Calibration techniques and performance evaluation of low-cost air pollution monitors at regulatory air monitoring sites

Clean Air Toolbox for Cities

Chang Wang[a], Daniel M. Westervelt[a,b], V. Faye McNeill[c]

[a]Lamont-Doherty Earth Observatory, Columbia University. Palisades, New York, USA
[b]Goddard Institute for Space Studies [c]Columbia University Department of Chemical Engineering

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Correspondnece to: Dan Westervelt, Ph.D.
danielmw@ldeo.columbia.edu

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute

1. Introduction

- Low cost sensors for air quality monitoring are revolutionizing air pollution data acquisition and dissemination
- There are many sensors available on the market, but quality varies
- **In order to trust these simple devices for widespread air quality data use, they must be properly evaluated and calibrated**
- Collocating the sensors against Federal Equivalent Method (FEM) instrumentation can be used for calibration
- Without correction/calibration, raw low cost sensor data should only be used for qualitative or comparative interest

2. Particulate matter instrumentation

Federal Equivalent Method (FEM)

Figure 1: Met-One BAM-1020

Figure 2: Teledyne T640

Figure 3: TEOM 1405DF

Optical (low cost) sensor:

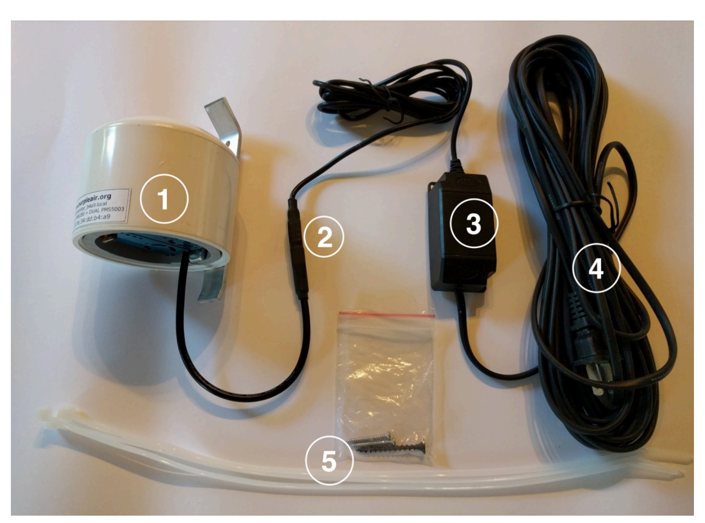

Figure 4: PurpleAir PA-II

Careful calibration/correction with FEM instrumentation is necessary

- Scattered light is measured and converted to particle mass concentration (requires assumptions about size distribution and shape of particles)
- Conversion algorithm is proprietary
- Indirect measurement of particle mass
- Cannot distinguish small particles (less than 300 nm)
- Reports data at ambient conditions
- Ambient humidity causes hygroscopic particle growth, altering light scattering coefficients

3. Past performance evaluation

- Many vendors with a big range in cost, quality, connectivity, etc.
- Reliability varies with temperature, humidity, pollutant mixture, sensor age
- Promising, but largely untested
- Validation frameworks are nascent
- Cost of sensor does not predict quality

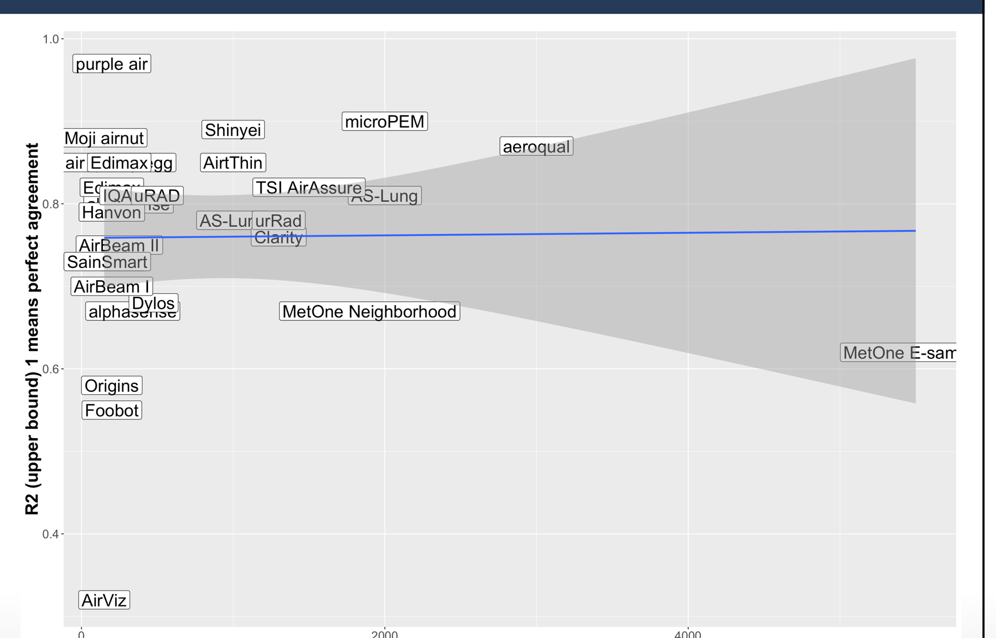

Figure 5: r^2 against FEM instrumentation versus cost for many low-cost sensors

4. Collocation at NYSDEC air monitoring sites

Figure 6: Left to Right: Queens Ncore (background) air monitoring site, Queens Near Road air monitoring site, Purple Air PA-II mounted at Queens Near Road, and map of sites

Collocations of PurpleAir PA-II at two monitoring sites:

- Queens NCore (urban background site)
  - Collocation occurred in April-May 2019
  - $PM_{2.5}$ measured by TEOM, Teledyne, and FRM (gravimetric)
  - NO_x, NO_y, BC, CO, O_3 Particle Number
- Queens Near Roadway (NR, source-influenced site)
  - Collocation from July to November 2019
  - $PM_{2.5}$ via TEOM

5. Performance evaluation of raw PurpleAir data

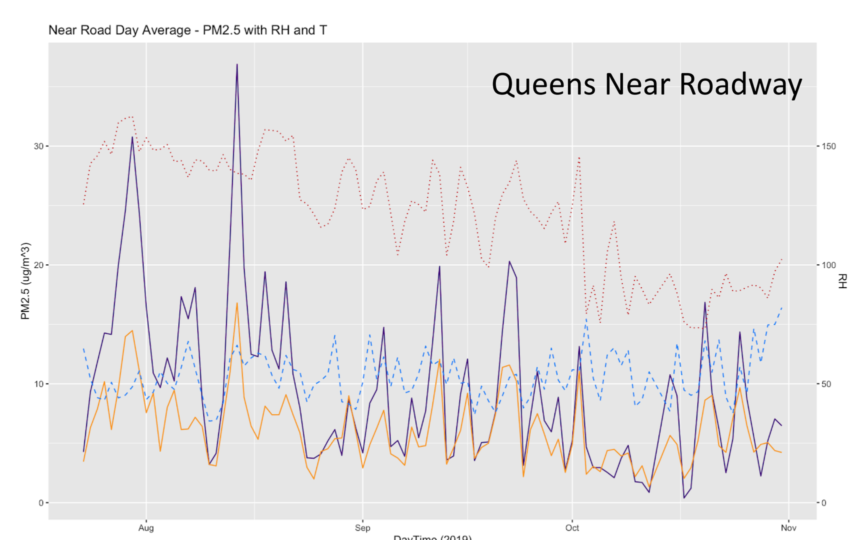

Figure 7: Daily mean $PM_{2.5}$ from PurpleAir (as reported), TEOM, RH, and T at the Queens NR site

- Raw Purple Air $PM_{2.5}$ at the Queens NR site is strongly correlated with TEOM $PM_{2.5}$ (Spearman r = 0.895)
- PurpleAir $PM_{2.5}$ is biased slightly high (mean bias = xx μg m^{-3})
- High RH explains some of the high bias in PurpleAir $PM_{2.5}$

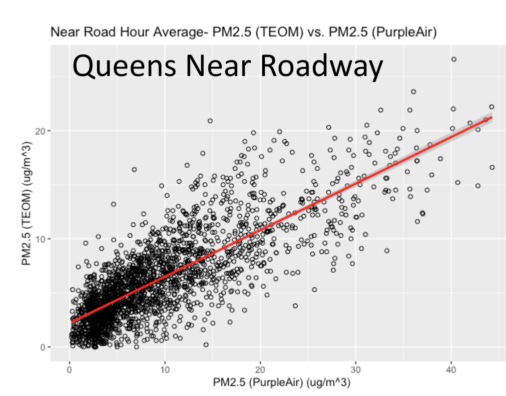

Figure 8: Scatterplot of hourly mean PM2.5 at Queens NR

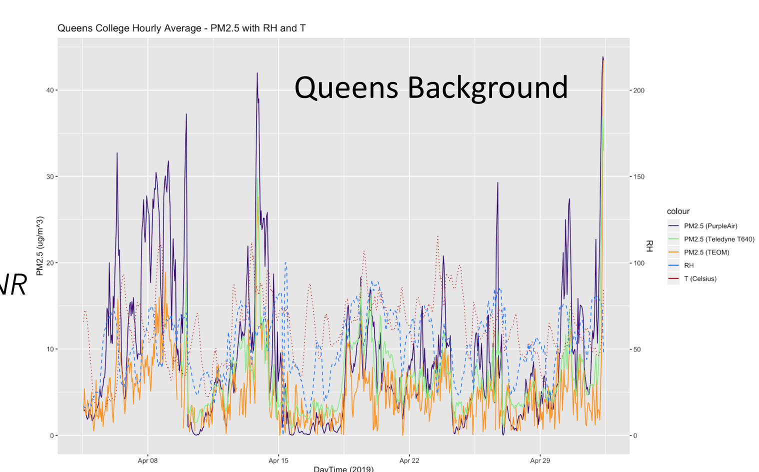

Figure 9: Hourly mean $PM_{2.5}$ from PurpleAir (as reported), TEOM,Teledyne, RH, and T at the Queens Background site

- Raw Purple Air $PM_{2.5}$ at the Queens background site is strongly correlated with TEOM $PM_{2.5}$ (Spearman r = 0.895) and Teledyne T640 (r = xx)
- PurpleAir $PM_{2.5}$ is biased slightly high (mean bias = xx μg m^{-3} TEOM, xx Teledyne)

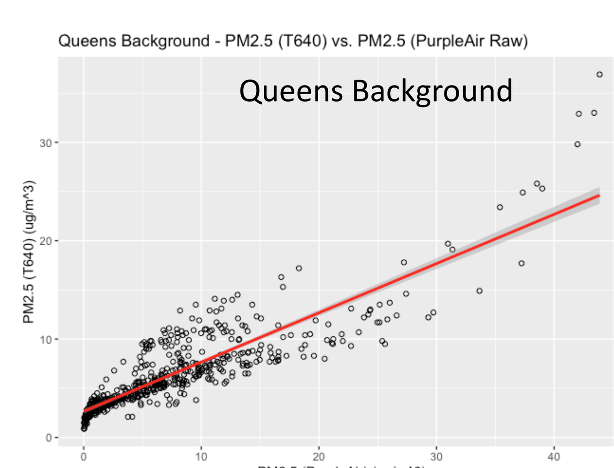

Figure 10: Scatterplot of hourly mean PM2.5 at Queens Background

6. Correction/Calibration towards FEM

$$[\text{corrected PM}_{2.5}] = \begin{cases} \beta_0 + \beta_1[\text{PPA PM}_{2.5}] + \beta_2 T + \beta_3 RH + \beta_4 \text{DP}(T,RH) & \text{if } [\text{PPA PM}_{2.5}] > 20\ {}^{\mu g}/_{m^3} \\ \gamma_0 + \gamma_1[\text{PPA PM}_{2.5}] + \gamma_2 T + \gamma_3 RH + \gamma_4 \text{DP}(T,RH) & \text{if } [\text{PPA PM}_{2.5}] \le 20\ {}^{\mu g}/_{m^3} \end{cases}$$

- Multiple linear regression correction method as described in Malings et al. (2019)
- Variables: raw PurpleAir $PM_{2.5}$, Temperature, Relative Humidity, and Dew Point

	ß0 / γ0	ß1 / γ1	ß2 / γ2	ß3 / γ3	ß4 / γ4
NR >20	36.7	0.46	-0.56	-0.38	0.50
NR <20	15.3	0.52	-0.24	-0.16	0.23
QB >20	39.2	0.86	-1.16	-0.77	1.44
QB <20	8.02	0.34	-0.13	-0.13	0.21

Table 1: Regression coefficients

	Spearman r	MAE (μg m^{-3})
Raw-NR	0.801	4.02
Corr-NR	0.817	1.83
Raw-QB	0.757 (0.88)	5.01 (3.02)
Corr-QB	0.849 (0.87)	1.65 (2.04)

Table 2: Summary statistics of correlation and mean absolute error between PurpleAir and TEOM at each site. Teledyne in parenthesis

- Mean absolute error (MAE) improves by with MLR correction model by 55% at NR and 67% at QB

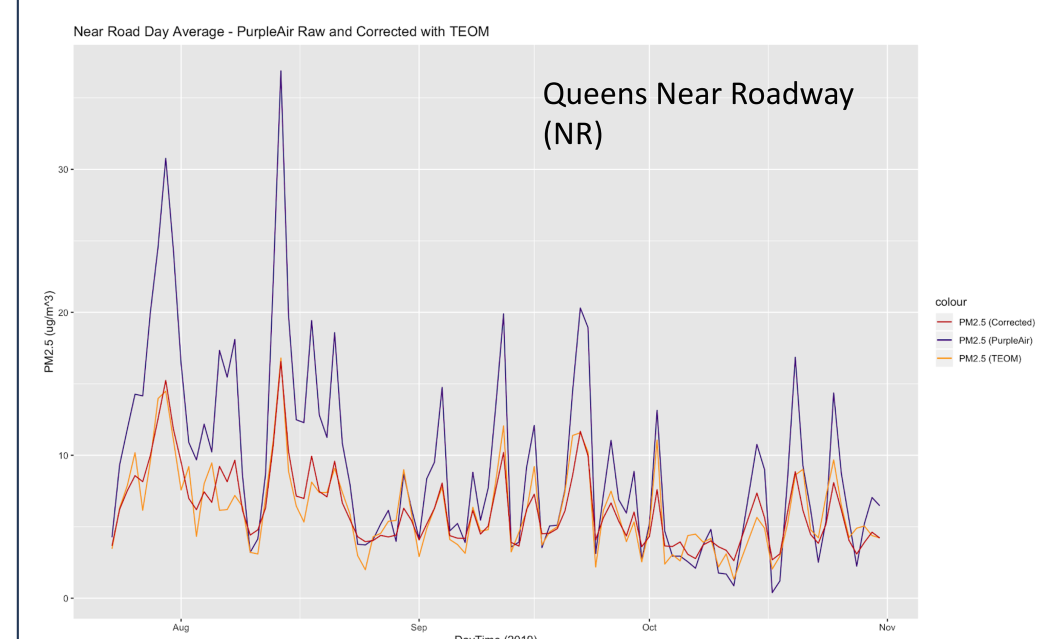

Figure 11: Daily mean $PM_{2.5}$ at Queens NR including corrected PurpleAir

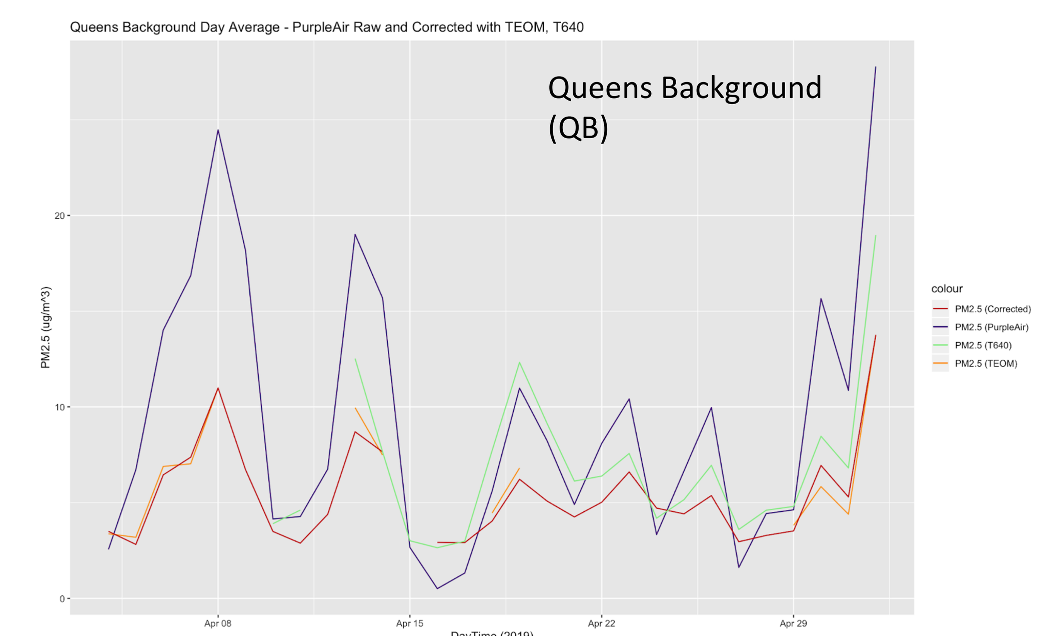

Figure 12: Daily mean $PM_{2.5}$ at Queens Background including corrected PurpleAir

7. Applying techniques in highly polluted environments

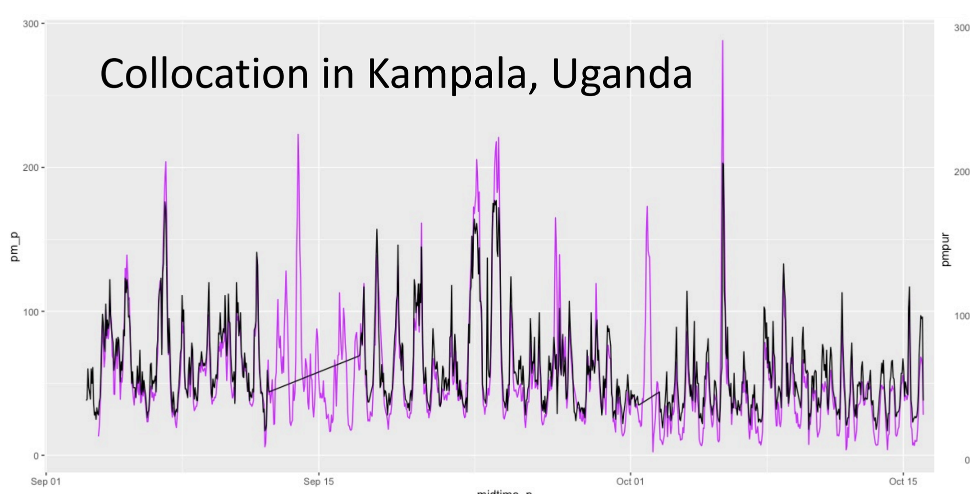

Figure 13: Comparison of collocated PurpleAir data (purple) and BAM-1020 PM2.5 at the US Embassy in Kampala, Uganda

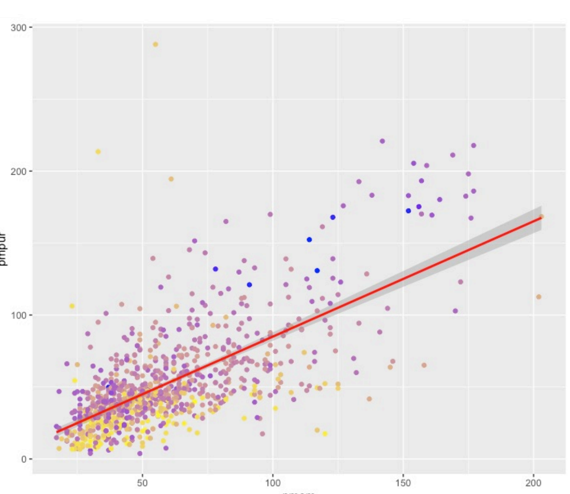

Figure 14: Scatterplot of PM2.5 data at the US Embassy in Kampala

- PurpleAir PM2.5 is biased high in Kampala, likely due to high relative humidity

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- Pilot projects and collocations underway in Kampala, Accra, Nairobi, Kinshasa, Lomé, and Brazzaville

8. Summary and conclusions

- Raw PurpleAir $PM_{2.5}$ is highly correlated with FEM observations at many locations
- Collocations and calibration factors can significantly improve PurpleAir mean absolute bias compared to TEOM or Teledyne (4 to 1.8 μg m^{-3} at NR, 5.01 to 1.65 μg m^{-3} at QB
- Low cost sensors can revolutionize air quality data and spur regulatory action; however, careful long-term local collocation with FEM instrumentation, correcting for optical sensor bias and drift, are necessary for the data to be quantitatively trustworthy