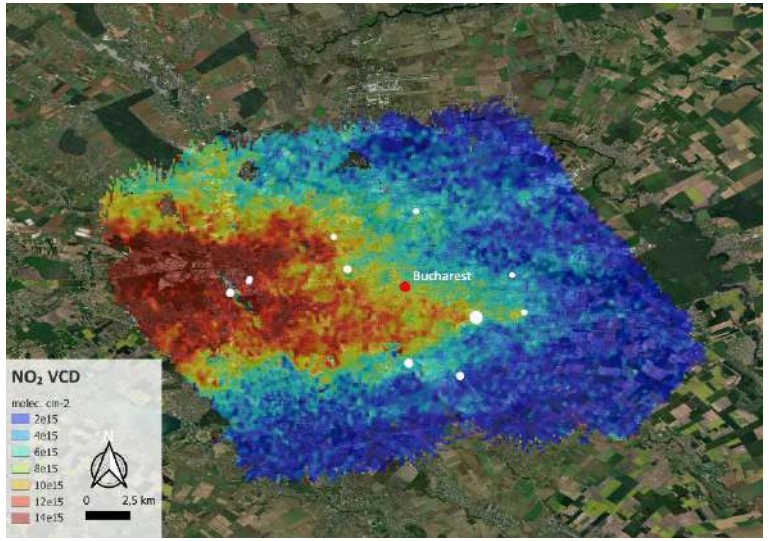
**05-07-2021 (Monday)**



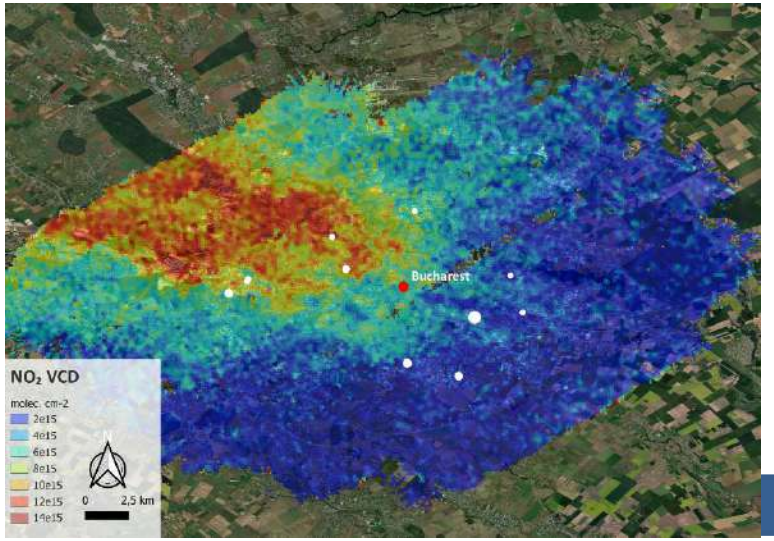

**10-07-2021 (Saturday)**




**29-10-2021 (Friday)**

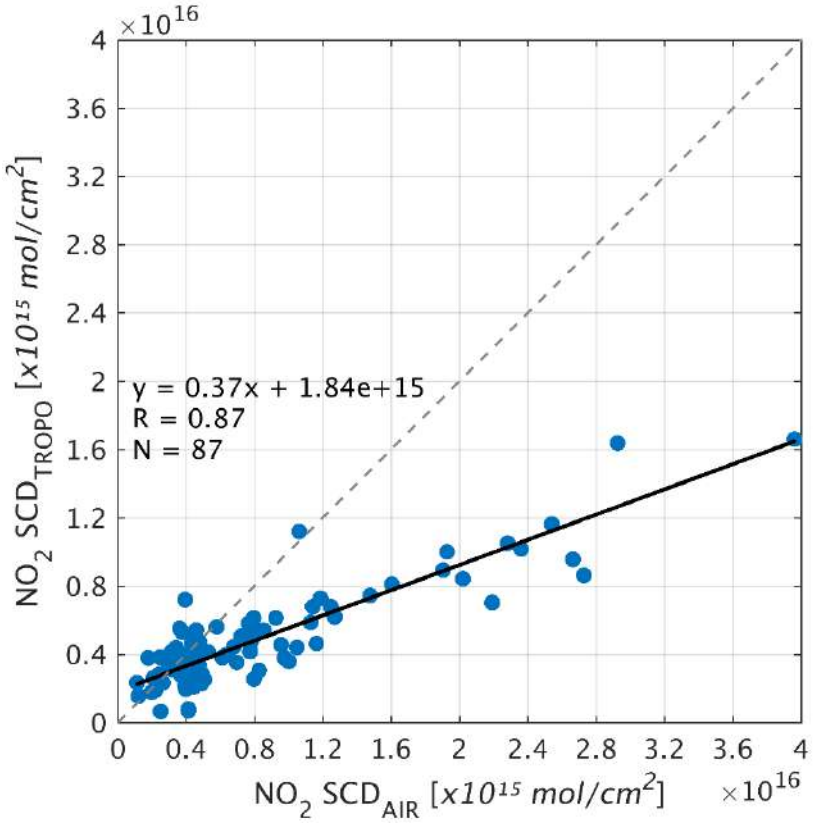



**23-12-2021 (Thursday)**

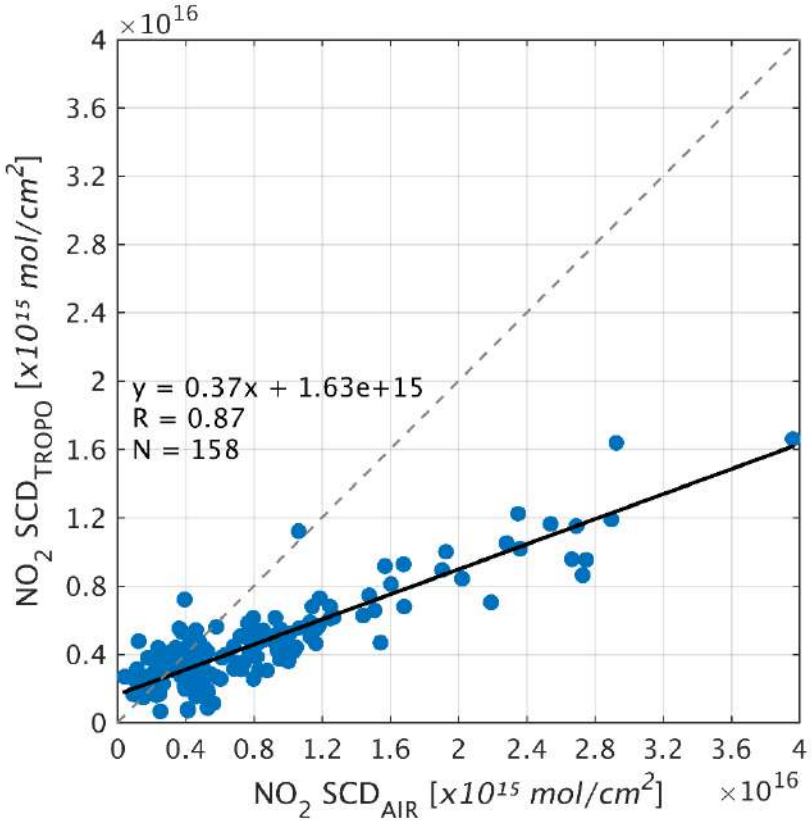


# Preliminary results (SCD) – Bucharest, RO

**Ensemble 4 flights (OFFL v2.2 - 50% overlap - <=1 hour)**

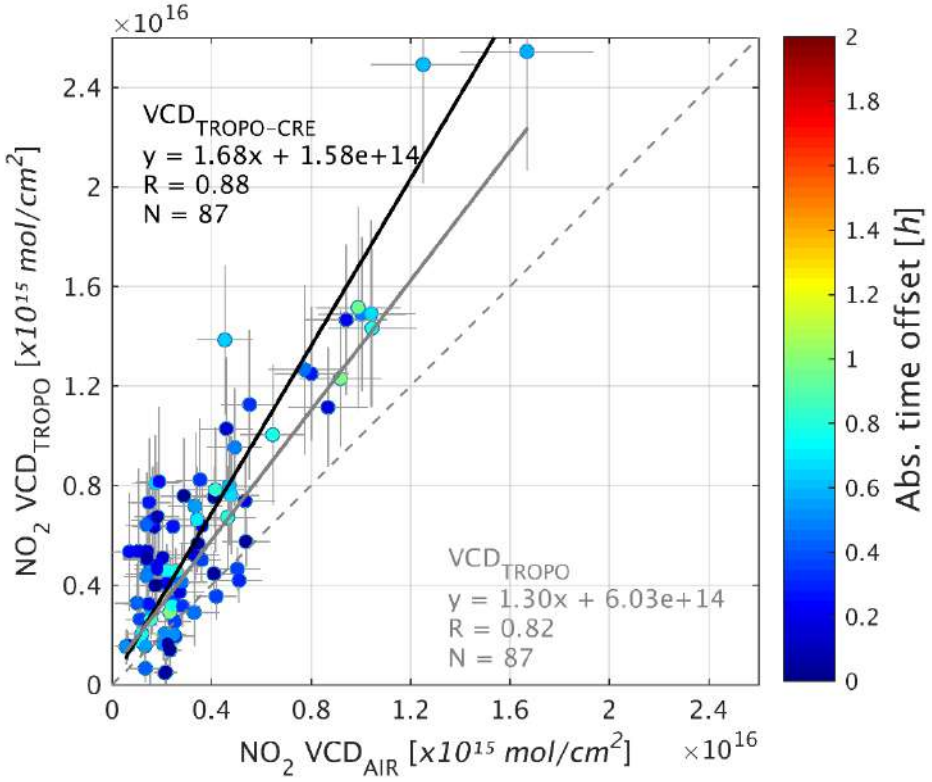


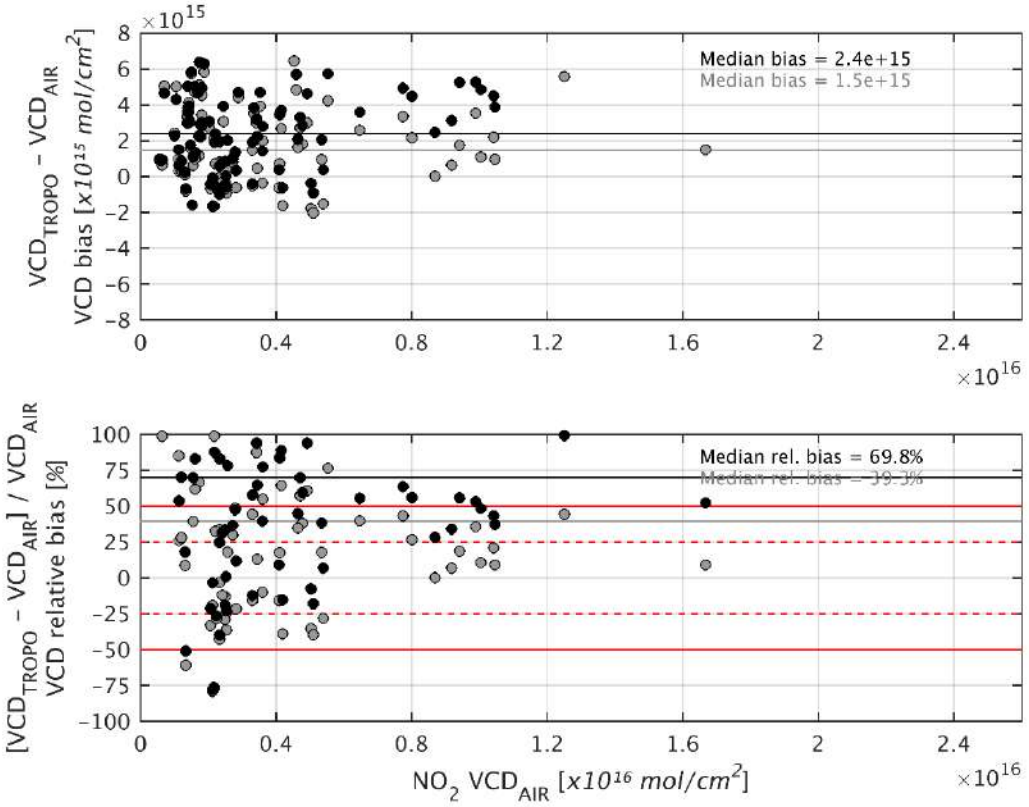

**Ensemble 4 flights (OFFL v2.2 – no spatiotemp. constraints)**



# Preliminary results (S5P $NO_2$ validation) – Bucharest

**Ensemble 4 flights (OFFL(-CAMS) v2.2 - 50% overlap - <=1 hour)**



# Conclusions – next steps

- **Central processor v1.1 (developed in context of ESA SVANTE/QA4EO projects)**
  - NetCDF CF data format for airborne imaging
  - Central processing code: DOAS spectral fitting + AMF computation
  - Airborne–satellite automatic independent validation tools
  - Important step to **harmonize/standardize data acquisition and processing** of airborne imaging data
- **Assessment of TROPOMI tropospheric $NO_2$ product**
  - Clear $NO_2$ patterns can be retrieved over urban/industrialised areas based on airborne imaging data
  - L2 TROPOMI NO2 VCDs are well correlated (R =0.95 (Berlin); R = 0.82 (Bucharest)) but biased (21% (Berlin); 40% (Bucharest)) with respect to airborne SWING retrievals.
  - CAMS product can have 20-30% impact on slope; small differences between OFFL and PAL for analysed period
  - Typically retrieved VCDs were relatively low for urban areas; mostly autumn conditions
- **Next steps**
  - Apply central processing and TROPOMI comparison tools on AirMAP data from Ruhr campaign
  - Process all available SWING data sets from recurrent flights → improve statistics
  - Further harmonize/standardize by best practice documents, joint standards, protocols, etc.

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# ...Thank you! Questions?

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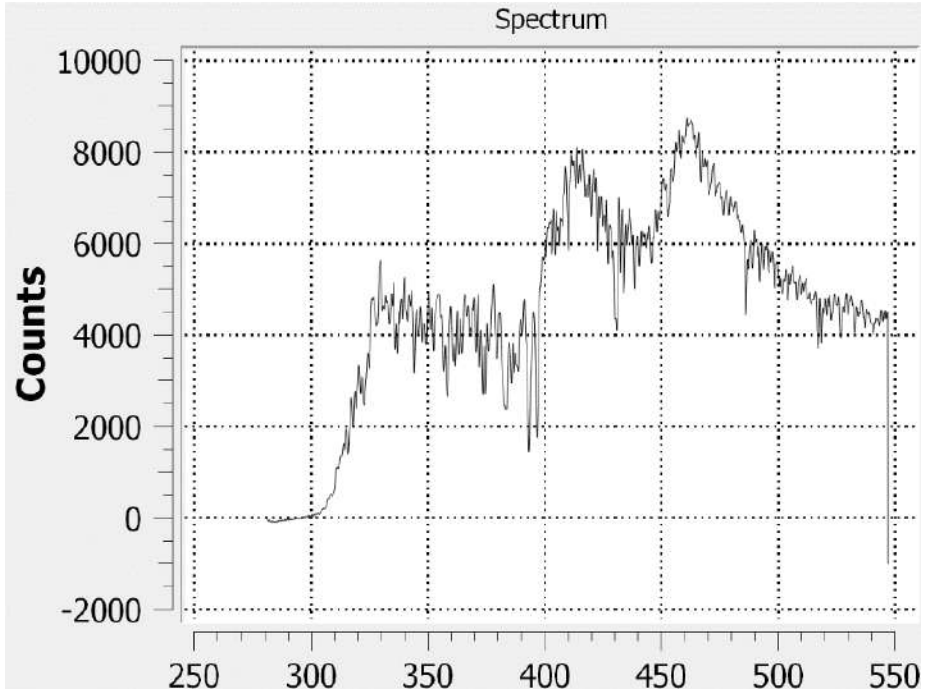
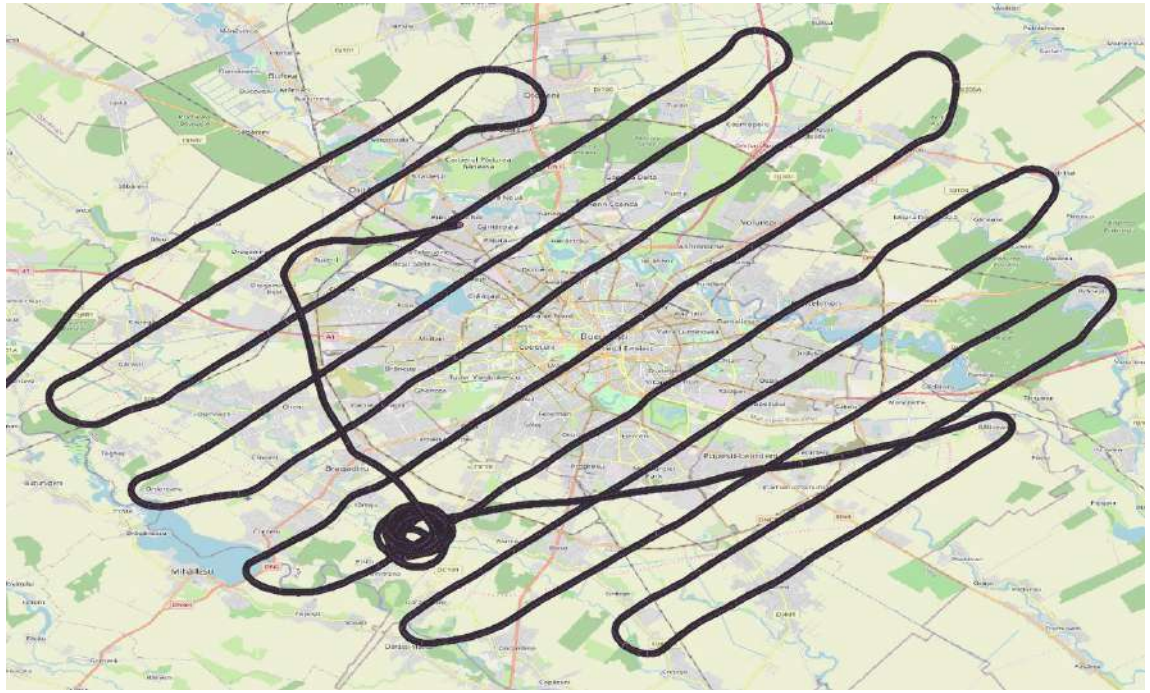
Contact: frederik.tack@aeronomie.be

# DOAS analysis and pre-processing

- **Post flight quicklooks – Raw data check**
  - Download of the SWING spectra and GPS-IMU data
  - Check of the spectra, fixing corrupted file if needed

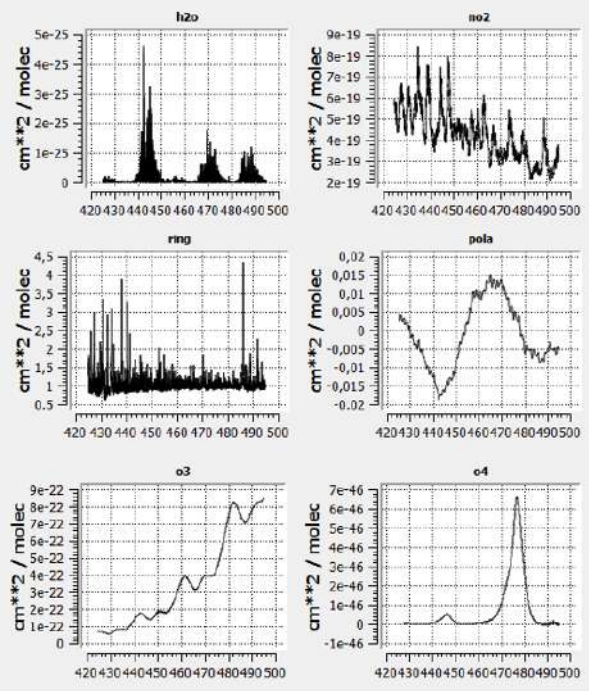


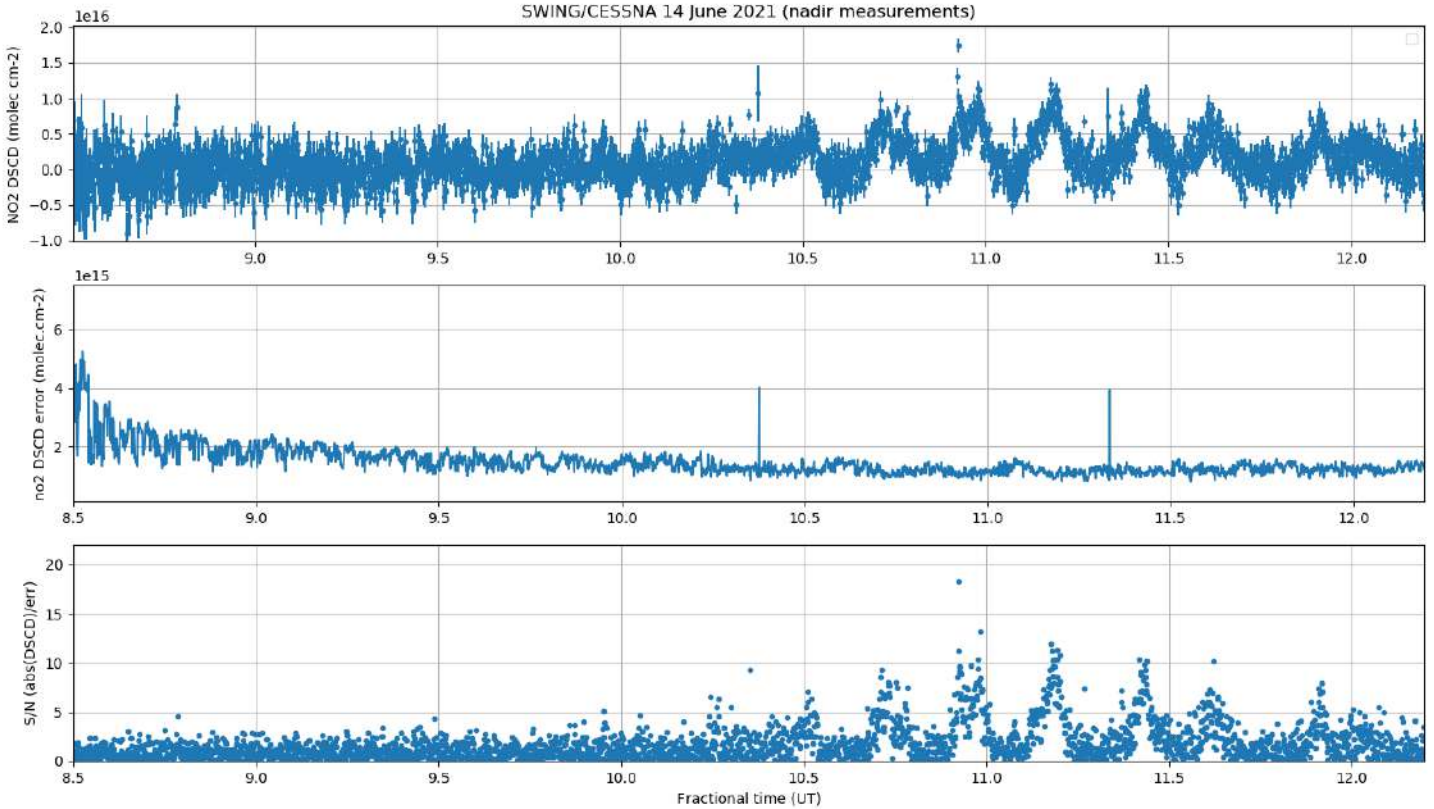
S5PVAL-RO/RAMOS Flight on 23-12-2021

# DOAS analysis and pre-processing

- **Post flight quicklooks – DOAS analysis**
  - DOAS analysis with a fixed reference spectrum (average of 25 SWING spectra)



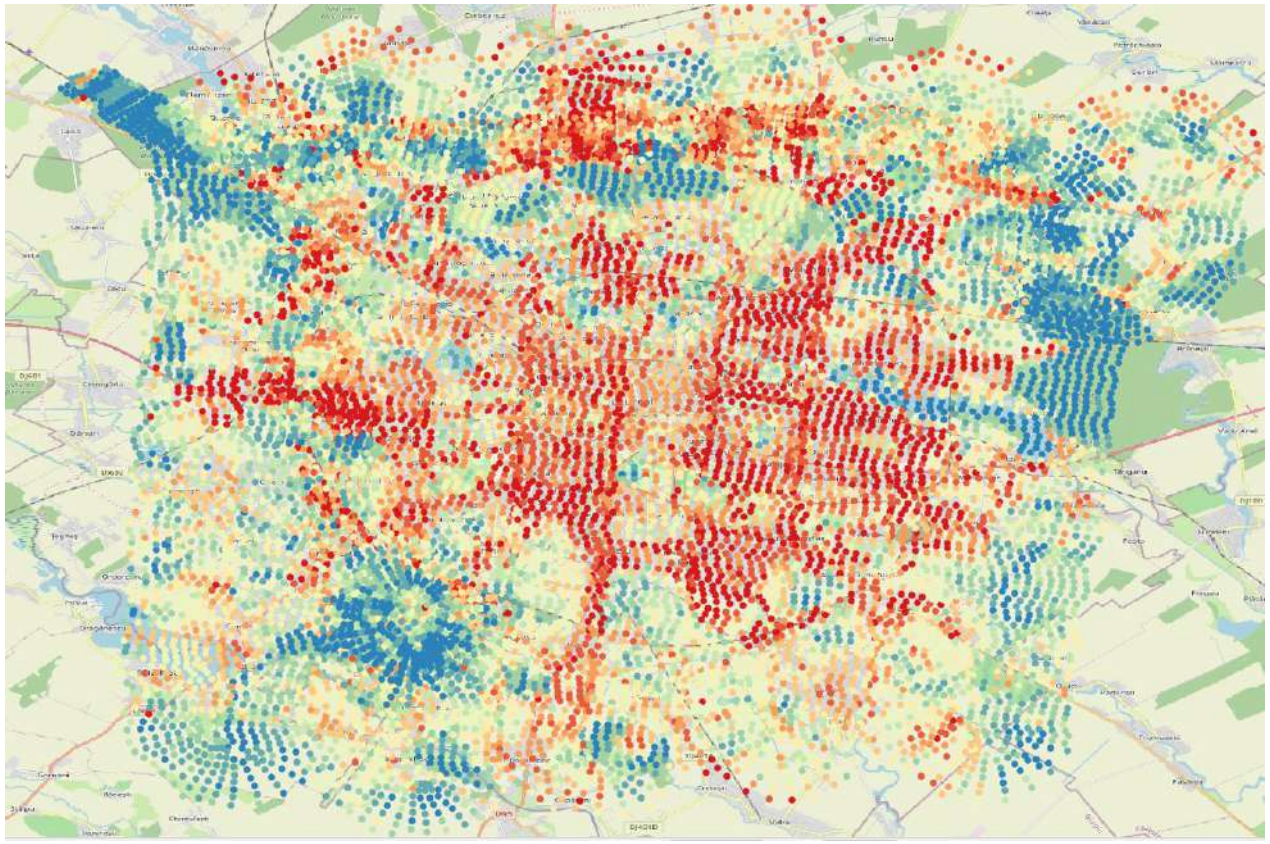

**Fitted cross-sections**




**S5PVAL-DE flight on 14-06-2021**

# DOAS analysis and pre-processing

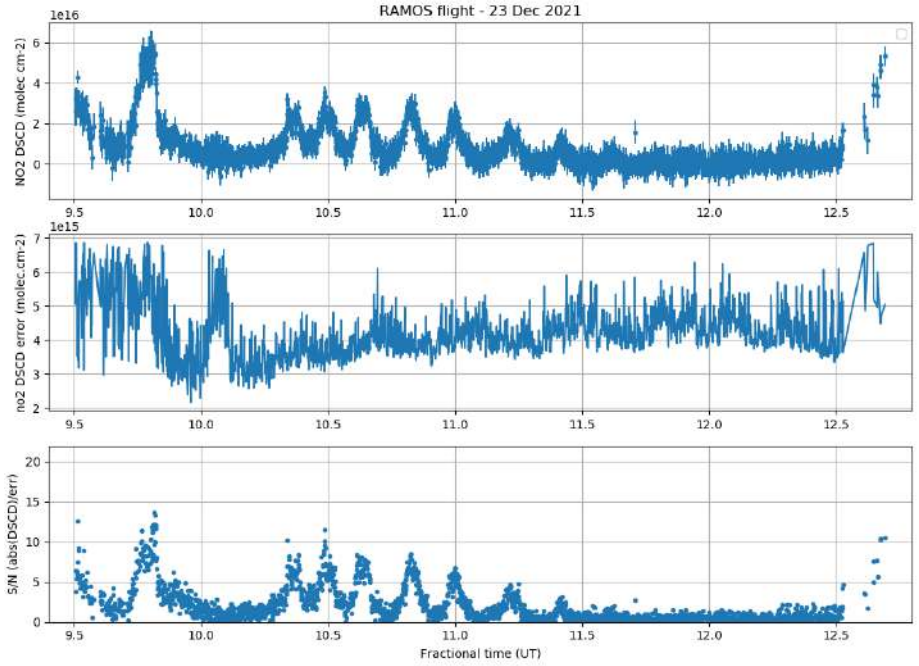
- **Post flight quicklooks – Georeferencing**
  - Georeference the DSCD with the GPS-IMU data
  - Check of the flux map vs ground albedo

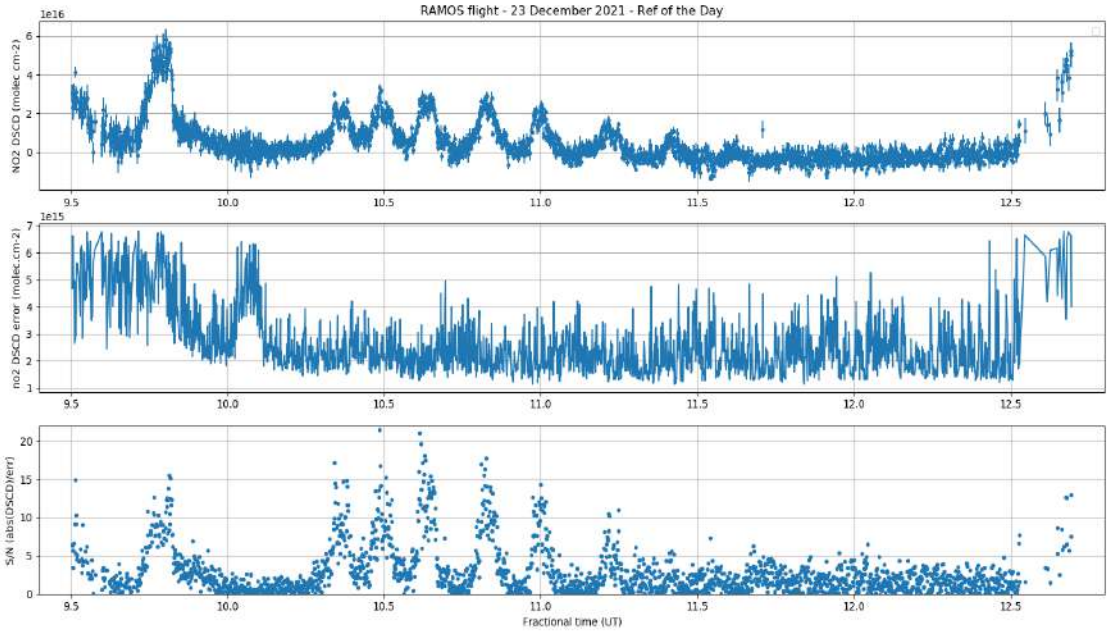


**S5PVAL-RO/RAMOS Flight on 11-11-2021**

# DOAS analysis and pre-processing

- **Input for central processing**
  - Finetuned DOAS analysis and georeferencing with a reference spectrum (average of 25 spectra) of the day
  - Fill metadata info for the day (operator, possible comment on weather, place and time of the reference, etc.)
  - Create input .nc file for central processing, discarding spectra with altitude<3000 m, NO2 fit RMS>1, and flagging $NO_2$ fit RMS>0.005

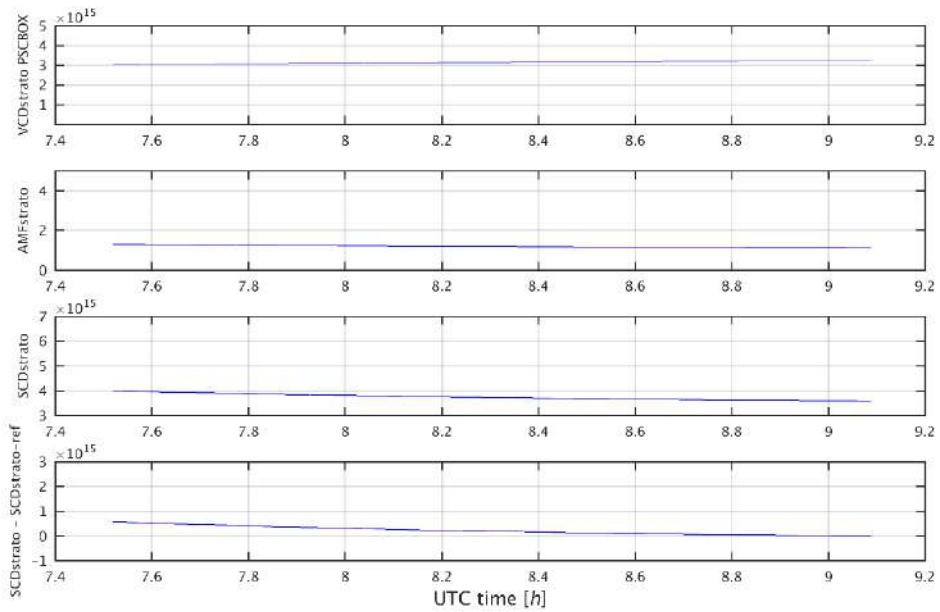


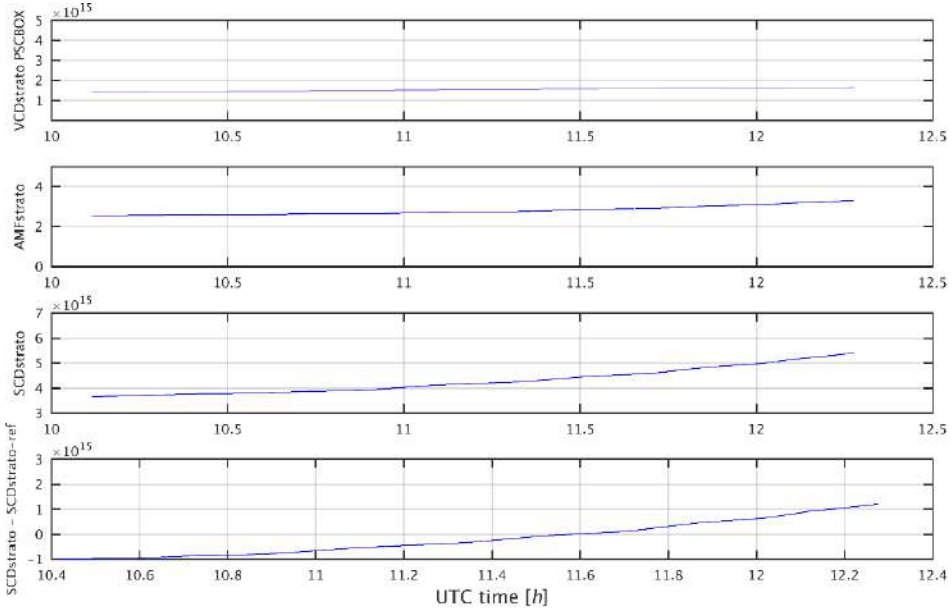
# DSCD → VCD processing

- **SCD stratospheric correction**
  - Compensates for **changes in the stratospheric field** between reference area and actual measurements
  - Based on 1) modeled SCDstrato from stacked box photochemical model PSCBOX, 2) averaged SCDstrato from coincident TROPOMI overpass for scaling, and 3) geometric AMF
  - Effect generally quite small (< 1e15 for 2h flight), but can become significant at larger SZA (autumn-winter flight) or long flight time with reference at start or end of flight

Flight on 01-07-2021



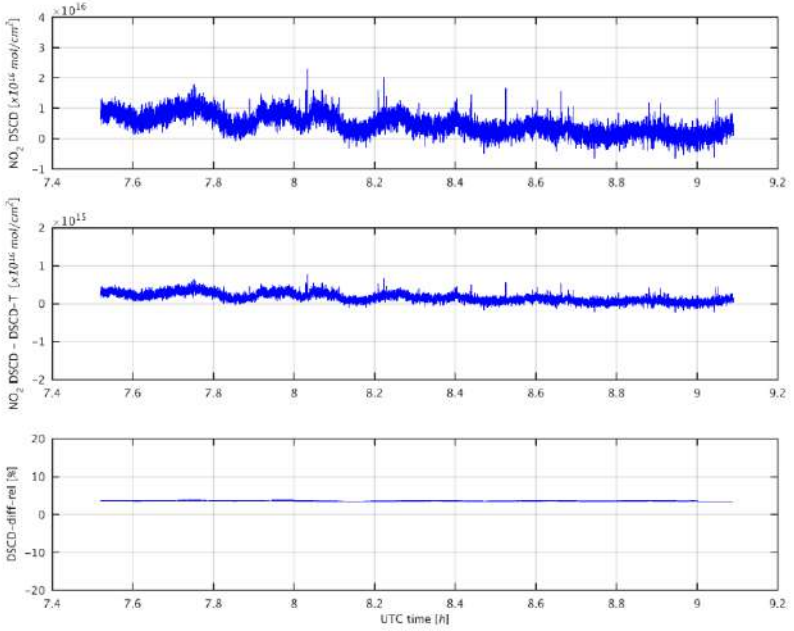

Flight on 23-12-2021



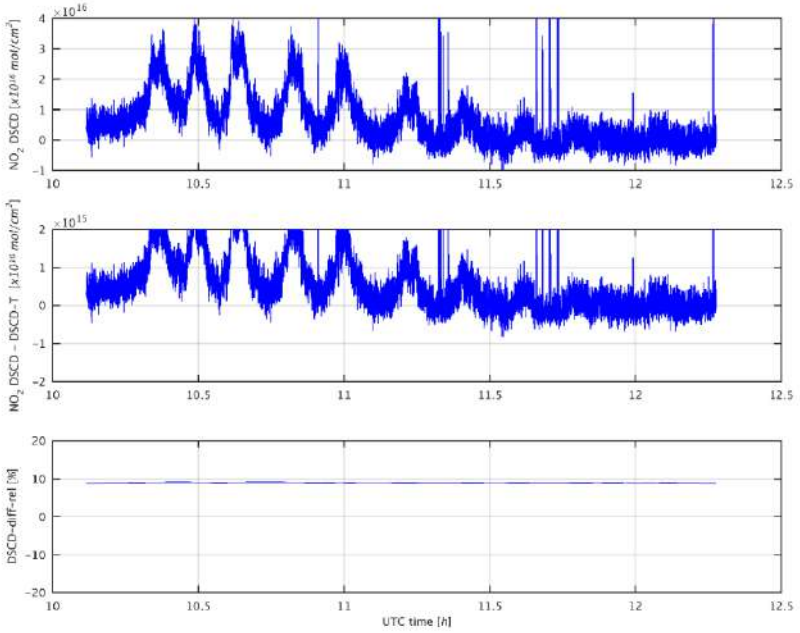
# DSCD → VCD processing

- **DSCD temperature correction**
  - Correct for **temperature dependence of $NO_2$ cross-section**
    - Teff = Tsurf - 6.5 * PBL / 2 → Laps rate of 6.5° per km
    - SCD_T = SCD * (1 + 0.0035 * (Teff - Tref))
  - Surface temperature obtained fom ERA-5 (global, hourly product at 0.25° spatial resolution)
  - Overestimation of about <5% (summer) to <10% (winter) on SCD when not corrected

Flight on 01-07-2021

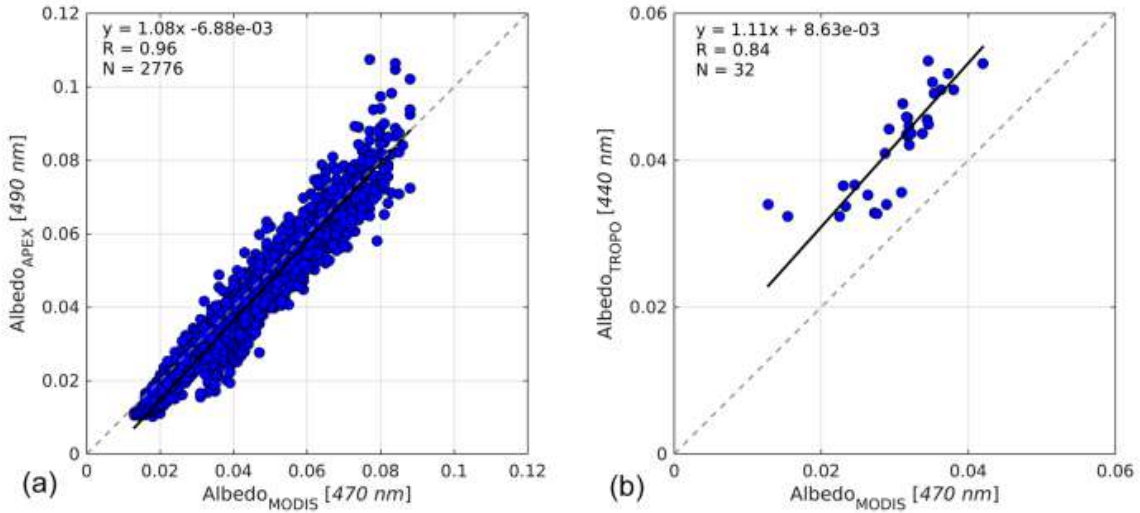



Flight on 23-12-2021



# DSCD → VCD processing

- **$AMF_{tropo}$ -- LIDORT 2.6 RTM** (Spurr, 2008)
- **Surface albedo in the fit window**
  - **User specified**, e.g. based on at-sensor radiance when absolutely calibrated
  - Or **interpolated on MODIS MCD43A3** Black-sky albedo / MCD43A1 BRDF L3 v006 product
  - Global products at **500 m resolution** produced daily using 16 days of Terra and Aqua MODIS data
  - Band 3 (470 nm) used for $NO_2$
  - MODIS MCD43A3 (BRDF) vs MCD43A1 (BSA) → impact of less than 2% on NO2 VCD
  - Product compared to OMI LER, used for TROPOMI albedo, in Tack et al. (2021). OMI LER tends to overestimate



# DSCD → VCD processing

- **$AMF_{tropo}$ -- LIDORT 2.6 RTM** (Spurr, 2008)
- **A priori $NO_2$ profile**
  - Box profile (based on ERA-5 PBL height) or interpolated TM-5 profile (1° spatial resolution)
  - Box profile (500 m) VS TM-5 model profile → VCDs 6-9% lower when model profile is used
  - Box profile (1000 m) VS TM-5 model profile → VCDs within 1%
- **Aerosol scenario (AOD, SSA, etc)**
  - based on CIMEL observations (if available)
  - Pure Rayleigh atmosphere
- VZA, SZA, RAA, analysis wavelength, platform altitude, etc. available in NetCDF file
- **Online computation for each airborne pixel → output are intensities and/or 1D Box-AMFs**