Universität Bremen

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Results from greenhouse gas retrievals for the CO2M mission using the FOCAL method

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Introduction

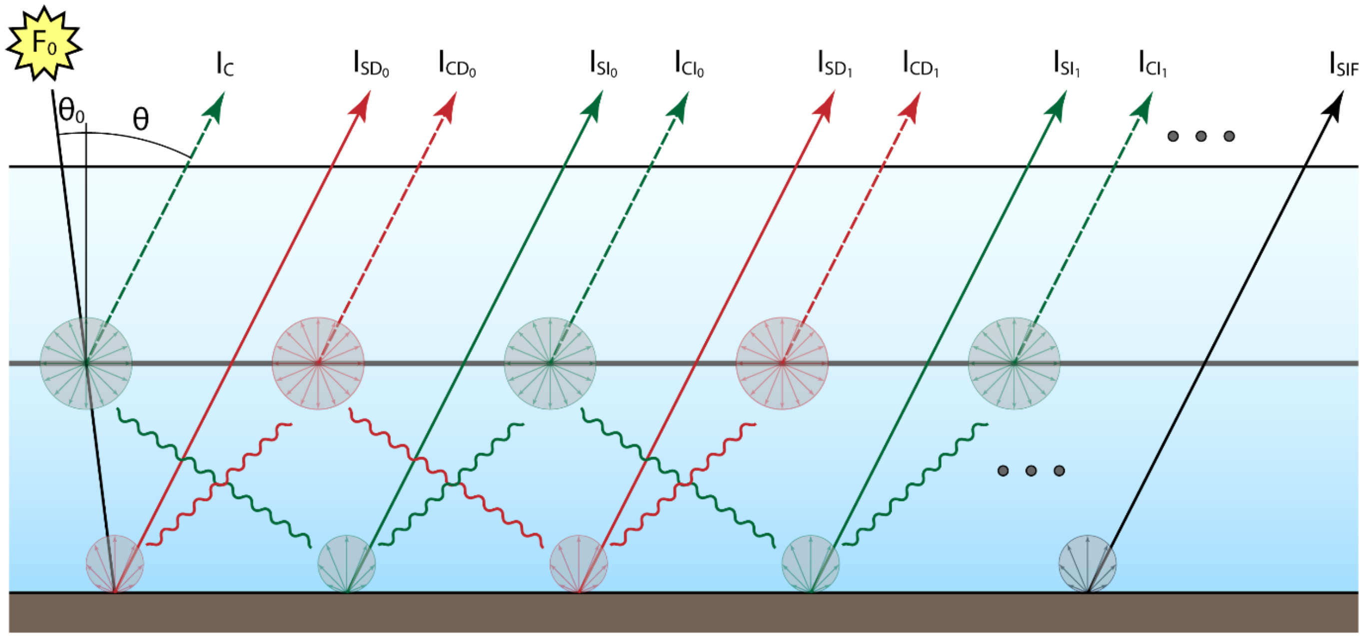
- The European CO2M mission:
  - Constellation of 3 satellites which will monitor global greenhouse gas concentrations
  - Instruments: CO2I (XCO_2, XCH_4, NO_2, SIF, …), MAP (aerosols), CLIM (clouds)
  - First satellite is planned to be launched in 2026

- Data processing:
  - Three different retrieval algorithms to derive XCO_2 and XCH_4 currently under development for the operational processing system @ EUMETSAT
  - One algorithm is based on the FOCAL (Fast atmOspheric traCe gAs retrievaL) method

- Challenges:
  - Requirements on data product quality are high:
    - Systematic XCO_2 error <= **0.5 ppm** (random: ~0.7 ppm)
    - Systematic XCH_4 error <= **5 ppb** (random: ~10 ppb)
  - Verification of requirements can currently only be done using simulated data

- First results for CO2M version of FOCAL presented in **Noël et al., AMT, 2024**
- Here:
  - Updated results using slightly improved input data (no major changes)
  - Focus is on XCO_2 systematic errors (most challenging requirement)

FOCAL Method



- Full physics retrieval based on optimal estimation
- Scattering is approximated by a single scattering layer
- Fast and accurate; suited for large data sets
- Successfully applied to measurements from OCO-2 (Reuter et al., Rem. Sens. 2017a,b), GOSAT and GOSAT-2 (Noël et al., AMT, 2021, 2022)

Performance Assessments

- Verification of requirement on XCO2 error (<= 0.5 ppm) requires some interpretation:

  - Requirements for systematic errors depend on application:

    - Quantification of **anthropogenic emissions:**
      Average inner-scene standard deviation ("high-pass filter") of the XCO_2 bias <= 0.5 ppm

    -> *Requires spatially highly resolved scene*
    (2 km x 2 km XCO_2 images with emission plume(s))

    - Quantification of **natural large scale fluxes:**
      Scene-to-scene standard deviation ("low-pass filter") of the scene-average XCO_2 bias <= 0.5 ppm

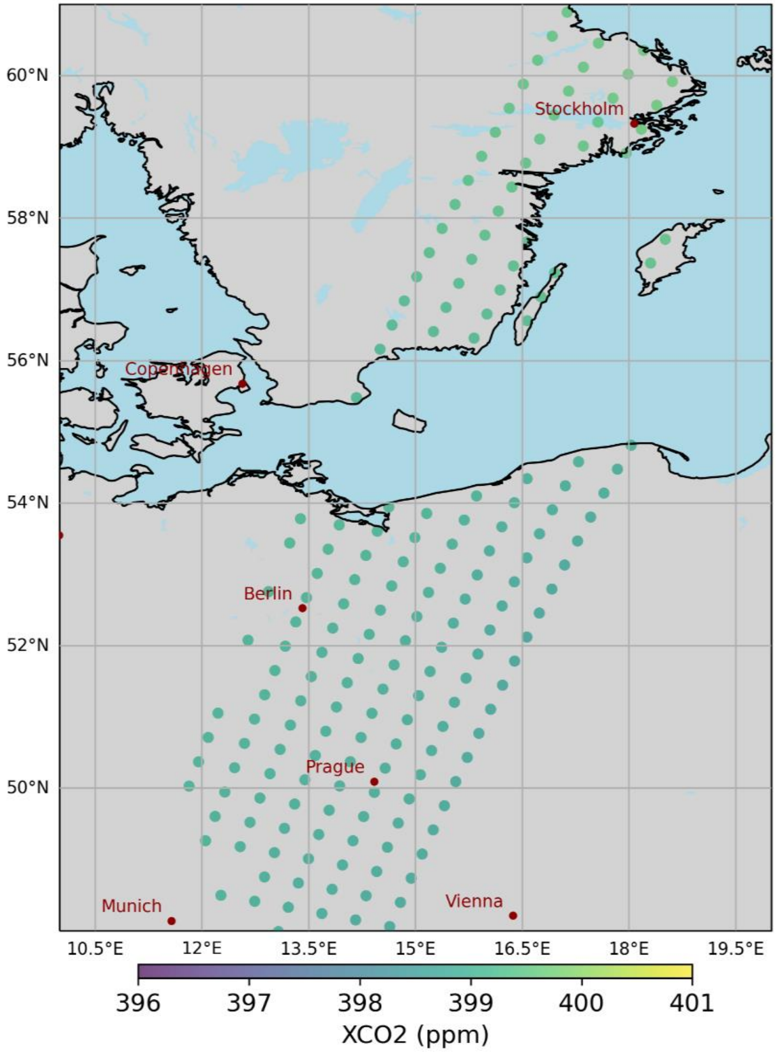
    -> *Requires global data covering a full year*
    (to consider possible long-term / large-scale errors)

  - Requirements are applicable for nadir/land/cloud-free only

Simulation of Input Data (1)

- Full-year global subset:
  - Subset contains every 15th ground pixel, every 20th scanline
    -> 300 times less data, but similar coverage
  - Radiances computed with SCIATRAN considering e.g. also aerosols and surface BRDF, clouds
  - Meteorology from ERA5, CO_2 etc. based on CAMS model data for 2015 (spatial resolution ~ 2° x 3°)
  - CO2M geometry provided by EUMETSAT
  - Only nadir, land (so far)
  - ~6 million spectra modelled (for each band, one year)

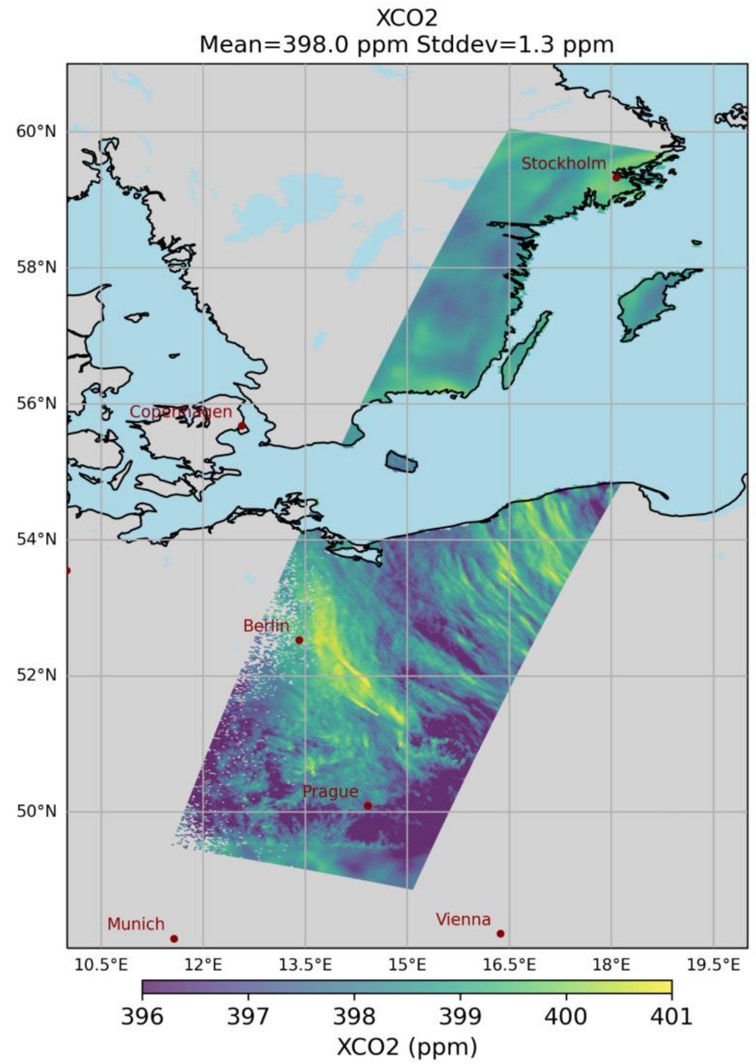
-> *Used for low-pass / large scale fluxes*



Simulation of Input Data (2)

- 'Berlin scene':
  - Full 3 min granule
  - ~67000 measurements, ~37000 land/cloud-free
  - Input radiances generated with SCIATRAN as for subset data
  - Based on high-spatial resolution (9 km) gases and meteorology from CAMS nature run model data for 'Berlin scene' provided by EUMETSAT
  - Contains e.g. power plants in eastern Germany

-> *Used for high-pass / anthropogenic emissions*



Processing of Data

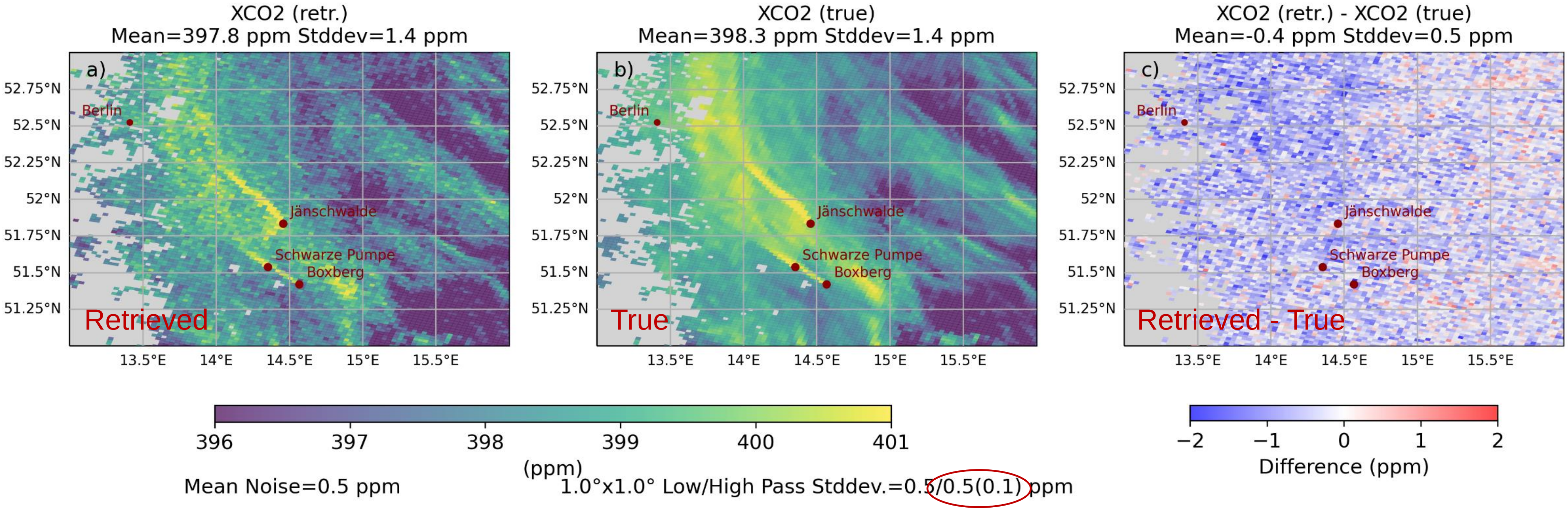
- Procedures aligned to what can be expected in the commissioning phase for real data

- Retrieval settings:
  - Random noise added to spectra -> as for real data
  - CAMS (input) data as a-priori -> as for real data -> best case for simulated data (no limitation, as shown using 400 ppm a-priori)
- Post processing:
  - Filtering (for e.g. outlier removal)
  - Bias correction (minimise systematic offsets)

- Generation of post processing data base:
  - Input data: Retrieval results for April 2015 (subset data), only filtered for convergence etc.
  - Assumed “true” values: CAMS data
  - Filter parameters/limits are determined using variance minimisation method:
    -> prescribe percentage of data to be filtered out (currently 15%, tbc)
    -> max. 10 parameter limits which reduce mean variance between retrieved and true value most
  - Bias correction based on machine learning regression (currently: gradient boosting, XGBoost)
    -> max. 10 best parameters for bias reduction and related data base

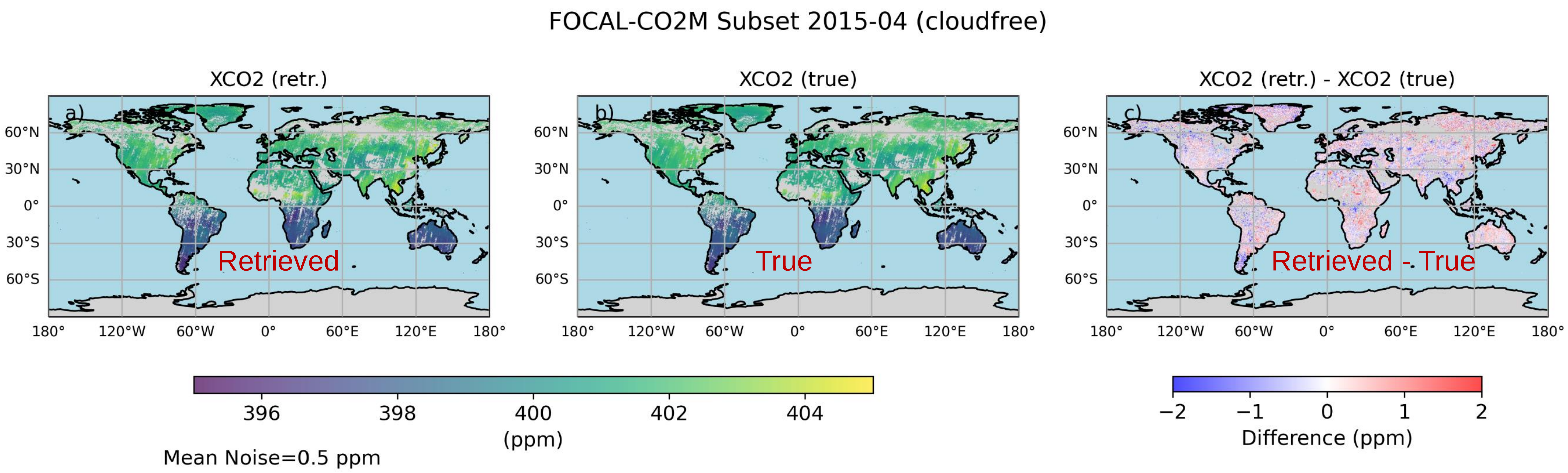
-> Post processing data base to be adapted during commissioning phase based on real data

Results: Power Plants in Berlin Scene



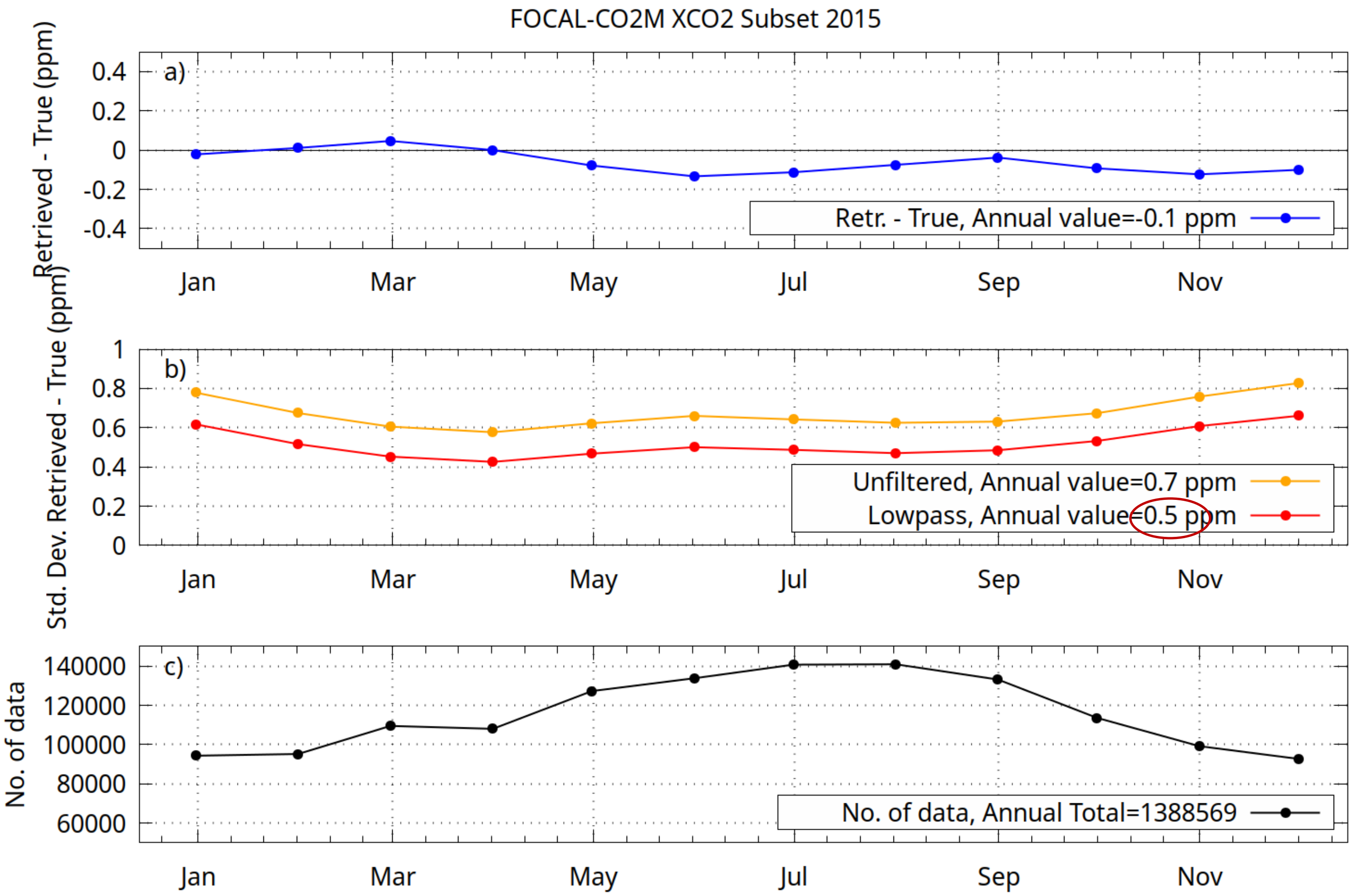
- Small systematic offset ~0.4 ppm (not relevant for emission determination)
- No plume structures visible in difference map
- Noise error similar to high-pass standard deviation -> high pass dominated by noise
- Estimate for noise subtracted: 0.1 ppm
- High-pass standard deviation 0.1 – 0.5 ppm
  (requirement: syst. error <= 0.5 ppm)

Results: Example for Subset Data



- Retrieved data reproduce all large-scale patterns
- Scatter in differences dominated by noise
- April 2015 (training month -> best case)

Results: Low-pass



- Mean standard deviations of low-pass filtered subset data (monthly & annually)
- Best results for April (training month)
- Slightly higher standard deviations in other months (always < 0.6 ppm)
- Improvements expected when using more months (full year data set?) for post processing data base generation

- Yearly average low-pass standard deviation 0.5 ppm (requirement: syst. error <= 0.5 ppm)

Conclusions

- The FOCAL retrieval has been successfully adapted to CO2M

- Performance test using simulated data (nadir land, cloud-free) show that the requirement of a systematic XCO_2 error of <= 0.5 ppm is fulfilled by the FOCAL retrieval:
  - For **natural large scale fluxes** (low-pass filter), based on a full year (sub-sampled) data set
  - For **anthropogenic emissions** (high-pass filter), based on a high-resolution scene

- Reasonable retrieval results are obtained up to AOD 0.5 (syst. offsets <= 0.2 ppm) (even without using external aerosol information as input) – *not shown here*

- Notes:
  - Requirements for XCH_4 have been checked in a similar way -> also fulfilled
  - Retrievals using simulated data for 2020 show similar results
  - All results are preliminary and based on simulated data
  - Analysis needs to be re-done with real measurements (esp. update of post-processing DB)
  - Further improvements possible by e.g. inclusion of aerosol information from MAP

-> Current results give good confidence that requirements can also be fulfilled for real measurements

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- Large parts of the calculations reported here were performed on HPC facilities of the IUP, University of Bremen, funded under DFG/FUGG grant INST 144/379-1 and INST 144/493-1.

Thank you for your attention!

Extra slides

Performance Assessments

- Verification of requirement on XCO2 error (<= 0.5 ppm) requires some interpretation:
  - Requirements for systematic errors depend on application:
    - Quantification of **anthropogenic emissions:**
      Average inner-scene standard deviation ("high-pass filter") of the XCO_2 bias <= 0.5 ppm
      -> Requires spatially highly resolved scene (2 km x 2 km XCO_2 images with emission plume(s))
    - Quantification of **natural large scale fluxes:**
      Scene-to-scene standard deviation ("low-pass filter") of the scene-average XCO_2 <= 0.5 ppm
      -> Requires global data covering a full year (to consider possible long-term / large-scale errors)

  - Requirements are applicable for nadir/land/cloud-free only

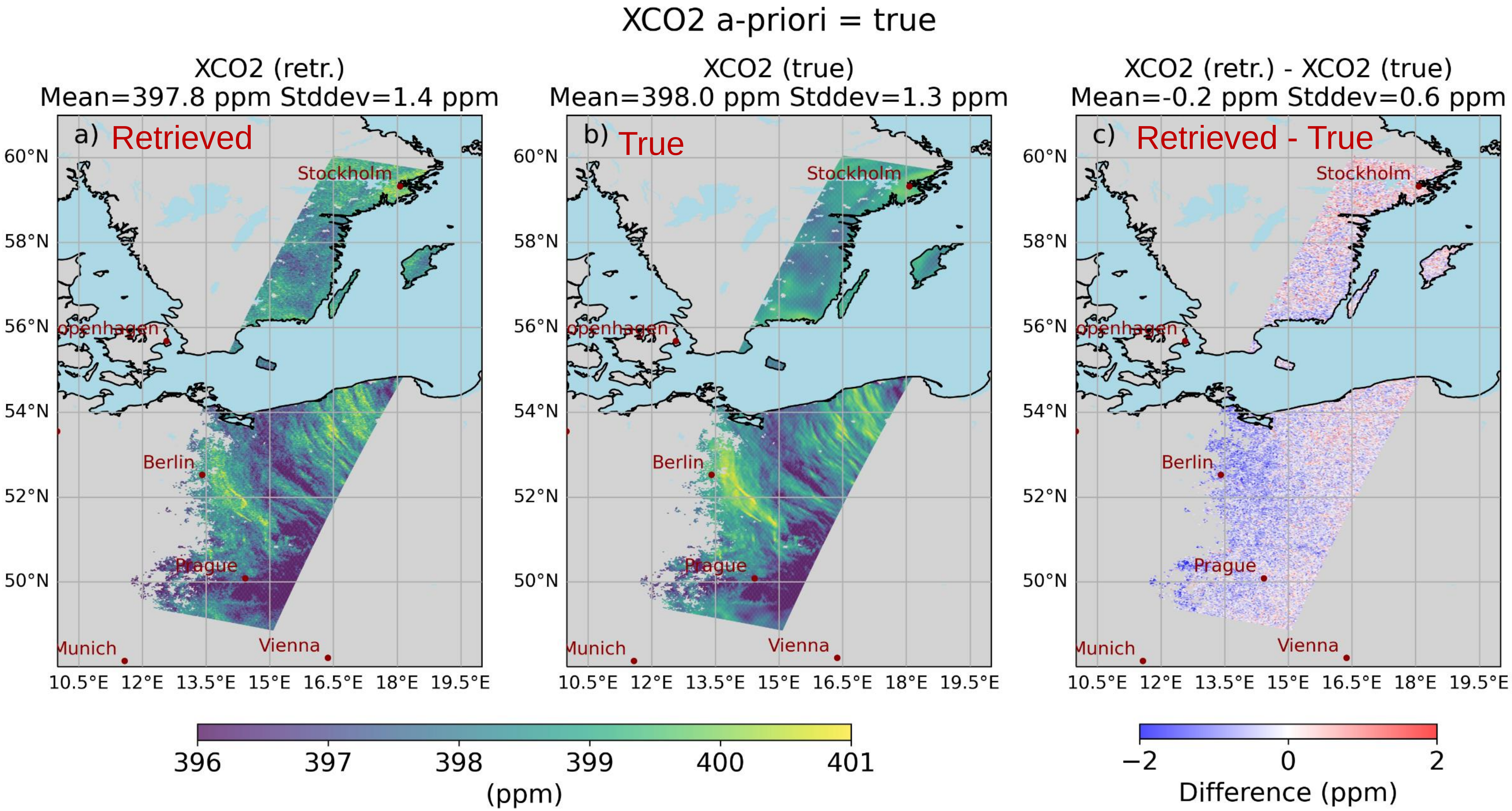
- Verification method:
  - Low-pass filtering:
    - Determine for each orbit a running average of the difference to the assumed true value within a 1° x 1° (tbc) lat/lon box -> *background XCO_2 bias*
    - Compute standard deviation of this background XCO_2 (for whole year), considering cos(lat) weights

    -> Check: Weighted standard deviation of all background values should be <= 0.5 ppm

  - High-pass filtering:
    - Apply low-pass filter to scene data -> *background XCO_2 bias*
    - Subtract background data from retrieved data -> *high-pass filter data*

    -> Check: Standard deviation of high-pass filter data should be <= 0.5 ppm

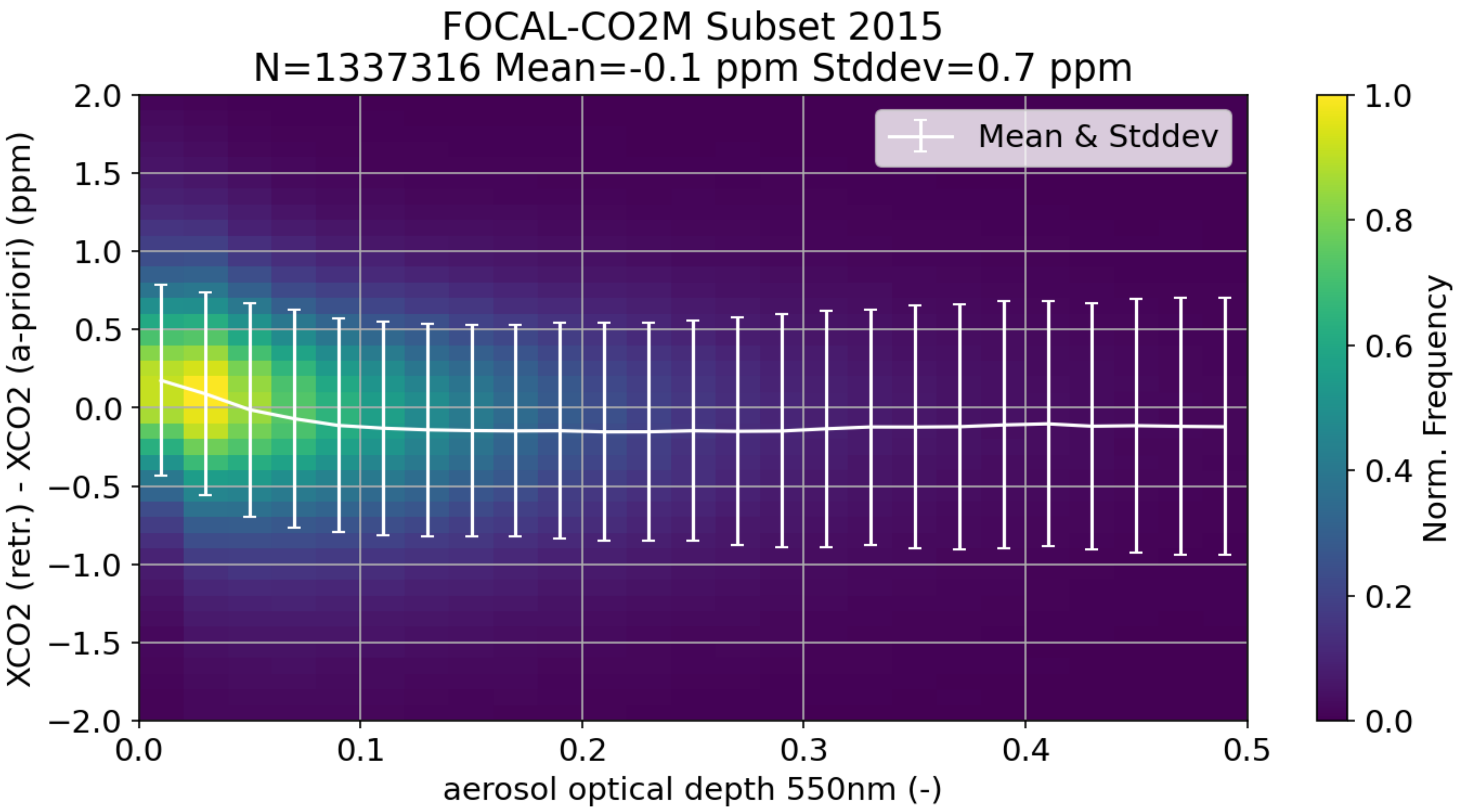
Results: Berlin Scene



Mean Noise=0.5 ppm   1.0°x1.0° Low/High Pass Stddev.=0.3/0.5(0.1) ppm

- Noise error similar to high-pass standard deviation (0.5 ppm) -> high-pass dominated by noise
- Very similar results when using fixed 400 ppm a-priori profile

Aerosol Dependence: 2015 Subset Data



- Retrievals should give valid results until AOD(550 nm) = 0.5
- SCIATRAN calculations for simulated data consider different aerosol types
- FOCAL retrieval does not explicitly consider aerosol (only one effective scattering layer)

- Small (< 0.2 ppm) systematic offsets due to aerosol for complete year
- Results may be improved when using extended training data for post-processing (not only April) and/or additional information from MAP
- FOCAL-CO2M is able to retrieve valid XCO_2 for AOD up to 0.5