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Laser-induced incandescence (LII) of aircraft-engine black carbon: sensitivity to laser fluence

BACKGROUND

- Incomplete combustion, e.g. within aircraft turbines, produces black carbon (BC) nanoparticles. These particles are aggregates of small (diameter 10–30 nm) solid spherules which are strongly light-absorbing from visible to infrared wavelengths and refractory up to ~4000 K [*Petzold2013*].
- BC exerts a major positive climate forcing globally, second only to CO_2, and has been associated with the detrimental health effects of air pollution including cardiovascular disease [*Bond2013*].
- Laser-induced incandescence (LII) is an established technique for engine-exhaust analytics and BC mass quantification. LII also provides information on the effective primary-particle size of BC aggregates.

LII: INSTRUMENT

Figure 1. One of two Artium LII 300 instruments used in this study. [www.artium.com]

- The commercially-available Artium LII 300 employs technology developed at the NRC [*Snelling2005*].
- A pulsed 1064 nm laser is used to heat BC to incandescence (~3000 K) while avoiding sublimation (~4000 K). The actual temperature is measured by two-colour pyrometry using the incandescent radiance measured at 442 nm and 716 nm.
- Combining the measured temperature with the measured intensity of incandescent radiation and the BC absorption function *E(m)*, BC mass concentrations M_{BC} can be calculated.
- *E(m)* is known to vary between BC samples. For example, *E(m)* varies with the degree of graphitization (maturity) of BC, which has been observed to vary between aircraft-engine samples *[VanderWal2014].*
- Variation in *E(m)* or other BC properties might hypothetically influence the LII response of a sample, consequently introducing a sensitivity of LII response to laser fluence.

RESEARCH GOAL

Determine the influence of laser fluence on the accuracy of LII measurements of BC mass concentrations for aircraft-engine emissions, under conditions of varying load and fuel type.

Figure 2. The V2527-A5 engine used in this study, mounted on the DLR ATRA A320 aircraft.

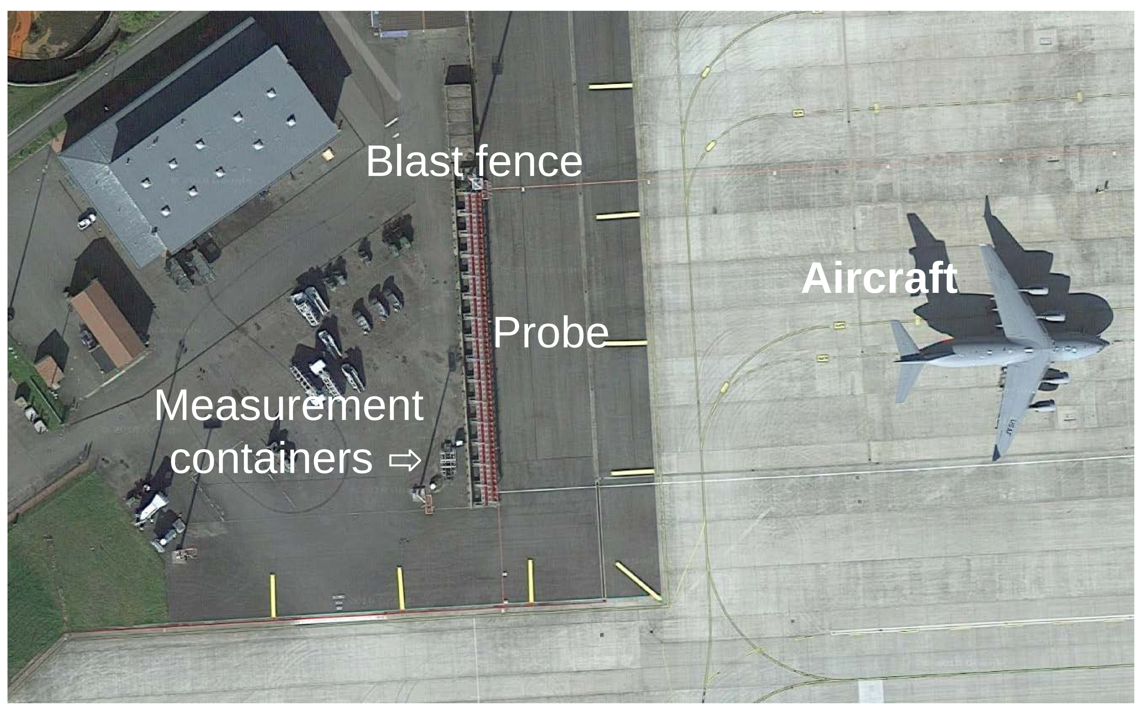

Figure 3. Sampling behind the D-ATRA Airbus A380.

EXPERIMENT

- BC produced by a V2527-A5 engine of DLR's D-ATRA aircraft was sampled ~40 m downstream of the engine through 60 °C heated lines to a sampling manifold.
- Two LII-300 instruments were operated in parallel.
- One LII-300 was operated in its standard configuration with laser fluence optimized for aircraft-engine BC; that is, fluence tuned to heat BC to ~4000 K.
- The laser fluence of the other LII-300 was varied from its reference setpoint to a minimum setpoint at which signals were approximately 50% lower, by increasing the laser's Q-switch delay past its optimal value. The setpoint was varied randomly rather than monotonically, and after every 3 measurements was returned to its reference value.

ANALYSIS

- The relative change of the LII signal due to changing laser fluence was calculated as:

$$R_{LII} = \frac{\text{BC conc. measured with modified fluence}}{\text{BC conc. measured with reference fluence}}$$

- Reduced-fluence BC concentrations were measured with a modified-fluence LII at 20 Hz. This instrument was also operated at its reference-fluence level for 10 of every 70 seconds. These data were interpolated and used to verify consistency between the reference- and reduced-fluence instruments.
- Before calculating R_{LII}, data were filtered to remove rapid changes in BC concentration and normalized to CO_2. This accounted for variations in ambient wind velocity and atmospheric mixing. Periods with low (<2 µg m^{-3}) BC concentration were not considered for analysis. Figure 4 shows the filtered data.

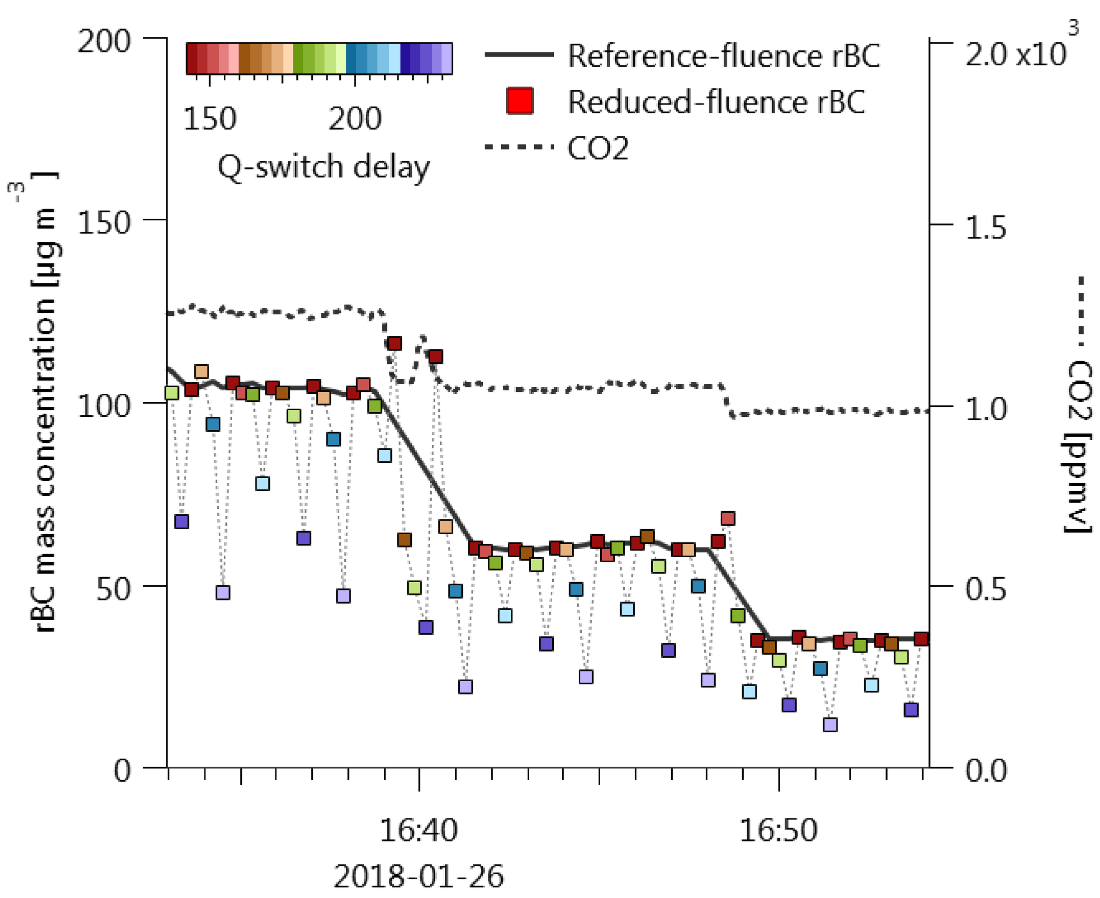

Figure 4. Time series of the raw data. Only one of the rBC mass concentrations time series is shown. The squares show the changing Q-switch delay (inversely related to laser fluence). The black solid line shows interpolated full-fluence data. The black dashed line shows CO_2 for reference.

RESULTS

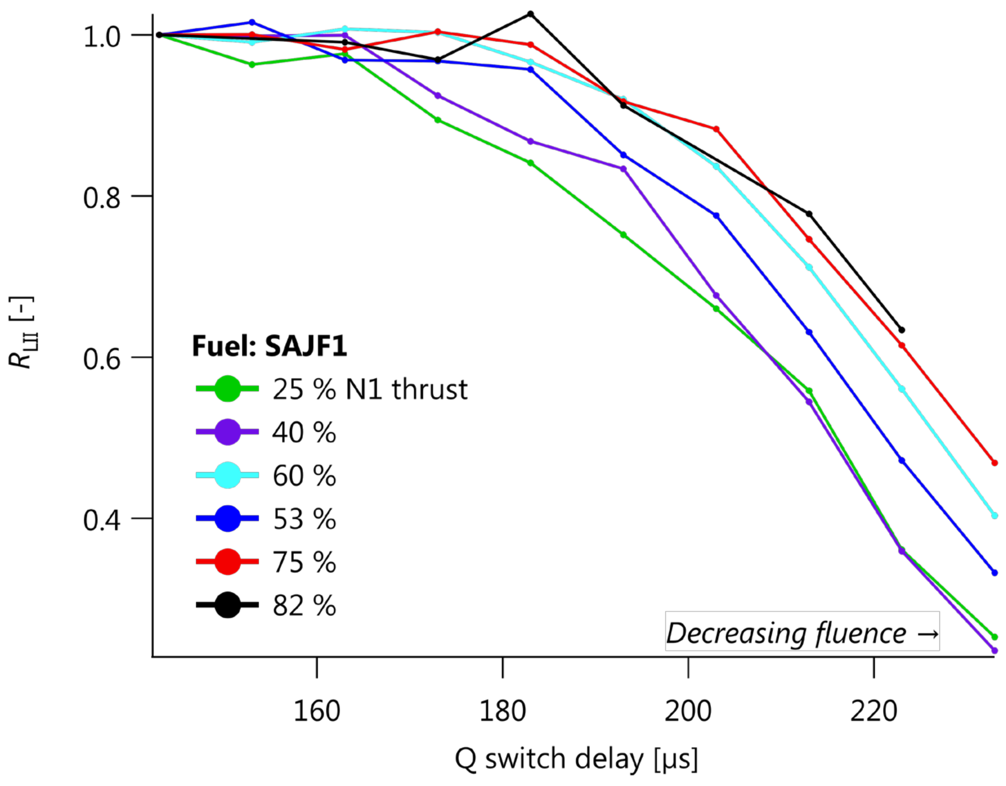

Figure 5. Ratio of BC concentrations quantified with lowered-fluence versus reference-fluence LII. The data are plotted, for a single fuel, as a function of Q-switch delay. Here, Q-switch delay corresponds to inverse fluence.

- Figure 5 summarizes the results of this study, for one fuel and various engine thrusts (defined by N1 fan speed). The results for 3 other fuels were similar.
- The LII response decreased for Q-switch delays above 163 µs, doing so more rapidly for lower engine thrusts.
- More-mature soot is expected for higher aircraft-engine thrusts [Vander Wal et al. 2014].
  - ➢ **Figure 5 suggests that immature soot (25% thrust) is more sensitive to laser fluence than mature soot (>60% thrust), in terms of its LII response.**
- The LII response was independent of laser fluence for the substantial range of Q-switch delays from 143 to 163 µs, for all thrusts and fuels investigated.
  - ➢ **The standard 143 µs configuration is well within the plateau regime where signals can be reliable quantified.**

SUMMARY AND CONCLUSIONS

- We systematically varied the laser fluence of a commercial LII system (Artium LII 300) using the Q-switch delay (inversely related to fluence) while sampling aircraft-engine BC generated from 4 different fuels.
- For all fuels and engine thrusts, no relationship was identified between laser fluence and calculated BC concentrations within a reasonable range of Q-switch delays (143 to 163 µs).
- The results support the use of LII for the quantification of aviation-engine BC, and for measuring emissions from aviation fuels including alternative fuel blends.

REFERENCES

[Snelling2005] Snelling, D.R., G. J. Smallwood, F. Liu, Ö.L. Gülder, and W. D. Bachalo. Appl. Optics, 44 (31), 2005. doi:10.1364/AO.44.006773

[Bond2013] Bond, T. C., S. J. Doherty, D. W. Fahey, P. M. Forster, et al. J Geophys. Res. 2013. doi:10.1002/jgrd.50171

[Petzold2013] Petzold et al. Atmos. Chem. Phys. 13 (16) 2013. doi:10.5194/acp-13-8365-2013

[VanderWal2014] Vander Wal et al. Combust. Flame 161 (2) 2014. doi:10.1016/j.combustflame.2013.09.003

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