Evaluation of a Multiwavelength Black Carbon (BC) Sensor

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Abstract

Black carbon (BC) emitted from incomplete combustion processes is often used as a marker for diesel exhaust, a known carcinogen, and is associated with adverse health effects in exposed communities. Although multiple instruments exist to measure BC, very few are tailored for sensor applications where light-weight, low-power, and insensitivity to environmental conditions allow for operation in the demanding environments encountered during unmanned aerial measurements or long-term fence line monitoring as conducted by the US EPA. Understanding these challenges, Aethlabs (San Francisco, CA) designed the MA200/MA350 multi-wavelength BC instrument.

BC measurement wish list

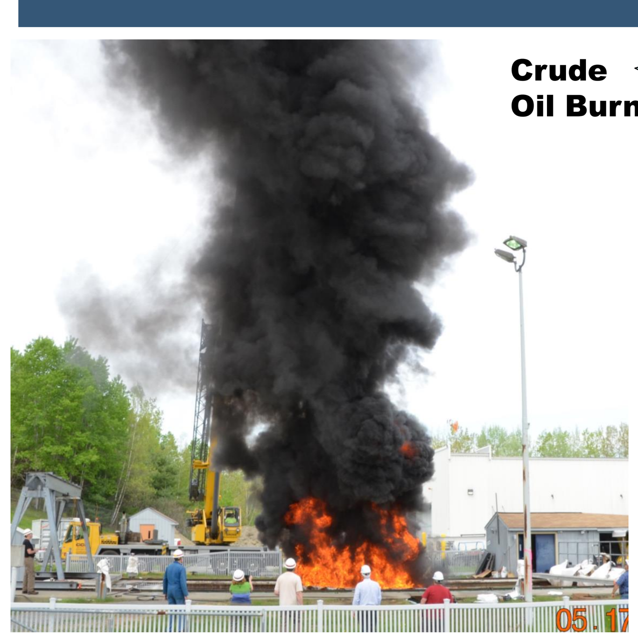
Desired Attribute	MA series	AE-51	Rack-mount instruments
Detect BC (or absorption) at one or more wavelengths	✓✓	✓	✓✓
Detection limit below typical ambient levels (< 0.1 μg/m³)	?	✓	✓✓
High correlation with existing BC measurements (r^2 > 0.8)	?	✓	✓✓
Light weight, small size, low power (i.e. UAV ready)	✓✓	✓	×
Weatherized, long term maintenance free operation (i.e. fenceline ready)	?	×	×

✓Meets or ✓✓ exceeds requirements ×Does not meet requirements ?Subject of our study

Research objective

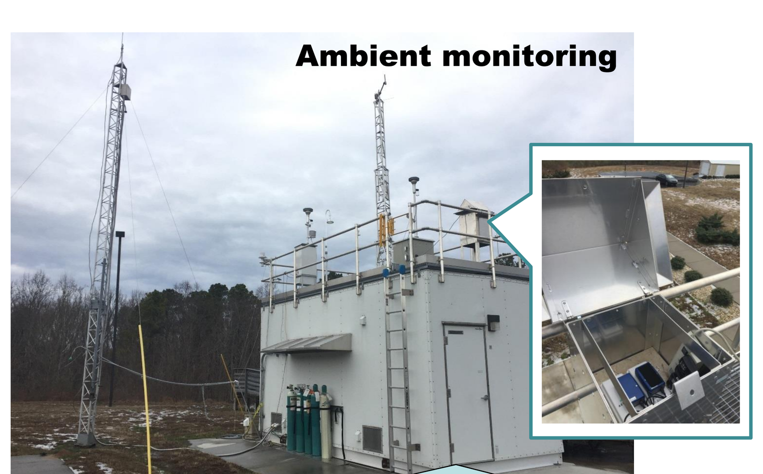
1) Verify a consistent calibration with other Aethalometers (single and multi-wavelength) and other BC/absorption instruments
2) Validate operating range, identify potential measurement artifacts with concentration, composition, RH, and Temp

Measurement Overview



Crude Oil Burn

microAeth (MA-350, AethLabs)
Photoacoustic Soot Spectrometer (PASS-3, DMT)



Ambient monitoring

MA350
microAeth (AE51, AethLabs)
Aethalometer (AE33, Magee)

Woodstoves

microAeth (MA350, AethLabs)
Aethalometer (AE33, Magee)
Semi-continuous elemental carbon(Sunset Labs)

We measured aerosols with:

- a wide range of concentrations (0.1 μg/m³ – 7 mg/m³)
- varying optical properties (strongly scattering/absorbing)
- varying ambient conditions (-4.9 < T< 33.1 ˚C, 11 < RH < 100%)

We applied DualSpot® correction to address well known filter loading artifact

Ambient sampling evaluation at AIRS site

Two MA350s and two AE51s were operated outside from Jan – May 2017. An AE33 with a sample drying system was operated within an environmentally controlled shelter.

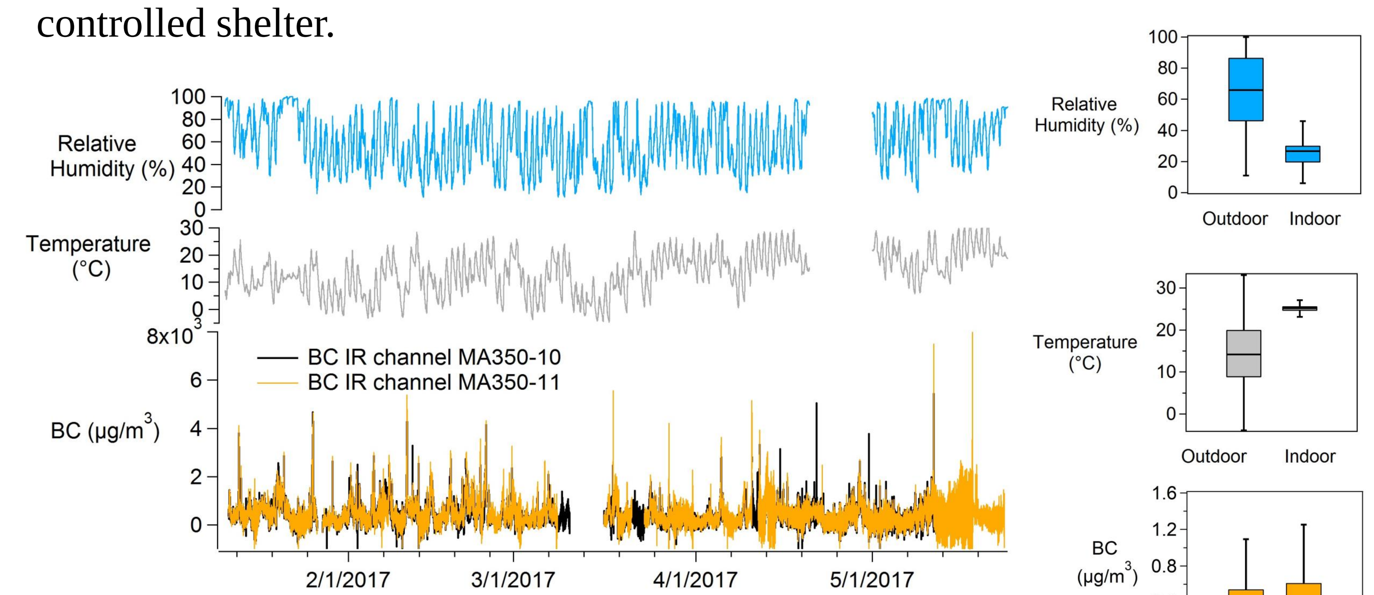


Figure 1. Time series and box plots of relative humidity, temperature, BC concentrations at the AIRS site during winter – spring of 2017

$$Noise = \frac{1}{n}\sum_{i=0}^{n} |BC_{i+1} - BC_i| ,$$

$$BC_{MA350} = \beta_1 + \beta_2\ BC_{AE33} + \beta_3\ T + \beta_4\ RH$$

Table 1. 1-minute average noise (not corrected)

Wavelength (nm) MA350/AE33	Campaign Noise (μg/m³)	
	MA350 -10/-11	AE33
UV – 375/370	0.09/0.12	0.06
Blue – 470	0.09/0.10	0.06
Green – 528/520	0.15/0.11	0.05
Red – 625/660	0.11/0.13	0.04
IR – 880 nm	0.16/0.19	0.04

Table 2. Multiple linear regression coefficients and adjusted R^2 values for MA350-10

Fit Parameters		BC	T	RH	
	β_1	β_2	β_3	β_4	R^2
BC_{AE33} not corrected	36.4	0.85			0.91
BC_{AE33}	17.4	0.95			0.85
BC_{AE33}, RH	-7.0	0.95		0.35	0.85
BC_{AE33}, T	46.8	0.96	-1.63		0.85
BC_{AE33}, RH, T	29.3	0.96	-1.26	0.16	0.85

- MA350 noise levels are ~ 1.5 – 5 times AE33 noise levels
- Strong correlation with AE33, but MA350 BC values are lower
- DualSpot® correction improves comparison but increases noise
- Minimal impact from relative humidity or temperature variation

Oil burn evaluation

Crude oil was burned in a wave tank, emitting strongly absorbing plumes with minimal amounts of organics.

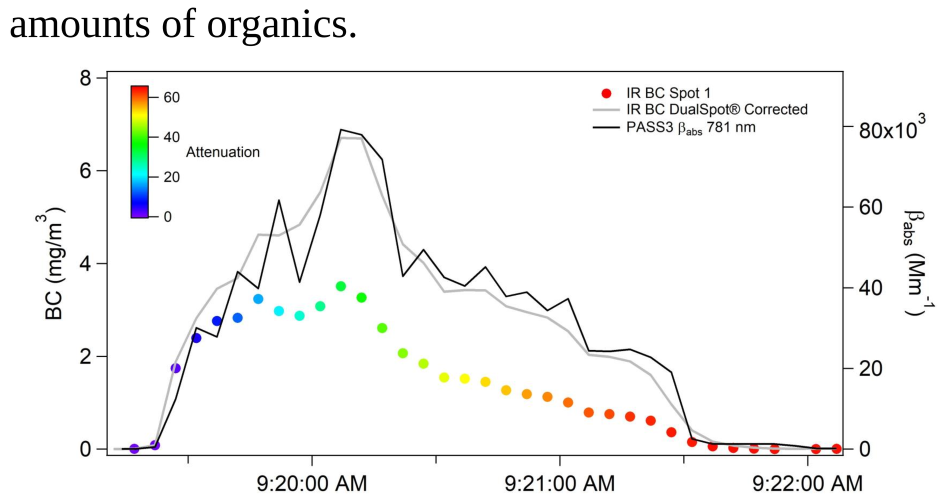


Figure 2. Time series of oil burning emissions

- Strong correlation with PASS-3 across multiple wavelengths (r^2 ~ 0.97)
- DualSpot® correction significantly improves correlation with PASS-3 (uncorrected r^2 ~ 0.87 to corrected r^2 ~ 0.97), which is not impacted by the filter loading artifact
- Loading artifact results in 20-60% lower mean BC concentration, depending on the attenuation range observed during the burn

Wood stove evaluation

Wood stove emissions testing

Wood stove tests were carried out with an EPA 2015 certified stove burning spruce crib wood at a low burn rate. Emissions were from both flaming and smoldering combustion regimes. Multiple continuous BC instruments and a semi-continuous elemental carbon instrument sampled diluted stove emissions.

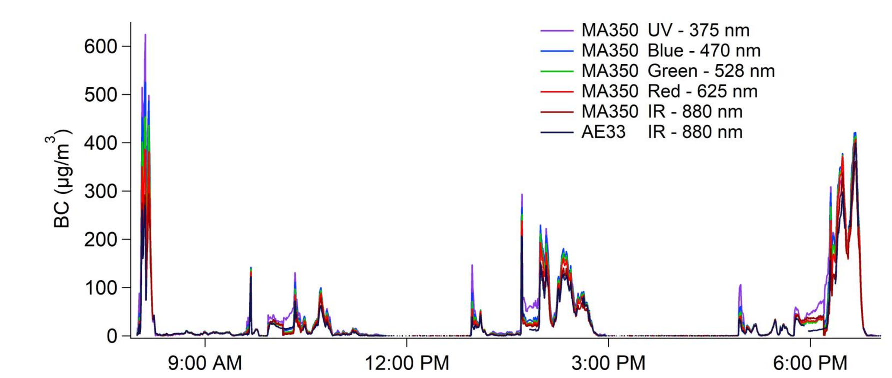


Figure 3. Time series of smoldering wood stove emissions

Table 3. Slope and R2 for a linear MA350 (y-data) vs AE33 (x-data) for each measurement wavelength

Wavelength (nm) MA350/AE33	Slope	R^2
UV – 375/370	0.828	0.951
Blue – 470	0.913	0.985
Green – 528/520	0.913	0.970
Red – 625/660	0.986	0.987
IR – 880	1.003	0.978

- MA350 BC is highly correlated with the AE33, even at high time resolution (r^2>0.97 at 5 s)
- The MA350 and AE33 BC agree within 10% at all visible wavelengths
- The MA350 UV channel is 17% lower than the AE33
- The MA350 and AE33 BC (880 nm) correlate strongly with EC, even at high organic carbon loadings
- The lower flow rate of the MA350 resulted in longer sampling times at high concentrations, resulting in 20% increase in data completeness compared to AE33

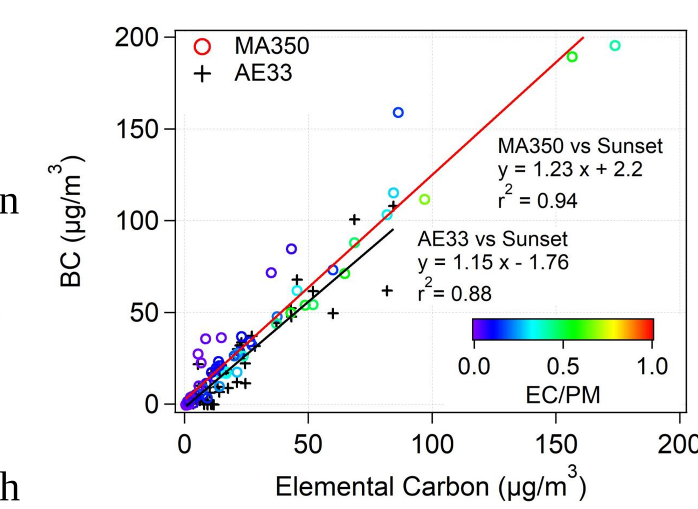


Figure 4. Scatter plot black carbon vs elemental carbon comparison

Conclusions

- The MA350 is minimally impacted by environmental parameters (i.e. RH and T)
- DualSpot® correction reduces error association with filter loading by up to 60%
- The MA350 concentrations at visible wavelengths are consistent with the AE33, ensuring consistency across instruments
- The MA350 performed well compared to other instruments for both source and ambient conditions
- Additional testing is need to determine the source of differences between the MA350 and the AE33 for the UV channel
- Evaluations were done with older firmware versions, ongoing improvements to instrument control still need to be evaluated