COMPARING PM_{10} MEASUREMENTS FROM CO–LOCATED HIGH VOLUME AIR SAMPLERS AND OPTICAL–SCATTER PARTICLE INSTRUMENTS IN RESIDENTIAL AREAS PERIPHERAL TO A MINE: COMMoN FEATURES, SUBTLETIES, AND POTENTIALLY FUNDAMENTAL LIMITS TO AGREEMENT

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Abstract

The MMG Rosebery mine in western Tasmania conducts a comprehensive dust monitoring program which includes dust-deposition gauges, high-volume air samplers (HVAS) and optical-scatter particle instruments (TSI DustTraks) at multiples sites in and around Rosebery. The HVASs are operated in a one-day-in-six cycle for TSP (and metals analysis) and for dust as PM_{10}. The DustTraks are operated at four sites co-located with the HVASs, and collect data at one-minute cadence. Two of these monitoring sites are located in residential areas where winter woodsmoke from domestic woodheaters also contributes to the PM_{10} measurement.
In late 2020 EPA Tasmania recommended MMG change from DustTrak II to DustTrak DRX to differentiate between the effects of woodsmoke and dust in the HVAS PM_{10} data for the two sites near residential areas. EPA Tasmania undertook to provide the initial calibrations of these DRXs, based on their ambient air network experience. The wintertime increase in $PM_{2.5}$ due to smoke is clearly distinguishable in the calibrated Rosebery DRX data.
The agreement between the HVAS and day-averaged DRX PM_{10} is often good, but discrepant days are present. Inspection of these data showed some association of the most discrepant instances and very short-duration spike-like DRX PM_{10} increases. It is hypothesised that these arise from local vehicle movements, resulting in a short-lived and spatially-localised dust event. The different sample rates (HVAS: 1 cubic metre per minute; DRX: 3 litres per minute) likely contribute to the differences in the derived PM_{10}, as do the different upper-size cut-off limits.
An analytical method is developed to specially incorporate the spike-signatures to augment the DRX data, giving an improved agreement with the HVAS PM_{10}. The work suggests there will be fundamental limitations to the agreement between HVAS and DRX measurements, but also that there is significant value in having the 1-minute DRX data along with the compliance HVAS PM_{10} measurements.

Keywords: PM_{10} ; Dust; High–Volume Sampler; DustTralk

1 Introduction

1.1 Air monitoring at Rosebery township

MMG Rosebery conducts environmental air monitoring at and near the Rosebery township, western Tasmania. High–Volume Air Samplers (HVAS) are used for compliance monitoring of dust as PM_{10} and metal analysis on one day in six, along with dust–deposition gauges. This is supported with continuous (1–minute cadence) optical–scatter measurements of suspended dust, initially with DustTrak II units (model 8530), which report only a single fraction (usually PM_{10}). By mid 2020 with indications that woodsmoke, especially in winter, may be confounding results for dust levels near to residential areas[1], EPA Tasmania advised that the DustTrak DRX (model 8533) would provide both PM$_{2.5}$ and PM$_{10}$ data, if the units were appropriately calibrated, allowing woodsmoke (as PM$_{2.5}$) and dust (as PM$_{10}$) to be differentiated. MMG installed DRXs at the two residential area sites in late 2020. As part of a now on-going program EPA Tasmania calibrates the MMG DRX DustTraks prior to deployments, and periodically reviews these data. The HVAS and DRX day–averaged PM$_{10}$ show general agreement, but also instances of significantly different PM$_{10}$. A detailed study, aspects of which are reported here, was undertaken to understand why these discrepancies arose.

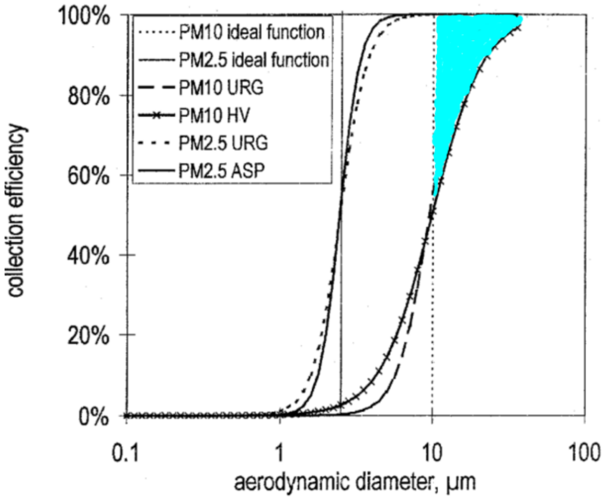

Figure 1: Collection efficiency of various size–selctive inlets, from Keywood et al, 1999. The blue shaded area represents the ‘leakage’ of particles larger than 10 μm through an HVAS PM$_{10}$ inlet.

2 HVAS and DRX DustTrak – similarities and differences

2.1 HVAS at Rosebery

The HVAS operates with a flow–rate of a nominal 1500 m^{-3} (cubic metres) per day[2]. Ambient air is drawn through a size–selective inlet to select PM$_{10}$ and passed through a pre–weighed particle filter, which is subsequently re–weighed. The resulting mass–concentration is a well–determined, traceable, gravimetric measurement.

The performance of typical size selective inlets for PM$_{10}$ and PM$_{2.5}$ was considered by Keywood et al, 1999. Figure 1, taken from that paper, shows the collection efficiency for a number of designs, including the HVAS PM$_{10}$ (labelled as HV PM$_{10}$). The blue shaded area has been added to the original figure, and shows the ‘leakage’ of particles larger than 10 μm through a nominal PM$_{10}$ HVAS inlet. Also some particle less than 10μm will be ‘filtered out’ by the HV inlet. The consequences of this for PM$_{10}$ measurement will depend on the particle–size distribution of the aerosols under study. i.e. the effect would likely be less if the ambient aerosols have few particles over say 5 μm in diameter, compared to when there are many $\sim$15 μm-sized particles present.

2.2 DRX at Rosebery

The DRX DustTraks operate continuously, and report a 60–second averaged value for PM$_{2.5}$ and PM$_{10}$. The DRX also reports PM$_1$, PM$_4$, and a quantity called PM$_{total}$. A zero–air calibration is also conducted once per hour to correct for possible base–line instrumental drifts. Firmware algorithms interpret the optical–scatter signal and assign particle size and particle number. (Note: For particles of inferred size less than 1 μm the DRX functions as a photometer, not a particle counter, as described by Wang et al, 2009.) These data are converted to an equivalent mass–fraction using on–board (effectively particle–density) calibrations. Calibration factors are user programmable. Different factors can be used for PM$_{2.5}$ and for the coarse fraction of PM$_{10}$ (i.e. PM$_{10}$ $-$PM$_{2.5}$), which are known as the Photometric Calibration Factor – PCF – and the Size Calibration Fctor – SCF – respectively (Wang et al. 2009). The reported mass–concentrations in field use must be considered as indicative: If the calibration factors are not appropriate for the aerosols being measured the mass–concentrations will be in error. However the DRX and similar optical–scatter particle instruments offer the advantages of low operating resource–costs and continuous high–temporal

[1] Alec Street and Giblin Street air stations. The DRX and HVAS instruments are approximately 4 metres apart at each site

[2] This is approximately 1 m^{-3} per minute.

[3] In Tasmania, elevated PM$_{2.5}$ is almost always from woodsmoke, while elevated PM$_{10}$ $-$PM$_{2.5}$ is mostly from sea–salt aerosols. The DRX calibration factors in use in Tasmania reflect this.

resolution data.

DRX DustTraks are also used in EPA Tasmania's near–statewide BLANkET ambient air monitoring network, which began in 2009. EPA Tasmania calibrates DRX $PM_{2.5}$ and PM_{10} mass–fraction channels against reference (Low–volume Air Sampler) and equivalent (TEOM) instruments[3], but has not made use of the PM_1 and PM_4 data as no calibration has been possible. Use has been made of the PM_{total} data at times as an *indication* of the presence of particles bigger than 10 μm. The upper size limit for PM_{total} is not specified, but is likely to be in the range of 12 μm to 15 μm and is also likely to vary from unit to unit, and potentially over time. PM_{total} data will be used in the work reported here.

The default sample flow of the DRX DustTrak is 3 litres per minute, which is significantly less than that of the HVAS. The DRX does not need mechanical particle–size segregation hardware (e.g. cyclones or impactors). The nominal upper–size cut at 10μm for the DRX would be close to the ideal PM_{10} function shown in Figure 1 if the algorithms are correct. This and the lower sample flow of the DRX compared to the HVAS suggests that the PM_{10} reported by both instruments could differ under certain circumstances.

3 PM_{10} : HVAS and 'raw' DRX

Figure 2 shows example comparison PM_{10} data between the HVAS and day–averaged DRX PM_{10} for the two near–residential stations at Alec St and Giblin St for an approximately 18 month interval from January 2022 to June 2023. The DRXs had been calibrated by EPA Tasmania for wood–smoke and sea–salt aerosol, as noted above, prior to deployment at Rosebery, with the aim of further comparing Rosebery field data to investigate if the calibration required revision. In winter elevated PM_{10} usually has a significant $PM_{2.5}$ contribution due to woodheater smoke, while in summer, away from bushfire intervals, $PM_{2.5}$ is usually lower. While the general trends in both the HVAS and day–averaged DRX PM_{10} data were similar, the DRX PM_{10} systematically underestimates the HVAS PM_{10} at Alec St in early 2023, while at Giblin St the DRX PM_{10} is generally lower, especially in early 2022 and early 2023. Note too that the days with the highest HVAS PM_{10} at both sites show much lower DRX PM_{10} .

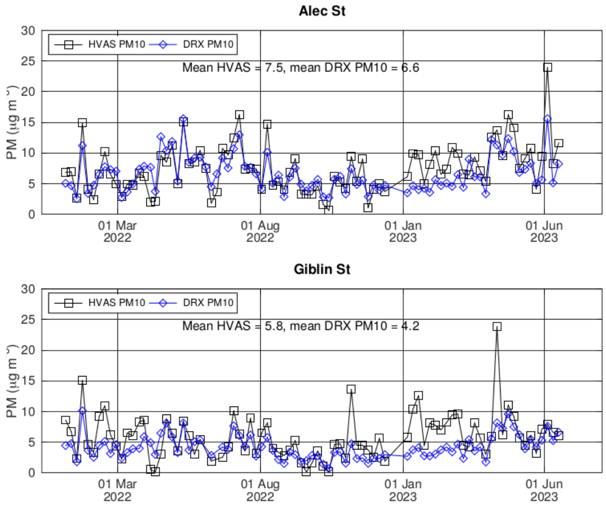

Figure 2: Comparison of the HVAS PM_{10} (black squares) and the raw, day-averaged DRX PM_{10} (blue diamonds) for the two Rosebery sites with co–located HVAS and DRX instruments, January 2022 to June 2023. Top: Alec St station; Lower: Giblin St station.

4 Exploring a better estimate of DRX 'PM_{10}'

Initial work seeking an improved level of agreement between the HVAS and DRX centred on adjusting the DRX PM_{coarse} (i.e. PM_{10} -$PM_{2.5}$) calibration factor, the SCF. However, it was apparent that adjusting this would not rectify the entire dataset: Adjusting the SCF to obtain better agreement in the summer–time data led to poorer agreement in winter. Sequentially adjusting the SCF then PCF ($PM_{2.5}$ calibration factor) to suit winter smoke resulted in poor agreement during summer bushfire intervals. Hence another approach appeared needed[4].

There is potential for the HVAS to pass particles bigger than 10 μm (Figure 1). The potential for improving the agreement between the HVAS PM_{10} and the DRX PM_{10} was explored by considering the DRX PM_{total}. We use a quantity we denote as PM_{big} which is arithmetically

$$\mathrm{PM_{big}} = \mathrm{PM_{total}} - \mathrm{PM_{10}} \tag{1}$$

that is, the DRX inferred mass–concentration for particles greater than 10 μm.

A number of trials were conducted exploring the

[4]The multi–year data set was compiled using different in–service DRXs over this interval, as instruments were changed for repair and maintenance. The analysis described here and later in the paper split the data set by instrument change dates as appropriate.

utility of using a function of the form

$$\text{Modified DRX PM}_{10} = A(DRX\ PM_{2.5}) + B(DRX\ PM_{coarse}) + C(DRX\ PM_{big}) \quad (2)$$

where the Modified DRX PM_{10} is to be close to the HVAS PM_{10} , and A, B, and C are constants that were, as part of the exploration, either set to unity, or were determined by a mathematical fit. Note that setting A and B to unity is, in effect, using the DRX calibration factors set prior to the deployment of each DRX.
Trials were conducted with A and B equal to unity, and with C determined in the fit. Trials were also made with A set to unity, and B and C determined in the fit, and also with all three of A, B and C being determined in the fitting. The best–fit values, when applied to the DRX measurements, where those that gave a Modified DRX PM_{10} closest to the HVAS PM_{10} data.
The fitting was conducted using the Singular Value Decomposition (SVD) method, rather than solving the least–squares normal equations. The SVD technique is less affected by measurement noise[5]. In general, it was found that while the fitting produced results that gave annual mean values for the modified DRX PM_{10} that were close to the annual mean HVAS PM_{10} , results for individual days were generally not improved. Hence simply including a contribution from the DRX PM_{big} did not resolve the discrepancies between HVAS and DRX PM_{10} .
On close inspection of the days with the most–discrepant HVAS and DRX PM_{10} values, some features were noted. For example, on the 6th of November 2022 at Giblin St the HVAS PM_{10} was among the highest seen at 13.6 μg m^{-3} , while the DRX PM_{10} was much lower at 4.7 μg m^{-3} . The times–series of the DRX data from Giblin St for the 6th of November 2022 is given in Figure 3. The top panel shows the data with a maximum y–scale of 25 μg m^{-3} to show the detail of the data. The lower panel shows the same data but with a maximum y–scale of 1000 μg m^{-3} to show the maximum value of a 'spike' in the data. The 'spike' was the highest signal of that type seen in the data in 2022. The relative sizes of the peak signal in $PM_{2.5}$ (∼100 μg m^{-3}), PM_{10} (∼700 μg m^{-3}), and PM_{total} (∼900 μg m^{-3}) are in general consistent with dust–signatures seen in DRX data collected by EPA Tasmania in other studies elsewhere in the state. It seemed more than co–incidental that this high spike occurred on a day when the HVAS recorded on the highest (non–bushfire) PM_{10} days thus far seen.

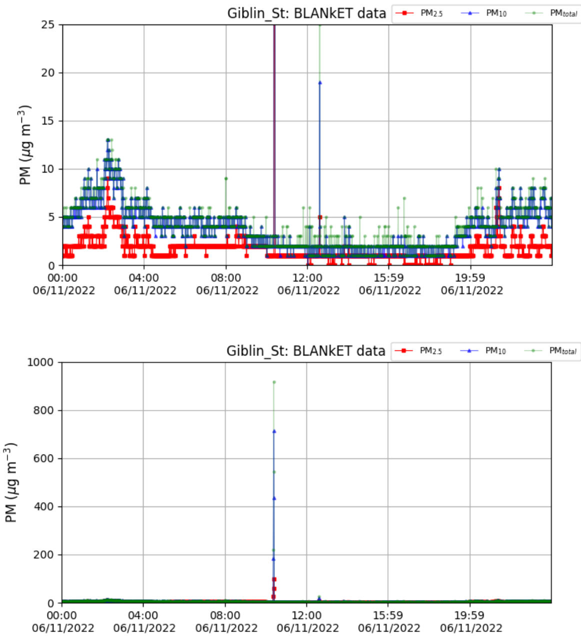

Figure 3: DRX data from Giblin St, 6th November 2022. Top panel: Time–series of $PM_{2.5}$ (red), PM_{10} (blue), and PM_{total} (green) with a maximum y–scale of 25 μg m^{-3} . Lower panel, as above, but with a maximum y–scale of 1000 μg m^{-3} .

The hypothetical question was asked of this 6th of November 2022 event: 'Could the difference in the HVAS PM_{10} and the DRX PM_{10} be due solely to a very–short–duration but very intense dust event, such as a dust cloud raised by a passing vehicle, that resulted in an extra ∼10 μg m^{-3} being recorded for the day's HVAS PM_{10} , but with a smaller (∼100 μg m^{-3}) PM_{total} spike recorded by the DRX?'. The HVAS samples at 1500 m^3 per 24 hours, or roughly 1 m^3 per minute. Hence, to record an extra 10 μg m^{-3} in the 24–hour measurement (so the HVAS value is 10 μg m^{-3} greater than the DRX) solely from a 1–minute event, the required HVAS sampled dust concentration in this 1 minute interal, *C*, can be found from:

$$13.6 = (1439)/(1440) \times\ 4.7 + C/(1440)\ \mu\text{g m}^{-3} \quad (3)$$

hence C∼12,800 μg m^{-3} , or 12.8 mg m^{-3}. This concentration is approximately 13 times the value recorded on the DRX PM_{total} at the time of the spike.
There are likely to be several potential explanations for the low DRX reading. One would be be if the dust particles present in the atmosphere included a significant portion greater than ∼12 μm to ∼15 μm in diameter, and

[5]In applying the SVD method in this way, it is necessary to set to zero the reciprocal of certain singular values in order to prevent observational errors (noise) dominating the solution.

hence which would not be recorded by the DRX, but are passed by the HVAS inlet (Figure 1). Another explanation would be if a dust–cloud raised by a passing vehicle was spatially non–uniform, the DRX may not sample enough of the cloud to obtain a representative average as compared to the HVAS sample. EPA Tasmania field–experience and a literature review supports the assertion that vehicle–raised dust can be of short–duration (∼1 minute) and spatially–variable on metre–scales.

5 'Spikes' – locally–raised dust

The premise is that spikes are the signature of localised, short–duration dust events, and that the dust particles may have light–scattering properties different to the background (smoke and sea–salt aerosol) particles for which the DRX has been calibrated. Hence in the following, the spikes will firstly be identified and removed from the daily mean PM_{total}[6], mathematically transformed by what is, potentially or effectively, a dust–specific calibration, then added back to give the what is called the 'augmented' DRX.

Inspection of the data indicated that PM_{coarse} (i.e. $PM_{10} - PM_{2.5}$) was rarely greater than 10 μg m^{-3} to 15 μg m^{-3} except when the data had the appearance of a significant 'spike'. Similarly PM_{big} ($PM_{total} - PM_{10}$) was rarely greater than 5 μg m^{-3} except for a spike. Hence thresholds of PM_{coarse}=20 and PM_{big}=15 μg m^{-3} were used to select spike–events in the data for both the Alec St and Giblin St data.

The data–sets were processed and spikes identified. Some basic diagnostic plots were produced to understand their character, such as daily and seasonal occurrence (see the appendix). At Alec St there is a clear clustering of PM_{coarse} and PM_{total} spike occurrence in the warmer months of the year. At Giblin St the seasonality is less marked, but still present. At Alec St the occurrence of PM_{coarse} spikes is less from midnight to near 07:00 hours, when spikes become far more common till mid–morning, withe PM_{big} spikes more prevalent during the middle of the day. For Giblin St there appears an interesting and marked peak for PM_{coarse} spikes near 05:00, with a general more frequent occurrence during the day until near 20:00. PM_{big} spikes can occur at any time, though there is a similar prevalence as for PM_{coarse} spikes from ∼05:00 to ∼20:00 hours.

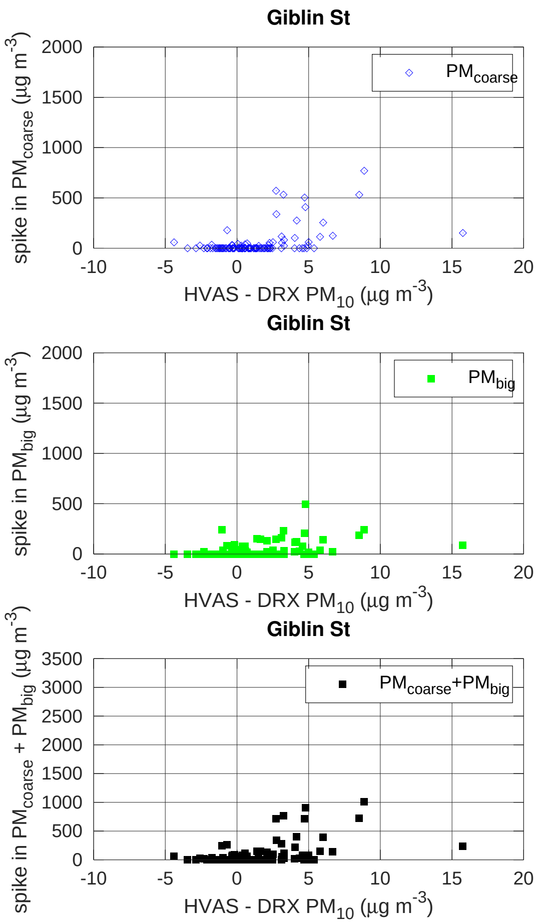

Figure 4: Data from Giblin St, showing scatter plots of the daily sum of the 'spike' signal versus the residual HVAS PM_{10} – raw DRX PM_{10}. Top panel: PM_{coarse} verus residuals; Middle panel: PM_{big} versus residuals; Lower panel: Sum of PM_{coarse} and PM_{big} versus residuals.

Figure 4 shows scatter plots of the daily–sum of the identified spikes plotted against the difference HVAS PM_{10} minus raw DRX PM_{10} for Giblin St. There is a tendency for the positive residuals to correlate with numerically greater summed spike values. (Note that residuals up to perhaps ±4 μg m^{-3} may arise from solely from measurement uncertainties.) Data from Alec St show a similar pattern, with large daily spike sums correlated with positive residuals, though with more scatter.
The functional form of the adopted equation is:

$$\begin{aligned} DRX = {} & [\mathrm{Mean}(\mathrm{PM_{total}}) - (\mathrm{spikes})] \\ & + C(PM_{coarse\ spikes})^{0.333} \\ & + B(PM_{big\ spikes})^{0.333}, \end{aligned} \tag{4}$$

where [Mean(PM_{total})-(spikes)] means the daily–mean PM_{total} without the contribution of

[6] PM_{total} will be used to produce a quantity to compare to the HVAS PM_{10}, due to the fact that the HVAS is sensitive to particles bigger than 10 μm.

spikes, $PM_{coarse\ spikes}$ and $PM_{big\ spikes}$ represent the total signal on a given day from the spikes, if any, and C ('coarse') and B ('big') are constants for a given DRX, to be found from the fit. The cube root (i.e. exponential of 0.333) was chosen from trial and error: If the DRX is not correctly sizing the 'spike' dust particles, the cube root would appear as a correction term. The SVD approach was used to solve for the C and B constants. As the DRX units were changed once at each site in the study interval the dataset were split appropriately. (See Table 1 in the appendix.)

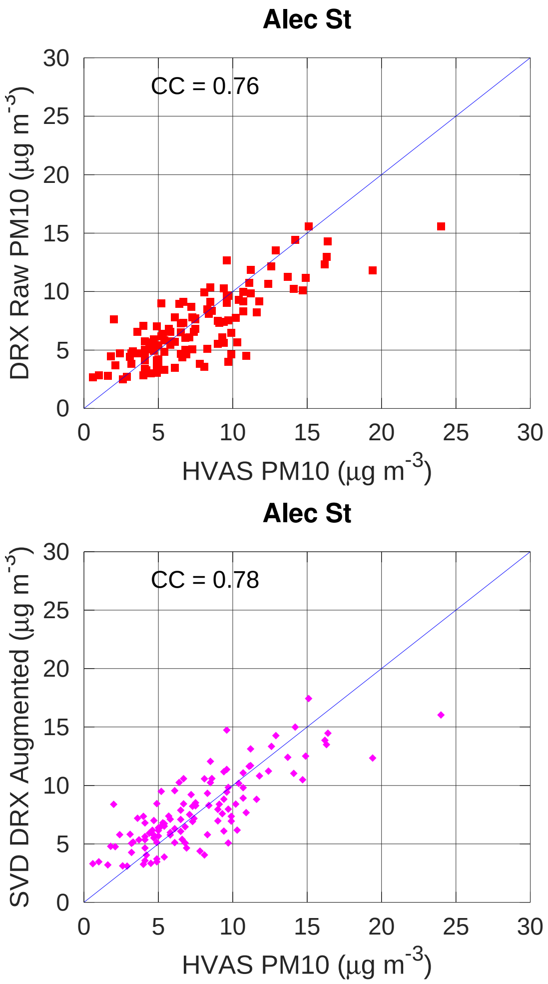

Figure 5: Alec St data. Top panel: Scatter plot of HVAS PM_{10} and 'raw' DRX PM_{10}. Lower panel: Scatter plot of HVAS PM_{10} and 'augmented' DRX.

Figures 5 and 6 show respectively for Alec St and Giblin St at top the scatter plots of the HVAS and DRX 'raw' PM_{10} (for January 2022 to December 2023), with the correlation co–efficient. The lower panels show scatter plots of HVAS PM_{10} and the 'augmented' DRX. At Alec St there is a slight improvement in the correlation. A significant improvement is seen for Giblin St. Several days remain discrepant. This may reflect a fundamental limit arising from very different sample flow rates and the few metre separation in instrument locations. Overall however, it appears that separately accounting for the 'spikes' results in an improved agreement between the instruments.

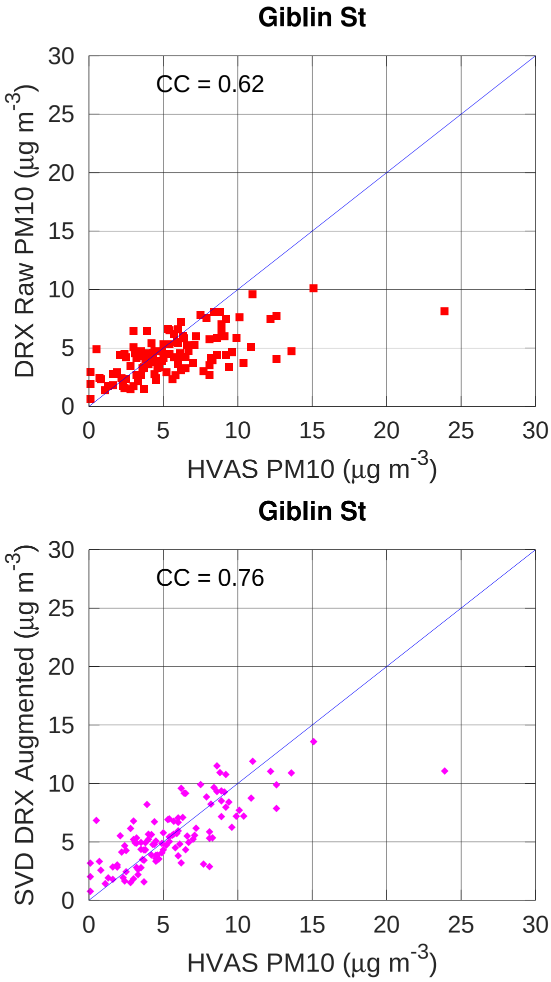

Figure 6: Giblin St data. Top panel: Scatter plot of HVAS PM_{10} and 'raw' DRX PM_{10}. Lower panel: Scatter plot of HVAS PM_{10} and 'augmented' DRX.

Acknowledgements

Ellis Cox, EPA Tasmania, is thanked for conducting the laboratory calibrations of the DRX units prior to their deployment at Rosebery.

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A Seasonal and Daily Occurrence of ‘spikes’, and results of the SVD fitting

Figures 7 and 8 show as a two–dimensional representation the time-of-year and time-of-day of the occurrence of the spikes in PM$_{coarse}$ and PM$_{big}$ for Alec St and Giblin St respectively for Janaury 2022 to June 2023. The symbol size is proportional to the size of the spike in μg m^{-3}. The spikes occur more often in the warmer months and also more often in daytime hours.

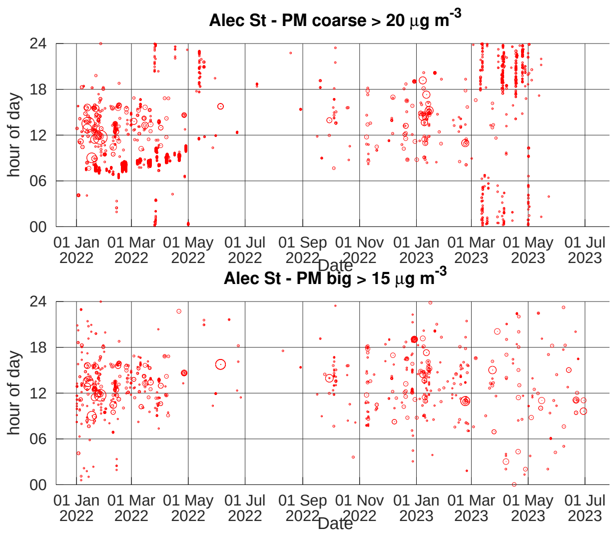

Figure 7: Two–dimensional representation of the occurrence of ‘spikes’ in the Alec St data, January 2022 to June 2023, Top panel: PM$_{coarse}$; Lower panel PM$_{big}$.

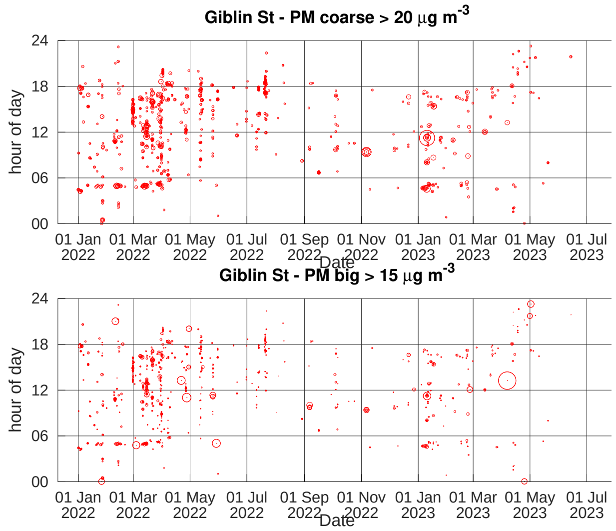

Figure 8: Two–dimensional representation of the occurrence of ‘spikes’ in the Giblin St data, January 2022 to June 2023, Top panel: PM$_{coarse}$; Lower panel PM$_{big}$.

The results for the C (‘coarse’) and B (‘big’) parameters from the SVD fits are given in Table 1. Two intervals are used as the DRX was changed once at each site in the study period. The DRX change at Alec St was on the 26th of October 2022, and at Giblin St on the 1st of April 2023.

Alec St	SVD C	SVD B
Interval 1	-0.06	-0.06
Interval 2	0.11	0.11
Giblin St	SVD C	SVD B
Interval 1	0.45	0.35
Interval 2	0.21	0.25

Table 1: C and B constants, by instrument interval, for data from January 2022 to December 2023.

For completeness, the time–series of HVAS PM$_{10}$, ‘raw’ DRX PM$_{10}$, and ‘augmented DRX’ for Alec St and Giblin St stations for the interval January 2022 to December 2023 are given in Figure 9. The improvement at Giblin St for the augmented DRX relative to the HVAS PM$_{10}$ is more marked than for the Alec St data.

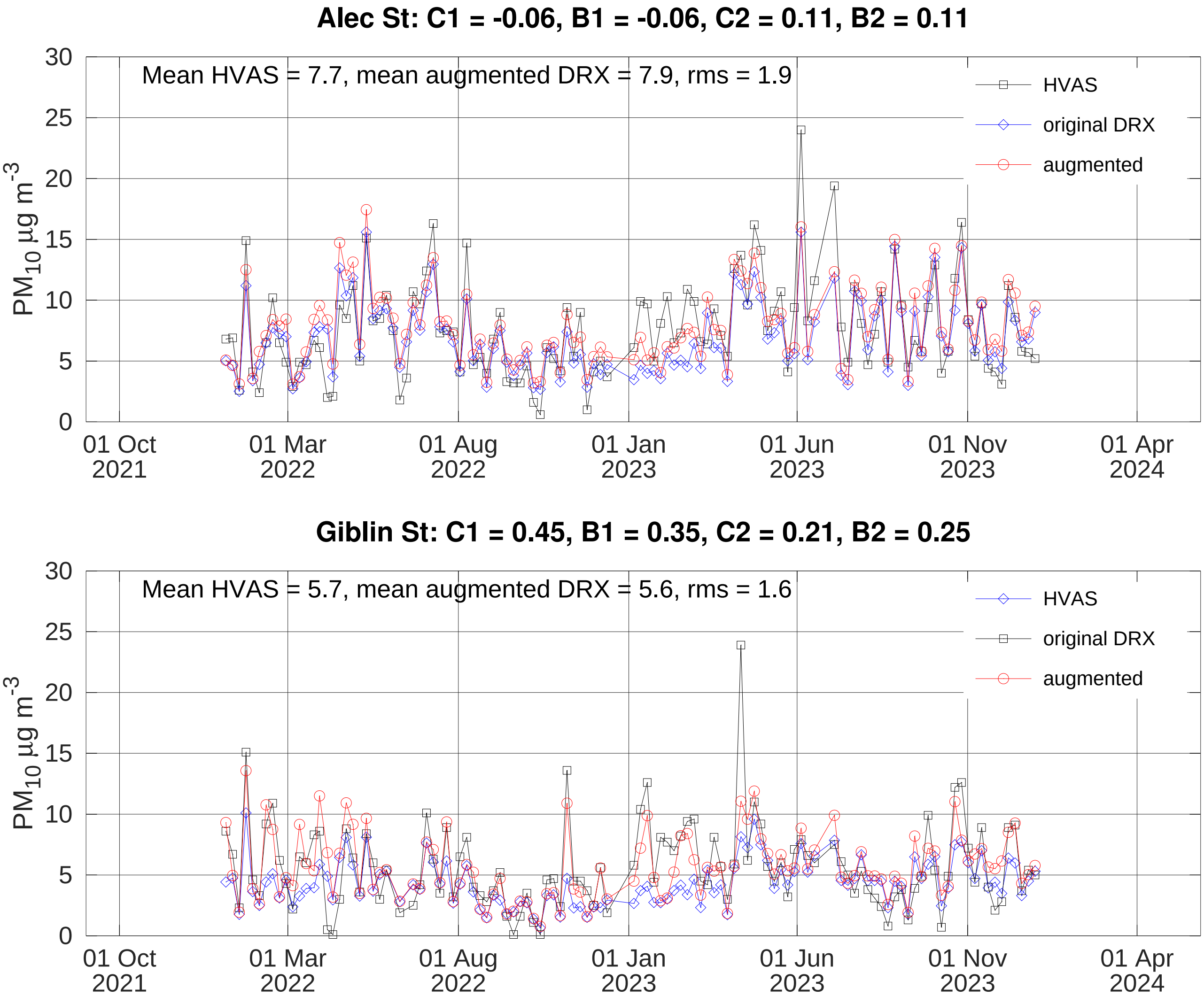

Figure 9: Time–series of Rosebery HVAS PM_{10} (black squares), raw DRX PM_{10} (blue diamonds), and 'augmented DRX' (red), January 2022 to December 2023. Upper panel: Alec St; Lower panel: Giblin St. The improvement at Giblin St for the augmented DRX relative to the HVAS PM_{10} is more marked than for the Alec St data.