[General comments]

This is a study to measure non-volatile (soot) particle concentrations in on-wing aircraft exhaust plume with a cutting-edge remote sensing technique (lidar). This is new and useful technique. The study is well-motivated and well-done. The manuscript is well-written. Therefore, it is worth publishing in this journal. I only have relatively minor comments to improve clarity and add some information.

[Specific comments]

(L151) "The range resolution of 10 cm and a time resolution of 1ms" is provided as the lidar (Cal sensor). What are the actual space and time resolutions when applied to the real aircraft exhaust plumes?

The spatial resolution of this LIDAR is approximately a few tens of cm, determined by the combined effects of the laser pulse duration, sensor bandwidth, and digitizer bandwidth. The temporal resolution, on the other hand, is directly related to the laser's pulse repetition frequency. In this case, the laser operates at 20 Hz, meaning a measurement is acquired every 50 ms. The sentence has been reformulated.

(L173) "all particles can be detected"… I assume there is a certain level of detection limit for particle size (diameter in nm) of this lidar technique. This information should be very important, therefore, please add such information.

The appropriate metric for the lidar detection limit is the backscatter coefficient, which depends on the particle number concentration and cross-section (approximately proportional to the particle volume squared, $\sim r^6$, in first order). In our laboratory experiments, our sensor successfully measured soot particles as small as 10 nm.

(L178) "…pool-fire and has been promising results"… How was the method validated and how accurate was the measurement data? Please provide that information with a few sentences.

In Ceolato, R., Bedoya-Velásquez, A.E., Fossard, F. et al. (Black carbon aerosol number and mass concentration measurements by picosecond short-range elastic backscatter lidar. Sci Rep 12, 8443 (2022). https://doi.org/10.1038/s41598-022-11954-7), the method was validated using a small-scale Jet A-1 kerosene pool fire as a controlled source of black carbon (BC) aerosols. Measurements from the CAL sensor were compared against expected aerosol properties using the RDG-FA model, which accounts for fractal aggregate morphology. The validation demonstrated that the system could resolve aerosol concentrations at centimetre-scale spatial resolution and millisecond temporal resolution, allowing highly detailed, real-time measurements. Overall, the study showed that the method could retrieve the BC number and mass concentrations at short ranges, providing reliable, contact-free data for short-range aerosol monitoring.

(L194) "about 50 meters"… Seeing from Fig.3 (right figure), isn't the distance from the lidar to the centerline of the exhaust plume 47 m?

Yes, that is correct. We initially proposed 50 cm as an approximation, but we have now corrected it to 47 cm.

(Fig.2) All the lidar instruments (laser, receiver, and sensor) are installed in the vehicle?

Yes. This is correct.

Is the beam stop installed to the aircraft body? Or is it installed farther (how far?) from the aircraft body? Please specify them.

The beam stop is installed further aways, approximately 100 m from the LIDAR.

(Fig.3) It seems the words "Colibri CAL-210" and "Sequence A" can be omitted. I assume the "Range (m)" is the "horizontal distance from the CAL sensor". Please specify it.

We have updated the figures and their captions accordingly.

(Fig.3) What is the detection limit of soot concentration in air (xx ug/m3). Please provide the information.

A dedicated laboratory calibration paper is currently in preparation to assess the performance and detection limits of the sensor.

(L243) "Interestingly, the concentrations do not increase linearly with thrust"… This trend was previously reported, such as shown in Fig.2 of Durdina et al. (2021).

The relationship between concentration and thrust appears to be engine-specific, and a similar trend has been observed in previous studies (e.g., Delhaye et al., Journal of Aerosol Science, 105, 48–63; see also data in the ICAO database).

(Table 1) What is the specific thrust percentage (such as 7%) of "intermediate, high, and idle"?

Measurements were performed at thrust settings of 10–20%, 50–55%, and 80–85%. Future experiments will include additional operating points to fully align with the ICAO LTO (Landing–TakeOff) cycle.

Are the concentrations at the centerline of the exhaust plumes?

Yes, this is correct.

Are the concentration levels comparable with the ones measured with the certification methods.

The order of magnitude is consistent with recent studies on the Rolls-Royce Trent XWB-84. According to the ICAO database, the maximum nvPM mass concentration is 2.381 mg/m³, which aligns with our measurements when accounting for the dilution factor, since our lidar observations were made downstream of the engine exit plane.

What is the distance of the measured point from the engine exit (along with the exhaust axis)? Please clarify them.

The distance from the engine exit was around 15m. This was added in the manuscript (L193).

(L316) There has been increasing evidence that lots of 10-20 nm class lubrication oil-derived volatile particles are emitted from aircraft engines (Yu et al., 2012; Fushimi et al., 2019; Ungeheuer et al., 2021). Can the lidar technique shown here detect such organic particles? If the authors can add some thoughts here, that would be great.

This study is part of our ongoing investigation, which aims to identify and distinguish the different components present in particulate matter (PM) emissions, thereby improving our understanding of their sources and characteristics.

[Technical/minor comments]

(L107-108) "kerosene number and mass concentration": Maybe this is about "the number and mass concentrations of kerosene combustion-derived soot". Please check and revise the sentence.

Thank you. We have modified it.

(L143) "Dobbins and Megaridis ?"… It may be a misprint.

The missing reference is added.

(Section 3.1 and 3.2) I think these sections should be moved to the method section.

(L228) "time-integrated…"… Is this 3-min averaged data? Please specify it.

Thank you. We have modified it.

[References]

- Durdina, L.; Brem, B. T.; Elser, M.; Schonenberger, D.; Siegerist, F.; Anet, J. G. Reduction of Nonvolatile Particulate Matter Emissions of a Commercial Turbofan Engine at the Ground Level from the Use of a Sustainable Aviation Fuel Blend. *Environ Sci Technol* **2021**, *55* (21), 14576-14585.
- Yu, Z.; Herndon, S. C.; Ziemba, L. D.; Timko, M. T.; Liscinsky, D. S.; Anderson, B. E.; Miake-Lye, R. C. Identification of lubrication oil in the particulate matter emissions from engine exhaust of in-service commercial aircraft. Environ Sci Technol 2012, 46 (17), 9630-9637.
- Fushimi, A.; Saitoh, K.; Fujitani, Y.; Takegawa, N. Identification of jet lubrication oil as a major component of aircraft exhaust nanoparticles. Atmos. Chem. Phys. 2019, 19 (9), 6389-6399.

- Ungeheuer, F.; van Pinxteren, D.; Vogel, A. L. Identification and source attribution of organic compounds in ultrafine particles near Frankfurt International Airport. Atmos. Chem. Phys. 2021, 21 (5), 3763-3775.

RC2:

The paper introduces the use of a short-range LIDAR to characterize aircraft particulate emissions. The paper and the techniques presented are interesting and certainly worth publication. Overall, the paper is well written, and the method is fairly solid. Some aspects might require some clarification, but I think the paper can be published with relatively minor changes addressing the comments below.

We greatly appreciate the reviewer's detailed corrections and insightful comments, which have markedly improved the quality and readability of our manuscript.

General comments

- The system measures the backscattering from particles, all particles in the sample volume (along the laser path). The authors assume and justify the hypothesis that all the particles at that distance from the aircraft are nonvolatile, and then they focus on soot. Perhaps some more discussion on how volatile particles, albeit in small concentrations, could still contribute to the signal would be useful. The next comment focuses on a related topic of terminology.

Volatile particulate matter (vPM) formation in aircraft exhaust plumes is a complex process that unfolds over specific distances and timescales downstream of the engine exit. The critical region for vPM formation typically extends from the engine exit to about 100–250 meters downstream. Most volatile particle nucleation and initial growth occur within the first 10 seconds and the first ~35 meters of the plume, which represents the key zone for understanding and potentially mitigating aviation-related ultrafine particle emissions. Consequently, in our near-field measurements (<20 meters downstream), we assume that vPM have not yet formed as aerosols and are therefore absent from the plume at such short distances.

- This is a terminology as well as a definition issue. The authors introduce the term nvPM and discuss it widely in the introduction but then in the method they use soot as subscript. So, the assumption appears to be that all nvPM are soot. I would tend to agree with this assumption but in that case, it would be necessary to mention that point explicitly early on and provide some basis supporting this assumption. In addition, then why introducing a new term that is not as widely used in the literature (as nvPM) and not just use soot all along, if here they are assumed to be the same? For example, nvPM could also include dust, obviously not emitted directly from a plane engine, although the turbulence generated by the jet could entrain dust from the local asphalt; this just to say that introducing the term nvPM is, in my opinion, unnecessary here and could actually be confusing. This is particularly true considering the inversion algorithm used here is based on RDG-FA with input parameters applicable specifically to soot. This terminology issue becomes even more confusing when, in section 3.3, the authors also introduce the term equivalent black carbon. My suggestion is to pick one (soot, nvPM, or BCeq) and use it consistently across the paper, again, because the MBC was calculated from RDG-FA for soot, the more natural term, in my opinion, would be just "soot".

We understand the reviewer's concerns, and we acknowledge that this terminology issue remains an ongoing topic in the field. While *soot* is the general term commonly used in combustion studies, *nvPM* has become the standard terminology in aviation emissions research, regulatory context (see ICAO databases) or industrial protocols (see SAE). Accordingly, we have removed the term *BCeq* from the manuscript and now refer exclusively to *soot* and *nvPM*. In addition, we have added a clarifying statement early in the paper noting that all nvPM are soot, as suggested.

- A comparison with other traditional techniques would have increased confidence in the technique. It is unfortunate, but understandable, that these additional measurements were not available for this work. This is mentioned in the concluding remarks.

We agree with the reviewer that such comparisons would strengthen confidence in the technique. To address this, two dedicated studies are currently in preparation: one involving laboratory experiments for controlled validation, and another based on field measurements using reference instruments.

- I am a little bit confused by the claimed spatial resolution of the system (see the relevant specific comment). Did the authors perform target tests to measure the true spatial resolution of the system?

Yes, before conducting measurements, a radiometric calibration is usually performed as part of the lidar performance tests. This procedure involves taking measurements on a hard target positioned at different known locations. This helps us verify the spatial resolution of the lidar and the overlap function. To accurately reconstruct the lidar's spatial resolution, we must also consider the laser pulse duration, sensor bandwidth, and digitizer bandwidth. Therefore, prior calculations related to these values are considered.

Specific comments

Line 22: As the sentence seems to suggest that nvPM is present only at T>350 °C, almost implying that once the T<350 °C , they would disappear. I would guess the authors refer to the forming conditions, not the "presence" condition (?).

Our intention was to specify the temperature conditions at which nvPM forms, not to suggest that nvPM disappears below 350°C. We have revised the sentence to clarify that these temperatures refer to formation conditions, not the persistence of the particles.

Line 52: "other optical methods" such as?

We have added examples of optical methods and rephrase the sentence.

First equality in equation (1): This range correction just accounts for the $1/r^2$ dependence. Isn't there also an overlap (overlap between the laser beam and the field of view) function to be accounted for here (in the first equality if S(r) is the raw signal)? The overlap function is separately mentioned just a couple of lines later and included in the second equality.

The overlap term was not explicitly addressed because, for short-range measurements, the system is optimized around the particle emission region. Under these conditions, the overlap function is close to unity, and its impact on the results is negligible.

Line 63: I can imagine that for modern aircraft, the plume is optically thin also due to the short path length, but how good is this approximation? Can one make a rough estimate using the lidar data directly?

Based on the maximum observed backscattering and a representative kerosene lidar ratio (Ceolato, R., Bedoya-Velásquez, A.E., Fossard, F. et al. Black carbon aerosol number and mass concentration measurements by picosecond short-range elastic backscatter lidar. Sci Rep 12, 8443 (2022). https://doi.org/10.1038/s41598-022-11954-7) for a 5 m thick layer and a LR~130, the transmittance is nearly 1, highlighting that our measurements correspond to a relatively thin layer, unlike thicker layers where transmittance rapidly diminishes.

Line 70: These sentences are a bit deceiving. Instruments like the PAX and CAPS are meant to measure absorption and extinction, respectively, not mass. Mass can just be derived from those measurements, if desired, using mass efficiencies.

These sentences have been rephrased.

Line 72: CAL was defined only in the abstract. Perhaps it would be good to redefine it here.

SR-EBL (name of the technique) is used here instead of CAL sensor for clarity.

Line 78: PDF of what? The size.

This sentence has been changed.

Line 78, again: how good is this assumption?

Various light-scattering theories can be used to calculate the soot differential backscattering cross-sections, including MSTM and DDA. Previous studies have shown that the Rayleigh–Debye–Gans with the fractal aggregate approximation (RDG-FA) provides a good estimate for backscattering (see. Ceolato, R., Bedoya-Velásquez, A.E., Fossard, F. et al. Black carbon aerosol number and mass concentration measurements by picosecond short-range elastic backscatter lidar. Sci Rep 12, 8443 (2022). https://doi.org/10.1038/s41598-022-11954-7, Ceolato, R. (2025). Lidar backscattering model for soot aerosols. Journal of Quantitative Spectroscopy and Radiative Transfer, 276, 107964, https://doi.org/10.1016/j.jqsrt.2025.107964)

Equation (7): consider adding a subscript (soot and eff, for effective) to ro.

The equation has been changed.

Line 96: Lorentz-Mie assumes more than just spherical shape; it assumes spherical symmetry.

This sentence has been changed.

Line 129: The acronym RDG-FA was already defined in the previous paragraph.

This sentence has been changed.

Line 135: This is probably not important, but being a short-range lidar, one would think that the scattering angle collected, albeit close to just PI, would have some narrow range around this angle, meaning that it is not exactly and only PI. How important is this deviation from exact backscattering?

This is an excellent point. Given that we employ a small field of view (<5 mrad) along with a narrow beam diameter and low divergence, we approximate the backscattering as being effectively at 180°.

Line 140: remove repeated "regimes"

This has been corrected.

Line 143: Issues with the Bobbins and Megaridis citation.

This has been corrected.

Line 150: In what sense is "forward-looking"? Is that meant to indicate that the beam is propagating horizontally? Also, what is meant by "multi-axial architecture"? Is it relevant here?

This has been corrected to avoid confusion.

Line 153: What is the beam waist after expansion?

3 mm after expansion. It has been updated in the manuscript

Line 156: Why use an achromat if a single wavelength is used?

A good point: an achromatic lens was employed to enable future multi-wavelength capabilities.

Line 157: The sentence starting with "This feature" is a bit mysterious. Perhaps the authors can add a sentence or two to explain this point.

This sentence has been clarified.

Line 161: Can the authors comment on this sampling rate? 1 GS/s corresponds to 1 ns at best, probably closer to 2 or more ns. Within this time, light travels about 30-60 cm, so how is a 10 cm resolution (mentioned in line 151) being achieved? This can be even worse if (as often is the case) the bandwidth of the system is lower than the sampling rate. What is the bandwidth of the PMT+digitizer system (the PMT bandwidth alone is already 1 GHz, as mentioned in Figure 1)? The resolution issue might be even worse if the pulse duration is indeed 6 ns, as mentioned in Figure 1.

Our digitizer samples at 1 GS/s (1 ns) with a 700 MHz analog front-end, while the PMT chain has a bandwidth of ~800 MHz, supporting sub meter features. However, the effective range resolution is limited by the laser pulse duration (~6 ns), resulting in ~0.9 m after convolution with the analog response. The text has been revised to use "tens of cm "instead of "tens cm" for clarity.

Line 165: "direct measurement" in what sense? It is a remote sensor after all, so inversion is always necessary, as mentioned by the authors earlier on. I understand what the authors mean here, but the term "direct" might be misleading. Perhaps something like "touchless" or similar words?

We have replaced "direct" and 'non invasive" by "Remote". Indeed, we have modified the title of the article according to your comment.

Line 169: Again, I think this is deceiving, because this is also a remote sensing technique. So, what other "remote sensing techniques" do they refer to?

We understand your disappointment and the term "Remote" will be used. The term "long-range" is added here for clarity.

Lines 172-173: The sentence "the sensitivity of SR-EBL means that all particles can be detected" is not clear to me. The sensitivity of the instrument has not been discussed; also, what does it mean "all particles"? Although unlikely, I could think of extreme cases where a soot particle is made up of just a very few monomers. Would that be detected by the sensor? I would think that would be unlikely. This is repeated in the following sentence. Again, I understand what the authors are trying to convey. I think they refer to possible particle losses for other techniques, but as such, the sentences could be misunderstood, and I would encourage the authors to rephrase and be more explicit.

We understand and have rephrased this sentence.

Lines 220-221: Either refer to previous work, or explain the adaptive gain system some more.

This sentence has been modified.

Line 227: Where in the figure does one see background aerosols? And how is that distinguished, considering the RDG-FA method to invert the signal applies only to soot, and background aerosol probably contains large fractions of other particles?

Background measurements are typically performed after completing the lidar calibration. These consist of clear-air profiles containing only ambient aerosol signals, which are later suppressed during data processing. Following this step, the measured backscatter is attributed solely to soot particles emitted by the engine—a procedure commonly referred to as background removal in lidar remote sensing. This sentence has been modified for clarity.

Line 231: How was it identified, and how was it determined to have a minimal influence?

Although wind fluctuations were identified, they primarily affected the standard deviation of the Gaussian plume retrieval while having negligible influence on its mean, as evidenced in the derived mass and number concentrations. A sentence has been added.

Lines 234-235: What was the reason for the shorter times?

The shorter acquisition times were chosen based on experimental preference rather than a specific constraint.

Line 244: Is it possible that the engine thrust simply would change the plume dilution due to the airflow? Quantifying the ratio of the plume height to spatial width (as provided by the CAL) might help to address that question.

This is indeed a plausible possibility. Additional measurements at different distances from the exhaust plane would help to further investigate this effect.

Line 169: k()->ko?

This has been corrected.

Line 280: "branching"? Maybe "backscatter". Also, the acronym MBC was already defined earlier.

This has been corrected.

Line 282: Why "as expected"?

This has been removed.

Line 308: How do you define "minimal" in this context?

We have revised the sentence to replace the term "minimal" with a more appropriate wording.