AirWatch: Does it Measure Particles or What?

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ABSTRACT

CSIRO's contribution to the educational and community AirWatch program included a 'filter soiling' technique for measuring airborne particle concentrations. This paper (i) describes the robust calibration process underlying the technique, (ii) shows that the technique actually measures black carbon concentrations rather than overall particulate matter concentrations, (iii) compares the results with a European black smoke calibration, demonstrating that the latter has been adjusted by a factor of two to account for organic components, and (iv) compares AirWatch measurements with ANSTO measurements of carbon and particles during the Australian Fine Particles Study (1999: http://www.cmar.csiro.au/e-print/open/CSIRO_AFP.pdf), showing good agreement with the sophisticated measurements of elemental carbon.

Keywords: Airwatch, particles, carbon, atmosphere, community.

INTRODUCTION

AirWatch began in Australia in 1995 as an initiative of the West Australian Department of Environmental Protection to promote an awareness of air quality issues to schools and the community. It was a response to the 'Perth Photochemical Smog Study' and the 'Perth Haze Study' of earlier years. In partnership with Western Australia, Victoria and Queensland agencies, CSIRO helped design several measurement components (Manins *et al.* 1996). AirWatch soon attracted support from other Environment Agencies, especially financial support from Environment Australia. AirWatch and Ms Jennifer Anderton of Department of Environmental Protection, Western Australia, won *The Allen Strom Eureka Prize for Environmental Education Programs* in 1999.

As recently as 2010 AirWatch received the Clean Air Society of Australia and New Zealand's Clean Air Achievement Award at the Western Australia branch's annual general meeting. See http://education.dec.wa.gov.au/airwatch/news/48-award-winning-airwatch.html.

One component of AirWatch has been a 'filter soiling' technique for measuring particles in the air. The equipment for this is also the basis for the technique for measuring nitrogen dioxide concentrations and for measuring airborne pollen.

Various State EPAs continue to promote versions of AirWatch but have mostly abandoned the 'filter soiling' technique for measuring particles, instead promoting a simple dustfall technique (NSW) or lending out a DustTrack (TSI DustTrack: http://www.tsi.com/dusttrak-ii-aerosol-monitor-8532/). In 2012 AirWatch in the WA Department of Environment and Conservation is focussed on monitoring and reducing energy consumption in schools.

Historically, exposure to smoke containing carcinogenic particles formed from partly or fully combusted hydrocarbon fuels has been the main concern of environment agencies. Particularly in Europe, in the 1950s and 60s the concern was with the measurement of 'black smoke', and in 1969 the 'smoke stain' or 'filter soiling' method, involving the optical assessment of the greyness of the exposed filter, was mandated by British Standard 1747 Part 2. WHO (1976) provides a perspective. Problems with this method include insensitivity to non-carbonaceous particles (*i.e.* those that are not black), the effects of moisture, and lack of specificity of particle sizes (*e.g.* Maynard, 2001). Furthermore, in developed countries 'black smoke' makes up a much smaller proportion of the particulate load than it did 50 years ago.

Today practically all good quality measurements by and for environment agencies use techniques that are size selective (because of the finding that it is the finer particles that have a greater impact on human health) and either directly or indirectly measure the concentration of particles in the air in real time or over periods specified in air quality standards such as 24 hours (NEPC 2011).

Even with its problems, the filter soiling technique continues to have a role in studies of combustion-related air pollution. For example Götschi *et al.* (2002) in an indoor/outdoor study of 'black smoke' and PM2.5 particulate matter in four European cities concluded that 'black smoke seizes a health-relevant fraction of fine particles to which people are exposed indoors and outdoors and exposure to which can be assessed by monitoring outdoor concentrations'. Janssen *et al.* (2011) discussed the utility of data on black carbon from black smoke measurements in assessing adverse health outcomes in urban areas as compared with PM2.5 and other measures.

So there is utility in the AirWatch particle measurement approach just so long as its limitations are understood.

The objectives of this paper are to

- provide a solid foundation for the AirWatch filter soiling particle measurement method since it continues to have a place in providing information to concerned individuals;
- quantify the limitations of the method, viz that it measures black carbon concentrations rather than overall particulate matter concentrations;
- compare results with a European black smoke calibration;
- compare results with measurements of carbon and particles during the Australian Fine Particles Study (Ayers *et al.* 1999).

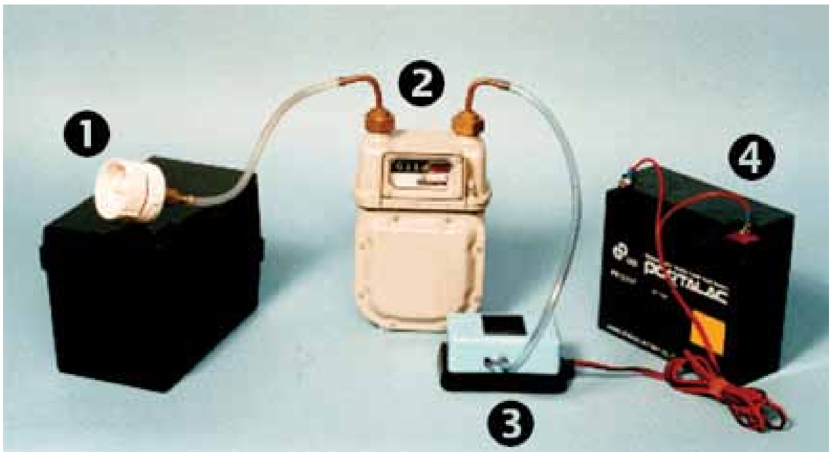

Figure 1. Basic AirWatch particle monitor: (1) filter holder, (2) flow meter, (3) vacuum pump, (4) battery.

THE AIRWATCH PARTICLE MONITOR

Over a period such as 24 hours aerosol is collected by low-volume active pumping onto a fibre-glass filter paper. Assuming that the visible aerosol on the filter is carbon, we can compare the 'greyness' of the filter with a calibrated 'grey scale' chart. Since we also measure the volume of air that has been drawn through the filter paper, and we know the relationship between greyness and mass of carbon on the filter, we can estimate the concentration of the particulate matter in the air and can expect to compare it with air quality standards.

The basic equipment is (refer to Figure 1):

1. The filter holder is an Advantec MFS PP-47 inline polypropylene unit that holds 47 mm diameter MS 2 grade fibre-glass filters, available from several suppliers including MicroAnalytix in Australia.

2. The chosen flow meter, a Toyo ML2500 gas meter with maximum flow rate of 3.0 m^3 h^{-1}, can be sourced from the manufacturer Dadong Dongfa Group in China (http://www.df-drgasmeter.com/en/Product/ProductDetail.aspx?ProductID=29). Similar G-series units (e.g. G2.5) can be purchased in small quantities through AliExpress.com.

3. The vacuum pump is the most problematic component. It must transfer enough air in the chosen sampling time to give a useful deposit on the filter: in practice this means at least 3–5 m^3.

   Some fish tank and bait pumps have proved suitable, but they do need to have a discrete inlet. These generally are capable of no more than 5 m^3 over 24 hours and some can be powered from a 12 V gel cell or motorcycle battery.

   For shorter sampling times a vacuum cleaner such as the 12 V unit available from Whitworths (https://www.whitworths.com.au/main_itemdetail.asp?item=91694), or any number of 230 V vacuum cleaners, so long as the flow rate is always kept below the maximum for the flow meter, can permit sampling periods as short as a few hours, and this can be important for sampling the influence of, for example, heavy vehicle traffic.

   With the recommended filter holder and a fish tank pump that provides a sample of approx. 4 m^3 over 24 hours, measurements determined that the inlet to the filter holder acts as a size-selective inlet with a characteristic of a little less than PM10 (the determination was done using the approach of Keywood *et al.* 2000). The monitor captures particles whose sizes are mostly less than 10 µm in diameter. Faster sampling using a vacuum cleaner would decrease the size range of particles collected.

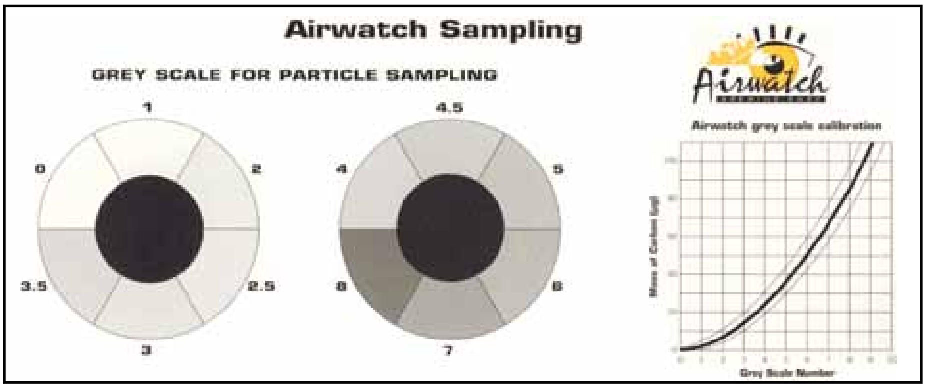

Figure 2. Calibration chart for AirWatch particle sampling.

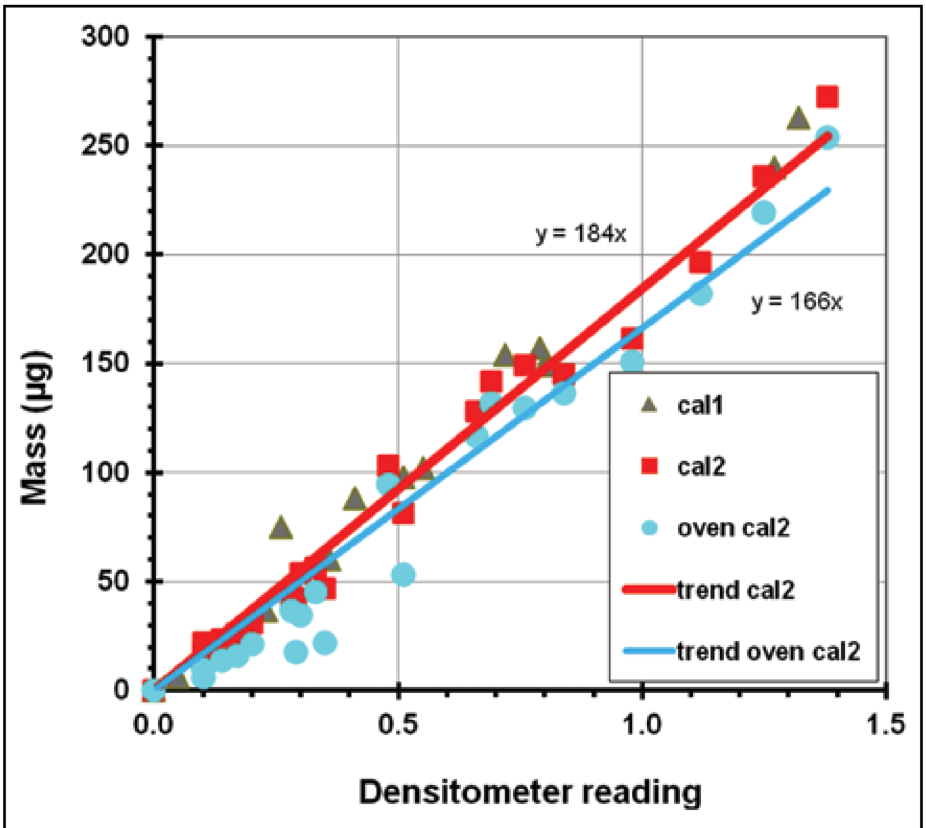

Figure 3. Calibration filter masses compared to densitometer readings show the influence of organic material on the filter masses. Filter weighings are two years apart (cal1, cal2) and after oven-drying (oven cal2). Trend lines are constrained to pass through zero in this and all other plots in this paper.

With a sample collected, the test filter paper is placed in the centre of a calibration chart ring so that the greyness of the filter can be estimated and so the weight of particles on the filter can be read off the chart (Figure 2).

CALIBRATION OF THE GREY SCALE

The Soot Source

Acetylene Flame: Use of an acetylene flame to generate carbon soot is regarded as the gold standard as it reportedly contains little organic carbon (VanderZalm *et al.* 1999). However, as also found by VanderZalm *et al.* (1999), trials using acetylene for AirWatch proved unsuccessful due to unsteadiness in the sizes of particles produced, leading to spotting on the filter paper. This spotting made it difficult to judge the shade of grey.

Kerosene Flame: For the present calibrations, which were repeated after two years with improved methodology, soot was made in a kerosene flame using a small lantern. A range of samples of varying greyness could be produced in a controlled manner. Each sampling event used two filters in parallel: a glass-fibre filter which collected for colour; and a polycarbonate filter which collected for weight. The flow rates for each were measured and adjusted to be the same. The polycarbonate filter material

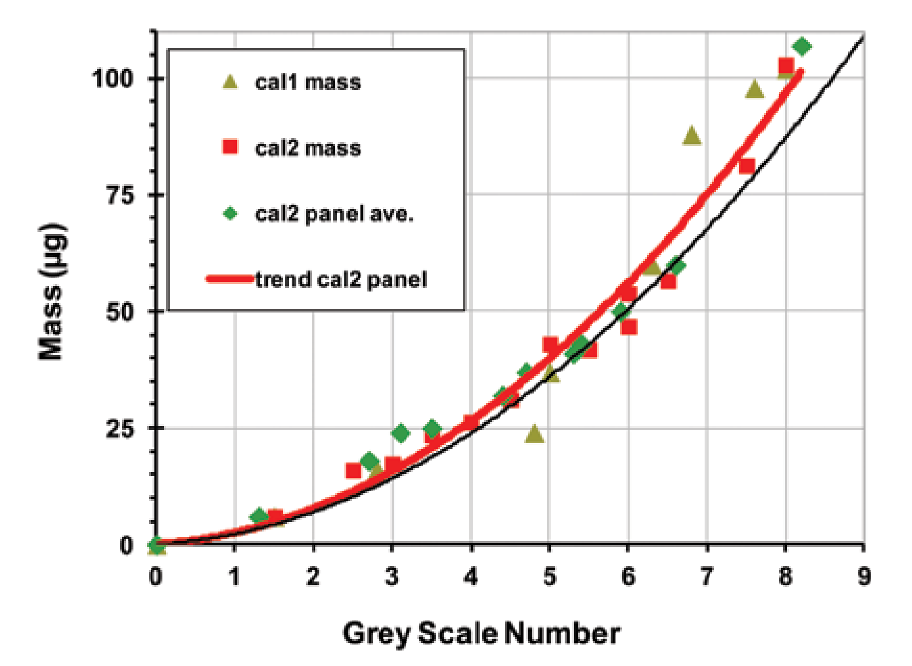

Figure 4. Mass of particles on test filters vs panel selection of segment number from the grey scale calibration chart (Figure 2). 'cal1' and 'cal2' are test filter data obtained two years apart. The black line is the 'cal2 panel' trend line reduced by 10% to account for organics.

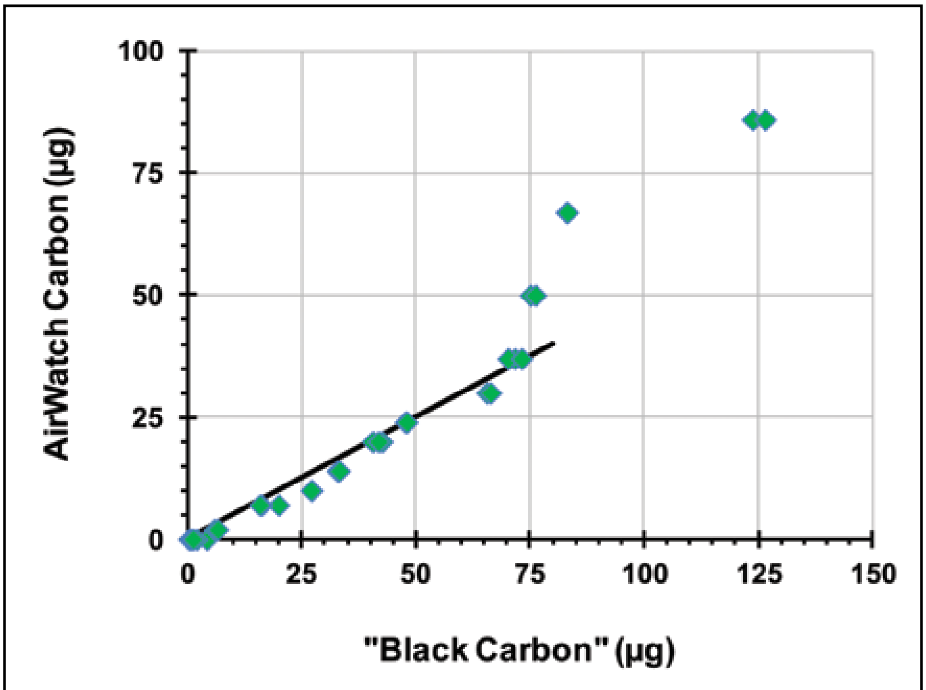

Figure 5. AirWatch grey scale results vs results from the 'smoke stain' M43D reflectometer. Filled diamonds are AirWatch 'cal2' values determined by a panel and reduced by 10% to account for organics. The trend line is for AirWatch concentrations less than 50 µg.

does not shed fibres (unlike glass-fibre filters) and static electricity build-up can be readily discharged (unlike Teflon filters, another possibility) so can be successfully weighed on a microbalance. In the field, sample weights of 50 µg or less are typically of interest.

Organics Contribution

A kerosene flame generates soot which contains other organic compounds and these contribute to the weight on the polycarbonate filter but not to the colour on the glass-fibre filter. To estimate the importance of this effect, samples on polycarbonate filters were dried and weighed, then placed in an oven to burn off any organics formed in the kerosene flame and reweighed immediately. Considerable time was spent determining the appropriate temperature and time in the oven and in hindsight this effort may not have been so successful, nor was it well documented.

The masses of the filters were plotted against the greyness value determined by a CSIRO-made densitometer. The densitometer uses reflected white light to give an objective determination of the visual appearance of the filters and is directly related to the observed appearance (Gillett, *pers com*). The results are shown in Figure 3.

There are small differences in the results between the earlier calibration exercise (cal 1) and the later one (cal 2). The reduced scatter for 'cal 2' results is attributable to improved methodology, in particular better control of electrostatic charges when weighing.

The results from the heating process used to drive off the organics present are shown as 'oven cal2' in Figure 3. While more scattered than for the unheated filters, the data for the heated filters show a reduction of weight. A trend line constrained to pass through zero gives a slope that is 10% lower than for the unheated filters, though an alternative interpretation could be an offset from the unheated results of approximately 16 µg. This could be due to some unintended overheating of all the samples but given the overall uncertainties of the method and the lack of information available, this alternative interpretation is not pursued further.

What is clear is that the AirWatch calibration data exhibit long-term repeatability. There appears to be a 10% over-estimate due to the presence of organic components.

The Grey Scale

To make the grey scale calibration chart for AirWatch users as shown in Figure 2, a set of twelve filter samples was selected for increasing shades of greyness and concomitant weight of carbon from the set of calibration filters. The apparent shades were matched to percentages in white of the Pantone Colour System 405C (a grey) for printing of the calibration chart. For example, grey scale number 1 matched 3% PMS405C; number 3 matched 10%; and number 5 matched 28%.

A panel of ten individuals was asked to match 15 filter samples against the segments of the printed grey scale (refer to Figure 2). Excluding the highest and lowest results, the biggest variation was one segment, with most choosing the same segment for each sample. Figure 4 shows the good agreement between the average weights inferred by the panel and the measured weights.

Since the test for organics contribution showed a 10% loading, this value has been subtracted from the constrained quadratic fit to give the black curve in Figure 4; this is the curve on the AirWatch Calibration Chart (Figure 2).

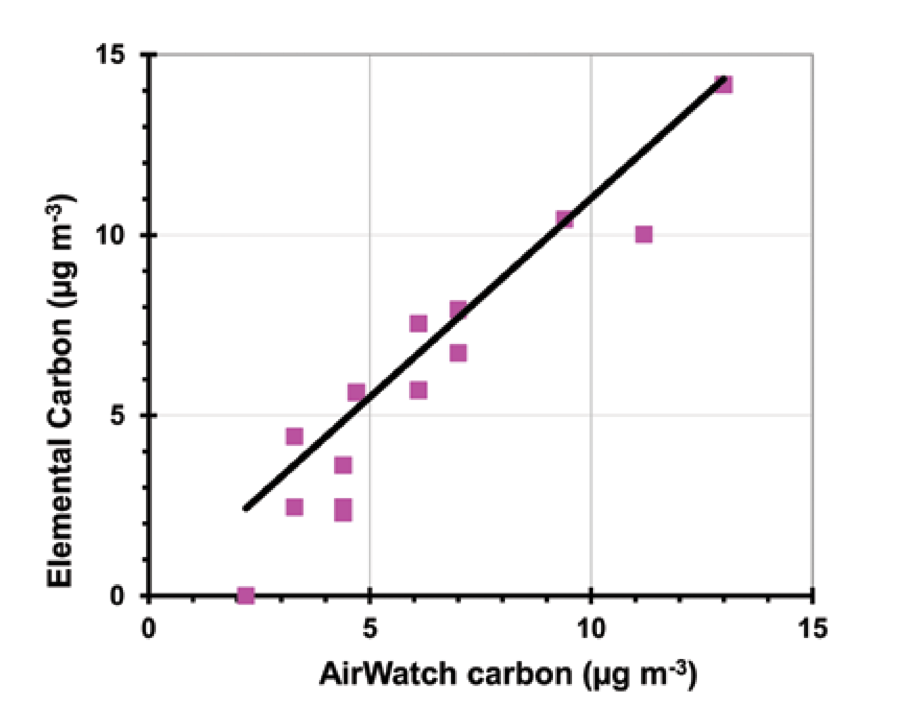

Figure 6. PM2.5 Elemental Carbon as determined by ANSTO compared with AirWatch particle concentration estimates on the 15 days during the AFP Study (Ayers *et al.* 1999) when AirWatch measurements were also made.

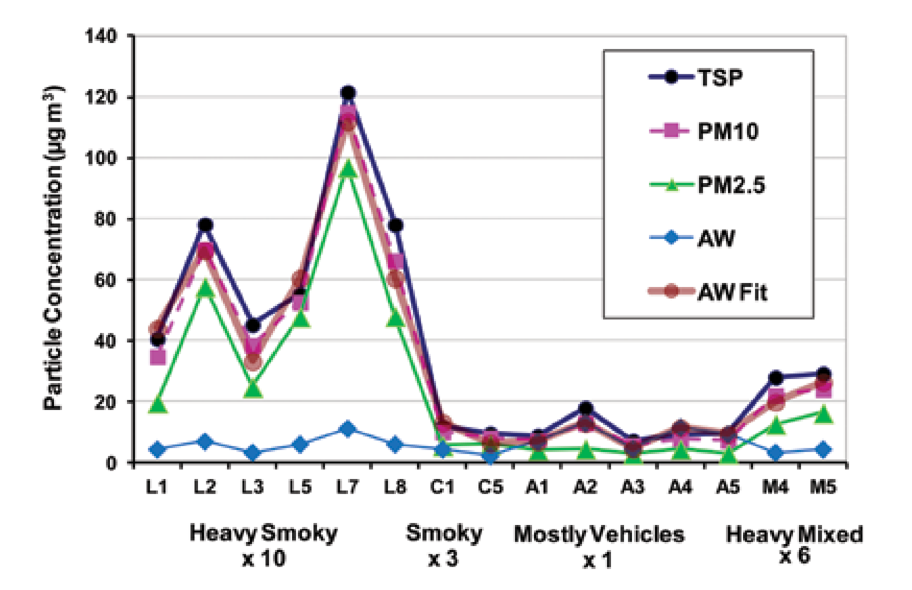

Figure 7. AFP (Ayers et al. 1999) and AirWatch measurements (AW) for Launceston (L1...L8), Canberra (C1...C2), Adelaide (A1...A5) and Melbourne (M4...M5) in winter. "AW Fit" are the AirWatch data multiplied by the weighting factors shown.

European Smoke Stain Calibration

Here the AirWatch grey scale and samples are compared against a European Standard Smoke calibration as used in the European smoke stain method (WHO 1976). In general, Standard Smoke mass concentrations are about half as big as concurrent high volume sampler data (Lee *et al.* 1972; Bailey and Clayton 1982) but with large variations due to varying organic and other non-dark material.

Monash University made available access to their EEL Smoke Stain Reflectometer model M43D (Diffusion Systems Ltd., London). This instrument is calibrated to British Standard 1747 Part 2. VanderZalm *et al.* (1999) discuss the application of this instrument for field measurement of aerosol.

The original AirWatch calibration samples were measured on the M43D and results for 'black carbon' compared. Figure 5 shows that the AirWatch filter results, as used in the calibration chart, are approximately half of the M43D 'black carbon' determination.

This result supports the conclusion that the AirWatch calibration chart is likely determining black carbon alone (see next section) and that results may need to be doubled to approximate M43D estimates of particle concentrations representative of European urban mixtures of organics and black carbon.

ELEMENTAL CARBON MEASUREMENTS

In a study of fine airborne particles in six Australian cities (the AFP Study, Ayers *et al.* 1999) CSIRO and ANSTO measured, amongst other things, PM10 and PM2.5 elemental carbon. ANSTO obtained results using a Laser Integrated Plate Method (Cohen *et al.* 2000), a variation of the light absorption method which has some relationship to the AirWatch approach of measuring black carbon.

On a total of 15 days in four of the cities, viz Melbourne (in the period 4–26 April), Canberra (4 May–3 June), Launceston (12 June–24 July) and Adelaide (2–26 August), simultaneous AirWatch sampling occurred at the same place. Figure 6 compares the results from the PM2.5 ANSTO elemental carbon measurements with AirWatch measurements. The trend line shows a close correspondence, supporting the contention that AirWatch is measuring airborne fine elemental carbon.

ORGANIC PARTICLE MEASUREMENTS

As well as elemental carbon, the AFP Study (Ayers *et al.* 1999) measurements included total suspended particulate matter (TSP), PM10, PM2.5 and estimated organic matter (EOM, defined as gravimetric aerosol, inorganic aerosol, elemental carbon mass concentration).

In Launceston smoke in the air was noticeable and EOM averaged 80% of PM10. In Canberra EOM was also high, averaging 50% of PM10, and was lower in Adelaide and Melbourne at approximately 40% of PM10. These observations greatly influence the results plotted in Figure 7. There the AFP results are compared with the AirWatch determinations ('AW' in Figure 7) for each of the occasions and cities for which coincident data are available. As has already been shown, AirWatch is effectively measuring elemental carbon and while this had a trend similar to the other results, its magnitude was much smaller. There was a lot of mass attributable to organic matter in the air samples.

Figure 7 also shows the result of applying different weighting factors to the AirWatch results for each city, as given along the bottom of the diagram. They range from 1x to 10x. These weighting factors are broadly in agreement with the EOM findings of the AFP Study. The Launceston AirWatch results are only about 10% of the measured PM10 particle concentrations due to high levels of organic smoke aerosol; in Melbourne the measured PM10 concentrations were six times as large as the AirWatch results; and in Adelaide the air characteristics were quite different with AirWatch results about the same as measured PM10 and larger than PM2.5.

DISCUSSION AND CONCLUSION

The filter soiling method used in AirWatch to measure particle concentrations has a robust underpinning with repeatable calibration data. The visual comparison of a sample with the Calibration Chart by the AirWatch user works well and gives results that compare well with methods employing a densitometer or reflectometer to judge the degree of soiling of the collection filter. The final AirWatch Calibration Chart is based on the masses from a set of calibration filters reduced by 10% to account for organics present.

By comparing the AirWatch data with ANSTO measurements in four Australian cities, it has been shown that AirWatch is able to measure fine elemental carbon in the atmosphere with low uncertainty. Elemental carbon was important in the past when there were many dirty industries and the roads were travelled by dirty vehicles. It is much less so now in Australia with cleaner industrial technologies and greatly improved diesel engines. It is to be hoped that the impact of the increasing numbers of diesels on the roads is more than offset in practice by the more stringent emission standards required of them.

The European smoke stain method of measuring airborne particles has been largely overtaken by direct mass measurement methods. Nevertheless health studies (*e.g.* Götschi *et al.* 2002; Janssen *et al.* 2011) continue to find utility from data on "black carbon" in urban environments as determined by filter soiling. The AirWatch carbon data are approximately half the "black carbon" estimates of particle concentrations relevant to European urban mixtures of organics and black carbon.

Much of the particle burden in Australian cities is organic. So application of the AirWatch particle method requires a weighting of the measurements to account for the difference between measured black carbon and the organics content. Winter results reported here show weighting factors of between 1x and 10x, dependent on conditions. Such a large range of weighting factors makes for a difficult quantitative application of AirWatch.

The assumption all along has been that the staining of the AirWatch filters is grey and that the shade of grey is due to carbon (soot) in the air. In rural regions, or in special conditions, it could be that the colour change is due to wind-blown soil, and may be a shade of brown. Then the application of AirWatch particle measurement method is even more difficult.

In conclusion, the AirWatch filter soiling method is useful for measuring black carbon, which approximates the burden of fine elemental carbon. In urban regions where the sources are dominantly hydrocarbon combustion, it provides a reasonable estimate of overall particle concentrations. Where there are substantial and unknown fractions of organic compounds present, such as in smoky, dusty or industrial areas, the AirWatch method is likely capable of no more than an indication of 'low', 'medium' or 'high' levels of overall particle concentrations.

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