The 'Next-Generation' Aethalometer®

Model AE33

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Summary

The new model AE33 Aethalometer is a very considerable improvement and modernization of the existing well-proven and rugged design. The enhanced features include:

- Patented 'Dual Spot' technology eliminates the data artifact due to filter loading.
- Analysis at multiple wavelengths identifies biomass emissions.
- Time resolution as rapid as 1 second permits studies of emission sources.
- Sample collection on Teflon-coated glass fiber filter tape reduces the effects of varying Relative Humidity (air-conditioner perturbations).
- Automatic flow calibration procedure using external standard ensures accuracy.
- Built-in 'zero' test from internal clean-air source checks leakage and noise.
- 'Span' test of optical detectors using external standards validates performance.
- Network connection provides remote access, operation and data retrieval.
- Front-panel USB ports provide local download without interruption of data.
- Low power consumption (25 W) permits off-grid use.
- Completely automatic operation upon power-up provides continuity.
- Hermetic seals prevent ingress of dust and moisture.
- Direct coupling to CO_2 sensor (optional accessory) integrates BC and CO_2 data.
- Direct coupling to meteorology sensor (optional accessory) reports P, T and RH, permits calculation of BC concentration data under 'local' conditions.

The ‘Next-Generation’ Aethalometer®
Model AE33

Magee Scientific and Aerosol Co. are pleased to announce the **‘Next Generation’ Aethalometer®**, Model AE33. This development incorporates scientific and technical advances designed to offer improved measurement performance, user features, communications and interface, and the ability to perform routine performance tests to verify correct operation. Most importantly, the new instrument incorporates the patented ***DualSpot™*** measurement method. This provides two significant advantages: elimination of the changes in response due to ‘aerosol loading’ effects; and a real-time calculation of the ‘loading compensation’ parameter which offers insights into aerosol optical properties, and has been interpreted in models of aerosol origins and aging.

The Model AE33 Aethalometer has been developed with input from the research and monitoring communities, and is designed for reliable operation under all conditions ranging from state-of-the-art research to compliance monitoring.

The leading innovations incorporated into the Model AE33 include:

1. The ***DualSpot™*** measurement method, which solves the effects common to <u>all</u> filter-based real-time monitors, in which the instrumental response factor shows a dependence on the loading of material on the filter.

2. Features for automatic ‘dynamic zero’ testing under a flow of internally-generated clean air; ‘span’ testing of the response of the optical sources and detectors; calibration of the response of the internal mass flow meters, if an external standard flow calibrator is connected; and validation of the photometric response by use of a kit of ‘Neutral Density’ optical filters whose properties may be traced to reference standards.

3. User and communications interfaces, permitting remote monitoring of operation; data retrieval; performance of internal tests; and reporting of ‘state-of-health’ parameters.

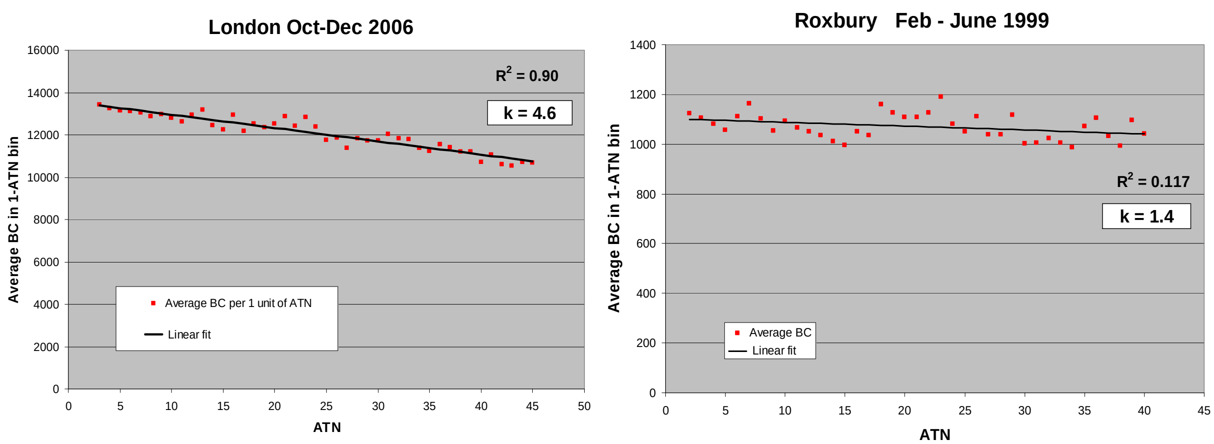
4. Modular construction designed for ease of routine maintenance service.

In addition to the above new features, the Model AE33 Aethalometer offers real-time aerosol absorption analysis at seven optical wavelengths, with time resolution to 1 second. This permits the measurement of optically-absorbing aerosols – ‘Black’ Carbon and ‘Brown’ Carbon components of particulate matter – in applications including routine monitoring of ambient air quality for regulatory purposes; measurements of the concentration of BC in urban, suburban, regional, rural and remote locations; source testing; and laboratory-based research.

1. *<u>'DualSpot™' technology</u>*

The Model AE33 Aethalometer uses the patented ***DualSpot™*** method to compensate for the 'spot loading effect'; and also to provide a real-time output of the 'loading compensation' parameter, which may provide additional information about the physical and chemical properties of the aerosol.

The 'spot loading effect' is a variable phenomenon which appears as a gradual reduction of instrumental response as the aerosol deposit density of the filter tape increases from zero to the predetermined limit of 'Maximum Attenuation'. When the filter tape advances to a fresh spot, the data undergoes a discontinuous jump from its previous lower value, calculated when the spot was heavily loaded; to a higher value, calculated from collection on a fresh spot at zero loading. In the Aethalometer the reduction of data at increasing loadings is well described by a linear function of attenuation, but its magnitude cannot be predicted: some aerosols in some locations in some seasons may show a small or zero 'loading effect'; while under other conditions, the effect may be larger and noticeable. Empirically, it is found that fresher aerosols closer to their combustion sources will show a larger 'spot loading effect'; while well-aged aerosols under atmospheric conditions of high chemical activity and oxidative processing may show an almost zero effect. The effect is revealed statistically by processing data collected over a large number of tape advances, representing many data points collected at loadings ('ATN values') ranging from zero to the preset maximum. The data is collected into bins according to loading (attenuation, ATN). If there is a systematic reduction of the calculated result as a function of loading, the data will show a clear negative slope, with the intercept representing the 'zero loading' value. Figure 1 illustrates two datasets from urban locations with loading effects either present or not.



<u>Figure 1</u>: Aethalometer data sorted and averaged according to loading (attenuation, ATN) on spot. Left: roadside location in London, UK; right: urban site in Boston (Roxbury), USA.

The London data show a systematic reduction at increasing loadings; while the Roxbury data do not. This demonstrates that any method intended to compensate for the 'spot loading effect' must be auto-adaptive and able to adjust dynamically to different situations. An instrument based on firmware with a fixed 'loading non-linearity' parameter will not operate correctly at all locations. The 'loading non-linearity' parameter must be measured.

It is clear that the effect, when present, is linear with loading ('ATN'). This can be represented as

$$\mathbf{BC}\ (\text{reported}) = \mathbf{BC}\ (\text{zero loading}) \ * \ \{ \ 1 \ - \ \boldsymbol{k} \cdot \mathbf{ATN} \ \}$$

where ***BC (zero loading)*** is the desired ambient BC value that would be obtained in the absence of any loading effect; and ***k*** is the 'loading compensation parameter' (similar to Virkkula et al., 2007).

The analysis of a large number of datasets from a wide variety of locations shows that this relationship is linear in all cases studied; but with different values of ***k***. It is therefore possible to eliminate the 'loading effect' of ***k*** by making two simultaneous identical measurements $\boldsymbol{BC_1}$ and $\boldsymbol{BC_2}$ at different degrees of loading $\boldsymbol{ATN_1}$ and $\boldsymbol{ATN_2}$.

$$\mathbf{BC_1} = \mathbf{BC} \ * \ \{ \ 1 \ - \ \boldsymbol{k} \cdot \mathbf{ATN_1} \ \}$$
$$\mathbf{BC_2} = \mathbf{BC} \ * \ \{ \ 1 \ - \ \boldsymbol{k} \cdot \mathbf{ATN_2} \ \}$$

From these two linear equations we may calculate the 'loading compensation parameter' ***k***; and the desired value of **BC** compensated back to zero loading.

The Model AE33 Aethalometer analyzes the Black Carbon component of aerosols on ***two parallel spots*** drawn from the same input stream, but collected at different rates of accumulation, i.e. at different values of ATN. By combining the data according to the above equations, the AE33 yields the value of **BC** extrapolated back to 'zero loading'; as well as a real-time output of the 'loading compensation parameter' ***k*** which provides insights into the aerosol nature and composition (see Figure 8 below). This process is performed in real time for all wavelengths: examination of the '***k***' values as a function of wavelength provides further information about the aerosol composition. An example of the real-time loading compensation process is shown in Fig. 2 for extreme concentrations of black carbon.

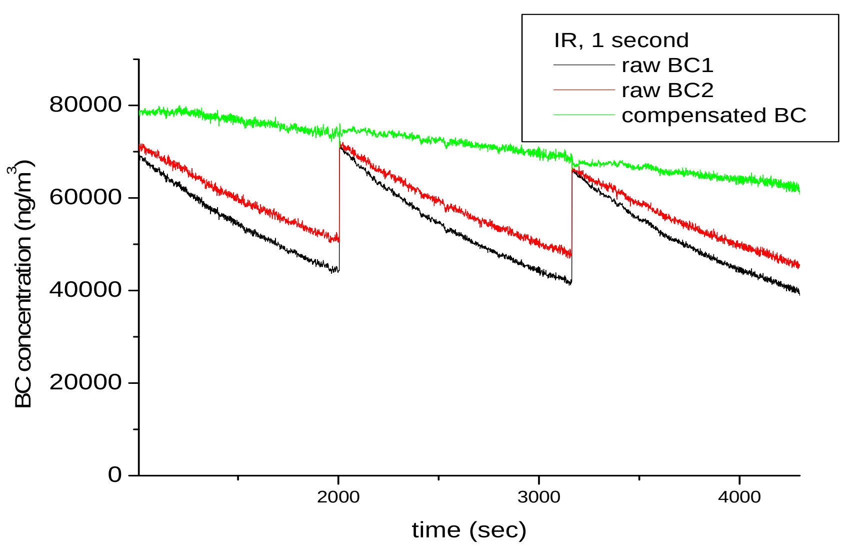


Figure 2: The time-series of AE33 raw and compensated BC concentrations with 1 second timebase – note the extreme concentrations and loading effects.

Note that ‘spot loading effects’ are also exhibited by other filter-based BC-measuring instruments (Kanaya et al., 2008; Virkkula, 2010; Hyvärinen et al., 2013). Published results show that the effect is not linear and consequently not readily amenable to mathematical compensation without making assumptions about the nature of the aerosol. Data from one such instrument is observed to saturate at BC concentrations above ~ 7 μg/m3 (Kanaya et al., 2008). and exhibit jumps at tape advances (Hyvärinen et al., 2013).

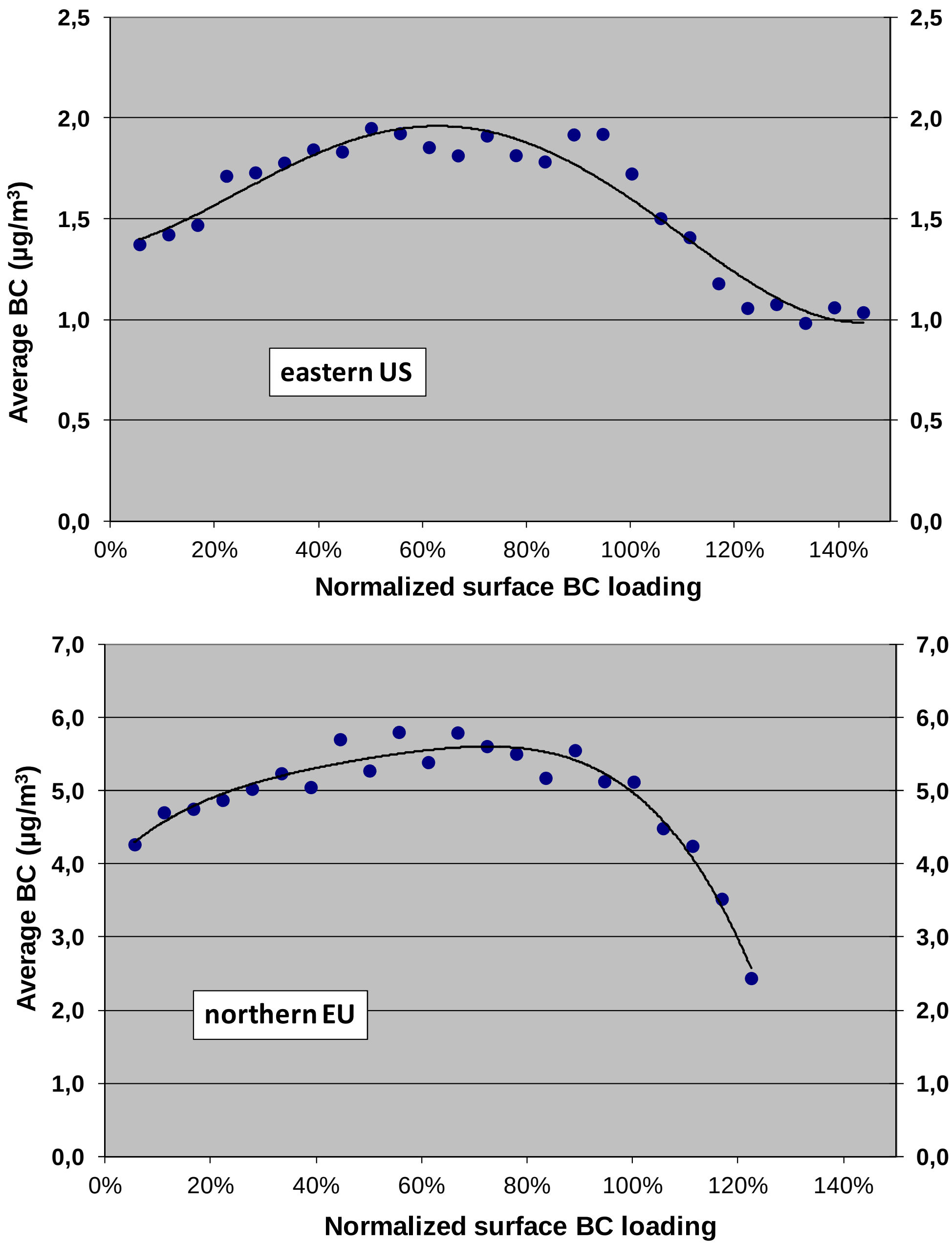


Figure 3: Loading effect in another filter-based BC-measuring instrument. Data sorted and averaged according to cumulative loading on spot; 1 month of data from the eastern US (top), and 1 week of data from northern Europe (bottom).

2. ***User and Communications Interfaces***

The Model AE33 Aethalometer incorporates the following user, data and communications features:

- Large color graphics touch-screen for data display and local user interface;
- USB ports for insertion of a memory stick for local data download;
- USB ports for connection of a keyboard, if necessary for initial setup of parameters, such as station identification;
- RS-232 COM port for data transmission to digital datalogger;
- Ethernet port for full network access and control, including
    i. Remote data acquisition, either batch or streaming
    ii. Remote retrieval of instrument status and state-of-health
    iii. Remote control of instrument operating parameters

3. ***Modular Construction***

The Model AE33 Aethalometer is constructed with a modular design, so that sub-units may be easily serviced. The only item requiring attention in routine use is cleaning of the optical insert to remove accumulated dust or other contamination which may be brought in with the sample air stream. The optical chamber is attached with a bayonet fitting for quick removal; easy cleaning; and reliable re-assembly. The entire instrument is hermetically sealed to reduce the entry of dust and moisture.

4. ***Automatic Zero and Span***

Zero

The Model AE33 Aethalometer offers the capability for automatically checking the 'zero-air' response of the instrument under dynamical operating conditions. This test is implemented by back-flushing the inlet connection with an excess flow of internally-filtered air and circulating the filtered air in the instrument. The data reported during this period are analyzed for the mean value and the point-to-point variation. The mean value should be close to zero under ideal conditions; any positive value greater than zero represents the leakage of BC-containing room air into the instrument's analytical zone. The point-to-point variation represents the instrument's measurement noise level under actual operating conditions of actual flow – i.e., a 'dynamic' test. The point-to-point variation when the time-base is set to one second is 60 times larger than the one-minute variation. In the example shown below, a one-second noise level of 125 ng/m³ is equivalent to only 2 ng/m³ when averaged up to one-minute time resolution.

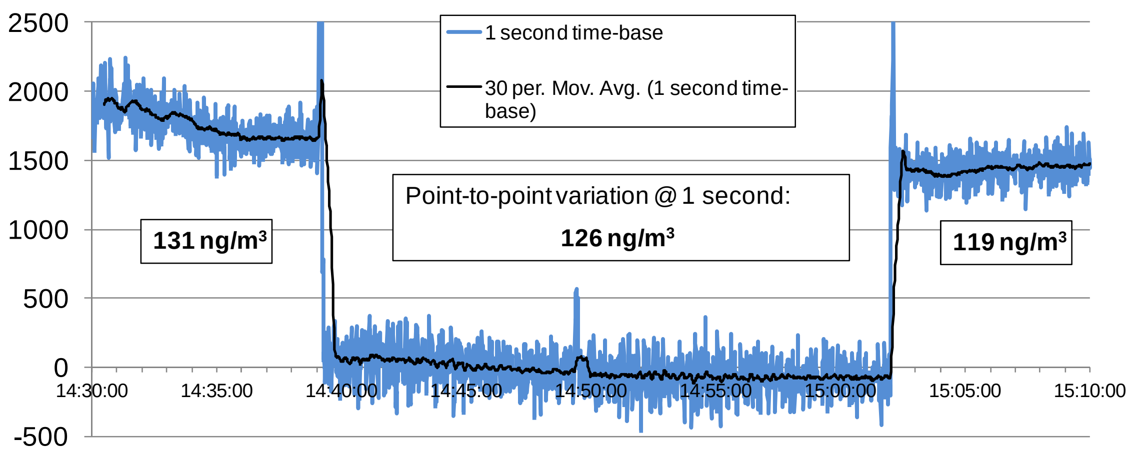


Figure 4: 'Zero-air' check. The Model AE33 Aethalometer switches from sampling ambient air to filtered air. One-second data is 60 times noisier than the one-minute average.

Span

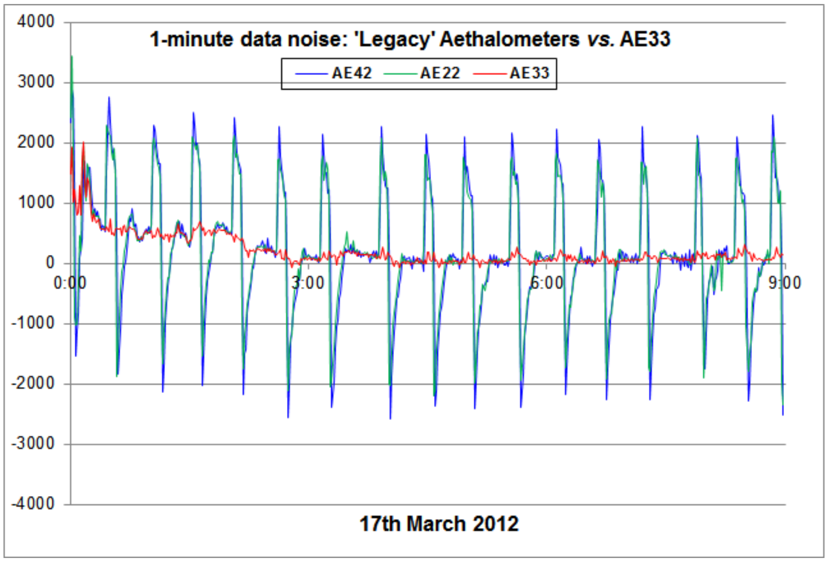
The response of the optical detectors of the Model AE33 Aethalometer may be verified by use of a kit of Neutral Density optical filters as shown in Figure 5 below. These are glass elements with a range of known and stable optical absorptions, from light to dark, which are traceable from manufacturing records back to primary standards. When these are inserted into the AE33 Aethalometer, the photodetectors will give a certain output signal. The stability and reproducibility of the relationship between optical signal and ND Filter density from one validation test to another; and the comparison with the original factory values; is a measure of the consistency of performance of the instrument's optics.

Figure 5: Optical Validation Kit consisting of traceable standard Neutral Density Optical Filters, which are inserted into the AE33 optical path to determine the reproducibility of the relationship between LED optical source intensity and detector response.

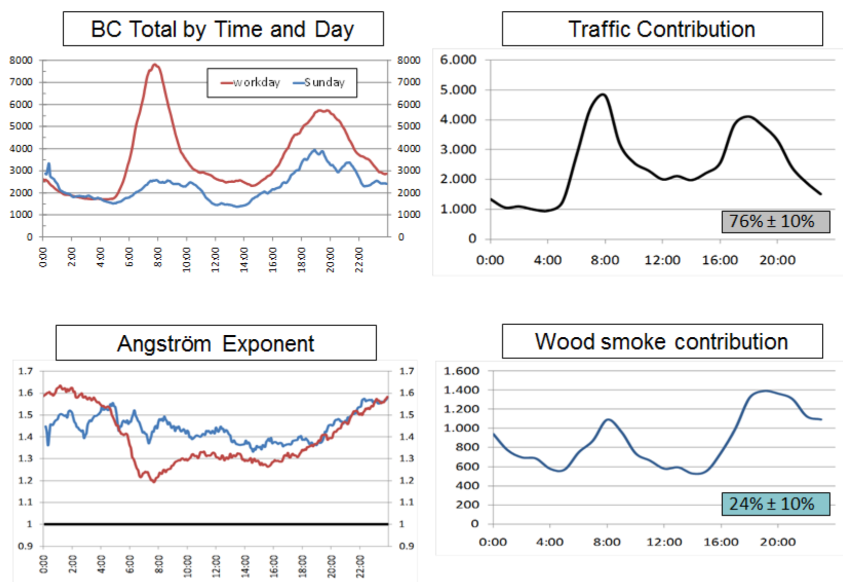
5. ***Summary and Illustrations***

The new model of Aethalometer, the AE33, is a very considerable improvement and modernization of the existing well-proven and rugged design. The enhanced features include:

a) Patented 'Dual Spot' technology to eliminate the data artifact due to filter loading.
    i. See Figure 2 above.
b) Analysis at multiple optical wavelengths with time resolution as rapid as 1 second (useful for direct combustion studies).
    ii. See Figure 2 above, showing 1-Hz data.
c) Sample collection on Teflon-coated glass fiber filter tape, to reduce the effects on the optical analysis of varying Relative Humidity (air-conditioner perturbations).
    iii. See Figure 6 below.
d) Instrument is hermetically sealed to prevent ingress of dust and moisture.
e) Built-in software analyzes the multi-wavelength data, to provide real-time source apportionment of the BC attributed to diesel or oil combustion; versus the BC attributed to biomass burning.
    iv. See Figure 7 below for scientific data example.
    v. See Figure 8 below for screen display example
f) Capability of direct coupling to CO_2 sensor (optional extra accessory), with integration of BC and CO_2 data. This permits direct, real-time determination of the Emission Factor of BC during combustion.
    vi. See Figure 9 below.
g) Capability of direct coupling to meteorology sensor for P, T and RH (optional extra accessory), with integration of data
h) Built-in 'zero' test from internal clean-air source.
    vii. See Figure 4 above.
i) Optional verification test of optical detectors, using externally-inserted optical standards.
    viii. See Figure 5 above.
j) Network connection for remote access, operation and data retrieval. Local data download from front-panel USB ports. Rear panel COM ports. Color touch-screen user interface.
k) Low power consumption (25 W), automatic operation upon power-up. May be operated at remote sites from off-grid inverter, batteries, and/or solar panels.



<u>Figure 6</u>: Perturbation of data induced by fluctuation in room air Relative Humidity when subject to an on-off cycling air-conditioner. "Legacy" instruments using quartz fiber tape show large perturbation, while the effects on the AE33 are greatly reduced. However, a Sample Stream Dryer (optional accessory) is recommended for best results.



<u>Source apportionment of mixture of traffic emissions and wood smoke by time-resolved Angström exponent analysis</u>

<u>Figure 7</u>: Example of analysis of multi-wavelength data to determine the 'Angstrom Exponent' of optical absorption by ambient aerosols, and separate the total BC into contributions from "traffic" versus "biomass smoke", according to the model of Sandradewi et al., 2008.

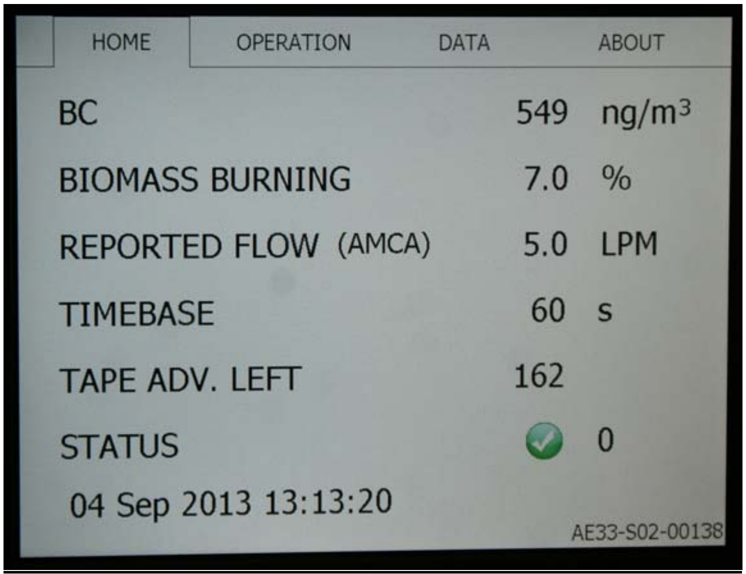


Figure 8: AE33 display screen showing spectral data analysis represented as a Percentage of total BC attributable to biomass burning

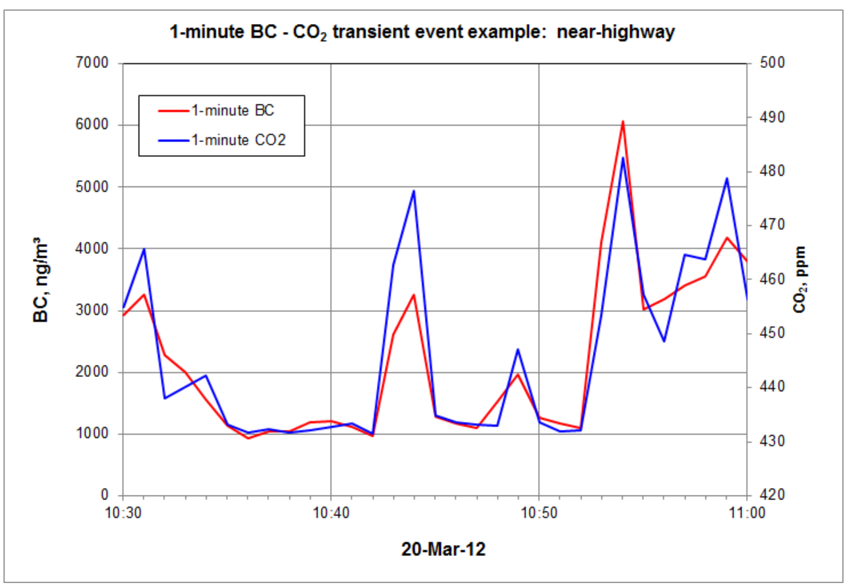


Figure 9: Highly-correlated BC and CO_2 data from integrated sensor with combined data stream. The correlations permit a determination of the BC Emission Factor of the source creating the transient plume.

6. ***References***

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7. Contact

www.mageescientific.com
www.aerosol.si

In Europe, Asia, and Africa, please contact:
Aerosol d.o.o., Kamniška 41, SI-1000 Ljubljana, Slovenia, EU
tel: +386 59 191 220
fax: +386 59 191 221

In the US, please contact:
Magee Scientific Corporation, 1916A M.L. King Jr. Way, Berkeley CA 94704, USA
tel: +1 510 845 2801
fax: +1 510 845 7137

or the distributor responsible for your country.

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