The Aethalometer™ for BC: What it is, What it does, Where it's Going

George Allen

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THE AETHALOMETER — AN INSTRUMENT FOR THE REAL-TIME MEASUREMENT OF OPTICAL ABSORPTION BY AEROSOL PARTICLES*

A.D.A. HANSEN, H. ROSEN, and T. NOVAKOV

Applied Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

ABSTRACT

We describe an instrument that measures the concentration of optically absorbing aerosol particles in real time. This absorption is normally due to black carbon, which is a good tracer for combustion emission. The minimum resolving times range from seconds in urban environments to minutes in remote locations. We present results obtained during operation on an aircraft. Due to the time resolution capability, we can determine the spatial distributions of absorbing aerosol. From the Greek word "αἰθαλοῦν," "to blacken with soot," we have named this instrument the aethalometer.

- 22 years later... The Aethalometer:
  Still a work in progress, still being defined, still being improved.

- <u>What this talk is not:</u>
  A summary of routine Aethalometer operational issues.

- For that, see:
  “Care and Feeding of Aethalometers™”
  G. Allen

Presented at:

U.S. EPA / NESCAUM Air Toxics Monitoring Workshop
Las Vegas, NV, October 9, 2003

==> on the NESCAUM web site at:
http://tinyurl.com/tflye (that’s t f l y e)

- What the Aethalometer is:

  Physically: A measure of the attenuation of a specific wavelength of light through a quartz fiber filter as it loads over time

  A rough estimate of BC (a surrogate of EC) and local traffic activity
  (see poster on BC spatial scale in Boston)

  For 2-wavelength Aethalometers, a fresh biomass burning indicator
  (see Wood Smoke Indicator presentation Tuesday 3:30)

- What it isn’t:

  A stable quantitative estimate of “EC” or “soot”

  A specific diesel PM indicator or quantitative measurement
  (unless used in a controlled sampling environment)

Two major issues:

1. Excessive short term thermal stability problems

    5-minute data are extremely noisy with even modest temperature cycling (quick-fix: styrofoam cooler solution)

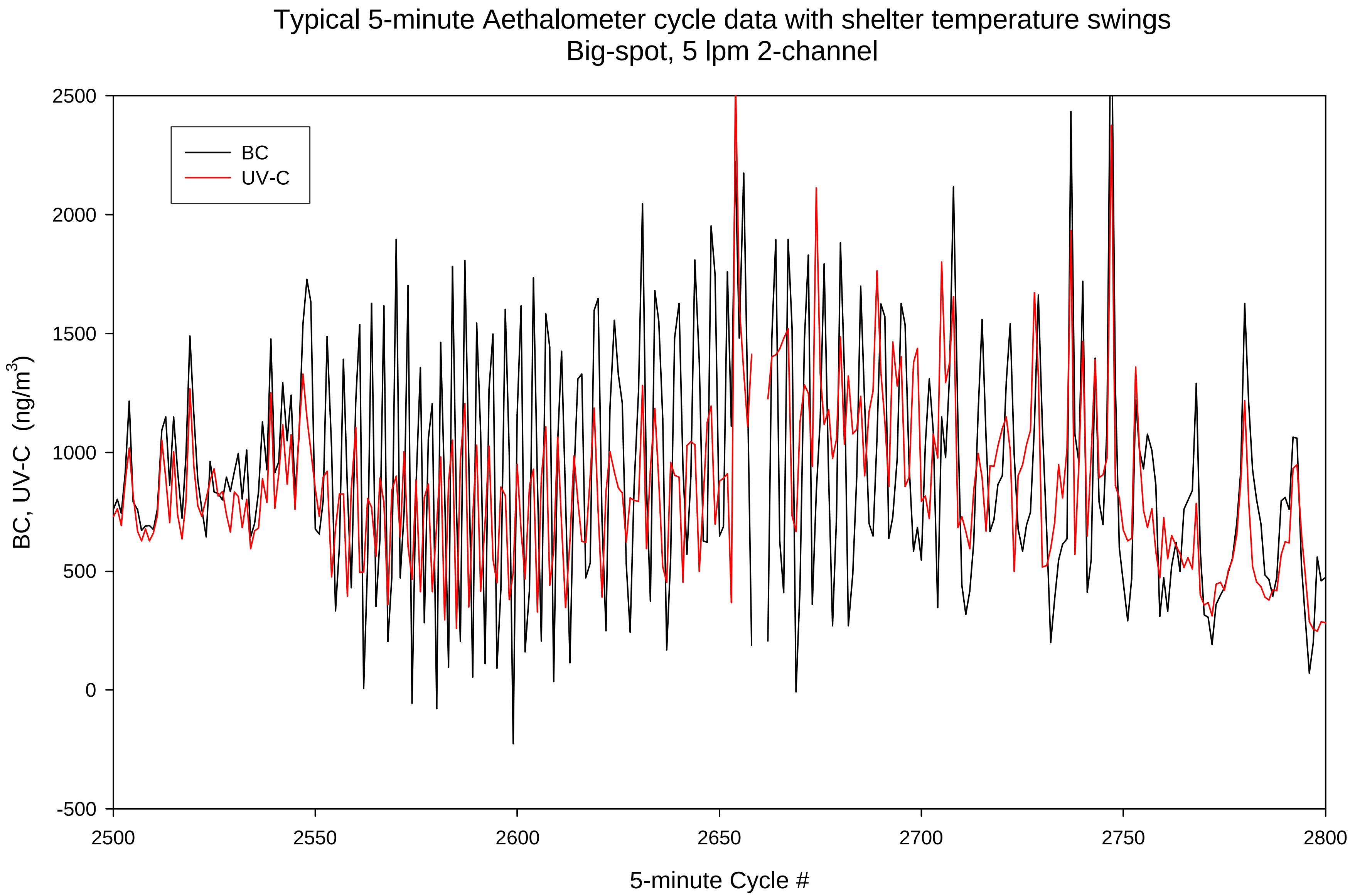
2a. Large (~2x, more for UVC) spot loading effect for “fresh soot”

==> results in under-measurement of BC and variable short term measurements (poor correlation of collocated instruments)

2b. Large (~1x) change in response to non-BC composition of aerosol

==> under certain conditions: “sample matrix effects”

-- enhanced response to BC



Typical 5-minute Aethalometer cycle data with shelter temperature swings
Big-spot, 5 lpm 2-channel
BC
UV-C
BC, UV-C (ng/m3)
2500
2000
1500
1000
500
0
-500
2500
2550
2600
2650
2700
2750
2800
5-minute Cycle #

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A Simple Procedure for Correcting Loading Effects of Aethalometer Data (IAC/AAAR Sept. 2006, St. Paul MN)

Aki Virkkula[1], Timo Mäkelä[1], Tarja Yli-Tuomi[2], Anne Hirsikko[3], Ismo K.Koponen[4], and Risto Hillamo[1]

[1]Finnish Meteorological Institute, Research and Development, FIN-00560 Helsinki, Finland

[2]National Public Health Institute, Department of Environmental Health, FIN-70701 Kuopio, Finland

[3]Department of Atmospheric Sciences, University of Helsinki, FIN-00014 Helsinki, Finland

[4]Department of Chemistry, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark

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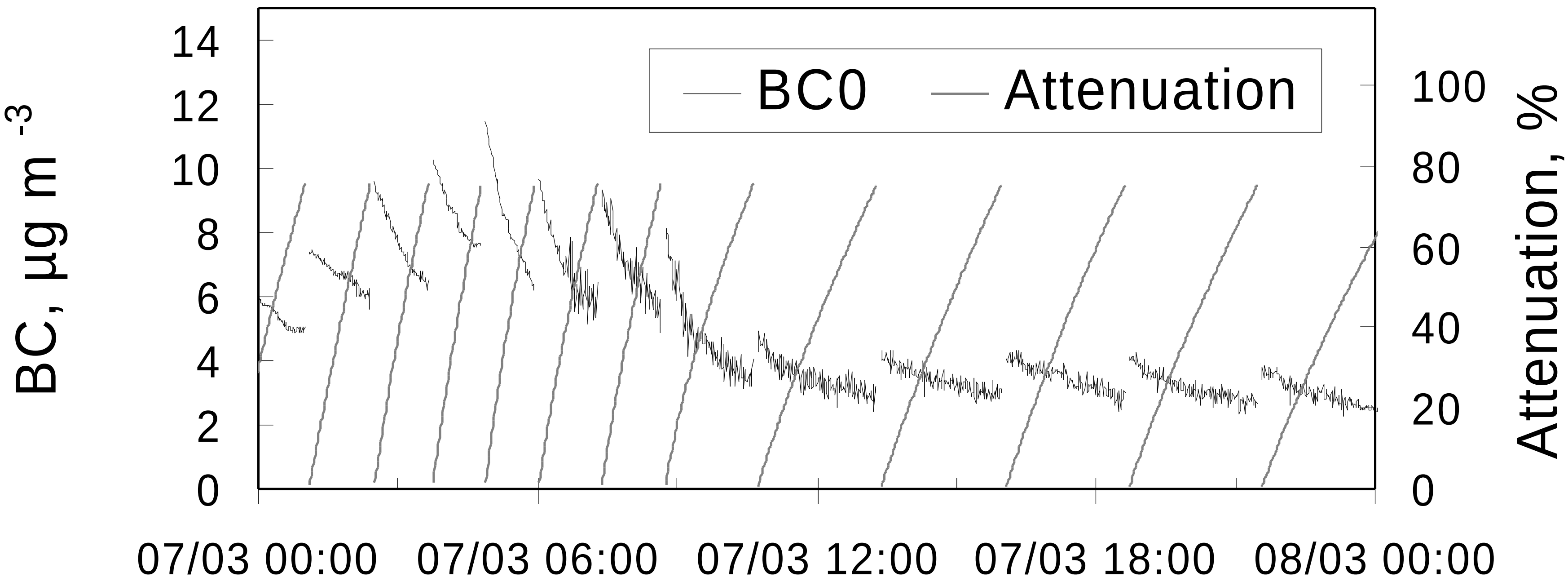
Motivation for the work



Algorithm development 1 / 4

Aethalometer calculates BC concentration (µg m^{-3}) from

$$BC = \frac{\sigma_{abs}}{\alpha_{abs}} = \frac{1}{\alpha_{abs}} \frac{A}{Q} \frac{\Delta ATN}{\Delta t}$$

σ_{abs} = absorption coefficient (m^{-1})
α_{abs} = mass absorption efficiency (m^2 g^{-1}) - not discussed here
A = spot area (cm^2)
Q = flow rate (LPM)
ΔATN = change of attenuation in time Δt

However:
It is well known, that the relationship between *ATN* change and BC concentration is not linear (e.g., Weingartner *et al*., 2003; Arnott *et al*., 2005)

Algorithm development 4 / 4

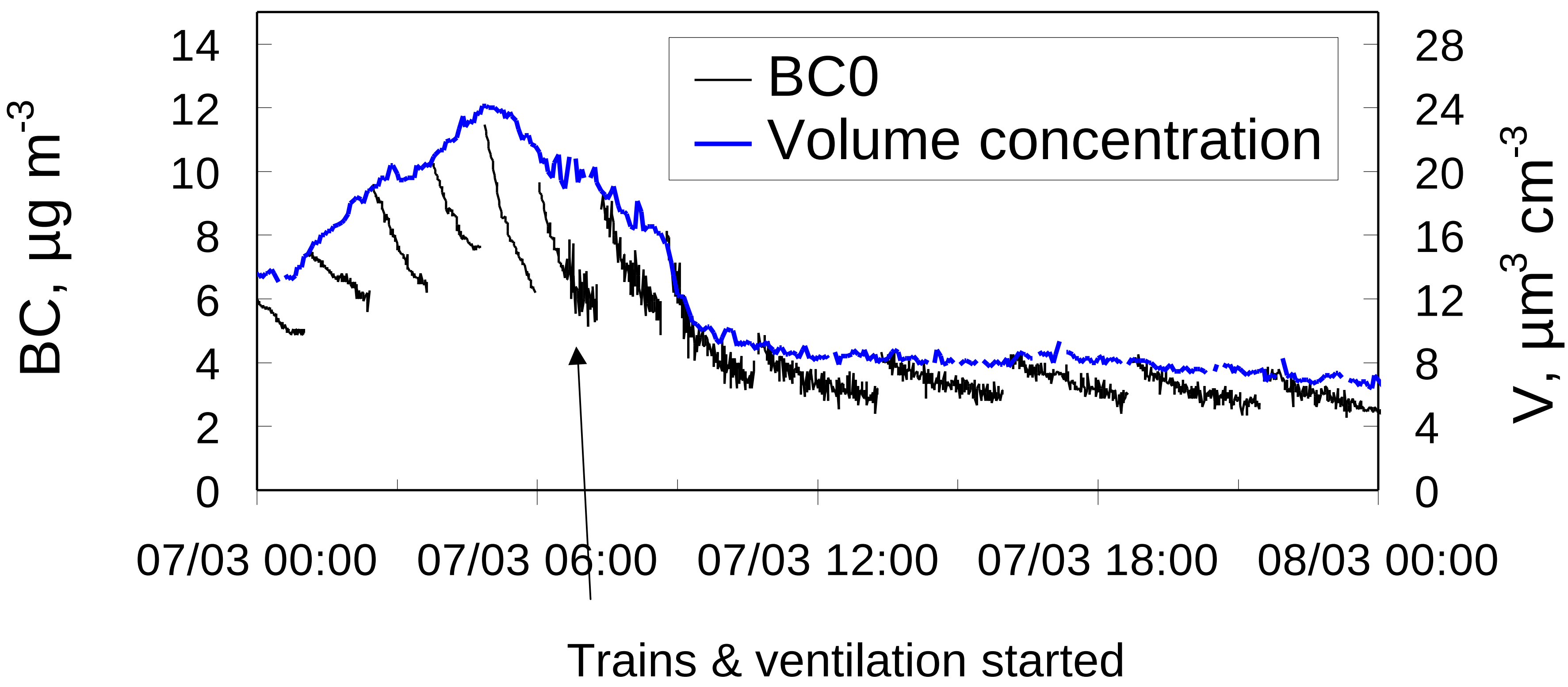
After the filter spot has been changed the first *ATN* ~ 0 so

$$BC_{CORRECTED}(t_{i,last}) = BC_{NON\text{-}CORRECTED}(t_{i+1,first})$$

and we can solve

$$k_i = \frac{1}{ATN(t_{i,last})}\left(\frac{BC_{NON-CORRECTED}(t_{i+1,first})}{BC_{NON-CORRECTED}(t_{i,last})} - 1\right)$$

k_i is then used for correcting all data obtained for filter spot *i*


BC, µg m-3
14
12
10
8
6
4
2
0
BC0
Volume concentration
28
24
20
16
12
8
4
0
V, µm3 cm-3
07/03 00:00
07/03 06:00
07/03 12:00
07/03 18:00
08/03 00:00
Trains & ventilation started

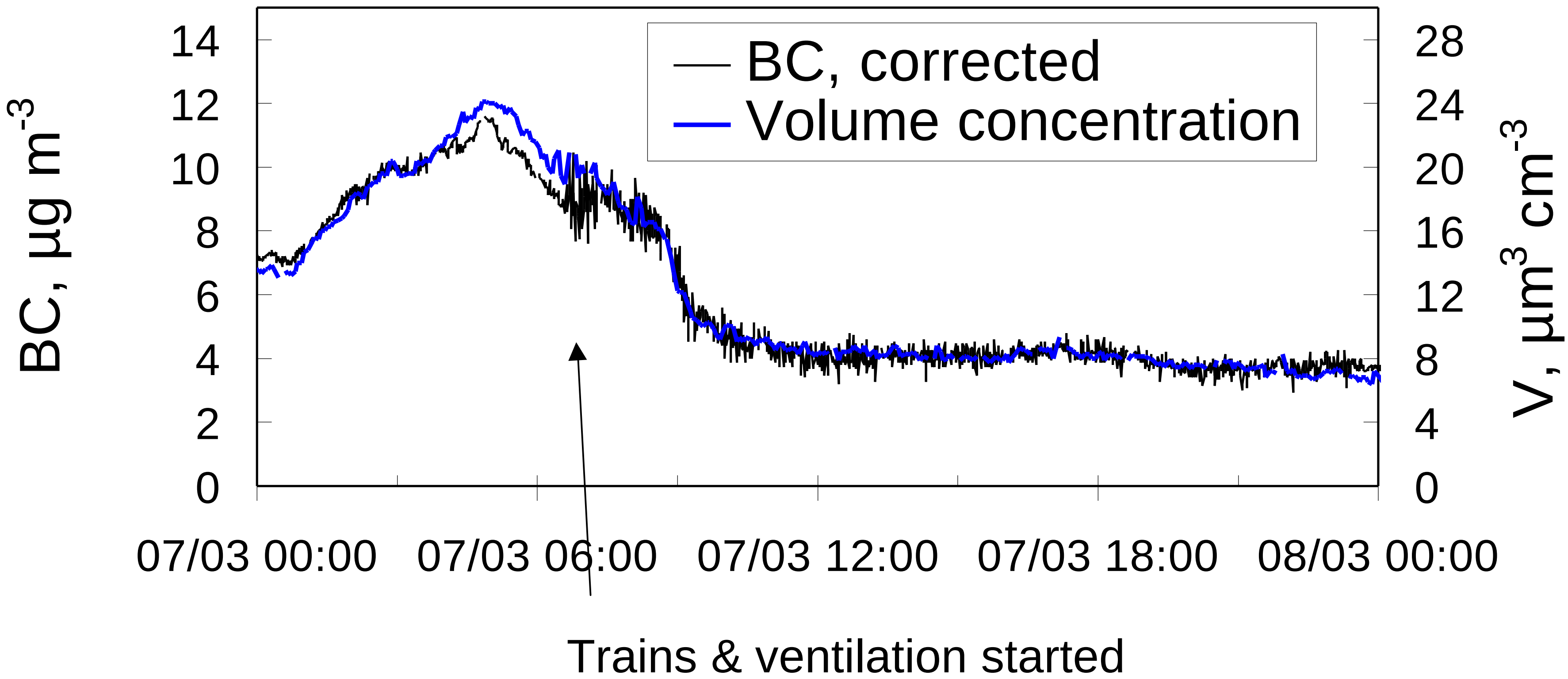

BC, corrected
Volume concentration
BC, µg m-3
V, µm3 cm-3
0
2
4
6
8
10
12
14
0
4
8
12
16
20
24
28
07/03 00:00
07/03 06:00
07/03 12:00
07/03 18:00
08/03 00:00
Trains & ventilation started

Table 1. Linear least squares slope of hourly BC vs SUNSET EC at the South Bronx.

Hourly Aethalometer BC is highly correlated with Sunset EC with $R^2 > 0.7$. However, from April to October BC is biased approx. 30% higher than EC whereas, from November to March BC is equal or lower than EC.

BC vs EC	slope	R2
Jul-05	1.3	0.9
Aug-05	1.2	0.86
Sep-05	1.2	0.86
Oct-05	1.19	0.7
Nov-05	1.02	0.78
Dec-05	0.82	0.78
Jan-06	0.98	0.81
Feb-06	1.05	0.88
Mar-06	1.03	0.83
Apr-06	1.4	0.76
May-06	1.31	0.85
Jun-06	1.31	0.85
Jul-06	1.39	0.85

Source: Oliver Rattigan, NY-DEC

PERGAMON

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Absorption of light by soot particles: determination of the absorption coefficient by means of aethalometers

E. Weingartner[a,*], H. Saathoff[b], M. Schnaiter[b], N. Streit[a], B. Bitnar[c], U. Baltensperger[a]

[a] *Laboratory of Atmospheric Chemistry, Paul Scherrer Institut, Villigen CH-5232, Switzerland*
[b] *Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, Villigen CH-5232, Switzerland*
[c] *Institute of Meteorology and Climate Research, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany*

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Abstract

During a soot aerosol measurement campaign the response of two different aethalometers (AE10 with white light and AE30 with multiwavelength capability) to several types of soot was investigated. Diesel soot, spark-generated carbon particles, and mixtures of these soot particles with ammonium sulfate and oxidation products of α-pinene were used in this evaluation. The determination of the particles light absorption coefficient (b_{abs}) with the AE10 aethalometer is a difficult task because of an ill-defined spectral sensitivity of this instrument. Provided that the proper numerical corrections are performed, the AE30 instrument allows for the measurement of b_{abs} over a wide spectral range ($\lambda = 450$–950 nm). During all experiments it was found that with increasing filter load the optical path in the aethalometer filter decreased. As a result, an increased underestimation of the measured aethalometer signals (b_{abs} or black carbon mass concentrations) occurs with increasing filter loads. This effect, which is attributed to a "shadowing" of the particles in the fiber matrix, is very pronounced for "pure" soot particles while almost negligible for aged atmospheric aerosols. An empirical correction for this bias is presented and requires information on the light scattering behavior (i.e. light scattering coefficient) of the sampled particles. Without this additional information, the applicability of the instruments is limited. Comparison with a reference method shows that multiple scattering in the nearly unloaded fiber filter is responsible for enhanced light absorption by a factor of about 2.14.

Keywords: Absorption coefficient; Black carbon; Light attenuation; Aethalometer calibration; Multiple scattering; Single scattering albedo

* Corresponding author. Tel.: +41-56-310-2405; fax: +41-56-310-4525.
E-mail address: ernest.weingartner@psi.ch (E. Weingartner).

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Towards Aerosol Light-Absorption Measurements with a 7-Wavelength Aethalometer: Evaluation with a Photoacoustic Instrument and 3-Wavelength Nephelometer

W. Patrick Arnott,[1] Khadeejeh Hamasha,[1] Hans Moosmüller,[1] Patrick J. Sheridan,[2] and John A. Ogren[2]
[1]*Desert Research Institute, Reno, Nevada, USA*
[2]*NOAA Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado, USA*

Two extreme cases of aerosol optics from the Reno Aerosol Optics Experiment are used to develop a model-based calibration scheme for the 7-wavelength aethalometer. The cases include those of very white and very dark aerosol samples. The former allows for an assessment of the scattering offset associated with this filter-based method, with the wavelength-dependent scattering measured from a 3-wavelength nephelometer, and interpolated and extrapolated to the 7 wavelengths of the aethalometer. A photoacoustic instrument operating at 532 nm is used to evaluate the filter loading effect caused by aerosol light absorption. Multiple scattering theory is used to analytically obtain a filter-loading correction function. This theory shows that the exponential behavior of light absorption in the strong multiple scattering limit scales as the square root of the total absorption optical depth rather than linearly with optical depth as is commonly assumed with Beer's law. The multiple scattering model also provides a theoretical justification for subtracting a small fraction of aerosol light scattering away from measured apparent light absorption by the filter method. The model is tested against ambient measurements and is found to require coefficients that are situation specific. Several hypotheses are given for this specificity, and suggested methods for reducing it are discussed. Specific findings are as follows. Simultaneous aerosol light-scattering measurements are required for accurate interpretation of aethalometer data for high aerosol single-scattering albedo. Instantaneous errors of up to ±50% are possible for uncorrected data, depending on filter loading. The aethalometer overpredicts black carbon (BC) concentration on a fresh filter and underpredicts BC on a loaded filter. BC and photoacoustic light absorption can be tightly correlated if the data are averaged over the full range of filter loadings and the aerosol source is constant. Theory predicts that the Aethalometer response may be sensitive to filter face velocity, and hence flow rate, to the extent that particle penetration depth depends on face velocity.

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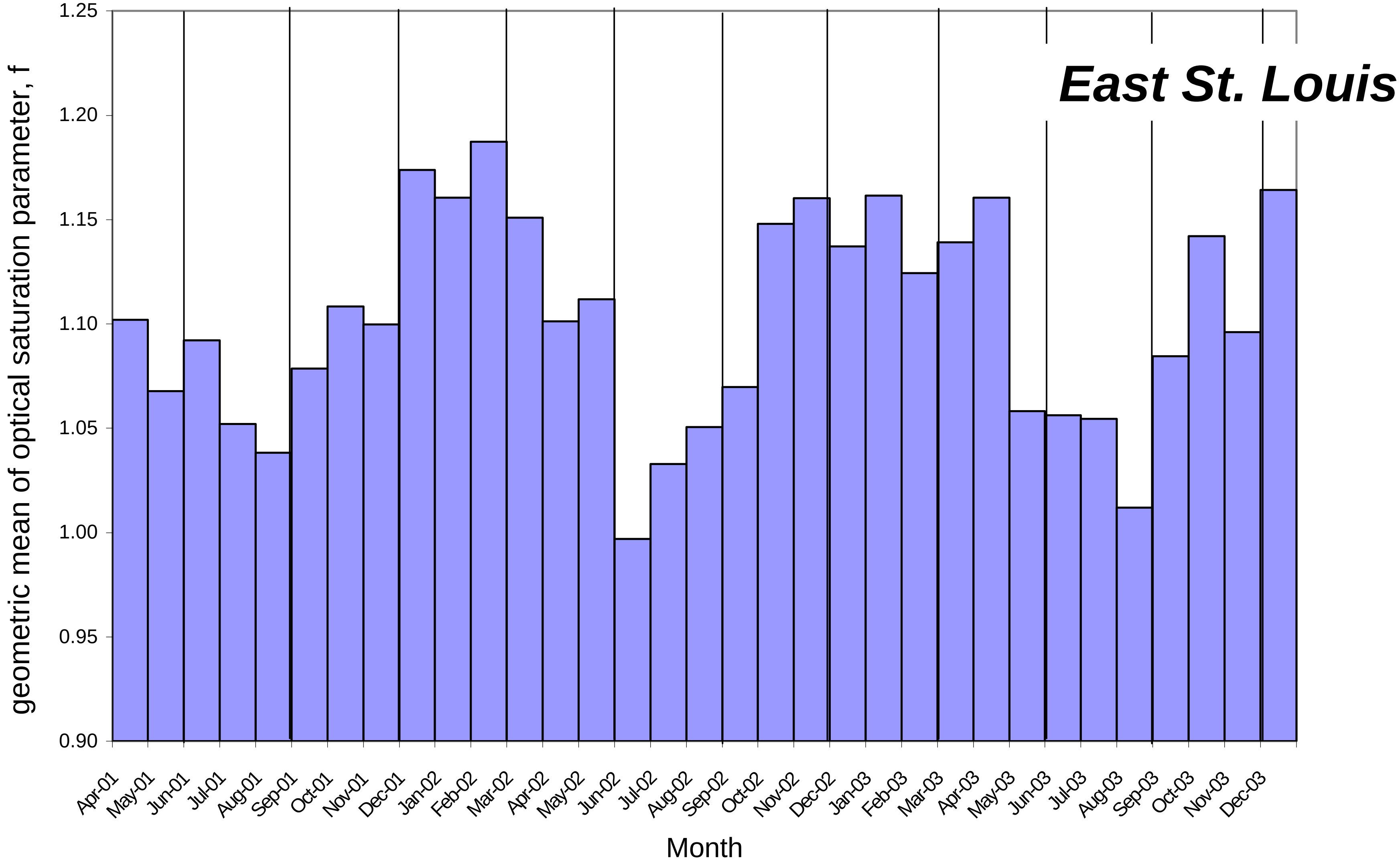
Address correspondence to W. Patrick Arnott, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA. E-mail: pat@dri.edu

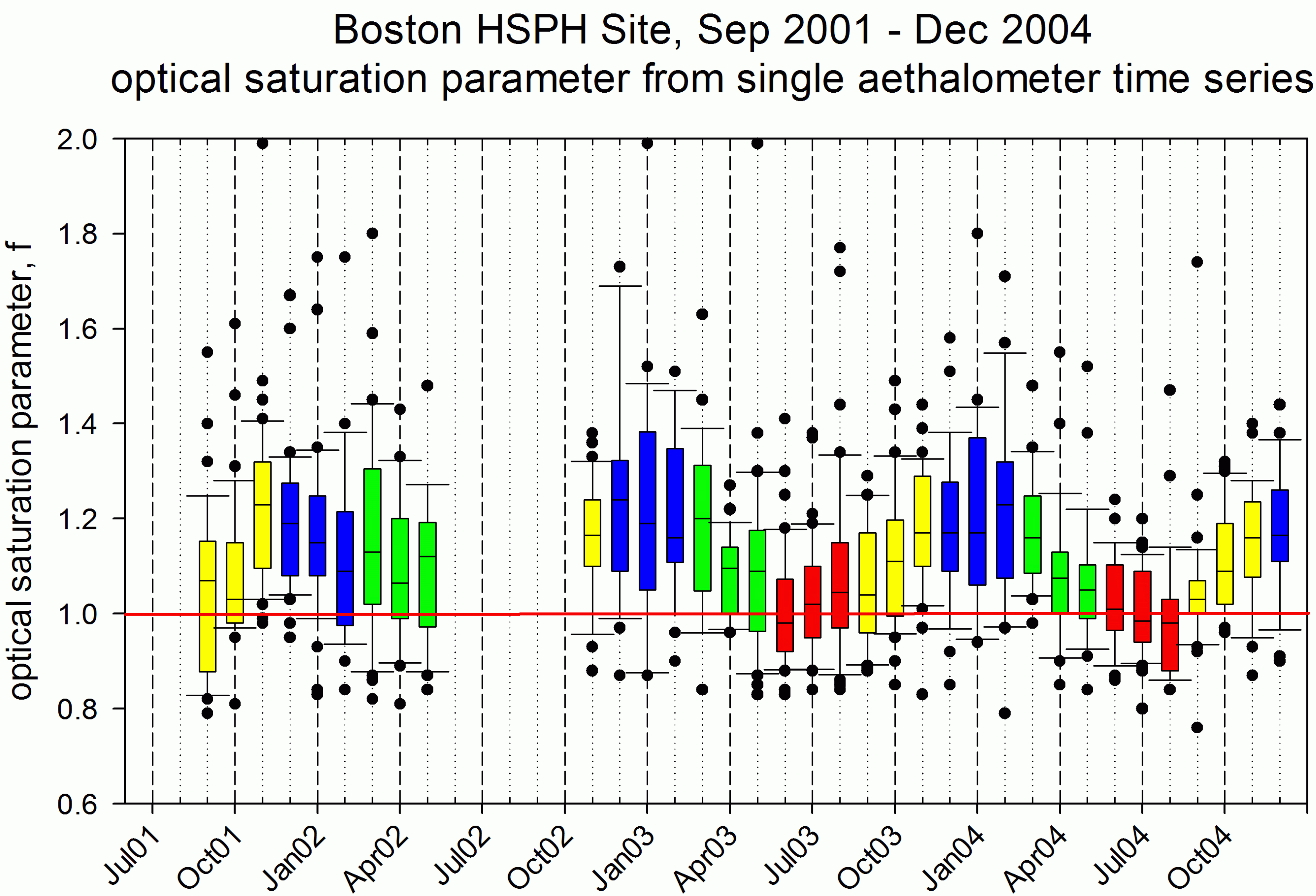
INTRODUCTION

Aerosol light-absorption measurements are important for health, climate, and visibility applications (Andreae 2001). The wavelength dependence of aerosol light absorption, nominally inverse with wavelength for soot and visible wavelengths, plays a significant role in obtaining soot loadings from remote sensing measurements (Sato et al. 2003). Soot deposition decreases snow albedo and tends towards favoring snow and ice melt (Warren and Wiscombe 1980; Grenfell et al. 1994; Hansen and Nazarenko 2004). The topic of soot in snow has its optical analogy in the contemporary instruments used to measure aerosol light absorption by filter methods. Aerosol light absorption is enhanced by roughly a factor of 2 when particles are deposited on quartz fiber filters in these instruments and by a factor of 1.4 or more on snow. The enhancement increases the signal-to-noise ratio for aerosol light-absorption measurements, although it does so at the cost of requiring an empirical calibration.

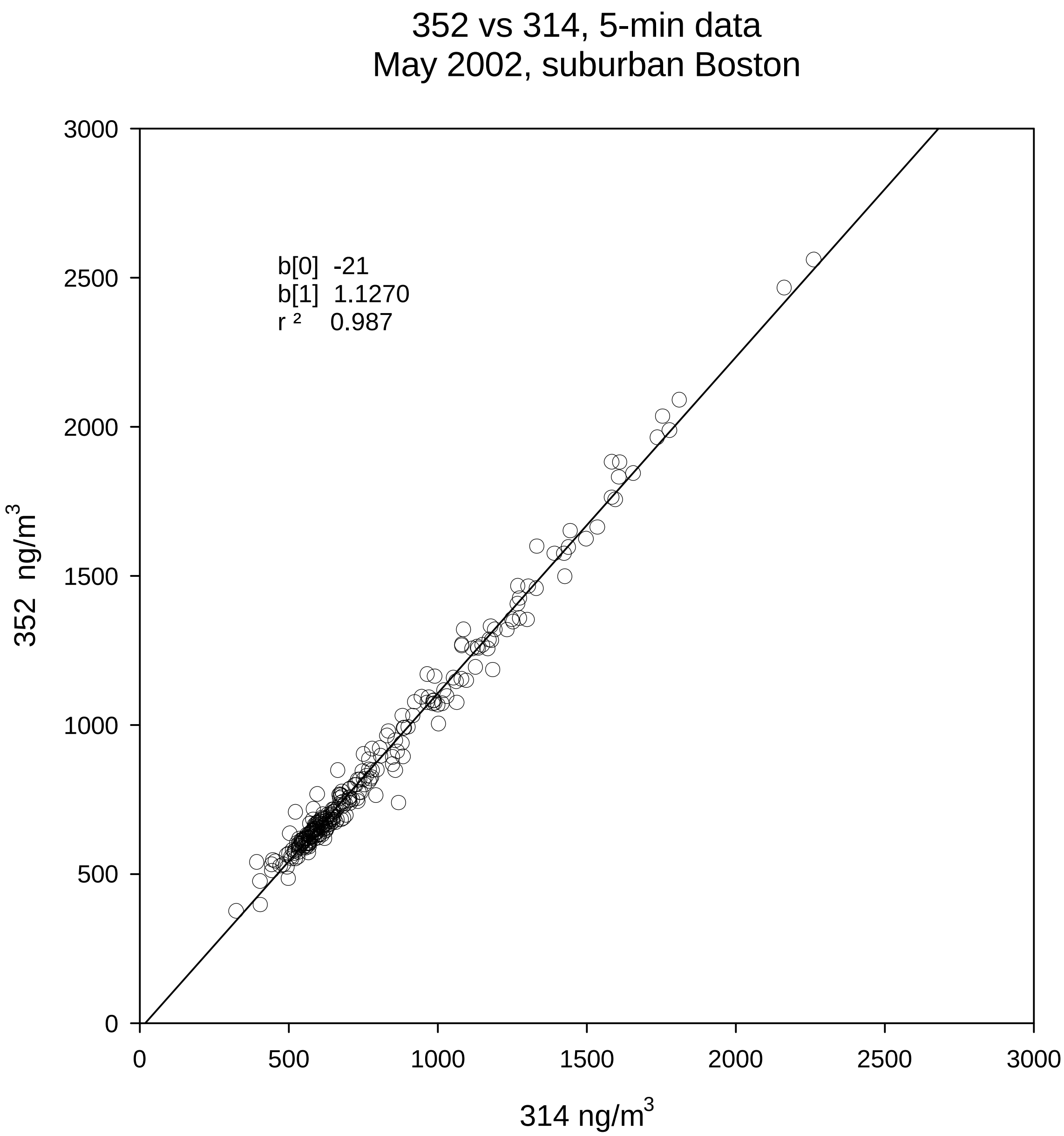
The Reno Aerosol Optics Experiment was conducted in June 2002 with the main purpose of evaluating the accuracy of aerosol light-absorption measurements. Most of the measurements were accomplished using well-characterized external mixtures of laboratory-generated ammonium sulfate and kerosene soot aerosol. A primary standard for measurement accuracy was provided by the difference of extinction and scattering measurements. Photoacoustic measurements of aerosol light absorption were in concert with the other primary standard measurement, extinction minus scattering. Details and summary results are described in Sheridan et al. (2005).

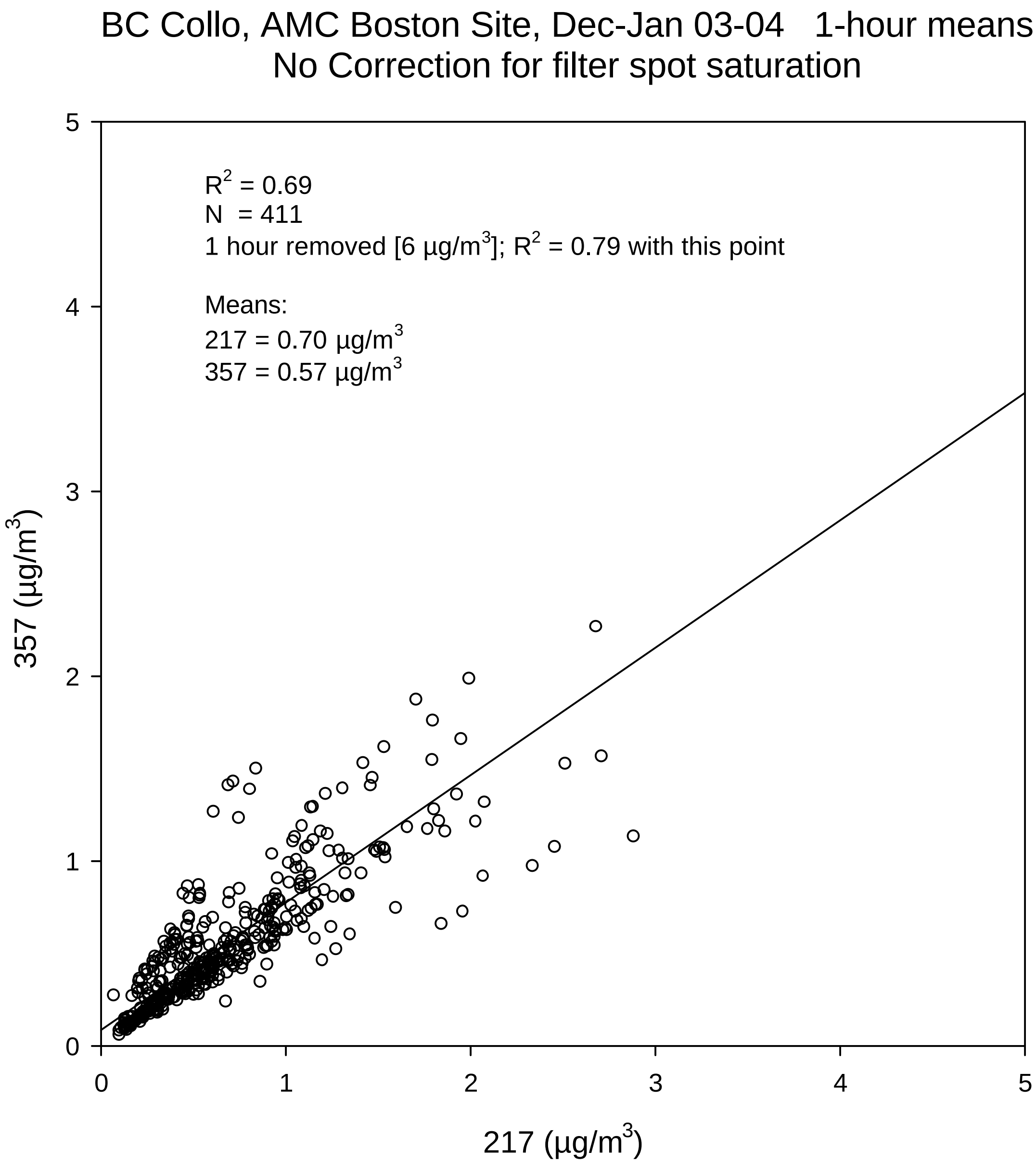
Seasonal Behavior in Soot Aerosol "Age" as Seen from the Extent of Aethalometer Optical Saturation



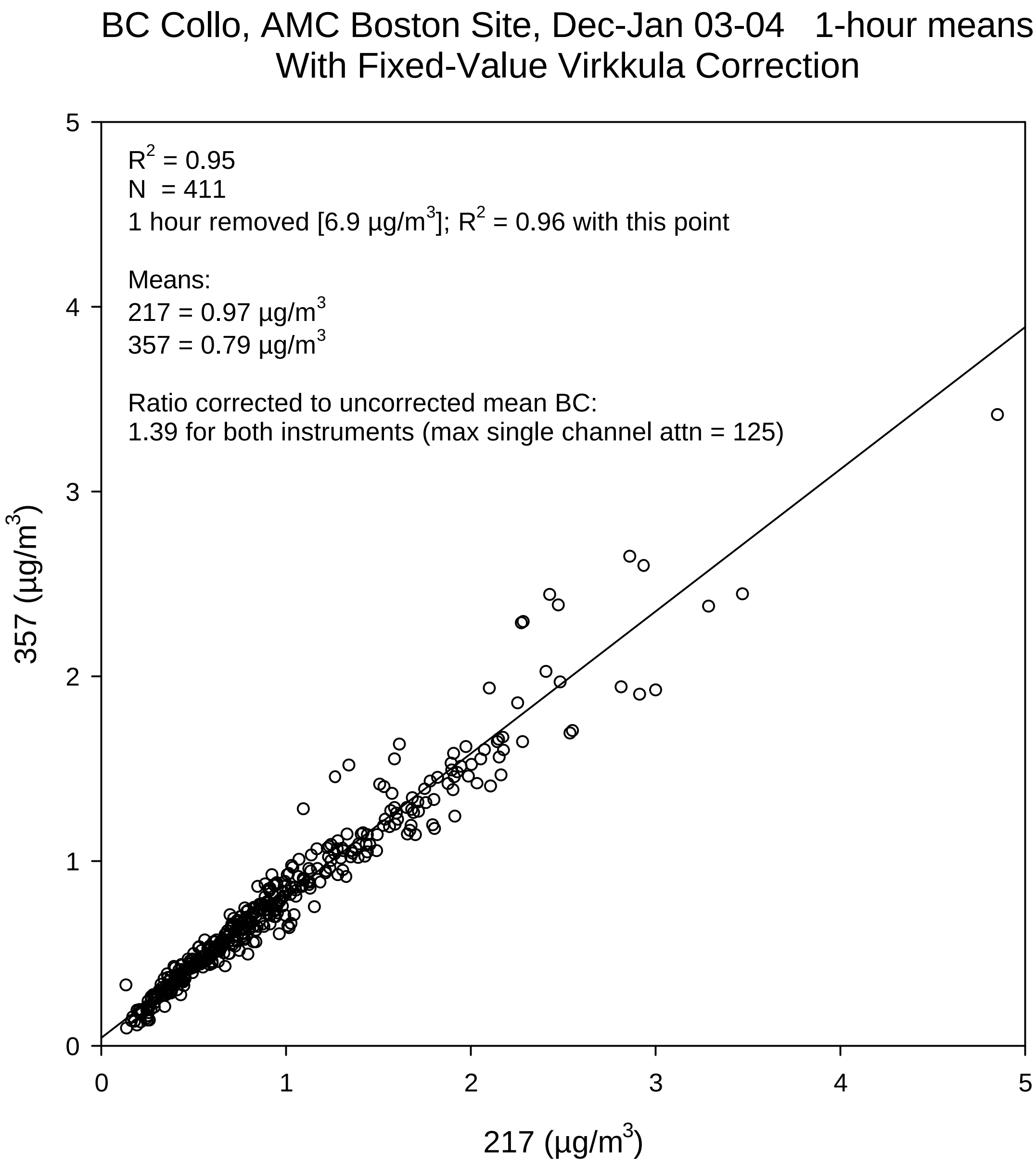


Boston HSPH Site, Sep 2001 - Dec 2004
optical saturation parameter from single aethalometer time series
optical saturation parameter, f
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Jul01
Oct01
Jan02
Apr02
Jul02
Oct02
Jan03
Apr03
Jul03
Oct03
Jan04
Apr04
Jul04
Oct04


352 vs 314, 5-min data
May 2002, suburban Boston
b[0] -21
b[1] 1.1270
r ² 0.987
352 ng/m3
314 ng/m3
0
500
1000
1500
2000
2500
3000



BC Collo, AMC Boston Site, Dec-Jan 03-04 1-hour means
No Correction for filter spot saturation
R2 = 0.69
N = 411
1 hour removed [6 µg/m3]; R2 = 0.79 with this point
Means:
217 = 0.70 µg/m3
357 = 0.57 µg/m3
357 (µg/m3)
217 (µg/m3)
0
1
2
3
4
5


BC Collo, AMC Boston Site, Dec-Jan 03-04 1-hour means
With Fixed-Value Virkkula Correction
R2 = 0.95
N = 411
1 hour removed [6.9 µg/m3]; R2 = 0.96 with this point
Means:
217 = 0.97 µg/m3
357 = 0.79 µg/m3
Ratio corrected to uncorrected mean BC:
1.39 for both instruments (max single channel attn = 125)
357 (µg/m3)
217 (µg/m3)
0
1
2
3
4
5

How much can these Aethalometer measurement matrix effects be reduced while keeping the method reasonably simple?

1. Collocated instruments should agree well on a 1-hour or less interval

2. Completely eliminated if the aerosol is fresh and mostly black

3a. Partially eliminated if the aerosol has lots of white-ish particles (BC is over-estimated from enhanced scattering)

3b. Drying the sample when ambient dewpoint is high should reduce the over-estimate.

For additional related information on this topic, see:
"Refining the interpretation of multi-wavelength Aethalometer data"
Turner and Roberts Poster, this meeting

The near future:

- Include the correction code into current production Aethalometers
- Embed the correction code into the next-generation Aethalometers (spring/summer 2007)
- Revise the “Turner/WUAQL Aeth Data Masher” to include correction
- Release a modified version of firmware for present generation of Aethalometers (984 software) with this correction
- ? Provide a drier option to minimize summer water-related effects
- Provide a thermally stable short-term measurement fix (5-min noise) ==> active optical feedback compensation