Proof-of-Concept: Dual-Instrument Optical Chamber for Enhanced Aerosol Typology Characterization

Authors: Corinna Kloss[1], Jean-Baptiste Renard[2], Vicheith Tan[1], Jochen Barthel[1], Gilles Chalumeau[2], Thomas Lecas[2], Gwenaël Berthet[2], Matthieu Jeannot[4], Armin Afchine[1], Tom Neubert[3], Marc von Hobe[1], Christian Rolf[1], Michaela I. Hegglin[1]

Affiliations: [1]Institute of Climate and Energy Systems - Stratosphere (ICE-4), Forschungszentrum Jülich GmbH, Germany, [2] Le Laboratoire de Physique et de Chimie de l'Environnement et de l'Espace (LPC2E), CNRS Orléans, France, [3]Institute of Technology and Engineering (ITE), Forschungszentrum Jülich GmbH, Germany, [4]Lify Air, Orléans, France
Contact: c.kloss@fz-juelich.de
Date: May 2025

Abstract

This study presents the development and preliminary validation of a dual-instrument aerosol measurement system, composed of two Light-weight Optical Aerosol Counter version 2 (LOAC2) optical particle counters, one of which includes a modified optical chamber (commercially available via MeteoModem). The aim is to improve aerosol typology classification by increasing the number of independent scattering angles from four (in standard LOAC2) to seven. This setup allows a more detailed assessment of the angular dependence of light scattering, which in turn enhances the ability to distinguish between aerosol types, including combustion, volcanic, metallic, and microplastic particles. First laboratory tests using different aerosols show that additional angles provide significantly more information on the scattering signal and therefore microphysical properties— information that is not accessible with conventional two- or four-angle configurations. These results highlight the potential of a multi-angle approach for more robust in situ aerosol classification. Some aspects, such as flow design and typology calibration, require further refinement.

Introduction and Motivation

Stratospheric aerosols significantly influence Earth's climate by scattering and absorbing radiation, thereby exerting a direct cooling effect on global surface temperatures (Solomon et al., 2011; Kremser et al., 2016). Historically, only volcanic eruptions were known to inject substantial amounts of aerosol and precursor gases into the upper troposphere and lower stratosphere (UTLS). However, recent extreme wildfire events, intensified by climate change, have demonstrated a comparable capacity to disturb stratospheric composition (Khaykin et al., 2020; Kloss et al., 2021), yielding measurable short-term global radiative forcing. Despite their relevance, the radiative effects of especially fire derived aerosols remain poorly constrained. Instrumentation like the nephelometer, as presented in Crepel et al. (1997) and Gayet et al. (1997), have already proven the advantages of deploying a multi-angle approach for in situ measurements for quantifying optical properties of large atmospheric aerosols in the troposphere, mainly clouds, including their typology. They detect the scattering of light at multiple scattering angles, for conclusions on the scattering phase function. However, such instrumentations are usually too heavy and too expensive to be spontaneously launched on flexible platforms, such as weather balloons. Therefore, they cannot be used in a rapidresponse manner to investigate the optical properties of unforeseeable events, like extreme wildfire plumes in the Upper Troposphere and Lower Stratosphere (UTLS). Nevertheless, the detailed aerosol characterization (in terms of refractive index and composition) is a necessary input and validation criteria for the global and regional chemistry-climate simulations and the resulting radiative forcing with its implications on the climate.

A light-weight approach is necessary to fulfill those criteria. To address this gap, we here investigate a first approach and preliminary tests of a novel aerosol measurement setup combining two optical particle counters (OPCs), Light-weight Optical Aerosol Counter version 2 (LOAC2) assembling an increased number of measurement angles, for enhanced typology classification. LOAC 2 (Renard et al., in preparation) is a newly developed Light weight Optical Particle Counter and is based on 15 years of experience and improvements of the established LOAC instrument (Renard et al., 2016). During validation campaigns and instrument comparison, LOAC2 has proven good agreement with satellite observations with ATLID on EarthCARE (Renard et al., in preparation).

The primary goal of the presented laboratory tests is the evaluation of the capability of this dual-instrument system to distinguish between various aerosol types (as they occur or potentially occur in the upper troposphere and lower stratosphere), including key aerosol types: Combustion aerosols, minerals, volcanic aerosols (sulfuric acid and ash) and water droplets. Further tests will include the investigation of metallic particles as they appear in the stratosphere after reentries of satellites, and microplastics.

Instrument set up (LOAC-F)

This proof-of-concept study tests the first prototype (LOAC-F) of an OPC development featuring multiple (>8) measurement angles, for the development of the Flying Light-weight Particle Property analysER (FLIPPER) instrument. This prototype combines two LOAC2 OPC measurement instruments:

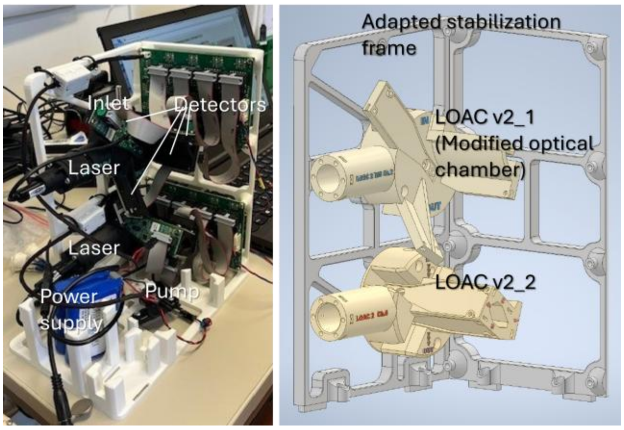

Figure 1: (left) Picture of the laboratory set up. (right) Schematic construction

- **LOAC2**: A compact OPC, commercially available at MeteoModem (https://www.meteomodem.com/) with four fixed scattering angles at 20°, 50°, 125°, and 145°.
- **LOAC2 with modified optical chamber**: A new optical unit with three distinct angles, sharing one common scattering angle with the commercially available LOAC2 with the four fixed scattering angles at 20°, 70°, 90°, and 110°.

Both chambers are mounted vertically in series (see Figure 1), sampling the **same air volume** via a shared **pump** (first by LOAC v2_1 then LOAC v2_2), ensuring synchronized particle detection. The full system currently weighs ~1.5 kg (including batteries, dual electronics, and thermal insulation), optimized for laboratory tests and first **balloon-borne in situ atmospheric measurements**.

Measured parameters:

- Particle concentration (cm^{-3}).
- Particle detection for a size range between **150 nm to 50 µm**.

- Typology information: To be tested how well particles of different types can be distinguished.

Laboratory tests

We tested four different ambient aerosol conditions with the dual-instrument set up, to test the capability of multiple angles to distinguish between different ambient aerosol types, as they can appear in the free atmosphere. For this, we make use of the speciation index, as described in Renard et al. (2016). The speciation index is an established parameter for LOAC observations to distinguish between various atmospheric aerosol types. It is obtained by combining measurements taken by the instrument at two different light scattering angles, making use of the different sensitivities of measured signal at different scattering angles according to the refractive index. Here we use the relation between the measured scattering signal at 20° with respect to 50°, 125°, 145°, 70°, 90°, and 110° (six speciation indices in total). Results are compared to a database for typology determination as it was established for LOAC (Renard et al., 2016, see their Figure 6,9,16 and 18 for typology determination examples). The configuration, as discussed in Renard et al., (2016) was established for LOAC, with ‘only’ two distinct measurement angles (at 12° and 60°) and a respective database for LOAC2 (with four distinct measurement angles) is in the process of establishment at LPC2E, CNRS in Orléans, France.

Indoor air

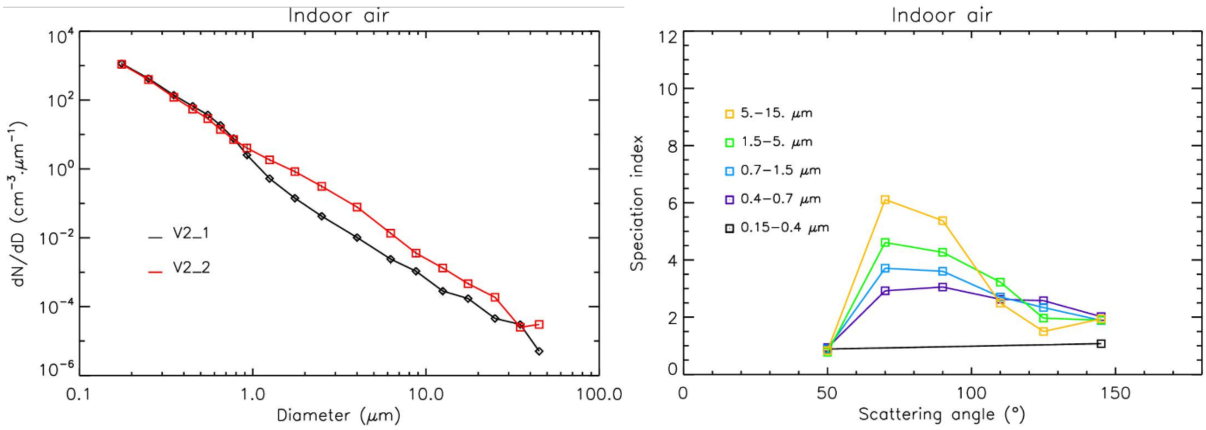

Figure 2: (left) Size distribution from the measurements at 20° scattering angle for the two LOAC2 (LOAC v2_1 and LOAC v2_2). (right) Speciation indexes for the different sizes of

Figure 2 presents the mean size distribution obtained with the two LOAC2 instruments. The concentrations of the submicron particles are in very good agreement, but the LOAC v2_2 (as shown in Figure 1) exhibits a higher concentration for particles larger than 1 µm. Previous laboratory tests with LOAC have shown the opposite trend due to sedimentation processes along the air stream within the instrument. We believe that the current airflow is not completely laminar, leading to a backflow phenomenon at the entrance of the second optical chamber for the largest particles, resulting in multiple crossings of the same particles within the laser beam. It should be noted that the current setup—with two serial chambers—was intentionally designed for simplified exploratory testing to assess the added value of using seven scattering angles for aerosol speciation. The final design will incorporate a single, homogeneous measurement chamber to avoid such artefacts. The speciation indices are presented in Figure 2 (right panel). Since the air contains a mixture of particles with varying compositions, no definitive conclusions can be drawn regarding particle typologies. Nevertheless, the absence of a speciation index in the 70–125° angle range for the first size class is indicative of the presence of carbonaceous particles.

Cement

We test cement dust in a laboratory environment as a means of investigating whether the LOAC-F set up is capable of detecting minerals (as they would potentially appear in volcanic ash emitted to the free atmosphere). Cement powder is therefore used as a surrogate for crustal/ash aerosols.

Figure 3 presents the mean size distribution for the cement sample, where the coarse mode is clearly detected. This time, the differences between the two curves are smaller, although once again the concentrations are higher for the LOAC v2_2. The speciation index curves, as shown in Figure 3 (right side) show values between 1 and 2 for particles below 5 µm, as expected for mineral white particles. The higher values for the 5-15 µm size range could be due to a statistical fluctuation related to the low particle concentrations.

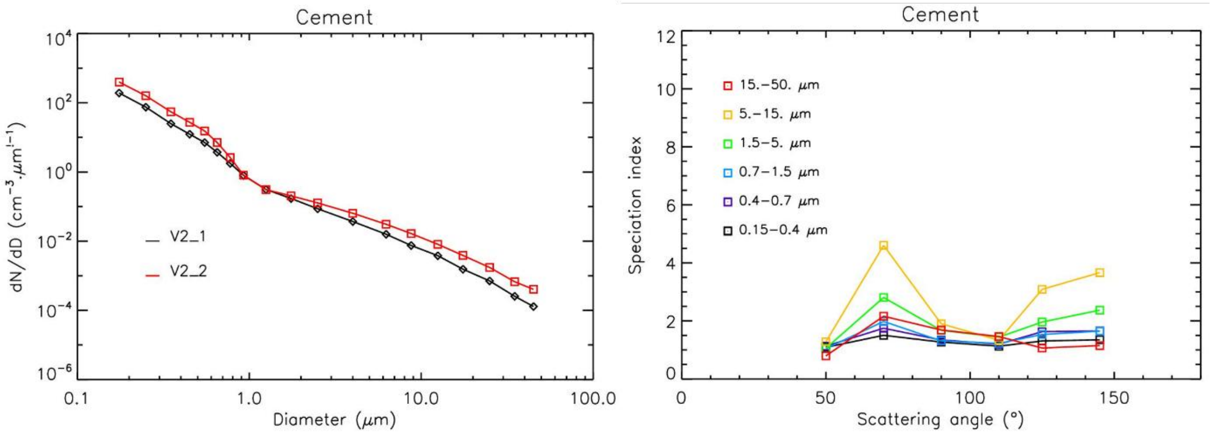

Figure 3: (left) Size distribution from the measurements at 20° scattering angle for the two LOAC2. (right) Speciation indexes for the different sizes of particles at the 6 scattering angles.

Water droplets

We generated water droplets by boiling water surrounded by ambient air to simulate cloud droplets and condensation nuclei, as they occur in the free atmosphere. Figure 4 shows the mean size distribution of the water droplets. In this case, the concentrations measured by the upper LOAC2—located closer to the inlet—are higher than those recorded

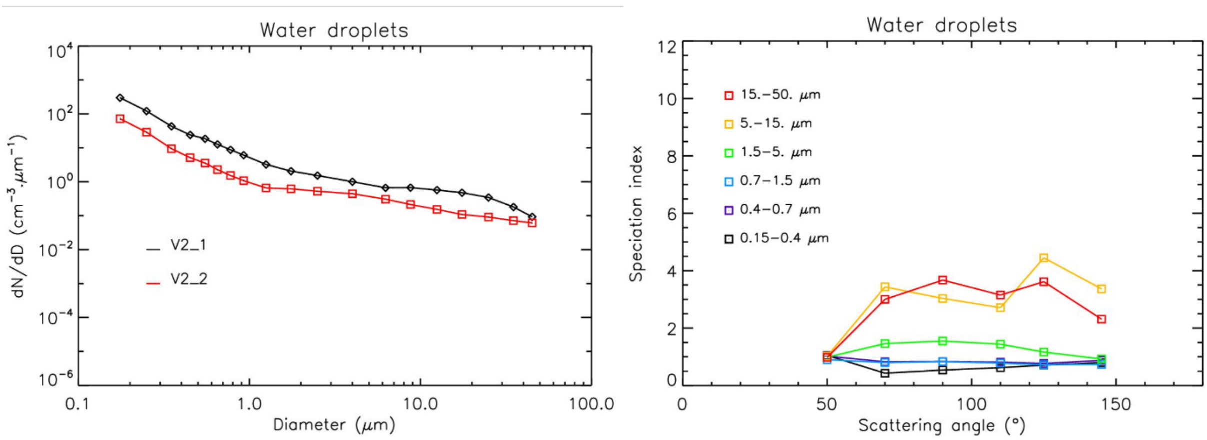

Figure 4: (left) Size distribution from the measurements at 20° scattering angle for the two LOAC2. (right) Speciation indexes for the different sizes of particles at the 6 scattering angles.

by the second LOAC2. This discrepancy could be attributed to droplet evaporation and/or condensation on the chamber walls during transport from the first to the second instrument. This may also explain the shift in the mode diameter from approximately 10 µm (as measured by the first LOAC2) to around 4 µm in the second LOAC2.

Notably, the previously observed discrepancy for larger particles is absent in this experiment. This may be because nearly spherical liquid droplets are more aerodynamic and are therefore transported more efficiently, with reduced backflow compared to heavier, irregular solid particles.

The speciation index curves (Figure 4, right panel) display the expected behavior for liquid particles: a higher speciation index at scattering angles >50° for larger droplet sizes.

Diesel soot in ambient air

We tested diesel soot in ambient air to investigate whether the LOAC-F setup can detect carbonaceous particles. The sample air was drawn from the exhaust of a diesel vehicle and captured immediately downwind.

Figure 5 presents the mean size distribution from measurements of diesel soot emitted into ambient air near the instrument. As observed previously, concentrations are higher in the 1–10 µm range for the second LOAC2, while the measurements for the largest particle sizes show good agreement between the two instruments. The elevated concentration of submicron particles, compared to previous measurement sessions, indicates that soot particles were successfully detected.

The speciation index curves (Figure 5, right panel) exhibit the highest values recorded to date, consistent with those previously established for carbonaceous particles using the conventional LOAC2 (Renard et al., in preparation). These results also show a strong angular dependence. Due to the low concentrations of carbon/soot particles, the speciation index could not be reliably retrieved for the largest size class (>15 µm).

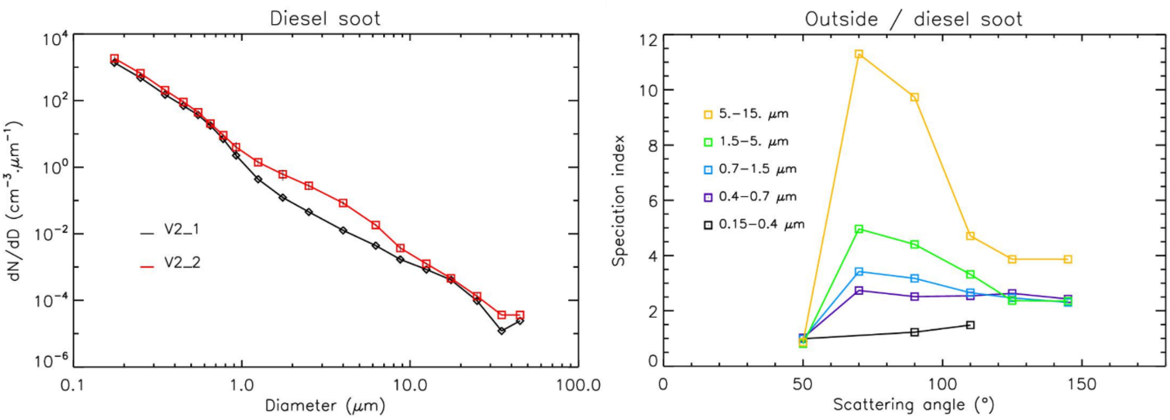

Figure 5: (left) Size distribution from the measurements at 20° scattering angle for the two LOAC2. (right) Speciation indexes for the different sizes of particles at the 6 scattering angles.

Comparison with equivalent (potential) tests using commercially available instrumentation (LOAC-F vs. LOAC and LOAC2)

Figure 6 illustrates the results of a typology investigation using the same aerosol samples, comparing the LOAC-F setup (seven scattering angles) with the commercially available LOAC2 (four angles) and the earlier LOAC (two angles, Renard et al., 2016). The comparison

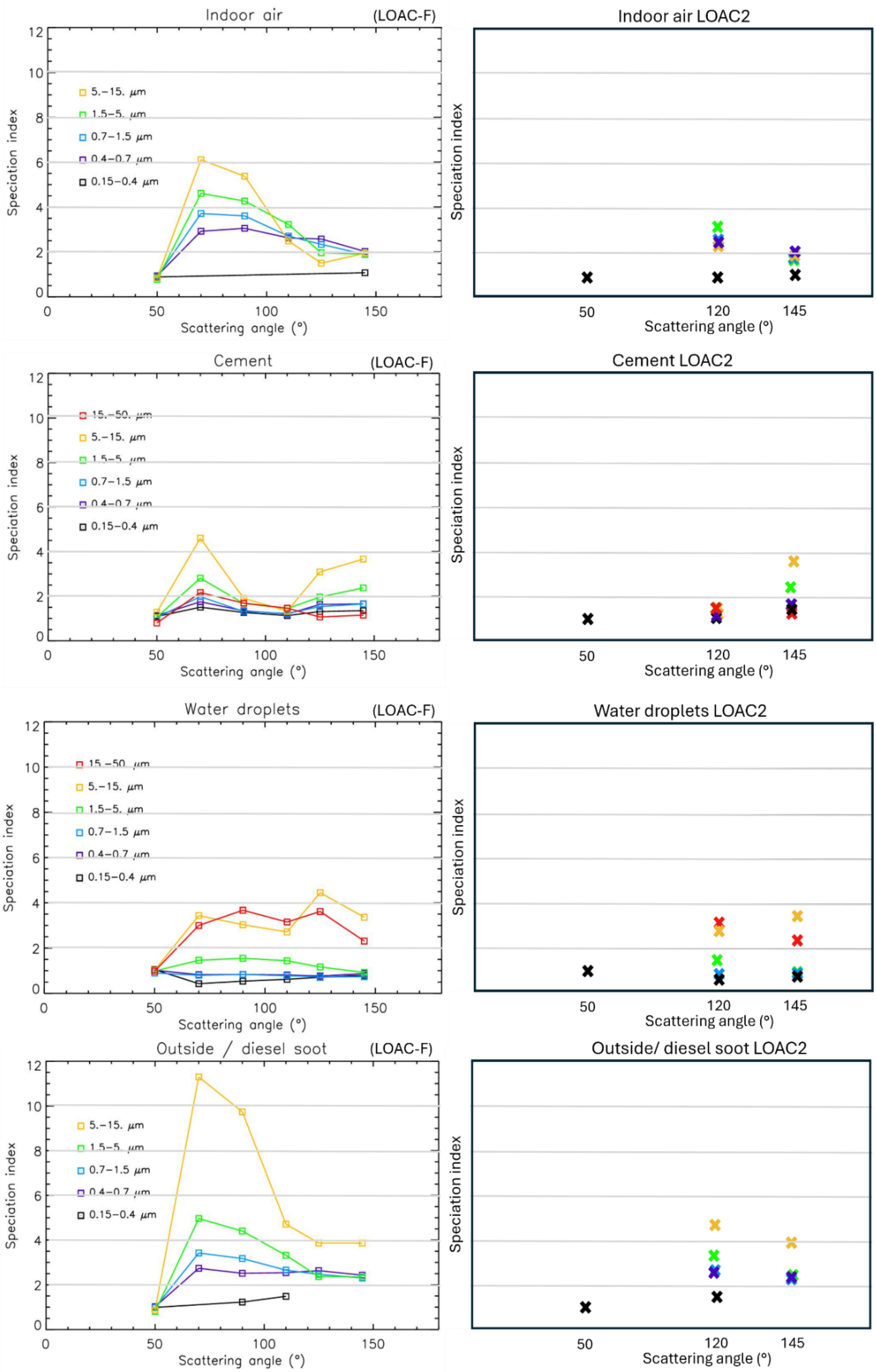

Figure 6: (left side) Speciation indices as shown in Figure 2-5, obtained with the help of the detected signal at 7 measurement angles from the LOAC-F set up. (right side) A schematic display of what the speciation index and typology determination graphic would have looked like for the same test (same ambient air sample) with LOAC2 (4 measurement angles).

reveals that increasing the number of detection angles substantially improves the resolution and interpretability of speciation indices across particle sizes.
In particular, the LOAC-F configuration captures **distinctive angular features** — especially in the 70°–110° range — that would remain entirely undetected by either LOAC or LOAC2. These mid-range angles often show strong size-dependent variation in the speciation index (e.g., a range from 1.3 to over 4.0 in the cement tests), contributing valuable contrast for distinguishing mineral from carbonaceous or liquid particles.
In contrast, the LOAC2's limited four-angle setup results in **flattened speciation curves**, where many typological features are compressed or entirely absent. For example, angles like 50° and 145° alone exhibit relatively low variability across particle sizes, limiting their discriminatory power. As such, LOAC2 provides **only partial insight into aerosol typology**, and while it marks an improvement over the original two-angle LOAC, it still lacks sufficient angular resolution to unambiguously identify complex or mixed aerosol types.
Notably, the original LOAC provides just **a single speciation index** (e.g., 20° vs. 60°), which often falls in a region of overlapping signals among different aerosol classes. This sparse angular sampling increases the risk of ambiguous or incorrect classification, particularly for mixed or non-spherical particles. In contrast, the LOAC-F setup offers a **richer typological fingerprint** by leveraging six independent speciation indices, enabling a more robust classification framework that better reflects the diversity and complexity of real atmospheric aerosols.

Conclusions and Outlook

Initial tests with the dual multi-angle LOAC2 setup demonstrate a significant improvement in aerosol typology determination compared to traditional optical particle counters (OPCs). By combining two LOAC2 instruments, the number of measurement angles is effectively increased, allowing for more precise characterization of the scattering properties of atmospheric aerosol particles, and thus, their classification. To further explore its capabilities in real-world conditions, the described dual-instrument setup will be deployed during upcoming balloon measurement campaigns in the Upper Troposphere and Lower Stratosphere (UTLS).

The dual-LOAC2 setup serves as a proof-of-concept for the ongoing development of the FLIPPER instrument, which will miniaturize and integrate multiple angular detectors into a compact design with one single chamber. FLIPPER aims to deliver high-fidelity aerosol classification, including reliable detection of aerosol mixtures and refined estimates of aerosol composition. The envisioned FLIPPER instrument will enable precise OPC-based observations and robust typology assessments on balloon-borne platforms.

Potential applications of FLIPPER include:

- Monitoring fire and volcanic plumes,
- Detection of anthropogenic particle emissions,
- Investigation of metallic debris from orbital reentry,
- Identification of microplastic presence in the free troposphere.

To fully unlock the capabilities of FLIPPER and enable rapid, in-situ typology resolution on a global scale, targeted funding is required to transition from this dual-instrument prototype to a miniaturized multi-angle OPC.

Collaborators

This study is a joint effort between:

- **ICE-4**, Forschungszentrum Jülich GmbH

- **LPC2E**, CNRS, Orléans
- **ITE,** Forschungszentrum Jülich GmbH
- In coordination with MeteoModem (LOAC2 manufacturer) and LifyAir

---

References

Crépel, O., Gayet, J. F., Fournol, J. F., and Oshchepkov, S.: A new airborne Polar Nephelometer for the measurement of optical and microphysical cloud properties – Part II: Preliminary tests, Ann. Geophys., 15, 460–470, doi:10.1007/s00585-997-0460-0, 1997.

Khaykin, S., Legras, B., Bucci, S., Sellitto, P., Isaksen, L., Tence, F., Bekki, S., Bourassa, A. E., Rieger, L. A., Zawada, D., Jumelet, J., and Godin-Beekmann, S.: The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude, Commun Earth Environ, 1, https://doi.org/https://doi.org/10.1038/s43247-020-00022-5, 2020.

Gayet, J. F., Crépel, O., Fournol, J. F., and Oshchepkov, S.: A new airborne polar Nephelometer for the measurements of optical and microphysical cloud properties – Part I: Theoretical design, Ann. Geophys., 15, 451–459, doi:10.1007/s00585-997-0451-1, 1997.

Kloss, C., Berthet, G., Sellitto, P., Ploeger, F., Taha, G., Tidiga, M., Eremenko, M., Bossolasco, A., Jégou, F., Renard, J.-B., and Legras, B.: Stratospheric aerosol layer perturbation caused by the 2019 Raikoke and Ulawun eruptions and their radiative forcing, Atmospheric Chemistry and Physics, 21, 535–560, https://doi.org/10.5194/acp-21-535-2021, https://acp.copernicus.org/articles/21/535/2021/, 2021.

Kremser, S., Thomason, L. W., von Hobe, M., Hermann, M., Deshler, T., Timmreck, C., Toohey, M., Stenke, A., Schwarz, J. P., Weigel, R., Fueglistaler, S., Prata, F. J., Vernier, J.-P., Schlager, H., Barnes, J. E., Antuña-Marrero, J.-C., Fairlie, D., Palm, M., Mahieu, E., Notholt, J., Rex, M., Bingen, C., Vanhellemont, F., Bourassa, A., Plane, J. M. C., Klocke, D., Carn, S. A., Clarisse, L., Trickl, T., Neely, R., James, A. D., Rieger, L., Wilson, J. C., and Meland, B.: Stratospheric aerosol—Observations, processes, and impact on climate, Reviews of Geophysics, **54**, 278–335, https://doi.org/10.1002/2015RG000511, 2016.

Renard, J.-B. et al. (in preparation): Technical validation of LOAC2 for aerosol typology.

Renard, J.-B., Dulac, F., Berthet, G., Lurton, T., Vignelles, D., Jégou, F., Tonnelier, T., Jeannot, M., Couté, B., Akiki, R., Verdier, N., Mallet, M., Gensdarmes, F., Charpentier, P.,Mesmin, S., Duverger, V., Dupont, J.-C., Elias, T., Crenn, V., Sciare, J., Zieger, P., Salter, M., Roberts, T., Giacomoni, J., Gobbi, M., Hamonou, E., Olafsson, H., Dagsson-Waldhauserova, P., Camy-Peyret, C., Mazel, C., Décamps, T., Piringer, M., Surcin, J., and Daugeron, D.: LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles – Part 1: Principle of measurements and instrument evaluation, Atmospheric Measurement Techniques, 9, 1721–1742, https://doi.org/10.5194/amt-9-1721-2016, 2016.

Solomon, S., Daniel, J. S., Neely, R. R., Vernier, J.-P., Dutton, E. G., and Thomason, L. W.: The Persistently Variable Background Stratospheric Aerosol Layer and Global Climate Change, Science, 333, 866–870, https://doi.org/10.1126/science.1206027, https://science.sciencemag.org/content/333/6044/866, 2011.

MeteoModem: https://www.meteomodem.com/