SECURE

ASSESSING LOW COST SENSORS

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Background: Atmospheric measurements

- **Optimal use of data and resource for air quality measurements**
- **A robust and reliable evidence base in the decision-making process**

1. Types of sensor
2. Types of cross-sensitivities
3. Types of confounding atmospheric and environmental properties
4. Where science should be heading?
5. Potential practical ways to cope with current technology (and developing technologies)
6. Which technologies in the future are likely to be most traceable?

Measurement and QC Frameworks: e.g. NO_2

- Global/WMO-GAW
- European research infrastructure
- European Long term monitoring
- European compliance monitoring
- National compliance monitoring (AURN)
- Local authority compliance monitoring (LAQN)
- Local authority and Agency AQ monitoring (other)
- Citizen science

Photolytic analysers;

- direct spectroscopic measurement
- Correction for inlet errors etc.
- Part of international calibration/round robins
- ACTRIS protocol daily calibration with traceable standard
- V. expensive/implementation variable

On-line chemiluminescence analysers

- Method defined by European compliance protocols
- Part of national calibration
- expensive

Off-line diffusion tubes

- Gas captured on coating, analysed in laboratory
- Methods defined by Working Groups
- Can be part of national intercomparison and bias correction
- Affordable but low resolutions (weeks)

On-line electrochemical sensors

- Gas-surface interactions = Voltage change
- Field testing underway
- New working group being established

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“Old technologies”: Possible reasons to move on

- Practical and economic constraints (e.g. cost and bulk of equipment), the use of automatic analysers is restricted to a limited number of roadside and background locations within a city.

- Localised air pollution hotspots may be overlooked or overemphasised when assessing regions, especially near heavily trafficked street canyons and intersections (Vardoulakis *et al.* doi:10.1016/j.atmosenv.2011.06.038)

- Large numbers of units not possible for model validation work

The 4 S's

Sensitivity

Selectivity

Stability

Suitability

Passive Metal Oxide Sensors

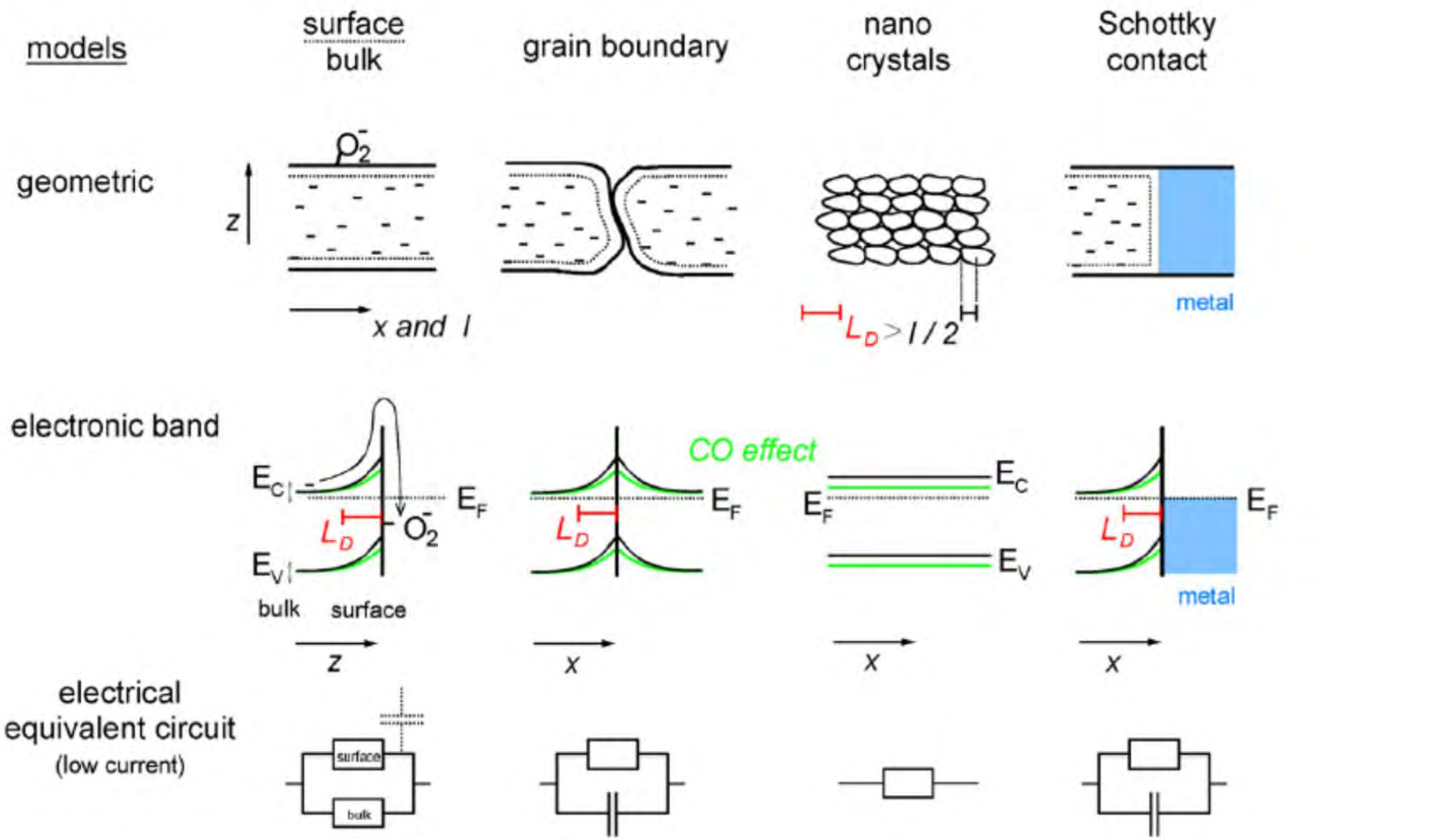

Fig. 6. Different conduction mechanisms and changes upon O_2 and CO exposure to a sensing layer in overview. This survey shows geometries, electronic band pictures and equivalent circuits. E_C minimum of the conduction band; E_V maximum of the valence band; E_F Fermi level; L_D Debye length. For details see [2].

N. Barsan et al. Sensors and Actuators B 121 (2007) 18–35

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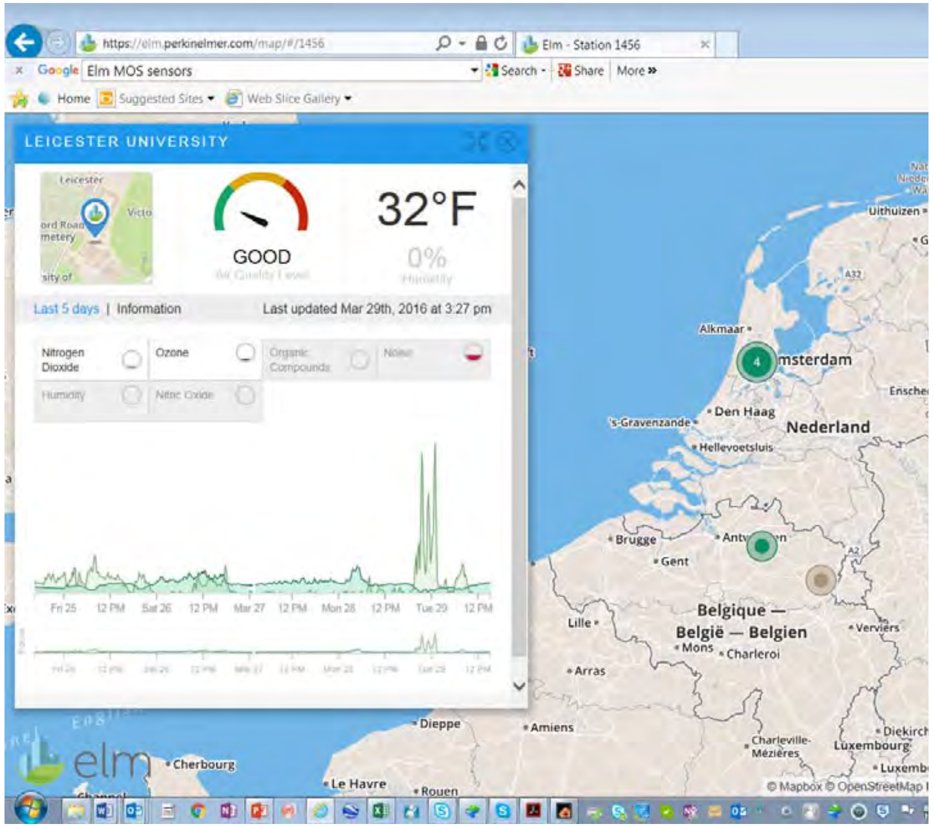
ELM (Perkin Elmer)



- **No** QA/QC or data analysis info on website

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1.What pollutants can Elm monitor?

2.Today, Elm can monitor ozone, particulates, volatile organic compounds, nitrogen dioxide, nitric oxide, noise, temperature, and humidity. In the future, Elm will monitor for other pollutants as well. Stay tuned to learn more.

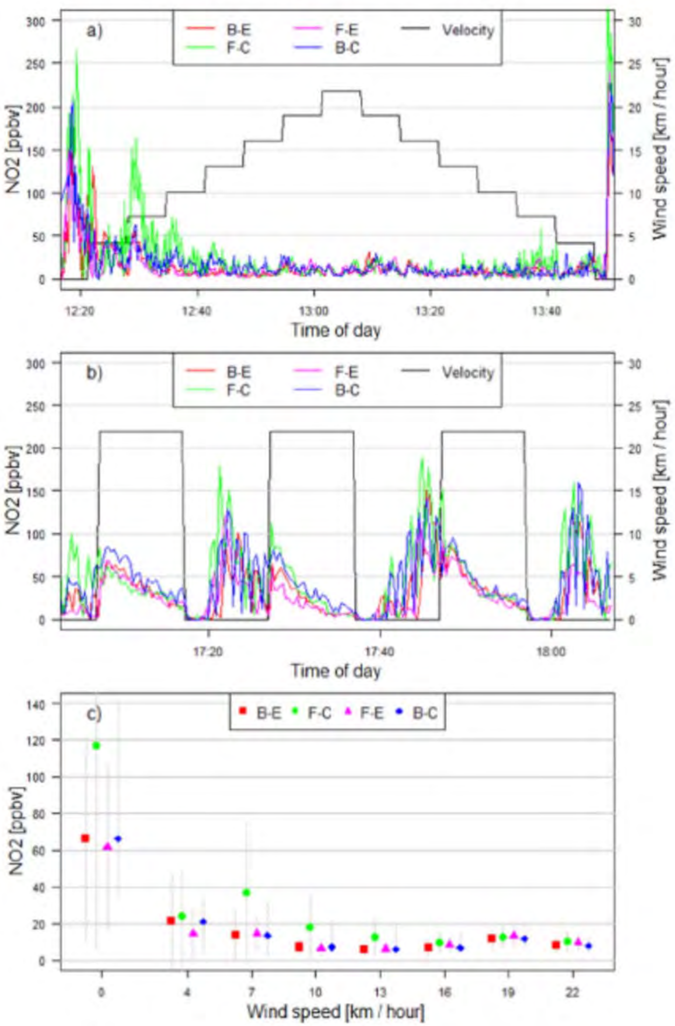
3.Does Elm data meet EPA standards for accuracy?

4.Elm is an indicative monitoring system that's complementary to existing EPA data stations and is meant to "fill in the gaps" and provide local information that matters. PerkinElmer continues to leverage its proven track record in EPA compliance, method development, and policy expertise to ensure that citizens can play an active role in understanding their air. We do this by understanding the data better than anyone and communicating it to everyone. Elm is not a federal reference method and does not provide data that should be used to determine regulatory compliance.

The effect of ego-motion on environmental monitoring

Lerner et al. Science of the Total Environment 533 (2015) 8–16

U. Lerner et al. / Science of the Total Environment 533 (2015) 8–16



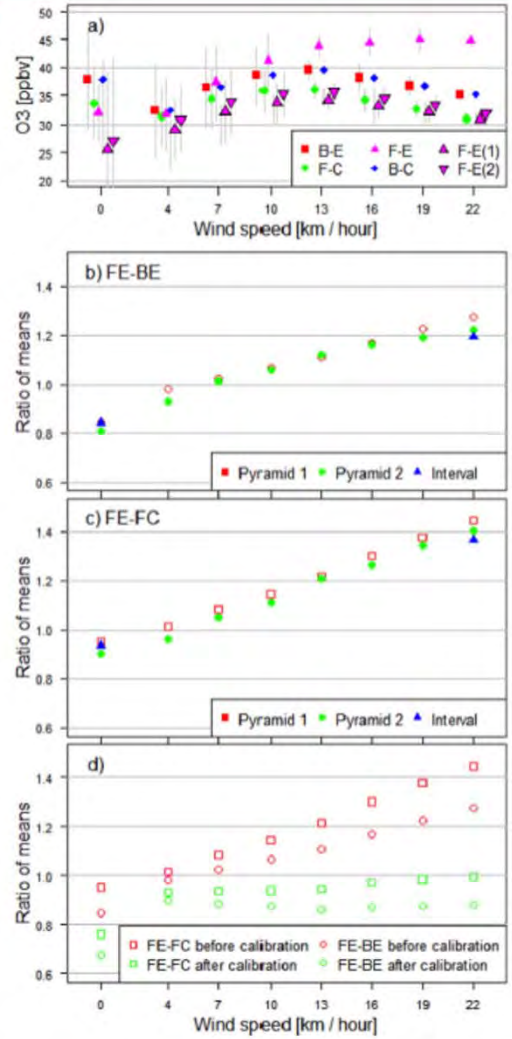


Fig. 4. O_3 wind tunnel measurements. (a) O_3 measured levels; and (b) F-E/B-E and (c) F-E/F-C ratios; (d) F-E/B-E and F-E/F-C before calibration (red squares and circles, respectively) and after (green, squares and circles correspondingly).

-the four units are marked as forward-exposed (F-E), forward-covered (F-C), backward-exposed (B-E) and backward-covered (B-C).

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ALPHASENSE: NO_2 sensor

PERFORMANCE			
	Sensitivity	nA/ppm at 2ppm NO_2	-160 to -320
	Response time	t_{90} (s) from zero to 2ppm NO_2	< 70
	Zero current	nA in zero air at 20°C	-25 to +50
	Noise*	±2 standard deviations (ppb equivalent)	12
	Range	ppm NO_2 limit of performance warranty	20
	Linearity	ppb error at full scale, linear at zero and 5ppm NO_2	< ±1
	Overgas limit	maximum ppm for stable response to gas pulse	50
	*** Tested with Alphasense ISB low noise circuit**		
LIFETIME	Zero drift	ppb equivalent change/year in lab air	0 to 20
	Sensitivity drift	% change/year in lab air, monthly test	-20 to -40
	Operating life	months until 50% original signal (24 month warranted)	> 24
ENVIRONMENTAL			
	Sensitivity @ -20°C	(% output @ -20°C/output @ 20°C) @ 2ppm NO_2	60 to 80
	Sensitivity @ 40°C	(% output @ 40°C/output @ 20°C) @ 2ppm NO_2	95 to 115
	Zero @ -20°C	nA	±10
	Zero @ 40°C	nA	70 to 200
CROSS SENSITIVITY	O_3	Filter capacity (ppm.hr) @ 2ppm O_3	> 500
	H_2S	sensitivity % measured gas @ 5ppm H_2S	< -80
	NO	sensitivity % measured gas @ 5ppm NO	< 5
	Cl_2	sensitivity % measured gas @ 5ppm Cl_2	< 80
	SO_2	sensitivity % measured gas @ 5ppm SO_2	< 5
	CO	sensitivity % measured gas @ 5ppm CO	< 3
	H_2	sensitivity % measured gas @ 100ppm H_2	< 0.1
	C_2H_4	sensitivity % measured gas @ 100ppm C_2H_4	< 0.5
	NH_3	sensitivity % measured gas @ 20ppm NH_3	< 0.2
	CO_2	sensitivity % measured gas @ 5% Vol CO_2	< 0.1
	Halothane	sensitivity % measured gas @ 100ppm Halothane	nd
KEY SPECIFICATIONS			
	Temperature range	°C	-30 to 40
	Pressure range	kPa	80 to 120
	Humidity range	% rh continuous	15 to 85
	Storage period	months @ 3 to 20°C (stored in sealed pot)	6
	Load resistor	Ω (ISB circuit is recommended)	33 to 100
	Weight	g	< 13

At the end of the product's life, do not dispose of any electronic sensor, component or instrument in the domestic waste, but contact the instrument manufacturer, Alphasense or its distributor for disposal instructions.

Note: "As applications of use are outside our control, the information provided is given without legal responsibility. Customers should test under their own conditions, to ensure that the sensors are suitable for their own requirements"

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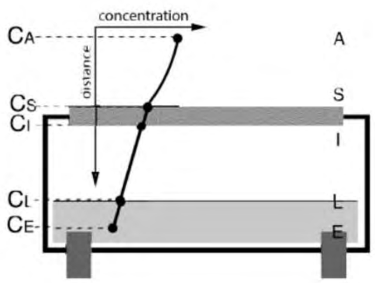
Electrochemical NO sensor study
Masson et al. Sensors 2015, 15, 27283-27302; doi:10.3390/s151027283



$$C = \frac{I - (b_1 + b_2 * I_z)}{b_3 + b_4 * exp(b_5 * T_c)}$$

Figure 1. Boundary points in an electrolytic cell denoting important physical interfaces.

The quality of data from electrolytic sensors depends on the circuitry as much as it does on the sensor itself.

The sensitivity of the Alphasense NO-B4 sensor, for example, is 0.5 to 0.85 nA/ppb. The target span of 0 to 100 ppb NO, a common ambient range, would translate at most to a raw signal span of 0 to 85 nA.

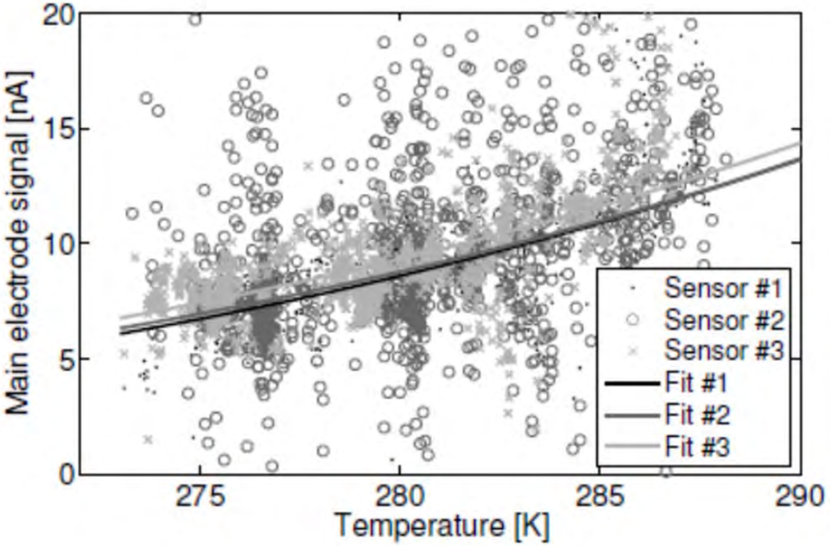
Amplifying and resolving such miniscule currents requires robust instrumentation with a high degree of noise attenuation

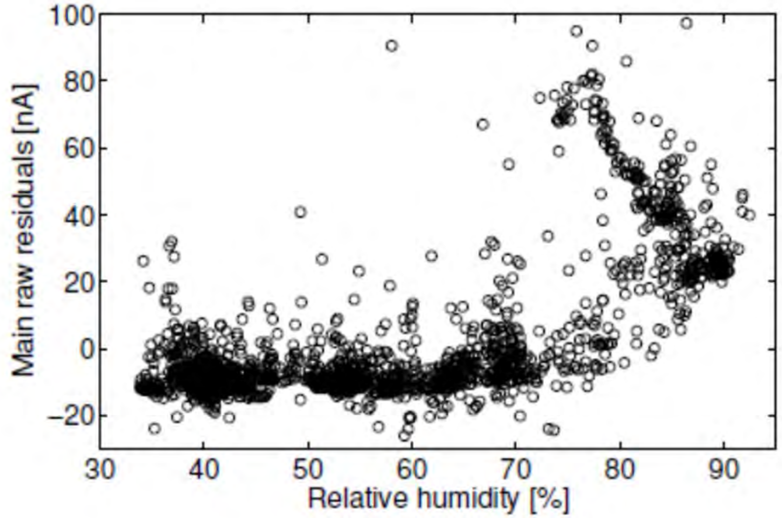
NO sensor study
Masson et al. Sensors 2015, 15, 27283-27302; doi:10.3390/s151027283

It was determined that the Alphasense B4 NO sensor often produced unpredictable responses during periods of humidity above approximately 75%, with or without the auxillary electrode.

A high-cost instrument will often cite measurement precision or uncertainty as a +/- value irrespective of the environment in which the reading is taken.

With low-cost sensors, the reading uncertainty is very much a function of external factors, a function that must be characterized in any robust monitoring implementation.





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NO sensor study
(Masson et al. Sensors 2015, 15, 27283-27302; doi:10.3390/s151027283

Electrolytic sensors demonstrate a predictable response to their target analyte when the sensor signals are corrected for confounding environmental factors.

Little inter-sensor variability among the Alphasense B4 sensors (**acceptable variability** for most ambient monitoring)

Two models derived explained here show similar performance when fit to a reference dataset.

The first model, which does not use the Alphasense B4-specific auxiliary electrode, showed poor performance when extrapolating from the variable space used to fit the model.

Findings suggest that a model without auxiliary electrode (Model 1) should only be used if its parameters are derived by fitting the model to the variable space within which the sensor will be used. This may prove an inconvenience if using a collocation method and if one wishes to use one model across many climates.

The sensor will need to be **deployed for a sufficient period of time to cover the variable space** (i.e., across seasons).

If reference measurements for other cross-sensitive gas species are present, they may be used as an additional correction factor, treated as contributing to the sensor current in proportion to the measured reference concentration.

A **temperature dependence on the sensitivity to other cross-sensitive species may also be included for greater fidelity**.

It is important to note that **different sensor types experience different levels of cross-sensitivity to confounding gas species, and site locations will have varying mixes of confounding species**.

Care should also be taken to **minimize changes in airflow over the sensor, as this will introduce changes in the sensor baseline and sensitivity**

AeroQual

Table S1. Specifications of Aeroqual S500

Gas Sensor	Range (ppm)	Minimum Detection Limit (ppm)	Accuracy of calibration	Resolution (ppm)	Operational range	
					Temp.	RH
Ozone	0-0.5	0.001	<±0.008 ppm 0-0.1 ppm; <±10% 0.1-0.5 ppm	0.001	0 to 40°C	10 to 90%
Nitrogen Dioxide	0-1	0.005	<±0.02 ppm 0-0.2 ppm; <±10% 0.2-1 ppm	0.001	0 to 40°C	10 to 90%

Note: the air quality ranges in Montreal from May to October 2014 were, according to Réseau de Surveillance de la Qualité de l'Air: for NO_2, 0.0-67.9ppb, average of 8.0 ppb, for O_3, 0.0-68.0 ppb, average of 22.4 ppb.

Table S2. Correction equations for sensors

Summer and fall (O_3)	$O_3(3)*1{,}05-12{,}93$ (R^2=0.81)
	$O_3(5)*0{,}84-2{,}07$ (R^2=0.81)
	$O_3(7)*1{,}05-2{,}27$ (R^2=0.85)
Summer (NO_2)	$NO_2(2)*0{,}53+0{,}01$ (R^2=0.70)
	$NO_2(6/8)*0{,}99-18{,}51$ (R^2=0.93)
Fall (NO_2)	$NO_2(4)*1{,}145-24{,}95$ (R^2=0.91)
	$NO_2(6)*1{,}35-57{,}60$ (R^2=0.60)
	$NO_2(8)*1{,}02+7{,}03$ (R^2=0.87)

Table S1. Specifications of Aeroqual S500 Gas Sensor Range (ppm) Minimum Detection Limit (ppm) Accuracy of calibration Resolution (ppm) Operational range Temp. RH Ozone 0-0.5 0.001

Aeroqual

A total of six correction equations were thus derived from this co-location (three for the three remaining O_3 sensors and similarly for the NO_2 sensors).

the high NO_2 levels obtained were partly due, as noticed earlier, to cross sensitivity: NO_2 sensors measured at the same time NO_2 and O_3. Indeed, NO_2 measured by Aeroqual relates better to the sum of NO_2 and O_3 measured by RSQA ($R^2 = 0.71$) than to NO_2 only ($R^2 = 0.04$).

AQ Mesh

NO2				
Version	v3.0	v3.5	v4.0	v4.1
Date	To December 2014	January 2015 – October 2015	Janaury 2015 – Q1 2016	Q2 2016 – present
NO2 sensor	Significant O3 cross-gas effect	O3-filtered	O3-filtered	O3-filtered
NO2 sensor characterisation	Manufacturer's data	Manufacturer's data	Manufacturer's data plus characterisation at factory	Quality check
Online processing	Correction for cross-gas effects and environmental factors	Correction for cross-gas effects and environmental factors	Correction for cross-gas effects and environmental factors	More sophisticated correction for cross-gas effects and environmental factors
Typical R2 against reference in co-location trials	0-0.3	0.1-0.7	0.5-0.8	0.7-0.95

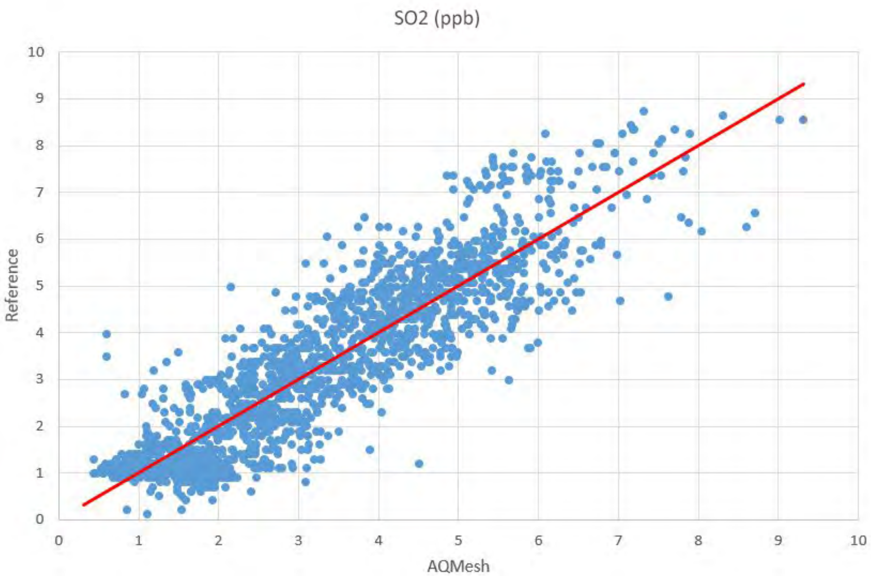
R2 of >0.6 for NO2 is generally considered to be a strong enough performance for AQMesh to be suitable for most air quality monitoring applications.

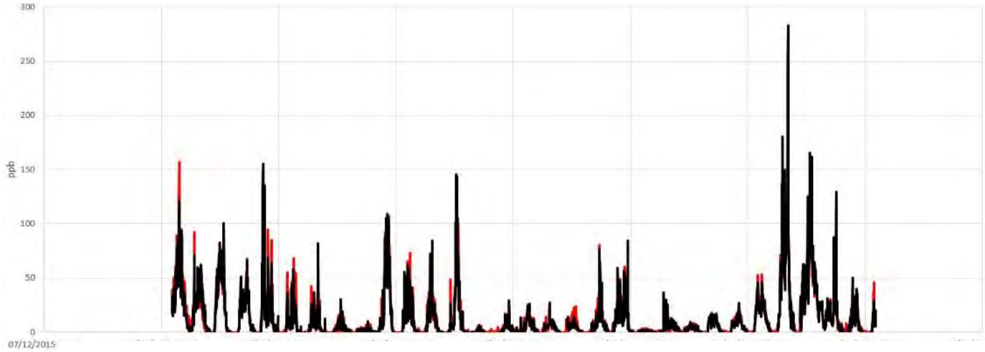
http://www.aqmesh.com/performance/aqmesh-performance/

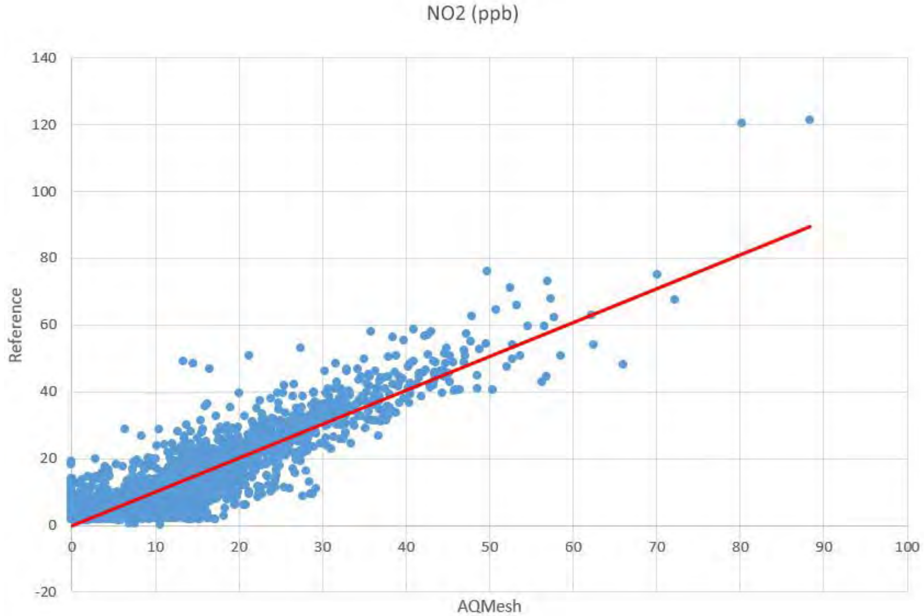
AQ Mesh case studies from Co. website

Scotland

London







- Looks like good data
- Not enough statistical information to judge
- r^2 is not enough.

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Responsibility Issues with new technologies

AQ Mesh caveats

- Product designs and specifications are subject to change without prior notice. The user is responsible for determining the suitability of the product.
- #1 From sensor manufacturer's specification.
- #2 Accuracy is what the sensors are capable of producing given stable temperature and humidity. This data was derived from independent lab tests. Standard test conditions are 20 deg C and 80% RH and in the absence of interfering gases.
- #3 The O3 reading is achieved using digital signal processing which requires a certain number of data points to give results that are comparable to the industry standard reference equipment. This will result in a straight line projected forward for the last section of processed O3 data. This data is retrospectively corrected as new data is delivered.
- #5 Electrochemical sensors carry a 12 month warranty. Exposure to relative humidity in excess of 85% for five or more days as validated by the on-board sensor will void the warranty.

Background: Atmospheric measurements

- **Optimal use of data and resource for air quality measurements**
- **A robust and reliable evidence base in the decision-making process**

1. Types of sensor – still developing
2. Types of cross-sensitivities do we know them all?
3. Types of confounding atmospheric and environmental properties mostly known but how to characterise clearly without significant extra cost easily?
4. Where science should be heading? Transparency and metrological quality assurance programmes
5. Potential practical ways to cope with current technology (and developing technologies) assessment, scientific studies, replacement technologies
6. Which technologies in the future are likely to be most traceable? Minatiurised IR (guess!!)

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SWOT analysis

Strengths:

Low cost sensor technologies have the potential to make a major difference to air quality improvements and to the transparency and availability of data

UK has strong metrological and atmospheric chemistry community who will be able to support development of standards (NPL, Defra intercomparisons, CEH, NCAS…)

Weaknesses:

Very little transparency and availability of data by manufacturers (science literature in the past 12 months beginning to catch up)

Users unable to access or test algorithms of integrated sensors

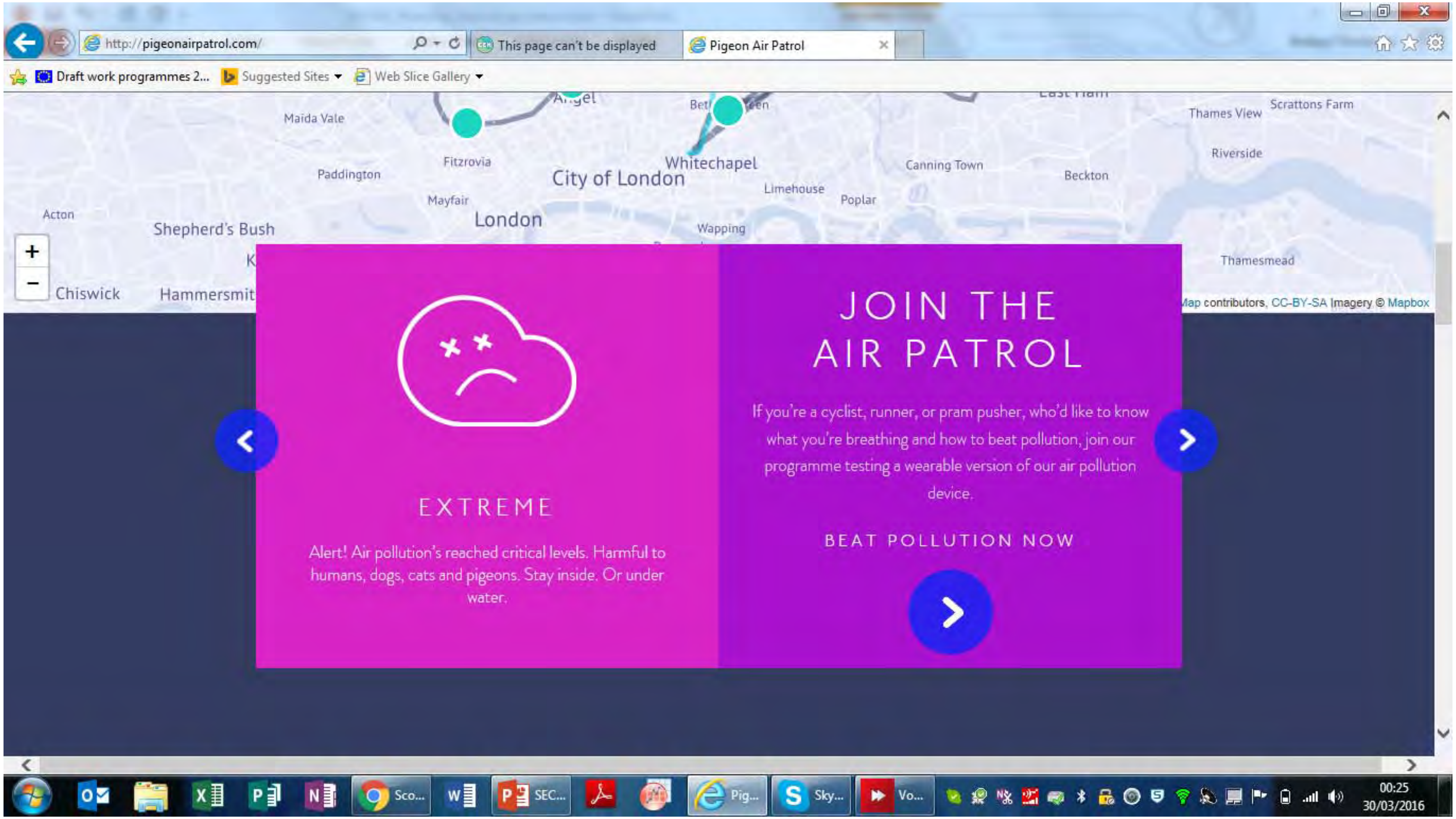
Currently little control or trading standards.

SWOT: Threats

http://www.blog.foe-scotland.org.uk/index.php/2013/12/

“However, advances are now being made with mobile air pollution monitors coming on to the market. Personal air pollution sensors which you can strap to yourself **give a much clearer picture of what air pollution levels are like** and how they vary from place to place. We would like to see much more of these made readily available so that people are able to access real live data on air pollution levels where they are. This would be the ideal way to give air pollution the visibility it needs so that there is a stronger public mandate for life-saving action on transport.”

SWOT: Threats



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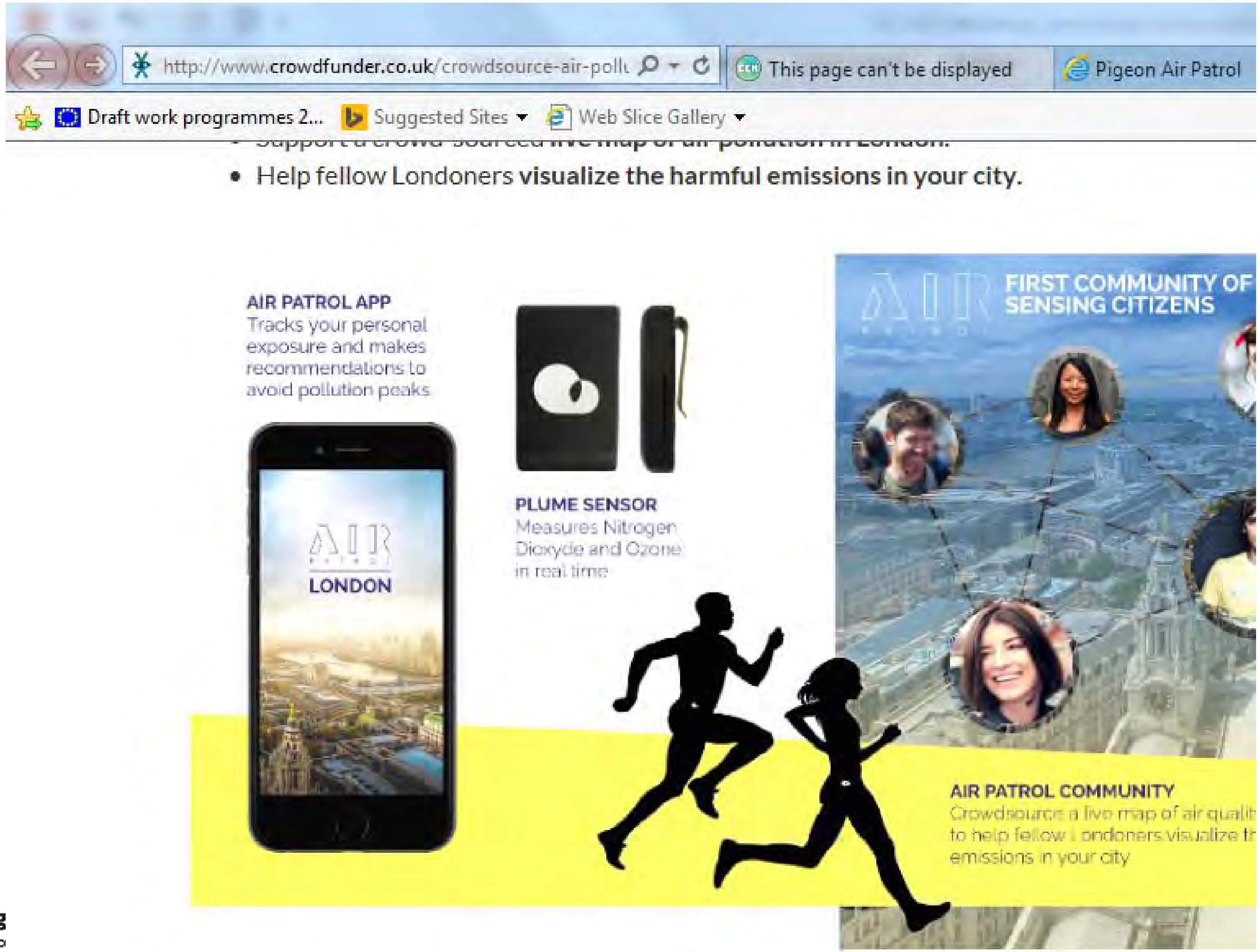
Responsible science or opportunism?

NO DATA …
ANYWHERE !!!



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SWOT

Opportunities

- High resolution good quality data is possible with low cost sensors
- Opportunity is there to integrate good practice with availability
- Core variables have been identified:
  - T (sensor unit and ambient)
  - RH
  - Wind speed
  - Core other pollutants
  - Sensor lifetime
  - Circuit board and EMF noise
  - …
- Capability to assess and integrate available. Confidence can be improved

New technologies

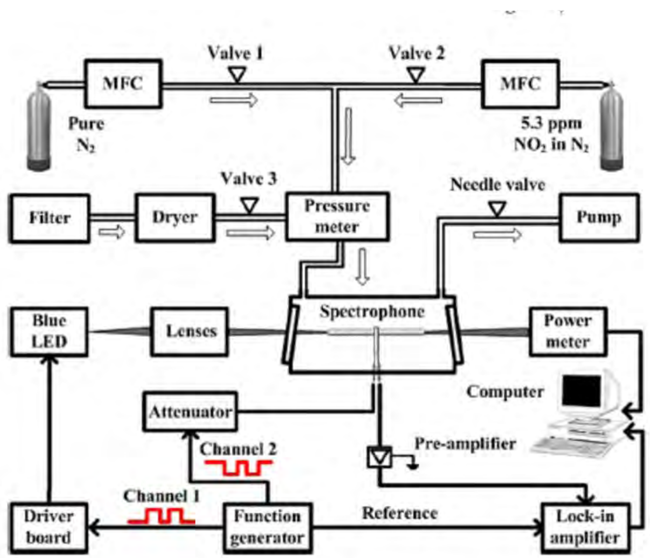

Fig. 1. Schematic of the E-MOCAM-based QEPAS system.

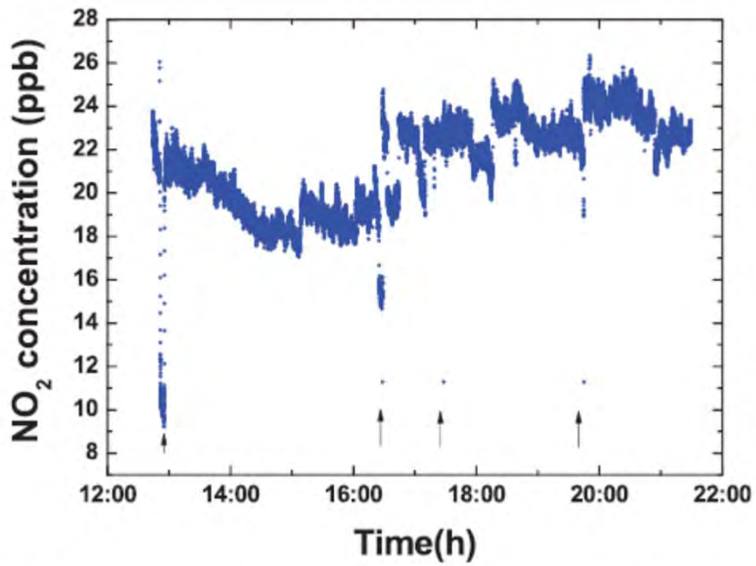

Fig. 6. NO_2 concentration monitoring on the campus of Shanxi University on May 15th, 2014, from 12:00 am to 21:00 pm. The calibration points are marked by the arrow symbols.

A novel electrical modulation cancellation method (E-MOCAM) is proposed to suppress the background noise in the case of the excitation light source with a poor beam quality. For its practical implementation, an E-MOCAM based on-beam QEPAS NO2 sensor by use of a commercial high-power wide-stripe LED is developed. The E-MOCAM ultimately suppressed the background noise caused by the stray light by three orders of magnitude. A 1 detection limit of 1.3 ppb (part per billion by volume) was achieved at1 s integration time in this experiment, which corresponds to a normalized noise equivalent absorption coefficient (NNEA) 4.2 × 10−9W cm−1Hz−1/2. A 9 h continuous on-line monitoring of ambient atmosphericNO2was carried out on the campus of Shanxi University.

Zheng et al. Sensors and Actuators B 208 (2015) 173–179

- Not low cost or mobile, but in theory molecule specific

Standards: What do we need?

- Facility/chamber testing and intercomparisons
- UK climate-relevant assured products for full annual cycles
- Better statistics from manufacturers (r^2 is not enough!)
- For gases a more complete interaction assessment: HONO, NO_3, PM contamination
- For particles clear calibrations for air mass types.
- Facilities and points of contact for impartial advice
- Confidence that the algorithm from the manufacturer will not change from year to year. If it does an update and details provided.

When do we need them?

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Bear in mind the scientific question the sensor is being used to address.