Performance Assessment of Low-Cost $PM_{2.5}$ Sensors

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Center for Study of Science, Technology and Policy (CSTEP)

April 2022

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Designed and edited by CSTEP

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Abbreviations and Acronyms

µg	Microgram
BAM	Beta attenuation monitor
CSTEP	Center for Study of Science, Technology and Policy
FEM	Federal equivalent method
LCS	Low-cost sensor
MAB	Mean absolute bias
NRMSE	Normalised root mean square error
PM	Particulate matter
PM_1	Particulate matter with a size less than or equal to 1 microns
PM_{10}	Particulate matter with a size less than or equal to 10 microns
$PM_{2.5}$	Particulate matter with a size less than or equal to 2.5 microns
R^2	Coefficient of determination
RMSE	Root mean square error

1. Background

Air pollution monitoring is an important aspect of air quality management. Strategically placed sensors can monitor air pollution and provide detailed information on air quality and its variability within a region. Low-cost sensors (LCSs) that measure $PM_{2.5}$ (particulate matter with a size less than or equal to 2.5 microns) are becoming increasingly popular for monitoring air pollution because of their low cost and portability. However, the low cost and portability come with trade-offs on data quality, reliability, and shelf life.

Most of the LCSs quantify $PM_{2.5}$ based on the light scattering technique, which is sensitive to environmental factors (e.g., humidity in the atmosphere) and the optical and microphysical properties of particulate matter (PM) in addition to the particle concentration. This can introduce bias in LCSs measurements of PM, thereby requiring evaluation before reporting/publishing. A common method of evaluating the performance of LCSs is by analysing the field collocation (side-by-side installation and collection of data using LCSs and a reference-grade instrument) data.

In this technical note, we report the performance of various LCSs by comparing their $PM_{2.5}$ measurements with a collocated reference-grade instrument.

2. Materials and Methods

2.1 Study Site and Study Period

The collocation experiments were conducted in Bengaluru, India. The instruments were installed on the roof terrace of the Center for Study of Science, Technology and Policy (CSTEP) at a height of ~10 m above the ground level and ~150 m away from the main road. Simultaneous $PM_{2.5}$ measurements from LCSs and a reference-grade instrument collected during the period December 2021 to April 2022 (4 months) are presented in this technical note.

2.2 Instrumentation

A beta attenuation monitor (BAM-1022, Met One Instruments, Grants Pass, USA)—certified as a federal equivalent method (FEM) class instrument by the United States Environmental Protection Agency (USEPA)—was used to measure near real-time (hourly) reference-grade $PM_{2.5}$. More details on BAM-1022 and its installation can be found in Prabhu et al. (2022). BAM-1022 is equipped with a meteorological sensor that can measure ambient relative humidity, temperature, and atmospheric pressure in addition to $PM_{2.5}$.

A suite of $PM_{2.5}$ measuring LCSs was installed next to BAM-1022 (under shade to protect from direct sunlight and rain). The LCSs measure $PM_{2.5}$ at a very high temporal resolution (as high as 1 Hz). Apart from $PM_{2.5}$, most of these sensors also measure PM_1 and PM_{10}. However, the evaluation carried out in this technical note is limited to $PM_{2.5}$ measurements. The LCSs installation is shown in Figure 1. The main features of LCSs are given in Table 1. The LCSs $PM_{2.5}$ data are averaged for one hour to match with the time resolution of BAM-1022 measurements.

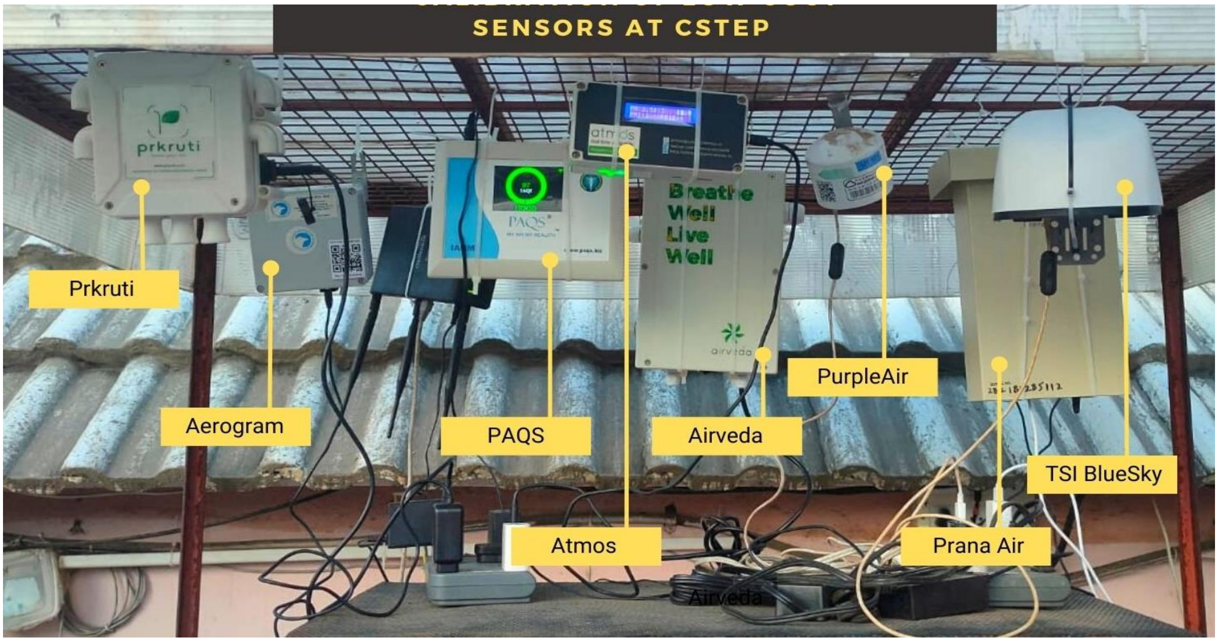

Figure 1: Collocated low-cost sensors

Table 1: LCSs used in the study

Name of the LCS	Laser counter	Pollutants	Logging/averaging interval
BlueSky	Sensirion	$PM_{2.5}$, PM_{10}	1 minute
Airveda	Nova	$PM_{2.5}$, PM_{10}	30 minutes
Aerogram	Plantower	PM_1, $PM_{2.5}$, PM_{10}	30 seconds
Prkruti	Winsen	$PM_{2.5}$, PM_{10}	15 minutes
Atmos I	Plantower	$PM_{2.5}$, PM_{10}	1 minute
Atmos II	Sensirion	$PM_{2.5}$, PM_{10}	1 minute
Prana Air	PAS-OUT-01	PM_1, $PM_{2.5}$, PM_{10}	30 seconds
PurpleAir	Plantower	PM_1, $PM_{2.5}$, PM_{10}	2 minutes
PAQS	Honeywell	$PM_{2.5}$, PM_{10}	30 minutes

2.3 Performance Metrics

The following metrics were used to evaluate the performance of LCSs: coefficient of determination (R^2), mean absolute bias (MAB), root mean square error (RMSE), and normalised root mean square error (NRMSE).

$$R^2 = \left(\frac{\sum_{i=1}^{n} L_i B_i - \frac{1}{n} \sum_{i=1}^{n} L_i \sum_{i=1}^{n} B_i}{\sqrt{\sum_{i=1}^{n} L_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} L_i\right)^2} \sqrt{\sum_{i=1}^{n} B_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} B_i\right)^2}} \right)^2 \quad \text{………………. (1)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (L_i - B_i)^2}{n}} \quad \text{………………. (2)}$$

$$MAB = \frac{\sum_{i=1}^{n} |L_i - B_i|}{n} \quad \text{………………. (3)}$$

$$NRMSE = \frac{RMSE}{\frac{1}{n} \sum_{i=1}^{n} B_i} \quad \text{………………. (4)}$$

L and *B* are the hourly LCS $PM_{2.5}$ and BAM-1022 $PM_{2.5}$, respectively, and *n* is the number of paired data points.

3. Results

Figure 2 shows scatter plots of BAM-1022-measured hourly $PM_{2.5}$ and LCSs-measured $PM_{2.5}$ hourly mean values. The 99 percentile value of the hourly BAM-1022-measured $PM_{2.5}$ during the study period is ~120 µg m^{-3}. The figure shows that the LCSs-measured $PM_{2.5}$ values are biased compared to BAM-1022 measurements. Most LCSs underestimated the BAM-1022 $PM_{2.5}$ while a few (primarily Plantower-based LCSs) overestimated at lower values (in the range of 0 to ~70 µg m^{-3}) and underestimated for higher concentrations. The level of disagreement between $PM_{2.5}$ measured by LCSs and BAM-1022 varied across LCSs. The MAB (RMSE) in LCSs $PM_{2.5}$ varied between 6.9 (10.3) µg m^{-3} and 30.8 (35.9) µg m^{-3}, and the highest value is observed for the PAQS sensor. The NRMSE values ranged between 0.24 and 0.82. The linearity (as inferred from the linear fit R^2) of the LCSs $PM_{2.5}$ with respect to BAM-1022 $PM_{2.5}$ also varied. The performance metrics of the individual sensors are given in Table 2.

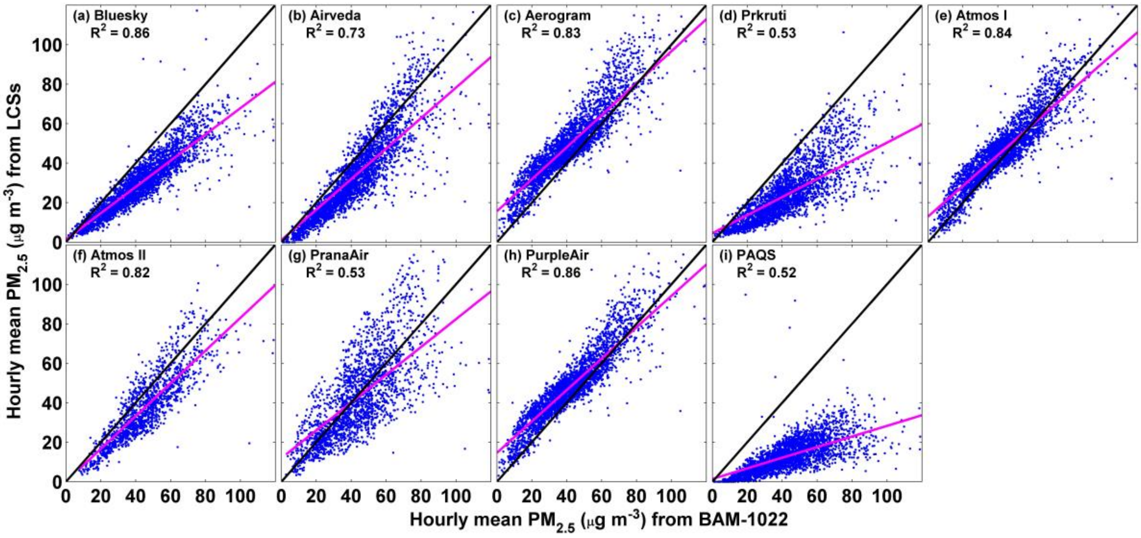

Figure 2: Scatter plots of hourly mean $PM_{2.5}$ from BAM-1022 and LCSs. The black and pink lines denote the 1:1 and least square linear fit, respectively.

Table 2: Performance metrics of LCSs $PM_{2.5}$ (n represents the number of paired data points)

Sensor	n	Slope	Intercept	R^2	MAB ($\mu g\ m^{-3}$)	RMSE ($\mu g\ m^{-3}$)	NRMSE
BlueSky	2880	0.66	1.39	0.86	13.6	16.9	0.38
Airveda	2891	0.77	1.07	0.73	10.7	15.3	0.35
Aerogram	2837	0.81	15.67	0.83	9.2	12.4	0.28
Prkruti	2582	0.46	4.51	0.53	18.6	24.5	0.58
Atmos I	2897	0.78	12.95	0.84	6.9	10.3	0.24
Atmos II	1387	0.83	0.06	0.82	10.0	12.5	0.27
Prana Air	2046	0.70	11.95	0.53	11.7	16.6	0.37
PurpleAir (cf_atm)	2836	0.80	14.65	0.86	7.9	10.9	0.25
PAQS	2880	0.27	1.39	0.52	30.8	35.9	0.82

Figures 3 and 4 examine the accuracy of the LCSs-measured ambient temperature (T in °C) and relative humidity (RH in %). Most of the LCSs, except PranaAir, overestimated the T and underestimated the RH. The highest deviation is observed in the measurements of T and RH by Atmos I.

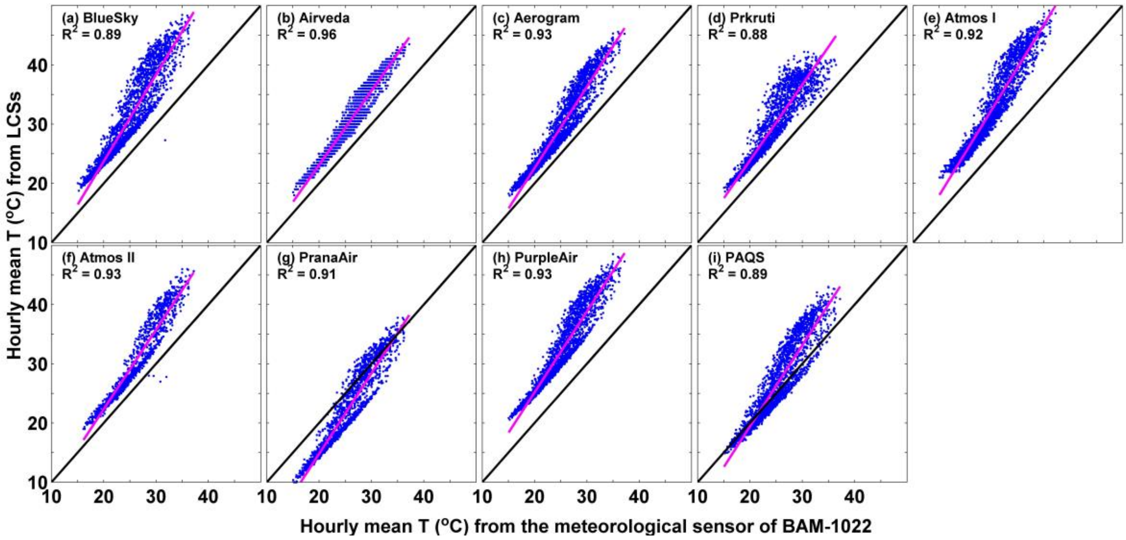

Figure 3: Scatter plots of hourly mean temperature (T, °C) from the meteorological sensor of BAM-1022 and LCSs. The black and pink lines denote the 1:1 and least square linear fit, respectively.

Table 3: Performance metrics of LCSs-measured temperature (n represents the number of paired data points)

Sensor	n	Slope	Intercept	R^2	MAB (°C)	RMSE (°C)	NRMSE
BlueSky	2939	1.47	-5.58	0.89	5.6	6.4	0.27
Airveda	2964	1.25	-1.85	0.96	4.1	4.4	0.18
Aerogram	2910	1.37	-4.84	0.93	4.1	4.7	0.20
Prkruti	2654	1.28	-1.70	0.88	4.9	5.4	0.23
Atmos I	2971	1.44	-3.60	0.92	7.0	7.5	0.31
Atmos II	1391	1.34	-4.49	0.93	4.3	4.9	0.19
Prana Air	2086	1.36	-12.43	0.91	4.0	4.4	0.18
PurpleAir	2909	1.37	-2.15	0.93	6.6	7.1	0.29
PAQS	2953	1.37	-8.04	0.89	2.1	2.9	0.12

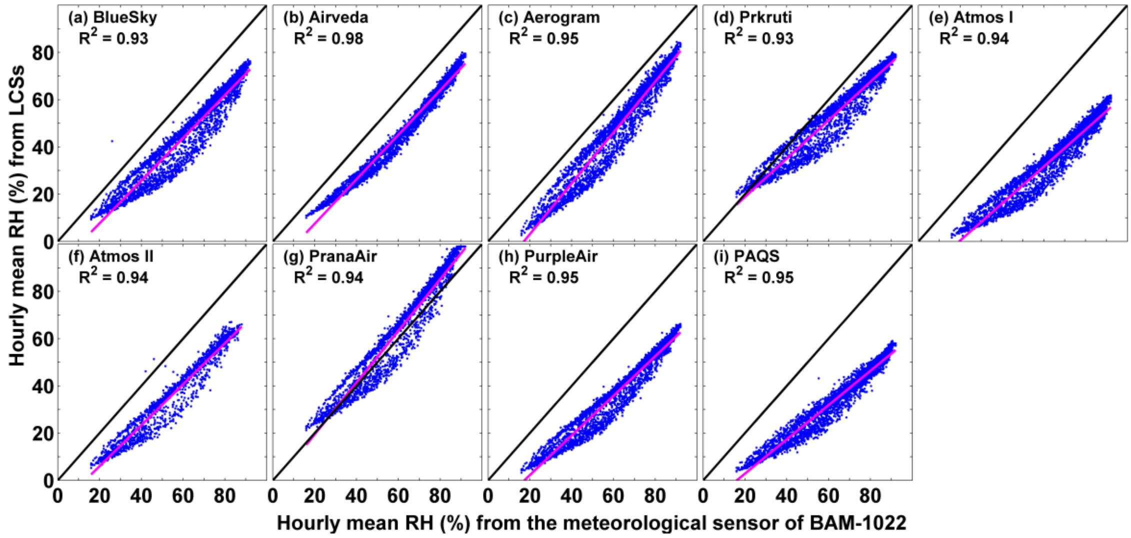

Figure 4: Scatter plots of hourly mean relative humidity (RH, %) from the meteorological sensor of BAM-1022 and LCSs. The black and pink lines denote the 1:1 and least square linear fit, respectively.

Table 4: Performance metrics of LCSs-measured relative humidity (n represents the number of paired data points)

Sensor	n	Slope	Intercept	R^2	MAB (%)	RMSE (%)	NRMSE
BlueSky	2939	0.90	-10.41	0.93	16.4	17.2	0.27
Airveda	2964	0.94	-11.33	0.98	15.0	15.3	0.24
Aerogram	2910	1.08	-18.40	0.95	13.6	14.5	0.23
Prkruti	2654	0.81	2.60	0.93	9.6	10.9	0.17
Atmos I	2971	0.78	-15.25	0.94	28.9	29.4	0.47
Atmos II	1391	0.87	-11.37	0.94	18.5	19.1	0.35
Prana Air	2086	1.10	-2.43	0.94	5.9	6.5	0.11
PurpleAir	2909	0.84	-14.55	0.95	24.7	25.1	0.40
PAQS	2953	0.73	-11.67	0.95	28.9	29.5	0.47

4. Limitations and Way Forward

The results obtained here are specific to (a) Bengaluru, (b) hourly $PM_{2.5}$, and (c) the range of $PM_{2.5}$ values observed during the study period. They might vary for other geographies and seasons. The PAQS monitor used in this study is intended for indoor measurements.

From the study, it is evident that $PM_{2.5}$, temperature, and relative humidity measurements of LCSs can capture trends. The uncorrected measurements can be used for qualitative information. For example, they can be used to identify specific days or locations that are more polluted than others. Given the affordability, portability, and ease of installation, LCSs can help give air quality information in areas with no monitoring. The high temporal resolution (compared to reference-grade instruments) is also useful in capturing short pollution events. However, for utility beyond qualitative characterisation, LCSs data need more processing. Compared to the reference-grade instrument, the LCSs used in the study exhibited bias. Therefore, LCSs measurements need corrections. Calibration models developed using data from local field collocation experiments can be used for these corrections. However, given the differences in measurements between different LCSs makes and models, the calibration models developed need to be make- or model-specific.

Using LCSs for high-quality air quality data is indeed a growing field of research. Studies have shown that the inclusion of temperature and relative humidity as predictors (in addition to $PM_{2.5}$) has significantly improved calibration models' performances. Several univariate, multivariate, and machine learning–based calibration models are suggested in Barkjohn et al. (2021) and deSouza et al. (2022). Also, best practices to be followed in establishing and maintaining LCS networks, calibration experiments, and data cleaning methods can be found in Duvall et al. (2021), Giordano et al. (2021), and Zimmerman (2022). As LCS technology is continuously developing, newer versions can be equipped with more accurately calibrated laser counters and meteorological sensors that could provide $PM_{2.5}$, temperature, and relative humidity measurements which are closer to reference-grade measurements.

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