Comparison of MAX-DOAS profiling algorithms during CINDI-2
Part 1: Aerosols

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The CINDI-2 Campaign

The second Cabauw Intercomparison campaign for Nitrogen Dioxide measuring Instruments (CINDI-2) took place at the Cabauw Experimental Site for Atmospheric Research (CESAR; Utrecht area, The Netherlands) from 25 August until 7 October 2016. An important objective of the campaign was to study the relationship between remote-sensing column- and profile-measurements of trace gases and aerosols with collocated reference ancillary observations. For this purpose, a CINDI-2 Profiling Task Team (CPTT) was created, involving 21 groups performing aerosol and trace gas vertical profile inversion using dedicated MAX-DOAS profiling algorithms, as well as the teams responsible for ancillary profile and surface concentration measurements (NO_2 analysers, NO_2 sondes, and LIDAR, CAPS, Long-Path DOAS, sun photometer, nephelometer, etc). The main purpose of the CPTT is to assess the consistency of the different profiling tools for retrieving aerosol extinction and trace gas vertical profiles through comparison exercises using commonly defined settings and to validate the retrievals with correlative observations.

Here we present an overview of the MAX-DOAS aerosol profile comparison results during CINDI-2. A companion poster (X5.381) presents the trace gas profile retrieval results.

Further EGU2017 presentations related to the CINDI-2 campaign:

- ***The Second Cabauw Intercomparison Campaign for Nitrogen Dioxide Measuring Instruments — CINDI-2 — Overview,*** *Arnoud Apituley et al., EGU-2017-10177 (oral)*
- ***First results of the CINDI-2 semi-blind MAX-DOAS intercomparison,*** *Karin Kreher et al., EGU2017-13927 (poster X5.379)*
- ***Comparison of MAX-DOAS profiling algorithms during CINDI-2 - Part 2: trace gases,*** *Francois Hendrick et al., EGU2017-8484 (poster X5.381)*

Retrieval of Vertical Profiles from MAX-DOAS Measurements

- MAX-DOAS instruments determine the integrated concentration differential slant column density, dSCD) along several light paths through the atmosphere.
- Trace gas and aerosol extinction profiles can be estimated from a sequence of measurements at different elevation angles.

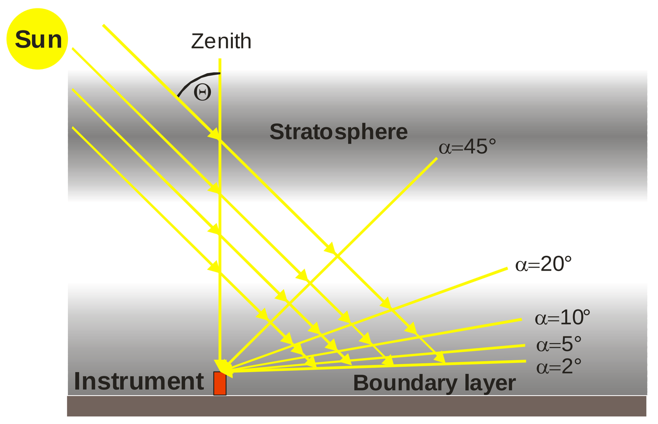

Fig. 1: Viewing geometry of MAX-DOAS measurements

The table below lists the institutes and algorithms participating in the comparison. They include both optimal estimation (OEM) and parametrized algorithms.

Group	Algorithm name + retrieval method
AIOFM	Priam;OEM + BePRO; OEM
BIRA-IASB	BePRO; OEM
CHIBA-U	JM2; Eight-component profiling tool combining OEM and parameterized profile shape (AOD/VCD and 3 parameters for profile shape)
CMA	Priam; OEM
CSIC	HeiPro; OEM
CU-Boulder	In-house developed profiling tool; pre-calculated weighting functions + OEM
DLR	BePRO; OEM
Fudan University	BePRO; OEM
INTA	In-house developed profiling tool; OEM
IUP-Bremen	BREAM; block-AMF approach for aerosols + OEM for trace gases
IUP-Heidelberg	HeiPro; OEM
KNMI	In-house developed profiling tool; Parameterized approach
LMU	In-house developed profiling tool; OEM
MPIC	Priam algorithm (OEM) and parameterized approach
NASA	In-house developed profiling tools; OEM + approach based on the determination of profile information from surface concentrations and vertical columns
Univ. of Toronto	HeiPro

Retrievals are performed at wavelengths of 360 and 477 nm on a 200 m vertical grid from the surface up to 4 km altitude using common settings for a priori constraints, pressure and temperature profiles, as well as aerosol optical properties → **see companion poster X5.381 by Hendrick et al.**

Averaging Kernels and Information Content

- The Averaging Kernels, $A = \frac{\partial \hat{x}}{\partial x}$, quantify the sensitivity of the retrieved profile $\hat{x}$ to the true atmospheric state x.
- The vertical resolution at a certain altitude is given by the width of the corresponding averaging kernel.
- The trace of the averaging kernel yields the number of independent pieces of information in the measurements (degrees of freedom for signal, DOF).

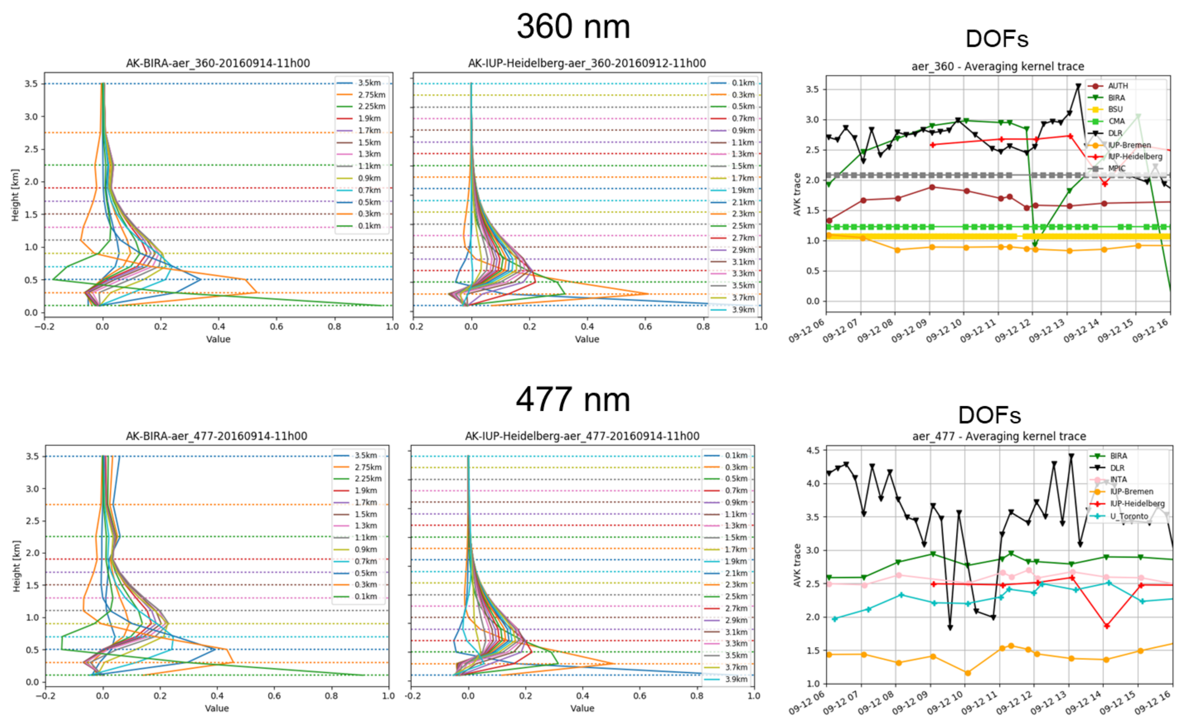

Fig. 2: Examples for clear-sky averaging kernels from the BIRA (left) and IUP-Heidelberg (centre) retrievals at 360 (top) and 477 nm (bottom). The DOFs from all groups using OEM algorithms are shown on the right.

- Retrieval is sensitive for the lowermost ~1.5 km of the atmosphere
- Highest sensitivity near the surface
- The mean DOF amounts to 1.8 and 2.5 at 360 and 477 nm, respectively

Aerosol extinction profiles

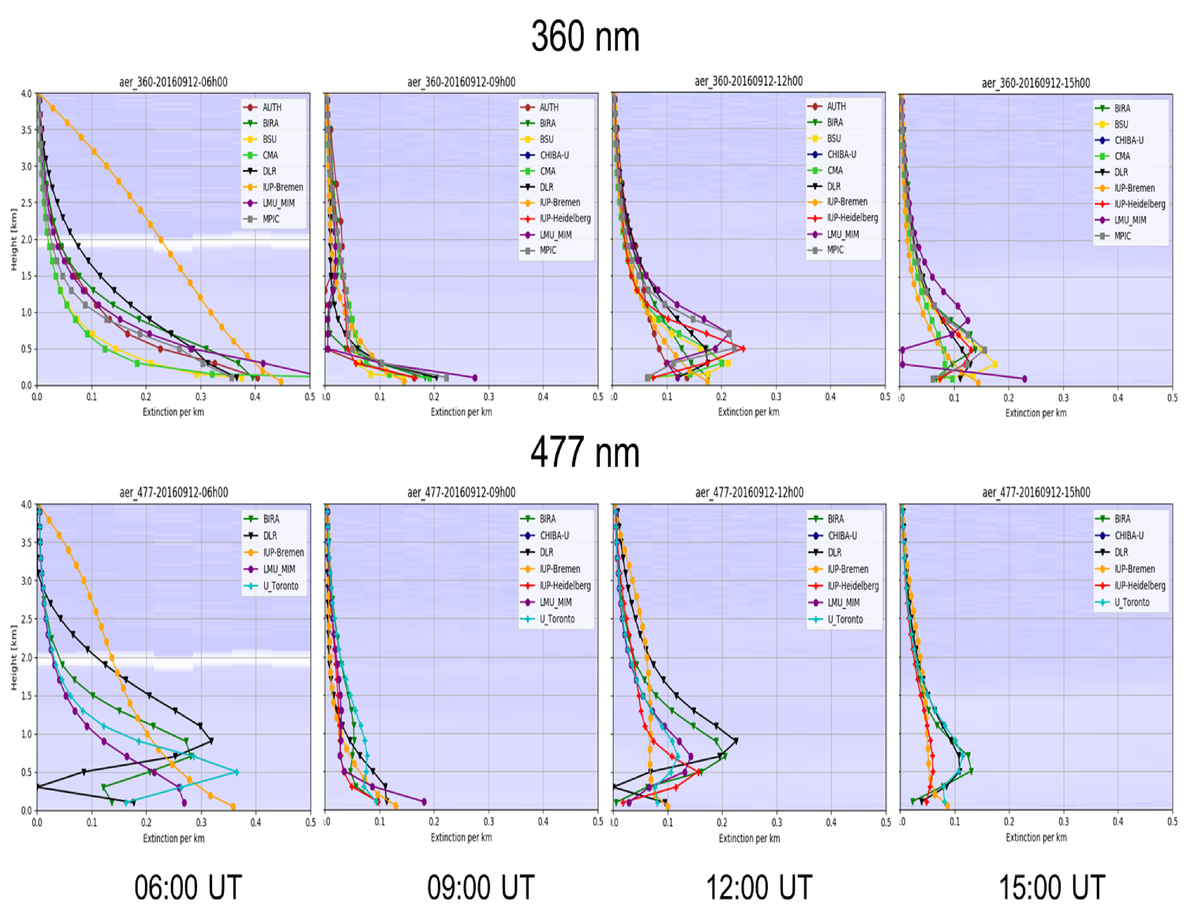

Fig. 3: Aerosol extinction profiles using free settings from all groups on 12. September 2016 at 360 (top) and 477 nm (bottom). The background shows the Ceilometer backscatter profile +/- 15 min around the nominal time, ranging from blue (low backscatter) to white (high backscatter)

- Aerosol extinction profiles show reasonable agreement for most retrieval algorithms
- Significant differences regarding the layer height occur when clouds are present (477 nm profiles at 6:00 UTC)

AOD – Comparison with Sun Photometer

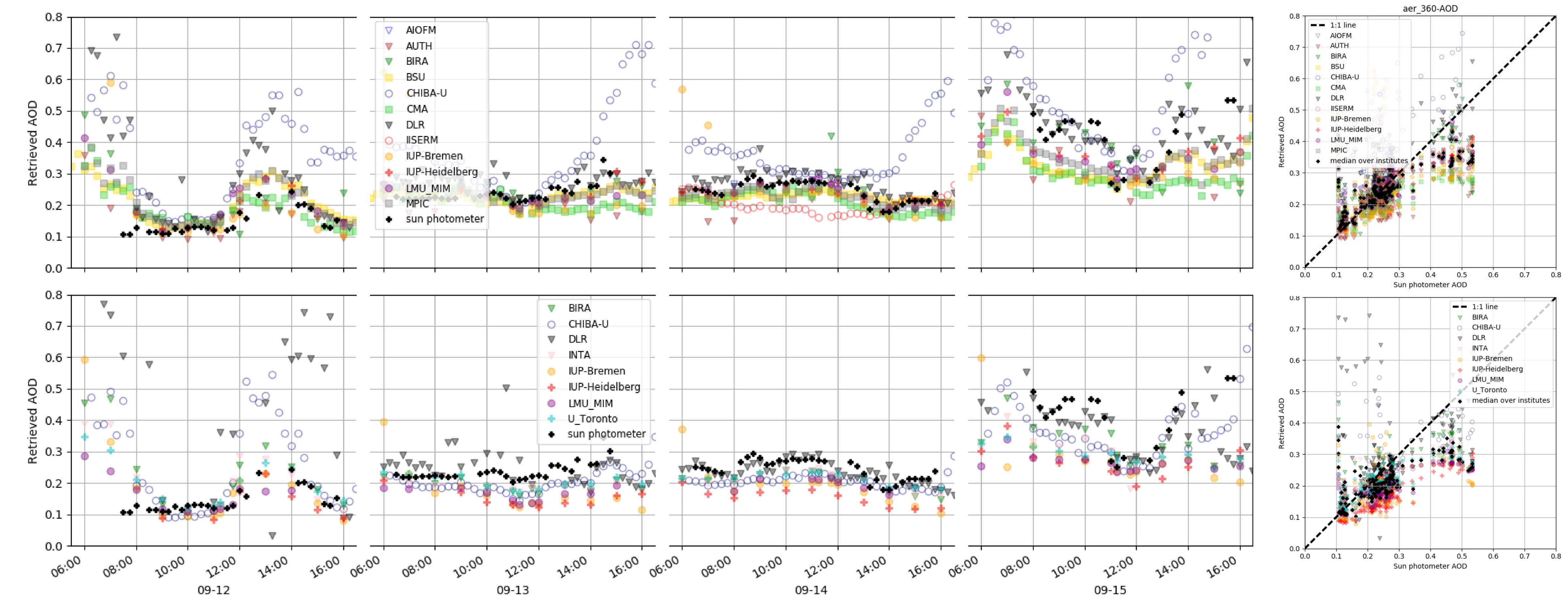

Fig. 4: Left: Time series of AOD retrieved from the individual participants (coloured symbols) and from Sun photometer (black diamonds) for a 4-day clear sky period. Right: Correlation between AOD from MAX-DOAS and Sun photometer. Top: 360 nm; bottom: and 477 nm. Sun photometer data courtesy of Bas Henzing, TNO.

	AOD - 360 nm			AOD - 477 nm		
	Slope	Intercept	R	Slope	Intercept	R
AIOFM	0.61	0.09	0.96	-	-	-
AUTH	0.60	0.06	0.81	-	-	-
BIRA	0.84	0.04	0.87	0.62	0.07	0.76
BSU	0.43	0.12	0.86	-	-	-
CHIBA-U	0.99	0.11	0.69	0.55	0.09	0.62
CMA	0.35	0.13	0.77	-	-	-
DLR	0.66	0.12	0.75	-12.33	4.68	-0.31
IISERM	-0.07	0.21	-0.09	-	-	-
INTA	-	-	-	0.47	0.10	0.72
IUP-Bremen	0.56	0.09	0.48	0.53	0.06	0.77
IUP-Heidelberg	0.67	0.07	0.93	0.52	0.03	0.89
LMU-MIM	0.59	0.10	0.85	0.46	0.07	0.83
MPIC	0.49	0.11	0.84	-	-	-
U-Toronto	-	-	-	0.47	0.10	0.82

Table 1: Regression parameters from the comparison of MAX-DOAS and sun photometer AOD. The colour scale indicates the level of deviation from the optimal value.

- AOD from most retrieval algorithms show reasonable agreement with co-located sun photometer measurements
- AOD comparison with sun photometer yields correlation coefficients > 0.9 for some groups
- AOD is systematically underestimated by MAX-DOAS (slope smaller than 1)
- Level of agreement with sun photometer usually better at 360 nm than at 477 nm.
- In contrast to sun photometer, MAX-DOAS can derive AOD also during periods of low visibility

Modelled and Measured dSCDs

- The level of agreement between modelled and measured O_4 dSCDs is an important indicator for the level of convergence and thus the quality of the retrieval.
- Fig. 5 shows exemplarily modelled vs. measured O_4 dSCDs at 360 nm for a clear sky day.
- Regression parameters listed in Table 2 indicate that some of the models do not achieve sufficient convergence.

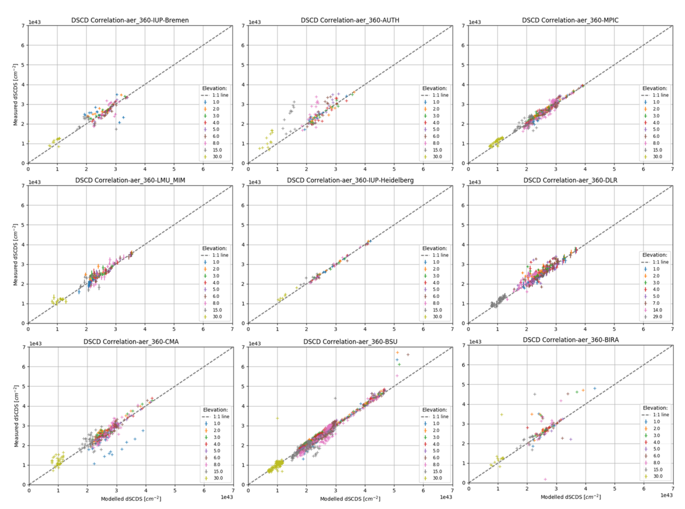

Fig. 5: Comparison of modelled and measured O_4 dSCD at 360 nm for 12. September 2016. The colour indicates the elevation angle.

	Aerosol - 360 nm			Aerosol - 477 nm		
	Slope	Intercept [10^{43} cm^{-2}]	R	Slope	Intercept [10^{43} cm^{-2}]	R
AIOFM	1.04	0.01	0.97	-	-	-
AUTH	0.89	0.10	0.88			
BIRA	0.76	0.46	0.88	0.99	0.03	0.99
BSU	0.95	0.13	0.98	-	-	-
CMA	0.93	0.18	0.94	-	-	-
DLR	0.96	0.06	0.98	0.68	0.62	0.69
IISERM	1.04	-0.11	0.96	-	-	-
INTA	-	-	-	1.00	0.01	0.99
IUP-Bremen	1.02	-0.01	0.93	1.00	-0.02	0.96
IUP-Heidelberg	1.03	-0.08	1.00	1.01	-0.06	0.99
LMU-MIM	0.97	0.05	0.98	0.93	0.36	0.96
MPIC	1.00	-0.02	0.99	-	-	-
U-Toronto	-	-	-	0.98	0.03	0.98

Table 2: Regression parameters from the comparison of modelled and measured O_4 dSCDs

Summary & Conclusions

- The MAX-DOAS measurements performed during CINDI-2 allow for a comprehensive comparison of existing profile retrieval algorithms.
- CINDI-2 Profiling Task Team consists of 21 participating groups, of which 15 have submitted data based on 10 different profile retrieval algorithms.
- First comparison of AOD with sun photometer measurements during clear-sky conditions shows reasonable to good agreement
- Vertical profiles from different groups are in reasonable agreement under clear-sky conditions, but vary significantly in the presence of clouds
- Next steps:
  - ➢ Comparison of retrievals for the whole duration of the campaign, including clouds and poor visibility
  - ➢ Comparison of aerosol extinction profiles with Raman Lidar and Ceilometer
  - ➢ Comparison of surface extinction with co-located in situ measurements (Nephelometer, MAAP, etc.)

Acknowledgments

The CINDI-2 Campaign and this study have been funded by the ESA projects CINDI-2 and FRM4DOAS (contracts No. 4000118533/16/I-SBo and 4000118181/16/I-EF, respectively). The CINDI-2 Campaign was hosted by the Royal Netherlands Meteorological Institute, de Bilt, The Netherlands.