BABYBLANKET: A LOW-COST, HIGHLY-PORTABLE, REAL-TIME, SMOKE-MONITORING STATION BASED ON THE DYLOS DC-1700 LASER PARTICLE COUNTER

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Abstract
The design and field performance of a low-cost, portable, real-time smoke-monitoring station is presented. The total station cost was well under $3000. The station can be transported in a small hatchback car, and can be deployed by one person. The system, known as ‘babyBLANKET’ is considered a “tier 3” system which will have applicability in instances such as where rapid deployment is needed, for sites with limited access and space, and where more expensive monitoring solutions may not be justified. The babyBLANKET station is based on a customised Dylos DC-1700 laser particle counter that provides particle counts in two size channels: 0.3 to 2.5 µm, and 2.5 to 10 µm. Meteorological data are collected by a Digitech USB weather station. A single-board linux-based ‘gumstix’ computer with a 3G modem provides data-logging and the connection for real-time data transfer.

The system has been tested in the late winters of 2012 and 2014 by co-locating with the existing BLANKET station at New Norfolk, Derwent Valley Tasmania. Woodheater smoke dominates the PM$_{2.5}$ fraction at New Norfolk in winter. The babyBLANKET system performance was very good in both seasons. In the 2014 deployment (12 September to 21 October), the hourly-averaged PM$_{2.5}$ mean residual between the Dylos derived PM$_{2.5}$ and the BLANKET PM$_{2.5}$ was -0.2 µg/m$^3$ with a standard deviation of 1.4 µg/m$^3$. For day averaged-data, the corresponding residual values were a mean of -0.1 µg/m$^3$ and standard deviation equal to 0.5 µg/m$^3$.

Keywords: Low-cost measurement, woodsmoke, PM$_{2.5}$, Tasmania.

1. Introduction

1.1. BLANKET and the need for increased monitoring
In 2009 the Tasmanian EPA Division commenced the deployment of a network of indicative air quality stations using optical particle counters over the state. This network, known as BLANKET (Base-Line Air Network of EPA Tasmania) provides real—time indicative PM$_{2.5}$, PM$_{10}$ and meteorological data via the EPA web pages. BLANKET has provided an unprecedented level of information concerning smoke concentration and movement over a wide area of Tasmania. (For more information please see http://epa.tas.gov.au/epa/BLANKET-reports.) The cost of a BLANKET station is around $25,000 to $30,000, or approximately 10% of a full-reference air monitoring station. The lower cost has allowed many more stations to be established for a given total cost, and hence has provided data over a much greater spatial-scale than would otherwise have been possible. However a BLANKET-type network providing complete cover over Tasmania would be a costly investment. Consequently, the EPA Division has been looking to design a very-low cost, easily deployable, indicative air quality station. This paper describes the design and testing of a ~$3000 air station for smoke and meteorological monitoring.

1.2. The Dylos DC-1700 particle counter
In 2012, the EPA Division purchased two Dylos DC-1700 air quality monitors for evaluation for ambient air monitoring devices. These are inexpensive (~US$500) laser-based indoor particle counters. The instrument appears to be designed for residential and non-critical industrial uses where indicative quality data are satisfactory for the
intended purposes. Air flow is provided by a low-pressure fan, rather than a pump.

The DC-1700 in its default configuration provides particle counts in two size ranges: from 0.5 µm to 2.5 µm, and 2.5 µm up to a nominal 10 µm limit. The specified co-incidence loss is 10% at a concentration of 2,000,000 particles per cubic foot. The units purchased by the EPA Division were slightly modified by the manufacturer at the EPA Division’s request to be potentially more suitable to Tasmanian conditions. This included reducing the lower-size cut-off from 0.5 µm to 0.3 µm to be more sensitive to smoke, and increasing the output data rate on the RS-232 port to 6 seconds compared to the default 1-minute. The Dylos DC-1700 also internally logs time-stamped data at 1-minute intervals for subsequent download.

Field tests of the Dylos units showed that a good correlation with BLANkET PM$_{2.5}$ was reliably obtained from a polynomial transformation of the small-channel particle count. Hence a low-cost station was designed that incorporated the DC-1700 to further test the concept. An issue noted in testing was the potential for the low-pressure, fan-driven, flow into the instrument to be disrupted in windy conditions.

2. The babyBLANkET station

2.1. Station requirements

A number of components were required to produce a complete ambient air station using the Dylos DC-1700 as the basis. These included a sample inlet design, which in principle should address the issues of wind affecting the sampling, noted above. Meteorological data are also required to help interpret the smoke concentration data. A heater to keep the Dylos ‘near room-temperature’ was considered necessary. This heater could also serve to precondition the sample air by warming it slightly above ambient temperature. This would lower the relative humidity to minimise the contribution of scattering from water vapour appearing in the particle counts.

The station instruments required an enclosure to protect them from the weather, and need to be mounted on a stand. The following sections outline the somewhat unconventional approaches taken to realise the concept.

2.2. Sample inlet

After some consideration, an inlet design was trialled that used two separate lengths of 100 mm x 70 mm rectangular section PVC downpipe connected to the inlet and outlet of the Dylos. The open ends of the downpipes were sealed. Five 12 mm-diameter holes were drilled through both of the 70 mm sides of the downpipe. The Dylos was mounted at 90° to its usual orientation (i.e. so it was no longer sitting on its base). The basic configuration is shown in Figure 1.

The inlet design was intended to reduce the effects of wind on sampling. Under calm conditions air can be drawn into the (10) holes in the inlet path, and after passing through the Dylos exits from the 10 holes of the outlet pipe. The potential for cross-talk between the inlet and outlet pipes is considered to be low.

Under windy conditions, the wind would be mostly expected to be horizontal, and would blow over the top and bottom of the PVC pipe with nearly equal velocity. The air pressure at the inlet and outlet of the Dylos should, to first order, be the same. The instrument manufacturer indicated this was the desired condition for optimum sampling.

Between the inlet/outlet holes in each PVC pipe and the Dylos itself is a section of stainless steel flywire. This was installed to prevent small insects from entering the sampling chamber. The flywire is held in place with silicon sealant. This sealant strip also prevents any rainwater that enters the PVC pipes from reaching the Dylos.

2.3. Meteorological data

The meteorological data are provided by a Digitech wireless meteorological station. These are around $200 in cost. A battery powered base-station with LCD display and data-logger communicate wirelessly to a sensor unit. The sensor unit measures barometric pressure, temperature, relative humidity, rainfall, wind speed and wind direction. Additionally, the console also measures ‘local’ temperature and relative humidity (i.e. inside the enclosure conditions). The sensor unit is powered by a solar cell and rechargeable batteries.
The on-board data-logger will store 4080 full meteorological records. This corresponds to 28 days of readings collected at a 10 minute data rate. The wind directions are recorded at the console only as one of eight cardinal points (e.g., north, north-east, east, etc.) giving a resolution of 45° for the wind direction. However, when reading the data directly, via a third-party software interface, sixteen cardinal point directions are available, i.e. a resolution of 22.5°. The ambient (outdoor) temperature sensor is reported by some users to read high in bright sunlight, which has been identified as being due to a poorly performing radiation shield. (An improved shield is available.) The limitations were not considered serious enough to prevent the Digitech being used in this prototype.

2.4. Heater for the system and inlet
The BLANKET stations use an EPA-made purpose-built inlet heater. This consists of a wire-wound temperature-servoed heater element wrapped around an inner cylinder comprising the air inlet, which is enclosed in an outer cylinder. Component parts and manufacturing take the cost of this to approximately $1500. A cheaper alternate was sought for the current prototype. Internet searches led to the identification of the Australian 'Pet Mat' carbon fibre heater as a possible solution. These heaters consist of a thin, flexible sheet comprising a carbon-fibre heater element. The smallest 'Pet Mat' heater is of low cost ($100), and runs at 12 V, delivering 6 W of heat. A mains adaptor is supplied with the unit. Order-of-magnitude calculations suggested this may be enough to keep the inside of a small, well-insulated enclosure near 20 C.
A mechanical thermostat is connected in series with the 12-V power lead to the Pet Mat. Closure temperature is about 3 degrees lower than the thermostat opening temperature. The thermostat thus works as a crude servo-system.

2.5. Enclosure and Insulation
In keeping with the prototype nature of the system, a plastic 25 litre storage container was purchased for $10. Foil-backed closed-cell foam insulation was installed on the bottom and sides of the container. Another piece was cut to sit on top of the side foam. A ‘snap’ fitting lid effectively seals the container. Openings were made at one end for the PVC inlet and outlet pipes. Silicon sealant was used to seal around the pipes, and also to hold the pipes in place. The Pet Mat sits on insulation at the bottom of the box. The Dylos rests on the Pet Mat. The met console is mounted on the inside of the box. A four-way power board is also mounted on the box side. The mains power is RCD protected.

2.6. Stand
In the prototype station a treated-timber (pine) stand was constructed to hold the enclosure. The cost of the timber was approximately $35. Construction took approximately 6 hours. Subsequent stations used a commercial powder-coated shelf unit (also about $35) as the stand. The prototype babyBLANKET station deployed at New Norfolk in 2012 is shown in Figure 2.

![Figure 2 – The babyBLANKET station (left) deployed next to the New Norfolk BLANKET station (right). The babyBLANKET inlet is on the side away from the camera.](image-url)
3. Field Performance

Two field trials were undertaken by co-locating the babyBLANKET prototype station next to the BLANKET station at New Norfolk, Tasmania. The first trial, with the prototype station was from 30th August to 12th November 2012. The second trial was with a station of slightly revised design from the 10th of September to the 22nd of October 2014. These dates are in general after the peak of the winter-time smoke, but were dictated by logistical and operational considerations. (Note: See also Appendix A for results from a 2015 July-August trial at Hadspen in north-central Tasmania.)

Separate Dylos DC-1700 units were used in the two trials. We have found the Dylos units can vary in sensitivity typically by 10 to 20%, occasionally by more. Hence each unit needs independent calibration for accurate field use.

3.1. Trial 1: 30 August-12 November 2012

Figure 3 shows the scatter plot of the BLANKET PM$_{2.5}$ (from the DRX DustTrak) and the Dylos small particle count from the interval 30th August to the 3rd of September 2012 (i.e. the first 5 days of the trial). The first five days were chosen to see if a working calibration could be obtained from a short-field comparison. A second-order polynomial was fitted to these data, the coefficients of which are given at the top of the plot. This polynomial was used to transform all subsequent Dylos field trial data from 2012 to a proxy PM$_{2.5}$.

A comparison of day-averaged PM$_{2.5}$ data from the BLANKET station and the babyBLANKET PM$_{2.5}$ (from the Dylos measurements) is shown in Figure 4 for the entire 2012 trial. Some data gaps were present in the Dylos time-series due to instrument stoppages. Overall however the agreement is very good.

![Figure 3 - Scatter plot of BLANKET (DRX) DustTrak) PM$_{2.5}$ (µg/m$^3$) and Dylos counts (from babyBLANKET) for the first 5 days of the 2012 trial](image)

Detail of the comparison of hourly-averaged data from the 2012 trial is given in Figure 5. Again there is a high measure of agreement between the two datasets. The good agreement also extends to the highest time-resolution of the data, as shown in Figure 6 which presents data for part of the interval of 3rd to the 4th of October 2012.

3.2. Trial 2: 10 September - 20 October 2014

The second field trial used a different Dylos instrument and included a real-time data reporting via the single-board linux computer and 3G modem, but otherwise the system was functionally identical to that used in 2012. Again, a polynomial was used to transform from Dylos small-particle count to PM$_{2.5}$ using the first week of sample data. This polynomial was then applied to all data taken during the second field trial.

![Figure 4 - Comparison of day-averaged PM$_{2.5}$ data (µg/m$^3$) from BLANKET (blue symbols) and babyBLANKET (red symbols) for the 2012 trial.](image)

Figure 7 shows the comparison of hourly-averaged (top panel) and day-averaged (lower panel) BLANKET and babyBLANKET PM$_{2.5}$ data for the 2014 trial. Again, there is a very good measure of consistency between the datasets. The hourly-averaged PM$_{2.5}$ mean residual between the babyBLANKET PM$_{2.5}$ and the BLANKET PM$_{2.5}$ was -0.2 µg/m$^3$ with a standard deviation equal to 1.4 µg/m$^3$. For day averaged-data, the corresponding residual values were a mean of -0.1 µg/m$^3$ and standard deviation equal to 0.5 µg/m$^3$.

3.3. Meteorological data comparison

The meteorological data from the two stations also compare favourably, as shown in Figure 8 where hourly-averaged data are presented for a subset of the 2014 trial interval. The lower angular-resolution of the babyBLANKET wind direction data is evident.
in the middle panel. There may also have been a small directional offset in the alignment of the wind vane zero, compared to the BLANkET station, during the babyBLANkET station set up. The babyBLANkET ambient temperature shows higher maxima on warm days, by a few degrees, compared to the BLANkET data, but otherwise the agreement is deemed satisfactory. Wind speeds measured by the two instruments also track closely.

Figure 5 - Comparison of hourly-averaged PM$_{2.5}$ data ($\mu$g/m$^3$) from BLANkET (blue symbols) and babyBLANkET (red symbols) for the interval 8 to 17 September 2012.

Figure 6 - Example comparison of PM$_{2.5}$ data ($\mu$g/m$^3$) from BLANkET (2-minute resolution, blue symbols) and babyBLANkET (1-minute resolution, red symbols) for part of the interval 3rd-4th October 2012.

Figure 7 - Comparison of PM$_{2.5}$ data ($\mu$g/m$^3$) as hourly-averaged (top) and daily-averaged (lower) from BLANkET (red symbols) and babyBLANkET (blue symbols) from the 2014 trial.

Figure 8 - Comparison of hourly-averaged meteorological data collected by the BLANkET and babyBLANkET stations in the 2014 trial. Only part of the trial data set is shown for clarity in the plot. The legend to the plots indicate the BLANkET ('BL') and babyBLANkET ('bB') data sets. Top panel: wind speed; middle panel: wind direction; lower panel: ambient temperature.

4. Discussion
The 2012 and 2014 field-trial data indicate the small-particle count from the Dylos counter can be satisfactorily transformed to an effective PM$_{2.5}$ ‘BLANkET’ measurement with a high level of reliability. The Dylos is stable on times-scales of order at least 2 months. A longer duration field trial is needed, but the results to date are encouraging. The low-cost ($200) meteorological station also appears to provide a satisfactory level of performance given the aims of the project.

As noted, in winter at New Norfolk the PM$_{2.5}$ aerosol mass fraction is dominated by woodsmoke from domestic heating, as is likely the case for most of Tasmania. The lack of other particle sources is
likely a significant factor that makes possible the derivation of a simple relationship between the Dylos count in the small-particle channel and the BLANKET (DRX DustTrak) PM$_{2.5}$ measurement.

As noted earlier, the babyBLANKET air inlet was designed to try to avoid sampling artefacts due to non-zero ambient wind speeds, where the concern is strong winds may prevent the Dylos sampling correctly. Analysis of the field trial data was undertaken to investigate the success or otherwise of this design. Table 1 shows the mean PM$_{2.5}$ residual (as babyBLANKET-BLANKET) and the mean BLANKET PM$_{2.5}$ binned in ranges of wind speeds for the 2014 trial. There is a suggestion that the mean residuals are slightly negative, of order -0.5 µg/m$^3$, for low wind speeds (e.g. below 4.5 km/hr), possibly indicating a slight PM$_{2.5}$ underestimate by babyBLANKET. However, environmentally at New Norfolk PM$_{2.5}$ is often greater at low wind speeds (i.e. more smoke on calm nights). This ‘underestimation at low wind’ may therefore be a dependence of the babyBLANKET measurement on the ambient PM$_{2.5}$ level (resulting from a small transformation effect in the use of the calibration polynomial) than on a sampling effect from ambient wind speed. In any case, the effect is small compared to the levels being measured, and can be regarded as being within experimental uncertainty. For wind speeds greater than 4.5 km/hr the mean residual is very slightly positive by around 0.05 µg/m$^3$. Hence there is no clear evidence from these data to suggest the Dylos is reading low under windy conditions.

Table 1. PM$_{2.5}$ residuals (babyBLANKET-BLANKET) binned by wind speed ranges from the 2014 field trial.

<table>
<thead>
<tr>
<th>Wind speed range (km/hr)</th>
<th>Mean residual PM$_{2.5}$ (bb-BL)</th>
<th>Mean PM$_{2.5}$ (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.5</td>
<td>-0.34</td>
<td>14.6</td>
</tr>
<tr>
<td>1.5-3.0</td>
<td>-0.50</td>
<td>8.2</td>
</tr>
<tr>
<td>3.0-4.5</td>
<td>-0.57</td>
<td>6.8</td>
</tr>
<tr>
<td>4.5-6.0</td>
<td>0.06</td>
<td>4.4</td>
</tr>
<tr>
<td>6.0-10.0</td>
<td>0.04</td>
<td>3.0</td>
</tr>
<tr>
<td>&gt;10.0</td>
<td>0.07</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The low-cost babyBLANKET station is not envisaged as a replacement for more sophisticated continuous monitoring systems, such as TEOMs and BAMs, or even the BLANKET instruments. It is considered as a ‘tier 3’ monitoring approach, with tier 1 being a reference or equivalent method, and tier 2 being an appropriately verified indicative instrument (such as BLANKET). Where babyBLANKET will have use is circumstances where rapid deployment is critical, or when for other reasons a more expensive and physically larger station would not or cannot be used.

For example, the babyBLANKET stations have been deployed at residential properties in response to complaints regarding woodheater smoke from neighbouring properties. In many such instances a station with a small physical footprint is a significant advantage both for the act of deployment and to minimise the impact of the station presence at the residence. Figure 9 shows a babyBLANKET deployed at a Hobart residence in 2014.

5. Conclusion

The babyBLANKET concept is in a real sense still under active development, but field trials of a prototype version have shown satisfactory levels of performance. The potential of such a low-cost, readily deployable system for woodsmoke monitoring in Tasmania is considered very high. At the time of writing several more stations are under construction. Further evaluation is planned.

Acknowledgments

We thank the Tasmanian Inland Fisheries Service for access to the New Norfolk site where the field trials were conducted. The name ‘babyBLANKET’ was coined by Angela Boyd (Hobart City Council). Mr. C. Stott brought the Dylos device to our notice. We thank Dylos Corporation (USA) for customising the DC 1700 units for our work.
Appendix

A. 2015 July-August field tests at Hadspen, north-central Tasmania

In late July 2015 the babyBLANkET station that was tested at New Norfolk in late winter 2014 was deployed for further tests at Hadspen in north-central Tasmania, again by co-locating with a BLANKET station.

The data obtained indicated the relationship seen at New Norfolk in 2014 between the Dylos small-particle count and PM$_{2.5}$ was still valid for the 2015 data. This is shown in Figure 10, where data collected in 2014 at New Norfolk are plotted in red and data from Hadspen in 2015 are plotted in blue.

It is seen that higher smoke concentrations were measured at Hadspen, but at lower levels the data are consistent with the New Norfolk data. The system was not in continuous use between the field tests in 2014 and 2015, but did undergo approximately two months of lab testing in early 2015. These data indicate the Dylos unit did not greatly change in sensitivity over the 11 months between the 2014 and 2015 field tests. If this is a typical result it suggests annual calibration would be sufficient for the Dylos DC-1700 instrument.

Figure 11 shows a comparison of day-averaged PM$_{2.5}$ between the BLANKET and babyBLANKET instruments for day-averaged PM$_{2.5}$ data from the Hadspen 2015 tests. The level of agreement is considered very good.
Figure 11 - Hadspen 2015 July-August field trial: Comparison of (calendar day) day-averaged BLANkET PM$_{2.5}$ (red symbols) and babyBLANKET PM$_{2.5}$ (green symbols).