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Calibration of Black Carbon Instruments with the CPMA-Electrometer Reference Mass Standard (CERMS)

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Outline

Background

- techniques for measuring black carbon (BC)
- standards for aerosol instrument calibration
- the CPMA-electrometer reference mass standard (CERMS)

Results

- calibration of a number of instruments
- calibration of an instrument with a number of sources

Mass closure

- demonstration of mass closure when compared to elemental carbon (EC) from thermal optical analysis (TOA)

Summary

Techniques for measuring black carbon (BC)

A non-exhaustive list of methods/instruments for measuring BC

Aerosol absorption methods

- CAPS PMssa

Photoacoustic methods

- PAX, MSS, PASS

Filter-based methods

- MAAP, PSAP, Aethalometer

→ equivalent black carbon (eBC)

Evolved carbon methods

- TOA

→ elemental carbon (EC)

Laser-induced incandescence

- LII 300, SP2

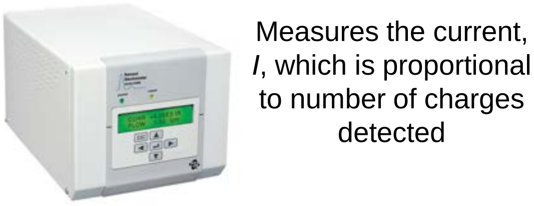
→ refractory black carbon (rBC)

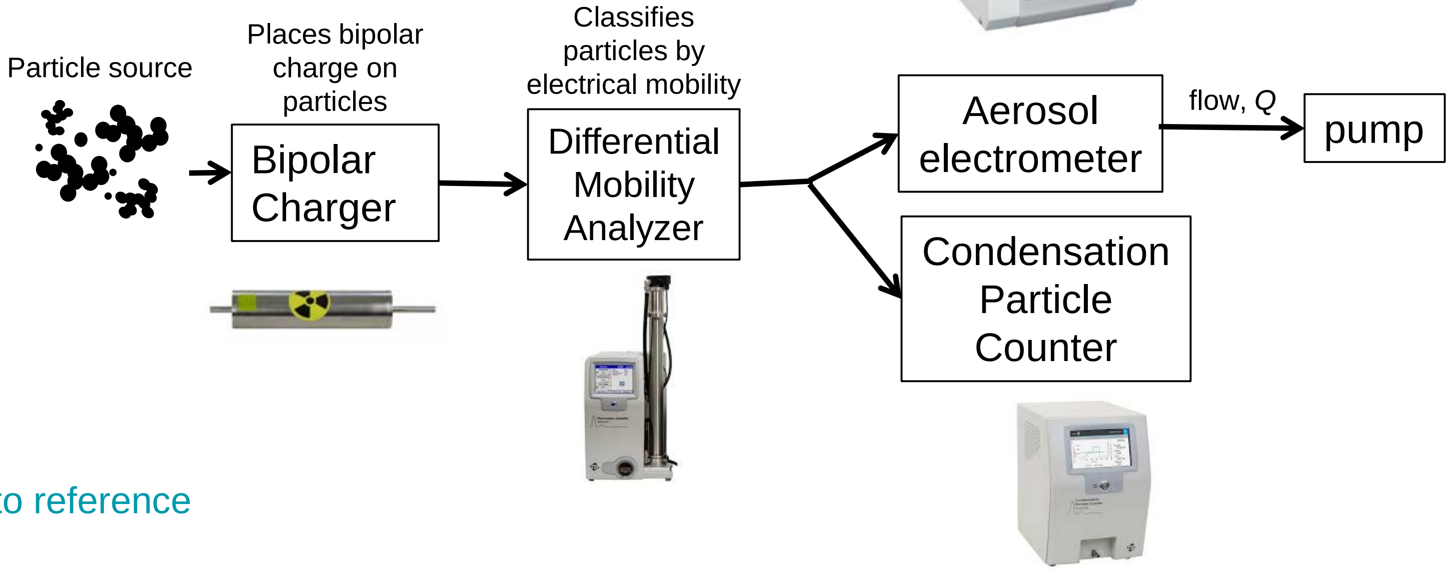
The reported values depend both on the characteristics of the source particles used in the calibration and the reference method applied, neither of which are unique or traceable

A. Petzold et al., “Recommendations for reporting black carbon measurements,” Atmos. Chem. Phys., vol. 13, no. 16, pp. 8365–8379, 2013, doi: 10.5194/acp-13-8365-2013

Calibration of Condensation Particle Counters

$N = I/Qe - N_{\text{multiply-charged}}$





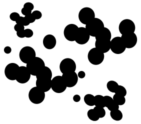
- charge
- classify
- compare to reference

ISO 27891-2015 - Aerosol particle number concentration — Calibration of condensation particle counters, 2015

CPMA-electrometer reference mass standard (CERMS)

$m_{total} = m_{+0} + M_1 I/Qe$

Particle source



Places a large electric charge on the particles

Unipolar charger

Classifies particles by mass-to-charge ratio

Centrifugal Particle Mass Analyzer

CPMA setpoint, M_1

Measures the current, I, which is proportional to number of charges detected

Aerosol electrometer

flow, Q

pump

Mass instrument to calibrate

- charge
- classify
- compare to reference

J. P. R. Symonds, K. S. J. Reavell, and J. S. Olfert, “The CPMA-electrometer system - A suspended particle mass concentration standard,” Aerosol Sci. Technol., vol. 47, no. 8, pp. 8–11, 2013, doi: 10.1080/02786826.2013.801547

Centrifugal Particle Mass Analyzer (CPMA)

CPMA mass/charge setpoint depends on three traceable parameters:

- rotational speed (traceable)
- voltage (traceable)
- radial dimensions of the classifier
  - (optional traceable gauging certificate available from Cambustion)

$$M_1 = \frac{M}{N_q} = \frac{eV}{\left(\frac{r_o + r_i}{2}\right)^2 \omega^2 \ln\left(\frac{r_o}{r_i}\right)}$$

Unlike a DMA, the setpoint does not depend upon the gas properties (such as viscosity and mean free path) or ambient conditions (temperature and pressure)

Classification not affected by particle morphology or composition

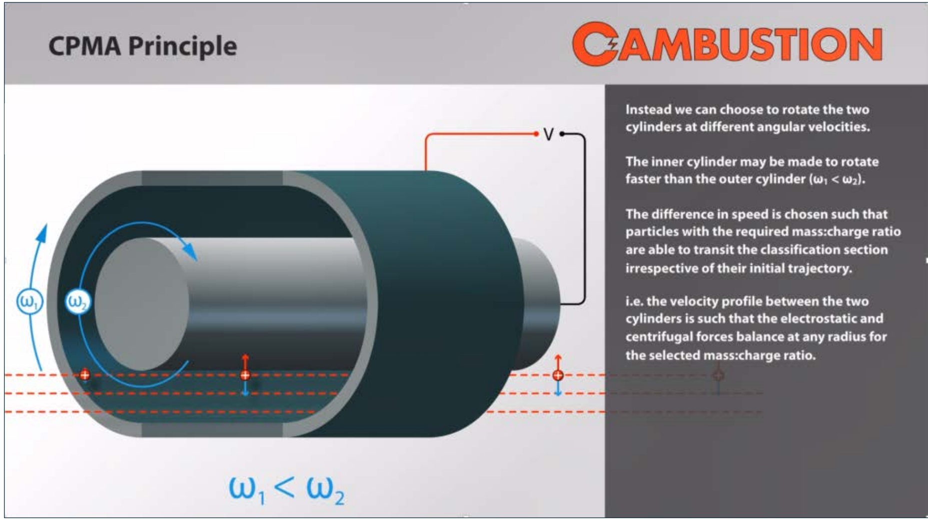


Image from Jon Symonds, Cambustion

Benefits of CERMS

All aspects of the CERMS technique are traceable to the SI

Measurement of a well-defined quantity: total post-CPMA suspended PM mass

CERMS has low uncertainty[1]

- Repeatability was 1.1% (k = 1)
- Intermediate precision was 2.1% (k = 1)
- Resulting **uncertainty (coverage factor, k = 2) was 3.0%**

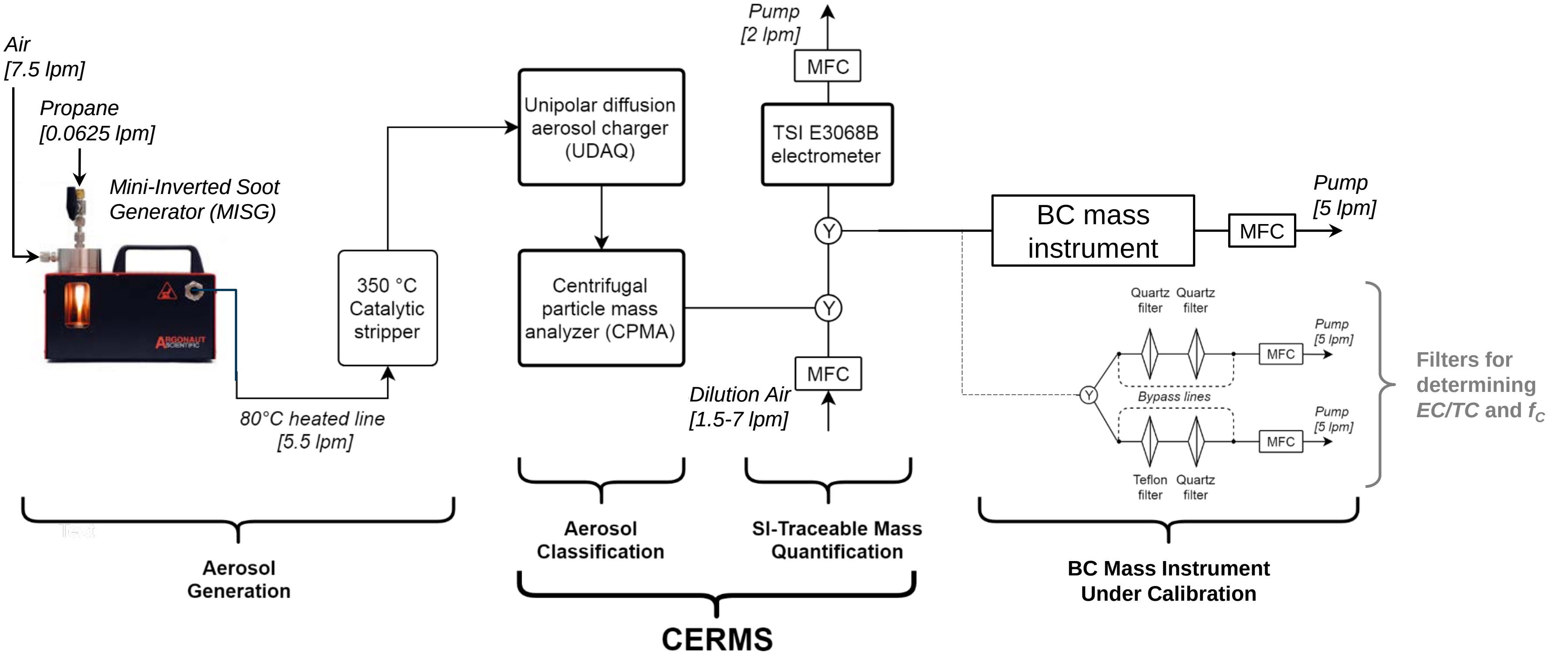
Rapid (<2 hours experiment time) with potential for same day determination of calibration factor

Additional benefits for determining aviation engine emissions BC mass

- Demonstrated to low concentrations (1 μg/m^3)
- on-site calibration
- gas turbine engine as the source of BC emissions

[1] J. Titosky, A. Momenimovahed, J. Corbin, K. Thomson, G. Smallwood, and J. S. Olfert (2019) Repeatability and intermediate precision of a mass concentration calibration system, Aerosol Science and Technology, 53, 701-711. doi:10.1080/02786826.2019.1592103

CERMS apparatus for calibration with lab soot generator



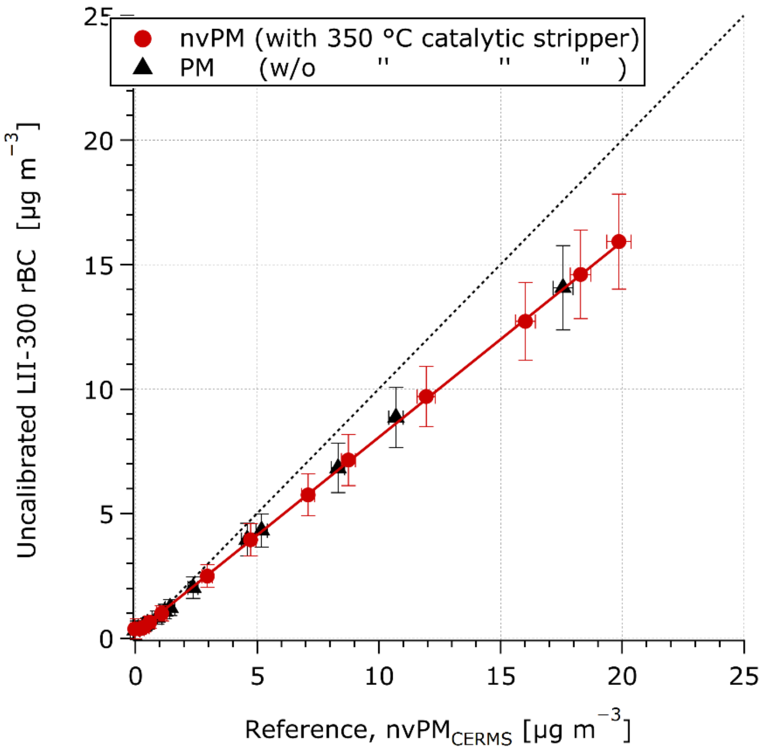
Calibration of LII 300 determined from CERMS with lab soot from MISG

When referenced to denuded soot (nvPM):

$$rBC = (0.78 \pm 0.05) \cdot nvPM_{CERMS} + (0.2 \pm 0.1)$$

- rBC is refractory black carbon (LII 300)
- residuals are in the range of ± 0.1 $\mu g/m^3$
- fit intercept nearly zero (below the LOD of the instrument)

- note that for this source, the effect of the catalytic stripper (VPR) is negligible

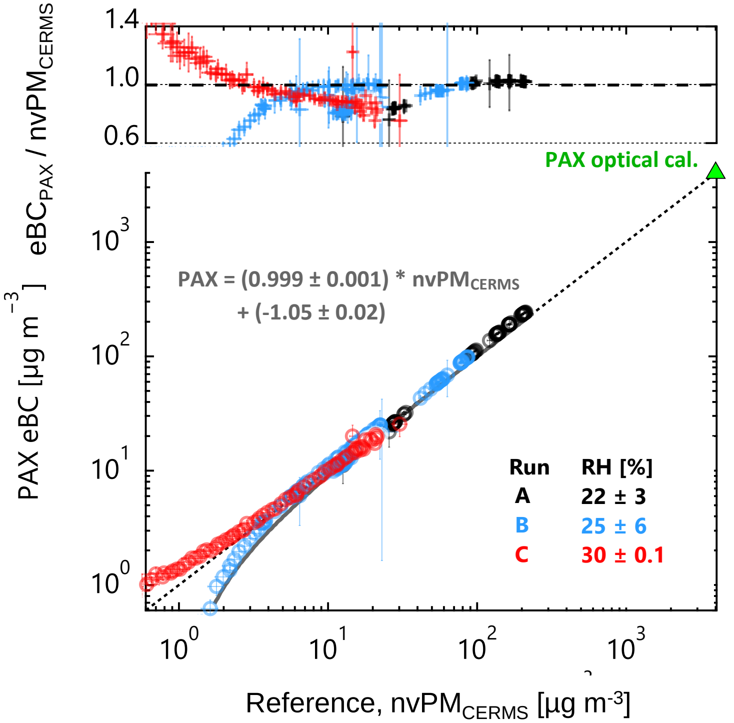


Calibration of PAX determined from CERMS with lab soot from MISG

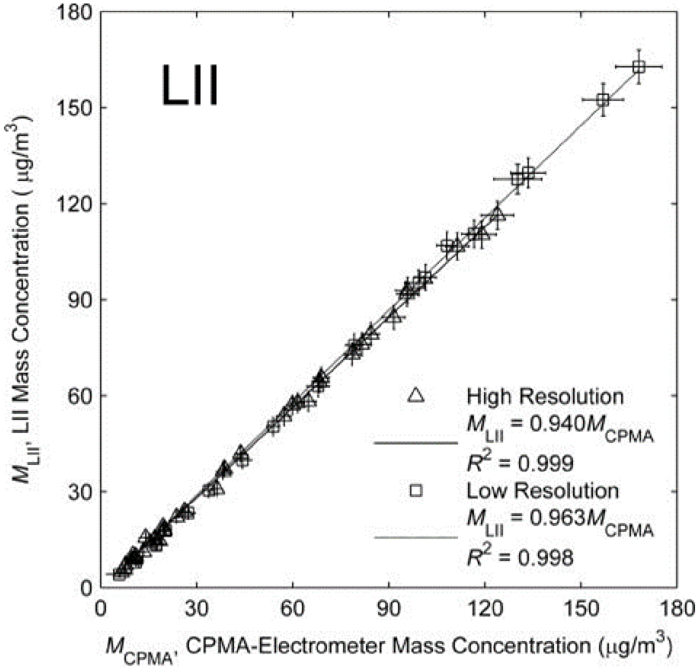
When referenced to nvPM,

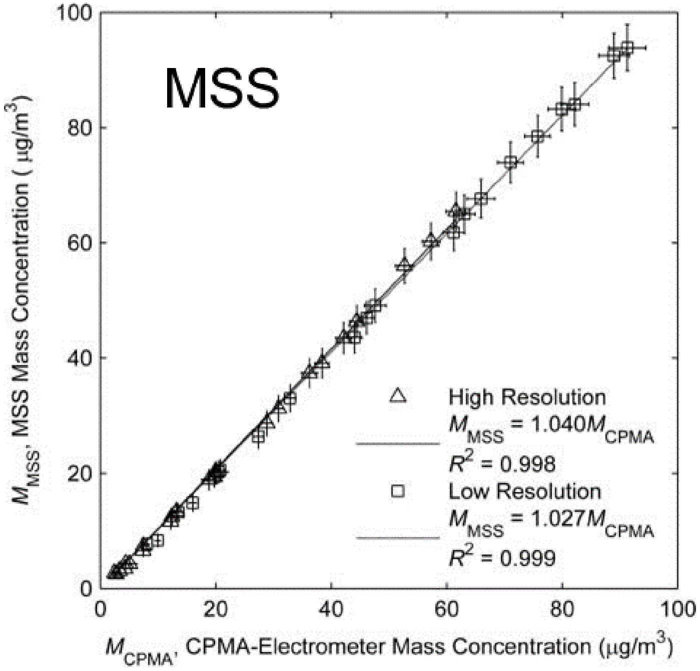
$$eBC = (0.999 \pm 0.001) \cdot nvPM_{CERMS} - (1.05 \pm 0.02)$$

- eBC is equivalent black carbon *(i.e., calculated from absorption measurements with light-absorption-per-gram assumed as 7.5 $m^2\ g^{-1}$ at 550 nm)*
- > 2 µg eBC m^{-3}, the calibration verifies the traditional optical PAX calibration
- < 2 µg eBC m^{-3}, RH-related baseline problems become evident: CERMS provides the LOD of the instrument

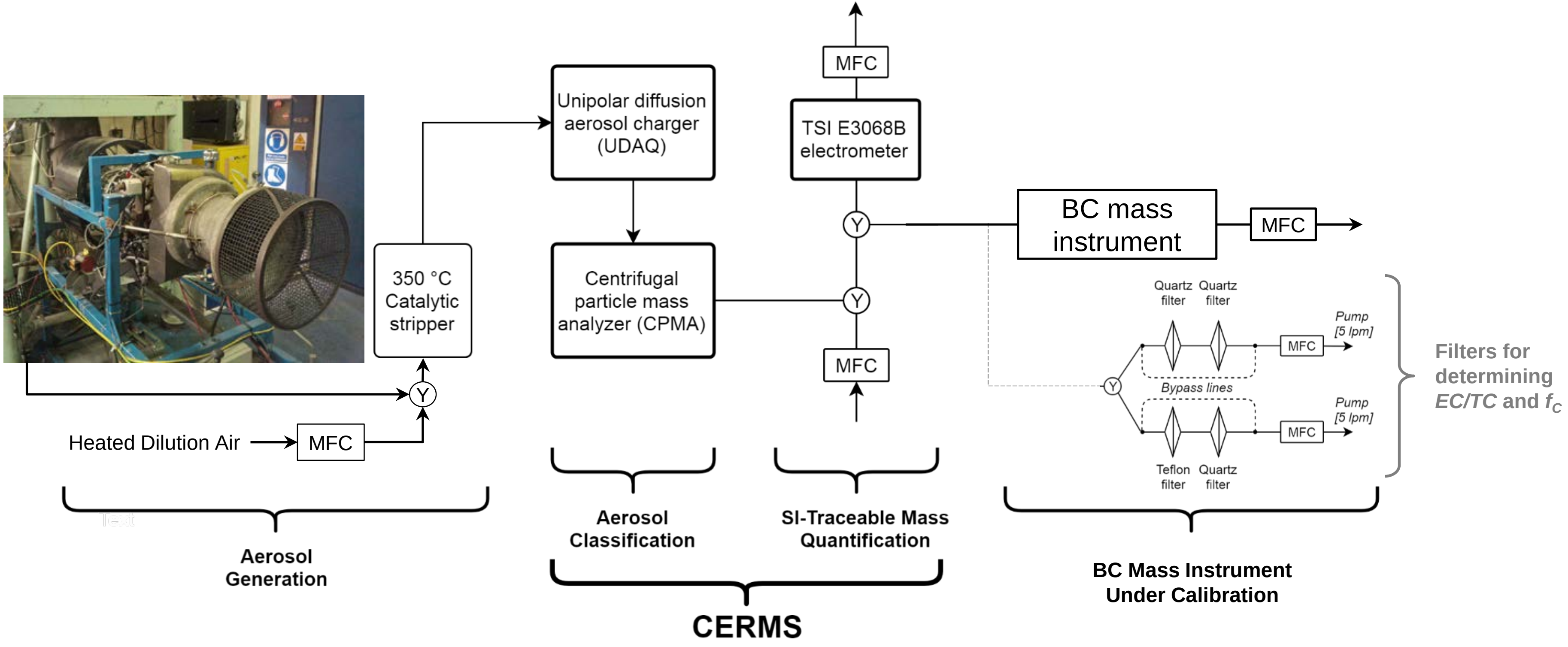


Calibration of LII 300 and MSS determined from CERMS with soot from large inverted burner





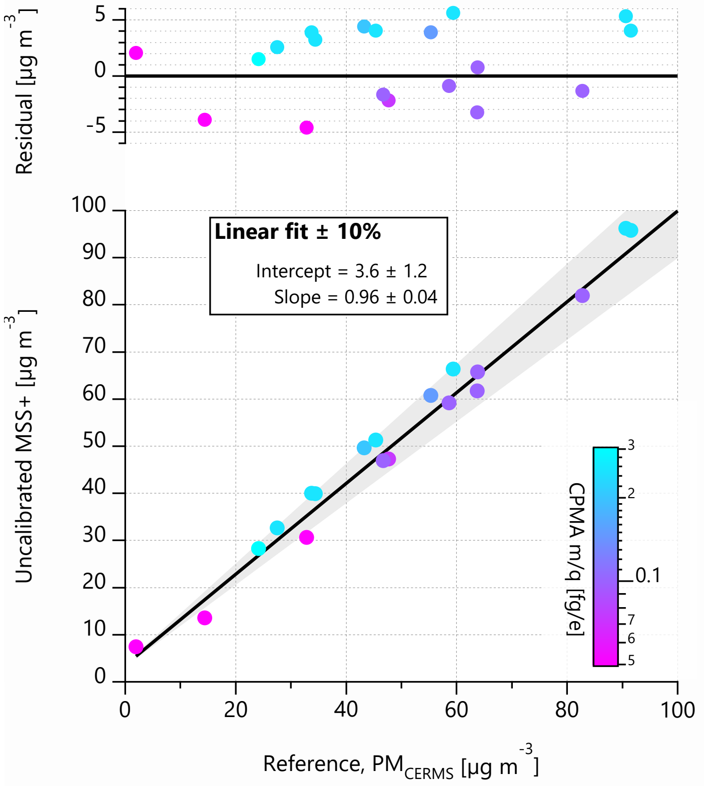
CERMS Apparatus for calibration of a mass instrument on a gas turbine engine



Calibration of MSS+ with CERMS using a gas turbine engine as the source – nvPM

Calibration Factor

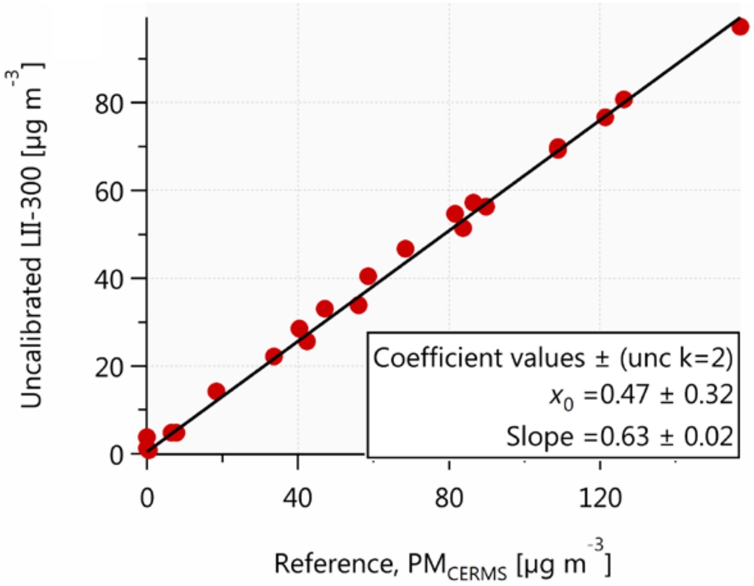
- Calibrated using the CERMS approach in under 2 hours, on-site at an OEM test cell
- For this MSS+, using the Gnome gas turbine engine as the source, the slope relating the LII response to nvPM is 0.96 ± 0.04 with a small offset due to baseline effects



Calibration of LII 300 with CERMS using a gas turbine engine as the source – nvPM

Calibration Factor

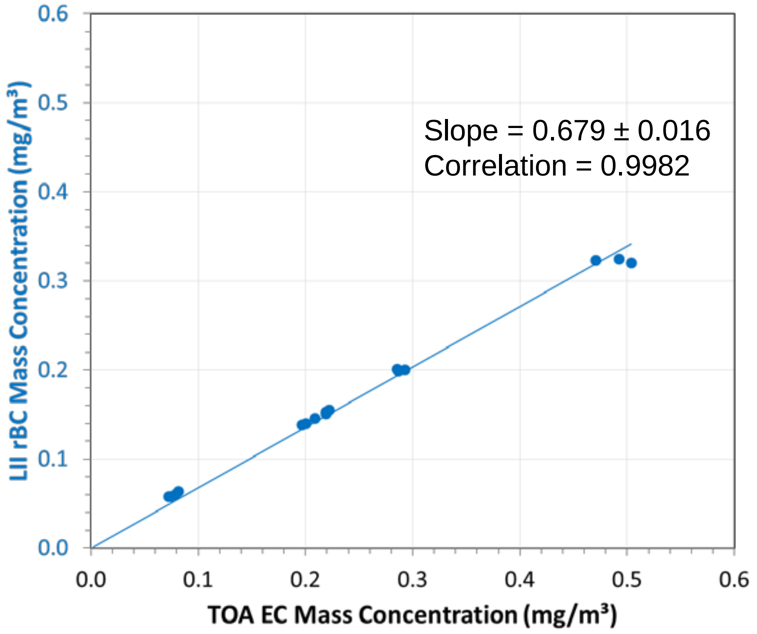
- Calibrated using the CERMS approach in under 2 hours, on-site at an OEM test cell
- For this LII 300, using the Gnome gas turbine engine as the source, the slope relating the LII response to nvPM is 0.63 ± 0.02



Calibration of LII 300 with TOA using Gnome as the source – EC

Calibration Factor

- Determined using the SAE ARP6320[1] method using EC collected on filters and thermal-optical analysis
- For the same LII 300, using the Gnome gas turbine engine as the source, the slope relating the LII response to EC is 0.68 ± 0.02
- The difference in slopes reflects the difference in mass between nvPM and EC

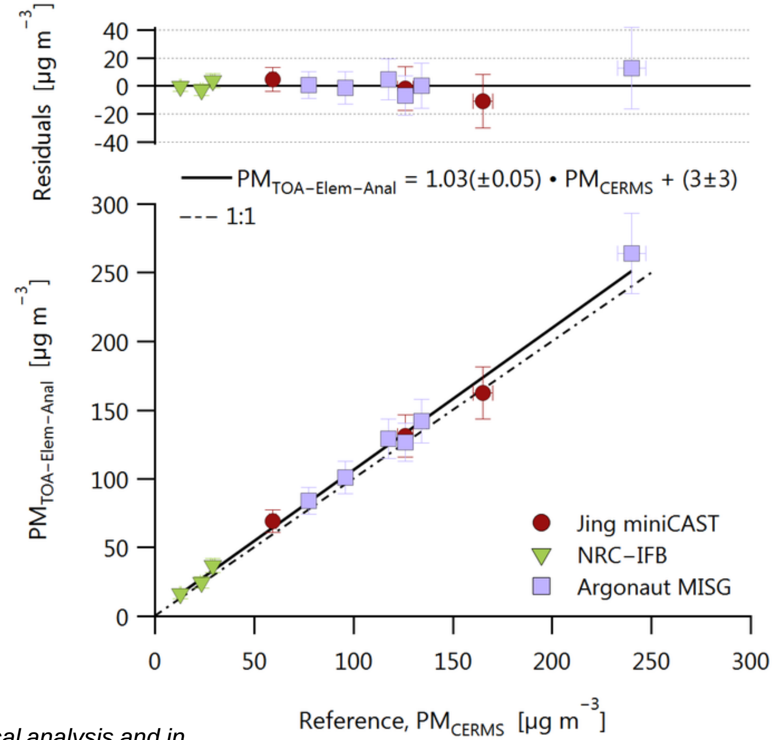


[1]SAE ARP6320 - Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines, 2018

Demonstration of Closure Between CERMS and PM Mass from TOA

Compare total PM mass from TOA to that from CERMS

- thermal-optical analysis (TOA) measures total carbon mass (TC), and operationally defines OC and EC fractions
- VOC contamination of the TOA filter was subtracted
- division of TC into OC and EC is often poorly defined for combustion samples
- as TC does not include all elements present in nvPM samples, it can be converted to total PM mass concentration
- %C is the mass fraction of carbon in the PM measured by elemental analysis (EA), f_C



J. C. Corbin *et al.* (2020) *Closure between particulate mass measured ex situ by thermal–optical analysis and in situ by the CPMA–electrometer reference mass system*, Aerosol Science and Technology, 54, 1293-1309. doi:10.1080/02786826.2020.1788710

Summary

CERMS (CPMA-Electrometer Reference Mass Standard) has been demonstrated for rapid, low uncertainty calibration of a range of BC instruments using a number of BC sources

This study has successfully demonstrated operation of a CERMS calibration of mass instruments using a gas turbine engine as the source

- Rapid (<2 hours experiment time) with same-day determination of calibration factor
- May be performed on-site
- Sensitive to very low concentrations, relevant to nvPM mass concentrations from modern gas turbine engines
- Instrument responses are linear with respect to CERMS regardless of instrument detection methodology or source

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THANK YOU

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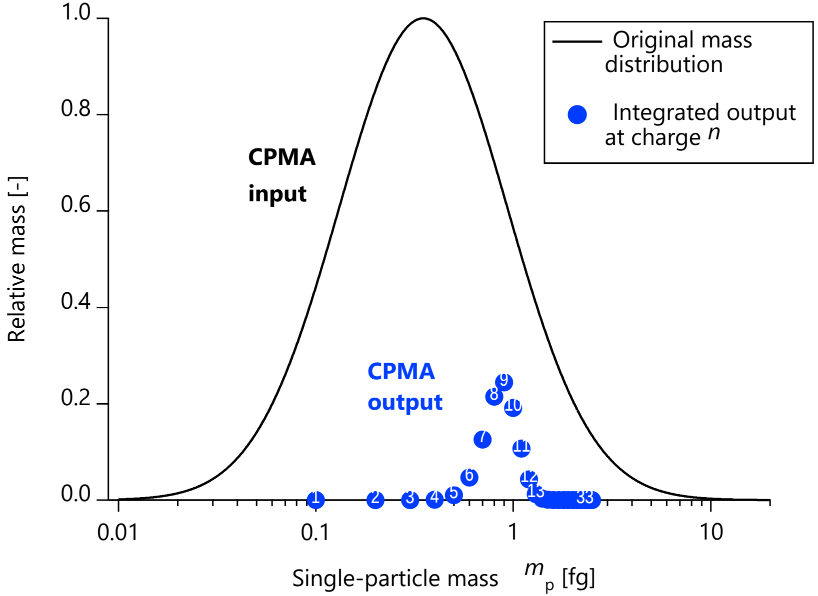
The CPMA

The CPMA classifies particles by mass/charge ratio

An aerosol electrometer measures total particulate charge,

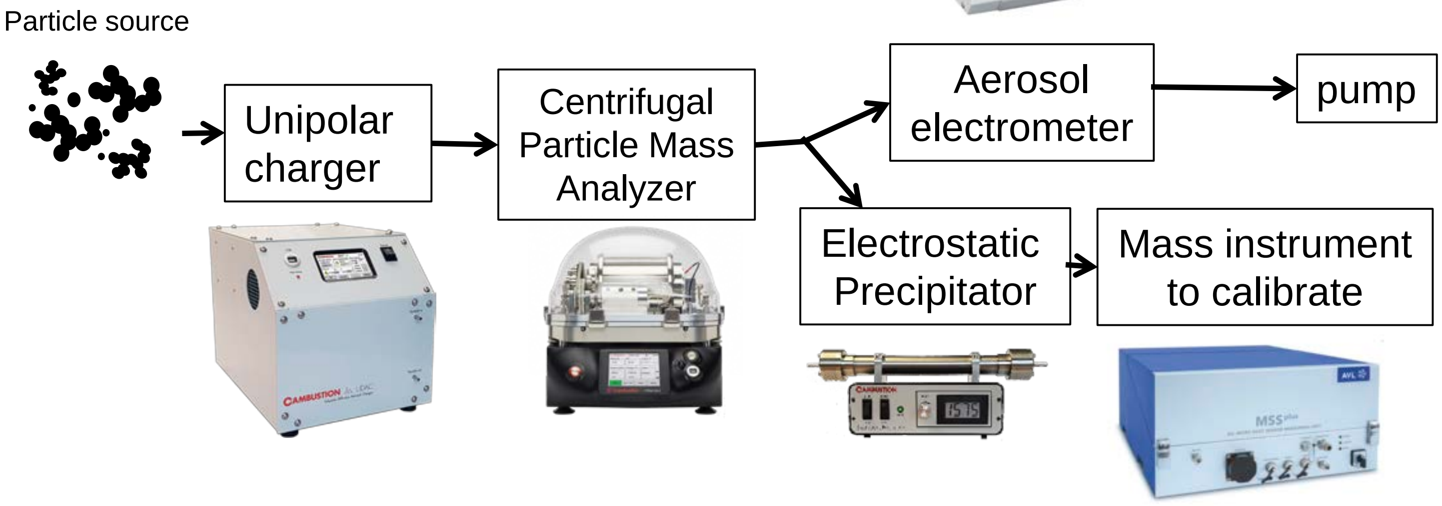
so a CPMA-electrometer measures total particulate mass



What about uncharged particles?

They are generally close to zero, even so, they can be directly measured using an electrostatic precipitator to remove charged particles

Measures the current, I, which is proportional to number of charges detected



M. Dickau, T. J. Johnson, K. Thomson, G. Smallwood and J. S. Olfert (2015) Demonstration of the CPMA-Electrometer System for Calibrating Black Carbon Particulate Mass Instruments, Aerosol Science and Technology, 49, 152-158, doi: 10.1080/02786826.2015.1010033