Performance Characteristics of Integrating Nephelometers in the Australian Outback

R. M. MITCHELL, S. K. CAMPBELL, AND Y. QIN

Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Canberra, Australian Capital Territory, Australia

J. L. GRAS

Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Aspendale, Victoria, Australia

(Manuscript received 16 June 2008, in final form 4 December 2008)

ABSTRACT

Radiance Research M903 nephelometers have been operated at remote Australian Outback sites since April 1998. This paper describes the calibration procedures applied to these instruments and reports on the noise performance and other operational issues. It is found that instrument noise leads to a detection limit of ~0.2 Mm⁻¹ in scattering coefficient at the 95% confidence interval for a 5-min integration. Changes in ambient temperature cause drift with a coefficient of ~0.06 Mm⁻¹ K⁻¹, leading to a typical diurnal drift of ~0.9 Mm⁻¹. Over the 10-yr deployment at an Outback station, the accuracy of the derived scattering coefficient is compromised by drifts in sensitivity and offset, in part related to gross changes in bandpass filter characteristics resulting from environmental degradation. A method is developed to track these changes. An uncertainty analysis suggests that the typical background scattering coefficient of ~10 Mm⁻¹ can be measured to within 15% at the 95% confidence level. For events where the scattering coefficient is ~100 Mm⁻¹, the uncertainty falls to ~5%. Correction factors are derived for angular truncation error and inlet efficiency for the particular inlet configuration adopted and illustrated via a case study using size distributions guided by collocated NASA Aerosol Robotic Network (AERONET) data.

1. Introduction

Since its development by Beuttell and Brewer (1949), the integrating nephelometer has played a significant role in the measurement of airborne particulate loading. The underlying principle of the most widely adopted configuration is that measurement of the scattering coefficient, defined as the effective light-scattering area presented by a medium per-unit volume, can be achieved optically by diffuse illumination of a sample volume over the hemisphere of scattering angles, with detection of the scattered radiance on the axis orthogonal to the central illumination direction. This optical integration means that, in principle, the scattering coefficient of the medium can be measured directly without detailed knowledge of the angular distribution of the scattering. In practice, there are limitations on the extent to which this can be realized in a practical instrument, as discussed in detail by Anderson et al. (1996) and Heintzenberg et al. (2006).

Heintzenberg and Charlson (1996) have reviewed the development of the integrating nephelometer and its expanding range of application. Although originally developed for visibility studies, nephelometers are finding increasing application in climate-related aerosol research as well. This follows because of the dominant role of the scattering coefficient and its vertical integral, the scattering optical depth, in contributing to the extinction of sunlight through the atmosphere. A key property in determining the radiative forcing resulting from aerosol is the single scattering albedo, defined as the ratio of scattering to extinction, where extinction is the sum of scattering and absorption. For the majority of globally significant aerosol types, the single scattering albedo ranges between 0.75 and 1.0. Measurement of this parameter can be obtained by combining a nephelometer measurement of the scattering coefficient with an independent measurement of the absorption coefficient (Chand et al. 2006).
Over the last decade, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has established an Aerosol Ground Station Network (AGSNet), with the aims of developing a climatology of significant Australian continental aerosol types, including biomass burning in the tropical north and wind-blown dust in the arid zone, and supporting validation of satellite aerosol products. The stations operate sun photometers that are affiliated with the National Aeronautics and Space Administration (NASA) Aerosol Robotic Network (AERONET; Holben et al. 1998). The calibration and performance of a number of sun photometers under Australian conditions was discussed by Mitchell and Forgan (2003), while Qin and Mitchell (2008) applied cluster analysis to inversions of aerosol optical properties to classify Australian episodic aerosol types.

In addition, the arid zone stations operate Radiance Research model M903 integrating nephelometers. These instruments were deployed to investigate the relation between the surface aerosol, as measured by the nephelometer, and the column aerosol, as measured by the sun photometer. Furthermore, nephelometers provide a continuous data record in contrast to the sun photometer’s daytime, clear-sky-only limitation. Unlike most nephelometer deployments, which are closely supervised, the CSIRO aerosol ground stations are remote and impractical to visit frequently. Hence the issue of instrument calibration is of paramount importance in assessing data quality and attains added significance in the present case where the data are to be analyzed for long-term trends.

This paper comprises two main parts. The first part sets out the calibration method applied to the nephelometers and then quantifies the uncertainties on the measurement of the scattering coefficient obtained over the 10-yr deployment period. The second part deals with instrumental nonidealities: in particular, estimating the relation between ambient aerosol scattering coefficient and that measured by the nephelometer, given the adopted inlet configuration.

2. Instrument configuration

Currently, CSIRO operates two aerosol ground stations in the Australian arid zone: one at Tinga Tingana (28.98°S, 139.99°E) in the Strzelecki Desert of South Australia and the other at Birdsville (25.90°S, 139.35°E) on the eastern fringe of the Simpson Desert in southwest Queensland. The Tinga Tingana nephelometer was originally deployed in April 1998, whereas the Birdsville station was established in August 2005. The location of the AGSNet stations is shown in Fig. 1.

The measurements reported here relate specifically to the operation of the nephelometers at Tinga Tingana, over the period April 1998–February 2007.

The nephelometer is mounted in a steel enclosure with its scattering chamber horizontal as shown in Fig. 2. Ambient air is drawn in through a downward-facing stainless steel inlet mounted above the enclosure, with the inlet positioned approximately 2 m above ground level. The cylindrical inlet is 90 mm high and has a 48-mm inner diameter. It is screened using 0.2-mm stainless steel mesh, attached via a supporting ring that limits the entrance aperture to 36 mm. Following this, sample air passes into stainless steel tubing with a 10-mm inner diameter, bent through 180°, over a diameter of 80 mm. The tube then passes through the top of the enclosure and thence via a short length of antistatic flexible tubing into the instrument. The scattering chamber is aspirated by a 50-mm miniature cooling fan attached to its outlet port. Sample air is drawn through the instrument at a rate of approximately 20 L min⁻¹.

The sample chamber is illuminated by a xenon flashlamp, firing at a frequency of 2.0 Hz, and the scattered energy is detected by a photomultiplier tube (PMT) after passing through a Wratten 58 green filter. When new this filter material has a center wavelength of 530 nm with full width at half maximum (FWHM) of approximately 60 nm, although the bandpass was found to change over time. Data are internally aggregated into
a 5-min running mean and regularly transferred to a custom built datalogger/control unit, from where they are accessible for download via satellite phone.

Two M903 instruments were deployed alternately at Tinga Tingana over the study period. The first of these, known as neph-1, covered the periods April 1998–April 2001 and March 2004–February 2007, with neph-2 filling the gap between April 2001 and March 2004. Maintenance between deployments included cleaning, bandpass filter replacement, and internal repainting as required. As discussed further in section 3e, the bandpass filter was found to degrade significantly over time and was replaced in February 2004 (neph-1) and April 2004 (neph-2).

3. Calibration and uncertainty analysis

The output response of the M903 nephelometer is assumed to be linearly dependent on the scattering coefficient of the medium in the sample chamber. Although the issue of linearity was not directly addressed in this study, linearity does not arise as a significant source of uncertainty in well-designed nephelometers (e.g., Anderson et al. 1996), so a linear response was assumed. Discussion with the manufacturer of the M903 (R. Weiss 2008, personal communication) suggested possible clipping of the response function under some circumstances, arising from the particular ratio method used in the analog-to-digital conversion process. However, examination of many major dust episodes over the study period showed no evidence for clipping in either nephelometer, even though scattering coefficients in excess of 6000 Mm$^{-1}$ were occasionally reported.

The actual linear response function applying at a particular time varies because of instrumental drift and is determined by calibration using standard gases with a known scattering coefficient. In this study, standard gases employed were particle-free air, used to ascertain the instrument “air-zero” point, and heptafluoropropane (HFC-227ea, also known as FM-200), used as an upscale reference or “span” gas. Adopted data for these reference gases at STP are shown in Table 1, together with corresponding data for chlorodifluoromethane (HCFC-22) because this was used in the evaluation of noise performance (see below). The scattering coefficient of particle-free air was taken from the M903 manual, which does not provide an uncertainty estimate. Hence, the instrument-independent standard uncertainty of 0.24% calculated by Anderson et al. (1996) over the spectral range 450–700 nm was adopted. The data on HFC-227ea were taken from Mitchell and Gras (2003), whereas HCFC-22 data are from Harrison (1977). In following sections, uncertainty contributions from instrument noise, response drift, and reference gas uncertainty are considered.

a. Noise performance

The contribution of noise to uncertainty in the scattering coefficient was ascertained by examining the signal when the instrument was filled with a reference gas and operated over an extended period. Suitable extended calibration periods were available for neph-1 on three occasions spanning four years and for neph-2 on one occasion. For neph-1, the raw data consisted of 2-Hz samples of the recorded scattering coefficient over periods between 20 and 30 min. These samples were filtered using a 5-min sliding window to determine running mean and standard deviation with the same time resolution as the operational data record. From this, the ensemble mean and standard deviation were obtained. For neph-2, 1-min signal averages were available. Standard deviations over a 5-min interval were found by dividing the 1-min standard deviations by $\sqrt{5}$, assuming that the noise is Gaussian.
The signal $y$, measured by the PMT, consists of the sum of light scattered by the medium in the chamber and the wall scatter,

$$y = \sigma + W.$$

For the M903, the wall scatter is expressed as a percentage of the air Rayleigh signal and listed on the instrument console. Table 2 summarizes the relevant data, whereas Fig. 3 plots standard deviation as a function of signal. This demonstrates similar noise performance for the two instruments and shows no indication of significant changes over time for neph-1. As expected, the noise increases with the signal level, although this increase is not well represented by the $\sqrt{y}$ variation that would follow if the signal were shot-noise limited. Instead, the data suggest that a linear variation may be more representative. Detailed examination of the signal shows low-frequency drifting of the signal over periods of several minutes, in addition to the high-frequency noise. Although the origin of the slow drifting is not clear, it may relate to positioning inaccuracies of the shutter that are periodically interposed over the exit aperture of the scattering chamber. This shutter is made of a light-diffusing material and provides an upscale reference to allow real-time compensation for any changes in flashlamp intensity.

Although Fig. 3 provides only tenuous evidence for a linear dependence of noise on signal, adoption of this form ensures a conservative estimate of system noise performance. The least squares fit to the data of Fig. 3 suggests that the standard uncertainty (68% confidence interval) may be written

$$u(y) = 0.11 + 0.00325y \text{ Mm}^{-1}.$$  \hspace{1cm} (1)

At the 95% confidence interval ($2u$), this implies a noise level of 0.22 Mm$^{-1}$ at low signal levels and a relative uncertainty because of noise of 0.65% at high signal levels.

### b. Temperature drift

Instrumental temperature sensitivity was measured by operating the instrument neph-1 for an extended period encompassing significant temperature variation, with the scattering chamber filled with particle-free air. For a period of $\sim 5$ h, during which the temperature varied by 12 K, a linear least squares fit yielded a temperature coefficient of 0.057 Mm$^{-1}$ K$^{-1}$, significant at the 95% confidence level. Assuming a typical diurnal temperature variation of $\sim 15$ K, the corresponding temperature drift is $\sim 0.9$ Mm$^{-1}$, or about 9% of the typical arid zone background level ($\sim 10$ Mm$^{-1}$). This is essentially negligible for large aerosol events of $\sim 100$ Mm$^{-1}$. However, temperature compensation should be applied for studies such as the diurnal variation of background aerosol.

### c. Drift in instrumental response

Because one aim of this deployment is to facilitate long-term change analysis, keeping track of drifts in instrumental response is crucial. To this end, zero and span calibrations were carried out before and after deployment and during all site maintenance visits. During these visits, nephelometer calibration was carried out by first performing an air-zero measurement for 30–45 min, by passing HEPA-filtered air through the instrument at approximately 5 L min$^{-1}$. A span calibration was then performed by passing HFC-227ea through the instrument for 20–30 min at a

![Table 1](image1.png)

Table 1. Adopted scattering coefficients and standard uncertainties for air, HCFC-22, and HFC-227ea at STP.

<table>
<thead>
<tr>
<th>Gas</th>
<th>$s^{ref}$ (Mm$^{-1}$)</th>
<th>$u(s^{ref})$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>14.27</td>
<td>0.24%</td>
<td>Anderson et al. (1996)</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>109.7</td>
<td>1.0%</td>
<td>Harrison (1977)</td>
</tr>
<tr>
<td>HFC-227ea</td>
<td>217.2</td>
<td>1.5%</td>
<td>Mitchell and Gras (2003)</td>
</tr>
</tbody>
</table>

![Table 2](image2.png)

Table 2. Data used to assess the noise performance of the nephelometers deployed at Tinga Tingana. The column labeled “Wall” lists the wall scatter expressed as a percentage of the scattering coefficient of air at STP.

<table>
<thead>
<tr>
<th>Date</th>
<th>Nephelometer</th>
<th>Gas</th>
<th>Duration (min)</th>
<th>Wall (%)</th>
<th>Signal (Mm$^{-1}$)</th>
<th>Std dev (Mm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 May 1999</td>
<td>neph-1</td>
<td>Air</td>
<td>20</td>
<td>32</td>
<td>18.83</td>
<td>0.173</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HFC-227ea</td>
<td>21</td>
<td></td>
<td>221.8</td>
<td>0.878</td>
</tr>
<tr>
<td>17 Apr 2001</td>
<td>neph-1</td>
<td>Air</td>
<td>25</td>
<td>38</td>
<td>19.73</td>
<td>0.221</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HFC-227ea</td>
<td>13</td>
<td></td>
<td>222.6</td>
<td>0.847</td>
</tr>
<tr>
<td>19 Aug 2003</td>
<td>neph-1</td>
<td>Air</td>
<td>27</td>
<td>41</td>
<td>20.05</td>
<td>0.172</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HFC-227ea</td>
<td>25</td>
<td></td>
<td>223.0</td>
<td>0.757</td>
</tr>
<tr>
<td>23 Apr 1999</td>
<td>neph-2</td>
<td>Air</td>
<td>86</td>
<td>18</td>
<td>19.14</td>
<td>0.143</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HCFC-22</td>
<td>28</td>
<td></td>
<td>104.4</td>
<td>0.377</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HFC-227ea</td>
<td>17</td>
<td></td>
<td>204.0</td>
<td>0.801</td>
</tr>
</tbody>
</table>
where ideally the slope parameter $S = 1$ and the intercept $I = 0$. Actual values of $S$ and $I$ were determined by observing the reported response to filtered air ($\sigma_0^{\text{rep}}$) and span gas ($\sigma_1^{\text{rep}}$) carried out during site maintenance visits. The slope and intercept were then calculated from

$$S = f(P, T) \left( \frac{\sigma_1^{\text{std}} - \sigma_0^{\text{std}}}{\sigma_1^{\text{rep}} - \sigma_0^{\text{rep}}} \right)$$

and

$$I = -\sigma_0^{\text{rep}} \frac{\sigma_1^{\text{std}} - \sigma_0^{\text{std}}}{\sigma_1^{\text{rep}} - \sigma_0^{\text{rep}}},$$

where $\sigma_0^{\text{std}}$ and $\sigma_1^{\text{std}}$ are the scattering coefficients of air and span gas at standard temperature and pressure, as shown in Table 1.

A listing of the slope and intercept parameters over the study period is shown in Table 3, together with standard uncertainties that follow from the quadrature sum of noise in the reported scattering coefficient, as defined by Eq. (1), and the uncertainty in the scattering coefficients of the reference gases, as listed in Table 1. The density factor $f(P, T)$ was not considered as a source of uncertainty because the pressure and temperature recorded by the nephelometer were not subject to significant random error.

Linear interpolation was used to obtain values of $S$ and $I$ between calibrations, giving rise to interpolation error because of the relative infrequency of field visits.

### Table 3. Calibration parameters of the two nephelometers during their deployment at Tinga Tingana. Dates marked with an asterisk preceded field HFC-227ea span calibrations, so a constant slope was adopted from the calibration of May 1999. Similarly, the slope and intercept between October 2006 and February 2007 were assumed to remain constant at their October 2006 values. On 3 May 1999, the instrument zero was reset manually, resulting in the subsequent large reduction in intercept. The standard uncertainty in the slope $u(S)$ is controlled by the uncertainty in the scattering coefficient of the span gas, whereas the uncertainty in the intercept $u(I)$ is dominated by noise.

<table>
<thead>
<tr>
<th>Date</th>
<th>Nephelometer</th>
<th>Slope ($u(S)$)</th>
<th>Intercept ($u(I)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02 Apr 1998</td>
<td>neph-1</td>
<td>1.17 ± 0.02</td>
<td>-1.55 ± 0.02</td>
</tr>
<tr>
<td>01 Jul 1998</td>
<td>neph-1</td>
<td>1.17 ± 0.02</td>
<td>-0.78 ± 0.02</td>
</tr>
<tr>
<td>03 May 1999</td>
<td>neph-1</td>
<td>1.17 ± 0.02</td>
<td>7.30 ± 0.02</td>
</tr>
<tr>
<td>04 May 1999</td>
<td>neph-1</td>
<td>1.17 ± 0.02</td>
<td>-0.13 ± 0.01</td>
</tr>
<tr>
<td>14 Oct 1999</td>
<td>neph-1</td>
<td>1.16 ± 0.02</td>
<td>-2.62 ± 0.15</td>
</tr>
<tr>
<td>16 Aug 2000</td>
<td>neph-1</td>
<td>1.09 ± 0.02</td>
<td>-2.89 ± 0.13</td>
</tr>
<tr>
<td>17 Apr 2001</td>
<td>neph-1</td>
<td>1.16 ± 0.02</td>
<td>-0.47 ± 0.14</td>
</tr>
<tr>
<td>02 Apr 2001</td>
<td>neph-2</td>
<td>1.10 ± 0.02</td>
<td>-0.37 ± 0.13</td>
</tr>
<tr>
<td>23 Sep 2002</td>
<td>neph-2</td>
<td>1.15 ± 0.02</td>
<td>-0.75 ± 0.14</td>
</tr>
<tr>
<td>19 Aug 2003</td>
<td>neph-2</td>
<td>1.13 ± 0.02</td>
<td>1.13 ± 0.15</td>
</tr>
<tr>
<td>02 Apr 2004</td>
<td>neph-2</td>
<td>1.14 ± 0.02</td>
<td>1.02 ± 0.15</td>
</tr>
<tr>
<td>16 Mar 2004</td>
<td>neph-1</td>
<td>1.02 ± 0.02</td>
<td>0.25 ± 0.14</td>
</tr>
<tr>
<td>25 Oct 2006</td>
<td>neph-1</td>
<td>0.97 ± 0.02</td>
<td>3.80 ± 0.14</td>
</tr>
<tr>
<td>28 Feb 2007</td>
<td>neph-1</td>
<td>0.97 ± 0.02</td>
<td>3.80 ± 0.14</td>
</tr>
</tbody>
</table>
calibrations combined with the significant changes in parameters between calibration events. This uncertainty was estimated by supposing that within any interval between calibrations, the actual change is bounded by upper and lower envelopes, for one of which all the change takes place by the midpoint of the interval, while for the other the change is confined to the latter half of the interval. This leads to a maximum additional uncertainty at the midpoint of a given interval equal to \( \frac{1}{2} \) the difference between the parameter values at either end of the interval.

The time series of slope and intercept, together with combined uncertainties including interpolation error, are shown in Fig. 4. The intercept shows large upward drifts from 1998 to 1999 and from 2004 to 2006, probably associated with aging of the bandpass filters, as discussed in section 3e. Toward the midpoints of these periods of rapid drift, the uncertainty budget is increasingly dominated by interpolation error.

**d. Uncertainty in aerosol scattering coefficient**

The combined uncertainty in aerosol scattering coefficient was obtained as the quadrature sum of component uncertainties following from Eq. (5), yielding

\[
u(s_{\text{scat}}) = \sqrt{[S u(s_{\text{rep}})]^2 + [s_{\text{rep}} u(S)]^2 + [f(T,P) u(f)]^2}.
\]

(8)

This allows determination of the standard uncertainty at any time as a function of the reported scattering coefficient.

Illustration of the resulting range in uncertainty is shown in Fig. 5. Data for this figure were obtained by calculating uncertainties for a range of scattering coefficients between 0 and 1000 Mm\(^{-1}\) at all calibration times listed in Table 3 and the midpoints between events where the interpolation error is at a maximum. From the range of uncertainties thus calculated, the minimum, mean, and maximum were plotted for each value of scattering coefficient. The plot shows standard uncertainties typically below 3% over most of the dynamic range, a figure primarily controlled by uncertainty in the slope parameter, following from uncertainties in the scattering coefficient of the span gas and interpolation error. Below 10 Mm\(^{-1}\) the uncertainty is usually controlled by interpolation error in the intercept, and is typically \(<1\) Mm\(^{-1}\) but can rise to \(\sim4\) Mm\(^{-1}\) during intervals when interpolation errors are large. Implications of these uncertainties for the measurement of Australian arid zone aerosol are further discussed in section 4c below.

**e. Bandpass filter degradation**

Bandpass filtering of the scattered light is carried out by a gelatin-based Wratten filter (green 58) adjacent to the PMT. Because the PMT housing is not sealed, operation under ambient air conditions can lead to filter degradation depending on the environmental conditions, which is problematic in view of the hygroscopic nature.
of the filter material. Scattered ultraviolet radiation from the xenon flashlamp may contribute to filter degradation, although the absolute intensity of all wavelengths after scattering is extremely small.

The filter on neph-1 was replaced during maintenance in February 2004. Its transmittance was measured using a spectroradiometer (Analytical Spectral Devices model ASD-6166), with an integrating sphere (Labsphere Inc. model URS-600) acting as a light source. The spectrum of a new Wratten 58 filter was also measured. The two transmittance spectra are compared in Fig. 6. The aged filter’s effective wavelength moved from 532 to 548 nm, and its FWHM increased from 59 to 103 nm. This confirms changing filter transmittance as a significant cause of instrument drift and underlines the need for regular calibration. Reference to Fig. 4 shows large increases in the value of the intercept following initial deployment in 1998 and again after filter replacement in 2004, consistent with an increase in filter transparency as a result of aging.

Bandpass filter degradation also presents an additional source of uncertainty in the reported scattering coefficient. Because the calibration procedure is referenced to Rayleigh scattering, the compensation is accurate to first order only if the test medium scatters as $\lambda^{-4}$. In the case of a medium that scatters as $\lambda^{-2n}$, the error scales as $\lambda^{4-2n}$, so for the above shift in center wavelength from 532 to 548 nm and an Ångström exponent of $n = 1$, the relative error is ~9%. However, this applies over the complete life of the filter in question. Frequent calibration has the potential to contain this uncertainty component, although its magnitude depends on the unknown rate of filter degradation and hence is difficult to quantify.

4. Relation between ambient and instrumental scattering coefficient

a. Truncation error

In the ideal case, the nephelometer scattering chamber is illuminated over the full hemisphere of scattering angles from 0° to 180°. Truncation error arises because of the practical difficulties of realizing this, so the reported scattering coefficient will generally underestimate the true scattering coefficient depending on the restriction on illumination. In addition, the integration over scattering angle $\theta$ ideally is weighted with a factor of $\sin \theta$ to compensate for the dependence of scattering path on angle. However, as discussed by Anderson et al. (1996), real nephelometers deviate from this ideal.

Heintzenberg et al. (2006) compared the performance of 12 nephelometers, including several Radiance Research M903 instruments, by simultaneously supplying all instruments with synthetic aerosols over a range of sizes. Despite limited a priori information on the M903, they obtained empirical estimates of both the truncation restriction and angular sensitivity function relative to the better-characterized TSI 3563 nephelometer. In particular, they found angular limits of 15°–165°, and sensitivity function

$$Z(\theta) = Z_{TSI}(\theta)(1 + \sin \theta)^{0.1},$$

where $Z_{TSI}(\theta)$ is the sensitivity function of the TSI 3563 nephelometer derived by Anderson et al. (1996). The ratio of actual response for the M903 to ideal response may be written

$$T = \frac{\sigma^{M903}}{\sigma^{M903}_{\text{ideal}}} = \frac{2\pi \int_{15}^{165} Z(\theta)F(\theta)d\theta}{2\pi \int_{0}^{180} \sin \theta F(\theta)d\theta},$$

where the function $F(\theta)$ is defined as the integral over particle size of the angular scattering function $f$ weighted by the particle size distribution and cross sectional area:

$$F(\theta) = \int_{0}^{\infty} f(\theta, m, s) \frac{dn}{ds} \pi \left(\frac{s}{2}\right)^2 ds,$$

where $f(\theta, m, s)$ is the scattering function for refractive index $m$ and particle diameter $s$ available from Mie theory, and $dn/ds$ is the size distribution. Note that this expression excludes the response to the scattered signal by the carrier gas, which is automatically removed by the instrument preprocessing software and the calibration method described above.

Because the truncation factor $T$ depends on the aerosol composition and size distribution, it will vary as the...
nature of the aerosol changes with time. The impact of truncation error on nephelometer response is further considered in section 4c below.

b. Inlet efficiency

Inlet efficiency was modeled following Baron and Willeke (2005, hereafter BW) as the product of aspiration efficiency and transmission efficiency. Aspiration efficiency was calculated from BW’s Eqs. (8–22), which for a downward-facing inlet reduces to the Laktionov (1973) equation,

\[ \eta_{\text{asp}} = 1 - 3\text{Stk} \sqrt{\frac{U_0}{U}}, \]

(12)

where Stk is the Stokes number defined with reference to the wind speed \( U_0 \) and clear aperture of the inlet (36 mm), and \( U \) is the airspeed within the inlet, based on a flow rate of 20 L min\(^{-1}\). According to BW, this formula is valid over the range \( 0.5 < \frac{U_0}{U} < 2 \), although some flexibility was suggested in one of BW’s source references, Hangal and Willeke (1990), who specified the range as \( 1.25 < \frac{U_0}{U} < 6.25 \). The latter range also appears in the spreadsheet compendium of aerosol-related calculations known as AEROCALC, largely based on BW, and was adopted here, implying an upper limit on wind speed of \( \leq 2 \) m s\(^{-1}\) in the present configuration.

The transmission efficiency of the inlet system was modeled as the product of three factors: inertial losses resulting from entrained particles impacting on the wall of the inlet, contraction losses at the interface between the 48-mm inlet and the 10-mm tubing, and losses in the 180° bend. Using BW’s Eqs. (8–25) and subsequent formulas, the inertial loss factor may be written

\[ \eta_{\text{inertia}} = \frac{1}{\sqrt{2}} \text{Stk} \sqrt{\frac{U_0}{U}}, \]

(13)

where, again, the Stokes number is defined with reference to the wind speed \( U_0 \) and clear aperture of the inlet (36 mm). Losses in the constriction were calculated from BW’s Eqs. (8–71):

\[ \eta_{\text{con}} = 1 - \left( 1 + \left( \frac{2\text{Stk}[1 - (d_i/d_o)^2]}{3.14 \exp(-0.0185\theta)} \right)^{-1.24} \right)^{-1}, \]

(14)

where \( d_i \) and \( d_o \) are the diameters of the inlet (48 mm) and tubing (10 mm), respectively, and \( \theta \) is the angle of the constriction, here equal to 90°. In Eq. (14), the Stokes number is based on the flow velocity in the 48-mm inlet, but the internal diameter of the tubing (10 mm). Inertial deposition in the 180° bend is modeled according to BW’s Eqs. (8–66):

\[ \eta_{\text{bend}} = 1 - \text{Stk}\phi, \]

(15)

where \( \phi \) is the bend angle in radians, and the Stokes number is referenced to the flow velocity in the tube and its internal diameter (10 mm).

The component efficiencies and their product, the inlet efficiency, were computed as a function of particle diameter for wind speeds of 0, 1, and 2 m s\(^{-1}\) for a flow rate of 20 L min\(^{-1}\). Figure 7 shows the resulting efficiencies for a wind speed of 1.0 m s\(^{-1}\). For mineral dust, a bulk density of 2500 kg m\(^{-3}\) was assumed. Losses in aspiration and within the bend are dominant, but only the aspiration efficiency varies with wind speed. Hence, the fixed inertial losses in the bend moderate the dependence of the inlet efficiency on wind speed. Overall inlet efficiency is shown in Fig. 8, where the 50% size cut is seen to reduce from 6.8 \( \mu \)m under calm conditions to 3.9 \( \mu \)m at a wind speed of 2 m s\(^{-1}\).

To illustrate the dependence of nephelometer performance on aerosol type, an additional set of calculations was performed for a smoke aerosol, as further discussed in the following section. The bulk density was assumed to be 1350 kg m\(^{-3}\) (Reid and Hobbs 1998). The resulting 50% size cuts are 9.3 \( \mu \)m under calm conditions and 5.3 \( \mu \)m at a wind speed of 2 m s\(^{-1}\).

c. Implications for measurement of Australian arid-zone aerosol

Characterization of wind-blown dust aerosol forms a major part of the rationale for the deployment of the arid zone stations. Hence, understanding instrument performance under dusty conditions is essential. In this section, we examine the implications of the above
analysis in relation to a significant dust event that took place at Tinga Tingana on 14 January 2003. Moderate Resolution Imaging Spectroradiometer (MODIS) imagery shown in Fig. 1 clearly indicates dust being deflated from the dry lakes to the south of Tinga Tingana and transported to the northwest over the station. The time series of scattering coefficient and wind speed for this event are shown in Fig. 9, where the nephelometer data have been corrected for instrument drift as described in section 3c. The main feature of the event is the correlated abrupt increase in wind speed and scattering coefficient that began at 1345 UTC 13 January 2003, when a threefold increase in wind speed was associated with a tenfold increase in scattering coefficient. Further increases in both wind speed and scattering coefficient took place over the next 3 h, with the scattering coefficient peaking at above 1000 Mm$^{-1}$. After falling from this peak to $\approx 100$ Mm$^{-1}$, the scattering coefficient continued at about this level into the daylight hours of 14 January. Sun photometer measurements obtained on this day showed aerosol optical depth at 500 nm ranging between 0.28 and 0.62.

AERONET inversion of almucantar data obtained between 0649 and 0830 UTC on 14 January were averaged to provide a microphysical characterization, including a size distribution. Figure 10 shows this size distribution (labeled “Dust”) together with a size distribution for a smoke aerosol. The latter was derived from classification of AERONET inversions over Australia and is representative of an aged biomass burning aerosol (Qin and Mitchell 2008).

Both aerosols show bimodal distributions, with the dust aerosol distinguished by a prominent coarse mode peaking at around 8-μm diameter in the volume-weighted representation, whereas for the smoke aerosol, the accumulation mode peaking at $\approx 0.2$ μm is dominant. Because the size distributions derived from AERONET represent column integrals, their relation to the near-surface nephelometer measurement depends on the degree of vertical mixing. In addition, limitations in the AERONET inversion itself mean that derived size distributions are approximate (Dubovik et al. 2000). With these caveats, the AERONET size distributions provide a useful guide to assessing the effects of nephelometer nonidealities and inlet efficiency discussed in previous sections.

Large-particle loss is considered by assuming that only particles below size $s_{\text{cut}}$ in diameter enter the nephelometer, then defining a size-restricted particulate scattering function

$$ F(\theta, s_{\text{cut}}) = \int_0^{s_{\text{cut}}} f(\theta, m, s) \frac{dn}{ds} \frac{s^2}{7^2} ds. \quad (16) $$

Using this, the size-restricted response of the M903 can be written

$$ \sigma^{M903}(s_{\text{cut}}) = 2\pi \int_{15}^{165} Z(\theta)F(\theta, s_{\text{cut}})d\theta, \quad (17) $$

whereas the response of an ideal nephelometer is

$$ \sigma^{\text{sca}}(s_{\text{cut}}) = 2\pi \int_0^{180} \sin \theta F(\theta, s_{\text{cut}})d\theta. \quad (18) $$

With these definitions, the truncation ratio can be written
whereas the correction factor for large-particle loss is

$$\psi_{M903}^{sca}(s_{cut}) = \frac{\sigma_{M903}^{sca}(s_{cut})}{\sigma_{M903}^{sca}(s_{max})},$$

where $s_{max}$ is the largest size bin used in the AERONET inversion (30 $\mu$m). The corresponding correction factor for an ideal nephelometer is given by

$$\psi_{sca}^{sca}(s_{cut}) = \frac{\sigma_{sca}(s_{cut})}{\sigma_{sca}(s_{max})}. \tag{21}$$

Plots of these functions for the dust aerosol are shown in Fig. 11. Truncation error leads to a relative response $T(s_{cut})$ that asymptotes to 0.53 for a cutoff diameter $>14$ $\mu$m, implying that the M903 response equates to 53% of the true scattering coefficient for this aerosol, assuming no loss of large particles at the inlet. This function increases with reduction in the cutoff radius due to the reduction in the poorly sampled forward scattering peak for a polydispersion with fewer large particles, reaching $\sim 0.9$ at $s_{cut} = 1.2$ $\mu$m.

The correction factors for the loss of large particles asymptote to 1 for cutoff diameters $>14$ $\mu$m. The factor for the ideal nephelometer falls more rapidly with decreasing particle size than for the M903, again due to the reduced sensitivity of the M903 at forward scattering angles. Cutoff diameters based on the 50% efficiency points from Fig. 8 are 6.8, 6.0, and 3.9 $\mu$m for wind speeds of 0, 1, and 2 m s$^{-1}$, respectively. Corresponding size cut correction factors $\psi_{M903}$ from Fig. 11 are 0.92, 0.90, and 0.78, respectively, indicating response reductions of 8%, 10%, and 22% for the loss of large particles with increasing wind speed.

Combining both effects, the response of an ideal nephelometer with no loss of large particles may be written

$$\sigma_{sca} = \frac{\sigma_{M903}^{sca}(s_{cut})}{T(s_{cut})\psi_{sca}^{sca}(s_{cut})}. \tag{22}$$

The product in the denominator of this equation is plotted in Fig. 11 for both dust and smoke aerosols. Because it is the product of functions trending in opposite directions, its range of variation is relatively restricted. Equivalently, the selective removal of large particles at the inlet reduces the impact of truncation error. For the dust aerosol with size cuts of 6.8, 6.0, and 3.9 $\mu$m, the denominator in Eq. (22) is 0.49, 0.48, and 0.41, respectively, implying multiplicative correction factors for this aerosol of 2.04, 2.08, and 2.44 at wind speeds of 0, 1, and 2 m s$^{-1}$, respectively.

Corresponding calculations were performed for the smoke aerosol mentioned earlier. Because of the lower bulk density of the smoke relative to the dust, 50% size cuts are significantly larger, namely, 9.3, 8.1, and 5.3 $\mu$m for wind speeds of 0, 1, and 2 m s$^{-1}$, respectively. The denominator of Eq. (22) in this case, also plotted in Fig. 11, shows much reduced size dependence relative to the
dust aerosol. This arises because of the reduced truncation error in view of the more diffuse scattering by the smoke aerosol. For the size cuts just quoted, the denominator of Eq. (22) is constant at 0.832 so the multiplicative correction factor is 1.20, independent of wind speed over this range.

Returning to the dust aerosol, Fig. 9 shows wind speeds during this event varying between 2 and 15 m s\(^{-1}\), well in excess of the range over which the inlet efficiency was characterized (0–2 m s\(^{-1}\)). The additional loss of large particles at higher wind speeds will lead to correction factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds. Because factors greater than 2.44, so that the scattering coefficient inferred from Eq. (22) should be viewed as a lower limit for these dust events involving high wind speeds.

Because reported scattering coefficients for major dust events are usually \(\sigma_{\text{M903}} > 1000 \text{ Mm}^{-1}\), this implies values of \(\sigma_{\text{scat}} > 2500 \text{ Mm}^{-1}\). The associated local visual range can be estimated from the Koschmieder (1924) relationship, \(3.9/\sigma_{\text{ext}}\), where \(\sigma_{\text{ext}}\) is the extinction coefficient at 550 nm. Because typical single scattering albedos for dust aerosols are \(~0.95\) in the midvisible (Dubovik et al. 2002), the implied visual range for these dust events is \(<1.6\) km.

5. Conclusions

This paper addresses some of the challenges posed by the remote and unattended operation of integrating nephelometers in the Australian Outback, through development of a calibration strategy and associated uncertainty analysis. In addition, the consideration of truncation error and inlet efficiency provides useful estimates of the relation between the ambient aerosol scattering coefficient and that measured by the M903 nephelometer with the adopted inlet configuration. The main findings of this work are as follows:

1) Instrument noise in the two M903 nephelometers included in this study suggests a detection limit of \(~0.2\) Mm\(^{-1}\) at the 95% confidence level for a 5-min integration. There is evidence that the noise varies quasi-linearly with signal, not with the square root as expected for shot noise.

2) Ambient temperature changes cause a drift in sensitivity, with a temperature coefficient of \(~0.06\) Mm\(^{-1}\) K\(^{-1}\). This leads to a diurnal drift of \(~0.9\) Mm\(^{-1}\), which is small in relation to significant dust episodes (>100 Mm\(^{-1}\)) but represents about 9% of the typical arid zone background, suggesting the need for temperature compensation for studies of nonepisodic aerosol.

3) Drift in instrument response sets the practical limit on the uncertainty of the scattering coefficient over the \(~10\)-yr deployment considered. Large changes in the transmission characteristics of the bandpass filter as a result of environmental degradation contribute to this drift. A calibration procedure developed to deal with the drift has residual uncertainties ranging from \(~15\)% for typical background aerosol scattering coefficients of 10 Mm\(^{-1}\) to \(~5\)% for scattering coefficients of >100 Mm\(^{-1}\).

4) A combined analysis of truncation error and inlet efficiency is carried out for aerosol size distributions guided by inversions of collocated sun photometer data. For a dust aerosol, the correction factor relating the scattering coefficient measured in the M903 to the ambient aerosol scattering coefficient varies from \(~2.0\) under calm conditions to \(~2.4\) for a wind speed of 2 m s\(^{-1}\). At the higher wind speeds often encountered during dust events, the latter result provides a lower bound for the correction factor. The corresponding correction factor for a smoke aerosol with dominant submicron mode is 1.2, independent of wind speed over the range \(~0–2\) m s\(^{-1}\).

Acknowledgments. The authors wish to thank Mr. R. Weiss for valuable discussions, and Mr. B. Petratis and Mr. I. Morrissey for technical support and field work assistance. This work was supported in part by funding from the Australian Department of Climate Change through the Australian Climate Change Science Program, and also by the Office of Biological and Environmental Research of the U.S. Department of Energy under contract 23662–001–01 3T as part of the Atmospheric Radiation Measurement Program.

REFERENCES


Chand, D., and Coauthors, 2006: Optical and physical properties of aerosol in the boundary layer and free troposphere over the Amazon basin during the biomass burning season. Atmos. Chem. Phys., 6, 2911–2925.


