

1 **Development of a New Correction Algorithm Applicable to any Filter-Based Absorption**  
2 **Photometer**

3 Hanyang Li<sup>1</sup>, Gavin R. McMeeking<sup>2</sup>, and Andrew A. May<sup>1</sup>

4 1 The Ohio State University Department of Civil, Environmental, and Geodetic Engineering,  
5 Columbus, Ohio, USA

6 2 Handix Scientific, LLC, Boulder, Colorado, USA

7 *Corresponding author: Andrew A. May ([may.561@osu.edu](mailto:may.561@osu.edu)).*

8 **Abstract**

9 Among the various measurement approaches to quantify light absorption coefficient ( $B_{\text{abs}}$ ), filter-  
10 based absorption photometers are dominant in monitoring networks around the globe. Numerous  
11 correction algorithms have been introduced to minimize the artifacts due to the presence of the  
12 filter in these instruments. However, from our recent studies conducted during the Fire Influence  
13 on Regional and Global Environments Experiment (FIREX) laboratory campaign, corrected filter-  
14 based  $B_{\text{abs}}$  remains biased high by roughly a factor of 2.5 when compared to a reference value  
15 using a photoacoustic instrument for biomass burning emissions. Similar over-estimations of  $B_{\text{abs}}$   
16 from filter-based instruments exist when implementing the algorithms on six months of ambient  
17 data from the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM)  
18 Southern Great Plains (SGP) user facility from 2013 (factor of roughly 3). In both datasets, we  
19 observed an apparent dependency on single scattering albedo (SSA) and absorption Ångström  
20 exponent (AAE) in the agreement between  $B_{\text{abs}}$  based on existing correction factors and the  
21 reference  $B_{\text{abs}}$ . Consequently, we developed a new correction approach that is applicable to any  
22 filter-based absorption photometer that includes light transmission from the filter-based instrument  
23 as well as the derived AAE and SSA. For the FIREX and SGP datasets, our algorithm results in  
24 good agreement between all corrected filter-based  $B_{\text{abs}}$  values from different filter-based  
25 instruments and the reference (slopes  $\approx 1$  and  $R^2 \approx 0.98$  for biomass burning aerosols and slopes  
26  $\approx 1.05$  and  $R^2 \approx 0.65$  for ambient aerosols). Moreover, for both the corrected  $B_{\text{abs}}$  and the derived  
27 optical properties (SSA and AAE), our new algorithms work better or at least as well as the two  
28 common PSAP-based correction algorithms. The uncertainty of the new correction algorithm is  
29 estimated to be  $\sim 10\%$ , considering the measurement uncertainties of the operated instruments.  
30 Therefore, our correction algorithm is applicable to any filter-based absorption photometer and  
31 has the potential to “standardize” reported results across any filter-based instrument.

32 **1. Introduction**

33 Light-absorbing atmospheric aerosols directly affect the Earth’s energy budget by absorbing solar  
34 radiation, leading to a warming effect when they are suspended in the atmosphere and to the  
35 melting of snow and ice following deposition (Bond and Bergstrom, 2006; Boucher, 2015; Horvath,  
36 1993). For decades, scientists have conducted field experiments around the globe to investigate  
37 how absorbing aerosols influence the atmospheric radiative balance and interact with clouds (e.g.,  
38 Andrews et al. (2011); Cappa et al. (2016); Lack et al. (2008b); Rajesh and Ramachandran (2018);  
39 Schwarz et al. (2008)). These experiments may be performed at fixed stations (e.g., observation  
40 sites maintained by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM)  
41 program or the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring

42 Division (GMD)) or on mobile platforms (e.g., car trailer, aircraft, and ship), typically involving  
43 the measurements of aerosol chemical, physical, and optical properties. Crucial to the  
44 quantification of the radiative forcing of absorbing aerosols are measurements of the absorption  
45 coefficient ( $B_{\text{abs}}$ ). For example, long-term monitoring of  $B_{\text{abs}}$  provides essential data to evaluate  
46 chemistry-climate model simulations (e.g., Chen et al. (2019); Vignati et al. (2010)), while  
47 intensive measurements of  $B_{\text{abs}}$  during short-term field campaigns allow for the investigation of  
48 optical properties that govern features of aerosol forcing (e.g., McMeeking et al. (2014); Olson et  
49 al. (2015)).

50 A variety of instruments have been used to measure  $B_{\text{abs}}$ , which generally classified into two large  
51 categories: filter-based techniques and photoacoustic techniques (Lack et al., 2014; Moosmüller  
52 et al., 2009). The major difference between the two categories of technique is that  $B_{\text{abs}}$  is measured  
53 after the aerosols are deposited on the filter media in the filter-based instruments, while the aerosols  
54 are characterized within an air stream in the photoacoustic instruments. Compared to the filter-  
55 based instruments, the photoacoustic instruments have the advantage of avoiding potential artifacts  
56 due to the contact of aerosols with filters; therefore, they are often used as the reference instruments  
57 in inter-comparison studies of aerosol absorption (e.g., Arnott et al. (2005); Davies et al. (2019);  
58 Jiang et al. (2018); Li et al. (2019); Schmid et al. (2006); Sheridan et al. (2005)).

59 Filter-based absorption photometers have been widely used at observational sites around the world  
60 due to their ease of operation and relatively low cost. Numerous instruments can be classified as  
61 filter-based absorption photometers including the Radiance Research Particle Soot Absorption  
62 Photometer (PSAP), the NOAA Continuous Light Absorption Photometer (CLAP), the Brechtel  
63 Manufacturing Tricolor Absorption Photometer (TAP), the Magee Scientific Aethalometer  
64 (AETH), and the Thermo Scientific Multi-Angle Absorption Photometer (MAAP). Operationally,  
65 all of these instruments are similar in that aerosols are deposited onto a filter and the reduction in  
66 the transmission ( $Tr$ ) of light by the particles (sometimes called attenuation ( $ATN$ )) is used to infer  
67  $B_{\text{abs}}$ . Where the instruments may differ is that some are multi-wavelength (multi- $\lambda$ ) instruments  
68 (e.g., 3 $\lambda$ -PSAP, CLAP, TAP, 7 $\lambda$ -AETH models), while others are not (e.g., 1 $\lambda$ -PSAP, other AETH  
69 models, MAAP).

70 One challenge with filter-based absorption photometers is that biases can arise due to the presence  
71 of the filter. For example, light scattering by particles loaded onto the filter or by the filter itself  
72 may affect the transmission of light (e.g., (Arnott et al., 2005; Bond et al., 1999)); non-absorbing  
73 material may result in absorption enhancement (e.g., (Cappa et al., 2008)); or organic vapors  
74 adsorbed to the filter may itself absorb light (e.g., (Subramanian et al., 2007)). Consequently,  
75 various correction algorithms exist to minimize these biases, but they are often specific only to  
76 certain instruments. For example, some are applicable to the PSAP, CLAP, and TAP (e.g., (Bond  
77 et al., 1999; Müller et al., 2014; Ogren, 2010; Virkkula, 2010; Virkkula et al., 2005)), while others  
78 are applicable to the AETH (e.g., (Arnott et al., 2005; Collaud Coen et al., 2010; Drinovec et al.,  
79 2017; Kirchstetter and Novakov, 2007; Schmid et al., 2006; Virkkula et al., 2007, 2015;  
80 Weingartner et al., 2003)).

81 Although the equations associated with these existing correction algorithms are different, they  
82 share some commonalities. For example, the filter-based absorption photometers are assessed  
83 using laboratory (e.g., ammonium sulfate, fullerene soot) or ambient aerosols during experiments  
84 which include reference measurements of  $B_{\text{abs}}$ . These reference measurements often include either  
85 direct photoacoustic  $B_{\text{abs}}$  or inferred  $B_{\text{abs}}$  as the difference between the extinction coefficient ( $B_{\text{ext}}$ )

86 and the scattering coefficient ( $B_{\text{scat}}$ ). Correction equations are developed by comparing data  
87 between the filter-based instrument and the reference instrument, where the equations often  
88 contain one term that accounts for filter loading effects and another that accounts for multiple-  
89 scattering effects. Consequently, the correction equations frequently incorporate both  $\text{Tr}$  and either  
90  $B_{\text{scat}}$  or the single-scattering albedo (SSA) to account for these effects. However, even when the  
91 correction algorithms are applied, potential issues can remain such as:

- 92 1. Corrected filter-based  $B_{\text{abs}}$  may remain biased high relative to a reference value of  $B_{\text{abs}}$  (e.g.,  
93 (Arnott et al., 2003; Davies et al., 2019; Lack et al., 2008a; Li et al., 2019; Müller et al., 2011a)).
- 94 2. Comparisons between the reference instrument and  $B_{\text{abs}}$  corrected by different algorithms can  
95 yield variable agreement (e.g., (Collaud Coen et al., 2010; Davies et al., 2019; Saturno et al.,  
96 2017)).
- 97 3. Corrected  $B_{\text{abs}}$  from different filter-based absorption photometers may not agree (e.g., (Davies  
98 et al., 2019; Müller et al., 2011a)).
- 99 4. Derived products (such as absorption Ångström exponents (AAE)) may differ based on the  
100 implemented correction algorithm (e.g., (Backman et al., 2014; Davies et al., 2019)).
- 101 5. The agreement between measurements of  $B_{\text{abs}}$  and estimates of  $B_{\text{abs}}$  by chemistry-climate  
102 models may vary based on the implemented correction algorithm (e.g., (Alvarado et al., 2016)).

103 The first three issues in this list may arise due to differences in aerosol optical properties between  
104 those used in deriving the correction equation and those associated with a given aerosol sample,  
105 and these issues can propagate through to the fourth issue. The final issue is arguably most  
106 important because evaluation of chemistry-climate models may be severely affected by the  
107 differences between different correction algorithms, which may inhibit the modeling community  
108 from providing accurate projections of future temperature and precipitation response.

109 In this work, we seek to address some of these issues. First, we evaluate the CLAP, TAP, and  
110 PSAP using two common PSAP-based correction algorithms, namely Bond et al. (1999) as  
111 updated by Ogren (2010) and Virkkula et al. (2005) as updated by Virkkula (2010). For brevity,  
112 we refer to these corrections as “B1999” and “V2005” for Bond et al. (1999) and Virkkula et al.  
113 (2005), respectively, incorporating their respective updates. In addition, we propose new  
114 correction algorithms that are applicable to any filter-based absorption photometer (e.g., CLAP,  
115 TAP, PSAP, and AETH) across multiple wavelengths by combining observed filter-based  $B_{\text{abs}}$   
116 with  $B_{\text{scat}}$  (e.g., from a co-located nephelometer (NEPH)) and reference  $B_{\text{abs}}$  (e.g., from a co-  
117 located photoacoustic instrument). However, in reality (e.g., at long-term observatories), reference  
118 values of  $B_{\text{abs}}$  are rare, and in some cases, complementary  $B_{\text{scat}}$  measurements may not exist;  
119 consequently, we also provide methods to correct filter-based  $B_{\text{abs}}$  data in these scenarios. To our  
120 knowledge, this is the first study to simultaneously evaluate B1999 and V2005 corrections on  
121 PSAP “successors” (i.e., CLAP and TAP) and to present a correction algorithm that is broadly  
122 applicable to any filter-based absorption photometer. Regarding the latter, even if our correction  
123 algorithm has its own limitations, its use can nevertheless standardize the reporting of  $B_{\text{abs}}$  in long-  
124 term datasets.

## 125 2. Methodology

126 We developed the general form for our correction algorithms using CLAP and TAP measurements  
127 collected from biomass burning (65 fires in total) during the Fire Influence on Regional to Global  
128 Environments Experiment (FIREX) laboratory campaign in 2016. By using biomass burning

129 emissions, we considered a dataset spanning a broader range of aerosol optical properties (SSA at  
130 652 nm: 0.14-0.98; AAE: 1.25-4.73) than has traditionally been used in developing these  
131 correction algorithms. We then conducted further evaluation and validation of the model using  
132 ambient data, specifically using CLAP measurements from the DOE ARM Southern Great Plains  
133 (SGP) user facility in Lamont, OK, USA (02/01/13 to 07/09/13). Our algorithms were then  
134 extended to the AETH data from the FIREX laboratory campaign and the PSAP data collected at  
135 the SGP site to verify the generalizability of the algorithms.

## 136 2.1. The FIREX campaign

### 137 2.1.1. Experimental setup

138 In October and November of 2016, we participated in the laboratory portion of the FIREX  
139 campaign to investigate the wildfire smoke and their impact on the atmosphere. During the  
140 campaign, over 100 burns took place at the U.S. Forest Service’s combustion facility at the Fire  
141 Sciences Laboratory (FSL). The fuels burned in this study are representative of western US  
142 ecosystems, such as spruce, fir, various pines, and “chaparral” biome (e.g., manzanita, chamise).  
143 (See Koss et al. (2018) and Selimovic et al. (2018) for more details).

144 A typical burn lasted for 1-3 hours depending on the smoke sampling strategies (e.g., stack burns  
145 versus room burns). During each burn, one or multiple “snapshots” of smoke (typical  $B_{\text{abs}}$  at 652  
146 nm ranged from 100 to 1200  $\text{Mm}^{-1}$ ) were transferred from the combustion room at FSL into a  
147 mixing chamber (210 L) through a long transfer duct (30 m in length, 8” in diameter). The smoke  
148 was then diluted by filter air (~230 LPM) in the chamber. Once the concentration in the chamber  
149 was stable (detected by the Photoacoustic Extinctionmeter (PAX) which was operated continuously  
150 through all fires), the smoke was passed to a suite of instruments to obtain aerosol and gas phase  
151 parameters. This chamber also served as an intermediate between the transfer duct and the  
152 instrumentation to minimize potential biases that arose due to different sample flow rates and  
153 sample locations of the instruments. A more detailed description of our experiments can be found  
154 in Li et al. (2019).

### 155 2.1.2. Measurements of aerosol optical properties

156 During the campaign, five instruments provided measurements of  $B_{\text{abs}}$  (CLAP, NOAA GMD; TAP,  
157 Brechtel Manufacturing Inc. (BMI); Aethalometer (Model AETH-31), Magee Scientific; and two  
158 PAXs (Model PAX-870 and PAX-405), Droplet Measurement Technologies) and two instruments  
159 provided measurements of  $B_{\text{scat}}$  (PAX-870 and PAX-405). The instruments included in the present  
160 work are summarized in Table 1.

161 Both CLAP and TAP provide  $B_{\text{abs}}$  measurements of the particles deposited on a filter, similar to  
162 PSAP. Different from PSAP, there are multiple filter spots (8 sample spots and 2 reference spots)  
163 cycling of one filter in CLAP and TAP, enabling the instruments to run continuously through two  
164 or three burns without changing filter. In the CLAP and TAP, sample illumination is provided by  
165 LEDs operated at three wavelengths (467, 528, and 652 nm). Here, we apply both B1999 and  
166 V2005 to CLAP and TAP data, similar to previous work (e.g., (Backman et al., 2014; Davies et  
167 al., 2019)).

168 The key differences between the CLAP and TAP during the FIREX campaign include:

- 169 1. The spot change of the CLAP was manually performed when  $T_r$  reached approximately 0.5  
170 (or ATN decreased to  $\sim 69$ ), while the TAP advanced to a new spot automatically with a  $T_r$   
171 threshold set to be 0.5.
- 172 2. The spot area, flow rate, and LED-detected wavelengths differed slightly (Table 1).
- 173 3. The CLAP recorded  $B_{\text{abs}}$  every one minute, while the TAP recorded  $B_{\text{abs}}$  every ten seconds. To  
174 enable the following analysis, we compute the 1-minute averages of TAP-derived parameters.
- 175 4. For the first portion of the campaign (the first 17 days of the 45-day campaign), Pallflex E70-  
176 2075S filters were used in the CLAP while Azumi filters (model 371M, Azumi Filter Paper  
177 Co., Japan) were used in the second portion of the campaign (due to a lack of availability of  
178 the Pallflex filters). The TAP was equipped exclusively with the Azumi filters throughout the  
179 campaign. We apply the filter correction recommended in Ogren et al. (2017) to the CLAP and  
180 convert from Pallflex to Azumi filters.
- 181 5. BMI substantially re-engineered the CLAP in their development of the TAP.

182 These differences resulted in variable agreement between the CLAP and TAP during FIREX;  
183 however, the two instruments did largely agree within experimental uncertainty (e.g., see Fig. S8  
184 and Fig. S13 in Li et al. (2019)).

185 A PAX measures  $B_{\text{abs}}$  and  $B_{\text{scat}}$  simultaneously for suspended particles using a modulated diode  
186 laser. We use these photoacoustic absorption measurements as the reference to evaluate the filter-  
187 based  $B_{\text{abs}}$  and develop our correction algorithms. To enable the evaluation of CLAP and TAP  
188 which operate at different wavelengths than the PAXs, we interpolate the measurements of  $B_{\text{abs}}$   
189 and  $B_{\text{scat}}$  to the wavelengths of 467, 528, and 652 nm using the values of AAE and scattering  
190 Ångström exponents (SAE), similar to Backman et al. (2014) and Virkkula et al. (2005).  
191 Theoretically, AAE and SAE fit absorption and scattering as power law functions of wavelength  
192 (Bergstrom et al., 2007).

193 Due to the numerous correction algorithms for the Aethalometer (e.g. (Arnott et al., 2005; Collaud  
194 Coen et al., 2010; Kirchstetter and Novakov, 2007; Saturno et al., 2017; Schmid et al., 2006;  
195 Virkkula et al., 2007; Weingartner et al., 2003)), we do not evaluate these in the present work to  
196 limit the scope. In fact, the majority of our focus is the B1999 and V2005 corrections to TAP and  
197 CLAP. However, we still test the performance of the new algorithms on the AETH to explore its  
198 applicability to that instrument.

## 199 2.2. Measurements of aerosol optical properties at the SGP observatory

200 The ambient data used in this manuscript are the ground-based aerosol data measured at the SGP  
201 observatory from 02/01/13 to 07/09/13 (archived at <https://www.archive.arm.gov/discovery/>). For  
202 evaluation purposes, we randomly select a range of dates during which the observations are valid  
203 (without incorrect, suspect, and missing data) and the PASS is operated after laser (532 nm)  
204 upgrade.

205 At the site, an impactor was used to switch the sampling between two cutoffs (particle diameter  
206  $<10 \mu\text{m}$  (PM10) in the first 30 minutes of each hour and  $<1 \mu\text{m}$  (PM1) in the latter 30 minutes of  
207 each hour). The aerosols exiting from the impactor were dried to RH less than 40% and passed to  
208 a CLAP, a PSAP, and two NEPHs. Moreover, a three-wavelength photoacoustic soot spectrometer  
209 (PASS-3) was operated at the site and measured  $B_{\text{abs}}$  and  $B_{\text{scat}}$  of the aerosols, but these aerosols  
210 did not pass through the impactor (e.g., characterizing total suspended particles (TSP)). Typical  
211  $B_{\text{abs}}$  and  $B_{\text{scat}}$  reported at the site ranged from 0 to  $10 \text{ Mm}^{-1}$  and 0 to  $50 \text{ Mm}^{-1}$  at 550 nm, respectively

212 (e.g., (Sherman et al., 2015)). Although the site is rural (clean background air), long-term transport  
213 aerosols (such as mineral dust, absorbing organic aerosols, and secondary organic aerosols (SOA))  
214 may affect the local aerosol properties (Andrews et al., 2019).

215 We preprocess the SGP data in three steps. First, due to the systematic difference of aerosol sizes  
216 between PASS-derived and filter-based absorption, we only include the PM10 observations,  
217 inherently assuming that any differences in the optical properties of PM10 and TSP are negligible.  
218 Then, we smooth the 1-second data into 10-minute averages. Thirdly, we estimate the detection  
219 limits at each of the three wavelengths in the PASS-3 using the data measured during the  
220 “background zero” periods (Allan, 1966) and discard the observations which are below the  
221 detection limits. With a 10-min-averaging-time, the detection limits ( $3\sigma$ ) for the PASS-3 are 0.78  
222  $\text{Mm}^{-1}$  (405 nm), 2.01  $\text{Mm}^{-1}$  (532 nm), and 0.30  $\text{Mm}^{-1}$  (781 nm). For the filter-based instruments,  
223 the detection limits are based on previous studies (See Table 1). Moreover, we only retain the  
224 observations that satisfy  $B_{\text{abs}}(405 \text{ nm}) > B_{\text{abs}}(532 \text{ nm}) > B_{\text{abs}}(781 \text{ nm})$  (or  $\text{AAE} > 0$ ), similar to  
225 Fischer and Smith (2018). As with the PAX data from the laboratory, we adjust the PASS-derived  
226  $B_{\text{abs}}$  to 467, 528, and 652 nm using the inferred AAE values for each 10-minute average.

### 227 2.3. Calibrations

228 Following Bond et al. (1999) and Ogren et al. (2010), the filter-based instruments were calibrated  
229 and corrected for sample area, flow rate, and filter type (see Li et al. (2019) for the FIREX data  
230 and Sherman et al. (2015) for the SGP data). Other than that, we did not do any verification beyond  
231 the manufacturer's calibration for the filter-based instruments. The SGP nephelometer  
232 measurements were corrected for truncation effects (Sherman et al., 2015). The FIREX  
233 photoacoustic measurements were calibrated by ammonium sulfate aerosol and fullerene soot (Li  
234 et al., 2019).

**Table 1** Summary of specifications for instruments relevant to this work.

Instrument	Flow rate (LPM)	Spot area (cm <sup>2</sup> )	Type of filter	Measured parameters	Response time	Measurement uncertainty	Detection limit (3 $\sigma$ , Mm <sup>-1</sup> )
PAX-870	1.0	-	-	B <sub>abs</sub> and B <sub>scat</sub> (870 nm)	1s	~11% (B <sub>abs</sub> ) ~17% (B <sub>scat</sub> ) (Nakayama et al., 2015)	0.47 (B <sub>abs</sub> ) 0.66 (B <sub>scat</sub> ) <sup>a</sup>
PAX-405	1.0	-	-	B <sub>abs</sub> and B <sub>scat</sub> (405 nm)	1s	4% (B <sub>abs</sub> ) 7% (B <sub>scat</sub> ) (Nakayama et al., 2015)	0.27 (B <sub>abs</sub> ) 0.60 (B <sub>scat</sub> ) <sup>a</sup>
PASS-3 <sup>b</sup>	1.0	-	-	B <sub>abs</sub> and B <sub>scat</sub> (405, 532, and 781 nm)	1s	4 %, 8 %, and 11 % (B <sub>abs</sub> ) (Nakayama et al., 2015)	0.78 (405 nm) 2.01 (532 nm) 0.30 (781 nm) <sup>a</sup>
NEPH <sup>b</sup>	7.5	-	-	B <sub>scat</sub> (450, 550, and 700 nm)	1s	10% (Anderson et al., 1996)	0.29 (450 nm) 0.11 (550 nm) 0.17 (700 nm) (5-min average) (Müller et al., 2011b)
CLAP	0.83 ± 0.02 (FIREX) 0.945 (SGP)	0.199 (FIREX) 0.195 (SGP)	Pallflex E70-2075S and Azumi filter (model 371M) <sup>c</sup>	B <sub>ATN</sub> and Tr <sup>d</sup> (467, 529, and 653 nm)	60s	30% (Ogren et al., 2017)	0.6 (1-min average), 0.12 (10-min average) (Ogren et al., 2017)
TAP	1.26 ± 0.01	0.253	Azumi filter (model 371M) <sup>c</sup>	B <sub>ATN</sub> and Tr <sup>d</sup> (467, 528, and 652 nm)	10s	30% (Laing et al., 2016)	2.67 (467 nm) 4.11 (528 nm) 2.13 (652 nm) (30-s average) (Davies et al., 2019)
AETH	2.4	0.5	quartz fiber sampling tape	B <sub>ATN</sub> and Tr (370, 470, 520, 590, 660, 880, and 950 nm)	120s	10% (Sedlacek, 2016)	0.1 (Sedlacek, 2016)
PSAP	1.0	0.178	Pallflex E70-2075W	B <sub>ATN</sub> and Tr <sup>d</sup> (470, 522, and 660 nm)	60s	~15% (Bond et al., 1999)	0.3 (Springston, 2016)

236 <sup>a</sup> The detection limits of PAX and PASS-3 are determined by Allan deviation analysis (Allan, 1966) of B<sub>abs</sub> during “background zero”.

237 <sup>b</sup> During the analysis of the data collected at the SGP, we use B<sub>abs</sub> derived by the PASS and B<sub>scat</sub> derived by the NEPH to yield the coefficients in the algorithms.

238 <sup>c</sup> Two types of filters were used during the FIREX campaign (See Sect. 2.1.2).

239 <sup>d</sup> The operating wavelengths of CLAP, TAP, and PSAP are stated slightly different by the instrument manufactures. We simply use 467, 528, and 652 nm throughout  
240 this manuscript.

241 **Table 2** Overview of the studies of B1999 and V2005 and the description of our experiments.

Study	Aerosol source	SSA subset	Range of $B_{abs}$ ( $Mm^{-1}$ )	Filter-based instrument for $B_{abs}$	Reference instrument for $B_{abs}$ <sup>a</sup>	Instrument for $B_{scat}$ <sup>a</sup>	Coefficient values in the correction algorithm <sup>b, c</sup>		
The study in B1999	Lab-generated aerosols, including various mixtures of nigrosin and ammonium sulfate	0.5-1 (550 nm)	0-800 (550 nm)	One- $\lambda$ PSAP (550 nm)	The difference between extinction (OEC) and scattering coefficient (NEPH) <sup>d</sup>	NEPH (450, 550, and 700 nm)	$C_1 = 0.016 \pm 0.023$ (550 nm) $C_2 = 1.55 \pm 0.25$ (550 nm) $C_3 = 1.02 \pm 0.17$ (550 nm)		
The laboratory study in V2005	Lab-generated aerosols, including various mixtures of kerosene soot, ammonium sulfate, and polystyrene latex	0.2-0.9 (530 nm)	0-800 (530 nm)	One- $\lambda$ PSAP (550 nm), three- $\lambda$ PSAP (467, 530, 660 nm)	The average of the PA (532 nm and 1064 nm) and the difference between extinction (OEC) and scattering coefficient (NEPH) <sup>d</sup>	NEPH (450, 550, and 700 nm)	467 nm $C_1 = 0.015$ $C_4 = 0.377 \pm 0.013$ $C_5 = -0.640 \pm 0.007$	530 nm $C_1 = 0.017$ $C_4 = 0.358 \pm 0.011$ $C_5 = -0.640 \pm 0.007$	660 nm $C_1 = 0.022$ $C_4 = 0.352 \pm 0.013$ $C_5 = -0.674 \pm 0.006$
The ambient study in V2005	Ambient aerosols measured during RAOS and NEAQS <sup>e</sup>	0.75-1 (530 nm)	0-15 (530 nm)	One- $\lambda$ PSAP (550 nm), three- $\lambda$ PSAP (467, 530, 660 nm)	PA (532 nm and 1064 nm)	NEPH (450, 550, and 700 nm)	$C_6 = 1.16 \pm 0.05$ $C_7 = -0.63 \pm 0.09$	$C_6 = 1.17 \pm 0.03$ $C_7 = -0.71 \pm 0.05$	$C_6 = 1.14 \pm 0.11$ $C_7 = -0.72 \pm 0.16$
FIREX <sup>f</sup>	Biomass burning aerosols under relatively controlled laboratory conditions	0.2 -1 (550 nm)	38-1800 (550 nm)	CLAP (467, 529, 652 nm), TAP (467, 528, 653 nm), AETH (370, 470, 520, 590, 660, 880, 950 nm)	PAX (405 nm and 870 nm)	PAX (405 nm and 870 nm)	See Table 4 and Tables S6-S10		
SGP (02/01/13 to 07/09/13) <sup>f, g</sup>	Ambient aerosols collected at the SGP user facility in Lamont, OK	0.75-1 (530 nm)	0-8 (550 nm)	CLAP (461, 522, 653 nm), PSAP (470, 522, 660 nm)	PASS (405, 532, and 781 nm)	NEPH (450, 550, and 700 nm)			

242 <sup>a</sup> The operating wavelengths are based on the manufacturer specifications.  
 243 <sup>b</sup> The coefficients provided in Table 2 are the values presented in Ogren (2010) and Virkkula (2010), which are updated from Bond et al. (1999) and Virkkula et al. (2005),  
 244 respectively.  
 245 <sup>c</sup> We reformulate the correction equations in the original publications to agree with Eq. (4)–(6) in this manuscript.  $C_1$  to  $C_7$  are the coefficients in the present work.  
 246 <sup>d</sup> OEC is optical extinction cell and PA is the instrument using photoacoustic technique.  
 247 <sup>e</sup> RAOS and NEAQS are Reno Aerosol Optics Study and New England Air Quality Study, respectively.  
 248 <sup>f</sup> The relative humidity (%) of the sampled aerosols from the FIREX and SGP study is  $29.3 \pm 3.3$  and  $26.1 \pm 13.94$ , respectively.  
 249 <sup>g</sup> The scatterplot of AAE and SAE for the SGP data can be found in Fig. S15. Our results of AAE and SAE are compared to the values reported for different NOAA Earth  
 250 System Research Laboratory (ESRL) observational sites in Schmeisser et al. (2017).

251 2.4. The correction algorithms

252 In filter-based instruments, the light intensities transmitted through the sample spot and blank spot  
253 of the filter are recorded as  $I_s$  and  $I_b$ , respectively. The logarithmic ratio of the two intensities at  
254 time  $t$  is defined as ATN using the Beer-Lambert law:

$$255 \quad \mathbf{ATN}(t) = -100 \times \ln \frac{I_s(t)}{I_b(t)} \quad 1$$

256 where  $\mathbf{ATN} = 0$  when beginning a new filter spot ( $t = 0$ ).

257 The ATN can be related to  $\mathbf{Tr}$  by normalizing  $I_s/I_b$  at time  $t$  relative to  $I_s/I_b$  at the start of a new  
258 filter spot ( $t = 0$ ):

$$259 \quad \mathbf{Tr}(t) = \frac{I_s(t)/I_b(t)}{I_s(0)/I_b(0)} = \exp\left(\frac{-\mathbf{ATN}(t)}{100}\right) \quad 2$$

260 The change of ATN over a time interval ( $\Delta t$ ) for the instrument operated at a volume flow rate of  
261  $Q$  and spot area of  $A$  yields the attenuation coefficient ( $\mathbf{B}_{\mathbf{ATN}}$ ) for that time interval:

$$262 \quad \mathbf{B}_{\mathbf{ATN}} = \frac{A}{Q \times \Delta t} \times \Delta \mathbf{ATN} \quad 3$$

263  $\mathbf{B}_{\mathbf{ATN}}$  is finally converted to  $\mathbf{B}_{\text{abs}}$  by applying correction algorithms. The general form of the  
264 correction algorithms presented for the PSAP in Bond et al. (1999) and Virkkula et al. (2005) can  
265 be summarized as:

$$266 \quad \mathbf{B}_{\text{abs}} = \mathbf{B}_{\mathbf{ATN}} \times f(\mathbf{Tr}) - C_1 \times \mathbf{B}_{\text{scat}} \quad 4$$

267 where  $f(\mathbf{Tr})$  is some function of  $\mathbf{Tr}$  (that may vary between approaches), correcting for the filter  
268 loading effect.  $C_1$  is a constant that may vary with wavelength; specifically, it is a penalty for the  
269 light scattering by the particles collected on the filter which may contribute to the quantification  
270 of ATN. In most atmospheric and laboratory studies,  $\mathbf{B}_{\text{scat}}$  is measured independently, typically  
271 using a co-located NEPH.

272 Besides the above mentioned B1999 and V2005 corrections, the constrained two-stream (CTS)  
273 correction proposed by Müller et al. (2014) can be also applied on PSAP-similar instruments. The  
274 CTS correction was developed based on the relationship between absorption optical depth and  $\mathbf{B}_{\text{abs}}$ .  
275 However, it is not straightforward to reformulate the CTS correction as a function of  $\mathbf{Tr}$  as those  
276 presented in Eq. (5) and Eq. (6). Thus, we exclude the  $\mathbf{B}_{\text{abs}}$  results corrected by the CTS correction  
277 in the following analysis. For those who are interested in the  $\mathbf{B}_{\text{abs}}$  results corrected by the CTS  
278 correction, we provide the correction results of our SGP-CLAP data in Fig. S9.

279 2.4.1. The B1999 correction

280 Bond et al. (1999) was the first study to present the correction algorithm for filter-based  
281 instruments. This empirical correction was originally developed for the PSAP operated at 550 nm  
282 using various mixtures of laboratory-generated nigrosin ( $\text{SSA} \approx 0.5$ ) and ammonium sulfate ( $\text{SSA}$   
283  $\approx 1$ ) with  $\mathbf{B}_{\text{abs}}$  ranged from 0 to 800  $\text{Mm}^{-1}$ .

284 After calibrating the flow rate and spot area of the PSAP, Bond et al. (1999) derived  $C_1 = 0.016$   
285 and defined  $f(\mathbf{Tr})$  as follows:

$$286 \quad f(\mathbf{Tr})_{\mathbf{B1999}} = \frac{1}{C_2 \times \mathbf{Tr} + C_3} \quad 5$$

287 Following an adjustment by Ogren (2010),  $C_2$  and  $C_3$  in Eq. (5) were updated to 1.55 and 1.02,  
288 respectively. These are the values used in the present work (Table 2) for B1999. Moreover, Ogren  
289 (2010) stated that the correction forms of Eq. (4) and Eq. (5) were valid for any wavelength, while  
290 additional experiments were needed to establish the equation parameters for the wavelengths other  
291 than 574 nm.

#### 292 2.4.2. The V2005 correction

293 Virkkula et al. (2005) developed a correction algorithm for both three-wavelength PSAP (467, 530,  
294 and 660 nm) and one-wavelength PSAP (574 nm) using the same functional form as Eq. (4). Since  
295 the operating wavelengths of the photoacoustic instruments and the NEPH were different from  
296 those of the PSAP, the measured photoacoustic  $B_{\text{abs}}$  and  $B_{\text{scat}}$  was extrapolated or interpolated to  
297 467, 530, and 660 nm, using inferred AAE and SAE respectively. In this study, the authors used  
298 various mixtures of kerosene soot, ammonium sulfate, and polystyrene latex (SSA ranged from  
299 0.2 to 0.9) with  $B_{\text{abs}}$  ranging from 0 to 800  $\text{Mm}^{-1}$  at 530 nm.

300 Different from the  $f(\text{Tr})$  in the B1999 correction which was a reciprocal function of  $\text{Tr}$ , the  $f(\text{Tr})$   
301 presented in V2005 was a multivariate linear function of the natural logarithm of  $\text{Tr}$  and  $\text{SSA}$   
302 (including an interaction term between the two):

$$303 \quad f(\text{Tr}(\lambda), \text{SSA}(\lambda))_{\text{V2005}} = C_4 + C_5 \times (C_6 + C_7 \times \text{SSA}(\lambda)) \times \ln(\text{Tr}(\lambda)) \quad 6$$

304 where the parameters in Eq. (6) vary with wavelengths. The parameters in V2005 were updated in  
305 Virkkula (2010) by correcting for flowmeter calibration (Table 2).

306 Due to the unknown values of  $\text{SSA}$  before deriving  $B_{\text{abs}}$ , Virkkula et al. (2005) provided a solution  
307 through an iterative procedure. In the iteration,  $B_{\text{abs}}$  is first calculated using the B1999 correction  
308 (e.g., Eq. (4) and Eq. (5)) and is then used to compute the initial guess of  $\text{SSA}$  for use in Eq. (6).  
309 The  $B_{\text{abs}}$  and  $\text{SSA}$  can be updated using Eq. (4) and Eq. (6) until convergence is reached.

#### 310 2.4.3. Refitting the coefficients in B1999 and V2005

311 With the reference measurements of  $B_{\text{abs}}$  from the photoacoustic instruments, we are able to refit  
312 the coefficients in the B1999 and V2005 corrections ( $C_2$  to  $C_7$  in Eq. (5) and Eq. (6)) using our  
313 data. Specifically, we use the Levenberg-Marquardt algorithm (1944) to iteratively fit the  
314 coefficients until the chi-square of the coefficients are minimized. The fitting is implemented using  
315 the “Curvefit” function in Igor Pro. It is worth noting that the derived coefficients may only be  
316 valid for the SGP and FIREX data. For aerosol properties different from our study, the optimal  
317 coefficients are likely to be different from the ones reported here. Hereafter, the B1999 and V2005  
318 results with refitted coefficients are referred to as “updated B1999” and “updated V2005”,  
319 respectively.

#### 320 2.4.4. The new correction

321 We develop a set of new correction algorithms with the same general form as Eq. (4) using the  
322 biomass burning emissions from 65 different burns during the FIREX laboratory study, providing  
323 a broader range of aerosol optical properties and aerosol concentrations than previous work. This  
324 was motivated by the disagreement that remained between filter-based and photoacoustic  
325 instruments, even after applying B1999 to the data (e.g., see Li et al. (2019) Fig. 4 and our Fig. 2  
326 below). These differences may persist because we were effectively extrapolating the B1999  
327 correction equation to values outside the range for which it was developed.

328 This new correction is developed based on multiple linear regression techniques with three  
 329 dependent variables of  $\ln(\text{Tr})$ ,  $\text{SSA}$ , and  $\text{AAE}$  and one independent variable of  $\text{B}_{\text{abs}}/\text{B}_{\text{ATN}}$  (Eq. (7)  
 330 – (9)). As with other correction equations, this model takes into account the influence of scattering  
 331 and weakly-absorbing materials, but we have the additional aim of developing a model that is  
 332 applicable to any filter-based absorption photometer.

333 Similar to the B1999 and V2005 corrections, this new model starts with the general form of Eq.  
 334 (4), re-written here to define  $\text{B}_{\text{scat}}$  in terms of  $\text{SSA}$  and  $\text{B}_{\text{abs}}$ .

$$335 \quad \mathbf{B}_{\text{abs}}(\lambda) = \mathbf{B}_{\text{ATN}}(\lambda) \times f(\mathbf{Tr}(\lambda)) - C_1 \times \frac{\text{SSA}(\lambda)}{1-\text{SSA}(\lambda)} \times \mathbf{B}_{\text{abs}}(\lambda) \quad 7$$

336 Re-arranging this equation to move all  $\text{B}_{\text{abs}}$  terms to the left-hand side yields:

$$337 \quad \mathbf{B}_{\text{abs}}(\lambda) = \mathbf{B}_{\text{atn}}(\lambda) \times g(\mathbf{Tr}(\lambda), \text{SSA}(\lambda)) \quad 8$$

$$338 \quad \text{where } g(\text{Tr}(\lambda), \text{SSA}(\lambda)) = f(\text{Tr}(\lambda)) \times \frac{1-\text{SSA}(\lambda)}{1-(1-C_1) \times \text{SSA}(\lambda)}.$$

339 We define a new function “g” that can be used in Eq. (8). Specifically, we construct a multivariate  
 340 linear model for “g”, introducing  $\text{AAE}$  as a dependent variable and including interaction terms  
 341 between  $\text{SSA}$ ,  $\text{AAE}$ , and  $\ln(\text{Tr})$ :

$$342 \quad g(\text{Tr}(\lambda), \text{SSA}(\lambda), \text{AAE}) = G_0 + G_1 \times \ln(\text{Tr}(\lambda)) + G_2 \times \text{SSA}(\lambda) + G_3 \times \text{AAE} + G_4 \times \ln(\text{Tr}(\lambda)) \times \text{SSA}(\lambda) + \\ 343 \quad G_5 \times \text{SSA}(\lambda) \times \text{AAE} + G_6 \times \ln(\text{Tr}) \times \text{AAE} + G_7 \times \text{SSA}(\lambda) \times \text{AAE} \times \ln(\text{Tr}(\lambda)) \quad 9$$

344 Equation (9) suggests that different combinations of  $\text{SSA}$ ,  $\text{AAE}$  and  $\ln(\text{Tr})$  can result in the same  
 345 value of “g” (i.e.,  $\text{B}_{\text{abs}}/\text{B}_{\text{ATN}}$ ); likewise, a given value of  $\text{B}_{\text{abs}}/\text{B}_{\text{ATN}}$  may have infinitely many points  
 346 with distinct slopes passing through it (Fig. S3). Although Eq. (9) is developed based on statistical  
 347 approaches, we attempt to relate this statistical model to physical effects. The coefficients  $G_1 - G_3$   
 348 are fairly straightforward, as these account for the influence of filter loading ( $G_1$ ), relative light  
 349 scattering by the aerosols ( $G_2$ ), and the brownness of the aerosols ( $G_3$ ). The interaction terms ( $G_4$   
 350 –  $G_7$ ) are more difficult in assigning a physical meaning; however, the interaction between filter  
 351 loading and relative light scattering ( $G_4$ ) is might be interpreted as an absolute light scattering by  
 352 the aerosols on the filter, while the interaction between filter loading and aerosol brownness ( $G_6$ )  
 353 is somewhat analogous to  $G_4$ . The three-way interaction between filter loading, scattering and  
 354 brownness of aerosols ( $G_7$ ) is required because of the three two-way interaction terms.

355 To further this physical interpretation of our statistical model (Eq. 9), we explore the relationship  
 356 between  $\frac{\text{B}_{\text{abs}}}{\text{B}_{\text{ATN}}}$  and  $\ln(\text{Tr})$ , which essentially follows a “ $y = m \cdot x + b$ ” form, where  $y$  is  $\frac{\text{B}_{\text{abs}}}{\text{B}_{\text{ATN}}}$  and  $x$  is  
 357  $\ln(\text{Tr})$ . The slope ( $m$ ) is defined as  $G_1 + G_4 \times \text{SSA} + G_6 \times \text{AAE} + G_7 \times \text{SSA} \times \text{AAE}$ , and the intercept  
 358 ( $b$ ) is defined as  $G_2 \times \text{SSA} + G_3 \times \text{AAE} + G_5 \times \text{SSA} \times \text{AAE}$ . Therefore, different combinations of  $\text{SSA}$   
 359 and  $\text{AAE}$  modulate this relationship between  $\frac{\text{B}_{\text{abs}}}{\text{B}_{\text{ATN}}}$  and  $\ln(\text{Tr})$ . For example, loading “black”  
 360 particles on the filter (e.g.,  $\text{AAE} \sim 1$  and  $\text{SSA} \sim 0.3$ ) tends to produce larger values of  $\frac{\text{B}_{\text{abs}}}{\text{B}_{\text{ATN}}}$ , while  
 361 loading “white” particles on the filter (e.g.,  $\text{AAE} \sim 3$  and  $\text{SSA} \sim 0.9$ ) tends to produce smaller values  
 362 of  $\frac{\text{B}_{\text{abs}}}{\text{B}_{\text{ATN}}}$  (see Fig. S3 of this work and Fig. 4 in Virkkula et al.(2005)). This relationship becomes  
 363 more complex when considering, e.g., mixed sulfate and black carbon particles;  $\text{SSA}$  can be high

364 while AAE is low, and the corresponding  $\frac{B_{\text{abs}}}{B_{\text{ATN}}}$  can be variable (also see Fig. S3). Therefore, in  
365 order to properly compensate for the effects of loading and aerosol optical properties, a multiple  
366 linear regression with interaction terms is introduced in Eq. (9).

367 A detailed description of the procedure for the model development (e.g., variable transformation  
368 (from Tr to  $\ln(\text{Tr})$ ), variable selection using best-subsets and stepwise approaches, and model  
369 assessment) is provided in the Supplementary Material. We evaluate the model by plotting  $\frac{B_{\text{abs}}}{B_{\text{ATN}}}$   
370 against aerosol properties not included in Eq. (9) (such as relative humidity and aerosol geometric  
371 mean diameter, which have been previously reported to bias corrections of filter-based  $B_{\text{abs}}$ ,  
372 (Moteki et al., 2010; Nakayama et al., 2010; Schmid et al., 2006)). The results are presented in Fig.  
373 S5-S7.

374 As in V2005, iteration is required in our algorithm because  $B_{\text{abs}}$  is dependent on knowledge of  
375 SSA and AAE, which themselves are dependent on  $B_{\text{abs}}$ . We propose the following iterative  
376 process to update SSA and AAE in the model.

- 377 1. Initialize AAE from  $B_{\text{ATN}}$  across the three wavelengths ( $B_{\text{ATN}} \sim \lambda^{-\text{AAE}}$ ) and initialize SSA for  
378 each wavelength using  $B_{\text{ATN}}$  from the filter-based absorption photometer and  $B_{\text{scat}}$  from a co-  
379 located NEPH, i.e.,  $\text{SSA}(\lambda) = \frac{B_{\text{scat}}(\lambda)}{B_{\text{scat}}(\lambda) + B_{\text{ATN}}(\lambda)}$ .
- 380 2. Yield an initial set of coefficients  $G_0$  through  $G_7$  for each wavelength to calculate  $g(\text{Tr}, \text{SSA},$   
381  $\text{AAE})$  in Eq. (9), using one of the Algorithms described in Sect. 2.5.
- 382 3. Calculate  $B_{\text{abs}}$  for each wavelength using Eq. (8).
- 383 4. Update AAE and SSA using  $B_{\text{abs}}$  calculated in Step 3.
- 384 5. Derive a new set of coefficient values.
- 385 6. Iterate Steps 3-5 until converged.

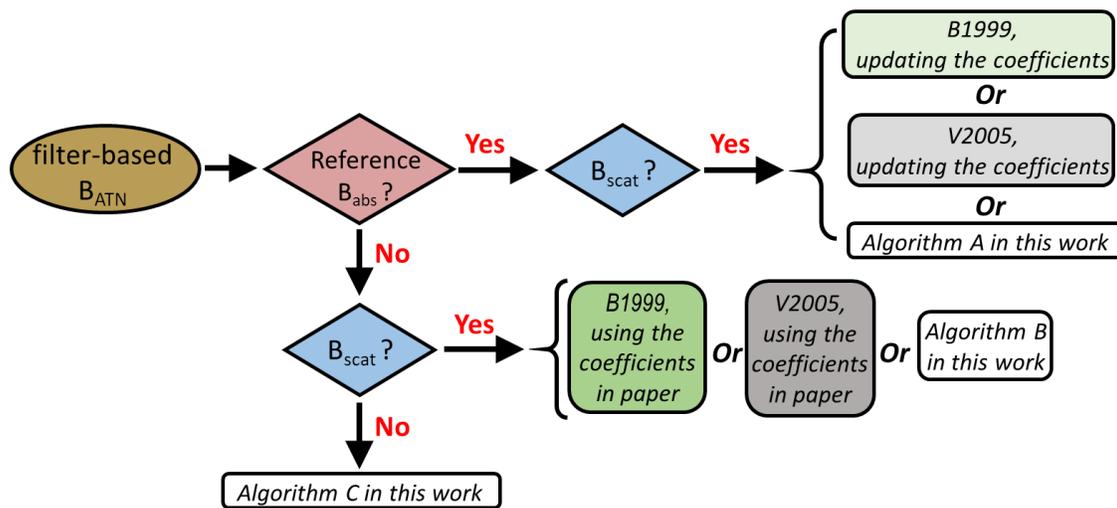
## 386 2.5. Application of correction algorithms

387 In developing a procedure for applying our algorithm, we envision three potential scenarios:

- 388 1. Algorithm A: The filter-based instrument is co-located with a NEPH and reference instrument  
389 providing  $B_{\text{abs}}$ . This scenario facilitates the computation of  $G_0$  through  $G_7$  in Eq. (9) (step 2 in  
390 the iterative process) as well as the derivation of new coefficients for existing correction  
391 algorithms. This scenario can also enable the develop of a new a set of coefficients that may  
392 be more appropriate for aerosol sources that we do not consider here.
- 393 2. Algorithm B: The filter-based instrument is co-located with a NEPH but not a reference  
394 instrument providing  $B_{\text{abs}}$ , which is perhaps the most likely scenario (at least at many long-  
395 term monitoring sites). This scenario requires an initial guess of the coefficients; we provide  
396 sets of these in Table 4 below for different filter-based instruments and aerosol sources.
- 397 3. Algorithm C: The filter-based instrument is deployed with neither a co-located NEPH nor a  
398 reference instrument providing  $B_{\text{abs}}$ . This scenario is the most challenging, because there are  
399 no measurements of  $B_{\text{scat}}$  to compute SSA; to address this issue, we propose the use of a non-  
400 linear relationship between SSA and AAE ( $\text{AAE} = a + b \times \text{SSA}^c$ ) to provide an initial guess of  
401 SSA in the iterations.

402 To aid in decision-making between algorithms, we developed a flow chart for selecting appropriate  
403 correction algorithm for CLAP, TAP, and PSAP (Fig. 1). Furthermore, Igor Pro (WaveMetrics,

404 Inc.) and Python (Version 3.7.5) based program for selecting and implementing our correction  
 405 algorithms can be found at <https://doi.org/10.5281/zenodo.3742342>.



406  
 407 **Figure 1.** The flow-chart for the application of correction algorithms on PSAP, CLAP, and TAP.  
 408 Similar logic is followed for the AETH.

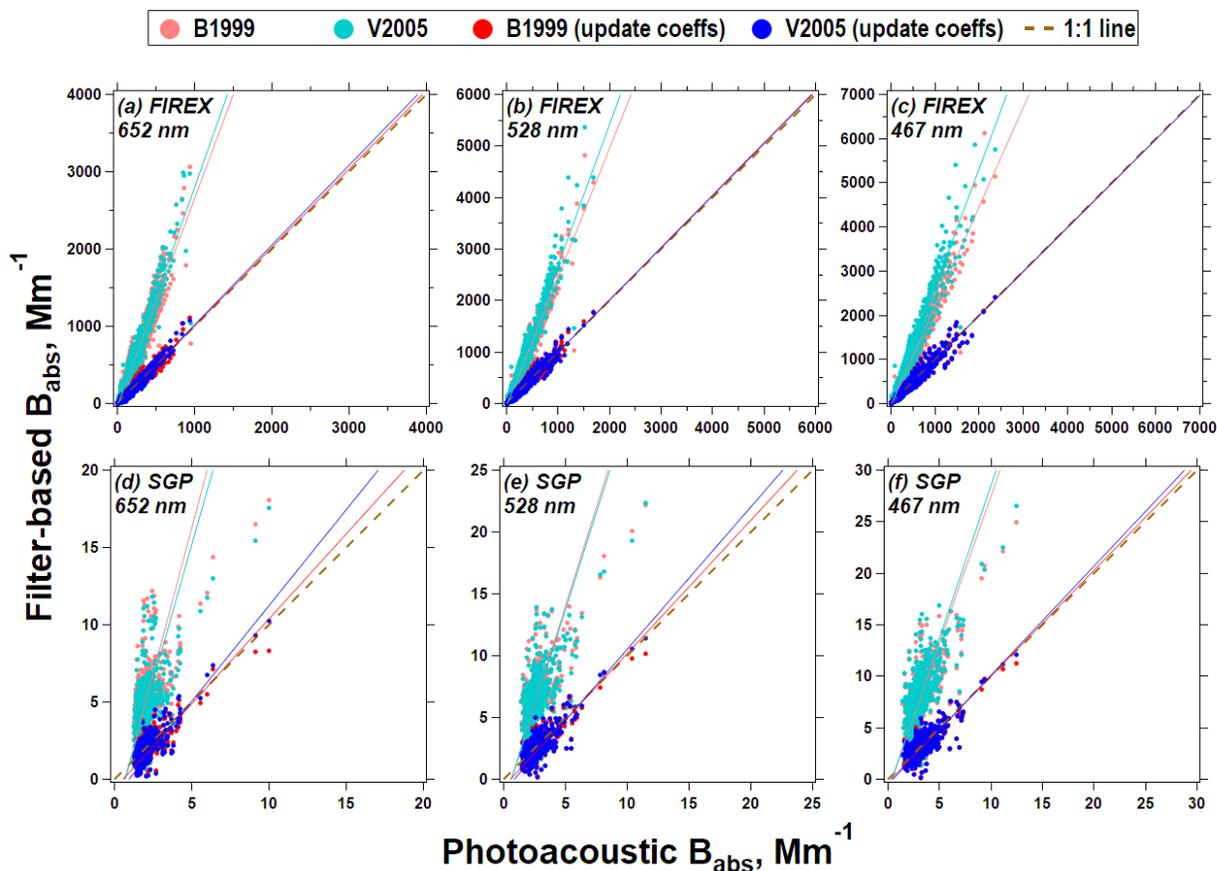
409 3. Results and discussion

410 3.1. Application of the previous algorithms on different aerosols

411 We first consider the application of the B1999 and V2005 corrections on different combinations  
 412 of aerosol type and filter-based absorption photometer. Specifically, we apply the two corrections  
 413 to the biomass burning data from the FIREX laboratory campaign (CLAP and TAP) as well as six  
 414 months of ambient data from the SGP site (CLAP and PSAP). In doing so, we use the “default”  
 415 coefficients recommended in B1999 and V2005 as well as “updated” coefficients that are  
 416 estimated via regression techniques. It is important to keep in mind that the updated coefficient  
 417 values of B1999 and V2005 (Table S7) are only valid for the aerosols investigated in this study.  
 418 Future experiments are needed to systematically determine how the coefficients in B1999 and  
 419 V2005 may change for different aerosol types. We focus on the results of the CLAP in the main  
 420 text, because a CLAP is the only instrument common to deployments for both FIREX and SGP.  
 421 The results of the TAP from FIREX and the PSAP from the SGP site can be found in the  
 422 Supplementary Material (Table S5 and Fig. S11).

423 Our inter-comparison between the corrected CLAP-derived  $B_{abs}$  and reference  $B_{abs}$  for the FIREX  
 424 and SGP data is provided in Fig. 2 and Table 3. For the FIREX measurements, both analyses (using  
 425 the “default” coefficients and updating the coefficients) suggest good correlation (coefficient of  
 426 determination ( $R^2$ ) > 0.9) between the CLAP and the reference across all three wavelengths.  
 427 Nevertheless, the corrections using the “default” coefficients result in over-prediction of  $B_{abs}$  by  
 428 factors of ~2.5. If we update the coefficients in the corrections, there is an obvious improvement  
 429 in the agreement (i.e., slope  $\approx$  1;  $R^2$  increases). The results are generally similar for SGP, although  
 430 the  $R^2$  for ambient data is generally lower for ambient data ( $R^2 < 0.7$ ). Decreased  $R^2$  may be due  
 431 to the lower aerosol concentrations measured in ambient air, which could lead to lower signal-to-  
 432 noise in the instruments. Moreover, it is worth mentioning that for both datasets (FIREX and SGP),

433 the corrected  $B_{\text{abs}}$  from different filter-based absorption photometers using the “default”  
 434 approaches does not agree with each other (slopes range from 0.69 to 1.40). However, after  
 435 updating the coefficients, the slopes approach unity (Table S6).



436  
 437 **Figure 2.** Inter-comparison between the CLAP-derived  $B_{\text{abs}}$  corrected by the B1999 and V2005  
 438 algorithms and the reference  $B_{\text{abs}}$  at 652, 528, and 467 nm for both FIREX and SGP data. The solid  
 439 lines represent linear regressions, while the dashed line is a 1:1 line.

440 **Table 3** Relationship between the CLAP-derived  $B_{\text{abs}}$  corrected by the B1999 and V2005  
 441 algorithms (including updated coefficients) and the reference  $B_{\text{abs}}$  at 652, 528, and 467 nm. The  
 442 relationship is achieved using major axis regression (Ayers, 2001). The value in parentheses  
 443 represents the coefficient of determination ( $R^2$ ) of the linear relationship.

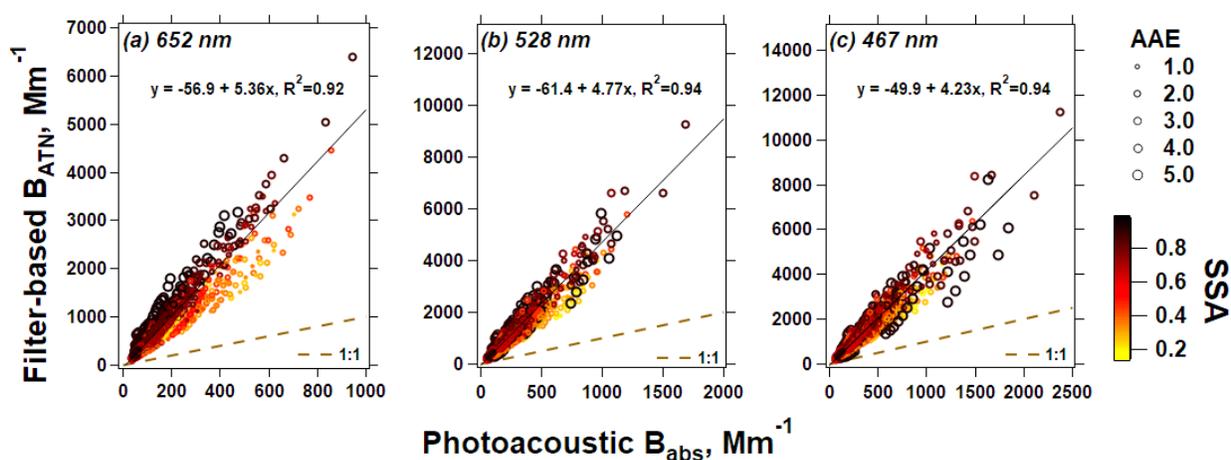
		652 nm	528 nm	467 nm
FIREX	B1999	$y = -39 + 2.69x$ (0.94)	$y = -49 + 2.50x$ (0.96)	$y = -45 + 2.26x$ (0.97)
	V2005	$y = -46 + 2.83x$ (0.96)	$y = -57 + 2.75x$ (0.96)	$y = -56 + 2.68x$ (0.96)
	B1999 (update coeffs)	$y = -8.4 + 1.02x$ (0.96)	$y = -7.7 + 1.01x$ (0.97)	$y = -3.4 + 1.00x$ (0.96)
	V2005 (update coeffs)	$y = -9.4 + 1.03x$ (0.97)	$y = -7.3 + 1.01x$ (0.97)	$y = -3.0 + 1.00x$ (0.96)
SGP	B1999	$y = -2.60 + 3.77x$ (0.41)	$y = -1.90 + 3.20x$ (0.49)	$y = -0.98 + 2.85x$ (0.55)
	V2005	$y = -2.50 + 3.54x$ (0.41)	$y = -2.00 + 3.15x$ (0.48)	$y = -1.10 + 2.96x$ (0.55)
	B1999 (update coeffs)	$y = -0.29 + 1.10x$ (0.60)	$y = -0.29 + 1.08x$ (0.63)	$y = -0.17 + 1.03x$ (0.65)
	V2005 (update coeffs)	$y = -0.57 + 1.24x$ (0.65)	$y = -0.50 + 1.15x$ (0.67)	$y = -0.27 + 1.06x$ (0.67)

445 In the FIREX data, there is an apparent dependency of the updated coefficients on the wavelength  
 446 of light, but more importantly, on the aerosol optical properties, namely SSA and AAE (Tables  
 447 S7-S9). However, in the ambient data from SGP, the dependency on optical properties is less  
 448 obvious (Tables S10-S11). Nevertheless, all of these coefficients differ from those reported in  
 449 B1999 and V2005 (again, derived for the PSAP rather than the CLAP), which highlights the  
 450 potential need to use coefficient values that are appropriate for the instrument being used, its  
 451 wavelength(s) of light, and optical properties that are representative of the sampled aerosols when  
 452 applying correction factors to  $B_{ATN}$ .

### 453 3.2. Application of the new algorithms to the FIREX data

454 The co-location of the CLAP, TAP, AETH, and PAX during FIREX allows us to apply each  
 455 algorithm (A, B, C) to these data. Similar to Sect. 3.1, we focus our discussion on the CLAP with  
 456 details on the TAP and AETH presented in the Supplementary Material (Fig. S11-S12). However,  
 457 we provide the recommended initial guesses in the new algorithms and the comparison of  
 458 absorption (corrected filter-based  $B_{abs}$  versus reference  $B_{abs}$ ) for all filter-based absorption  
 459 photometers in Table 4 and Table 5 to help readers quickly retrieve key information of our  
 460 algorithms.

461 Figure 3 provides a comparison between the uncorrected  $B_{ATN}$  from the CLAP at all three  
 462 wavelengths, as well as photoacoustic  $B_{abs}$  interpolated to those wavelengths using AAE. For each  
 463 wavelength, the slopes are significantly greater than one. Moreover, there is an apparent  
 464 dependency on SSA and AAE in the agreement between the instruments. This is most obvious in  
 465 Fig. 3a (652 nm), where data with lower SSA and lower AAE (smaller markers, “brighter”  
 466 colors) fall below the best-fit line, while data with higher SSA and higher AAE (larger markers,  
 467 “darker” colors) fall above the best-fit line. This phenomenon is less clear in Fig. 3b-3c, but an  
 468 apparent dependency on SSA and AAE remains, which highlights the need to include both of these  
 469 optical properties (and appropriate interaction terms) when correcting  $B_{ATN}$  values.



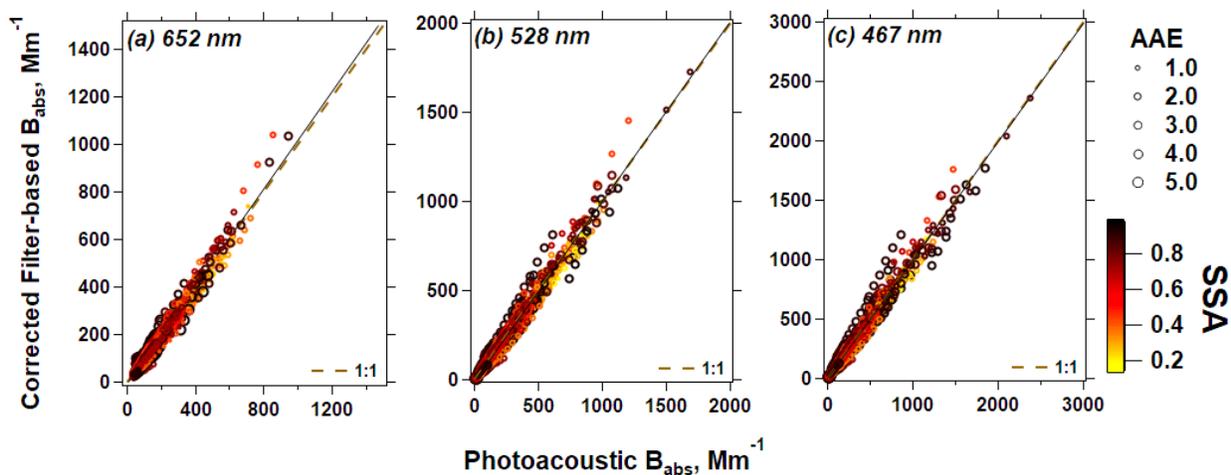
470  
 471 **Figure 3.** Comparison of the uncorrected CLAP-derived  $B_{ATN}$  and the reference  $B_{abs}$  at 652, 528,  
 472 and 467 nm for the FIREX data. The data points are colored by the corresponding SSA at the given  
 473 wavelength. The size of data points reflects their AAE quantified by the two PAX. The solid line  
 474 represents the linear regression, while the dashed line is a 1:1 line.

475 We first apply “Algorithm A” to the CLAP  $B_{ATN}$  data in Fig. 3. Using the reference  $B_{abs}$  values  
 476 from the PAX (in addition to  $B_{scat}$  values), we are able to derive a set of coefficients that enable  
 477 the correction of the data (Table 4). Corrected CLAP values are presented in Fig. 4 with the linear  
 478 relationships presented in Table 5. The slope for each wavelength is very close to the 1:1 line,  
 479 suggesting that our approach works well in correcting these data. Moreover, the heteroscedasticity  
 480 that exists in Fig. 3 has been minimized after correction, and there are no apparent trends in how  
 481 the data are organized in Fig. 4 due to the aerosol optical properties.

482 **Table 4** Coefficient values for Eq. (9) derived using “Algorithm A”. We recommend these as the  
 483 initial guesses when implementing “Algorithm B”<sup>a</sup>.

		$G_0$	$G_1$	$G_2$	$G_3$	$G_4$	$G_5$	$G_6$	$G_7$
CLAP (FIREX)	652 nm	0.27	-0.16	-0.18	-0.05	0.18	0.08	-0.01	0.03
	528 nm	0.30	-0.28	-0.18	-0.07	0.25	0.10	0.13	-0.17
	467 nm	0.32	-0.38	-0.20	-0.08	0.33	0.12	0.24	-0.31
TAP (FIREX)	652 nm	0.45	-0.45	0.07	-0.19	0.94	0.10	0.26	-0.35
	528 nm	0.54	-0.51	0.02	-0.26	0.76	0.20	0.38	-0.44
	467 nm	0.62	-0.59	-0.07	-0.32	0.73	0.29	0.53	-0.60
CLAP (SGP)	652 nm	0.37	-0.18	-0.34	-0.11	0.30	0.18	-0.36	0.41
	528 nm	0.40	-0.15	-0.42	-0.14	0.10	0.24	-0.17	0.25
	467 nm	0.43	-0.16	-0.45	-0.16	0.07	0.27	-0.06	0.12
PSAP (SGP)	652 nm	0.24	0.35	-0.16	-0.04	-0.47	0.07	-0.57	0.73
	528 nm	0.30	0.48	-0.26	-0.10	-0.67	0.17	-0.63	0.77
	467 nm	0.35	0.49	-0.34	-0.15	-0.69	0.23	-0.55	0.79
AETH (FIREX)	950 nm	0.47	0.17	0.01	-0.27	-0.4	0.25	-0.12	0.27
	880 nm	0.34	0.13	0.13	-0.17	0	0.10	-0.13	0.12
	660 nm	0.28	0.09	0.11	-0.12	0.15	0.05	-0.12	0.03
	590 nm	0.16	-0.08	0.26	-0.03	0.59	-0.08	-0.02	-0.19
	520 nm	0.16	-0.05	0.14	-0.01	0.54	-0.07	-0.02	-0.21
	470 nm	0.14	-0.05	0.06	0	0.53	-0.05	-0.02	-0.17
	370 nm	0.13	-0.09	0.11	0	0.59	-0.06	-0.01	0.01

484 <sup>a</sup> The coefficients derived from FIREX may be more appropriate for biomass burning aerosols, and  
 485 the coefficients derived from SGP may be more appropriate for rural background environments in  
 486 the absence of marine aerosols and dust (see Fig. S15).  
 487



488  
 489 **Figure 4.** As in Fig. 3, but the CLAP-based  $B_{\text{ATN}}$  values have been corrected using our “Algorithm  
 490 A”.

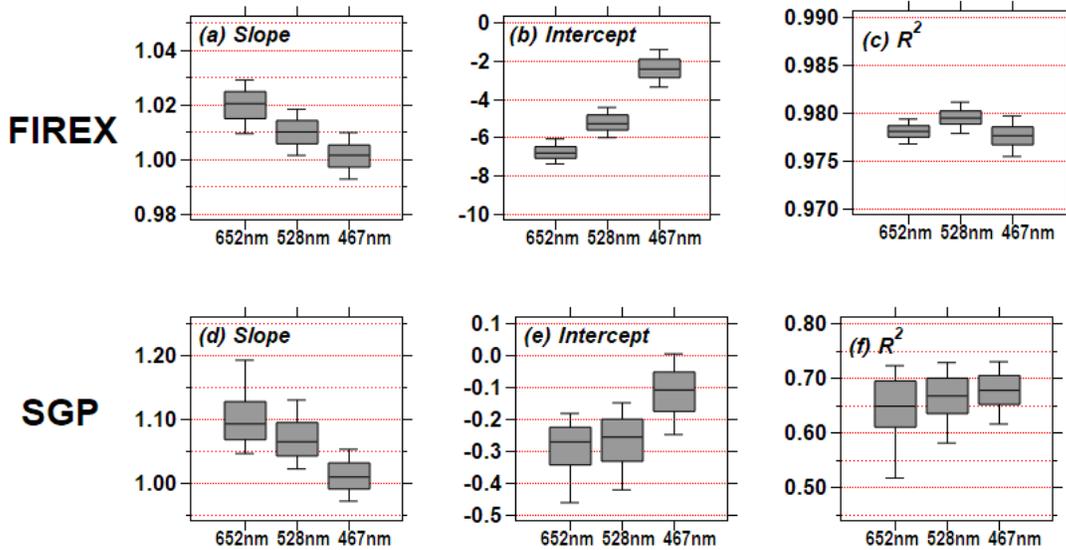
491 **Table 5** Relationship between the filter-based  $B_{\text{abs}}$  corrected by “Algorithm A” and the reference  
 492  $B_{\text{abs}}$  at the operating wavelengths for the filter-based instrument. The relationship is achieved using  
 493 major axis regression (Ayers, 2001). The value in the parentheses represents the coefficient of  
 494 determination ( $R^2$ ) for the linear relationship.

		652 nm	528 nm	467 nm	
FIREX	CLAP	$y = -7.8 + 1.02x$ (0.98)	$y = -6.2 + 1.01x$ (0.98)	$y = -3.2 + 1.00x$ (0.98)	
	TAP	$y = -10 + 1.00x$ (0.87)	$y = -13 + 0.99x$ (0.87)	$y = -16 + 0.99x$ (0.88)	
SGP	CLAP	$y = -0.25 + 1.08x$ (0.68)	$y = -0.21 + 1.05x$ (0.67)	$y = -0.04 + 0.99x$ (0.68)	
	PSAP	$y = -0.28 + 1.10x$ (0.43)	$y = -0.24 + 1.06x$ (0.55)	$y = -0.07 + 1.00x$ (0.62)	
FIREX	AETH	950 nm	880 nm	660 nm	590 nm
		$y = -3.19 + 1.01x$ (0.82)	$y = -3.92 + 1.02x$ (0.85)	$y = -5.97 + 1.03x$ (0.88)	$y = -5.63 + 1.02x$ (0.90)
		520 nm	470 nm	370 nm	-
		$y = -2.36 + 0.99x$ (0.90)	$y = 2.93 + 0.95x$ (0.88)	$y = 18.38 + 0.89x$ (0.80)	-

495  
 496 We next investigate the repeatability of the coefficient values presented in Table 4 by randomly  
 497 selecting half of the measurements ( $N = 1338$ ) from the whole FIREX dataset. By implementing  
 498 “Algorithm A” to the extracted observations, we obtain new coefficient values for  $G_0$  to  $G_7$ . This  
 499 is repeated 1000 times to obtain a distribution of coefficient values (Fig. S13). The extraction  
 500 approach mimics the process of obtaining new biomass burning datasets, so that we can estimate  
 501 the variability of these derived coefficients. From Fig. S13 and Table S12, the derived coefficients  
 502 are mostly insensitive to the different randomly-extracted datasets; most of the quartile deviation  
 503 (defined as  $(Q3-Q1)/2$ , where  $Q1$  and  $Q3$  are the first and third quartile respectively) is within 0.05,  
 504 except  $G_4$  which has a quartile deviation of  $\sim 0.08$ . Consequently, the coefficient values obtained  
 505 in “Algorithm A” appear to be reasonable initial guesses to correct filter-based absorption  
 506 measurements during biomass burning events when the reference  $B_{\text{abs}}$  is unavailable, such as in  
 507 “Algorithm B” and “Algorithm C”.

508 We next implement “Algorithm B” to the CLAP  $B_{\text{ATN}}$  data from Fig. 3 using the initial guesses of  
 509 the coefficients derived from “Algorithm A” (Table 4) along with reference  $B_{\text{scat}}$  values. To get a

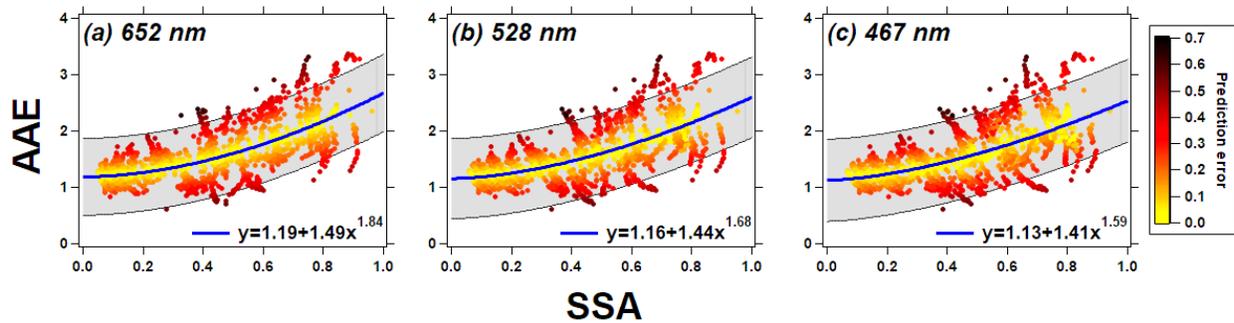
510 sense of the variability in the results, we randomly select half of the data and applied the correction;  
 511 this process is repeated 1000 times. For each iteration, we compare the corrected  $B_{\text{abs}}$  from the  
 512 CLAP to the reference  $B_{\text{abs}}$  from the PAX; the resulting slope, intercept, and  $R^2$  values are  
 513 summarized as box-and-whisker plots in Fig. 5. For all three wavelengths, the slopes are close to  
 514 unity, and there is good correlation between the two absorption measurements ( $R^2 \approx 0.98$ ), which  
 515 indicates that the good performance seen in Fig. 4 is independent of the reference  $B_{\text{abs}}$   
 516 measurements and our algorithm is able to correct “new”  $B_{\text{ATN}}$ . Consequently, when scattering  
 517 measurements are co-located with filter-based absorption measurements, our new correction  
 518 algorithm performs well.



519

520 **Figure 5.** The box-and-whisker plots for the slope, intercept, and  $R^2$  of the relationship between  
 521 the CLAP-derived  $B_{\text{abs}}$  (corrected by “Algorithm B” in the present work) and PAX-derived  $B_{\text{abs}}$  for  
 522 all three wavelengths. For details on how these values were generated, please refer to the text.

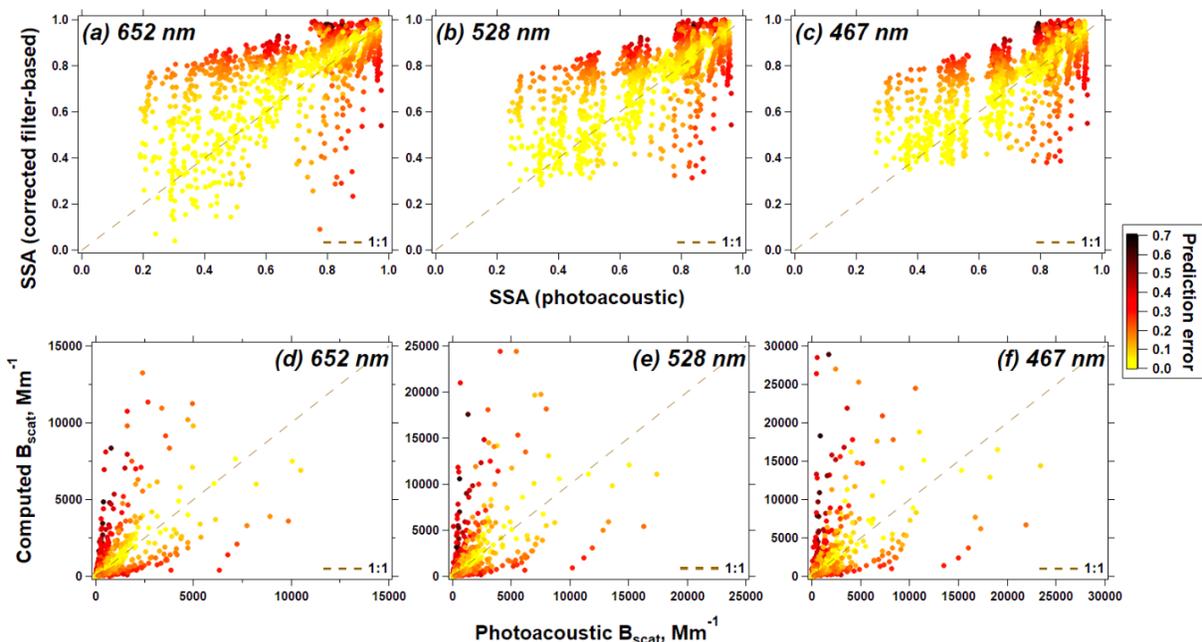
523 Lastly, we apply “Algorithm C” to the data in Fig. 3. However, we first require a functional  
 524 relationship between AAE and SSA, because in this scenario, the CLAP  $B_{\text{ATN}}$  values are the only  
 525 data input to the algorithm (and therefore, SSA is unknown). Liu et al. (2014) proposed that a  
 526 power function can describe this relationship ( $\text{AAE} = a + b \times \text{SSA}^c$ ); we present these data from  
 527 FIREX along with power function fits (and associated prediction intervals) in Fig. 6. To define  
 528 AAE in this figure, we fit a power-law relationship to the three  $B_{\text{ATN}}$  values from the CLAP;  
 529 similarly, we define SSA using interpolated  $B_{\text{scat}}$  from the PAX and  $B_{\text{ATN}}$  from the CLAP (The  
 530 rationale for using  $B_{\text{ATN}}$  is that if “Algorithm C” were to be implemented in practice, only  $B_{\text{ATN}}$   
 531 would be available). In Fig. 6, the data points are colored by “prediction error”, effectively a metric  
 532 to quantify how well the power function reproduces the individual data points. Although there is  
 533 a fair amount of error in some of these points, we still obtain an SSA-AAE relationship required  
 534 to initialize “Algorithm C”.



535

536 **Figure 6.** AAE plotted against SSA for the FIREX data. In the figures, AAE was computed using a  
 537 power-law fit across all three wavelengths, and SSA was computed using the interpolated  $B_{\text{scat}}$   
 538 from the two PAX and the reported  $B_{\text{ATN}}$  from the CLAP. The data points are colored by their  
 539 prediction error ( $(\text{“true” AAE} - \text{“calculated” AAE}) / \text{“calculated” AAE}$ ).

540 Even though there is uncertainty in the SSA vs. AAE relationship used in “Algorithm C”, after  
 541 corrections have been applied, the filter-based  $B_{\text{abs}}$  for the CLAP agrees well with the independent  
 542 reference  $B_{\text{abs}}$ ; the slopes for all wavelengths are slightly greater than 1 (1.03-1.05) and the  $R^2$   
 543 values are all high (0.97-0.98). However, even though the absorption measurements are corrected  
 544 well, there still remains large uncertainties in values of inferred scattering. Examples of this are  
 545 provided in Fig. 7, where we compare the SSA inferred from the PAX to the SSA inferred from  
 546 “Algorithm C” as well as  $B_{\text{scat}}$  for each wavelength. Generally speaking, data that are better  
 547 represented by the SSA vs. AAE relationship (i.e., smaller prediction error) results in better  
 548 agreement with the reference for both SSA and  $B_{\text{scat}}$ , but there is also a clear divergence from the  
 549 1:1 line in Fig. 7a-c as SSA decreases. Therefore, even though “Algorithm C” performs well at  
 550 correcting filter-based  $B_{\text{ATN}}$  to agree with the reference  $B_{\text{abs}}$ , estimates of final SSA values should  
 551 be considered to be uncertain.



552  
 553 **Figure 7.** Comparison of SSA (a-c) and  $B_{\text{scat}}$  (d-f) at the three wavelengths for the FIREX data.  
 554 Vertical axis: values output from “Algorithm C”; horizontal axis: values calculated using the  
 555 photoacoustic  $B_{\text{abs}}$  and  $B_{\text{scat}}$ .

556 To explore the generalization of the new algorithms across different instruments, we next apply  
 557 our algorithms to the other filter-based absorption photometers operated during the FIREX study  
 558 (TAP and AETH). Consistent with what we observed for the CLAP results, the corrected TAP-  
 559 and AETH-derived  $B_{\text{abs}}$  is in good agreement with the photoacoustic  $B_{\text{abs}}$  (as demonstrated in Table  
 560 4 and Table 5, as well as Fig. S11-S12). Moreover, the corrected  $B_{\text{abs}}$  from the three filter-based  
 561 instruments agrees with each other for all three wavelengths (Table 6), confirming the consistency  
 562 of our algorithm.

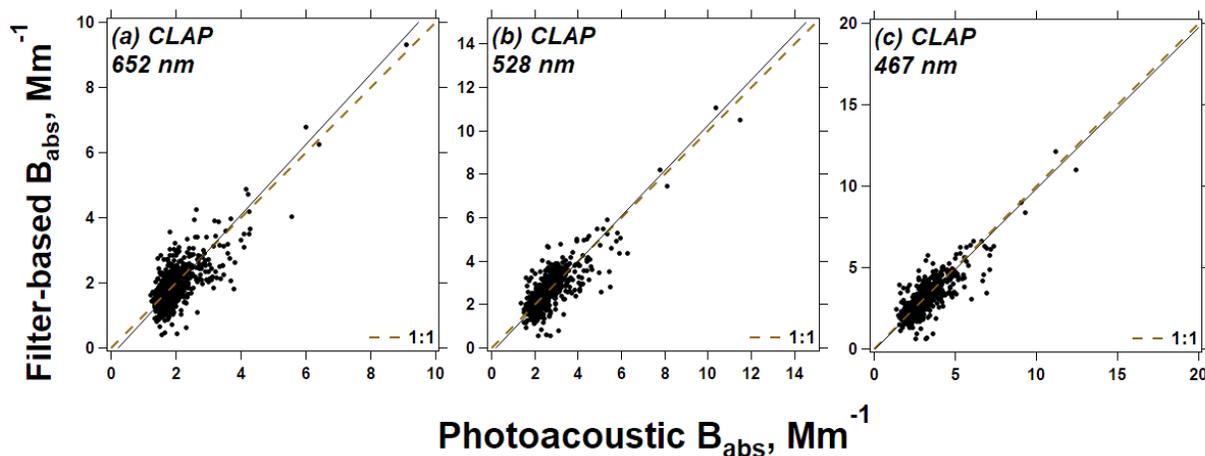
563 **Table 6** Inter-comparison between different filter-based  $B_{\text{abs}}$  corrected by “Algorithm A” in the  
 564 present work. The value in the parentheses represents the coefficient of determination ( $R^2$ ) of the  
 565 linear relationship.

	FIREX: CLAP vs. TAP	FIREX: CLAP vs. AETH	FIREX: TAP vs. AETH	SGP: CLAP vs. PSAP
652 nm	$y = 1.84 + 1.02x$ (0.89)	$y = 4.17 + 0.94x$ (0.87)	$y = -0.31 + 0.99x$ (0.82)	$y = -0.04 + 0.99x$ (0.70)
528 nm	$y = 5.75 + 1.02x$ (0.88)	$y = 3.70 + 0.91x$ (0.85)	$y = -6.38 + 0.98x$ (0.82)	$y = -0.11 + 1.02x$ (0.73)
467 nm	$y = 10.57 + 1.01x$ (0.88)	$y = 0.45 + 0.98x$ (0.83)	$y = -13.62 + 1.04x$ (0.79)	$y = -0.11 + 1.02x$ (0.76)

566  
 567 **3.3. Application of the new algorithms to ambient data**

568 To test our algorithms further, we extended our work to ambient data collected the DOE SGP site  
 569 during the time period which the PASS-3 was operational. From the SGP data, we derived a  
 570 different set of coefficients for ambient data using “Algorithm A”, which differ from those derived  
 571 for FIREX (Table 4). The results presented in Fig. 8 and Table 5 suggest that our new algorithm  
 572 works at least as well as B1999 and V2005 on this dataset (both with updated coefficients). The

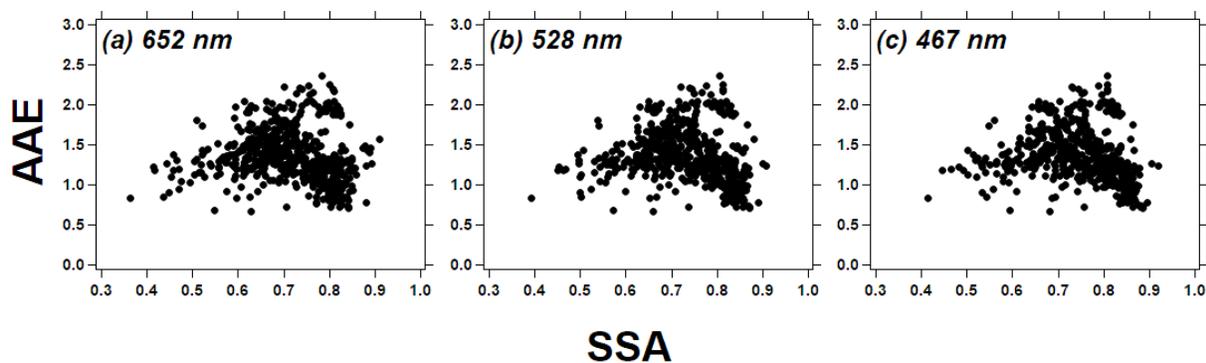
573 repeatability of the coefficient values in “Algorithm A” is confirmed for the SGP measurements  
574 using the same procedure as described in Sect. 3.2 (see results in Fig. S13 and Table S12).



575  
576 **Figure 8.** Inter-comparison between the CLAP-derived  $B_{abs}$  corrected by “Algorithm A” in the  
577 present work and reference  $B_{abs}$  at 652, 528, and 467 nm for the ambient data at the SGP study  
578 area. The solid line represents the linear regression, while the dashed line is a 1:1 line.

579 On the SGP data, we see similar performance to the FIREX data when we apply “Algorithm B”,  
580 where we again sampled half of the CLAP data, used the initial guesses derived in “Algorithm A”,  
581 and repeated this process 1000 times. Although the slopes tend to be larger than 1 (i.e., the  
582 corrected CLAP  $B_{abs}$  remains high relative to the PASS  $B_{abs}$ ), the results still represent an  
583 improvement over B1999 and V2005 using their recommended coefficients for their correction  
584 equations.

585 Implementing “Algorithm C” is challenging for ambient data, because there is no distinct power  
586 function relationship in AAE vs. SSA (Fig. 9); this is consistent with other field studies reporting  
587 both SSA and AAE (e.g., Backman et al. (2014) and Lim et al. (2018)). Our approach described  
588 here is only appropriate for ambient aerosols that follow a power function, such as sites impacted  
589 by biomass burning. Nevertheless, we did apply this to a subset of the SGP data where the AAE-  
590 SSA prediction error is within 30% ( $N = 86$ ), and for this subset of data, “Algorithm C” works  
591 fairly well (slopes  $\approx 0.95$ ; see Fig. S14). Therefore, while “Algorithm C” may have utility for  
592 ambient data, we advise caution when using this algorithm since the aerosols influencing the site  
593 may not be represented by a clear AAE-SSA power function (e.g., when biomass burning and  
594 coarse aerosols are equally prevalent at a long-term monitoring site).



595  
 596 **Figure 9.** AAE plotted against SSA for the SGP ambient data. The power law fit ( $AAE = a + b \times SSA^c$ )  
 597 is performed on SSA ( $SSA = B_{scat}/(B_{scat} + B_{ATN})$ ) and AAE computed by three-wavelength  $B_{ATN}$ .

598 These new algorithms are also applicable to the PSAP deployed at the SGP site. The results of the  
 599 correction for the PSAP are presented in Table 5 and Fig. S11, and the recommended initial guesses  
 600 when implementing “Algorithm B” to PSAP- $B_{ATN}$  at ambient environments are given in Table 4.  
 601 As expected, there is good agreement between corrected PSAP- and CLAP- $B_{abs}$  (Table 6).

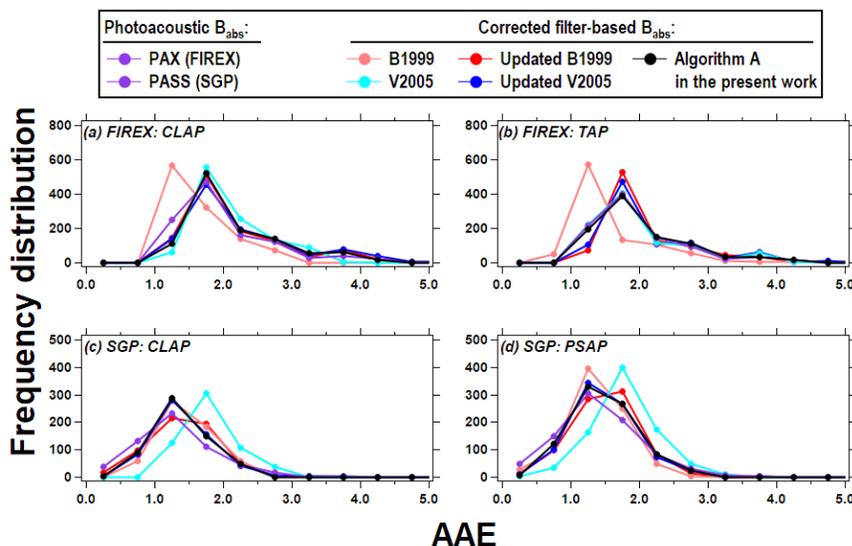
602 To investigate if our algorithms are suitable to correct  $B_{abs}$  obtained from different ambient  
 603 environments, the aerosol properties from the SGP site are compared to those from the other  
 604 NOAA/ESRL observational sites. We use the similar “AAE-SAE space” as that in Cappa et al.  
 605 (2016) and Schmeisser et al. (2017) to infer dominant aerosol types (e.g., BC, BrC, dust, mixed  
 606 dust/BC/BrC, see Fig. S15). Our results of AAE and SAE overlap with most of the values from  
 607 the NOAA/ESRL sites, except when marine aerosols or dust contribute to the local aerosol  
 608 emissions. Though none of the NOAA/ESRL sites fall into the clusters of BC or BC/BrC, some of  
 609 our data can represent the optical properties of aerosols from these clusters. Therefore, we highlight  
 610 that our algorithm developed by the SGP data may have the potential to be generalized to a variety  
 611 of environmental conditions, but we would need to validate this using observations from more  
 612 studies.

### 613 3.4. Impact of the implemented correction algorithm on aerosol optical properties

614 In addition to the direct comparisons of  $B_{abs}$  between the filter-based and photoacoustic  
 615 measurements, we compare derived optical properties (AAE and SSA) from different instruments  
 616 to assess the algorithms’ performance on derived aerosol optical properties. For example, we have  
 617 discussed the discrepancy of SSA between the filter-based and photoacoustic measurements when  
 618 implementing “Algorithm C” in Sect. 3.2. In this section we will more broadly discuss the impact  
 619 of different correction algorithms on AAE and SSA.

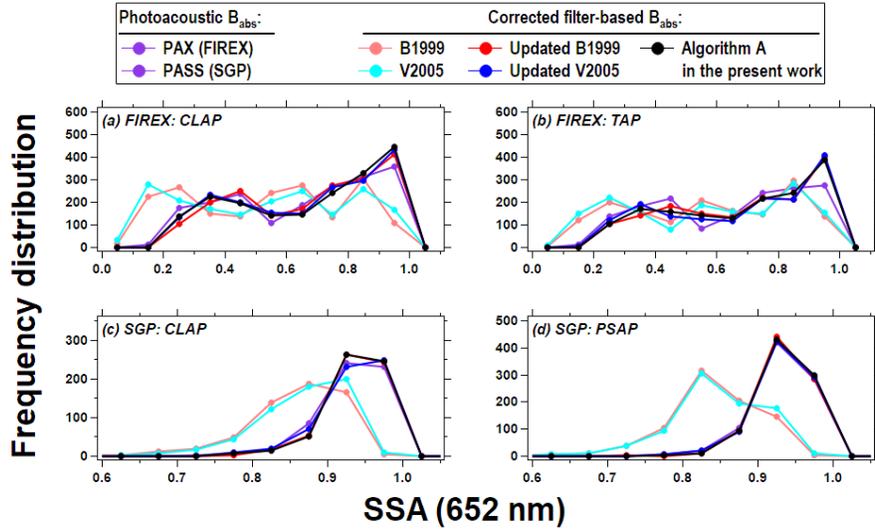
620 In Fig. 10, we present the frequency distribution of AAE for both FIREX and SGP data generated  
 621 from different campaign/instrument pairs using different correction approaches. For the FIREX  
 622 data (Fig. 10a-b), most corrections (with the exception of the “default” B1999) are consistent with  
 623 the photoacoustic data, while for the SGP data (Fig. 10c-d), most corrections (with the exception  
 624 of “default” V2005) are consistent with the photoacoustic data. However, updating the coefficients  
 625 for B1999 and V2005 improves the agreement with the photoacoustic data. The 50% difference  
 626 that exists between the B1999 and V2005 algorithms in all panels in Fig. 10 are consistent with  
 627 previous studies. For example, both Backman et al. (2014) and Davies et al. (2019) found that the

628 V2005-derived AAE is greater than B1999-derived AAE by 33% to 50% for ambient aerosols.  
 629 Therefore, we highlight that the default coefficients in B1999 and V2005 may have some  
 630 limitations when deriving AAE using the corrected  $B_{\text{abs}}$ ; instead, updating the coefficients or using  
 631 the new algorithm proposed in this work may yield more robust AAE results.



632  
 633 **Figure 10.** The frequency distribution of AAE calculated for different instrument/correction  
 634 combinations of multi-wavelength  $B_{\text{abs}}$ .

635 Similar to Fig. 10, we also investigate the distribution of SSA computed by using corrected  $B_{\text{abs}}$   
 636 along with  $B_{\text{scat}}$ . We provide the results at 652 nm as an example in the main text (Fig. 11); figures  
 637 for 528 nm and 467 nm can be found in the Supplementary Material (Fig. S16 and S17). For both  
 638 FIREX and SGP data, the SSA obtained using the new algorithm agree very well with the B1999  
 639 and V2005 but only when their coefficients have been updated. Calculations of SSA using B1999  
 640 and V2005 with their recommended coefficients suggest that these values may be biased low,  
 641 which follows the over-estimation of corrected  $B_{\text{abs}}$  demonstrated in Fig. 2.

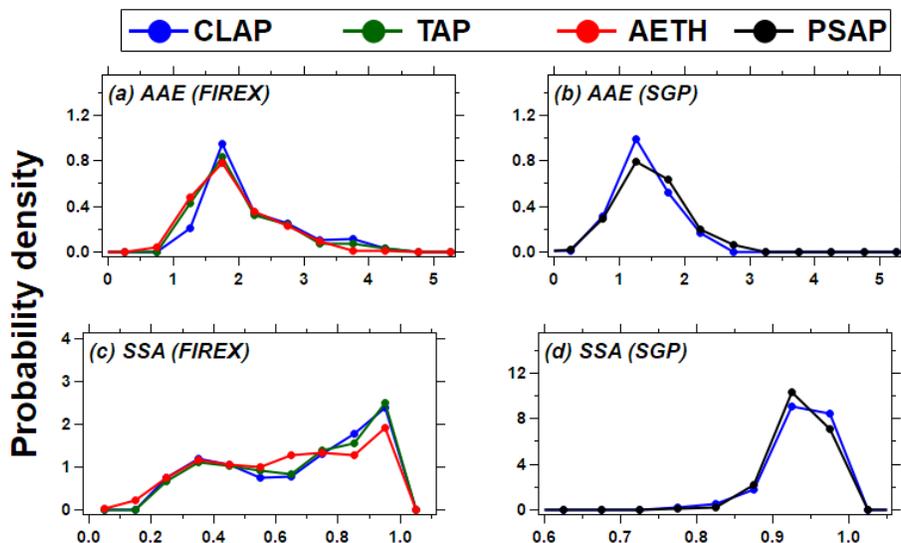


642

643 **Figure 11.** The frequency distribution of SSA (652 nm) calculated for different  
 644 instrument/correction combinations of  $B_{abs}$  and  $B_{scat}$ .

645 Moreover, we plot similar figures as Fig. 10-11 using all algorithms (A, B, and C). As shown in  
 646 Fig. S18, the results using “Algorithm B” agrees very well with those using “Algorithm A”, but  
 647 the use of “Algorithm C” results in some obvious discrepancies compared to the photoacoustic  
 648 reference, again highlighting the potential for large uncertainty using this algorithm.

649 In Fig. 12, we directly compare the distributions of both AAE and SSA at 652 nm for all of the  
 650 filter-based absorption photometers considered here, using our “Algorithm A” to correct the  $B_{ATN}$   
 651 data. For both datasets, after the corrections have been applied, there are only marginal differences  
 652 of the AAE (Fig. 10a and 10b) derived by different instruments. Similarly, there is good agreement  
 653 among the SSA values when using corrected- $B_{abs}$  from different instruments (Fig. 10c and 10d).  
 654 Overall, the derived properties using the new correction are consistent across all instruments,  
 655 suggesting its generalizability.



656  
 657 **Figure 12** The probability density of AAE and SSA (652 nm) derived by different filter-based  
 658 photometers  $B_{\text{abs}}$  (corrected by “Algorithm A” in the present work). Note that the number of total  
 659 observations vary across instruments.

### 660 3.5. Uncertainty of the new algorithms

661 In this section, we estimate the uncertainty of the new algorithms due to both measurement  
 662 uncertainties of the instruments and the uncertainties of parameter computation. We then simulate  
 663 the propagated uncertainty in the corrected filter-based  $B_{\text{abs}}$  reported in this paper.

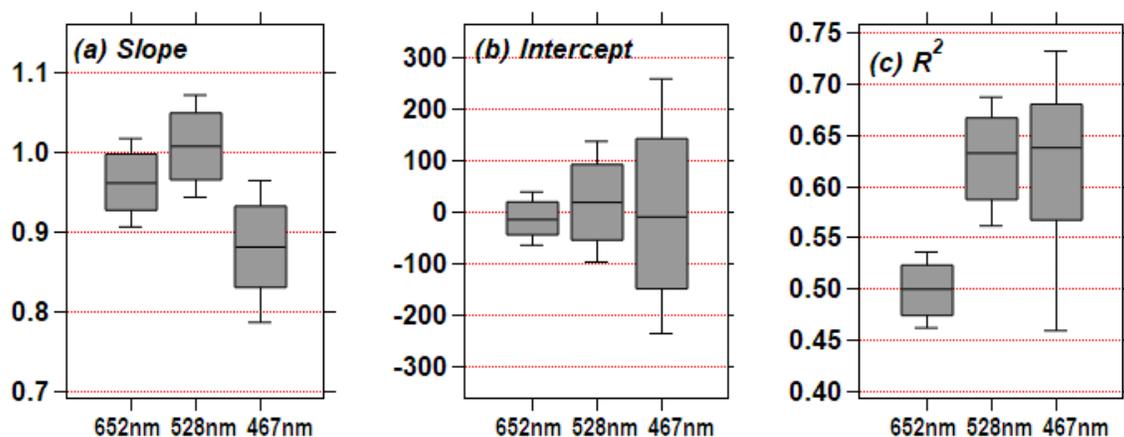
664 Measurement uncertainties of the instruments considered here have been reported in previous work  
 665 (e.g., (Anderson et al., 1996; Nakayama et al., 2015; Ogren et al., 2017; Sherman et al., 2015)) and  
 666 are summarized in Table 1. The typical sources of measurement uncertainty of the aerosol  
 667 instruments include: 1) instrument noise (often associated with the averaging time); 2) calibration  
 668 uncertainties (such as the accuracy of the operating wavelengths and the properties of the  
 669 calibration materials); 3) standard temperature and pressure (STP) correction uncertainties  
 670 (Sherman et al., 2015); and 4) flow rate uncertainties. Additional uncertainties that are specific to  
 671 filter-based absorption photometers include spot size and filter medium corrections (Bond et al.,  
 672 1999; Ogren et al., 2017). Regardless, these values all tend to be  $\leq 30\%$ , which is consistent with  
 673 other commonly-used aerosol instrumentation.

674 Because correction algorithms for filter-based absorption instruments also require aerosol optical  
 675 properties, the algorithms’ performance will be affected by these values as well. For example,  
 676 uncertainties in SSA are directly related to uncertainties associated with  $B_{\text{abs}}$  and  $B_{\text{scat}}$ , which are  
 677 both included in our simulations. However, capturing uncertainties in AAE is more complex, as  
 678 AAE can be computed by either “ $2\lambda$  fit” (a linear fit using  $B_{\text{abs}}$  at two wavelengths) or “ $3\lambda$  fit”  
 679 (same as the power fit used in the present work). Davies et al. (2019) used the  $3\lambda$  fit to calculate  
 680 AAE and compared this to calculations using 662 nm and 785 nm (i.e.,  $\text{AAE}_{662/785}$ ), finding that  
 681 the  $3\lambda$  results was about 50% greater. Moreover, similar differences (-35% to 85%) can exist  
 682 comparing two different  $2\lambda$  combinations ( $\text{AAE}_{440/870}$  and  $\text{AAE}_{675/870}$ ), depending on the  
 683 contribution of brown carbon to absorption at 440 nm (Wang et al., 2016). However, based on Fig.  
 684 S19 and S20, we demonstrate small ( $< \sim 10\%$ ) differences in the calculated values of AAE using

685 our Algorithm A using different  $2\lambda$  combinations for linear fits and the  $3\lambda$  power-law fit, when  
 686 considering both FIREX and SGP data. Consequently, we do not include AAE calculation  
 687 uncertainty in our simulation.

688 In our simulations, the propagated uncertainty of corrected  $B_{\text{abs}}$  is estimated by implementing the  
 689 new algorithm to datasets in which filter-based  $B_{\text{ATN}}$ , reference  $B_{\text{abs}}$ , and  $B_{\text{scat}}$  are subject to  
 690 measurement uncertainties. The full procedure is outlined in the Supplementary Material, but we  
 691 provide a brief overview of our Monte Carlo approach here. First, we create a synthetic dataset ( $n$   
 692  $= 500$  records) that defines  $B_{\text{abs}}$  at 652 nm and AAE that is intended to represent biomass burning.  
 693 Values of  $B_{\text{ATN}}$  and SSA are then computed using the relationships presented in Fig. 3 and Fig. 6,  
 694 respectively. Respective uncertainties associated with each of these values are applied following  
 695 Table 1, assuming that these follow a normal distribution. We then applied “Algorithm B” to the  
 696  $B_{\text{ATN}}$  dataset, repeated 1000 times, to quantify overall uncertainty associated with our correction  
 697 algorithm.

698 Figure 13 provides a graphical summary of our uncertainty simulation results, which was derived  
 699 by fitting linear equations to the “true”  $B_{\text{abs}}$  value (that we defined) and the “corrected”  $B_{\text{abs}}$  values  
 700 (outputs of each iteration). Considering the slopes (Fig. 12a), our algorithm can generally  
 701 reproduce the “true” value within 10% at 652 nm and 528 nm, but the performance is slightly  
 702 degraded at 467 nm. The median intercept for our simulations is close to zero, but the interquartile  
 703 range increases with decreasing wavelength (Fig. 12b), suggesting that the uncertainty may  
 704 increase at shorter wavelengths. The coefficients of determination (Fig. 12c) range from 0.47 (652  
 705 nm) to 0.68 (467 nm), showing that the algorithm may be less precise if large measurement  
 706 uncertainties exist. Even though these sources of uncertainty exist when implementing our  
 707 correction algorithms and propagate through to the corrected values, we argue that our new  
 708 algorithm will “standardize” uncertainties across corrected  $B_{\text{abs}}$  values from filter-based absorption  
 709 photometers. Moreover, the new algorithms perform, at least, better than the previous algorithms  
 710 with “default” coefficients, or as well as the previous algorithms with updated coefficients.



711  
 712 **Figure 13.** The box-and-whisker plots (slope, intercept, and  $R^2$ ) for the Monte Carlo simulation of  
 713 the relationship between the CLAP-derived  $B_{\text{abs}}$  (corrected by “Algorithm B” in the present work)  
 714 and “true”  $B_{\text{abs}}$  for all three wavelengths.

#### 715 4. Conclusions

716 Filter-based absorption instruments are widely used at global observational sites due to their  
717 relatively low cost, fast response, and easy operation. Despite the existence of different correction  
718 algorithms to correct the filter-based  $B_{\text{abs}}$  measurements, these are not “standardized” as  
719 differences in corrected  $B_{\text{abs}}$  values exist across different instrument/correction combinations, even  
720 when the instruments are co-located. This study provides a systematic evaluation of the previous  
721 correction algorithms (B1999 and V2005 corrections) on the CLAP and similar instruments (TAP  
722 and PSAP) using both laboratory-generated biomass burning emissions and ambient aerosols. We  
723 also developed new correction algorithms that are applicable to any filter-based absorption  
724 photometer (e.g., PSAP, CLAP, TAP, AETH), which will have utility for any historic or future  
725 filter-based absorption measurements and which have the potential to standardize absorption  
726 coefficients across all filter-based instruments. This latter point is demonstrated in Table 6 and Fig.  
727 12 in that there is good agreement across all filter-based absorption photometers when applying  
728 our corrections to both biomass burning and ambient data. In practice, we anticipate that our  
729 Algorithm B will be most common, because at long-term monitoring sites, filter-based absorption  
730 photometers are typically co-located with a nephelometer.

731 Using the existing corrections on our CLAP measurements, we find that the corrected  $B_{\text{abs}}$   
732 overestimate photoacoustic  $B_{\text{abs}}$  by factors of  $\sim 2.6$  (biomass burning aerosols) and  $\sim 3.2$  (ambient  
733 aerosols). Similar overestimations of absorption by filter-based instruments are seen in the results  
734 of TAP from the FIREX study and PSAP deployed at the SGP. Comparing between B1999 and  
735 V2005,  $B_{\text{abs}}$  corrected by the two corrections differ by  $-6\%$  to  $18\%$ . These discrepancies in our  
736 results are consistent with those reported for the inter-comparisons between filter-based and  
737 photoacoustic absorption instruments (e.g., (Arnott et al., 2003; Davies et al., 2019; Li et al., 2019;  
738 Müller et al., 2011a)).

739 Overall, our new developed algorithms (A, B, and C) perform well on correcting  $B_{\text{abs}}$  for different  
740 filter-based absorption photometers (CLAP, TAP, PSAP, and AETH) from both biomass burning  
741 and ambient measurements. Our work suggests that if the filter-based instrument is co-operated  
742 with a reference absorption instrument and a NEPH at field for a period, researchers can compute  
743 site-specific initial guesses (same as “Algorithm A” in the present work). Otherwise, either  
744 “Algorithm B” or “Algorithm C” proposed in this paper can be used to correct the filter-based  
745 measurements. In “Algorithm B” when a filter-based absorption photometer is co-located with a  
746 NEPH but without a reference instrument, the set of coefficients yield in this work (Table 4) can  
747 be used as initial guesses to implement the algorithm. In “Algorithm C” when a filter-based  
748 absorption photometer is operated by itself, a “representative” relationship between AAE and SSA  
749 can be used to estimate SSA from AAE at each step in the iterative process, but we advise caution  
750 if this relationship is not monotonic (e.g., as in the ambient data from SGP and from Backman et  
751 al. (2014) and Lim et al. (2018)). The only scenario not included in the present work is that the  
752 filter-based absorption photometer is co-located with a reference absorption instrument, but no  
753 instrument for scattering. However, under this scenario, one could simply use the photoacoustic  
754  $B_{\text{abs}}$  data because no filter-induced biases exist for those instruments.

755 In terms of the aerosol optical properties (AAE and SSA) computed by different corrections, the  
756 new algorithm suggests no bias of AAE and SSA when compared to that derived by updated-  
757 B1999 and updated-V2005 for both aerosol datasets.

758 However, the new algorithm is not without limitations. First, we used the photoacoustic  $B_{\text{abs}}$  as the  
759 reference to develop the algorithm and the initial guess of the coefficients; meanwhile, some  
760 studies argue that photoacoustic absorption is not a “ground truth” (e.g., (Lack et al., 2006; Lewis  
761 et al., 2008)). Thus, we simulate the propagated uncertainty of our algorithms considering the  
762 measurement uncertainties due to the photoacoustic  $B_{\text{abs}}$  (as well as  $B_{\text{ATN}}$  and  $B_{\text{scat}}$ ) and find that  
763 the corrected  $B_{\text{abs}}$  can be biased by -17% to 5%, depending on the operated wavelength. Although  
764 potential bias due to the precision of photoacoustic  $B_{\text{abs}}$  cannot be excluded, using our new  
765 algorithm to correct the filter-based  $B_{\text{abs}}$  will at least eliminate correction-related biases among  
766 different filter-based instruments. Second, we only tested the algorithms with data from biomass  
767 burning and ambient measurements. It is unclear how the algorithms will work for other absorbing  
768 aerosols (e.g., dominated by fossil fuel emissions or mineral dust). Further evaluation of the  
769 performance of the new algorithm on other aerosol sources may help to address this issue.  
770 Regardless, we argue that our approach can standardize reported absorption coefficients at long-  
771 term monitoring sites, which has the potential to yield a better data set with which to evaluate  
772 chemistry-climate models.

773 **Code and data availability.** The code for the algorithm was initially written in Igor Pro  
774 (WaveMetrics Inc.) and has been developed to be accessible through either Python (Version 3.7.5)  
775 or Igor Pro. The implementation of our algorithm is available at  
776 <https://doi.org/10.5281/zenodo.3742342>. The FIREX aerosol products are available at  
777 <https://esrl.noaa.gov/csd/project/firex>. The SGP aerosol products are available at  
778 <https://www.archive.arm.gov/discovery/> (February 2013–July 2013, 36° 36' 18.0" N, 97° 29' 6.0"  
779 W: Southern Great Plains Central Facility, data set accessed 01/16/19).

780 **Author contributions.** HL developed the model, conducted the evaluations, and drafted the  
781 manuscript. AAM and GRM edited the manuscript and obtained funding.

782 **Competing interests.** The authors declare that they have no conflict of interest.

783 **Acknowledgements.** The authors would like to thank Allison Aiken (Los Alamos National  
784 Laboratory) for useful discussions regarding the SGP PASS-3 data. The authors greatly  
785 acknowledge Vanessa Selimovic, and Robert Yokelson from University of Montana for lending  
786 us the PAX-405; Patrick Sheridan, John Ogren, and Derek Hageman from NOAA for lending us  
787 the CLAP; and Anthony Prenni from the National Park Service for lending us the AETH during  
788 the FIREX campaign. We also thank Nick Good (Colorado State University), Jim Roberts (NOAA)  
789 and Carsten Warneke (NOAA) for their on-site support at FSL.

790 **Financial support.** The authors and FIREX data were supported by NOAA Climate Program  
791 Office Grant NA16OAR4310109. The ambient data at SGP site in Lamont (OK, USA) were  
792 obtained from the atmospheric radiation measurement (ARM) user facility, a U.S. Department of  
793 Energy (DOE) Office of Science user facility managed by the Office of Biological and  
794 Environmental Research.

795 **Review statement.** The authors thank Associate Editor Paolo Laj for handling this submission and  
796 the anonymous reviewers for their valuable comments.

797 5. References

- 798 Allan, D. W.: Statistics of atomic frequency standards, *Proc. IEEE*, 54(2), 221–230,  
799 doi:10.1109/PROC.1966.4634, 1966.
- 800 Alvarado, M. J., Lonsdale, C. R., Macintyre, H. L., Bian, H., Chin, M., Ridley, D. A., Heald, C.  
801 L., Thornhill, K. L., Anderson, B. E., Cubison, M. J., Jimenez, J. L., Kondo, Y., Sahu, L. K., Dibb,  
802 J. E. and Wang, C.: Evaluating model parameterizations of submicron aerosol scattering and  
803 absorption with in situ data from ARCTAS 2008, *Atmos. Chem. Phys.*, 16(14), 9435–9455,  
804 doi:10.5194/acp-16-9435-2016, 2016.
- 805 Anderson, T. L., Covert, D. S., Marshall, S. F., Laucks, M. L., Charlson, R. J., Waggoner, A. P.,  
806 Ogren, J. A., Caldow, R., Holm, R. L., Quant, F. R., Sem, G. J., Wiedensohler, A., Ahlquist, N. A.  
807 and Bates, T. S.: Performance Characteristics of a High-Sensitivity, Three-Wavelength, Total  
808 Scatter/Backscatter Nephelometer, *J. Atmos. Ocean. Technol.*, 13(5), 967–986, doi:10.1175/1520-  
809 0426, 1996.
- 810 Andrews, E., Sheridan, P. J. and Ogren, J. A.: Seasonal differences in the vertical profiles of  
811 aerosol optical properties over rural Oklahoma, *Atmos. Chem. Phys.*, 11(20), 10661–10676,  
812 doi:10.5194/acp-11-10661-2011, 2011.
- 813 Andrews, E., Sheridan, P. J., Ogren, J. A., Hageman, D., Jefferson, A., Wendell, J., Alástuey, A.,  
814 Alados-Arboledas, L., Bergin, M., Ealo, M., Hallar, A. G., Hoffer, A., Kalapov, I., Keywood, M.,  
815 Kim, J., Kim, S.-W., Kolonjari, F., Labuschagne, C., Lin, N.-H., Macdonald, A., Mayol-Bracero,  
816 O. L., McCubbin, I. B., Pandolfi, M., Reisen, F., Sharma, S., Sherman, J. P., Sorribas, M. and Sun,  
817 J.: Overview of the NOAA/ESRL Federated Aerosol Network, *Bull. Am. Meteorol. Soc.*, 100(1),  
818 123–135, doi:10.1175/BAMS-D-17-0175.1, 2019.
- 819 Arnott, W. P., Moosmüller, H., Sheridan, P. J., Ogren, J. A., Raspert, R., Slaton, W. V., Hand, J.  
820 L., Kreidenweis, S. M. and Collett, J. L.: Photoacoustic and filter-based ambient aerosol light  
821 absorption measurements: Instrument comparisons and the role of relative humidity, *J. Geophys.*  
822 *Res.*, 108(D1), 4034, doi:10.1029/2002JD002165, 2003.
- 823 Arnott, W. P., Hamasha, K., Moosmüller, H., Sheridan, P. J. and Ogren, J. A.: Towards Aerosol  
824 Light-Absorption Measurements with a 7-Wavelength Aethalometer: Evaluation with a  
825 Photoacoustic Instrument and 3-Wavelength Nephelometer, *Aerosol Sci. Technol.*, 39(1), 17–29,  
826 doi:10.1080/027868290901972, 2005.
- 827 Ayers, G. P.: Comment on regression analysis of air quality data, *Atmos. Environ.*, 35(13), 2423–  
828 2425, doi:10.1016/S1352-2310(00)00527-6, 2001.
- 829 Backman, J., Virkkula, A., Vakkari, V., Beukes, J. P., Van Zyl, P. G., Josipovic, M., Piketh, S.,  
830 Tiitta, P., Chiloane, K., Petäjä, T., Kulmala, M. and Laakso, L.: Differences in aerosol absorption  
831 Ångström exponents between correction algorithms for a particle soot absorption photometer  
832 measured on the South African Highveld, *Atmos. Meas. Tech.*, 7(12), 4285–4298,  
833 doi:10.5194/amt-7-4285-2014, 2014.
- 834 Bergstrom, R. W., Pilewskie, P., Russell, P. B., Redemann, J., Bond, T. C., Quinn, P. K. and Sierau,  
835 B.: Spectral absorption properties of atmospheric aerosols, *Atmos. Chem. Phys.*, 7(23), 5937–5943,  
836 doi:10.5194/acp-7-5937-2007, 2007.

- 837 Bond, T. C. and Bergstrom, R. W.: Light absorption by carbonaceous particles: An investigative  
838 review, *Aerosol Sci. Technol.*, 40(1), 27–67, doi:10.1080/02786820500421521, 2006.
- 839 Bond, T. C., Anderson, T. L. and Campbell, D.: Calibration and Intercomparison of Filter-Based  
840 Measurements of Visible Light Absorption by Aerosols, *Aerosol Sci. Technol.*, 30(6), 582–600,  
841 doi:10.1080/027868299304435, 1999.
- 842 Boucher, O.: *Atmospheric Aerosols*, Springer Netherlands, Dordrecht., 2015.
- 843 Cappa, C. D., Lack, D. A., Burkholder, J. B. and Ravishankara, A. R.: Bias in Filter-Based Aerosol  
844 Light Absorption Measurements Due to Organic Aerosol Loading: Evidence from Laboratory  
845 Measurements, *Aerosol Sci. Technol.*, 42(12), 1022–1032, doi:10.1080/02786820802389285,  
846 2008.
- 847 Cappa, C. D., Kolesar, K. R., Zhang, X., Atkinson, D. B., Pekour, M. S., Zaveri, R. A., Zelenyuk,  
848 A. and Zhang, Q.: Understanding the optical properties of ambient sub- and supermicron  
849 particulate matter: results from the CARES 2010 field study in northern California, *Atmos. Chem.  
850 Phys.*, 16(10), 6511–6535, doi:10.5194/acp-16-6511-2016, 2016.
- 851 Chen, S., Russell, L. M., Cappa, C. D., Zhang, X., Kleeman, M. J., Kumar, A., Liu, D. and  
852 Ramanathan, V.: Comparing black and brown carbon absorption from AERONET and surface  
853 measurements at wintertime Fresno, *Atmos. Environ.*, 199, 164–176,  
854 doi:10.1016/j.atmosenv.2018.11.032, 2019.
- 855 Collaud Coen, M., Weingartner, E., Apituley, A., Ceburnis, D., Fierz-Schmidhauser, R., Flentje,  
856 H., Henzing, J. S., Jennings, S. G., Moerman, M., Petzold, A., Schmid, O. and Baltensperger, U.:  
857 Minimizing light absorption measurement artifacts of the Aethalometer: evaluation of five  
858 correction algorithms, *Atmos. Meas. Tech.*, 3(2), 457–474, doi:10.5194/amt-3-457-2010, 2010.
- 859 Davies, N. W., Fox, C., Szpek, K., Cotterell, M. I., Taylor, J. W., Allan, J. D., Williams, P. I.,  
860 Trembath, J., Haywood, J. M. and Langridge, J. M.: Evaluating biases in filter-based aerosol  
861 absorption measurements using photoacoustic spectroscopy, *Atmos. Meas. Tech.*, 12(6), 3417–  
862 3434, doi:10.5194/amt-12-3417-2019, 2019.
- 863 Drinovec, L., Gregorič, A., Zotter, P., Wolf, R., Bruns, E. A., Prévôt, A. S. H., Petit, J.-E., Favez,  
864 O., Sciare, J., Arnold, I. J., Chakrabarty, R. K., Moosmüller, H., Filep, A. and Močnik, G.: The  
865 filter-loading effect by ambient aerosols in filter absorption photometers depends on the coating  
866 of the sampled particles, *Atmos. Meas. Tech.*, 10(3), 1043–1059, doi:10.5194/amt-10-1043-2017,  
867 2017.
- 868 Fischer, D. Al and Smith, G. D.: A portable, four-wavelength, single-cell photoacoustic  
869 spectrometer for ambient aerosol absorption, *Aerosol Sci. Technol.*, 52(4), 393–406,  
870 doi:10.1080/02786826.2017.1413231, 2018.
- 871 Horvath, H.: Atmospheric light absorption—A review, *Atmos. Environ. Part A. Gen. Top.*, 27(3),  
872 293–317, doi:10.1016/0960-1686(93)90104-7, 1993.
- 873 Jiang, Y., Yang, J., Gagné, S., Chan, T. W., Thomson, K., Fofie, E., Cary, R. A., Rutherford, D.,  
874 Comer, B., Swanson, J., Lin, Y., Van Rooy, P., Asa-Awuku, A., Jung, H., Barsanti, K., Karavalakis,  
875 G., Cocker, D., Durbin, T. D., Miller, J. W. and Johnson, K. C.: Sources of variance in BC mass  
876 measurements from a small marine engine: Influence of the instruments, fuels and loads, *Atmos.*

877 Environ., 182, 128–137, doi:10.1016/j.atmosenv.2018.03.008, 2018.

878 Kirchstetter, T. W. and Novakov, T.: Controlled generation of black carbon particles from a  
879 diffusion flame and applications in evaluating black carbon measurement methods, *Atmos.*  
880 *Environ.*, 41(9), 1874–1888, doi:10.1016/j.atmosenv.2006.10.067, 2007.

881 Koss, A. R., Sekimoto, K., Gilman, J. B., Selimovic, V., Coggon, M. M., Zarzana, K. J., Yuan, B.,  
882 Lerner, B. M., Brown, S. S., Jimenez, J. L., Krechmer, J., Roberts, J. M., Warneke, C., Yokelson,  
883 R. J. and de Gouw, J.: Non-methane organic gas emissions from biomass burning: identification,  
884 quantification, and emission factors from PTR-ToF during the FIREX 2016 laboratory experiment,  
885 *Atmos. Chem. Phys.*, 18(5), 3299–3319, doi:10.5194/acp-18-3299-2018, 2018.

886 Lack, D. A., Lovejoy, E. R., Baynard, T., Pettersson, A. and Ravishankara, A. R.: Aerosol  
887 Absorption Measurement using Photoacoustic Spectroscopy: Sensitivity, Calibration, and  
888 Uncertainty Developments, *Aerosol Sci. Technol.*, 40(9), 697–708,  
889 doi:10.1080/02786820600803917, 2006.

890 Lack, D. A., Cappa, C. D., Covert, D. S., Baynard, T., Massoli, P., Sierau, B., Bates, T. S., Quinn,  
891 P. K., Lovejoy, E. R. and Ravishankara, A. R.: Bias in Filter-Based Aerosol Light Absorption  
892 Measurements Due to Organic Aerosol Loading: Evidence from Ambient Measurements, *Aerosol*  
893 *Sci. Technol.*, 42(12), 1033–1041, doi:10.1080/02786820802389277, 2008a.

894 Lack, D. A., Lerner, B., Granier, C., Baynard, T., Lovejoy, E., Massoli, P., Ravishankara, A. R.  
895 and Williams, E.: Light absorbing carbon emissions from commercial shipping, *Geophys. Res.*  
896 *Let.*, 35(13), L13815, doi:10.1029/2008GL033906, 2008b.

897 Lack, D. A., Moosmüller, H., McMeeking, G. R., Chakrabarty, R. K. and Baumgardner, D.:  
898 Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: A review  
899 of techniques, their limitations and uncertainties, *Anal. Bioanal. Chem.*, 406(1), 99–122,  
900 doi:10.1007/s00216-013-7402-3, 2014.

901 Laing, J. R., Jaffe, D. A. and Hee, J. R.: Physical and optical properties of aged biomass burning  
902 aerosol from wildfires in Siberia and the Western USA at the Mt. Bachelor Observatory, *Atmos.*  
903 *Chem. Phys.*, 16(23), 15185–15197, doi:10.5194/acp-16-15185-2016, 2016.

904 Levenberg, K.: A method for the solution of certain non-linear problems in least squares, *Q. Appl.*  
905 *Math.*, 2(2), 164–168, 1944.

906 Lewis, K., Arnott, W. P., Moosmüller, H. and Wold, C. E.: Strong spectral variation of biomass  
907 smoke light absorption and single scattering albedo observed with a novel dual-wavelength  
908 photoacoustic instrument, *J. Geophys. Res. Atmos.*, 113(16), 1–14, doi:10.1029/2007JD009699,  
909 2008.

910 Li, H., Lamb, K. D., Schwarz, J. P., Selimovic, V., Yokelson, R. J., McMeeking, G. R. and May,  
911 A. A.: Inter-comparison of black carbon measurement methods for simulated open biomass  
912 burning emissions, *Atmos. Environ.*, 206, 156–169, doi:10.1016/j.atmosenv.2019.03.010, 2019.

913 Lim, S., Lee, M., Kim, S.-W. and Laj, P.: Sulfate alters aerosol absorption properties in East Asian  
914 outflow, *Sci. Rep.*, 8(1), 5172, doi:10.1038/s41598-018-23021-1, 2018.

915 Liu, S., Aiken, A. C., Arata, C., Dubey, M. K., Stockwell, C. E., Yokelson, R. J., Stone, E. A.,  
916 Jayarathne, T., Robinson, A. L., DeMott, P. J. and Kreidenweis, S. M.: Aerosol single scattering

917 albedo dependence on biomass combustion efficiency: Laboratory and field studies, *Geophys. Res.*  
918 *Let.*, 41(2), 742–748, doi:10.1002/2013GL058392, 2014.

919 McMeeking, G. R., Fortner, E., Onasch, T. B., Taylor, J. W., Flynn, M., Coe, H. and Kreidenweis,  
920 S. M.: Impacts of nonrefractory material on light absorption by aerosols emitted from biomass  
921 burning, *J. Geophys. Res. Atmos.*, 119(21), 12,272–12,286, doi:10.1002/2014JD021750, 2014.

922 Moosmüller, H., Chakrabarty, R. K. and Arnott, W. P.: Aerosol light absorption and its  
923 measurement: A review, *J. Quant. Spectrosc. Radiat. Transf.*, 110(11), 844–878,  
924 doi:10.1016/j.jqsrt.2009.02.035, 2009.

925 Moteki, N., Kondo, Y. and Nakamura, S.: Method to measure refractive indices of small  
926 nonspherical particles: Application to black carbon particles, *J. Aerosol Sci.*, 41(5), 513–521,  
927 doi:10.1016/j.jaerosci.2010.02.013, 2010.

928 Müller, T., Henzing, J. S., de Leeuw, G., Wiedensohler, A., Alastuey, A., Angelov, H., Bizjak, M.,  
929 Collaud Coen, M., Engström, J. E., Gruening, C., Hillamo, R., Hoffer, A., Imre, K., Ivanow, P.,  
930 Jennings, G., Sun, J. Y., Kalivitis, N., Karlsson, H., Komppula, M., Laj, P., Li, S.-M., Lunder, C.,  
931 Marinoni, A., Martins dos Santos, S., Moerman, M., Nowak, A., Ogren, J. A., Petzold, A., Pichon,  
932 J. M., Rodriguez, S., Sharma, S., Sheridan, P. J., Teinilä, K., Tuch, T., Viana, M., Virkkula, A.,  
933 Weingartner, E., Wilhelm, R. and Wang, Y. Q.: Characterization and intercomparison of aerosol  
934 absorption photometers: result of two intercomparison workshops, *Atmos. Meas. Tech.*, 4(2), 245–  
935 268, doi:10.5194/amt-4-245-2011, 2011a.

936 Müller, T., Laborde, M., Kassell, G. and Wiedensohler, A.: Design and performance of a three-  
937 wavelength LED-based total scatter and backscatter integrating nephelometer, *Atmos. Meas. Tech.*,  
938 4(6), 1291–1303, doi:10.5194/amt-4-1291-2011, 2011b.

939 Müller, T., Virkkula, A. and Ogren, J. A.: Constrained two-stream algorithm for calculating  
940 aerosol light absorption coefficient from the Particle Soot Absorption Photometer, *Atmos. Meas.*  
941 *Tech.*, 7(12), 4049–4070, doi:10.5194/amt-7-4049-2014, 2014.

942 Nakayama, T., Kondo, Y., Moteki, N., Sahu, L. K., Kinase, T., Kita, K. and Matsumi, Y.: Size-  
943 dependent correction factors for absorption measurements using filter-based photometers: PSAP  
944 and COSMOS, *J. Aerosol Sci.*, 41(4), 333–343, doi:10.1016/j.jaerosci.2010.01.004, 2010.

945 Nakayama, T., Suzuki, H., Kagamitani, S., Ikeda, Y., Uchiyama, A. and Matsumi, Y.:  
946 Characterization of a Three Wavelength Photoacoustic Soot Spectrometer (PASS-3) and a  
947 Photoacoustic Extinctionmeter (PAX), *J. Meteorol. Soc. Japan. Ser. II*, 93(2), 285–308,  
948 doi:10.2151/jmsj.2015-016, 2015.

949 Ogren, J. A.: Comment on “ Calibration and Intercomparison of Filter-Based Measurements of  
950 Visible Light Absorption by Aerosols ,” *Aerosol Sci. Technol.*, 44(December), 589–591,  
951 doi:10.1080/02786826.2010.482111, 2010.

952 Ogren, J. A., Wendell, J., Andrews, E. and Sheridan, P. J.: Continuous light absorption photometer  
953 for long-term studies, *Atmos. Meas. Tech.*, 10(12), 4805–4818, doi:10.5194/amt-10-4805-2017,  
954 2017.

955 Olson, M. R., Victoria Garcia, M., Robinson, M. A., Van Rooy, P., Dietenberger, M. A., Bergin,  
956 M. and Schauer, J. J.: Investigation of black and brown carbon multiple-wavelength-dependent

957 light absorption from biomass and fossil fuel combustion source emissions, *J. Geophys. Res.*  
958 *Atmos.*, 120(13), 6682–6697, doi:10.1002/2014JD022970, 2015.

959 Rajesh, T. A. and Ramachandran, S.: Black carbon aerosol mass concentration, absorption and  
960 single scattering albedo from single and dual spot aethalometers: Radiative implications, *J.*  
961 *Aerosol Sci.*, 119(January), 77–90, doi:10.1016/j.jaerosci.2018.02.001, 2018.

962 Saturno, J., Pöhlker, C., Massabò, D., Brito, J., Carbone, S., Cheng, Y., Chi, X., Ditas, F., Hrab  
963 De Angelis, I., Morán-Zuloaga, D., Pöhlker, M. L., Rizzo, L. V., Walter, D., Wang, Q., Artaxo, P.,  
964 Prati, P. and Andreae, M. O.: Comparison of different Aethalometer correction schemes and a  
965 reference multi-wavelength absorption technique for ambient aerosol data, *Atmos. Meas. Tech.*,  
966 10(8), 2837–2850, doi:10.5194/amt-10-2837-2017, 2017.

967 Schmeisser, L., Andrews, E., Ogren, J. A., Sheridan, P., Jefferson, A., Sharma, S., Kim, J. E.,  
968 Sherman, J. P., Sorribas, M., Kalapov, I., Arsov, T., Angelov, C., Mayol-Bracero, O. L.,  
969 Labuschagne, C., Kim, S.-W., Hoffer, A., Lin, N.-H., Chia, H.-P., Bergin, M., Sun, J., Liu, P. and  
970 Wu, H.: Classifying aerosol type using in situ surface spectral aerosol optical properties, *Atmos.*  
971 *Chem. Phys.*, 17(19), 12097–12120, doi:10.5194/acp-17-12097-2017, 2017.

972 Schmid, O., Artaxo, P., Arnott, W. P., Chand, D., Gatti, L. V., Frank, G. P., Hoffer, A., Schnaiter,  
973 M. and Andreae, M. O.: Spectral light absorption by ambient aerosols influenced by biomass  
974 burning in the Amazon Basin. I: Comparison and field calibration of absorption measurement  
975 techniques, *Atmos. Chem. Phys.*, 6(11), 3443–3462, doi:10.5194/acp-6-3443-2006, 2006.

976 Schwarz, J. P., Spackman, J. R., Fahey, D. W., Gao, R. S., Lohmann, U., Stier, P., Watts, L. A.,  
977 Thomson, D. S., Lack, D. A., Pfister, L., Mahoney, M. J., Baumgardner, D., Wilson, J. C. and  
978 Reeves, J. M.: Coatings and their enhancement of black carbon light absorption in the tropical  
979 atmosphere, *J. Geophys. Res.*, 113(D3), D03203, doi:10.1029/2007JD009042, 2008.

980 Sedlacek, A. J.: DOE/SC-ARM-TR-156 Aethalometer™ Instrument Handbook, DOE Office of  
981 Science Atmospheric Radiation Measurement (ARM) Program., 2016.

982 Selimovic, V., Yokelson, R. J., Warneke, C., Roberts, J. M., de Gouw, J., Reardon, J. and Griffith,  
983 D. W. T.: Aerosol optical properties and trace gas emissions by PAX and OP-FTIR for laboratory-  
984 simulated western US wildfires during FIREX, *Atmos. Chem. Phys.*, 18(4), 2929–2948,  
985 doi:10.5194/acp-18-2929-2018, 2018.

986 Sheridan, P. J., Arnott, W. P., Ogren, J. A., Andrews, E., Atkinson, D. B., Covert, D. S.,  
987 Moosmüller, H., Petzold, A., Schmid, B., Strawa, A. W., Varma, R. and Virkkula, A.: The Reno  
988 Aerosol Optics Study: An Evaluation of Aerosol Absorption Measurement Methods, *Aerosol Sci.*  
989 *Technol.*, 39(1), 1–16, doi:10.1080/027868290901891, 2005.

990 Sherman, J. P., Sheridan, P. J., Ogren, J. A., Andrews, E., Hageman, D., Schmeisser, L., Jefferson,  
991 A. and Sharma, S.: A multi-year study of lower tropospheric aerosol variability and systematic  
992 relationships from four North American regions, *Atmos. Chem. Phys.*, 15(21), 12487–12517,  
993 doi:10.5194/acp-15-12487-2015, 2015.

994 Springston, S. R.: DOE/SC-ARM-TR-176 Radiance Research Particle Soot/Absorption  
995 Photometer Instrument Handbook, DOE Office of Science Atmospheric Radiation Measurement  
996 (ARM) Program (United States)., 2016.

- 997 Subramanian, R., Roden, C. A., Boparai, P. and Bond, T. C.: Yellow Beads and Missing Particles:  
998 Trouble Ahead for Filter-Based Absorption Measurements, *Aerosol Sci. Technol.*, 41(6), 630–637,  
999 doi:10.1080/02786820701344589, 2007.
- 1000 Vignati, E., Karl, M., Krol, M., Wilson, J., Stier, P. and Cavalli, F.: Sources of uncertainties in  
1001 modelling black carbon at the global scale, *Atmos. Chem. Phys.*, 10(6), 2595–2611,  
1002 doi:10.5194/acp-10-2595-2010, 2010.
- 1003 Virkkula, A.: Correction of the Calibration of the 3-wavelength Particle Soot Absorption  
1004 Photometer ( $3\lambda$  PSAP), *Aerosol Sci. Technol.*, 44(8), 706–712,  
1005 doi:10.1080/02786826.2010.482110, 2010.
- 1006 Virkkula, A., Ahlquist, N. C., Covert, D. S., Arnott, W. P., Sheridan, P. J., Quinn, P. K. and  
1007 Coffman, D. J.: Modification, calibration and a field test of an instrument for measuring light  
1008 absorption by particles, *Aerosol Sci. Technol.*, 39(1), 68–83, doi:10.1080/027868290901963,  
1009 2005.
- 1010 Virkkula, A., Mäkelä, T., Hillamo, R., Yli-Tuomi, T., Hirsikko, A., Hämeri, K. and Koponen, I.  
1011 K.: A simple procedure for correcting loading effects of aethalometer data, *J. Air Waste Manag.*  
1012 *Assoc.*, 57(10), 1214–1222, doi:10.3155/1047-3289.57.10.1214, 2007.
- 1013 Virkkula, A., Chi, X., Ding, A., Shen, Y., Nie, W., Qi, X., Zheng, L., Huang, X., Xie, Y., Wang,  
1014 J., Petäjä, T. and Kulmala, M.: On the interpretation of the loading correction of the aethalometer,  
1015 *Atmos. Meas. Tech.*, 8(10), 4415–4427, doi:10.5194/amt-8-4415-2015, 2015.
- 1016 Wang, X., Heald, C. L., Sedlacek, A. J., de Sá, S. S., Martin, S. T., Alexander, M. L., Watson, T.  
1017 B., Aiken, A. C., Springston, S. R. and Artaxo, P.: Deriving brown carbon from multiwavelength  
1018 absorption measurements: method and application to AERONET and Aethalometer observations,  
1019 *Atmos. Chem. Phys.*, 16(19), 12733–12752, doi:10.5194/acp-16-12733-2016, 2016.
- 1020 Weingartner, E., Saathoff, H., Schnaiter, M., Streit, N., Bitnar, B. and Baltensperger, U.:  
1021 Absorption of light by soot particles: Determination of the absorption coefficient by means of  
1022 aethalometers, *J. Aerosol Sci.*, 34(10), 1445–1463, doi:10.1016/S0021-8502(03)00359-8, 2003.
- 1023