

## Response to Comments from Reviewer #3 AMT-2019-55

The authors would like to sincerely thank the reviewer #3 for the careful review of the manuscript and the very constructive comments which helped improve the manuscript. The reviewer's comments are in italics, the summaries of our responses are in plain font, and the changes in the manuscript are in **bold red text**. Page and line numbers refer to the original document.

5 We also appended a marked-up manuscript version to the end of the responses to better show all the changes made from this review.

### Reviewer #3

#### Major Comments:

10 *1. Data are interpolated for both monitor types (LCS and reference). Why not perform analyses to validate your interpolation? For instance, by removing data of similar size to what is missing from non-missing periods and applying the same interpolation? How much consecutive data is interpolated? An hour here or there, or larger chunks of time?*

**Response:** We thank the reviewer for bringing up the validity of interpolation. Mathematically, the GPR model can operate without requiring data from all the stations to be non-missing on each day by relying on only the non-missing stations' covariance information on each day for inference. In this paper, the choice of attempting to interpolate all the stations' missing data first was made based on practical reasons. Specifically, interpolating prior to the GPR inference allows matrix inversions to be shared, greatly speeding the algorithm. To elaborate, with 59 daily-averaged data points, the algorithm with interpolating all the stations' missing data first takes ~10 mins to run 22 times (a complete 22-fold leave-one-out cross-validation) while the algorithm without any interpolation takes ~200 mins to run 22 times. If a complete 22-fold leave-one-out cross-validation takes 200 mins to run, it will be unrealistic to implement the simulation experiments shown in Section 3.3. We are mentioning these because **we would like to prove that interpolating data for both reference and low-cost nodes is an appropriate methodology for this paper by showing that the accuracies of model prediction on the 22 reference nodes with and without interpolation are statistically the same**. The comparison of the model prediction percent errors for the 22 reference stations with and without interpolation is shown in the newly added Table S1 (see below). The percent errors for all the stations are essentially the same with only one exception of station Vasundhara whose error without interpolation is 10 % lower than that with interpolation. The Delhi-wide mean percent errors averaged over the 22 reference stations are also essentially the same (30 % and 29 % for with and without interpolation, respectively). We used the Wilcoxon signed-rank test (Wilcoxon, 1945) to prove that the two related paired samples (i.e., the percent errors for the 22 reference stations with and without interpolation) are statistically the same. The Wilcoxon signed-rank test is a non-parametric version of the parametric paired t-test (involving two related/matched samples/groups) that requires no specific

distribution on the measurements (unlike the parametric paired t-test that assumes a normal distribution). We conducted a two-sided test which has the null hypothesis that the percent errors for the 22 reference stations with and without interpolation are the same (i.e.,  $H_0$ : with = without) against the alternative that they are not the same (i.e.,  $H_1$ : with  $\neq$  without). The p-value of the test is 0.07. The level of statistical significance was chosen to be 0.05, which means that the null hypothesis (i.e.,  $H_0$ : with = without) cannot be rejected when the p-value is 0.07, above 0.05. Therefore, interpolating data for both reference and low-cost nodes is appropriate for this paper because the accuracies of model prediction on the 22 reference nodes with and without interpolation are not distinct based on the Wilcoxon signed-rank test result. Regarding **how much consecutive data is interpolated and an hour here or there, or larger chunks of time**, all the periods over which 1 h data were interpolated for each site are already illustrated in **Fig. S1** (also mentioned on Page 5, lines 21-22); we also already specified on Page 5, lines 8-10 that the interpolation was implemented on the 1 h averaged measurements for each station; additionally, the comparison of 1 h  $PM_{2.5}$ 's percentage completeness with respect to the entire sampling period (i.e., from January 1, 2018 00:00 to March 31, 2018 23:59, Indian Standard Time, IST, in total 90 days, 2160 hours) before and after missing data imputation for both reference and low-cost nodes is already provided in Table 1 (this means that a 10 % increase in the percentage completeness after interpolation is equivalent to a total of ~216 hours of data being interpolated); We believe these pieces of information are sufficient for readers to have a good understanding of how much data (the exact number of hours) was interpolated for each station and whether the interpolation for each station was done an hour here and there or over a large chunk of time. Again, **we would like to emphasize that the interpolation approach in this paper has little effect on the model's overall prediction accuracy considering all the 22 reference stations and does not affect any of the conclusions in this paper**. We have now added the validation of our interpolation approach to Sect. 3.2.1 of the manuscript, including showing the comparison of accuracies of model prediction on the 22 reference nodes with and without interpolation in the newly added Table S1 and proving that they are not distinct based on the Wilcoxon signed-rank test. We have now also modified Table 1 caption to make it more informative about how to interpret the percentage data completeness such as indicating that a 10 % increase in the percentage completeness after interpolation is equivalent to 216 hours of 1 h data being interpolated.

Modified text on Page 5, lines 6–10:

**“While mathematically the GPR model can operate without requiring data from all the stations to be non-missing on each day by relying on only each day's non-missing stations' covariance information to make inference, we practically required concurrent measurements of all the stations in this paper to drastically increase the speed of the algorithm (~10 mins to run a complete 22-fold leave-one-out CV, up to ~20 times faster) by avoiding the expensive computational cost of excessive amount of matrix inversions that can be incurred otherwise. We therefore linearly interpolated the 1 h  $PM_{2.5}$  values for the hours with missing measurements for each station, after which we averaged the hourly data to daily resolution as the model inputs. We validate our interpolation approach in Sect. 3.2.1 by showing that the model accuracies with and without interpolation are statistically the same.”**



Added text on Page 9, line 13:

“In this paper, we interpolated the missing 1 h PM<sub>2.5</sub> values for all the reference and low-cost stations to fulfil our requirement of concurrent measurements of all the stations. This approach drastically increased the speed of the algorithm (up to ~20 times faster) by avoiding the expensive computational cost of excessive amount of matrix inversions that can be incurred from relying on only each day’s non-missing stations’ covariance information to make inference. Here we prove that the interpolation is an appropriate methodology for this paper by demonstrating that the model prediction percent errors for the 22 reference stations with and without interpolation are statistically the same. The comparison of the errors for each station can be found in Table S1. Table S1 shows that the percent errors for all the stations are essentially the same with only one exception of station Vasundhara whose error without interpolation is 10 % lower than that with interpolation. The Delhi-wide mean percent errors with (30 %) and without interpolation (29 %) are also essentially the same. We further used the Wilcoxon signed-rank test (Wilcoxon, 1945) to prove that the two related paired samples (i.e., the percent errors for the 22 reference stations with and without interpolation) are indeed statistically the same. The Wilcoxon signed-rank test is a non-parametric version of the parametric paired t-test (involving two related/matched samples/groups) that requires no specific distribution on the measurements (unlike the parametric paired t-test that assumes a normal distribution). We conducted a two-sided test which has the null hypothesis that the percent errors for the 22 reference stations with and without interpolation are the same (i.e.,  $H_0$ : with = without) against the alternative that they are not the same (i.e.,  $H_1$ : with  $\neq$  without). The p-value of the test is 0.07. The level of statistical significance was chosen to be 0.05, which means that the null hypothesis (i.e.,  $H_0$ : with = without) cannot be rejected when the p-value is 0.07, above 0.05. Therefore, interpolating missing 1 h PM<sub>2.5</sub> data for both reference and low-cost nodes is appropriate for this paper because the accuracies of model prediction on the 22 reference nodes with and without interpolation are not distinct based on the Wilcoxon signed-rank test result.”

Added Table S1:

**Table S1: Comparison of the GPR model 24 h prediction percent errors for the 22 reference nodes across the 22-fold leave-one-out CV with and without interpolating the missing 1 h PM2.5 values for all the reference and low-cost stations.**

Reference nodes	Percent error	
	with interpolation	without interpolation
Anand Vihar	32 %	31 %
Aya Nagar	38 %	37 %
Burari Cross	39 %	38 %
CRRJ Mathura Road	21 %	21 %
DTU	36 %	35 %
Faridabad	18 %	17 %
IGI Airport Terminal–3	32 %	32 %
IHBAS, Dilshad Garden	41 %	42 %
ITO	14 %	12 %
Lodhi Road	41 %	39 %
Mandir Marg	14 %	13 %
North Campus	24 %	24 %
NSIT Dawarka	19 %	20 %
Punjabi Bagh	20 %	20 %
Pusa	70 %	69 %
R K Puram	20 %	20 %
Sector125 Noida	23 %	21 %
Sector62 Noida	60 %	60 %
Shadipur	22 %	22 %
Sirifort	18 %	16 %
US Embassy	18 %	18 %
Vasundhara, Ghaziabad	44 %	34 %
Delhi-wide mean	30 %	29 %
SD	14 %	15 %

5 Modified Table 1 caption:

“Table 1: Delhi PM sensor network sites along with the 1 h data **percentage** completeness **with respect to the entire sampling period (i.e., from January 1, 2018 00:00 to March 31, 2018 23:59, Indian Standard Time, IST; in total 90 days, 2160 hours)** before and after **1 h** missing-data imputation for each individual site. **Note that a 10 % increase in the**

percentage data completeness after 1 h missing-data imputation is equivalent to ~216 hours of 1 h data being interpolated.”

2. *Speaking of interpolation and missingness: Are data missing in any specific pattern? That is, are areas that are typically reading higher levels of pollution more likely to have missing data? Do missing data occur most often on certain days (weekdays vs weekends)? Is missingness associated with ambient temperature, time of day, etc? Are certain monitors more prone to missingness?*

**Response:** We thank the reviewer for his/her scientific rigor by bringing up the informative missingness. All the periods over which 1 h data were interpolated for each site are already illustrated in Fig. S1 (also mentioned on Page 5, lines 21-22).

We believe that there is no obvious pattern in the data missingness. The low-cost sensors generally had a higher percentage of data missingness than the reference instruments. This is expected as the low-cost sensors should be overall less robust to ambient conditions than the costly reference instruments that are well-built and thoroughly-tested. Certain low-cost sensors (e.g., S.D.A. Park, Naraina Vihar, and Hiran Kudna) had higher fractions of data missingness than the rest of the low-cost sensors. This is not surprising either given that the quality of these low-cost packages’ electronic circuitry can vary drastically from one package to another, especially considering that the 10 low-cost nodes in this study were the very first generation/prototype of the “Atmos” devices (designed and built on our own) when we first started to build our network and we were still trying to figure out how to improve the electronic circuitry’s quality and stability. We are leaning toward not classifying these two trends as patterns in the data missingness. We have now clarified that there is no obvious pattern in the data missingness in both the manuscript and Fig. S1.

Added text on Page 5, line 22:

“... in Fig. S1. **There is no obvious pattern in the data missingness.**”

Modified Figure S1 caption:

“Figure S1: Periods over which 1 h data were available for each individual site before and after missing-data imputation and a total of 59 24 h aggregated observations common to all the nodes in the network used for the on-the-fly calibration feasibility test. **The top 10 sites (i.e., from S.D.A. Park to AIIMS) are the low-cost sites and the remaining sites (i.e., from Vasundhara to Anand Vihar) are the reference sites. Note that there is no obvious pattern in the data missingness.**”

3. *Relatedly, QA/QC procedures for reference monitors are not described. While this data can be hard to obtain from the relevant Indian agencies, it is important to more strongly highlight this as a potential shortcoming or to find out more data on how and how often reference monitors are maintained and calibrated.*

**Response:** Unlike the U.S. Embassy, the relevant Indian agencies did not provide any QA/QC (quality assurance/quality control) remark in any of their regulatory monitoring stations’ datasets. This was mentioned in the manuscript on Page 5,

lines 4-6. We were unable to find such information including the QA/QC procedures (e.g., how and how often reference monitors are maintained and calibrated) anywhere else either. Due to lack of relevant QA/QC information (such as error flags) to exclude any measurement, all of the hourly PM<sub>2.5</sub> concentrations of the 21 monitoring stations operated by the Indian agencies were assumed to be correct. We have now more strongly highlighted this as a potential shortcoming for this study.

Modified text on Page 5, lines 5-6:

“however, the same procedure was not applied to the remaining 21 Indian government monitoring stations ~~due to lack of relevant information~~ because neither the relevant Indian agencies provided QA/QC remarks or error flags in any of their regulatory monitoring stations’ datasets nor can we obtain the QA/QC procedures (e.g., how and how often reference monitors are maintained and calibrated) for these reference monitors. Due to lack of relevant QA/QC information to exclude any measurement, all of the hourly PM<sub>2.5</sub> concentrations of the 21 monitoring stations operated by the Indian agencies were assumed to be correct. We would like to highlight this as a potential shortcoming of using the measurements from the Indian government monitoring stations.”

4. Is any correction – of raw signal or for temperature and/or humidity – performed by the LCS platform? Are any filters applied at the LCS station or in the cloud? Describe more fully.

**Response:** No correction or filter of any kind was applied to the raw signals of the low-cost nodes over the cloud platform before we downloaded the data. We have now clarified this in the manuscript.

Added text on Page 5, line 13:

“...were downloaded using our custom-designed Application Program Interface (API). **No correction or filter of any kind was applied to the raw signals of the low-cost nodes over the cloud platform before we downloaded the data.**”

5. Can you provide and compare data from the India Meteorology Department for average temp and RH across the period you performed measurements and for the 59 days of data you used? Are they statistically distinct?

**Response:** We retrieved the 30 min temperature and relative humidity (RH) data from the station at the Indira Gandhi International (IGI) Airport. We used the Wilcoxon rank-sum test, also called Mann-Whitney U test (Wilcoxon, 1945; Mann and Whitney, 1947) to evaluate if the daily-averaged temperature and RH measurements from the IGI Airport for the entire sampling period (i.e., from January 1 to March 31, 2018, 90 days) were statistically the same as those for the 59 days over which our algorithm was analyzed in this study. The Wilcoxon rank-sum test is a non-parametric version of the parametric t-test (involving two independent samples/groups) that requires no specific distribution on the measurements (unlike the parametric t-test that assumes a normal distribution). We did not use a paired test here because the two groups had different sample sizes (i.e., 59 and 90, respectively). We conducted a two-sided test which has the null hypotheses that the daily-averaged temperature and RH measurements for the 90 days ( $19 \pm 5$  °C,  $59 \pm 14$  %) and the 59 days ( $20 \pm 5$  °C,  $59 \pm 12$  %) were the same (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}}$  /  $\text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) against the alternatives that they were

not the same (i.e.,  $H_1$ :  $\text{Temperature}_{59 \text{ days}} \neq \text{Temperature}_{90 \text{ days}}$  /  $\text{RH}_{59 \text{ days}} \neq \text{RH}_{90 \text{ days}}$ ). The p-values for the RH and temperature comparisons are 0.59 and 0.28, respectively. The level of statistical significance was chosen to be 0.05, which means that the null hypotheses (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}}$  /  $\text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) cannot be rejected when the p-values are both above 0.05. Therefore, the daily-averaged temperature and RH measurements from the IGI Airport for the entire sampling period and for the 59 days were not statistically distinct. Based on the reviewer 2's comments, we have also added the discussion about our attempt to include RH correction in our algorithm and the possible reasons why no improvements were observed in the manuscript under a new subsection Sect. 3.2.3. The results of RH and temperature measurement comparisons between the 90 days and the 59 days are also placed under this new subsection Sect. 3.2.3.

Added text on Page 10, line 20:

### 3.2.3 RH adjustment to the algorithm

We attempted RH adjustment to the algorithm by incorporating an RH term in the linear regression models, where the RH values were the measurements from each corresponding low-cost sensor package's embedded Adafruit DHT22 RH and temperature sensor. However, there was no improvement in the algorithm's accuracy after RH correction. A plausible explanation is regarding the infrequently high RH conditions during the winter months in Delhi and stronger smoothing effects at longer averaging time intervals (i.e., 24 h). Our previous work (Zheng et al., 2018) suggested that the PMS3003  $\text{PM}_{2.5}$  weights exponentially increased only when RH was above ~70%. The Delhi-wide average of the 3-month RH measured by the 10 low-cost sites was found to be  $55 \pm 15$  %. Only 17 % and 6 % of these RH values were greater than 70 % and 80 %, respectively. The infrequently high RH conditions can cause the RH-induced biases insignificant. Additionally, our previous work found that even though major RH influences can be found in 1 min to 6 h  $\text{PM}_{2.5}$  measurements, the influence significantly diminished in 12 h  $\text{PM}_{2.5}$  measurements and was barely observable in 24 h measurements. Therefore, longer averaging time intervals can smooth out the RH biases.

Additionally, while our algorithm was analyzed over the 59 available days in this study, the daily-averaged temperature and RH measurements for the entire sampling period (i.e., from January 1 to March 31, 2018, 90 days) were statistically the same as those for the 59 days. To support this statement, we conducted the Wilcoxon rank-sum test, also called Mann-Whitney U test (Wilcoxon, 1945; Mann and Whitney, 1947) on the daily-averaged temperature and RH measurements from the Indira Gandhi International (IGI) Airport. The Wilcoxon rank-sum test is a non-parametric version of the parametric t-test (involving two independent samples/groups) that requires no specific distribution on the measurements (unlike the parametric t-test that assumes a normal distribution). We did not use a paired test here because the two groups had different sample sizes (i.e., 59 and 90, respectively). We conducted a two-sided test which has the null hypotheses that the daily-averaged temperature and RH measurements for the 90 days

( $19 \pm 5$  °C,  $59 \pm 14$  %) and the 59 days ( $20 \pm 5$  °C,  $59 \pm 12$  %) were the same (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) against the alternatives that they were not the same (i.e.,  $H_1$ :  $\text{Temperature}_{59 \text{ days}} \neq \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} \neq \text{RH}_{90 \text{ days}}$ ). The p-values for the temperature and RH comparisons are 0.28 and 0.59, respectively. The level of statistical significance was chosen to be 0.05, which means that the null hypotheses (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) cannot be rejected when the p-values are both above 0.05. Therefore, the daily-averaged temperature and RH measurements from the IGI Airport for the entire sampling period and for the 59 days were not statistically distinct.

#### Minor Comments:

*P1, L15 – insert comma after “sites is questionable”*

10 **Response:** Thanks, we have made the suggested change.

Modified text on Page 1, line 15:

“...sites is questionable, as calibration factors typically vary with...”

*P1, L19 – insert comma after Delhi*

15 **Response:** Thanks, we have made the suggested change.

Modified text on Page 1, line 19:

“We evaluated our method for Delhi, where the  $\text{PM}_{2.5}$  measurements...”

*P1, L20 – rephrase – perhaps “available for 59 days. . .” If you elect to keep the word “valid”, describe what makes the data valid*

20 **Response:** Thanks, we have made the suggested change.

Modified text on Page 1, line 20:

“available **for** 59 days from January 1, 2018 to March 31, 2018...”

25 *P2, L15 – add “with” between “follow-up” and “routine”*

**Response:** Thanks, we have made the suggested change.

Modified text on Page 2, line 15:

“...initial calibration by collocation with reference analyzers before field deployment and follow-up **with** routine recalibration.”

30 *P3, L18 – whole sentence is very long, but specifically, for item 3), rephrase “auto-detect the faulty and auto-correct drift nodes” to (perhaps) “auto- detect faulty and auto-correct nodes with drift”*

**Response:** Thanks, we have rephrased item 3).

Modified text on Page 3, line 18:

“...auto-detect faulty **nodes** and auto-correct **the drift of nodes** within a network via computational simulation, ...”

5 *P4, L15 – replace “our” with “the”*

**Response:** Thanks, we have made the suggested change.

Modified text on Page 4, line 15:

“...KairosDB as **the** primary fast scalable time series database built on Apache Cassandra, ...”

10 *P5, L12-13 – describe the API, or remove mention of it s*

**Response:** Thanks, we have removed mention of the API.

Modified text on Page 5, lines 12-13:

“Hourly uncalibrated PM<sub>2.5</sub> measurements from 10 Atmos low-cost nodes across Delhi between January 1, 2018 and March 31, 2018 were downloaded **from our low-cost sensor cloud platform.**”

15

*P5, L16 – add “ ‘s “ to location*

**Response:** Thanks, we have made the suggested change.

Modified text on Page 5, line 16:

“..., the **locations** physical accessibility, ...”

20

*P6 – describe more fully the “standardization” that occurs*

**Response:** We agree with the reviewer on that the standardization process should be more fully described. All the PM<sub>2.5</sub> measurements of the 31 nodes over 59 available days used for GPR model hyperparameters training were standardized at once. The standardization was performed by first concatenating all these training PM<sub>2.5</sub> measurements (from the 31 nodes over 59 days), then subtracting their mean  $\mu_{training}$  and dividing them by their standard deviation  $s_{training}$  (i.e., transforming all the training PM<sub>2.5</sub> measurements to have a zero mean and unit variance). The standardization was only done to the data used for training/optimizing the hyperparameters of the GPR model (i.e., all the PM<sub>2.5</sub> measurements of the 31 nodes over 59 valid days). The holdout node’s PM<sub>2.5</sub> measurements were never used to calculate the  $\mu_{training}$  and  $s_{training}$ .

Modified text on Page 6, lines 23-27:

30 “**In the next step (step three in Fig. 3), a GPR model was fit to each day  $t$ ’s 31 nodes (i.e., 10 initialized low-cost nodes and 21 reference nodes) as described in Eq. (4). Prior to the GPR model fitting, all the PM<sub>2.5</sub> measurements of the 31 nodes over 59 valid days used for GPR model hyperparameters training were standardized. The standardization was performed by first concatenating all these training PM<sub>2.5</sub> measurements (from the 31 nodes over 59 days), then**



subtracting **their** mean  $\mu_{training}$  and **dividing them by their standard deviation**  $s_{training}$  (i.e., transforming **all the training** PM<sub>2.5</sub> measurements to have a zero mean and unit variance). **It is worth noting that assuming the mean function  $\mu \in \mathbb{R}^{31}$  to be 0 along with standardizing all the training PM<sub>2.5</sub> samples in this study is one of the common modelling formulations on the GPR model and the simplest one. More complex formulations including a station-specific mean function (lack of prior information for this project), a time-dependent mean function (computationally expensive), and a combination of both were not considered for this paper. After the standardization of training samples, the GPR was trained to maximize the log marginal likelihood over all 59 days using Eq. 5 and using an L-BFGS-B optimizer (Byrd et al., 1994)."**

10 *P8, L14 – rephrase “Spatially, the global average. . .” – is this the average across all LCS and reference monitors? Or? And if it is the average across all, then does “spatially” apply?*

**Response:** The average is across only the 22 reference stations not including any low-cost sensor (as mentioned on Page 8, line 13). We have now removed “spatially”.

Modified text on Page 8, lines 13-14:

15 **“Spatially, The global average of the 3-month mean PM<sub>2.5</sub> across the 22 reference stations was found to be  $138 \pm 31 \mu\text{g m}^{-3}$ .”**

*P9, L3 – insert comma after “decent”; consider rephrasing (what does decent mean in this context?)*

**Response:** Thanks, we have replaced “decent” with “reasonably accurate”.

Modified text on Page 9, line 3:

20 **“Although the technique’s performance is reasonably accurate, especially considering the minimal amount of field work involved, ...”**

25 *P9, L8-13 – While I understand that GPR would have done better absent local sources, is that realistic for these types of urban environments in places like India or China? Or even in the US, in places like Queens, Oakland, or Atlanta? Isn’t the spatial heterogeneity exactly why many are considering more spatially and temporally resolved monitoring networks?*

**Response:** We are only confident that in order to use GPR for calibration, the low-cost sensors cannot be placed at sites where local sources are dominant. Even for urban environments that are dominated by regional sources, it is still not hard to find places that are under heavy influence of local sources. Even for urban environments where local sources are prevalent, it is still realistic to find some background stations with careful siting. If low-cost sensors must be placed at sites that are under strong local impact for some specific monitoring purposes (e.g., nodes that measure roadside pollutants or restaurant food-cooking emissions within neighborhoods), then calibration by collocation with reference instruments first might be the only solution as we believe that hardly any model has the ability to account for fine-grained local contributions and accurately calibrate such sensors. The simulation results in this study seem to suggest that GPR is more robust to local source disturbance (i.e., spatial heterogeneity) when detecting faulty nodes and the drift of nodes. This finding indicates that when

facing strong spatial heterogeneity, even though it may be challenging for GPR to calibrate low-cost sensors well, GPR holds great promise as a useful algorithm for large-scale sensor network management.

Text remains unmodified.

5 *P10, L14 – Neither of these sites are really background sites in the way they are traditionally thought of.*

**Response:** We agree that neither of these sites are really background sites in the way they are traditionally thought of. The only reason we called them background sites is because the two sites had the lowest mean PM<sub>2.5</sub> concentrations of ~71 and 73 µg m<sup>-3</sup> (and significantly lower than the Delhi-wide mean of 138 µg m<sup>-3</sup>) during the sampling period among 24 reference instruments across Delhi. But as shown in Gani et al. (2019), black carbon (BC) had a constantly year-round local influence on the IITD site, potentially due to trucks (and other diesel vehicles) as discussed in their Section 3.5. As discussed in their Section 3.4.1, the many industrial sites in the northwest of Delhi that use HCl for steel pickling were arguably the local source that had the strongest influence on the downwind IITD site during winter. The predominantly northwestern wind during winter transported extreme levels of chloride concentrations to IITD. The single one brief organic episode during winter (discussed in their Section 3.4.2) that was due to bonfires burning during the Lohri Festival should be a minor local source to the IITD site when looking at the whole winter. Therefore, considering the huge amount of local influences on the IITD site and possibly on the MRU site as well, we decided to remove our estimate of Delhi's PM<sub>2.5</sub> regional-to-local ratio based on the assumption that these two sites are background sites and instead reference the estimate of Delhi's PM<sub>1</sub> regional/local contribution given in Gani et al. (2019).

Modified text on Page 10, lines 12-19:

20 ~~“In this study, our MRU and IITD sites are similar to the IITM site from the studies by Tiwari et al. (2012 and 2015), which are all on campus and free from major pollution sources and therefore qualified to be regional background sites. The PM<sub>2.5</sub> regional background concentration during winter in Delhi was then estimated to be approximately 72 µg m<sup>-3</sup>. The global mean of the 22 reference sites was 138 µg m<sup>-3</sup>, thus the mean local contribution across Delhi was roughly 66 µg m<sup>-3</sup>. Clearly this 1:1 regional to local ratio did not fully support the technique. Alternatively, prior information about urban PM<sub>2.5</sub> spatial patterns such as high spatial resolution annual average concentration basemap from air pollution dispersion models can dramatically improve the on the fly calibration performance by correcting for the concentration range specific biases (Schneider et al., 2017). Gani et al. (2019) estimated that Delhi's local contribution to the composition-based submicron particulate matter (PM<sub>1</sub>) was ~30 to 50 % during winter and spring months. Clearly the huge amount of local influence in Delhi did not fully support our technique.”~~

30

Added reference on Page 15, line 18:

~~“Gani, S., Bhandari, S., Seraj, S., Wang, D. S., Patel, K., Soni, P., Arub, Z., Habib, G., Hildebrandt Ruiz, L., and Apte, J. S.: Submicron aerosol composition in the world's most polluted megacity: the Delhi Aerosol Supersite study, Atmos. Chem. Phys., 19, 6843-6859, <https://doi.org/10.5194/acp-19-6843-2019>, 2019.”~~

P12, L10 – Perhaps rephrase to “The following questions remain:” or somesuch

**Response:** Thank you for pointing out this grammatical error. We have now corrected it.

Modified text on Page 12, line 11:

5 “Questions **which** remain unsolved are ...”

Figure 2 – consider different shapes and colors (in B&W, the colors are not distinguish- able)

**Response:** We thank the reviewer for pointing this out. We have now changed the reference stations’ icon to triangle and the reference stations’ text font to italic, so that readers can differentiate between reference and low-cost nodes even when the manuscript is printed in black and white.

Modified Figure 2:

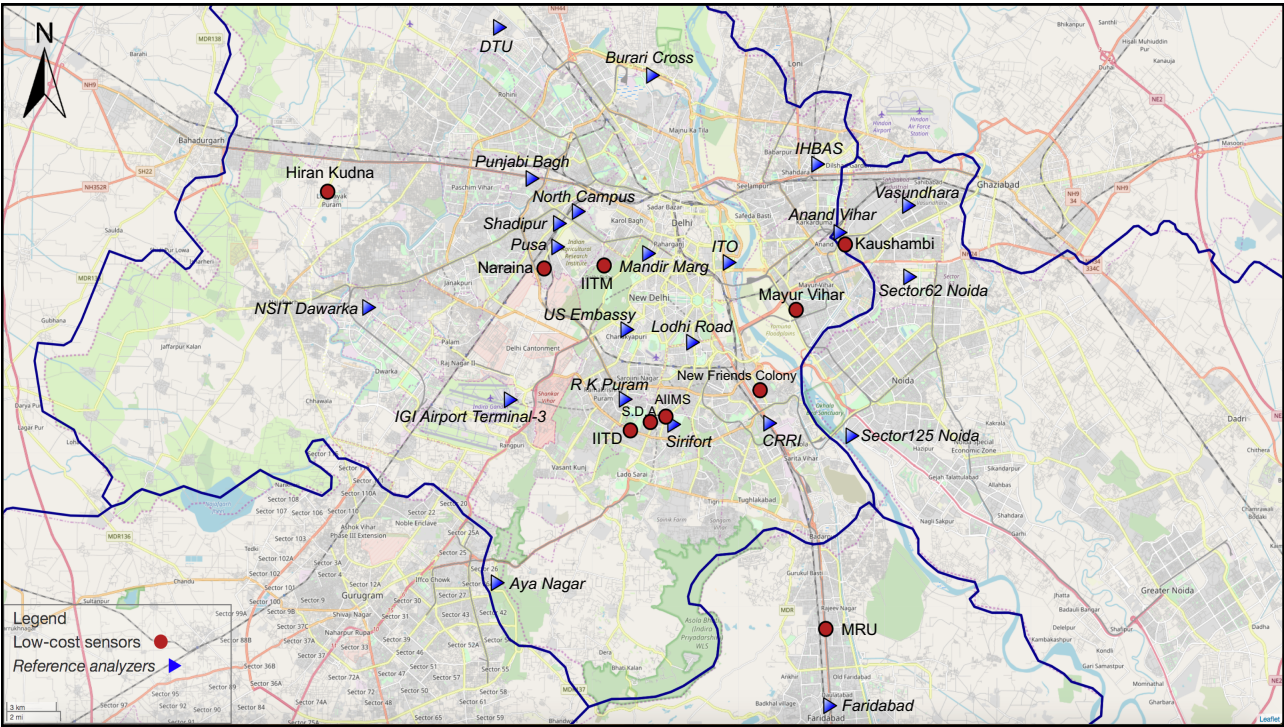


Figure 2: Locations of the 22 reference nodes (**triangle icons with italic text**) and 10 low-cost nodes (**circle icons**) that form the Delhi PM sensor network.

Modified text on Page 4, lines 30-31:

“Figure 2 visualizes the spatial distribution of these 22 reference monitors (**triangle icons with italic text**) and ...”

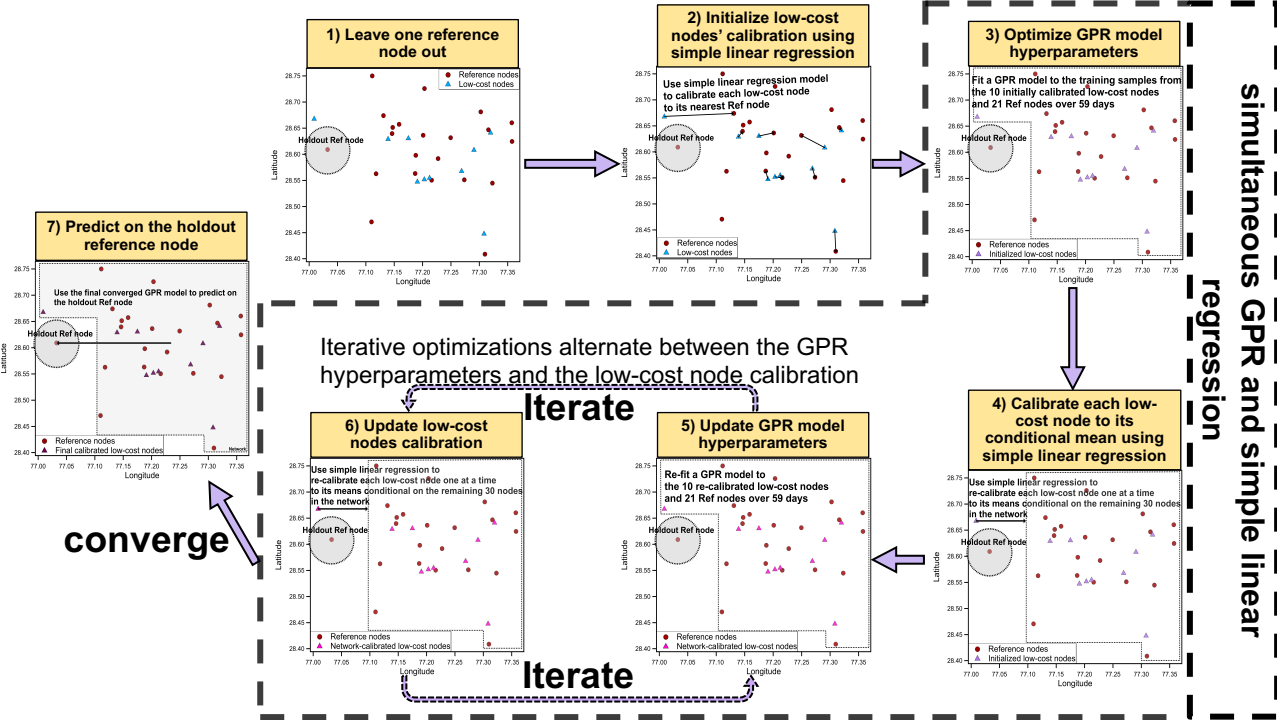
Modified text on Page 5, lines 13-14:

“Figure 2 shows the sampling locations of these 10 low-cost nodes as **circle icons** and ...”

Figure 3 – a more elaborate caption may help better explain the flow (for instance, a sentence for each step)

**Response:** We have now expanded the Figure 3 caption to help better carry readers through the algorithm and we have now revised Figure 3 to make it more informative about and more accurately reflect the entire process.

Modified Figure 3:



**Figure 3: The flow diagram illustrating the simultaneous GPR and simple linear regression calibration algorithm. In step one, for each of the 22-fold leave-one-out CVs, one of the 22 reference nodes is held out of modelling for the model predictive performance evaluation in step seven; in step two, fit a simple linear regression model between each low-cost node  $i$  and its closest reference node's  $PM_{2.5}$ , initialize low-cost node  $i$ 's calibration model to this linear regression model, and calibrate the low-cost node  $i$  using this model; in step three, first initialize the GPR hyperparameters to  $[0.1, 50, 0.01]$  and then update/optimize the hyperparameters based on the training samples from the 10 initially calibrated low-cost nodes and 21 reference nodes over 59 days; in step four, first compute each low-cost node  $i$ 's means conditional on the remaining 30 nodes given the optimized GPR hyperparameters, then fit a simple linear regression model between each low-cost node  $i$  and its conditional means, update low-cost node  $i$ 's calibration model to this new linear regression model, and re-calibrate the low-cost node  $i$  using this new model; in step five and six, iterative optimizations alternate between the GPR hyperparameters and the low-cost node calibrations using the approaches described in step three and four, respectively, until the GPR hyperparameters converged; in step seven, predict the 59-day  $PM_{2.5}$  measurements of the holdout reference node given the finalized GPR hyperparameters and the low-cost node calibrations.**

# Gaussian Process regression model for dynamically calibrating and surveilling a wireless low-cost particulate matter sensor network in Delhi

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**Abstract.** Wireless low-cost particulate matter sensor networks (WLPMNSs) are transforming air quality monitoring by providing PM information at finer spatial and temporal resolutions; however, large-scale WLPMNS calibration and maintenance remain a challenge because the manual labor involved in initial calibration by collocation and routine recalibration is intensive, the transferability of the calibration models determined from initial collocation to new deployment sites is questionable, as calibration factors typically vary with urban heterogeneity of operating conditions and aerosol optical properties, and the stability of low-cost sensors can develop drift or degrade over time. This study presents a simultaneous Gaussian Process regression (GPR) and simple linear regression pipeline to calibrate and monitor dense WLPMNSs on the fly by leveraging all available reference monitors across an area without resorting to pre-deployment collocation calibration. We evaluated our method for Delhi, where the PM<sub>2.5</sub> measurements of all 22 regulatory reference and 10 low-cost nodes were available ~~in-for~~ 59 ~~valid~~ days from January 1, 2018 to March 31, 2018 (PM<sub>2.5</sub> averaged  $138 \pm 31 \mu\text{g m}^{-3}$  among 22 reference stations) using a leave-one-out cross-validation (CV) over the 22 reference nodes. We showed that our approach can achieve an overall 30 % prediction error (RMSE:  $33 \mu\text{g m}^{-3}$ ) at a 24 h scale and is robust as underscored by the small variability in the GPR model parameters and in the model-produced calibration factors for the low-cost nodes among the 22-fold CV. We revealed that the accuracy of our calibrations depends on the degree of homogeneity of PM concentrations, and decreases with increasing local source contributions. As by-products of dynamic calibration, our algorithm can be adapted for automated large-scale WLPMNS monitoring as simulations proved its capability of differentiating malfunctioning or singular low-cost nodes within a network via model-generated calibration factors with the aberrant nodes having slopes close to 0 and intercepts close to the global mean of true PM<sub>2.5</sub> and of tracking the drift of low-cost nodes accurately within 4 % error for all the simulation scenarios. The simulation results showed that ~20 reference stations are optimum for our solution in Delhi and confirmed that low-cost nodes can extend the spatial precision of a network by decreasing the extent of pure interpolation among only reference stations. Our solution has substantial



implications in reducing the amount of manual labor for the calibration and surveillance of extensive WLPMSNs, improving the spatial comprehensiveness of PM evaluation, and enhancing the accuracy of WLPMSNs.

## 1 Introduction

5 Low-cost air quality (AQ) sensors that report high time resolution data (e.g.,  $\leq 1$  h) in near real time offer excellent potential for supplementing existing regulatory AQ monitoring networks by providing enhanced estimates of the spatial and temporal variabilities of air pollutants (Snyder et al., 2013). Certain low-cost particulate matter (PM) sensors demonstrated satisfactory performance benchmarked against Federal Equivalent Methods (FEMs) or research-grade instruments in some previous field studies (Holstius et al., 2014; Gao et al., 2015; SCAQMD, 2015a–b; Jiao et al., 2016; Kelly et al., 2017; Mukherjee et al., 2017; SCAQMD, 2017a–c; Crilley et al., 2018; Feinberg et al., 2018; Johnson et al., 2018; Zheng et al., 10 2018). Application-wise, low-cost PM sensors have had success in identifying urban fine particle (PM<sub>2.5</sub>, with a diameter of 2.5  $\mu$ m and smaller) hotspots in Xi'an, China (Gao et al., 2015), mapping urban air quality with additional dispersion model information in Oslo, Norway (Schneider et al., 2017), monitoring smoke from prescribed fire in Colorado, US (Kelleher et al., 2018), measuring a traveler's exposure to PM<sub>2.5</sub> in various microenvironments in Southeast Asia (Ozler et al., 2018), and building up a detailed city-wide temporal and spatial indoor PM<sub>2.5</sub> exposure profile in Beijing, China (Zuo et al., 2018).

15 On the down side, researchers have been plagued by calibration-related issues since their emergence. One common brute force solution is initial calibration by collocation with reference analyzers before field deployment and follow-up with routine recalibration. Yet, the transferability of these pre-determined calibrations at collocation sites to new deployment sites is questionable as calibration factors typically vary with operating conditions such as PM mass concentrations, relative humidity, temperature, and aerosol optical properties (Holstius et al., 2014; Austin et al., 2015; Wang et al., 2015; Lewis and Edwards, 2016; Crilley et al., 2018; Jayaratne et al., 2018; Zheng et al., 2018). Complicating this further, the pre-generated calibration curves may only apply for a short term as the stability of low-cost sensors can develop drift or degrade over time (Lewis and Edwards, 2016; Jiao et al., 2016; Hagler et al., 2018). Routine recalibrations which require frequent transit of the deployed sensors between the field and the reference sites are not only too labor intensive for a large-scale network but also 25 still cannot address the impact of urban heterogeneity of ambient conditions on calibration models (Kizel et al., 2018).

As such, calibrating sensors on-the-fly while they are deployed in the field is highly desirable. Takruri et al. (2009) showed that the Interacting Multiple Model (IMM) algorithm combined with the Support Vector Regression (SVR)-Unscented Kalman Filter (UKF) can automatically and successfully detect and correct low-cost sensor measurement errors in the field; 30 however, the implementation of this algorithm still requires pre-deployment calibrations. Fishbain and Moreno-Centeno (2016) designed a self-calibration strategy for low-cost nodes with no need for collocation by exploiting the raw signal differences between all possible pairs of nodes. The learned calibrated measurements are the vectors whose pairwise

differences are closest in normalized projected Cook-Kress (NPCK) distance to the corresponding pairwise raw signal differences given all possible pairs over all time steps. However, this strategy did not include reference measurements in the self-calibration procedure, and therefore the tuned measurements were still essentially raw signals (although instrument noise was dampened). An alternative calibration method involves chain calibration of the low-cost nodes in the field with only the first node calibrated by collocation with reference analyzers and the remaining nodes calibrated sequentially by their respective previous node along the chain (Kizel et al., 2018). While this node-to-node calibration procedure proved its merits in reducing collocation burden and data loss during calibration/relocation/recalibration and accommodating the influence of urban heterogeneity on calibration models, it is only suitable for relatively small networks because calibration errors propagate through chains and can inflate toward the end of a long chain (Kizel et al., 2018).

In this paper, we introduce a simultaneous Gaussian Process regression (GPR) and simple linear regression pipeline to calibrate PM<sub>2.5</sub> readings of any number of low-cost PM sensors on the fly in the field without resorting to pre-deployment collocation calibration by leveraging all available reference monitors across an area (e.g., Delhi N 28.6139, E 77.2089). The proposed strategy is theoretically sound since the GPR (also known as Kriging) can capture the spatial covariance inherent in the data and has been widely used for spatial data interpolation (e.g., Holdaway, 1996; Di et al., 2016; Schneider et al., 2017) and the simple linear regression calibration can adjust for disagreements between low-cost sensor and reference instrument measurements and lead to more consistent spatial interpolation. This paper focuses on 1) quantifying experimentally the daily performance of our dynamic calibration model in Delhi during winter season based on model prediction accuracy on the holdout reference nodes during leave-one-out cross-validations (CV) and low-cost node calibration accuracy; 2) revealing the potential pitfalls of employing a dynamic calibration algorithm; 3) demonstrating the ability of our algorithm to auto-detect ~~the~~ faulty nodes and auto-correct the drift of nodes within a network via computational simulation, therefore the practicality of adapting our algorithm for automated large-scale sensor network monitoring; and 4) studying computationally the optimal number of reference stations across Delhi to support our technique and the usefulness of low-cost sensors for extending the spatial precision of a sensor network. To the best of our knowledge, this is the first study to apply such a non-static calibration technique to a wireless low-cost PM sensor network in a heavily polluted region such as India and the first to present methods of auto-monitoring dense AQ sensor networks.

## 2 Materials and methods

### 2.1 Low-cost node configuration

The low-cost packages used in the present study (dubbed “Atmos”) shown in Fig. 1a were developed by Respirer Living Sciences (<http://atmos.urbansciences.in/>, last access: 30 November 2018) and cost ~ USD 300 per unit. The Atmos monitor measures 20.3 cm L × 12.1 cm W × 7.6 cm H, weighs 500 g, and is housed in an IP65 (Ingress Protection rating 65) enclosure with a liquid crystal display (LCD) on the front showing real-time PM mass concentrations and various debugging



messages. It includes a Plantower PMS7003 sensor (~ USD 25; dimension: 4.8 cm L × 3.7 cm W × 1.2 cm H) to measure PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> mass concentrations, an Adafruit DHT22 sensor to measure temperature and relative humidity, and an ultra-compact Quectel L80 GPS model to retrieve accurate locations in real time. The operating principle and configuration of PMS7003 are similar to its PMS1003, PMS3003, and PMS5003 counterparts and have been extensively discussed in previous studies (Kelly et al., 2017; Zheng et al., 2018; and Sayahi et al., 2018, respectively). The inlet and outlet of PMS7003 were aligned with two slots on the box to ensure unrestricted airflow into the sensor. The PM and meteorology data are read over the serial TTL interface every three seconds, aggregated every 1 min in memory on the device, before being transmitted by a Quectel M66 GPRS module through the mobile 2G cellular network to an online database. The Atmos can also store the data on a local microSD card in case of transmission failure. Users have the option to configure the frequencies of data transfer and logging to 5, 10, 15, 30, and 60 minutes via a press key on the device and are able to view the settings on the LCD. All components of the Atmos monitors (key parts are labelled in Fig. 1b) are integrated to a custom-designed printed circuit board (PCB) which is controlled by a STMicroelectronics microcontroller (model STM32F051). Each Atmos was continuously powered up by a 5V 2A USB wall charger but also comes with a fail-safe 3.7V–2600 mAh rechargeable Li-ion battery in case of power outage that can last up to 10 hours at a 1 min transmission frequency and 20 hours at a 5 min frequency.

The Atmos network's server architecture was also developed by Respirer Living Sciences and built on the following open-source components: KairosDB as ~~our~~ the primary fast scalable time series database built on Apache Cassandra, custom-made Java libraries for ingesting data and for providing XML/JSON/CSV-based access to aggregated time series data, HTML5/JavaScript for creating the front-end dashboard, and LeafletJS for visualizing Atmos networks on maps.

## 2.2 Data description

### 2.2.1 Reference PM<sub>2.5</sub> data

Hourly ground-level PM<sub>2.5</sub> concentrations from 21 monitoring stations operated by the Central Pollution Control Board (CPCB), the Delhi Pollution Control Committee (DPCC), the India Meteorological Department (IMD), and the Uttar Pradesh and Haryana States Pollution Control Boards (SPCBs) (<https://app.cpcbcr.com/ccr/#/caaqm-dashboard/caaql-landing>, last access: 18 September 2018) and from one monitoring station operated by the U.S. Embassy in New Delhi ([https://www.airnow.gov/index.cfm?action=airnow.global\\_summary#India\\$New\\_Delhi](https://www.airnow.gov/index.cfm?action=airnow.global_summary#India$New_Delhi), last access: 18 September 2018) were available in our study domain of Delhi and its satellite cities including Gurgaon, Faridabad, Noida, and Ghaziabad from January 1, 2018 to March 31, 2018 (winter season) and were used as the reference measurements in our Delhi PM sensor network. The topographical, climatic, and air quality conditions of Delhi are well documented by Tiwari et al. (2012 and 2015) and Gorai et al. (2018). Briefly, Delhi experiences unusually high PM<sub>2.5</sub> concentrations over winter season due to a combination of increased biomass burning for heating, shallower boundary layer mixing height, diminished wet scavenging

by precipitation, lower wind speed, and trapping of air pollutants by the Himalayan topology. Figure 2 visualizes the spatial distribution of these 22 reference monitors (~~triangle icons with italic text~~~~red icons~~) and Table 1 lists their latitudes and longitudes. No station of the 22 reference monitors is known for regional background monitoring. The complex local built environment in Delhi arising from the densely and intensively mixed land use (Tiwari, 2002) and the significant contributions to air pollution from all vehicular, industrial (small scale industries and major power plants), commercial (diesel generators and tandoors), and residential (diesel generators and biomass burning) sectors (CPCB, 2009; Gorai et al., 2018) render the PM<sub>2.5</sub> concentrations relatively unconnected to the land-use patterns. We removed 104 1 h observations (labeled invalid and missing) from the U.S. Embassy dataset based on its reported QA/QC (quality assurance/quality control) remarks; however, the same procedure was not applied to the remaining 21 Indian government monitoring stations because neither the relevant Indian agencies provided QA/QC remarks or error flags in any of their regulatory monitoring stations' datasets nor can we obtain the QA/QC procedures (e.g., how and how often reference monitors are maintained and calibrated) for these reference monitors. Due to lack of relevant QA/QC information to exclude any measurement, all of the hourly PM<sub>2.5</sub> concentrations of the 21 monitoring stations operated by the Indian agencies were assumed to be correct. We would like to highlight this as a potential shortcoming of using the measurements from the Indian government monitoring stations due to lack of relevant information. GPR requires concurrent measurements of all the stations but certain stations had a high fraction of missing values. Therefore, to maximize the number of complete concurrent observations for modelling in order to significantly increase the model accuracy, While mathematically the GPR model can operate without requiring data from all the stations to be non-missing on each day by relying on only each day's non-missing stations' covariance information to make inference, we practically required concurrent measurements of all the stations in this paper to drastically increase the speed of the algorithm (~10 mins to run a complete 22-fold leave-one-out CV, up to ~20 times faster) by avoiding the expensive computational cost of excessive amount of matrix inversions that can be incurred otherwise. ~~we~~ We therefore linearly interpolated the 1 h PM<sub>2.5</sub> values for the hours with missing measurements for each station, after which we averaged the hourly data to daily resolution as the model inputs. We validate our interpolation approach in Sect. 3.2.1 by showing that the model accuracies with and without interpolation are statistically the same.

## 2.2.2 Low-cost node PM<sub>2.5</sub> data

Hourly uncalibrated PM<sub>2.5</sub> measurements from 10 Atmos low-cost nodes across Delhi between January 1, 2018 and March 31, 2018 were downloaded from our low-cost sensor cloud platform using our custom-designed Application Program Interface (API). No correction or filter of any kind was applied to the raw signals of the low-cost nodes over the cloud platform before we downloaded the data. Figure 2 shows the sampling locations of these 10 low-cost nodes as circle icons~~blue icons~~ and Table 1 specifies their latitudes and longitudes. In our current study, the factors governing the siting of these nodes consist of the ground contact personnel availability, the resource availability such as strong mobile network signal and 24/7 main power supply, the locations' physical accessibility, and some other common criteria for sensor deployment (e.g., locations away from major pollution sources, situated in a place where free flow of air is available, and

protected from vandalism and extreme weather). Similar to the preprocessing of the reference PM<sub>2.5</sub> data, we linearly interpolated the missing hourly PM<sub>2.5</sub> for each low-cost node and then aggregated the hourly data at a daily interval. The comparison of initial 1 h PM<sub>2.5</sub>'s completeness with that of after missing data imputation for both reference and low-cost nodes is detailed in Table 1 and the periods over which data were imputed for each site are illustrated in Fig. S1. There is no obvious pattern in the data missingness. To remove the prospective outliers such as erroneous surges/nadirs existing in the datasets of the 21 Indian government reference nodes and the 10 low-cost nodes or unreasonable interpolated measurements introduced during handling the missing data, we employed the Local Outlier Factor (LOF) algorithm with 20 neighbors considered (a number that works well in general) to remove a conservative ~10% of the 32-dimensional (22 reference + 10 low-cost nodes) 24 h PM<sub>2.5</sub> datasets. LOF is an unsupervised anomaly detection method that assigns each multi-dimensional data point an LOF score, defined as the ratio of the average local density of its  $k$  nearest neighboring data points ( $k = 20$  in our study) to its own local density, to measure the relative degree of isolation of the given data point with respect to its neighbors (Breunig, et al., 2000). Normal observations tend to have LOF scores near 1 while outliers significantly larger than 1. The LOF therefore identifies the outliers as those multi-dimensional observations with the top  $x\%$  ( $x = 10$  in our study) LOF scores. A total of 59 days' PM<sub>2.5</sub> measurements common to all 32 nodes in the network were left (see Fig. S1) and used for our model evaluation.

### 2.3 Simultaneous GPR and simple linear regression calibration model

Figure 3 shows the overall schema for the simultaneous GPR and simple linear regression dynamic calibration model. Under the context of not knowing beforehand the true calibration factors for the low-cost nodes, a leave-one-out CV approach (i.e., holding one of the 22 reference nodes out of modelling each run for model predictive performance evaluation) was adopted as a surrogate to estimate our proposed model accuracy of calibrating the low-cost nodes. For each of the 22-fold CV, 31 node locations (denoted  $\Gamma = \{\mathbf{x}_1, \dots, \mathbf{x}_{31}\}$ ) were available, where  $\mathbf{x}_i$  is the latitude and longitude of node  $i$ . Let  $y_{it}$  represent the daily PM<sub>2.5</sub> measurement of node  $i$  on day  $t$  and  $\mathbf{y}_t \in \mathbb{R}^{31}$  denote the concatenation of the daily PM<sub>2.5</sub> measurements recorded by the 31 nodes on day  $t$ . Given a finite number of node locations, a Gaussian Process (GP) becomes a Multivariate Gaussian Distribution over the nodes in the form of:

$$\mathbf{y}_t | \Gamma \sim N(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \quad (1)$$

where  $\boldsymbol{\mu} \in \mathbb{R}^{31}$  represents the mean function (assumed to be  $\mathbf{0}$  in this study) and  $\boldsymbol{\Sigma} \in \mathbb{R}^{31 \times 31}$  with  $\Sigma_{ij} = K(\mathbf{x}_i, \mathbf{x}_j; \theta)$  represents the covariance function/kernel function.

For simplicity's sake, the kernel function was set to a squared exponential (SE) covariance term to capture the spatially-correlated signals coupled with another component to constrain the independent noise:

$$K(\mathbf{x}_i, \mathbf{x}_j; \theta) = \sigma_s^2 \exp\left(-\frac{\|\mathbf{x}_i - \mathbf{x}_j\|_2^2}{2l^2}\right) + \sigma_n^2 \mathbf{I} \quad (\text{Rasmussen and Williams, 2006}) \quad (2)$$

where  $\sigma_s^2$ ,  $l$ , and  $\sigma_n^2$  are the model hyperparameters (to be optimized) that control the signal magnitude, characteristic length-scale, and noise magnitude, respectively.

What separates our method from standard GP applications is the simultaneous incorporation of calibration for the low-cost nodes using a simple linear regression model into the spatial model. Linear regression has previously been shown to be effective at calibrating PM sensors (Zheng et al., 2018). Initially (step two in Fig. 3), each low-cost node was calibrated based on its closest reference node (Eq. 3) to bridge disagreements between low-cost and reference node measurements which led to a more consistent spatial interpolation and a faster convergence during model optimization. In the next step (step three in Fig. 3) After standardizing the PM<sub>2.5</sub> measurements for each node by subtracting the mean and scaling to unit variance (i.e., transforming the PM<sub>2.5</sub> measurements to have a zero mean and unit variance), a GPR model was fit to each day's 31 nodes (i.e., 10 initialized low-cost nodes and 21 reference nodes) as described in Eq. (4), and step three in Fig. 3. Prior to the GPR model fitting, all the PM<sub>2.5</sub> measurements of the 31 nodes over 59 valid days used for GPR model hyperparameters training were standardized. The standardization was performed by first concatenating all these training PM<sub>2.5</sub> measurements (from the 31 nodes over 59 days), then subtracting their mean  $\mu_{training}$  and dividing them by their standard deviation  $s_{training}$  (i.e., transforming all the training PM<sub>2.5</sub> measurements to have a zero mean and unit variance). It is worth noting that assuming the mean function  $\mu \in \mathbb{R}^{31}$  to be 0 along with standardizing all the training PM<sub>2.5</sub> samples in this study is one of the common modelling formulations on the GPR model and the simplest one. More complex formulations including a station-specific mean function (lack of prior information for this project), a time-dependent mean function (computationally expensive), and a combination of both were not considered for this paper. After the standardization of training samples, ~~Then~~ the GPR was trained to maximize the log marginal likelihood over all 59 days (using Eq. 5) and using an L-BFGS-B optimizer (Byrd et al., 1994). To avoid bad local minima, several random hyperparameter initializations were tried and the initialization with the best log marginal likelihood was chosen.

$$\mathbf{r}_i = \begin{cases} \mathbf{y}_i, & \text{if reference node} \\ \alpha_i \cdot \mathbf{y}_i + \beta_i, & \text{if low - cost node} \end{cases} \quad (3)$$

$$\mathbf{r}_t | \Gamma \sim N(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \quad (4)$$

where  $\alpha_i$  and  $\beta_i$  are the slope and intercept, respectively, of the calibration equation for low-cost node  $i$  based on its closest reference node;  $\mathbf{r}_i$  is all the daily PM<sub>2.5</sub> measurements of either the initially-calibrated low-cost node  $i$  or reference node  $i$ ; and  $\mathbf{r}_t$  is the concatenation of all 31 nodes' PM<sub>2.5</sub> measurements on day  $t$ .

$$\arg \max_{\boldsymbol{\theta}} L(\boldsymbol{\theta}) = \arg \max_{\boldsymbol{\theta}} \sum_{t=1}^{59} \log p(\mathbf{r}_t | \boldsymbol{\theta}) = \arg \max_{\boldsymbol{\theta}} -0.5 \cdot 59 \cdot \log |\boldsymbol{\Sigma}_{\boldsymbol{\theta}}| - 0.5 \sum_{t=1}^{59} \mathbf{r}_t^T \boldsymbol{\Sigma}_{\boldsymbol{\theta}}^{-1} \mathbf{r}_t \quad (5)$$

where  $\boldsymbol{\theta}$  is a vector of  $\sigma_s^2$ ,  $l$ , and  $\sigma_n^2$ .

Once the optimum  $\boldsymbol{\theta}$  for the (initial) GPR was found, we used the learned covariance function to find the mean of each low-cost node  $i$ 's Gaussian Distribution conditional on the remaining 30 nodes within the network (i.e.,  $\mu_{A|B}^{it}$ ) on day  $t$  as described mathematically in Eq. (6)–(8) and repeatedly did so until all 59 days'  $\mu_{A|B}^{it}$  (i.e.,  $\boldsymbol{\mu}_{A|B}^t$ ) were found and then re-

calibrated that low-cost node  $i$  based on the  $\mu_{A|B}^i$ . This procedure is summarized graphically in Fig. 3 step four and was performed iteratively for all low-cost nodes one at a time. The reasoning behind this step is given in the Supplement. A high-level interpretation of this step is that the target low-cost node is calibrated by being weighted over the remaining nodes within the network and the  $\Sigma_{AB}^{it} \Sigma_{BB}^{it}{}^{-1}$  term computes the weights. In contrast to the inverse distance weighting interpolation which will weight the nodes used for calibration equally if they are equally distant from the target node, the GPR will value sparse information more and lower the importance of redundant information (suppose all the nodes are equally distant from the target node) as shown in Fig. S2.

$$p\left(\begin{bmatrix} r_A^{it} \\ r_B^{it} \end{bmatrix}\right) = N\left(\begin{bmatrix} r_A^{it} \\ r_B^{it} \end{bmatrix}; \begin{bmatrix} \mu_A^{it} \\ \mu_B^{it} \end{bmatrix} \begin{bmatrix} \Sigma_{AA}^{it} & \Sigma_{AB}^{it} \\ \Sigma_{BA}^{it} & \Sigma_{BB}^{it} \end{bmatrix}\right) \quad (6)$$

$$r_A^{it} | r_B^{it} \sim N(\mu_{A|B}^{it}, \Sigma_{A|B}^{it}) \quad (7)$$

$$\mu_{A|B}^{it} = \mu_A^{it} + \Sigma_{AB}^{it} \Sigma_{BB}^{it}{}^{-1} (r_B^{it} - \mu_B^{it}) \quad (8)$$

where  $r_A^{it}$  and  $r_B^{it}$  are the daily PM<sub>2.5</sub> measurement(s) of the low-cost node  $i$  and the remaining 30 nodes on day  $t$ ;  $\mu_A^{it}$ ,  $\mu_B^{it}$ , and  $\mu_{A|B}^{it}$  are the mean (**vector**) of the partitioned Multivariate Gaussian Distribution of the low-cost node  $i$ , the remaining 30 nodes, and the low-cost node  $i$  conditional on the remaining 30 nodes, respectively, on day  $t$ ; and  $\Sigma_{AA}^{it}$ ,  $\Sigma_{AB}^{it}$ ,  $\Sigma_{BA}^{it}$ ,  $\Sigma_{BB}^{it}$ , and  $\Sigma_{A|B}^{it}$  are the covariance between the low-cost node  $i$  and itself, the low-cost node  $i$  and the remaining 30 nodes, the remaining 30 nodes and the low-cost node  $i$ , the remaining 30 nodes and themselves, and the low-cost node  $i$  conditional on the remaining 30 nodes and itself, respectively, on day  $t$ .

Iterative optimizations alternated between the GPR covariance function and the low-cost node measurements (Fig. 3 steps five and six) until the GPR parameters  $\Theta$  converged. The final GPR was used to predict the 59-day PM<sub>2.5</sub> measurements of the holdout reference node (Fig. 3 step seven) following the Cholesky decomposition algorithm (Rasmussen and Williams, 2006) with the standardized predictions being transformed back to the original PM<sub>2.5</sub> measurement scale at the end. Metrics including root mean square errors (RMSE, Eq. 9) and percent errors defined as RMSE normalized by the average of the true measurements of the holdout reference node in this study (Eq. 10) were calculated for each fold and further averaged over all 22 folds to assess the accuracy and sensitivity of our simultaneous GPR and simple linear regression calibration model.

$$\text{RMSE} = \sqrt{\frac{1}{59} \|\mathbf{y}_i - \hat{\mathbf{y}}_i\|_2^2} \quad (9)$$

where  $\mathbf{y}_i$  and  $\hat{\mathbf{y}}_i$  are the true and model predicted 59 daily PM<sub>2.5</sub> measurements of the holdout reference node  $i$ .

$$\text{Percent error} = \frac{\text{RMSE}}{\text{avg. holdout reference PM}_{2.5} \text{ conc.}} \quad (10)$$

### 3 Results and discussion

#### 3.1 Spatial variation of PM<sub>2.5</sub> across Delhi

Figure 4a presents the box plot of the daily averaged PM<sub>2.5</sub> at each available reference site across Delhi from January 1, 2018 to March 31, 2018. The Vasundhara and DTU sites were the most polluted stations with the PM<sub>2.5</sub> averaging  $194 \pm 104 \mu\text{g m}^{-3}$  and  $193 \pm 90 \mu\text{g m}^{-3}$ , respectively. The Pusa and Sector 62 sites had the lowest mean PM<sub>2.5</sub>, averaging  $86 \pm 40 \mu\text{g m}^{-3}$  and  $88 \pm 36 \mu\text{g m}^{-3}$ , respectively. ~~Spatially, the~~ global average of the 3-month mean PM<sub>2.5</sub> ~~of across~~ the 22 reference stations was found to be  $138 \pm 31 \mu\text{g m}^{-3}$ . This pronounced spatial variation in mean PM<sub>2.5</sub> in Delhi (as reflected by the high SD of  $31 \mu\text{g m}^{-3}$ ) coupled with the stronger temporal variation for each station even at a 24 h scale (range:  $35\text{--}104 \mu\text{g m}^{-3}$ , see Fig. 4a) caused nonuniform calibration performance of the GPR model across Delhi, as detailed in Sect. 3.2.

#### 3.2 Assessment of GPR model performance

The optimum values of the GPR model parameters including the signal variance ( $\sigma_s^2$ ), the characteristic length-scale ( $l$ ), and the noise variance ( $\sigma_n^2$ ) are shown in Fig. S3. The  $\sigma_s^2$ ,  $l$ , and  $\sigma_n^2$  from the 22-fold leave-one-out CV averaged  $0.53 \pm 0.02$ ,  $97.89 \pm 5.47 \text{ km}$ , and  $0.47 \pm 0.01$ , respectively. The small variability in all the parameters among all the folds indicates that the model is fairly robust to the different combinations of reference nodes. The learned length-scale can be interpreted as the modeled spatial pattern of PM<sub>2.5</sub> being relatively consistent within approximately 98 km, suggesting that the optimized model majorly captures a global trend rather than fine-grained local variations.

##### 3.2.1 Accuracy of reference node prediction

We start by showing the accuracy of model prediction on the 22 reference nodes using leave-one-out CV (when the low-cost node measurements were included in our spatial prediction). Without any prior knowledge of the true calibration factors for the low-cost nodes, the holdout reference node prediction accuracy is a statistically sound proxy for estimating how well our technique can calibrate the low-cost nodes. The performance scores (including RMSE and percent error) for each reference station sorted by the 3-month mean PM<sub>2.5</sub> in descending order are listed in Table 2. An overall 30 % prediction error (equivalent to an RMSE of  $33 \mu\text{g m}^{-3}$ ) at a 24 h scale was achieved on the reference nodes following our calibration procedure. Although the technique's performance is ~~decent-reasonably accurate~~, especially considering the minimal amount of field work involved, its calibration error is nearly 3 times higher than the one of the low-cost nodes that were well calibrated by collocation with an environmental  $\beta$ -attenuation monitors (E-BAM) in our previous study (error: 11 %; RMSE:  $13 \mu\text{g m}^{-3}$ ) under similar PM<sub>2.5</sub> concentrations at the same temporal resolution (Zheng et al., 2018). The suboptimal on-the-fly mapping accuracy is a result of the optimized model's ability to simulate only the global trend well. From a different perspective, the GPR method would have modeled the spatial pattern of PM<sub>2.5</sub> in Delhi well had the natural spatial covariance among the nodes not been disturbed by the complex and prevalent local sources there. As a substantiation of the flawed local PM<sub>2.5</sub> variation modelling, the reference node mapping accuracy follows a pattern with relatively quality

prediction for those nodes whose means close to the global mean (e.g., global mean  $\pm$  SD as highlighted with shading in Table 2) while poor prediction for the means wide of the global mean (and particularly in the lower end).

In this paper, we interpolated the missing 1 h PM<sub>2.5</sub> values for all the reference and low-cost stations to fulfil our requirement of concurrent measurements of all the stations. This approach drastically increased the speed of the algorithm (up to ~20 times faster) by avoiding the expensive computational cost of excessive amount of matrix inversions that can be incurred from relying on only each day's non-missing stations' covariance information to make inference. Here we prove that the interpolation is an appropriate methodology for this paper by demonstrating that the model prediction percent errors for the 22 reference stations with and without interpolation are statistically the same. The comparison of the errors for each station can be found in Table S1. Table S1 shows that the percent errors for all the stations are essentially the same with only one exception of station Vasundhara whose error without interpolation is 10 % lower than that with interpolation. The Delhi-wide mean percent errors with (30 %) and without interpolation (29 %) are also essentially the same. We further used the Wilcoxon signed-rank test (Wilcoxon, 1945) to prove that the two related paired samples (i.e., the percent errors for the 22 reference stations with and without interpolation) are indeed statistically the same. The Wilcoxon signed-rank test is a non-parametric version of the parametric paired t-test (involving two related/matched samples/groups) that requires no specific distribution on the measurements (unlike the parametric paired t-test that assumes a normal distribution). We conducted a two-sided test which has the null hypothesis that the percent errors for the 22 reference stations with and without interpolation are the same (i.e.,  $H_0$ : with = without) against the alternative that they are not the same (i.e.,  $H_1$ : with  $\neq$  without). The p-value of the test is 0.07. The level of statistical significance was chosen to be 0.05, which means that the null hypothesis (i.e.,  $H_0$ : with = without) cannot be rejected when the p-value is 0.07, above 0.05. Therefore, interpolating missing 1 h PM<sub>2.5</sub> data for both reference and low-cost nodes is appropriate for this paper because the accuracies of model prediction on the 22 reference nodes with and without interpolation are not distinct based on the Wilcoxon signed-rank test result.

It is of particular interest to validate the value of establishing a relatively dense wireless sensor network in Delhi by examining if the addition of the low-cost nodes can truly lend a performance boost to the spatial interpolation among sensor locations. We juxtapose the interpolation performance using the full sensor network (including both the reference and low-cost nodes) with that using only the reference nodes in Fig. 5. In this context, the unnormalized RMSE is less representative than the percent error of the model interpolation performance because of the unequal numbers of overlapping 24 h observations for all the nodes (59 data points) and for only the reference nodes (87 data points). The comparison revealed that the inclusion of the 10 low-cost devices on top of the regulatory grade monitors can reduce mean and median interpolation error by roughly 2 %. While only a marginal improvement at the scale of 10, the outcome hints that densely-deployed low-cost nodes can have great promise of significantly decreasing the amount of pure interpolation among sensor



locations, therefore benefitting the spatial precision of a network. We will explore more about the significance of the low-cost nodes for the network performance in Sect. 3.3.3.

### 3.2.2 Accuracy of low-cost node calibration

Next we describe the technique's accuracy of low-cost node calibration. The model-produced calibration factors are shown in Fig. 6. The intercepts and slopes for each unique low-cost device varied little among all the 22 CV folds, reiterating the stability of the GPR model. The values of these calibration factors resemble those obtained in the previous field work, with slopes comparable to South Coast Air Quality Management District's evaluations on the Plantower PMS models (SCAQMD, 2017a–c) and intercepts comparable to our Kanpur, India post-monsoon study (Zheng et al., 2018).

Two low-cost nodes (i.e., MRU and IITD) were collocated with two E-BAMs throughout the entire study. This allows us to take their model-derived calibration factors and calibrate the corresponding raw values of the low-cost nodes before computing the calibration accuracy based on the ground truth (i.e., E-BAM measurements). Figures 7a and 7b show the scatterplots of the collocated E-BAM measurements against the model-calibrated low-cost nodes at the MRU and the IITD sites, respectively. The two sites had similarly large calibration errors (~50 %) because their concentrations were both near the lower end of PM<sub>2.5</sub> spectrum in Delhi. These high error rates echo the conditions found at the comparatively clean Pusa and Sector 62 reference sites. The scatterplots also reveal the reason why the technique especially has trouble calibrating low-concentration sites—the technique overpredicted the PM<sub>2.5</sub> concentrations at the low-concentration sites to match the levels as if subject to the natural spatial variation. The washed-out local variability after model calibration more obviously manifests in Fig. 4b, which stands in marked contrast to the true wide variability across the reference sites (Fig. 4a). In other words, the geostatistical techniques can calibrate the low-cost nodes dynamically, with the important caveat that it is effective only if the degree of urban homogeneity in PM<sub>2.5</sub> is high (e.g., the local contributions are as small a fraction of the regional ones as possible or the local contributions are prevalent but of similar magnitudes). Otherwise, quality predictions will only apply for those nodes whose means are close to the global mean. Gani et al. (2019) estimated that Delhi's local contribution to the composition-based submicron particulate matter (PM<sub>1</sub>) was ~30 to 50 % during winter and spring months. Clearly the huge amount of local influence in Delhi did not fully support our technique. In this study, our MRU and IITD sites are similar to the IITM site from the studies by Tiwari et al. (2012 and 2015), which are all on campus and free from major pollution sources and therefore qualified to be regional background sites. The PM<sub>2.5</sub> regional background concentration during winter in Delhi was then estimated to be approximately 72  $\mu\text{g m}^{-3}$ . The global mean of the 22 reference sites was 138  $\mu\text{g m}^{-3}$ , thus the mean local contribution across Delhi was roughly 66  $\mu\text{g m}^{-3}$ . Clearly this ~1:1 regional to local ratio did not fully support the technique. Alternatively, prior information about urban PM<sub>2.5</sub> spatial patterns such as high spatial resolution annual average concentration basemap from air pollution dispersion models can dramatically improve the on-the-fly calibration performance by correcting for the concentration range-specific biases (Schneider et al., 2017).

### 3.2.3 RH adjustment to the algorithm

We attempted RH adjustment to the algorithm by incorporating an RH term in the linear regression models, where the RH values were the measurements from each corresponding low-cost sensor package's embedded Adafruit DHT22 RH and temperature sensor. However, there was no improvement in the algorithm's accuracy after RH correction. A plausible explanation is regarding the infrequently high RH conditions during the winter months in Delhi and stronger smoothing effects at longer averaging time intervals (i.e., 24 h). Our previous work (Zheng et al., 2018) suggested that the PMS3003 PM<sub>2.5</sub> weights exponentially increased only when RH was above ~70%. The Delhi-wide average of the 3-month RH measured by the 10 low-cost sites was found to be  $55 \pm 15$  %. Only 17 % and 6 % of these RH values were greater than 70 % and 80 %, respectively. The infrequently high RH conditions can cause the RH-induced biases insignificant. Additionally, our previous work found that even though major RH influences can be found in 1 min to 6 h PM<sub>2.5</sub> measurements, the influence significantly diminished in 12 h PM<sub>2.5</sub> measurements and was barely observable in 24 h measurements. Therefore, longer averaging time intervals can smooth out the RH biases.

Additionally, while our algorithm was analyzed over the 59 available days in this study, the daily-averaged temperature and RH measurements for the entire sampling period (i.e., from January 1 to March 31, 2018, 90 days) were statistically the same as those for the 59 days. To support this statement, we conducted the Wilcoxon rank-sum test, also called Mann-Whitney U test (Wilcoxon, 1945; Mann and Whitney, 1947) on the daily-averaged temperature and RH measurements from the Indira Gandhi International (IGI) Airport. The Wilcoxon rank-sum test is a non-parametric version of the parametric t-test (involving two independent samples/groups) that requires no specific distribution on the measurements (unlike the parametric t-test that assumes a normal distribution). We did not use a paired test here because the two groups had different sample sizes (i.e., 59 and 90, respectively). We conducted a two-sided test which has the null hypotheses that the daily-averaged temperature and RH measurements for the 90 days ( $19 \pm 5$  °C,  $59 \pm 14$  %) and the 59 days ( $20 \pm 5$  °C,  $59 \pm 12$  %) were the same (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) against the alternatives that they were not the same (i.e.,  $H_1$ :  $\text{Temperature}_{59 \text{ days}} \neq \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} \neq \text{RH}_{90 \text{ days}}$ ). The p-values for the temperature and RH comparisons are 0.28 and 0.59, respectively. The level of statistical significance was chosen to be 0.05, which means that the null hypotheses (i.e.,  $H_0$ :  $\text{Temperature}_{59 \text{ days}} = \text{Temperature}_{90 \text{ days}} / \text{RH}_{59 \text{ days}} = \text{RH}_{90 \text{ days}}$ ) cannot be rejected when the p-values are both above 0.05. Therefore, the daily-averaged temperature and RH measurements from the IGI Airport for the entire sampling period and for the 59 days were not statistically distinct.

### **3.3 Simulation results**

While the exact values of the calibration factors derived from the GPR model fell short of faithfully recovering the original picture of PM<sub>2.5</sub> spatiotemporal gradients in Delhi, these values of one low-cost node relative to another in the network (Sect.

3.3.1) or relative to itself over time (Sect. 3.3.2) turned out to be useful in facilitating automated large-scale sensor network monitoring.

### 3.3.1 Simulation of low-cost node failure or under heavy influence of local sources

One way to simulate the conditions of low-cost node failure or under heavy influence of local sources is to replace their true  
 5 signals with values from random number generators so that the inherent spatial correlations are corrupted. In this study, we simulated how the model-produced calibration factors change when all (10), nine, seven, three, and one of the low-cost nodes within the network malfunction or are subject to strong local disturbance. We have three major observations from evaluating the simulation results (Fig. 8 and Fig. S4). First, the normal calibration factors are quite distinct from those of the low-cost nodes with random signals. Compared to the normal values (see Fig. 8 bottom right panel), the ones of the low-cost  
 10 nodes with random signals have slopes close to 0 and intercepts close to the global mean of true  $PM_{2.5}$  in Delhi (most clearly shown in Fig. 8 top left panel). Second, the calibration factors of the normal low-cost nodes are not affected by the aberrant nodes within the network (see Fig. 8 top right, middle left, middle right, and bottom left panels). These two observations indicate that the GPR model enables automated and streamlined process of instantly spotting any malfunctioning or singular low-cost nodes within a large-scale sensor network. Third, the performance of the GPR model seems to be rather  
 15 uninfluenced by changing the true signals to random numbers (see Fig. S4, 33 % error rate when all low-cost nodes are random vs. baseline 30 % error rate). One possible explanation is that the prevalent and intricate air pollution sources in Delhi have already dramatically weakened the natural spatial correlations. This means that a significant degree of randomness has already been imposed on the low-cost nodes in Delhi prior to our complete randomness experiment. Nevertheless, our not so accurate on-the-fly calibration model has created a useful algorithm for supervising large-scale  
 20 sensor networks in real time as a by-product.

### 3.3.2 Simulation of low-cost node drift

We further investigated the feasibility of applying the GPR model to track the drift of low-cost nodes accurately over time. We simulated drift conditions by first setting random percentages of intercept and slope drift, respectively, for each individual low-cost node and for each simulation run. Next, we adjusted the signals of each low-cost node over the entire  
 25 study period given these randomly selected percentages using Eq. (11). Then, we rebuilt a GPR model based on these drift-adjusted signals and evaluated if the new model-generated calibration factors matched our expected predetermined percentage drift relative to the true (baseline) calibration factors.

$$\mathbf{y}_{i\_drift} = \frac{\mathbf{y}_i}{(1 - \text{percentage slope drift}_i)} + \frac{\text{percentage intercept drift}_i \cdot \text{true intercept}_i}{(1 - \text{percentage slope drift}_i) \cdot \text{true slope}_i} \quad (11)$$

30 where  $\mathbf{y}_i$ ,  $\text{true intercept}_i$ ,  $\text{true slope}_i$ ,  $\text{percentage intercept drift}_i$ ,  $\text{percentage slope drift}_i$ , and  $\mathbf{y}_{i\_drift}$  are a vector of the true signals, the standard model-derived intercept, the standard model-derived slope, the randomly generated percentage of

intercept drift, the randomly generated percentage of slope drift, and a vector of the drift-adjusted signals, respectively, over the full study period for low-cost node  $i$ .

The performance of the model for predicting the drift was examined under a variety of scenarios including assuming that all (10), eight, six, four, and two of the low-cost nodes developed various degrees of drift such as significant (11 %–99 %), marginal (1 %–10 %), and a balanced mixture of significant and marginal. The testing results for 10, six, and two low-cost nodes are displayed in Table 3 and those for eight and four nodes are in Table ~~S4~~S2. Overall, the model demonstrates excellent drift predictive power with less than 4 % errors for all the simulation scenarios. The model proves to be most accurate (within 1 % error) when low-cost nodes only drifted marginally regardless of the number of nodes drift. In contrast, significant and particularly a mixture of significant and marginal drifts might lead to marginally larger errors. We also notice that the intercept drifts are slightly harder to accurately capture than the slope drifts. Similar to the simulation of low-cost node failure/under strong local impact as described in Sect 3.3.1, the performance of the model for predicting the measurements of the 22 holdout reference nodes across the 22-fold leave-one-out CV was untouched by the drift conditions (see Fig. S5). This unaltered performance can be attributable to the fact that the drift simulations only involve simple linear transformations as shown in Eq. (11). The quality drift estimation has therefore presented another convincing case of how useful our original algorithm can be applied to dynamically monitoring dense sensor networks, as a by-product of calibrating low-cost nodes. We can rebuild a model such as every week using a rolling window (to keep the number of observations for model construction roughly unchanged) to assess the drifts in the model space over time. After that, the true calibration factors obtained from the initial collocation with reference instruments prior to deployment can be adjusted accordingly based on the model-estimated drifts. This procedure allows for real-time drift corrections to low-cost node measurements.

### 3.3.3 Optimal number of reference nodes

Questions which remain unsolved are 1) what the optimum or minimum number of reference instruments is to sustain this technique and 2) if the inclusion of low-cost nodes can effectively assist in lowering the technique's calibration/mapping inaccuracy. It is interesting to note that optimizing the model's calibration accuracy can not only directly fulfill the fundamental calibration task, but also help better the sensor network monitoring capability as an added bonus. To address these two outstanding issues, we randomly sampled subsets of all the 22 reference nodes within the network in increments of one node (i.e. from 1 to 21 nodes) and implemented our algorithm with and without incorporating the low-cost nodes, before finally computing the mean percent errors in predicting all the holdout reference nodes. To get the performance scores as close to truth as possible but without incurring excessive computational cost in the meantime, the sampling was repeated 100 times for each subset size. The calibration error in this section was defined as the mean percent errors in predicting all the holdout reference nodes further averaged over 100 simulation runs for each subset size.

Figure 9 describes the 24 h calibration percent error rate of the model as a function of the number of reference stations used for modelling with and without involving the low-cost nodes. The error rates generally decrease as the number of reference instruments increases (full network: from ~40 % with 1 node to ~29 % with 21 nodes; network excluding low-cost nodes: from ~43 % to ~30 %) but are somewhat locally variable and most pronounced when five, seven, and eight reference nodes are simulated. These bumps might simply be the result of five, seven, and eight reference nodes being relatively non-ideal (with regard to their neighboring numbers) for the technique, although the possibility of non-convergence due to the limited 100 simulation runs for each scenario cannot be ruled out. The 19 or 20 nodes emerge as the optimum numbers of reference nodes with the lowest errors of close to 28 %, while 17 to 21 nodes all yield comparably low inaccuracies (all below 30 %). The pattern discovered in our research shares certain similarities with Schneider et al. (2017) who studied the relationship between the accuracy of using colocation-calibrated low-cost nodes to map urban AQ and the number of simulated low-cost nodes for their urban-scale air pollution dispersion model and kriging-fueled data fusion technique in Oslo, Norway. Both studies indicate that at least roughly 20 nodes are essential to start producing acceptable degree of accuracy. Unlike Schneider et al. (2017) who further expanded the scope to 150 nodes by generating new synthetic stations from their established model and showed a “the more, the merrier” trend up to 50 stations, we restricted ourselves to only realistic data to investigate the relationship since we suspect that stations created from our model with approximately 30 % errors might introduce large noise which could misrepresent the true pattern. We agree with Schneider et al. (2017) that such relationships are location-specific and cannot be blindly transferred to other study sites. At last, including low-cost nodes in the model building can most of the time reduce the model’s errors notably when more than nine reference nodes are sampled (i.e., when the number of simulated reference nodes is favorable for carrying out the technique). And for the comparatively ideal 17–20 nodes, we even observed approximately non-overlapping 95 % confidence intervals, suggesting significantly lower errors are yielded when low-cost nodes are incorporated. The accuracy gains are still relatively minor because of the suboptimal size of the low-cost node network (i.e., 10). We postulate that once the low-cost node network scales up to 100s, the model constructed using the full network information can be more accurate than the one with only the information of reference nodes by considerable margins.

## 4 Conclusions

This study introduced a simultaneous GPR and simple linear regression pipeline to calibrate wireless low-cost PM sensor networks (up to any scale) on the fly in the field by capitalizing on all available reference monitors across an area without the requirement of pre-deployment collocation calibration. We evaluated our method for Delhi where 22 reference and 10 low-cost nodes were available from January 1, 2018 to March 31, 2018 (global average of the 3-month mean PM<sub>2.5</sub> among 22 reference stations:  $138 \pm 31 \mu\text{g m}^{-3}$ ) using a leave-one-out CV over the 22 reference nodes. We demonstrated that our approach can achieve excellent robustness and decent accuracy, as underscored by the low variability in the GPR model parameters and model-produced calibration factors for low-cost nodes and by an overall 30 % prediction error (equivalent to

an RMSE of  $33 \mu\text{g m}^{-3}$ ) at a 24 h scale, respectively, among the 22-fold CV. Closer investigations into 1) the large model calibration errors ( $\sim 50\%$ ) at two Atmos regional background sites (3-month mean  $\text{PM}_{2.5}$ :  $\sim 72 \mu\text{g m}^{-3}$ ) where our E-BAMs were collocated; 2) the similarly large model prediction errors at the comparatively clean Pusa and Sector 62 reference sites; 3) and the washed-out local variability in the model calibrated low-cost sites revealed that the performance of our technique (and more generally the geostatistical techniques) can calibrate the low-cost nodes dynamically, but effective only if the degree of urban homogeneity in  $\text{PM}_{2.5}$  is high (e.g., the local contributions are as small a fraction of the regional ones as possible or the local contributions are prevalent but of similar magnitudes). Otherwise, quality predictions will only apply for those nodes whose means are close to the global mean. Despite our algorithm's non-ideal calibration accuracy for Delhi, it holds the promise of being adapted for automated and streamlined large-scale wireless sensor network monitoring and of significantly reducing the amount of manual labor involved in the surveillance and maintenance. Simulations proved our algorithm's capability of differentiating malfunctioning or singular low-cost nodes within a network and of tracking the drift of low-cost nodes accurately with less than 4 % errors for all the simulation scenarios. Finally, our simulation results confirmed that the low-cost nodes are beneficial for the spatial precision of a sensor network by decreasing the extent of pure interpolation among only reference stations, highlighting the substantial significance of dense deployments of low-cost AQ devices for a new generation of AQ monitoring network.

Two directions are possible for our future work. The first one is to expand both the longitudinal and the cross-sectional scopes of field studies and examine how well our solution works for more extensive networks in a larger geographical area over longer periods of deployment (when sensors are expected to actually drift, degrade, or malfunction). This enables us to validate the practical use of our method for calibration and surveillance more confidently. The second is to explore the infusion of information about urban  $\text{PM}_{2.5}$  spatial patterns such as high-spatial-resolution annual average concentration basemap from air pollution dispersion models (Schneider et al., 2017) into our current algorithm to further improve the on-the-fly calibration performance by correcting for the concentration range-specific biases.

### Data availability

The data are available upon request to Tongshu Zheng ([tongshu.zheng@duke.edu](mailto:tongshu.zheng@duke.edu)).

### Competing interests

Author Ronak Sutaria is the founder of Respirer Living Sciences Pvt. Ltd, a startup based in Mumbai, India which is the developer of the Atmos low-cost AQ monitor. Ronak Sutaria ~~only was~~ involved in developing and refining the hardware of Atmos and its server and dashboard and in deploying the sensors, but not in data analysis. Author Robert Caldow is the director of engineering at TSI and only responsible for the funding and technical support, but not for data analysis.

## Acknowledgments

Sachchida N. Tripathi and Ronak Sutaria are supported under the Research Initiative for Real-time River Water and Air Quality Monitoring program funded by the Department of Science and Technology, Government of India and Intel Corporation, and administered by the Indo-US Science and Technology Forum. The authors would like to thank CPCB, DPCC, IMD, SPCBs, and AirNow DOS (Department of State) for providing the Delhi 1 h reference PM<sub>2.5</sub> measurements used in the current study.

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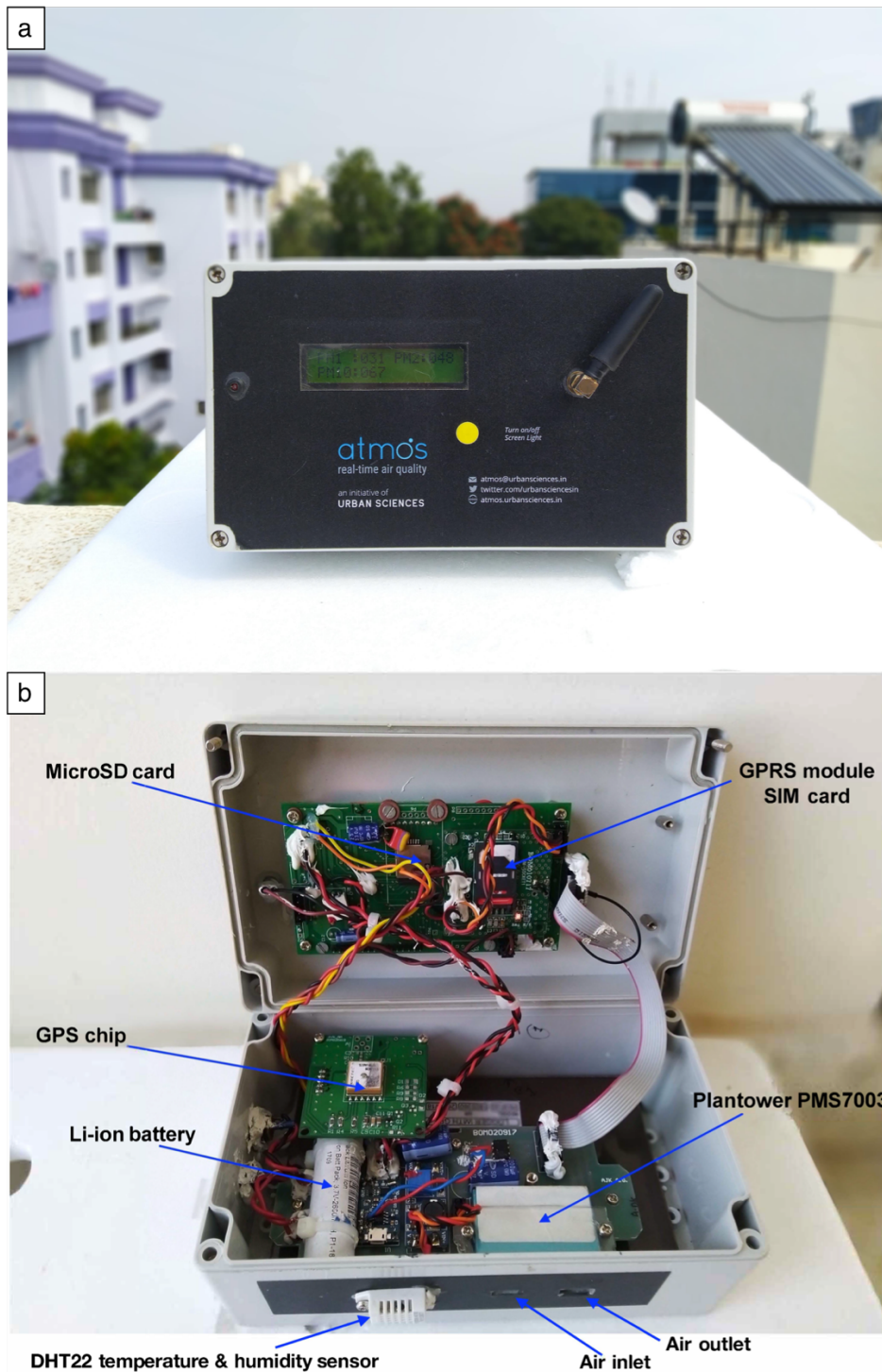
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**Figure 1: (a) Front view of the low-cost node. (b) Key components of the low-cost node.**





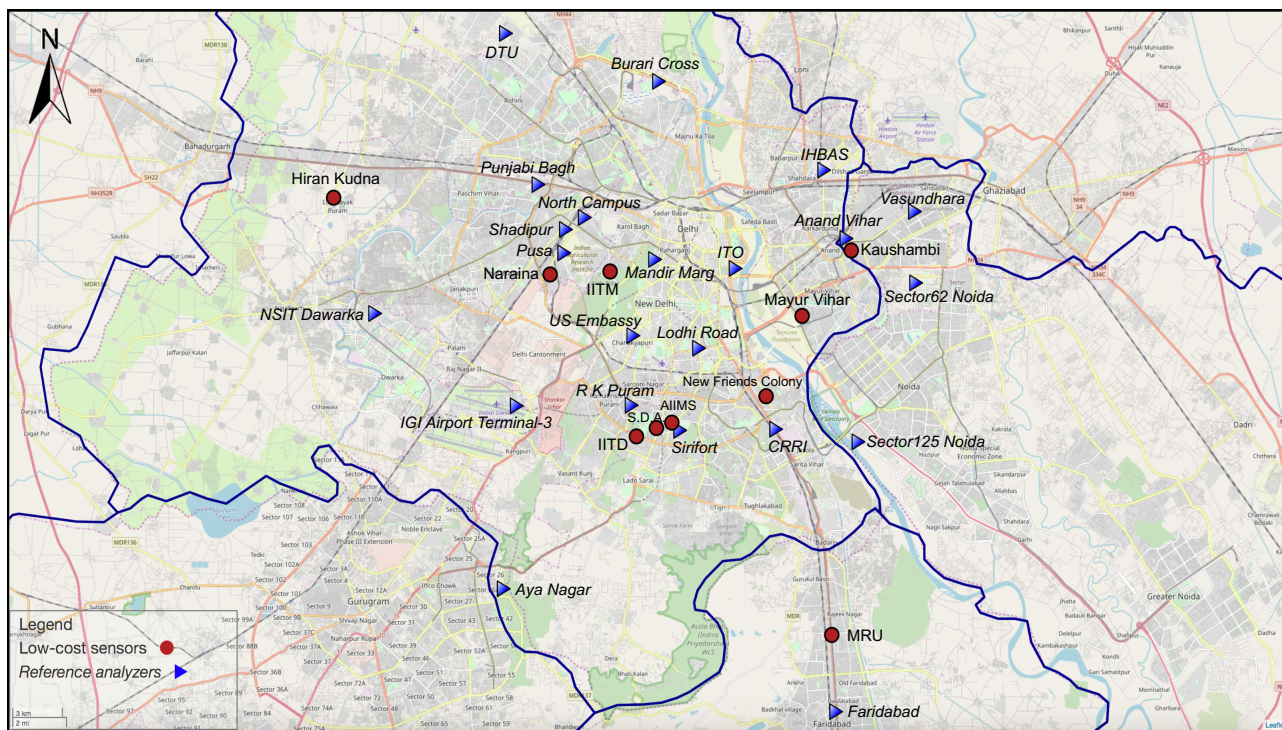
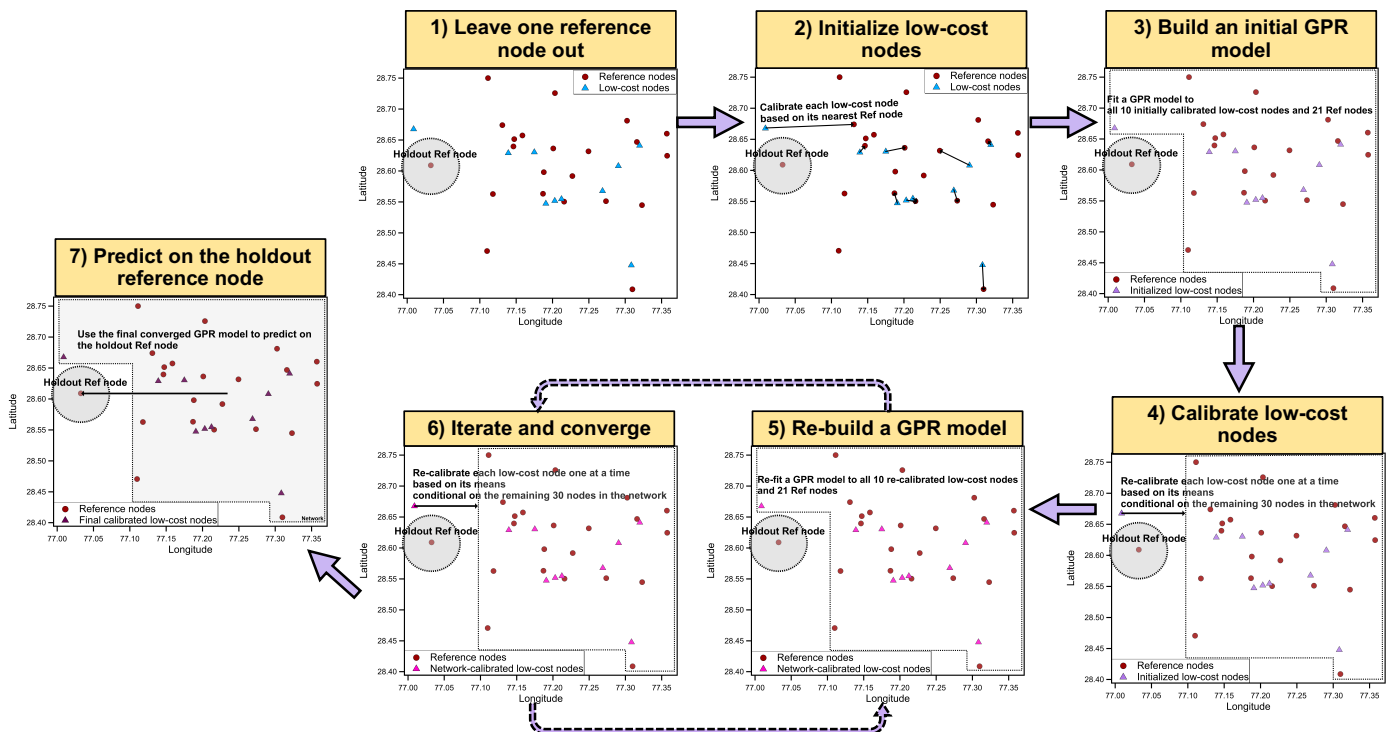
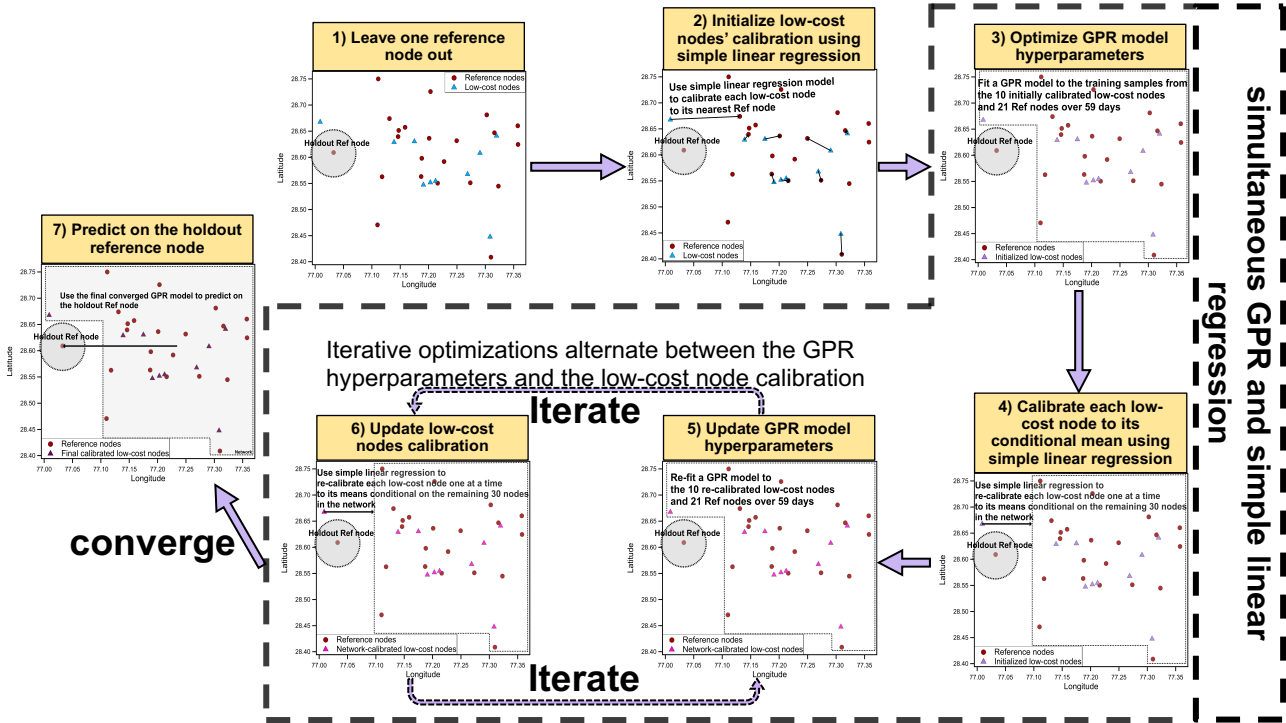


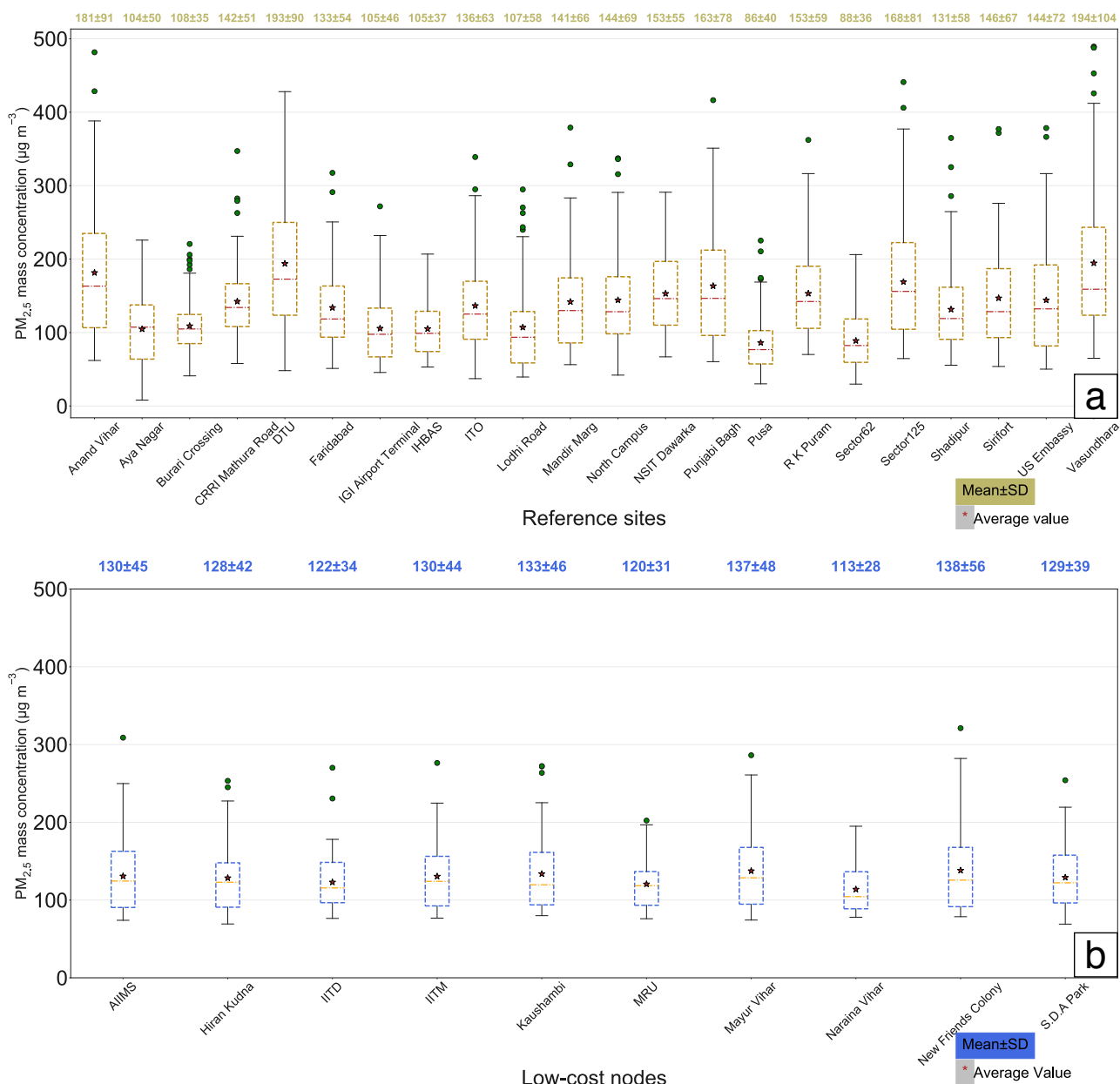
Figure 2: Locations of the 22 reference nodes (triangle icons with *italic text*) and 10 low-cost nodes (circle icons) that form the Delhi PM sensor network.





**Figure 3: The flow diagram illustrating overall schema for the simultaneous GPR and simple linear regression calibration model algorithm. In step one, for each of the 22-fold leave-one-out CVs, one of the 22 reference nodes is held out of modelling for the model predictive performance evaluation in step seven; in step two, fit a simple linear regression model between each low-cost node  $i$  and its closest reference node's  $PM_{2.5}$ , initialize low-cost node  $i$ 's calibration model to this linear regression model, and calibrate the low-cost node  $i$  using this model; in step three, first initialize the GPR hyperparameters to  $[0.1, 50, 0.01]$  and then update/optimize the hyperparameters based on the training samples from the 10 initially calibrated low-cost nodes and 21 reference nodes over 59 days; in step four, first compute each low-cost node  $i$ 's means conditional on the remaining 30 nodes given the optimized GPR hyperparameters, then fit a simple linear regression model between each low-cost node  $i$  and its conditional means, update low-cost node  $i$ 's calibration model to this new linear regression model, and re-calibrate the low-cost node  $i$  using this new model; in step five and six, iterative optimizations alternate between the GPR hyperparameters and the low-cost node calibrations using the approaches described in step three and four, respectively, until the GPR hyperparameters converged; in step seven, predict the 59-day  $PM_{2.5}$  measurements of the holdout reference node given the finalized GPR hyperparameters and the low-cost node calibrations.**





**Figure 4: a) Box plots of the 24 h aggregated true ambient PM<sub>2.5</sub> mass concentrations measured by the 22 government reference monitors across Delhi from January 1 to March 31, 2018. b) Box plots of the low-cost node 24 h aggregated PM<sub>2.5</sub> mass concentrations calibrated by the optimized GPR model. In both a) and b), mean and SD of the PM<sub>2.5</sub> mass concentrations for each individual site are superimposed on the box plots.**

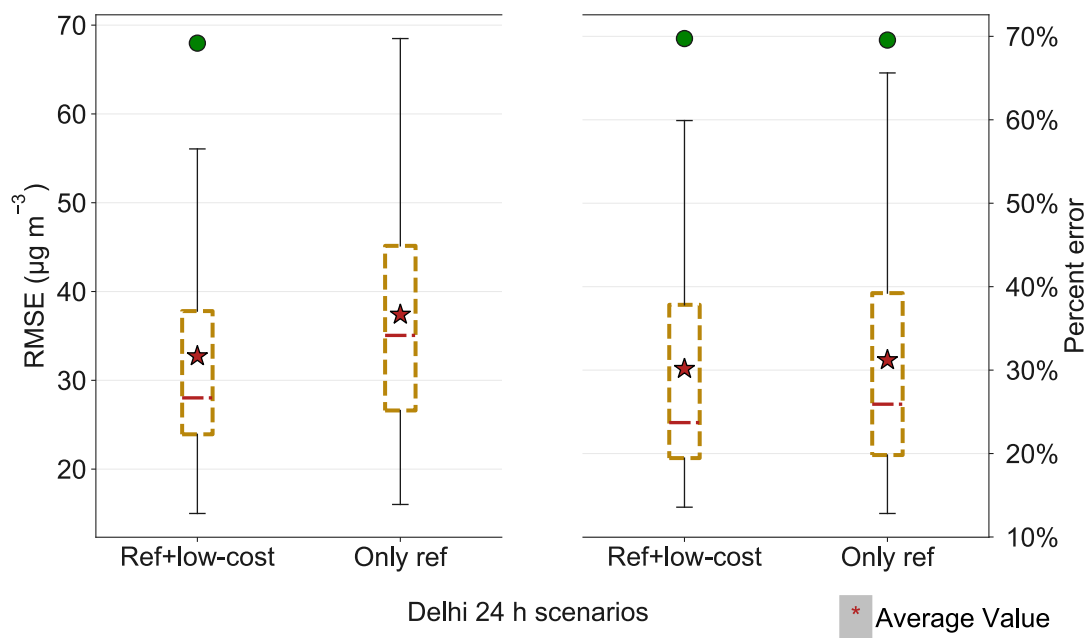
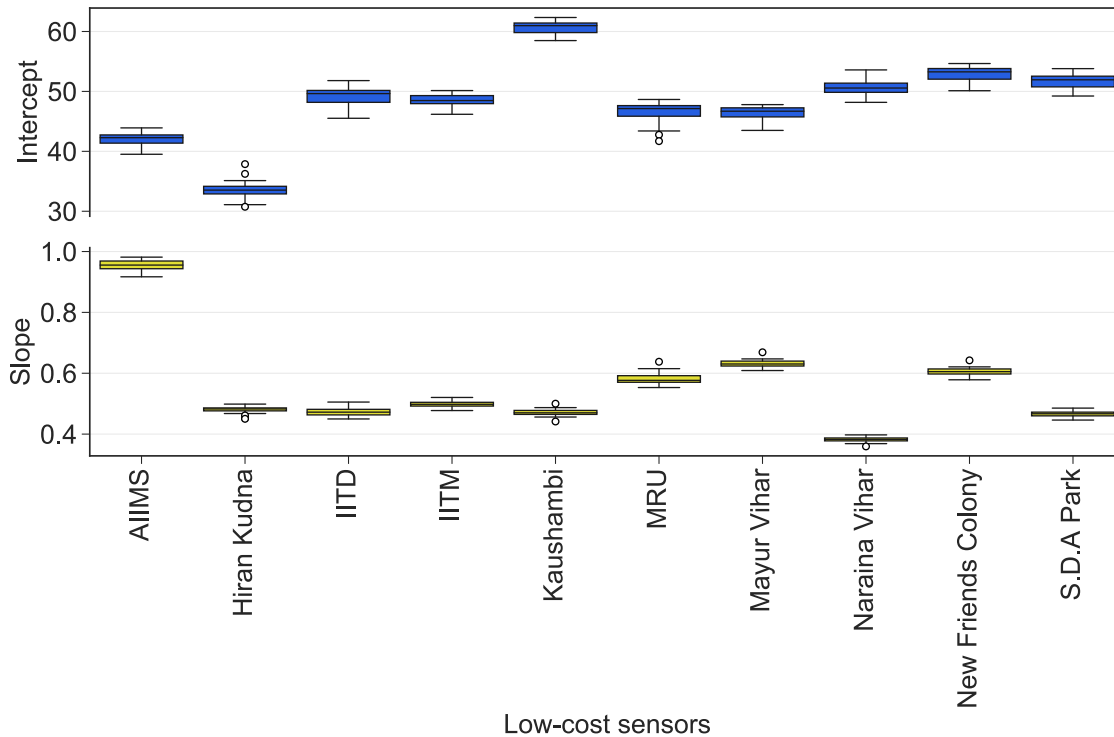
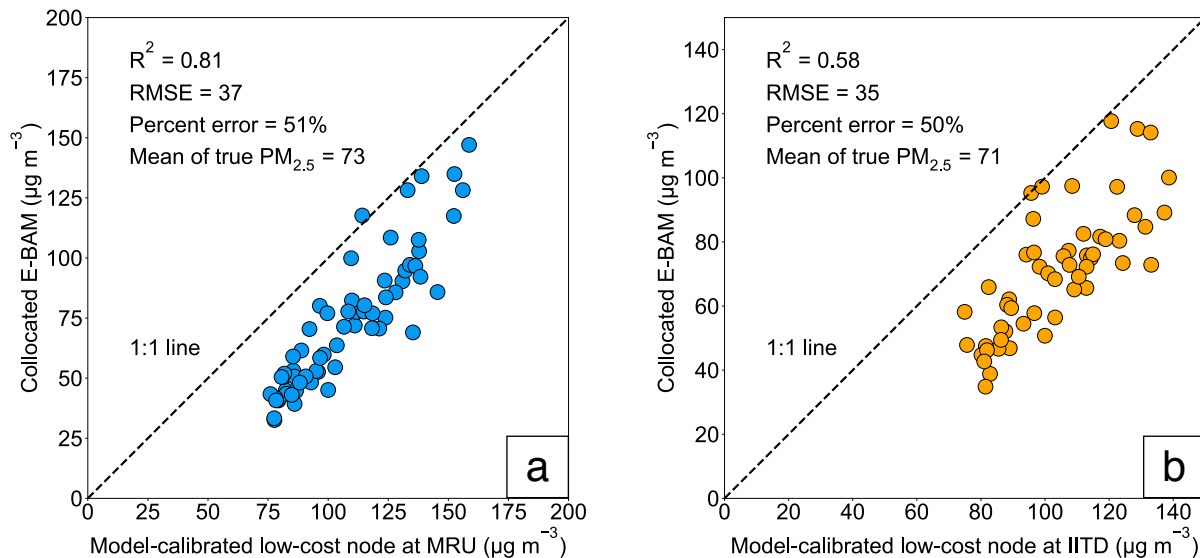


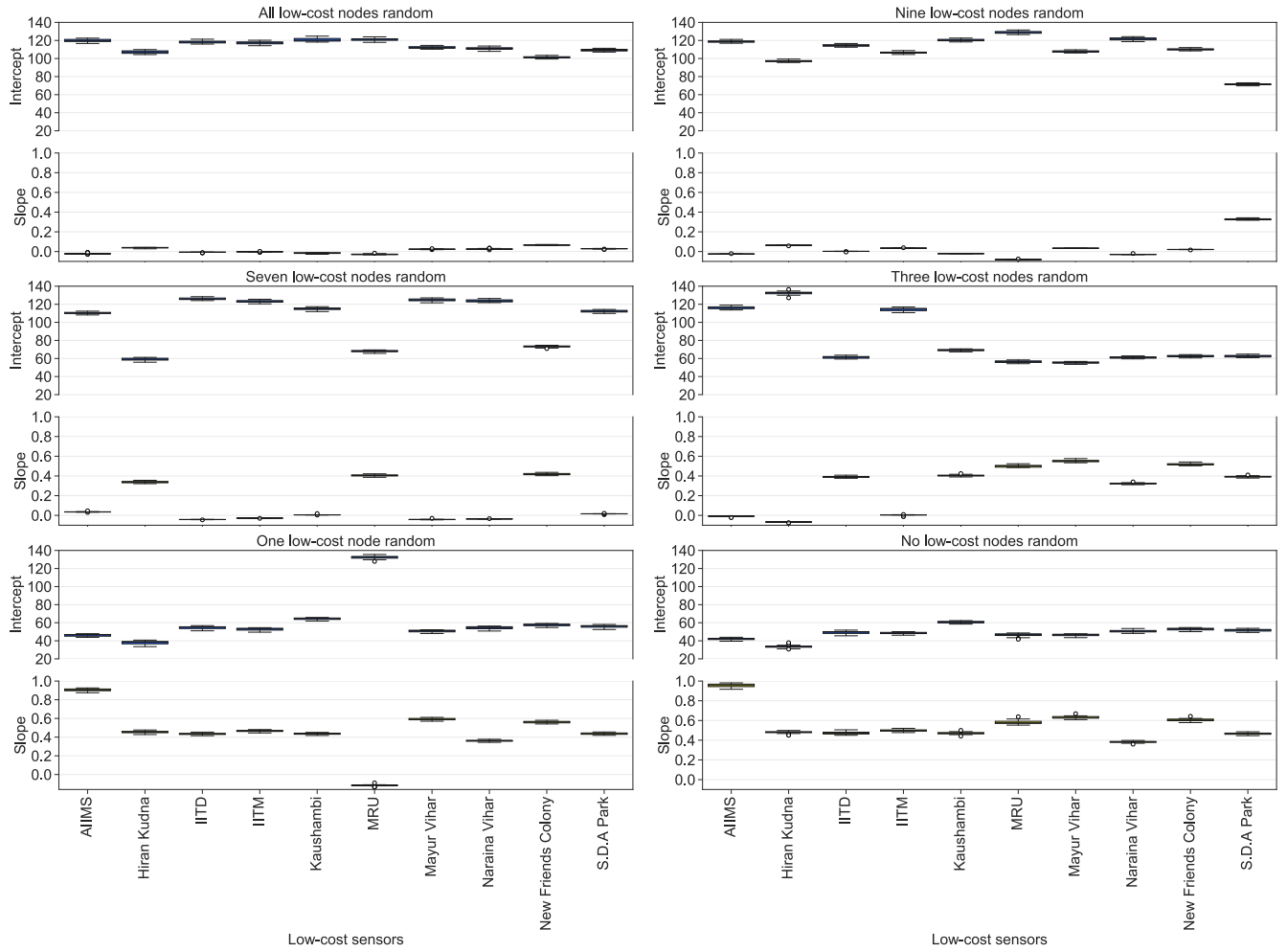
Figure 5: Box plots of the GPR model 24 h performance scores (including RMSE and percent error) for predicting the measurements of the 22 holdout reference nodes across the 22-fold leave-one-out CV under two scenarios — using the full sensor network by including both reference and low-cost nodes and using only the reference nodes for the model construction. Note both scenarios were given the initial parameter values and bounds that maximize the model performance.



**Figure 6: Box plots of the learned calibration factors (i.e., intercept and slope) for each individual low-cost node from the 22 optimized GPR models across the 22-fold leave-one-out CV.**



**5 Figure 7: Correlation plots comparing the GPR model-calibrated low-cost node  $\text{PM}_{2.5}$  mass concentrations to the collocated E-BAM measurements at a) MRU and b) IITD sites. In both a) and b), correlation of determination ( $R^2$ ), RMSE, percent error, and mean of the true ambient  $\text{PM}_{2.5}$  mass concentrations throughout the study (from January 1 to March 31, 2018) are superimposed on the correlation plots.**



**Figure 8: Learned calibration factors for each individual low-cost node from the optimized GPR models by replacing measurements of all (top left), nine (top right), seven (middle left), three (middle right), one (bottom left), and zero (bottom right) of the low-cost nodes with random integers bounded by the min and max of the true signals reported by the corresponding low-cost nodes. Note that the nine, seven, three, and one low-cost nodes (whose true signals are replaced with random integers) were randomly chosen.**

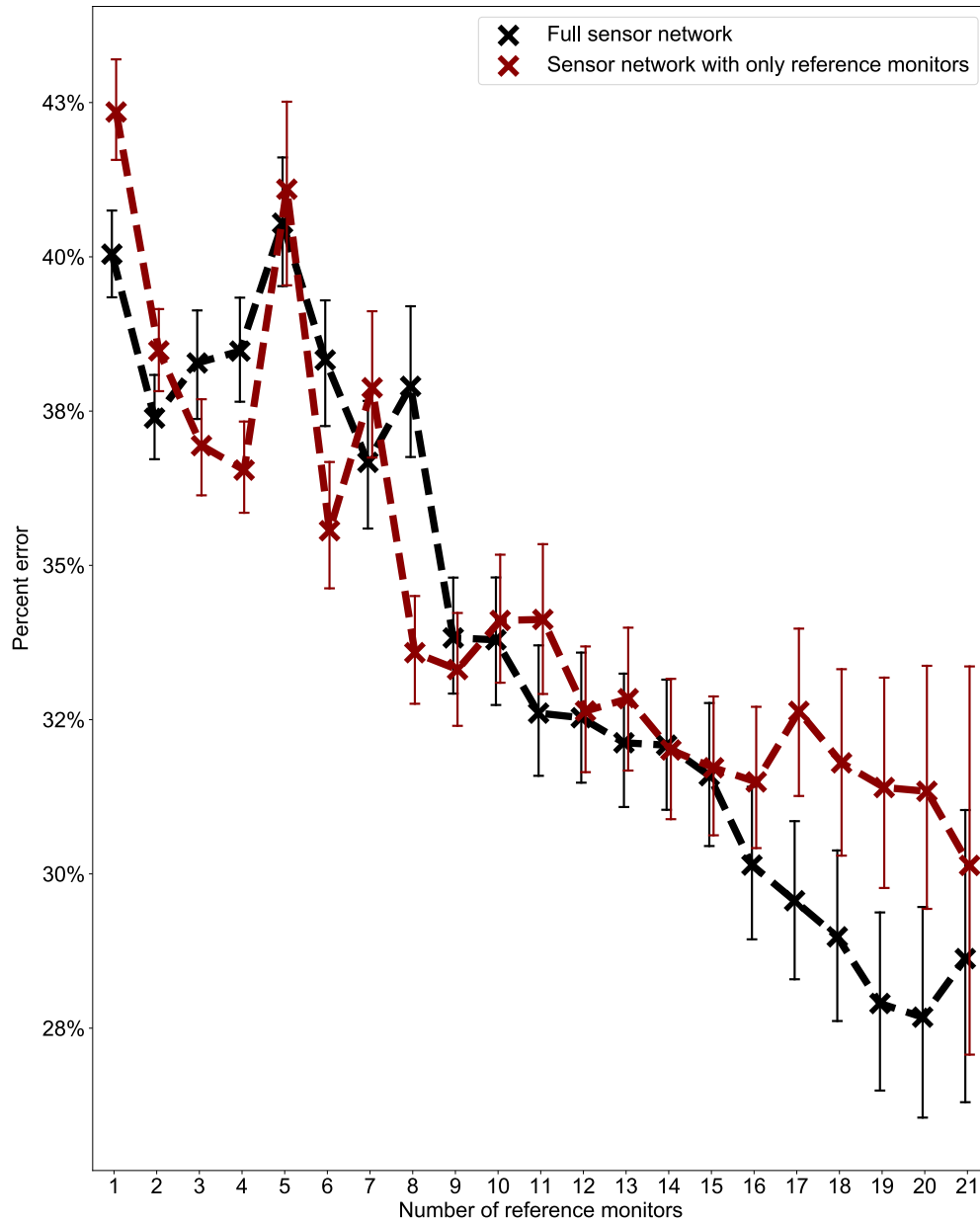


Figure 9: Average 24 h percent errors of the GPR model for predicting the holdout reference nodes in the network as a function of the number of reference stations used for the model construction under two scenarios — using the full sensor network information by including both reference and low-cost nodes and using only the reference nodes for the model construction. Note each data point (mean value) is derived from 100 simulation runs. The error bars indicating 95 % CI of the means are based on 1000 bootstrap iterations. All scenarios were given the initial parameter values and bounds that maximize the model performance.

**Table 1: Delhi PM sensor network sites along with the 1 h data percentage completeness with respect to the entire sampling period (i.e., from January 1, 2018 00:00 to March 31, 2018 23:59, Indian Standard Time, IST; in total 90 days, 2160 hours) before and after 1 h missing-data imputation for each individual site. Note that a 10 % increase in the percentage data completeness after 1 h missing-data imputation is equivalent to ~216 hours of 1 h data being interpolated.**

Category	Site names	Latitude	Longitude	Initial 1 h data completeness	1 h data completeness after missing-data imputation
Reference	Anand Vihar	N 28.6468350	E 77.3160320	88 %	100 %
	Aya Nagar	N 28.4706914	E 77.1099364	97 %	100 %
	Burari Cross	N 28.7258390	E 77.2033350	98 %	100 %
	CRRI Mathura Road	N 28.5512005	E 77.2735737	98 %	100 %
	Delhi Technological University (DTU)	N 28.7500499	E 77.1112615	96 %	100 %
	Faridabad	N 28.4088421	E 77.3099081	98 %	100 %
	IGI Airport Terminal-3	N 28.5627763	E 77.1180053	95 %	100 %
	IHBAS, Dilshad Garden	N 28.6811736	E 77.3025234	98 %	100 %
	ITO Metro Station (ITO)	N 28.6316945	E 77.2494387	98 %	100 %
	Lodhi Road	N 28.5918245	E 77.2273074	93 %	100 %
	Mandir Marg	N 28.6364290	E 77.2010670	96 %	100 %
	North Campus	N 28.6573814	E 77.1585447	94 %	100 %
	NSIT Dawarka	N 28.6090900	E 77.0325413	95 %	100 %
	Punjabi Bagh	N 28.6740450	E 77.1310230	94 %	100 %
	Pusa	N 28.6396450	E 77.1462620	99 %	100 %
	R K Puram	N 28.5632620	E 77.1869370	95 %	100 %
	Sector62 Noida	N 28.6245479	E 77.3577104	93 %	99 %
	Sector125 Noida	N 28.5447608	E 77.3231257	90 %	97 %
	Shadipur	N 28.6514781	E 77.1473105	97 %	100 %
	Sirifort	N 28.5504249	E 77.2159377	78 %	100 %
	US Embassy	N 28.5980970	E 77.1880330	95 %	100 %
	Vasundhara, Ghaziabad	N 28.6603346	E 77.3572563	100 %	100 %
Low-cost	All India Institute of Medical Science (AIIMS)	N 28.5545006	E 77.2124023	89 %	100 %
	Hiran Kudna	N 28.6674995	E 77.0089035	80 %	97 %
	Indian Institute of Technology Delhi (IITD)	N 28.5473003	E 77.1909027	88 %	99 %
	Indian Institute of Tropical Meteorology (IITM)	N 28.6303400	E 77.1750400	98 %	100 %
	Kaushambi	N 28.6410008	E 77.3199005	84 %	100 %
	Manav Rachna University (MRU)	N 28.4477005	E 77.3084030	87 %	100 %
	Mayur Vihar	N 28.6079998	E 77.2906036	85 %	93 %
	Naraina Vihar	N 28.6289005	E 77.1391983	70 %	79 %
	New Friends Colony	N 28.5676994	E 77.2687988	99 %	100 %
	S.D.A. Park	N 28.5517006	E 77.2031021	66 %	97 %

5 **Table 2: Summary of the GPR model 24 h performance scores (including RMSE and percent error) for predicting the measurements of the 22 holdout reference nodes across the 22-fold leave-one-out CV when the full sensor network is used. The mean of the true ambient PM<sub>2.5</sub> mass concentrations throughout the study (from January 1 to March 31, 2018) for each individual reference node is provided. The reference nodes with the means of true PM<sub>2.5</sub> inside the range of [global mean  $\pm$  SD, i.e., 138  $\pm$  31] are indicated with shading.**

Reference nodes	RMSE ( $\mu\text{g m}^{-3}$ )	Percent error	Mean of true PM <sub>2.5</sub> ( $\mu\text{g m}^{-3}$ )
Vasundhara, Ghaziabad	68	44 %	195
DTU	56	36 %	194
Anand Vihar	47	32 %	181
Sector125 Noida	31	23 %	169
Punjabi Bagh	26	20 %	163
NSIT Dawarka	25	19 %	153
R K Puram	26	20 %	153
Sirifort	22	18 %	147
US Embassy	21	18 %	144
North Campus	27	24 %	144
CRRRI Mathura Road	27	21 %	142
Mandir Marg	16	14 %	142
ITO	15	14 %	136
Faridabad	21	18 %	133
Shadipur	23	22 %	132
Burari Cross	36	39 %	109
Lodhi Road	34	41 %	107
IGI Airport Terminal-3	29	32 %	106
Aya Nagar	34	38 %	105
IHBAS, Dilshad Garden	38	41 %	105
Sector62 Noida	47	60 %	89
Pusa	48	70 %	86
Global mean	33	30 %	138
SD	13	14 %	31

**Table 3: Comparison of predetermined percentages of drift to those estimated from the GPR model for intercept and slope, respectively, for each individual low-cost node, assuming all (10), six, and two of the low-cost nodes developed various degrees of drift such as significant (11 %–99 %), marginal (1 %–10 %), and a balanced mixture of significant and marginal. Note the sensors that drifted, the percentages of drift, and which sensors drifted significantly or marginally are randomly chosen. The results reported under each scenario are based on averages of 10 simulation runs.**

Drift category	Low-cost nodes	All low-cost nodes drift				Six low-cost nodes drift				Two low-cost nodes drift			
		Intercept drift (%)		Slope drift (%)		Intercept drift (%)		Slope drift (%)		Intercept drift (%)		Slope drift (%)	
		True	Estimated	True	Estimated	True	Estimated	True	Estimated	True	Estimated	True	Estimated
Significant	AIIMS	58 %	57 %	54 %	54 %	74 %	71 %	46 %	47 %	0 %	-1 %	0 %	-1 %
	Hiran Kudna	43 %	30 %	50 %	52 %	66 %	61 %	53 %	53 %	62 %	64 %	45 %	44 %
	IITD	51 %	52 %	52 %	51 %	0 %	-1 %	0 %	-2 %	0 %	1 %	0 %	-3 %
	IITM	54 %	53 %	56 %	55 %	61 %	58 %	48 %	48 %	0 %	-1 %	0 %	-2 %
	Kaushambi	61 %	62 %	73 %	72 %	70 %	70 %	49 %	48 %	0 %	0 %	0 %	-2 %
	MRU	55 %	56 %	56 %	56 %	58 %	61 %	41 %	39 %	0 %	-1 %	0 %	-2 %
	Mayur Vihar	60 %	65 %	48 %	47 %	0 %	1 %	0 %	-3 %	0 %	1 %	0 %	-3 %
	Naraina Vihar	56 %	54 %	76 %	76 %	0 %	-4 %	0 %	1 %	0 %	-1 %	0 %	-1 %
	New Friends Colony	66 %	68 %	68 %	67 %	55 %	55 %	48 %	47 %	59 %	61 %	37 %	36 %
	S.D.A. Park	53 %	47 %	48 %	50 %	0 %	-4 %	0 %	2 %	0 %	-1 %	0 %	0 %
Mean absolute difference		3 %		1 %		2 %		1 %		1 %		2 %	
50 % significant and 50 % marginal	AIIMS	4 %	2 %	5 %	6 %	0 %	-4 %	0 %	2 %	0 %	1 %	0 %	-2 %
	Hiran Kudna	51 %	42 %	51 %	52 %	50 %	42 %	50 %	52 %	0 %	1 %	0 %	-2 %
	IITD	6 %	4 %	6 %	6 %	5 %	2 %	6 %	8 %	0 %	0 %	0 %	-2 %
	IITM	56 %	52 %	40 %	40 %	64 %	58 %	47 %	48 %	0 %	1 %	0 %	-3 %
	Kaushambi	60 %	60 %	42 %	41 %	5 %	2 %	5 %	7 %	0 %	0 %	0 %	-2 %
	MRU	6 %	5 %	4 %	3 %	0 %	-6 %	0 %	3 %	6 %	3 %	5 %	5 %
	Mayur Vihar	57 %	59 %	55 %	55 %	5 %	2 %	5 %	6 %	0 %	1 %	0 %	-2 %
	Naraina Vihar	4 %	0 %	5 %	7 %	0 %	-4 %	0 %	2 %	57 %	65 %	64 %	63 %
	New Friends Colony	6 %	5 %	6 %	5 %	0 %	-3 %	0 %	2 %	0 %	-1 %	0 %	-1 %
	S.D.A. Park	53 %	48 %	61 %	61 %	59 %	58 %	64 %	64 %	0 %	0 %	0 %	-1 %
Mean absolute difference		3 %		1 %		4 %		2 %		2 %		2 %	
Marginal	AIIMS	5 %	5 %	5 %	4 %	8 %	8 %	5 %	5 %	0 %	0 %	0 %	-1 %
	Hiran Kudna	3 %	4 %	6 %	5 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
	IITD	5 %	6 %	7 %	5 %	7 %	8 %	5 %	4 %	6 %	7 %	5 %	4 %
	IITM	5 %	5 %	5 %	5 %	0 %	0 %	0 %	-1 %	0 %	0 %	0 %	-1 %
	Kaushambi	5 %	5 %	5 %	4 %	5 %	6 %	7 %	6 %	0 %	0 %	0 %	-1 %
	MRU	5 %	7 %	4 %	2 %	6 %	8 %	5 %	3 %	5 %	7 %	6 %	4 %
	Mayur Vihar	7 %	7 %	5 %	4 %	0 %	1 %	0 %	-1 %	0 %	1 %	0 %	-1 %
	Naraina Vihar	6 %	6 %	7 %	6 %	7 %	7 %	6 %	5 %	0 %	0 %	0 %	-1 %
	New Friends Colony	7 %	8 %	7 %	5 %	0 %	1 %	0 %	-2 %	0 %	1 %	0 %	-1 %
	S.D.A. Park	5 %	5 %	7 %	6 %	6 %	6 %	6 %	6 %	0 %	0 %	0 %	-1 %
Mean absolute difference		1 %		1 %		1 %		1 %		1 %		1 %	



### Reasoning behind step four of the schema for the simultaneous GPR and simple linear regression calibration model

Once the optimum  $\Theta$  for the (initial) GPR was found, we used the learned covariance function to find the mean of each low-cost node  $i$ 's Gaussian Distribution conditional on the remaining 30 nodes within the network (i.e.,  $\mu_{A|B}^{it}$ ) on day  $t$  as described mathematically in Eq. (S1)–(S4) and repeatedly did so until all 59 days'  $\mu_{A|B}^{it}$  (i.e.,  $\mu_{A|B}^i$ ) were found and then recalibrated that low-cost node  $i$  based on the  $\mu_{A|B}^i$ . This procedure was performed iteratively for all low-cost nodes one at a time.

$$p\left(\begin{bmatrix} r_A^{it} \\ r_B^{it} \end{bmatrix}\right) = N\left(\begin{bmatrix} r_A^{it} \\ r_B^{it} \end{bmatrix}; \begin{bmatrix} \mu_A^{it} \\ \mu_B^{it} \end{bmatrix}, \begin{bmatrix} \Sigma_{AA}^{it} & \Sigma_{AB}^{it} \\ \Sigma_{BA}^{it} & \Sigma_{BB}^{it} \end{bmatrix}\right) \quad (S1)$$

$$r_A^{it} | r_B^{it} \sim N(\mu_{A|B}^{it}, \Sigma_{A|B}^{it}) \quad (S2)$$

$$\mu_{A|B}^{it} = \mu_A^{it} + \Sigma_{AB}^{it} \Sigma_{BB}^{it-1} (r_B^{it} - \mu_B^{it}) \quad (S3)$$

$$\Sigma_{A|B}^{it} = \Sigma_{AA}^{it} - \Sigma_{AB}^{it} \Sigma_{BB}^{it-1} \Sigma_{BA}^{it} = a \text{ constant for low-cost node } i \text{ regardless of day } t = \Sigma_{A|B}^i \quad (S4)$$

where  $r_A^{it}$  and  $r_B^{it}$  are the daily PM<sub>2.5</sub> measurement(s) of the low-cost node  $i$  and the remaining 30 nodes on day  $t$ ;  $\mu_A^{it}$ ,  $\mu_B^{it}$ , and  $\mu_{A|B}^{it}$  are the mean (**vector**) of the partitioned Multivariate Gaussian Distribution of the low-cost node  $i$ , the remaining 30 nodes, and the low-cost node  $i$  conditional on the remaining 30 nodes, respectively, on day  $t$ ; and  $\Sigma_{AA}^{it}$ ,  $\Sigma_{AB}^{it}$ ,  $\Sigma_{BA}^{it}$ ,  $\Sigma_{BB}^{it}$ , and  $\Sigma_{A|B}^{it}$  are the covariance between the low-cost node  $i$  and itself, the low-cost node  $i$  and the remaining 30 nodes, the remaining 30 nodes and the low-cost node  $i$ , the remaining 30 nodes and themselves, and the low-cost node  $i$  conditional on the remaining 30 nodes and itself, respectively, on day  $t$ .

The reasoning behind recalibrating each low-cost node  $i$  based on the  $\mu_{A|B}^i$  is given as follows:

The conditional log-likelihood under the Univariate Gaussian distribution on day  $t$  is:

$$\log p(r_A^{it} | r_B^{it}) = \text{constant} - 0.5 \Sigma_{A|B}^{it-2} (r_A^{it} - \mu_{A|B}^{it})^2 \quad (S5)$$

Then the complete log-likelihood over all 59 days is therefore given by:

$$\sum_{t=1}^{59} \log p(r_A^{it} | r_B^{it}) = \text{constant} - \text{positive constant} \cdot \sum_{t=1}^{59} (r_A^{it} - \mu_{A|B}^{it})^2 \quad (S6)$$

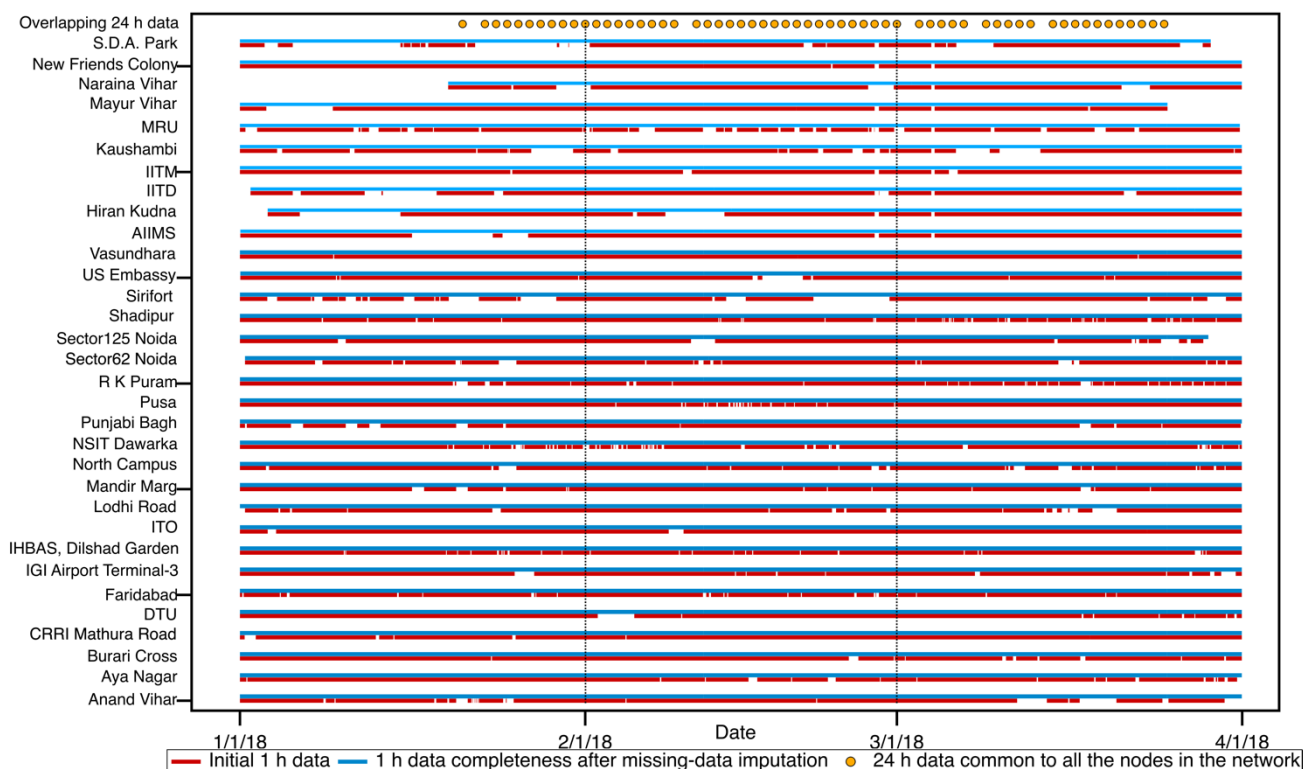
The objective is to maximize the complete log-likelihood over all 59 days (i.e., S6), that is equivalent to minimizing the term of  $\sum_{t=1}^{59} (r_A^{it} - \mu_{A|B}^{it})^2$ :

$$\max_{r_A^i} \sum_{t=1}^{59} \log p(r_A^{it} | r_B^{it}) = \min_{r_A^i} \|r_A^i - \mu_{A|B}^i\|_2^2 \quad (S7)$$

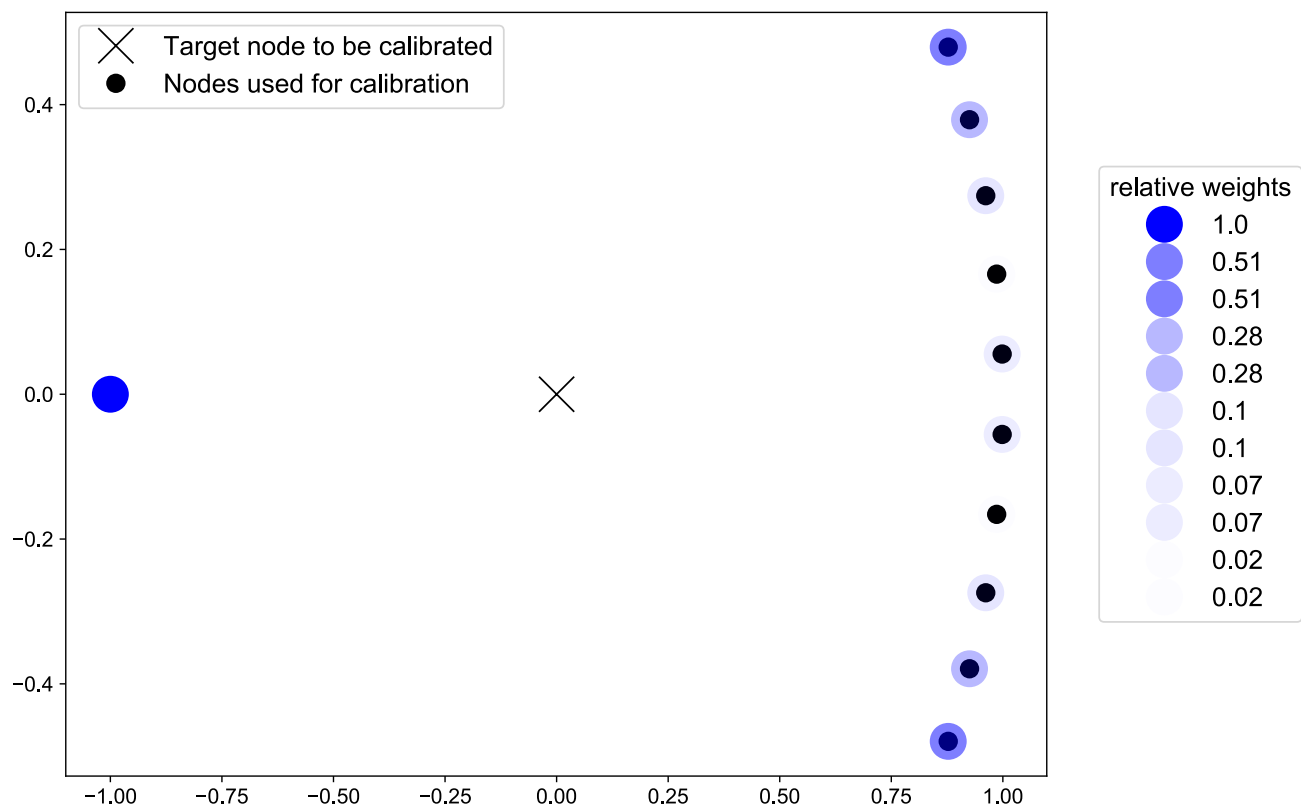
$$\text{and } r_A^i = Y_i \beta_i \quad (S8)$$

where  $\mathbf{Y}_i = \begin{bmatrix} 1 & y_{it} \\ \vdots & \vdots \\ 1 & y_{i59} \end{bmatrix}$  and  $\boldsymbol{\beta}_i$  is a vector of the intercept and slope (to be learned) of the simple linear regression calibration equation for low cost node  $i$ .

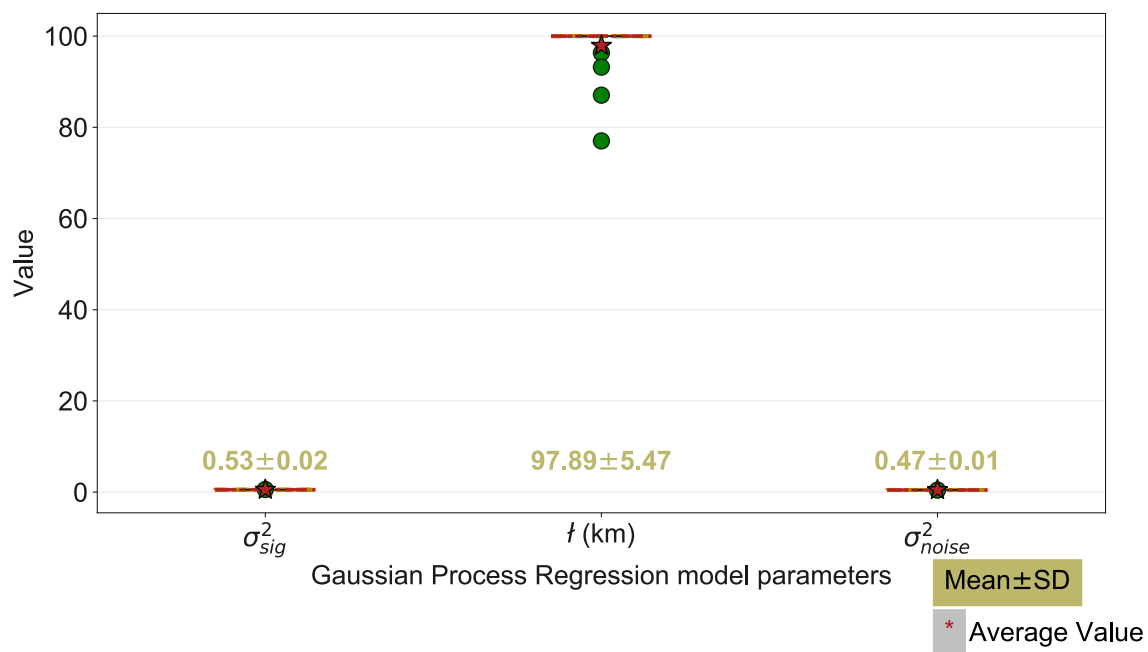
And to minimize  $\|\mathbf{Y}_i \boldsymbol{\beta}_i - \boldsymbol{\mu}_{A|B}^i\|_2^2$  is then equivalent to optimizing a simple linear regression model to re-calibrate the raw  
5 low-cost node signals based on the mean of each node's Gaussian Distribution conditional on the remaining 30 nodes within the network (i.e.,  $\boldsymbol{\mu}_{A|B}^i$ ).



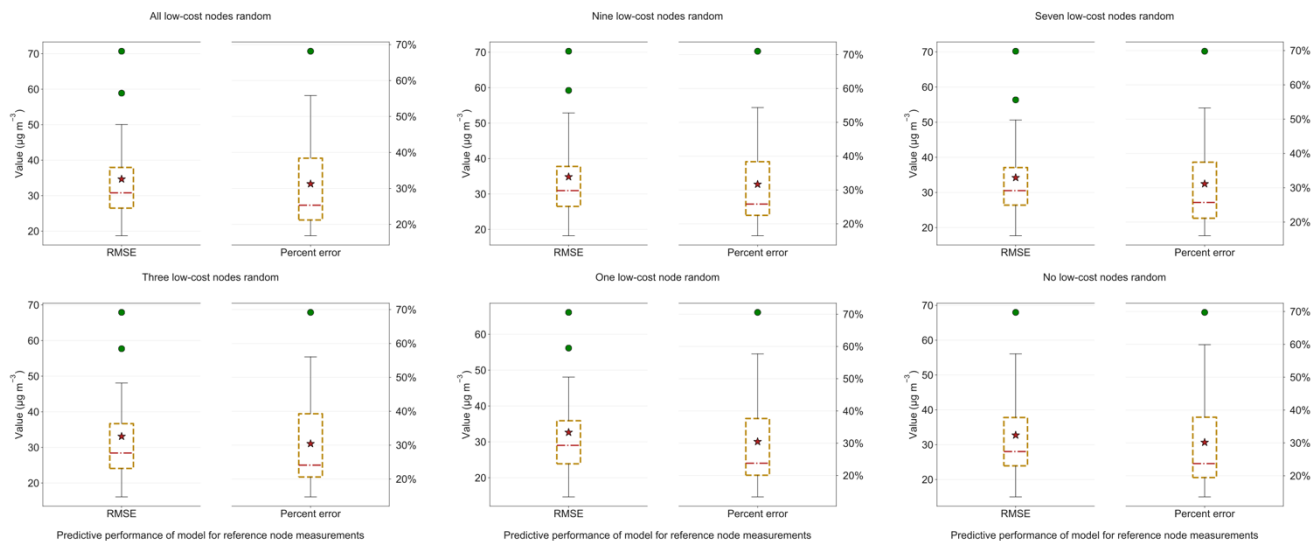
**Figure S1: Periods over which 1 h data were available for each individual site before and after missing-data imputation and a total of 59 24 h aggregated observations common to all the nodes in the network used for the on-the-fly calibration feasibility test. The top 10 sites (i.e., from S.D.A. Park to AIIMS) are the low-cost sites and the remaining sites (i.e., from Vasundhara to Anand Vihar) are the reference sites. Note that there is no obvious pattern in the data missingness.**



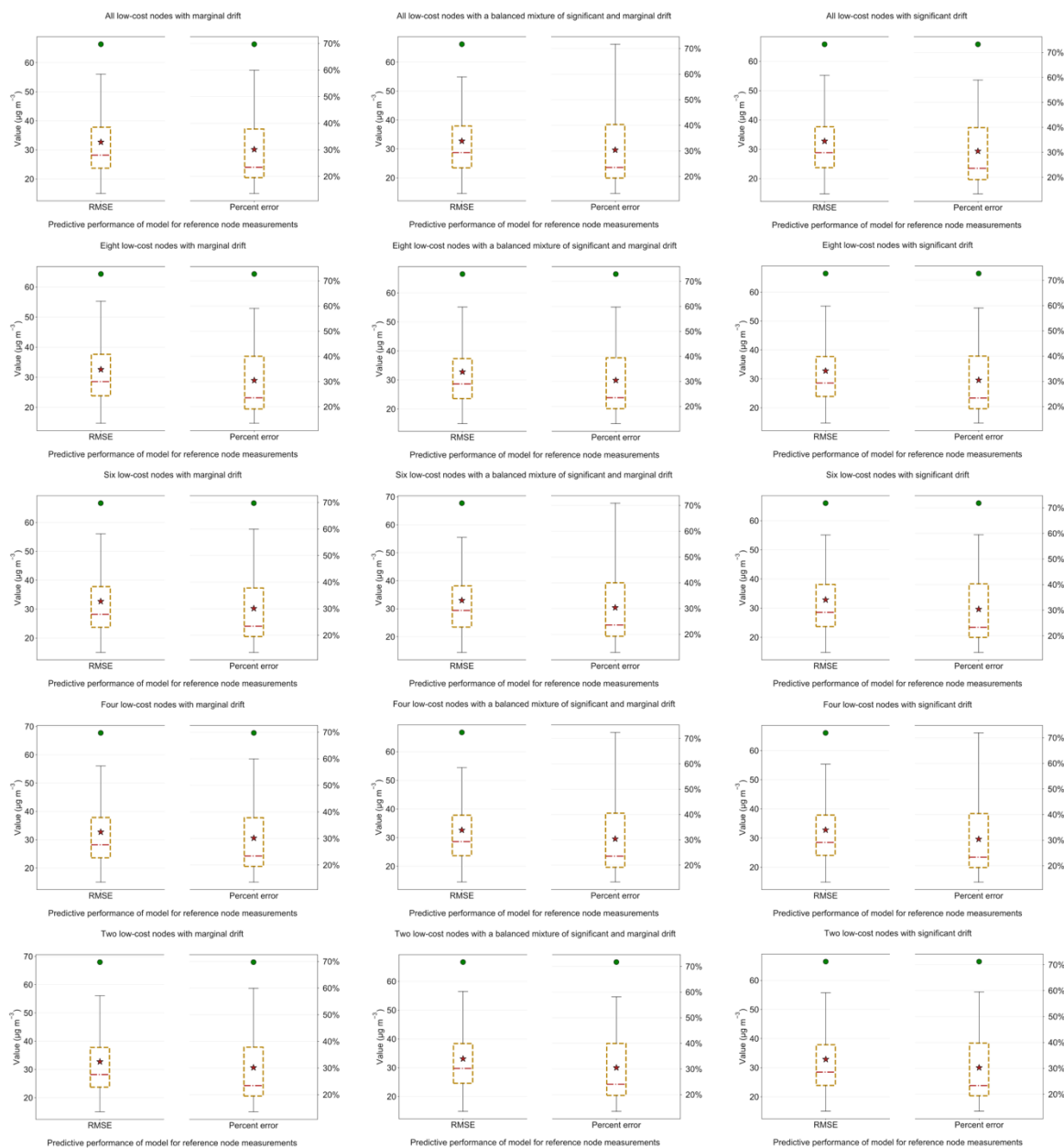
**Figure S2:** Simplified illustration of the relative importance (i.e., importance normalized by the max value) of each node within the network when using GPR to calibrate the target low-cost node and when all the nodes used for calibration are equally distant from the target node.



**Figure S3: Box plots of the learned optimum Gaussian Process Regression model parameters including the signal variance ( $\sigma_{sig}^2$ ), the characteristic length scale ( $l$ ), and the noise variance ( $\sigma_{noise}^2$ ) from the 22-fold leave-one-out cross-validation. The mean and SD of each parameter are superimposed on the box plots.**



**Figure S4: Gaussian Process Regression model 24 h performance scores (including RMSE and percent error) for predicting the measurements of the 22 holdout reference nodes across the 22-fold leave-one-out cross-validation using the full sensor network, when measurements of all (top left), nine (top center), seven (top right), three (bottom left), one (bottom center), and zero (bottom right) of the low-cost nodes are replaced with random integers bounded by the min and max of the true signals reported by the corresponding low-cost nodes.**



**Figure S5: Gaussian Process Regression model 24 h performance scores (including RMSE and percent error) for predicting the measurements of the 22 holdout reference nodes across the 22-fold leave-one-out cross-validation using the full sensor network, when measurements of two (bottom/1<sup>st</sup> row), four (2<sup>nd</sup> row), six (3<sup>rd</sup> row), eight (4<sup>th</sup> row), and all ten (top/5<sup>th</sup> row) of the low-cost nodes developed significant (11 %–99 %, left column), marginal (1 %–10 %, right column), and a balanced mixture of significant and marginal drifts. Note the sensors that drifted, the percentages of drift, and which sensors drifted significantly or marginally are randomly chosen. The results reported under each scenario are based on averages of 10 simulation runs.**

**Table S1: Comparison of the GPR model 24 h prediction percent errors for the 22 reference nodes across the 22-fold leave-one-out CV with and without interpolating the missing 1 h PM<sub>2.5</sub> values for all the reference and low-cost stations.**

Reference nodes	Percent error	
	with interpolation	without interpolation
<u>Anand Vihar</u>	<u>32 %</u>	<u>31 %</u>
<u>Aya Nagar</u>	<u>38 %</u>	<u>37 %</u>
<u>Burari Cross</u>	<u>39 %</u>	<u>38 %</u>
<u>CRRI Mathura Road</u>	<u>21 %</u>	<u>21 %</u>
<u>DTU</u>	<u>36 %</u>	<u>35 %</u>
<u>Faridabad</u>	<u>18 %</u>	<u>17 %</u>
<u>IGI Airport Terminal-3</u>	<u>32 %</u>	<u>32 %</u>
<u>IHBAS, Dilshad Garden</u>	<u>41 %</u>	<u>42 %</u>
<u>ITO</u>	<u>14 %</u>	<u>12 %</u>
<u>Lodhi Road</u>	<u>41 %</u>	<u>39 %</u>
<u>Mandir Marg</u>	<u>14 %</u>	<u>13 %</u>
<u>North Campus</u>	<u>24 %</u>	<u>24 %</u>
<u>NSIT Dawarka</u>	<u>19 %</u>	<u>20 %</u>
<u>Punjabi Bagh</u>	<u>20 %</u>	<u>20 %</u>
<u>Pusa</u>	<u>70 %</u>	<u>69 %</u>
<u>R K Puram</u>	<u>20 %</u>	<u>20 %</u>
<u>Sector125 Noida</u>	<u>23 %</u>	<u>21 %</u>
<u>Sector62 Noida</u>	<u>60 %</u>	<u>60 %</u>
<u>Shadipur</u>	<u>22 %</u>	<u>22 %</u>
<u>Sirifort</u>	<u>18 %</u>	<u>16 %</u>
<u>US Embassy</u>	<u>18 %</u>	<u>18 %</u>
<u>Vasundhara, Ghaziabad</u>	<u>44 %</u>	<u>34 %</u>
<u>Delhi-wide mean</u>	<u>30 %</u>	<u>29 %</u>
<u>SD</u>	<u>14 %</u>	<u>15 %</u>



**Table S2:** Comparison of pre-determined percentages of drift to those estimated from the Gaussian Process Regression model for intercept and slope, respectively, for each individual low-cost node, assuming eight and four of the low-cost nodes developed various degrees of drift such as significant (11 %–99 %), marginal (1 %–10 %), and a balanced mixture of significant and marginal. Note the sensors that drifted, the percentages of drift, and which sensors drifted significantly or marginally are randomly chosen. The results reported under each scenario are based on averages of 10 simulation runs.

Drift category	Low-cost nodes	Eight low-cost nodes drift				Four low-cost nodes drift			
		Intercept drift (%)		Slope drift (%)		Intercept drift (%)		Slope drift (%)	
		True	Estimated	True	Estimated	True	Estimated	True	Estimated
Significant	AIIMS	55 %	54 %	55 %	55 %	0 %	-2 %	0 %	0 %
	Hiran Kudna	57 %	43 %	54 %	56 %	47 %	42 %	54 %	54 %
	IITD	68 %	70 %	61 %	61 %	0 %	-1 %	0 %	-1 %
	IITM	0 %	-2 %	0 %	-1 %	0 %	-2 %	0 %	-1 %
	Kaushambi	0 %	-1 %	0 %	-1 %	0 %	-1 %	0 %	-1 %
	MRU	45 %	46 %	52 %	51 %	0 %	-4 %	0 %	1 %
	Mayur Vihar	56 %	59 %	48 %	47 %	42 %	44 %	57 %	56 %
	Naraina Vihar	63 %	61 %	57 %	57 %	51 %	51 %	48 %	48 %
	New Friends Colony	53 %	53 %	57 %	57 %	70 %	71 %	39 %	38 %
	S.D.A. Park	55 %	50 %	55 %	56 %	0 %	-4 %	0 %	2 %
Mean absolute difference		3 %		1 %		2 %		1 %	
50 % significant and 50 % marginal	AIIMS	0 %	-1 %	0 %	-1 %	0 %	-1 %	0 %	-1 %
	Hiran Kudna	47 %	40 %	58 %	58 %	0 %	-9 %	0 %	3 %
	IITD	57 %	62 %	58 %	57 %	0 %	0 %	0 %	-2 %
	IITM	6 %	5 %	6 %	3 %	4 %	3 %	7 %	6 %
	Kaushambi	4 %	4 %	5 %	1 %	0 %	0 %	0 %	-2 %
	MRU	47 %	54 %	55 %	53 %	0 %	-1 %	0 %	-1 %
	Mayur Vihar	56 %	62 %	46 %	43 %	44 %	48 %	70 %	68 %
	Naraina Vihar	5 %	3 %	4 %	3 %	58 %	56 %	46 %	47 %
	New Friends Colony	6 %	7 %	6 %	2 %	5 %	6 %	6 %	3 %
	S.D.A. Park	0 %	-3 %	0 %	1 %	0 %	-3 %	0 %	2 %
Mean absolute difference		3 %		2 %		2 %		2 %	
Marginal	AIIMS	5 %	6 %	4 %	3 %	0 %	0 %	0 %	-1 %
	Hiran Kudna	6 %	6 %	7 %	6 %	0 %	0 %	0 %	0 %
	IITD	6 %	7 %	6 %	4 %	0 %	1 %	0 %	-1 %
	IITM	5 %	5 %	5 %	4 %	0 %	0 %	0 %	-1 %
	Kaushambi	5 %	5 %	5 %	4 %	5 %	6 %	7 %	6 %
	MRU	7 %	9 %	4 %	2 %	7 %	8 %	5 %	4 %
	Mayur Vihar	0 %	1 %	0 %	-1 %	6 %	7 %	4 %	3 %
	Naraina Vihar	6 %	7 %	6 %	5 %	0 %	0 %	0 %	-1 %
	New Friends Colony	0 %	1 %	0 %	-2 %	0 %	1 %	0 %	-1 %
	S.D.A. Park	5 %	6 %	4 %	3 %	7 %	7 %	5 %	4 %
Mean absolute difference		1 %		1 %		1 %		1 %	