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Helping our world work better

ASTM Standards for the Performance Evaluation of Outdoor Air Quality Sensors

Geoff Henshaw, Aeroqual Ltd

Who is ASTM International ?

- ASTM is a global organisation for the development of voluntary consensus standards.
- Founded in 1898 by Charles B. Dudley a chemist with the Pennsylvania Railroad.
- Every member/interest has an equal say in the activity: manufacturers, users, consumers, consultants, Government agencies.
- Membership includes over 30,000 of the world's leading technical experts
- More than 12,500 standards published
- Membership fees: $75 pa individual

ASTM Consensus Process

- All members have the opportunity (and a
  encouraged) to provide input.
- All responses must be considered and
  resolved by the technical committee.
- The process strongly supports private and
  public sector cooperation.
- Technical committees meet twice per yea
  in Spring and Fall.

ASTM Committee D22- Air Quality

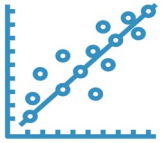
450 members, 175 active standards, 9 Subcommittees

D22.01	Quality Control
D22.03	Ambient Atmospheres and Source Emissions
D22.04	Workplace Air Quality
D22.05	Indoor Air
D22.07	Sampling and Analysis of Asbestos
D22.08	Analysis of Microorganisms
D22.11	Meteorology
D22.12	Sampling and Analysis of Lead
D22.13	Compressed Air Quality

Why do we need performance standards for air sensors ?

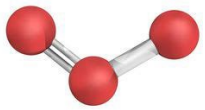
- Provide users with a reliable way of comparing the performance of commercially available air sensors.
- Provide manufacturers and developers with performance targets to aim for.
- Provide users with information to set their data quality expectations from sensors.
- Inform agencies and regulators of the evolving performance of sensors

WK64899 Practice for the Performance Evaluation of Ambient Outdoor Air Quality Sensors and Sensor-based Instruments for Portable and Fixed-Point Measurements



Establishes standardized laboratory and field tests for evaluating outdoor air quality sensors.

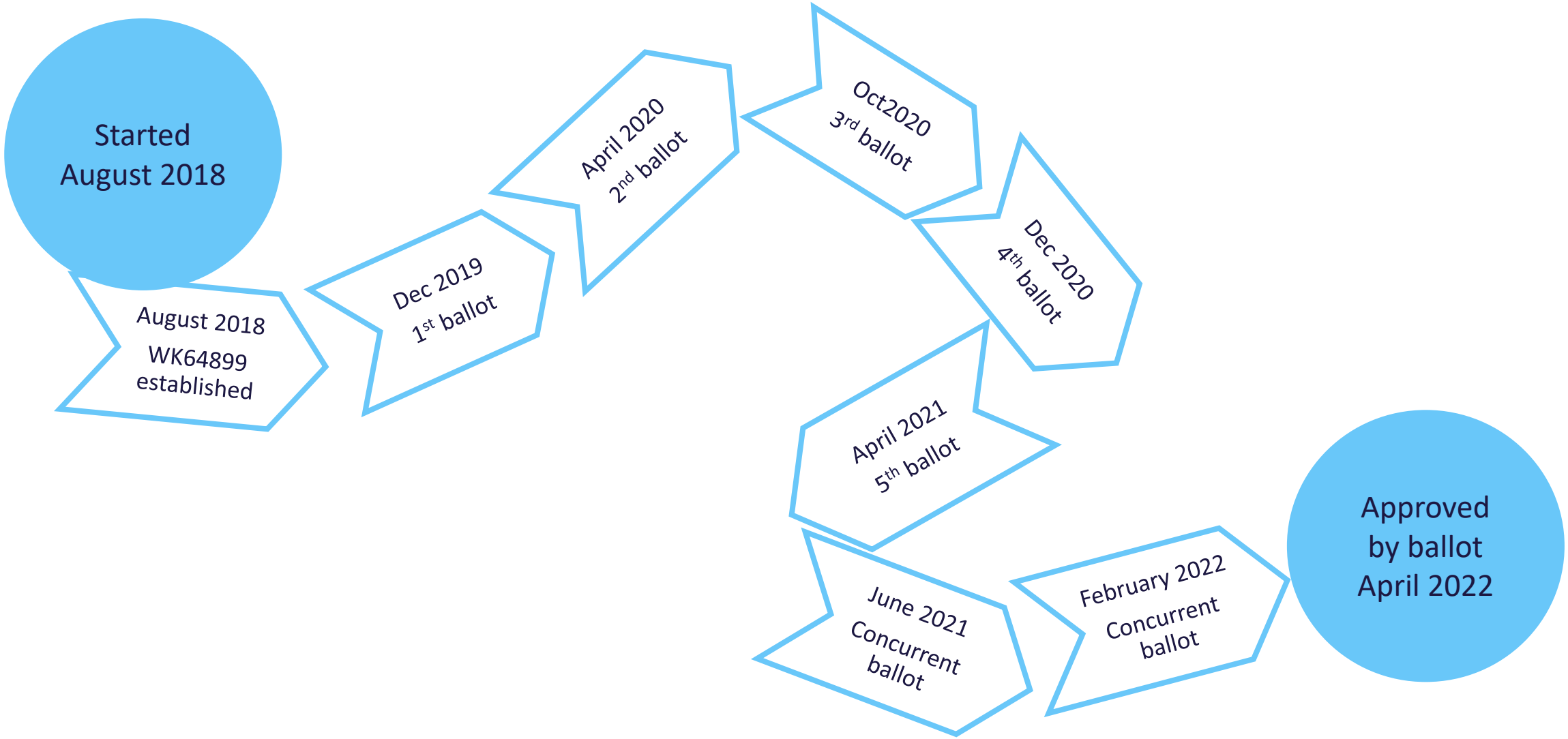
Technology agnostic - except does not apply to remote measurement technologies, such as open path, lidar or imaging technology.



Focus on six ambient pollutants: $PM_{2.5}$, PM_{10}, SO_2, O_3, CO and NO_2

Testing is to be performed by a competent entity (eg ISO 17025 certified)

ASTM WK64899 timeline



Laboratory tests

- Laboratory tests are done prior to the field tests.
- Tests are performed on two identical units and treated independently.

Gases: O_3, NO_2, CO, SO_2

Reference: Test gases and FEM analyzers

- Lack of fit (Linearity test)
- Zero repeatability
- Span repeatability
- Lower detection limit
- Short term drift at zero and span
- Temperature sensitivity
- Cross-interferences at zero and span

Particles: $PM_{2.5}$ and PM_{10}

Reference: Monodisperse aerosols and FEM PM instruments

- Lack of fit (Linearity test)
- Zero repeatability
- Span repeatability
- Lower detection limit
- Short term drift at zero and span

Laboratory tests

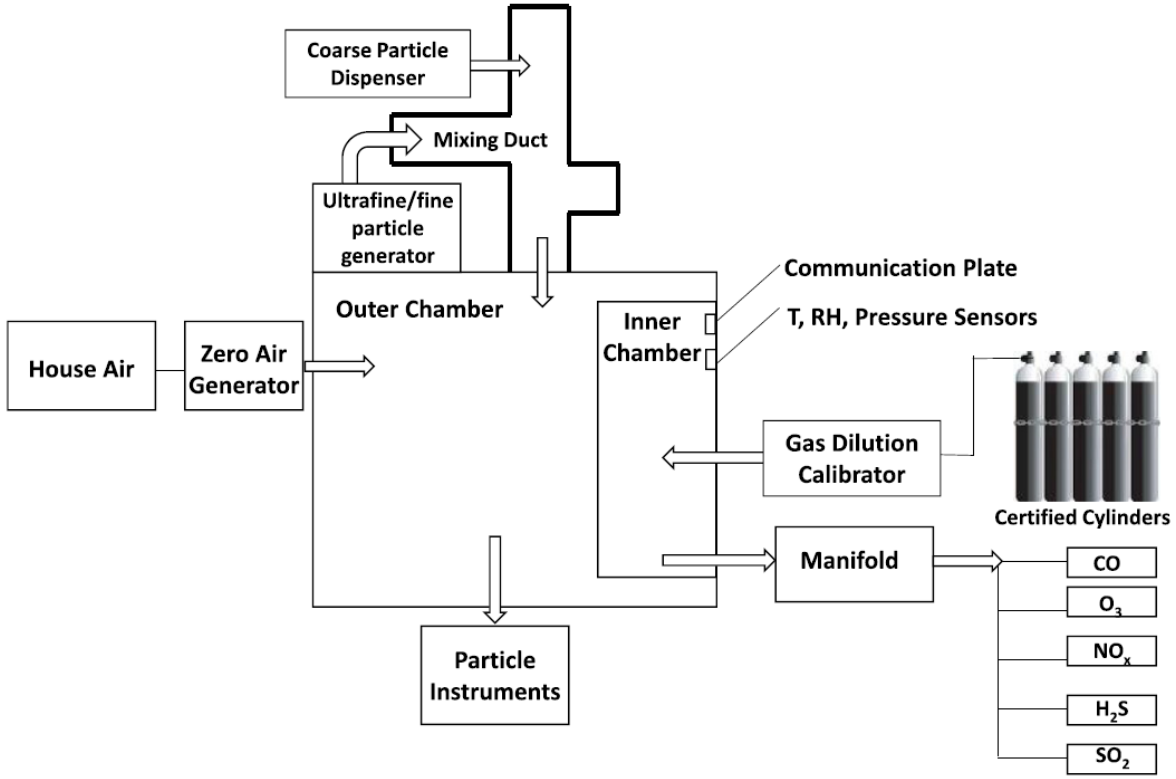
Laboratory testing requires an environmental test chamber with control of temperature and humidity.

Atmospheric Environment, Vol 171, (2017), p82-90

Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions

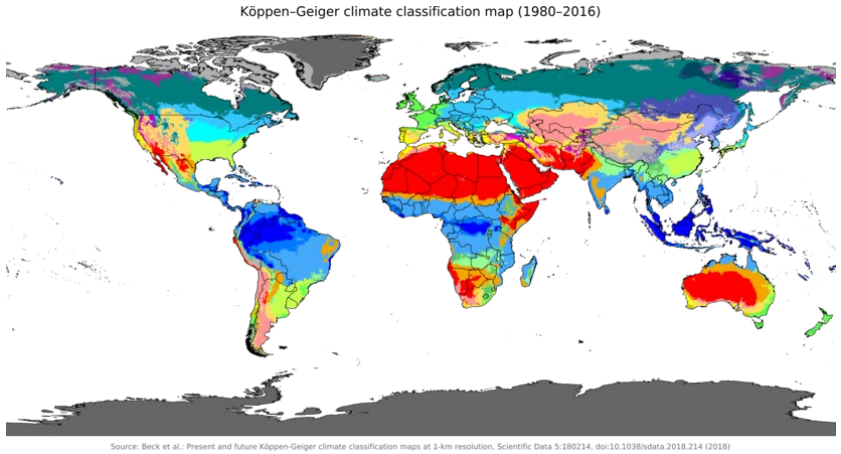
Vasileios Papapostolou, Hang Zhang, Brandon J. Feenstra, Andrea Polidori*

South Coast Air Quality Management District, Diamond Bar, CA 91765, USA



Field tests

- The six week field test is undertaken at two test sites with different primary climate types.
- Two identical units are tested.
- One week calibration period prior to the start of the test.



Gases: O_3, NO_2, CO, SO_2

- Field reproducibility
- Data capture rate
- Field comparability (hourly)
  - r^2, slope, bias, MAE, RMSE, nRMSE

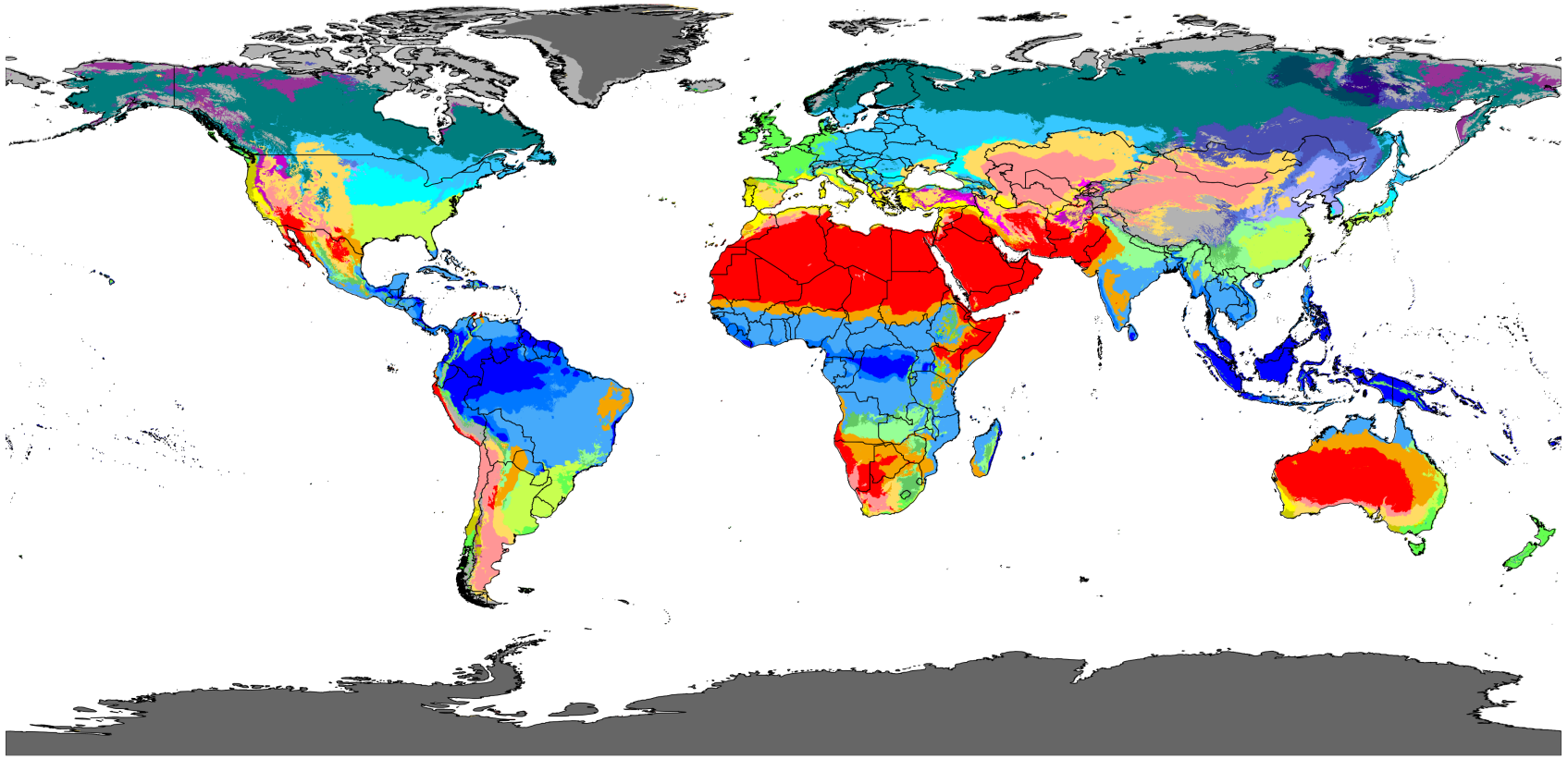
Particles: $PM_{2.5}$ and PM_{10}

(>30% PM coarse required for PM_{10})

- Field reproducibility
- Data capture rate
- Field comparability (24-hourly)
  - r^2, slope, bias, MAE, RMSE, nRMSE

Köppen Climate Classification

Köppen–Geiger climate classification map (1980–2016)



Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

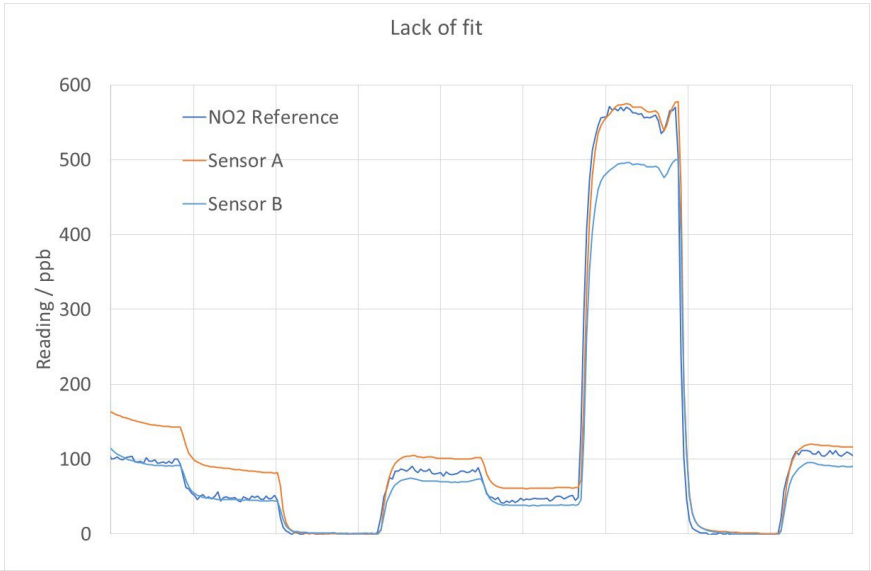
Laboratory test – Lack of fit: NO_2 sensors

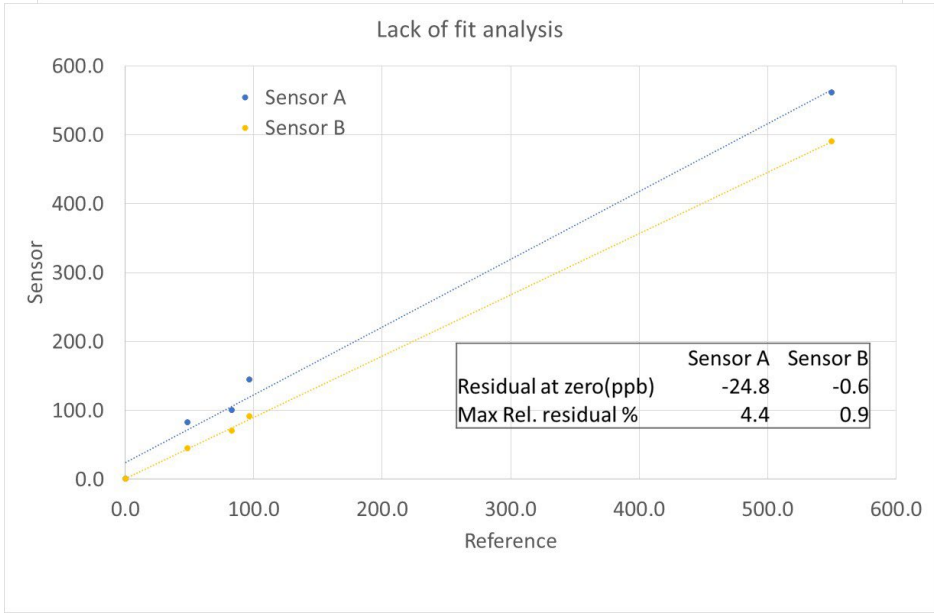
Lack of fit is an indication of how well the sensor measurements fit a linear response curve.

The residual at zero (r_z) and the maximum relative residual (r_{max}) are the two parameters calculated from a 5 point concentration curve.

Example of two different NO_2 sensors

	sensor A1	sensor B1
r_Z	-24.8 ppb	-0.6 ppb
r_{max}	4.4 %	0.9%





Laboratory test -Temperature response: NO_2 sensors

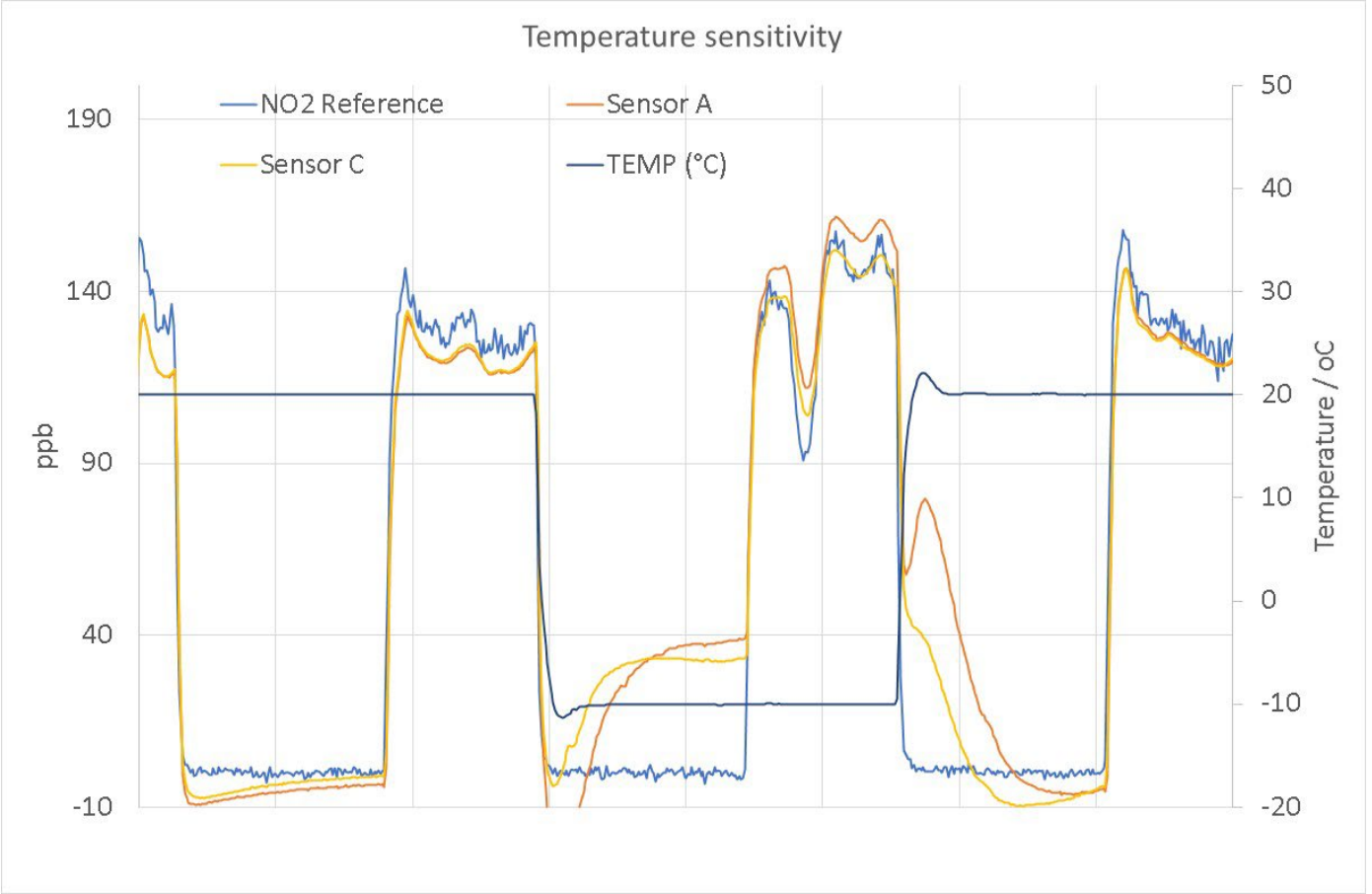
Calculates the effect of temperature on gas response

$$b_{temp} = \left| \frac{(C_2 - C_1)}{(T_2 - T_1)} \right|$$

Test performed at constant dewpoint.

It was observed that many electrochemical sensors show a transient response to a step change in temperature so a wait time has been included.

Sensor A1: 0.8 ppb/^{o}C
Sensor B1: 0.9 ppb/^{o}C



Field test : O_3 sensor

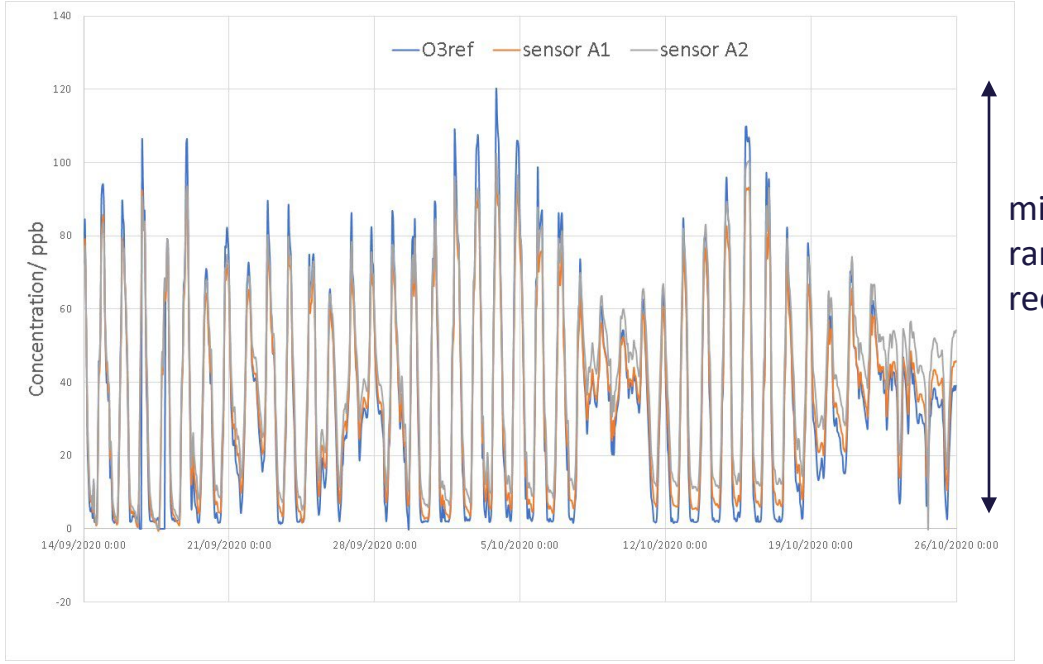
Field test location: CA Koppen classification: C

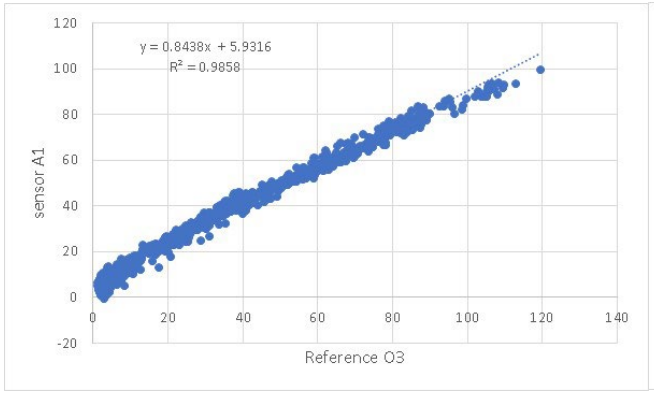
Field reproducibility between sensors

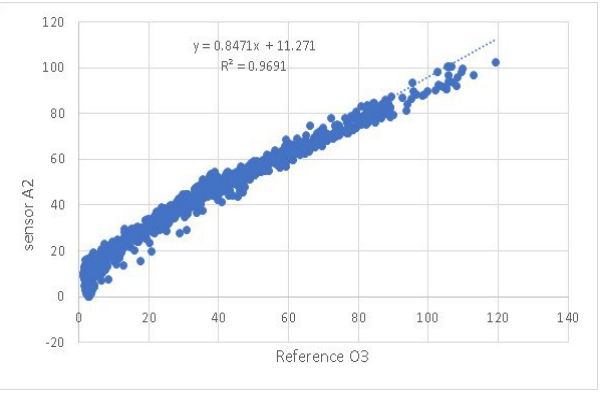
$$S_{r,f} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_{1,i}-X_{2,i})^2}{2n}}}{c} \times 100$$ (hourly average) : 11.9%

sensor A1 :	r2	0.986
	slope	0.844
	bias	5.9 ppb
	MAE	4.2 ppb
	RMSE	5.5 ppb
	%data capture	100%
sensor A2: r2		0.969
	slope	0.847
	bias	11.3
	MAE	7.5 ppb
	RMSE	8.5 ppb
	% data capture	100%

6 week time series of hourly values







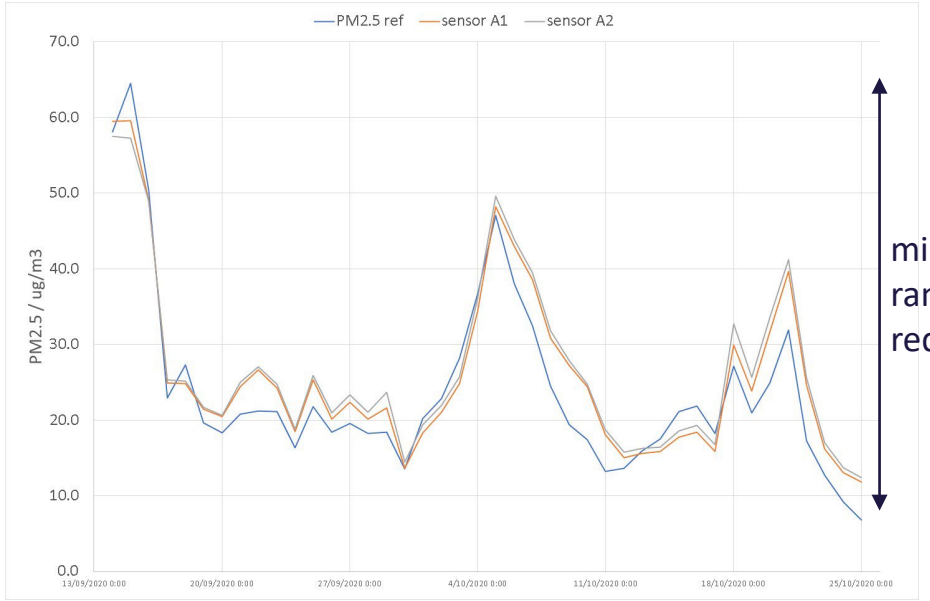
Field test: $PM_{2.5}$ sensor

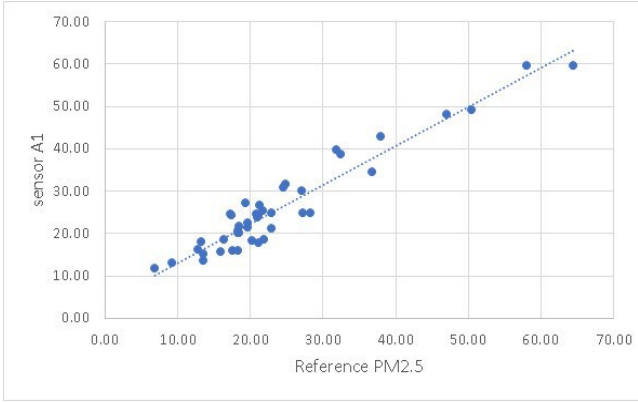
Field test location: CO Koppen classification: D

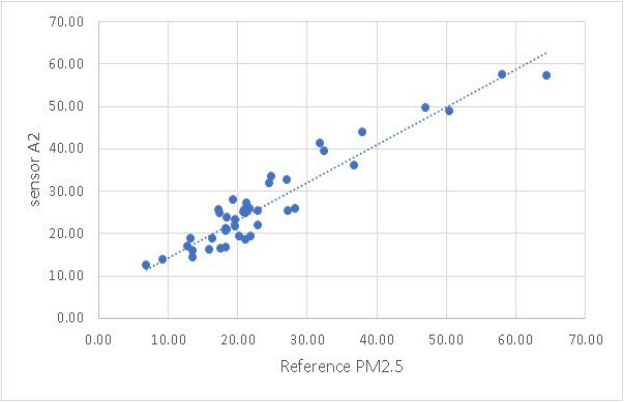
Field reproducibility (24 hr average): 3.3 %

sensor A1 :	r2	0.920
	slope	0.920
	bias	4.0 ug/m3
	MAE	3.4 ug/m3
	RMSE	4.0 ug/m3
	%data capture	100%
sensor A2: r2		0.905
	slope	0.889
	bias	5.4 ug/m3
	MAE	3.9 ug/m3
	RMSE	4.6 ug/m3
	% data capture	100%

6 week time series of 24 hour values







WK74812 Specification for Ambient Outdoor Air Quality Sensors and Sensor based instruments for Portable and Fixed Point Measurement.

- Establishes performance criteria for ambient outdoor air quality sensors based on the evaluation described in WK64899.
- Status: First draft submitted for discussion by Work Committee. Expect first ballot by October 2022.
- Designates 3 levels of performance (c.f CEN/TS 17660-1) for gas and PM sensors
- Classification is based on lowest result achieved by any of the test sensors.
- Possible designation format as Class X.Y where X is the classification according to laboratory test results and Y is the classification according to field test.
- If a sensor measures multiple pollutants, each pollutant will get an independent classification.

X XXXX

A1.2 Specification for O_3, NO_2, SO_2

	Parameter	Class 1			Class 2			Class 3		
Laboratory Tests										
Lack of fit	r_z	5nmol/mol			10 nmol/mol			15 nmol/mol		
	r_{max}	5%			10%			10%		
	r^2	>0.95			>0.9			>0.8		
Zero Repeatability	S_0	1 nmol/mol			2 nmol/mol			5 nmol/mol		
Span Repeatability	S_s	3 nmol/mol			6 nmol/mol			10 nmol/mol		
Minimum Detection Limit	**MDL**	3nmol/mol			6 nmol/mol			15 nmol/mol		
Short Term Zero Drift	D_z	2 nmol/mol			4 nmol/mol			8 nmol/mol		
Short Term Span Drift	D_s	5%			10%			20%		
Temperature Sensitivity	b_{temp}	1 nmol/mol/°C			2 nmol/mol/°C			3 nmol/mol/°C		
		O_3	NO_2	SO_2	O_3	NO_2	SO_2	O_3	NO_2	SO_2
Cross-Interferences at Zero										
H_2O	$x_{int,z}$ (nmol/mol)	10	10	10	20	20	30	30	30	30
SO_2		5	5	-	10	10	-	20	20	-
NO_2		5	-	5	10	-	10	20	-	30
NO		5	5	5	10	10	10	20	20	30
O_3		-	5	5	-	10	10	-	20	30
CO		5	-	-	10	-	-	20	-	-
Cross-Interferences at Span										
H_2O	$x_{int,c}$ (nmol/mol)	10	10	10	20	20	30	30	30	30
SO_2		5	5	-	10	10	-	20	20	-
NO_2		5	-	5	10	-	10	20	-	20
NO		-	5	-	-	10	-	-	20	-
O_3		-	5	5	-	10	10	-	20	20
CO		5	-	-	10	-	-	20	-	-
Field Tests										
Sites 1 and 2										
Field Reproducibility	$S_{r,f}$	5%			10%			15%		
Data Capture Rate	**DCR**	>90%			>90%			>75%		
Field Comparability	**Intercept**	5 nmol/mol			10 nmol/mol			15 nmol/mol		
	slope	0.9 to 1.1			0.8 to 1.2			0.7 to 1.3		
	R^2	0.92			0.85			0.7		
	MAE	5 nmol/mol			10 nmol/mol			15 nmol/mol		
	RMSE	6 nmol/mol			11 nmol/mol			16 nmol/mol		
	nRMSE	0.1			0.2			0.3		

Other ASTM standards for air sensors

Outdoor

- WK72475 – *Practice* for Real-time Fugitive Dust Monitoring by Point Sampling on Construction and Other Industrial Sites

Indoor

- D8405 - *Test Method* for Evaluating $PM_{2.5}$ Sensors or Sensor Systems Used in Indoor Air Applications. Published 2021

- WK74360 - *Test Method* for Evaluating CO_2 Indoor Air Quality Sensors or Sensor Systems Used in Indoor Applications

Summary

- ASTM WK64899 is a standard practice for the evaluation of outdoor air sensors.
  - WK86899 comprises both laboratory and field test components.
  - A number of air sensors have been evaluated using the standard demonstrating its applicability to a wide range of sensor types.
  - WK64899 was approved by ASTM D22 committee ballot April 2022.
  - Publication will occur later this year.

- ASTM WK74812 is a specification for outdoor air sensors.
  - Criteria established for each test in WK64899.
  - Current draft has three classes of performance.
  - Estimated publication is 2023

Acknowledgements

- The 40 members of the ASTM WK64899 and WK74812 work committees (sensor manufacturers, air quality agencies, EPA, Env consultants, NGOs)
- Raul Dominguez, D22.03 chair
- South Coast AQMD and the AQ-SPEC programme for valuable feedback.
- US EPA and the Air Sensors workshops 2018/2019 which initiated conversations about performance validation of air sensors.

Questions ?

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