Experience of global small sensor co-location comparison studies with AQMesh

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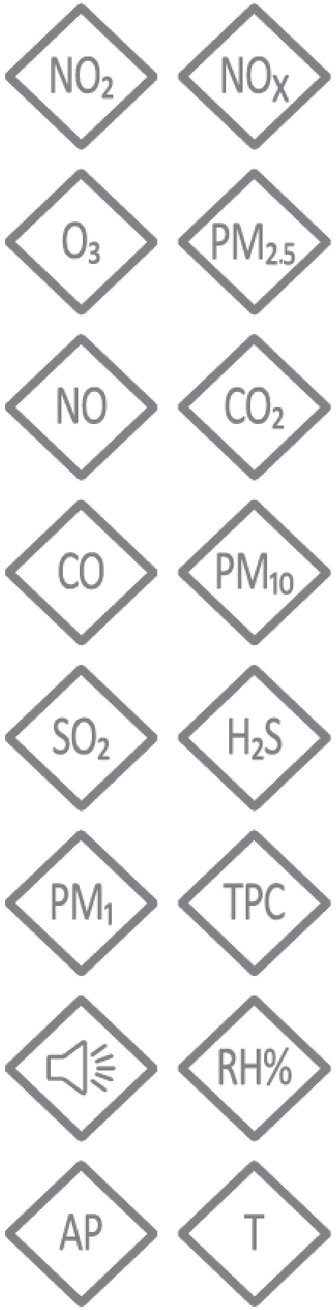
AQMesh

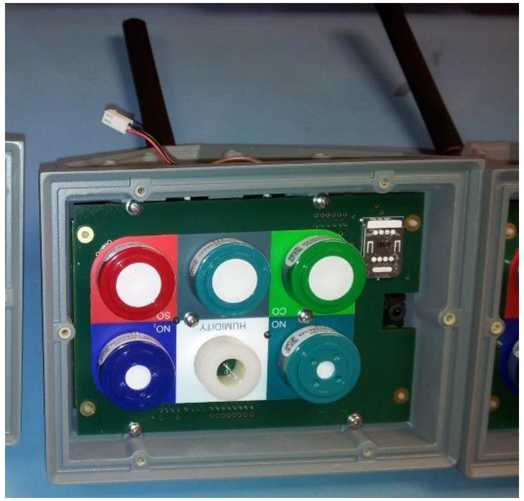


What is AQMesh?

- Emerged from MESSAGE project 2006-9 in UK
  - Potential for low cost sensors in the environment
- Developed in partnership with University of Cambridge
- Ambition to improve spatial resolution of air quality monitoring networks
- Small sensor system for ambient air quality monitoring
  - Practical instrument for long-term outdoor use
  - Cloud processing of sensor output with secure online data access
- Started measuring 5 gases: NO, NO_2, O_3, CO, SO_2

Ambient gas monitoring with AQMesh

- Electrochemical sensors
  - Alphasense B4
- v3.0 released for sale in 2013
  - NO, NO_2, O_3, CO, SO_2
- **Started collecting global datasets comparing co-located reference / FEM readings**
- Biggest issues:
  - Cross-gas effects
    - Particularly NO_2/O_3
  - Effect of temperature



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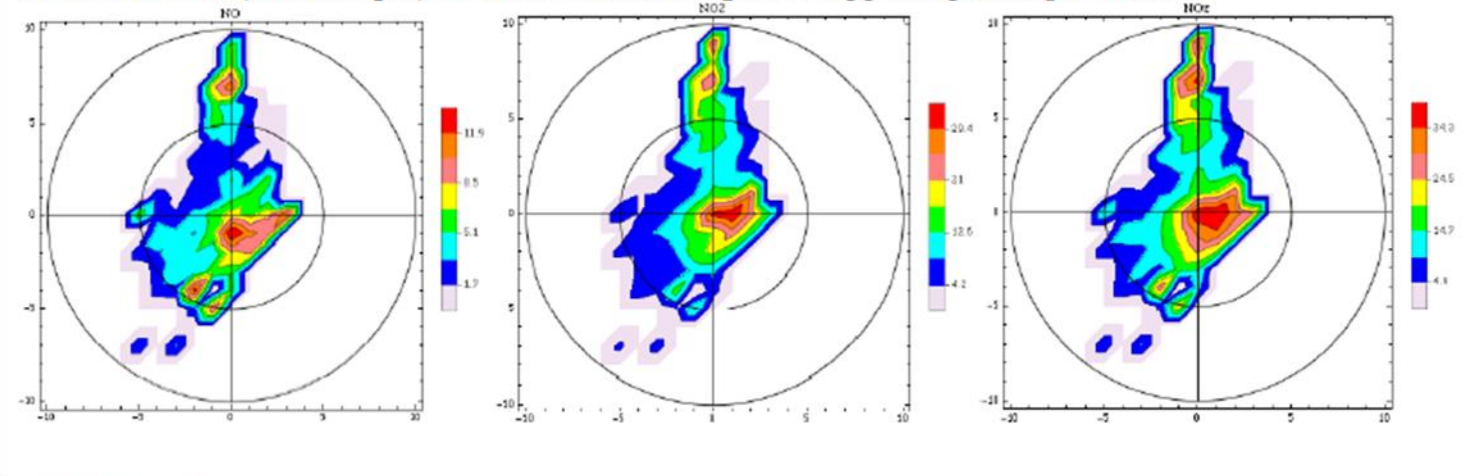
v3.0 performance
(2013-14)

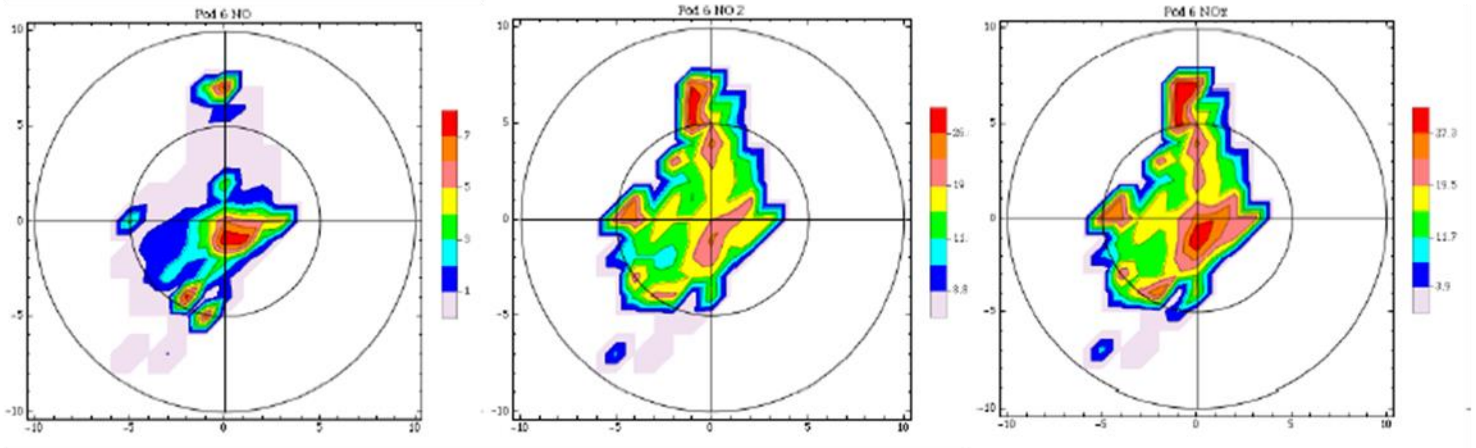
- Pollution events identified
- R^2 poor at short intervals, eg: 15 mins
- Some information captured
  - Source apportionment results similar for co-located reference and AQMesh
- Conclusion:
  - Not good enough

Reference equipment

NO/NO_2/NOx (left to right) vs wind direction/speed, suggesting multiple sources.



AQMesh

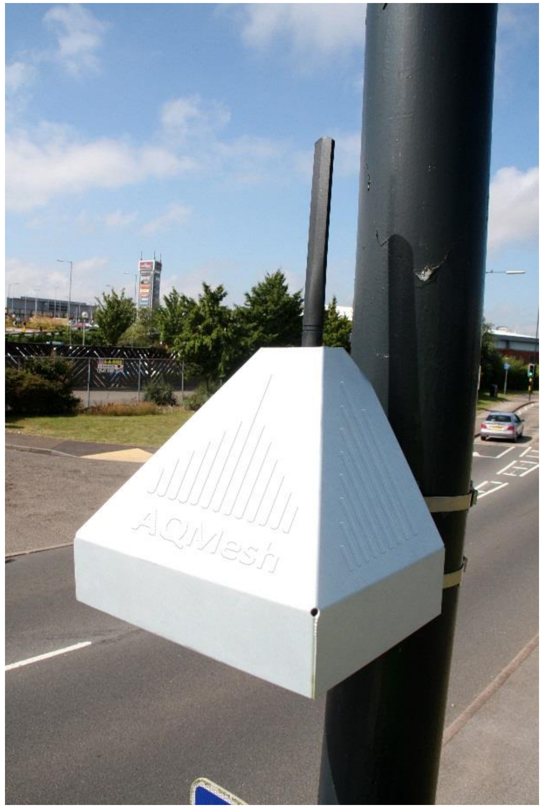


Analysis carried out by Professor Rod Jones, University of Cambridge

AQMesh

Developments and public evaluation (2014-15)

- Key developments
  - Sun shield introduced
  - Breakthrough with ozone filter on NO_2 sensor
  - Sensor characterisation extended via ambient co-location with FEM
  - Improvements in calculations / ‘algorithms’ – as a traceable version
  - v4.0
- Public studies
  - Citi-Sense
    - 200+ AQMesh pods
    - (Sensors not characterised at factory due to funding structure)
    - Various studies published
  - EUNetAir
    - Aveiro, Portugal
- In 2016 still significant temperature effects
- v4.1 commercially unreleased AI attempt to ‘find the signal’



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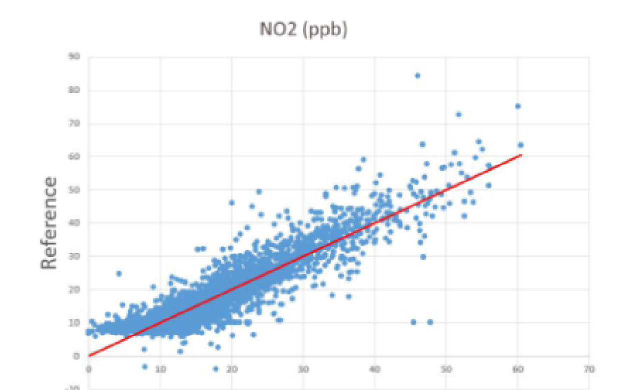
v4.0 results
(published on aqmesh.com)

- Typically
  - NO_2 , O_3 and CO R^2 0.5 – 0.8
  - NO R^2 > 0.8 (in most conditions)
- Example co-location Colorado
  - October to December 2015
  - NO R^2 0.99
  - NO_2 R^2 0.75
  - O3 R^2 0.59
- Not yet consistent performance across the full range of conditions
- Local scaling against reference offering significant improvement in accuracy

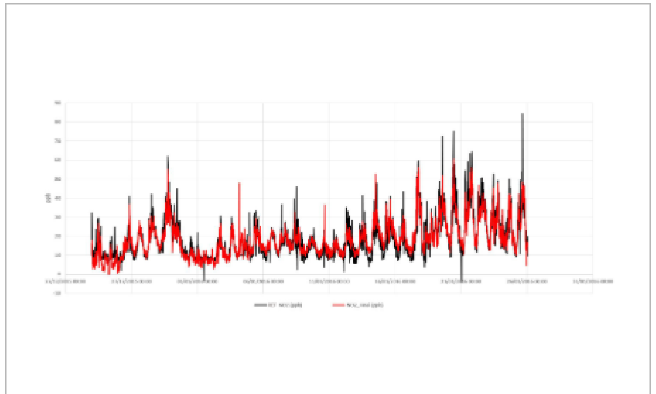
NO2 results Sweden, December 2015

Testing resulted in R2 values of 0.83

Parameter	NO2
R2 Value	0.83



Click to view correlation plot



Click to view time series plot

Date	December 2015 – January 2016
Location	Sweden
Version of Algorithm	v4.0
Averaged sample interval	15 minutes

Recent developments (v4.2.3)

- NO_2 sensor O_3-filtered and improved response at higher ambient temperatures
- Factory quality check, accuracy and precision tests
- Optimised electronic set-up and performance enhancements below LOD

Measurement	Limit of confidence	Typical precision to ref (R^2)	Typical mean pre-scaled accuracy (MAE)
NO	< 5 ppb	>0.9	+/- 5 ppb
NO_2	< 10 ppb	>0.85	+/- 10 ppb
NO_X	< 10 ppb	>0.9	+/- 10 ppb
O_3	< 5 ppb	>0.9	+/- 10 ppb
CO	< 0.05 ppm	>0.8	+/- 0.3 ppm
SO_2	< 10 ppb	>0.7	+/- 10 ppb
H_2S	< 5 ppb	>0.7	+/- 5 ppb
CO_2	< 1 ppm	>0.9	+/- 30 ppm

See datasheet / tech spec on www.aqmesh.com

Now at the point where R^2 < 0.8 sets us looking at the performance comparison…

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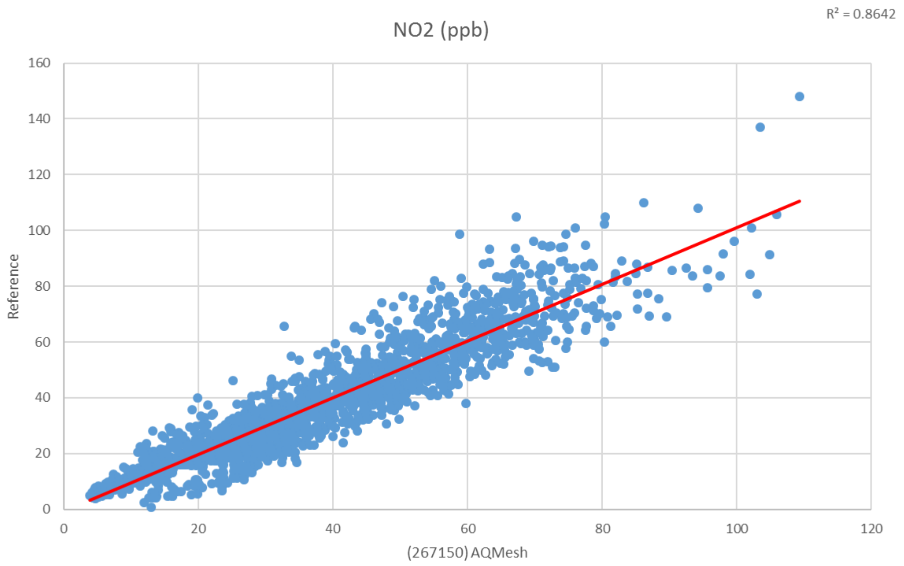
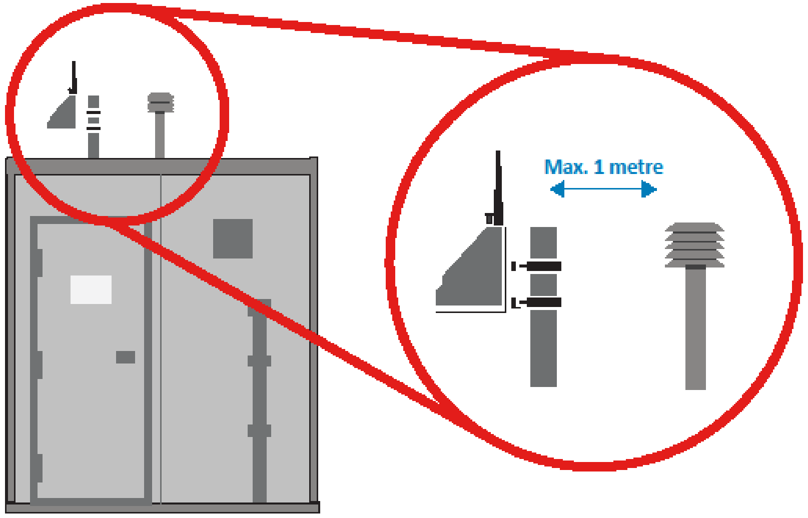
Measuring performance

- Critical for any comparison that the devices to be compared are located very close to each other
  - Multiple pods
  - Reference equipment
  - Diffusion tubes
- Beware reference readings – low R^2 may result from poorly maintained stations or unratified data





See *The Challenges and Benefits of Local Air Quality Monitoring on AQMesh.com*

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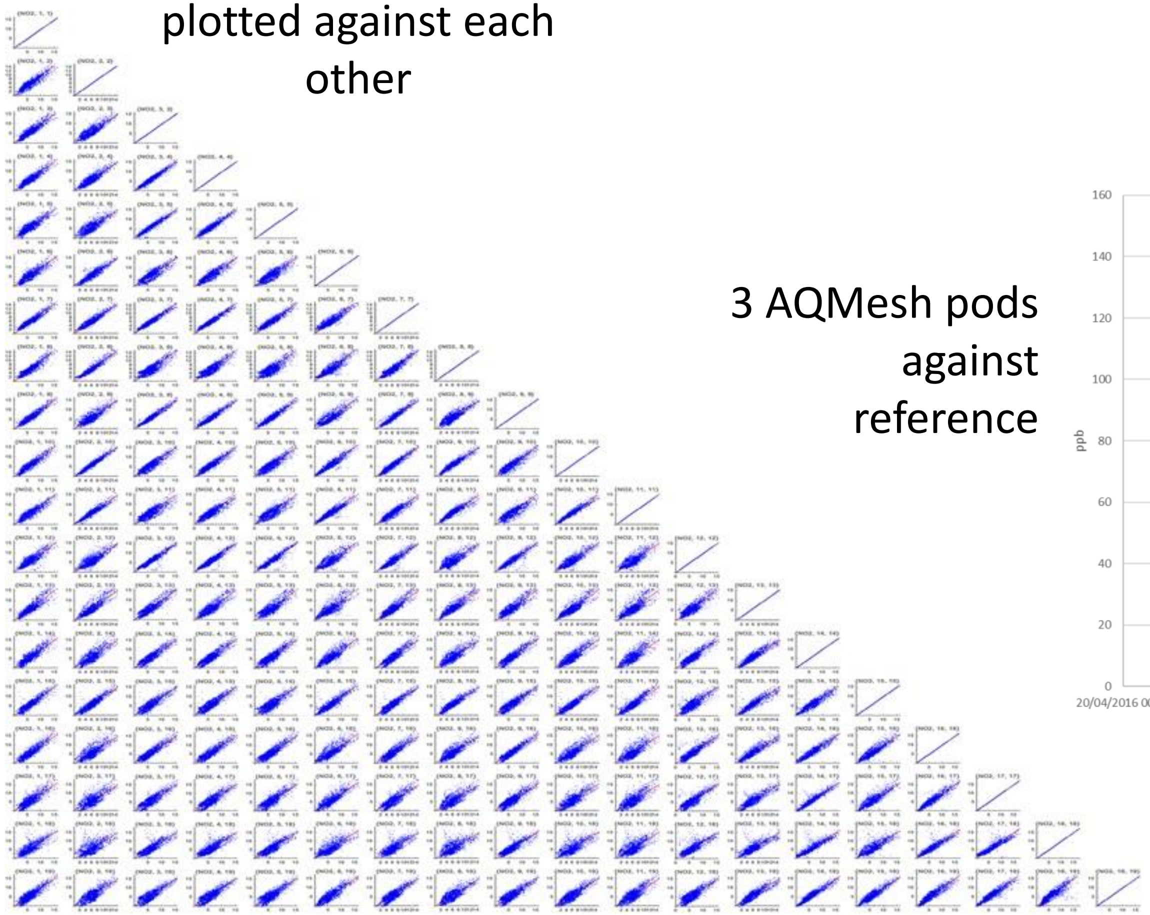
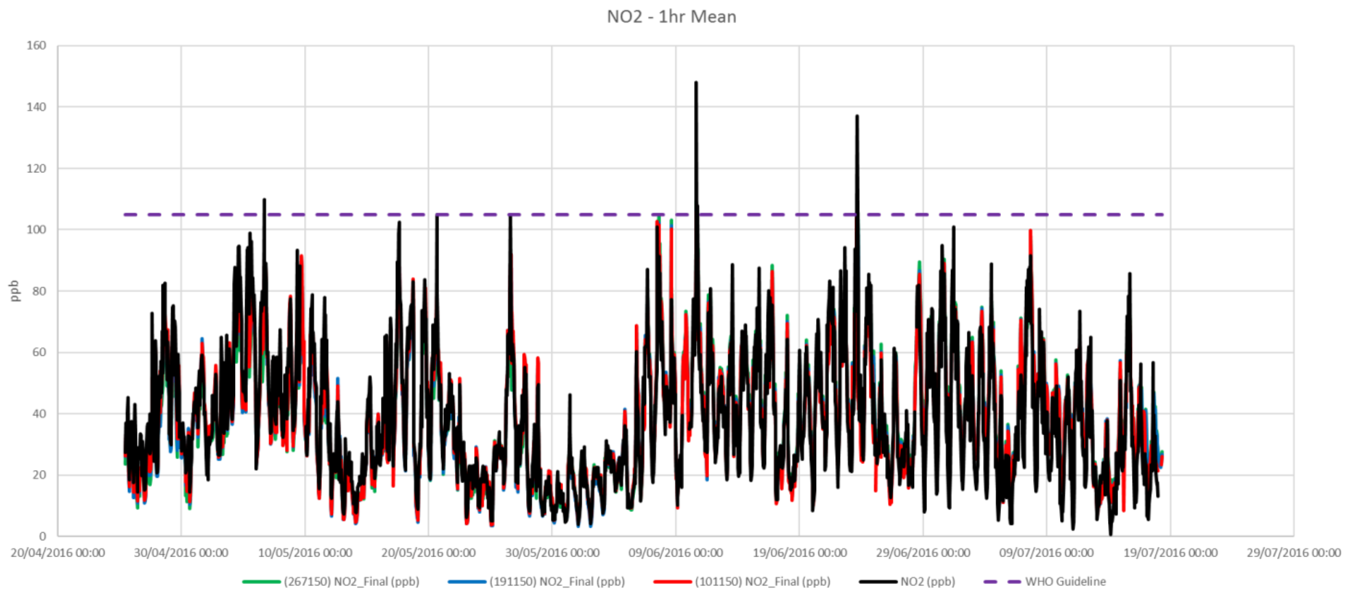
Data legitimacy through precision and accuracy

1. Do all pods in the same place measure the same?
2. Do pods measure the same as reference?

20 co-located pods plotted against each other



3 AQMesh pods against reference



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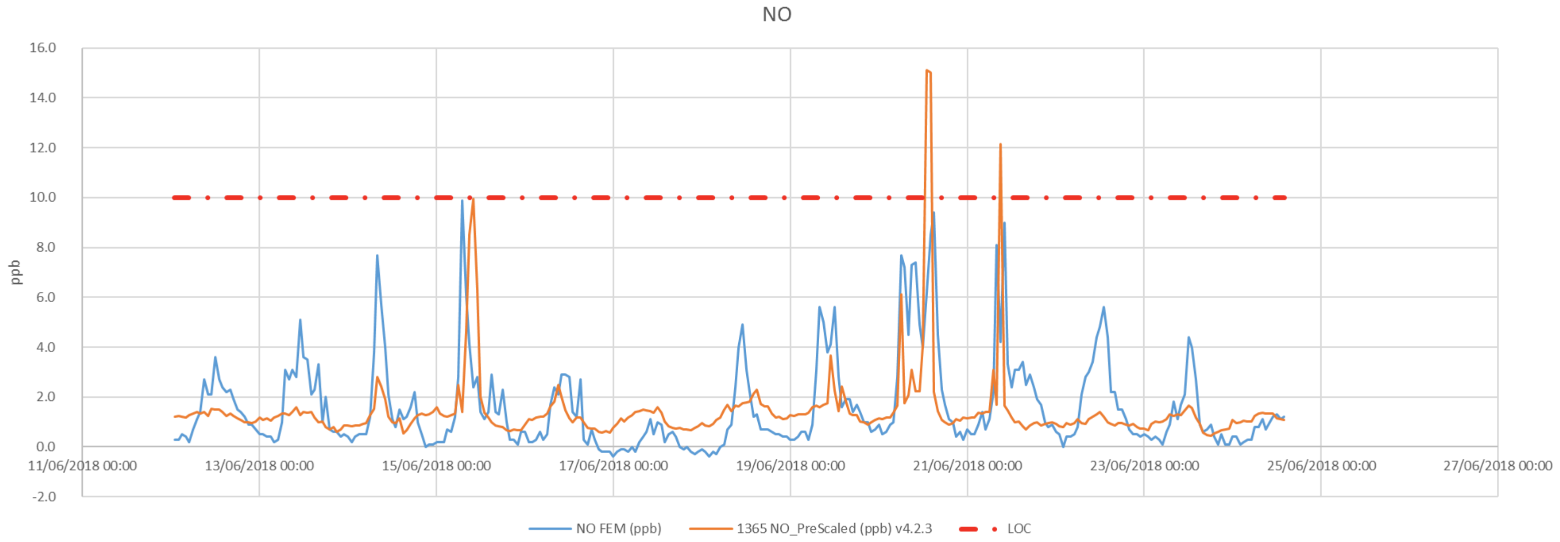
Limit of detection…or confidence?

- ‘Limit of Detection’ versus ‘Limit of Confidence’
  - Sensors capable of detecting target gas down to 0ppb
  - Interference can mask target gas signal
    - Temperature, humidity, electronic noise, interfering gases, etc
    - Limiting and compensating for this noise is an important factor in design of the product and algorithms
  - ‘Limit of confidence’
    - Gas level below which - <u>in the least favourable conditions</u> - we are not confident distinguishing the gas signal
    - Below this value measurements are within a few ppb of the target gas value (accuracy) but precision is lower
    - These values are still presented - important when averaging to longer periods



AQMesh

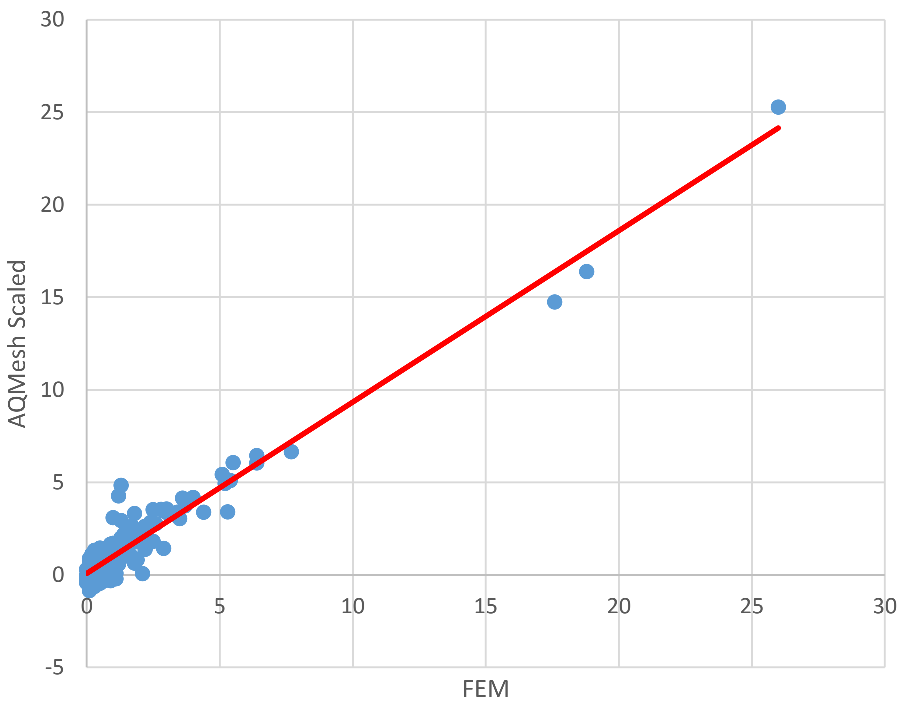
Current production version

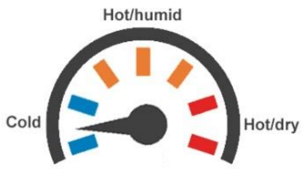
v4.2.3

(Please visit Booth 42 or www.aqmesh.com/performance
for a more leisurely review and more examples)

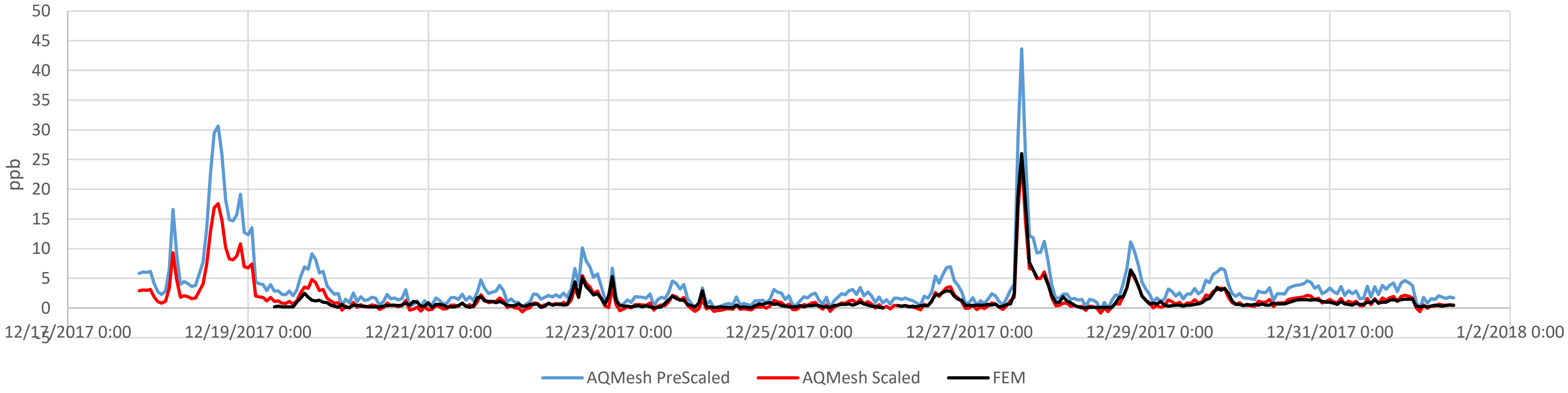
AQMesh

R^2		0.93
Accuracy (MAE)	**PreScaled**	**Scaled**
	1.73	0.45
Accuracy (RMSE)	**PreScaled**	**Scaled**
	2.42	0.65
Averaging interval		60 minute
Conditions		Cold
Region		Minnesota, US
Location		Urban background
Date		Dec 2017 – Jan 2018
Processing version		v4.2.3

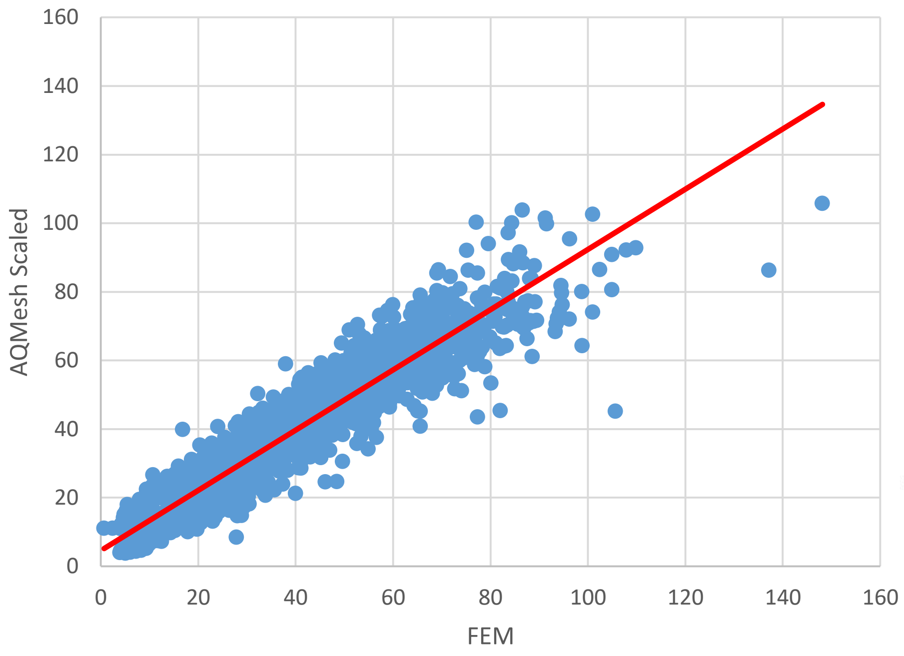




ppb

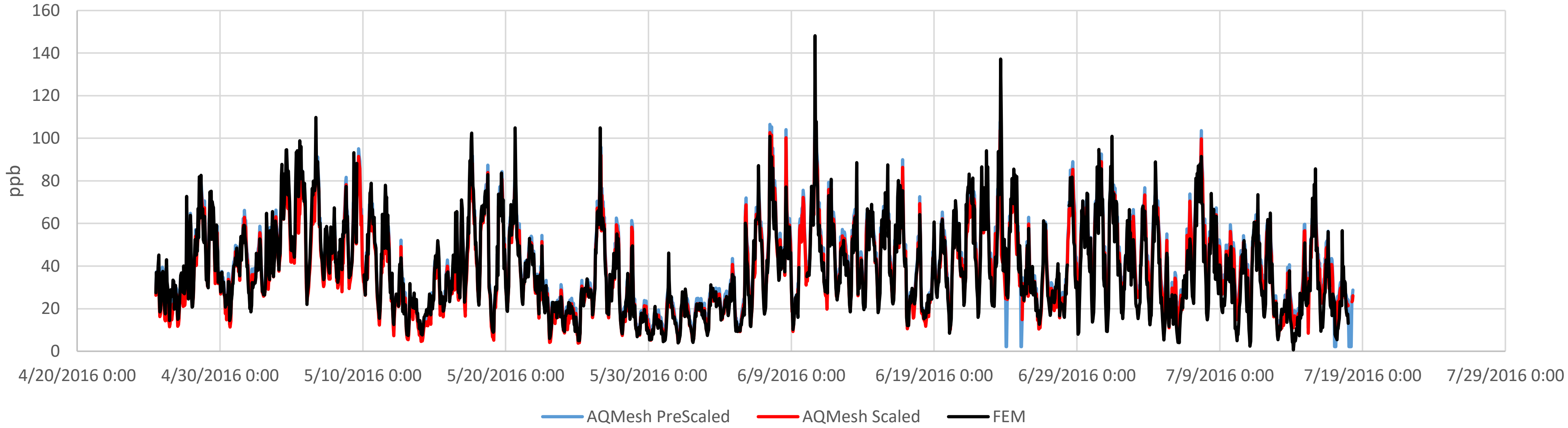


R^2		0.89
Accuracy (MAE)	PreScaled	Scaled
	4.50	5.09
Accuracy (RMSE)	PreScaled	Scaled
	6.17	7.14
Averaging interval		60 minute
Conditions		Hot, humid
Region		London, UK
Location		Urban roadside
Date		Apr – Jul 2016
Processing version		v4.2.3



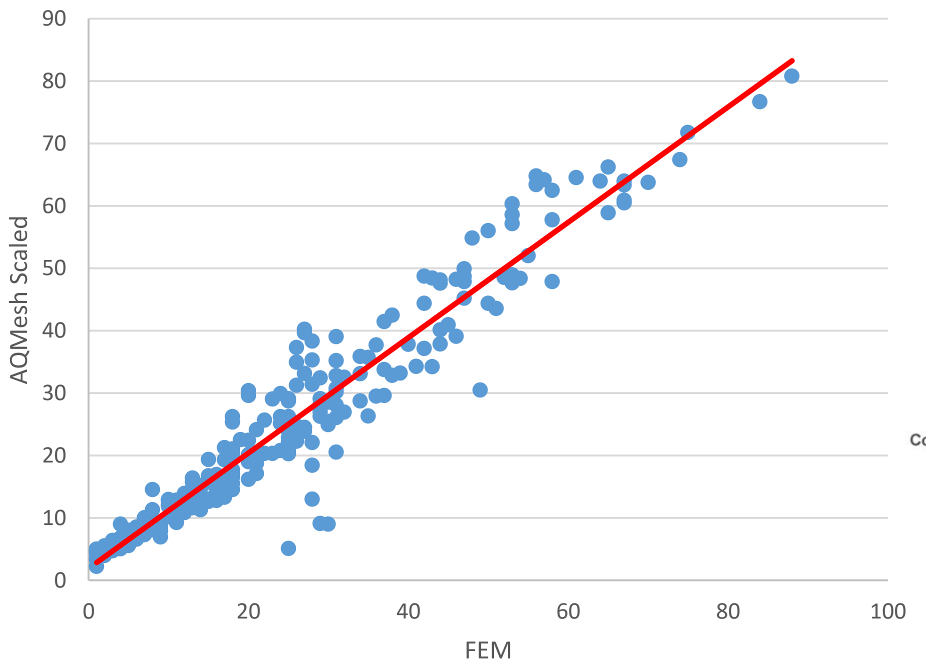
NO_2

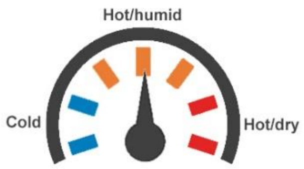
ppb



AQMesh

R2	0.92	
Accuracy (MAE)	**PreScaled**	**Scaled**
	3.71	3.70
Accuracy (RMSE)	**PreScaled**	**Scaled**
	5.22	5.04
Averaging interval	60 minute	
Conditions	Hot, humid	
Region	Southern USA	
Location	Industrial	
Date	June 2018	
Processing version	v4.2.3	





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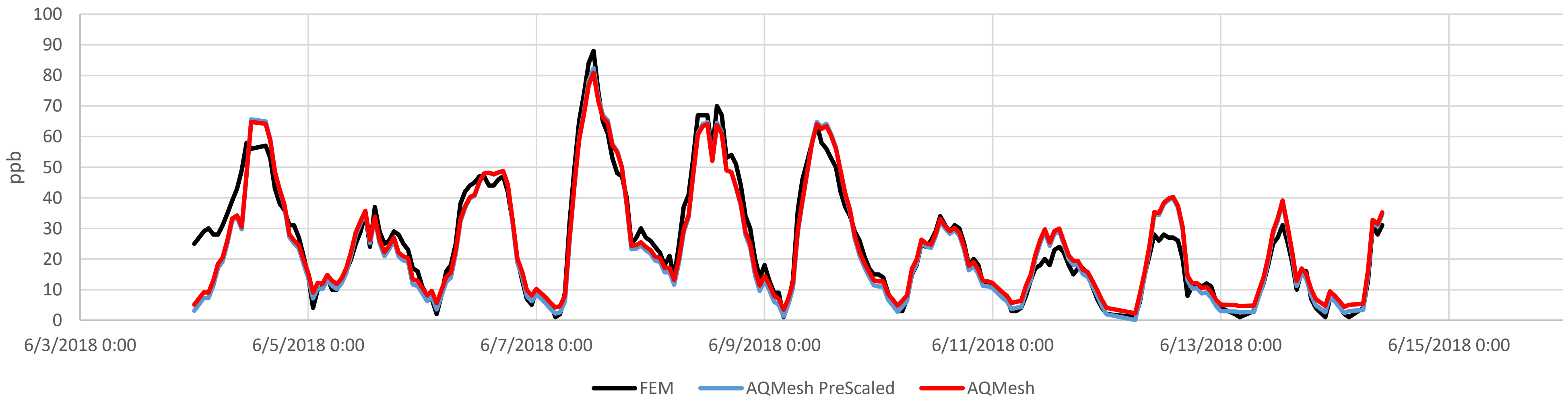
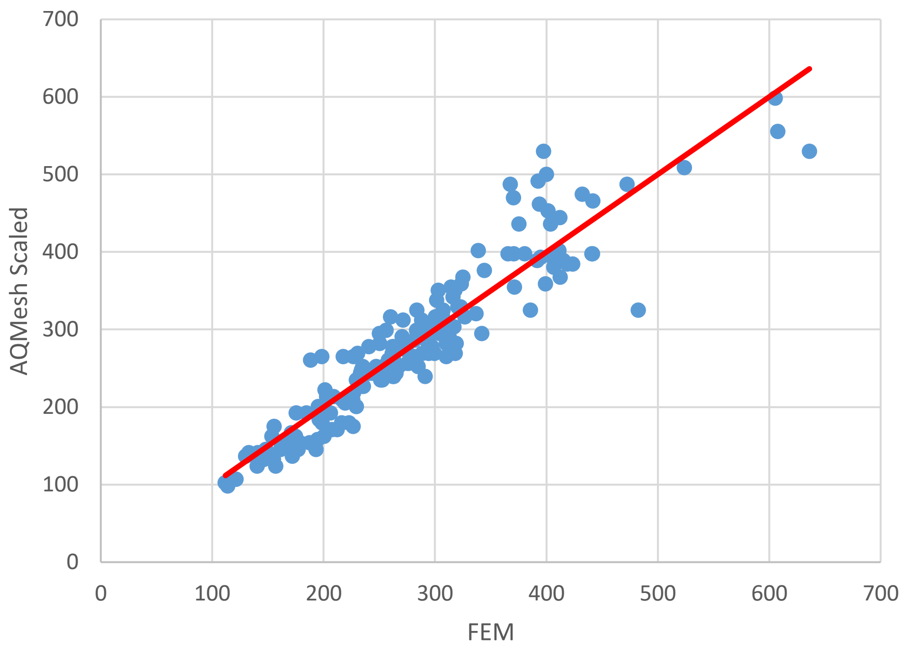
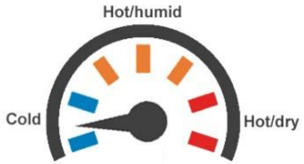


AQMesh

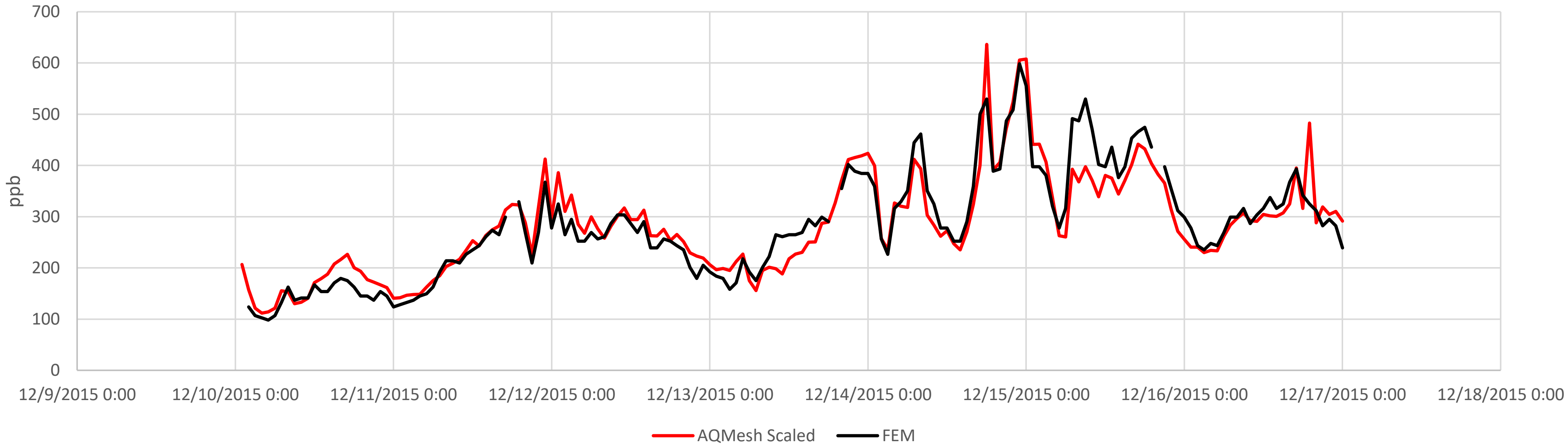
R^2		0.87
Accuracy (MAE)	**PreScaled**	**Scaled**
	335.25	27.25
Accuracy (RMSE)	**PreScaled**	**Scaled**
	349.30	37.01
Averaging interval		60 minute
Conditions		Cold
Region		Western Europe
Location		Urban
Date		December 2015
Processing version		v4.2.3



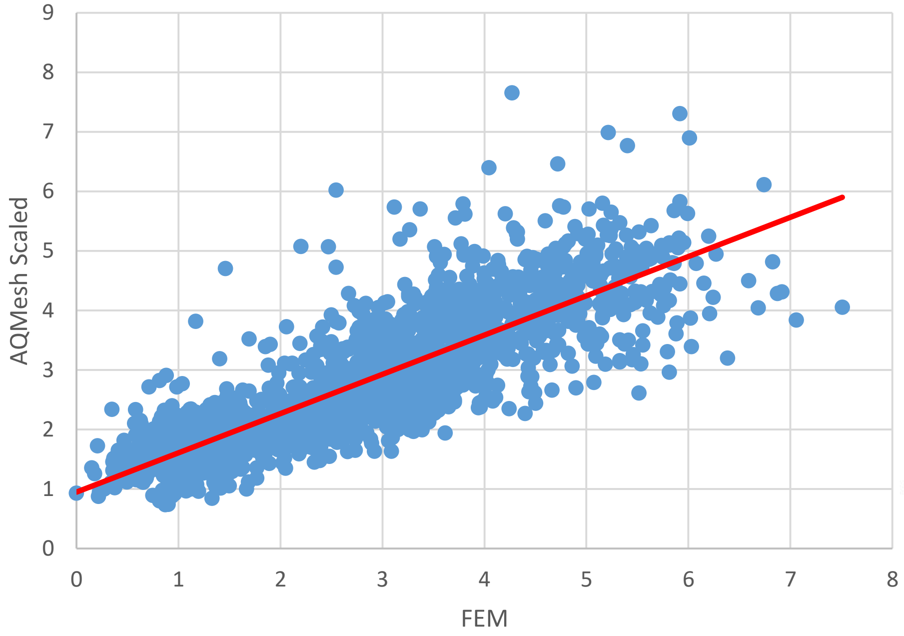
CO



ppb

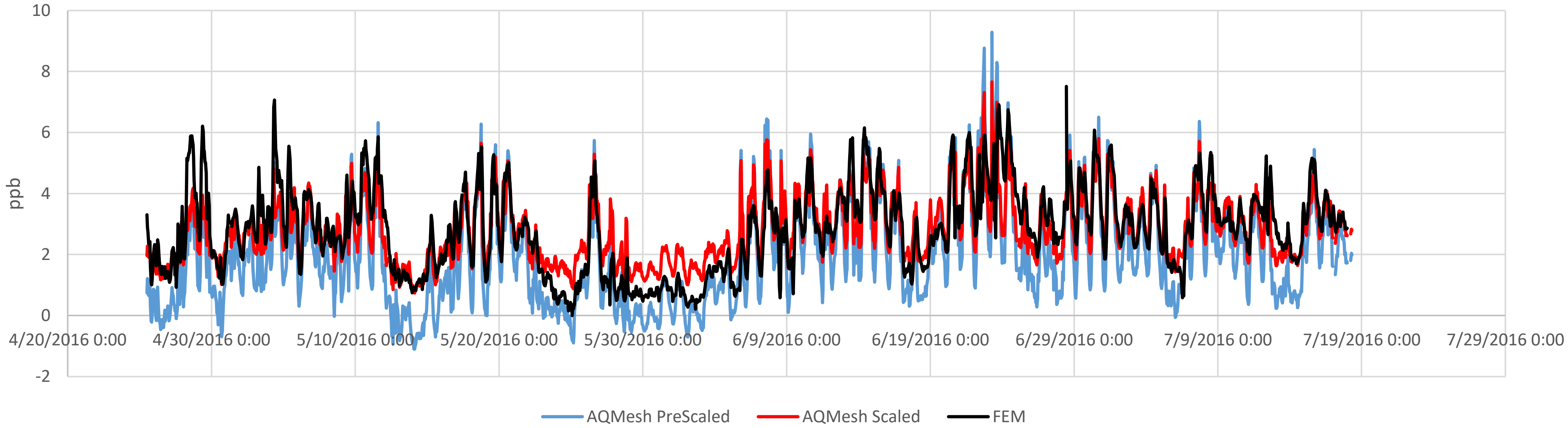


R^2		0.70
Accuracy (MAE)	PreScaled	Scaled
	1.37	0.57
Accuracy (RMSE)	PreScaled	Scaled
	1.51	0.83
Averaging interval		60 minute
Conditions		Hot, humid
Region		London, UK
Location		Urban roadside
Date		Apr – Jul 2016
Processing version		v4.2.3



SO_2

ppb



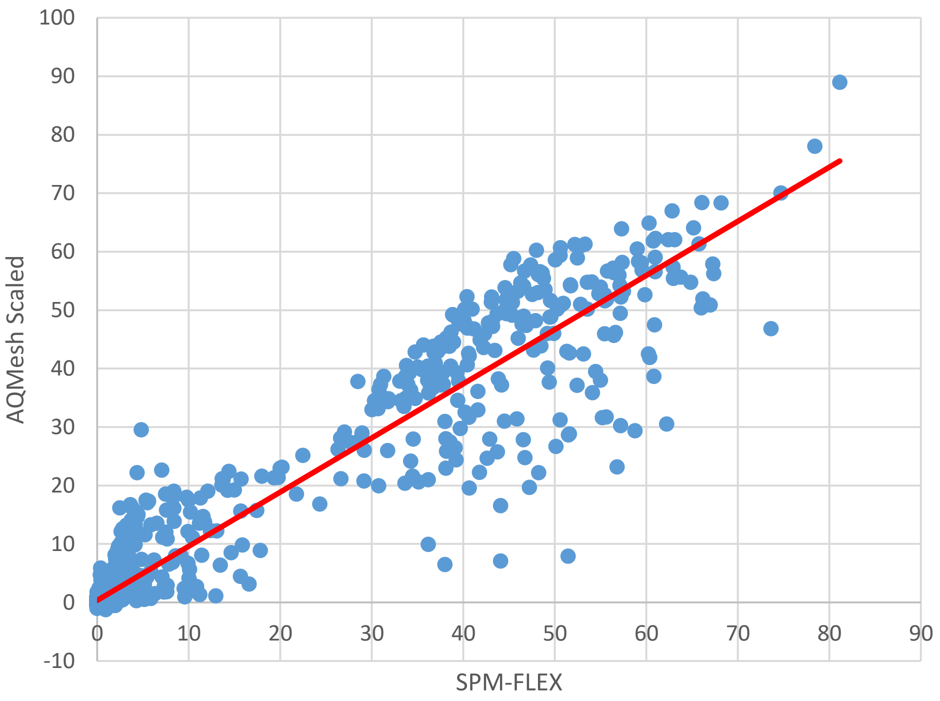
New gas options: CO_2 and H_2S

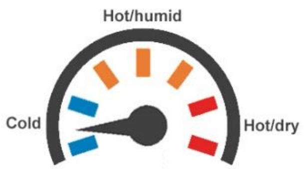
- CO_2
  - NDIR sensor
  - Tested against Picarro reference on city rooftop
    - R^2 value of 0.93
    - MAE (mean absolute error) < 20ppm
  - Precision: pod-to-pod R^2 0.98 and 0.99 for 20 co-located pods
  - Opportunity to identify combustion plumes
    - Proportions of pollutants

- H_2S
  - Electrochemical sensor
  - Tested at sewage / wastewater treatment plant
  - Against Honeywell SPM Flex
  - R^2 0.87 over a measurement range of 0-150ppb

AQMesh

R^2		0.93
Accuracy (MAE)	**PreScaled**	**Scaled**
	1.26	1.27
Accuracy (RMSE)	**PreScaled**	**Scaled**
	3.62	3.57
Averaging interval		60 minutes
Conditions		Cold
Region		United Kingdom
Location		Wastewater treatment
Date		May 2017 – Sep - 2017
Processing version		v4.2.3





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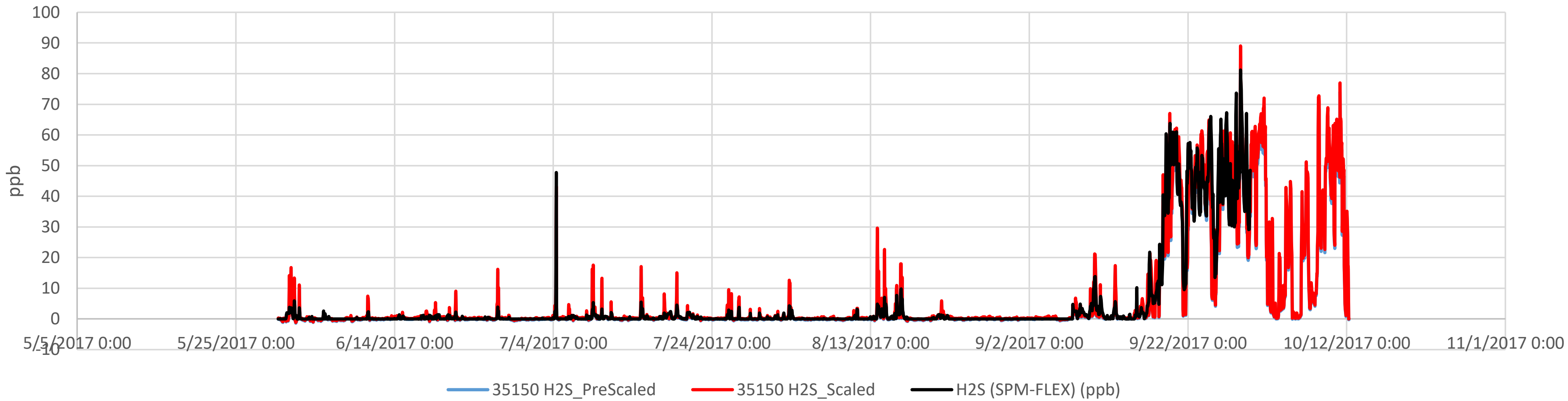
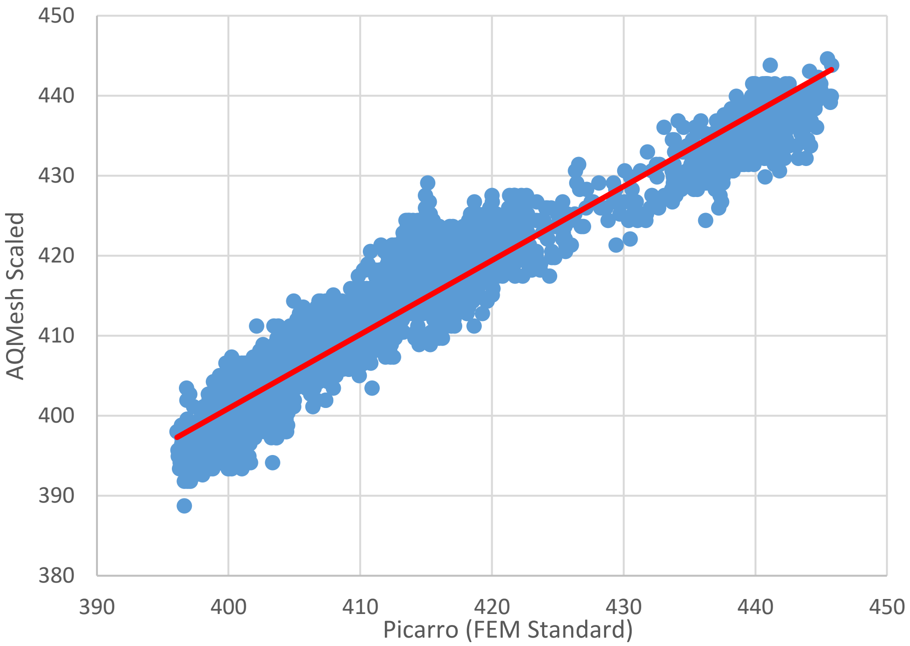
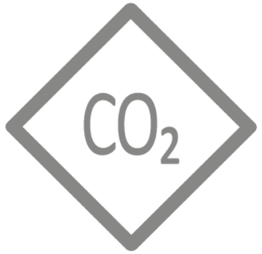
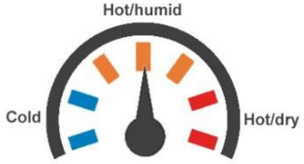


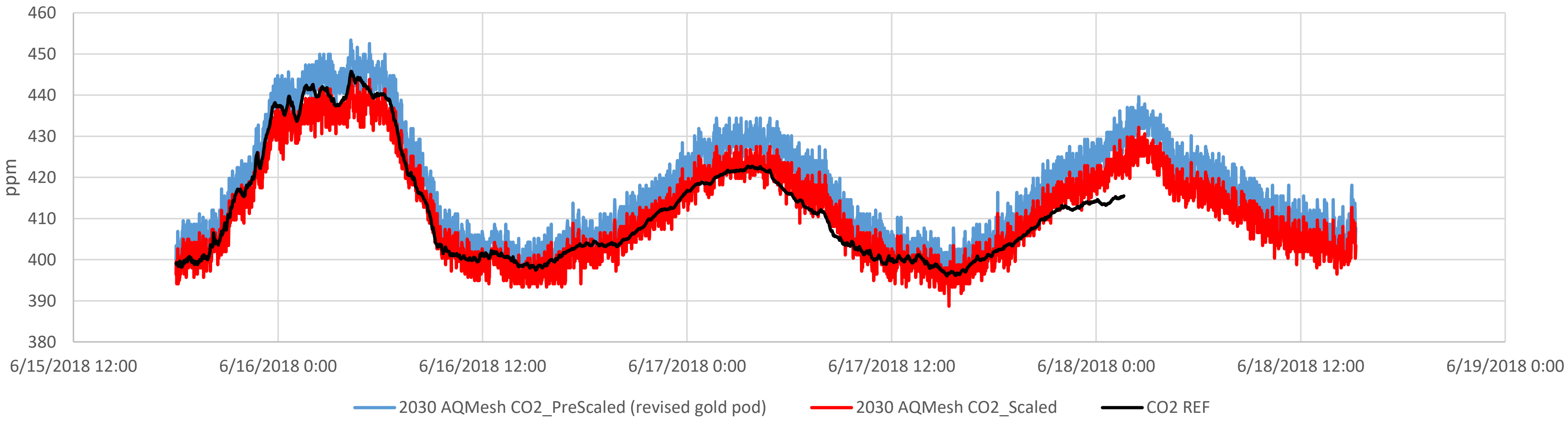
R2	0.93	
Accuracy (MAE)	**PreScaled**	**Scaled**
	3.96	2.39
Accuracy (RMSE)	**PreScaled**	**Scaled**
	4.66	2.93
Averaging interval	1 minute	
Conditions	Hot, variable humidity	
Region	Western Europe	
Location	Cambridge, UK	
Date	June 2018	
Processing version	V4.2.3	







ppm

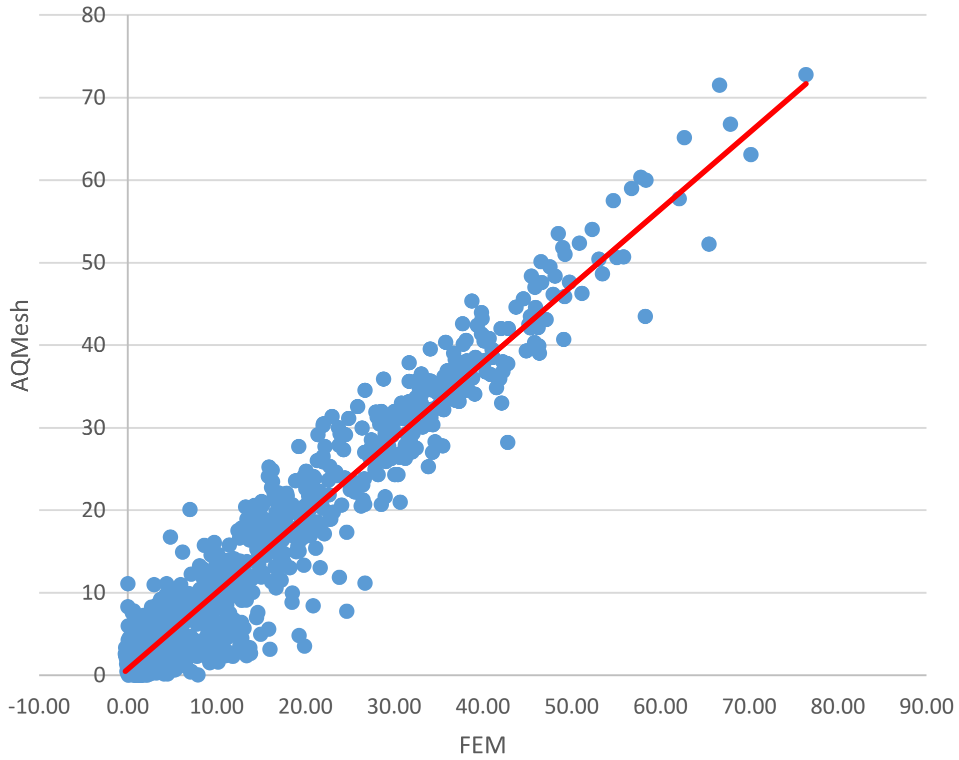


v5.0 (Q4 2018-)

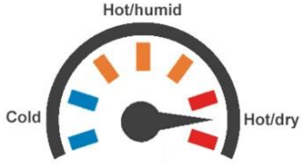
- NO & NO_2
  - Improved compensation in hotter climates
  - Improved "out of the box" (pre-scaled) accuracy
- O_3 & CO
  - Improved "out of the box" accuracy
    - CO typical pre-scaled accuracy (MAE) ±50ppb
- H_2S introduced
- Sensor destabilisation identified
  - Extreme or fast-changing environments

AQMesh

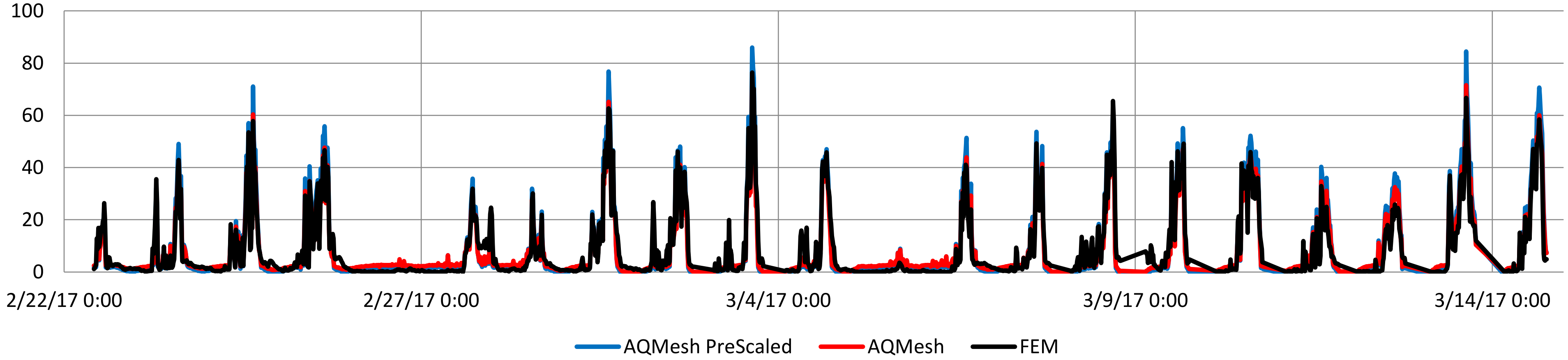
R^2		0.91
Accuracy (MAE)	PreScaled	Scaled
	2.63	2.16
Accuracy (RMSE)	PreScaled	Scaled
	3.80	3.02
Averaging interval		15 minute
Conditions		Hot, dry, desert
Region		Southern California, US
Location		Roadside
Date		Feb 2017 – Apr 2017
Processing version		v5.0



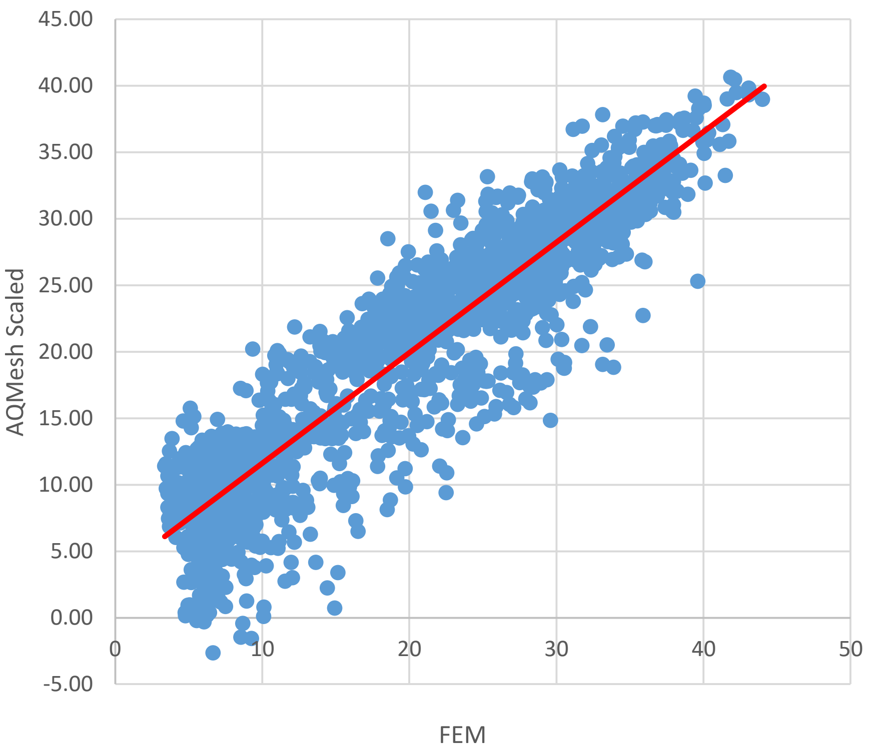
NO

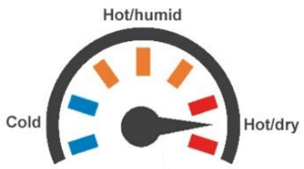


ppb



R^2		0.83
Accuracy (MAE)	**PreScaled**	**Scaled**
	3.20	3.10
Accuracy (RMSE)	**PreScaled**	**Scaled**
	4.15	3.94
Averaging interval		15 minute
Conditions		Hot, dry, desert
Region		Southern California, US
Location		Roadside
Date		Feb 2017 – Mar 2017
Processing version		v5.0





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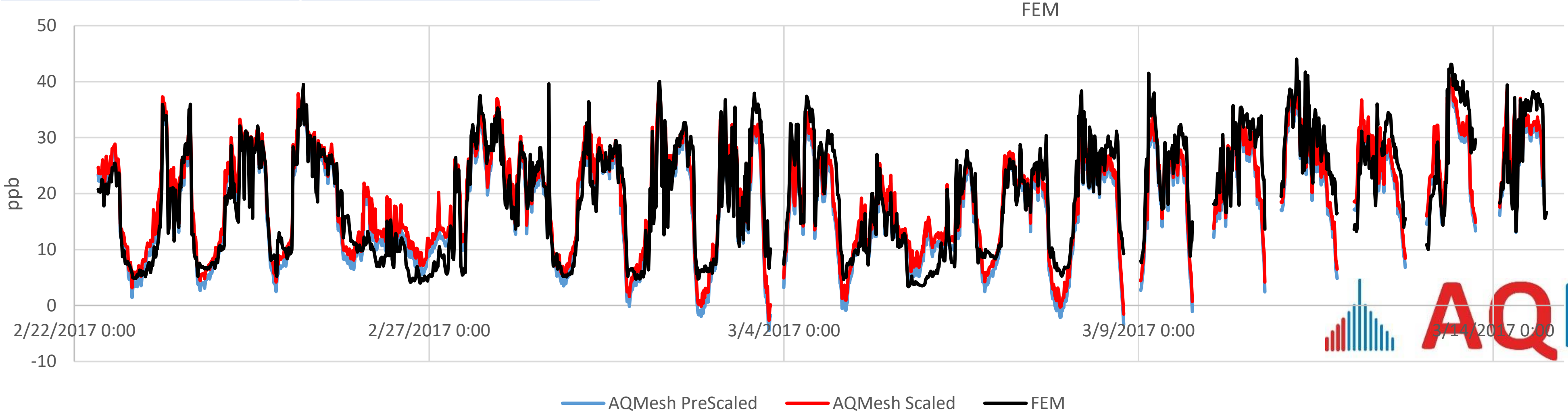


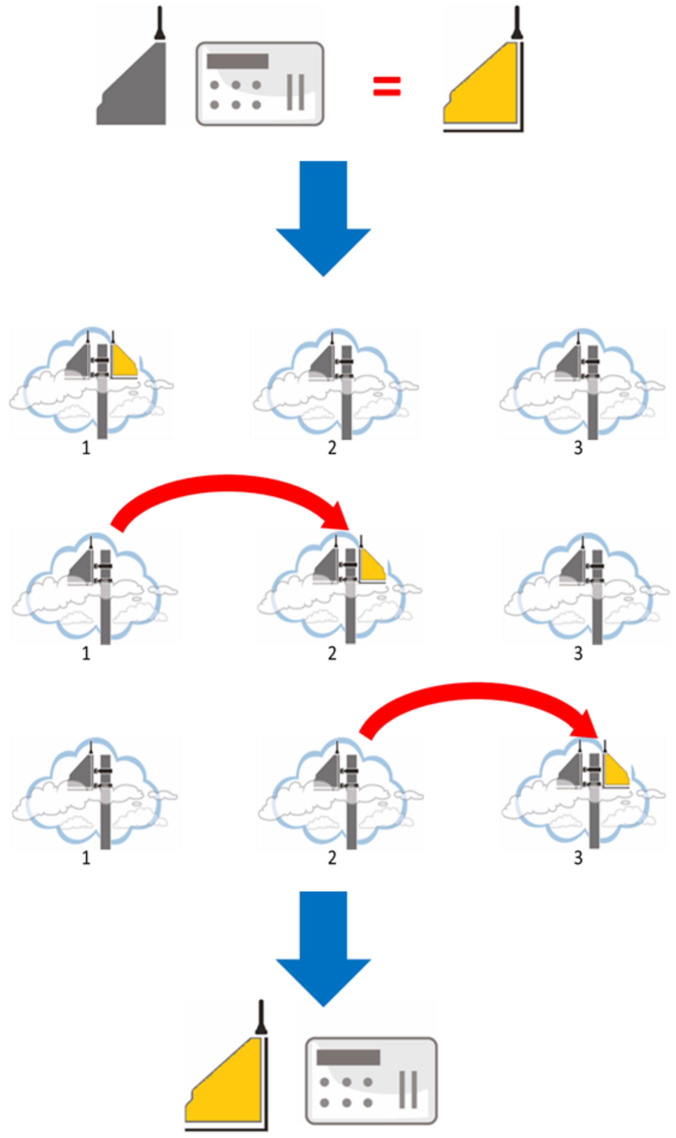
QA/QC

- Three main points that we can manage
  - At manufacture
    - Some sensors rejected
    - Sensor and component variation
    - Factory scaling
  - At data delivery
    - Low confidence or erroneous data points flagged
      - Failed sensors
      - Environmental destabilisation
      - A growing list…
  - Users training: Standard Operating Procedure
- Looking forward to guidance from US and EU authorities

AQMesh

User protocols

- AQMesh Standard Operating Procedure
  - Recommended best practise for optimised accuracy
  - Comparison with co-located FEM to calculate slope and offset
    - ‘Gold pod’ procedure
    - Diffusion tubes
  - Slope and offset input on server and applied to readings going forward
- “Out of the box” / without local scaling
  - Valuable for many applications
    - Where FEM not available
    - Relative measurements are key
    - Accuracy still around ± 5-10ppb
    - “Pre-scaled”



AQMesh

Since 2013 AQMesh is or has been in use in…

- UK
- France
- Spain
- Belgium
- Netherlands
- Norway
- Sweden
- Finland
- Italy
- Australia
- Singapore
- Indonesia
- USA
- Brazil
- Canada
- Azerbaijan
- Israel
- Slovakia
- Malta
- Iraq
- Austria
- Germany
- South Africa
- China
- United Arab Emirates
- Ireland
- Trinidad
- Myanmar
- Serbia
- Czech Republic
- Nicaragua
- Saudi Arabia
- Slovenia
- Bangladesh

AQMesh

Applications

- Transport monitoring
  - Major road routes
  - Specific traffic corridors
  - Mitigation measures
  - Traffic tunnels, eg: UK, France, Switzerland
    - QA/QC challenge
  - Pedestrian subways
  - Monitoring around airports,
    - Saudi Arabia, (CU Heathrow study)
  - Ports – UK (various), Rotterdam & Hamburg

AQMesh

Applications

- Urban hotspot identification / monitoring
  - Cities, towns
  - Around communities or schools
- Construction developments
  - Planning: before and after to measure impact
    - Oxford shopping centre
  - Targeted areas
    - Cambridge congested traffic corridor
- Construction activity
  - On-site dust and generator pollution
  - Surrounding area / off-site dust / emissions
- Industrial
  - Source apportionment around industrial sites, eg: oil facility: Azerbaijan, Iraq, USA
  - Mining: South Africa, Australia
  - "West and North-east shore of Myanmar by Ministry of Resources and Environmental Conservation. These areas are common for fisheries and cold storage seafood for export and some off-shore oil and gas stations."
  - Fence line alerts

AQMesh

Applications

- Smart cities
  - Hyperlocal network
    - London (C40), Minneapolis, Newcastle
  - Clean air zones
    - London Bridge, Tooley street
- Research projects
  - Variation in air quality at height
    - High rise building vents / windows
    - Impact of industrial stack emissions on nearby buildings
  - Assessment of impact of pollution mitigation measures
    - Green barriers
    - Road surface treatment
  - Impact of volcanic activity
    - Nicaragua, Hawaii
  - Complementing modelling
    - NILU and CERC papers
  - Distinguishing between local and regional / remote sources of pollution, eg: Cambridge

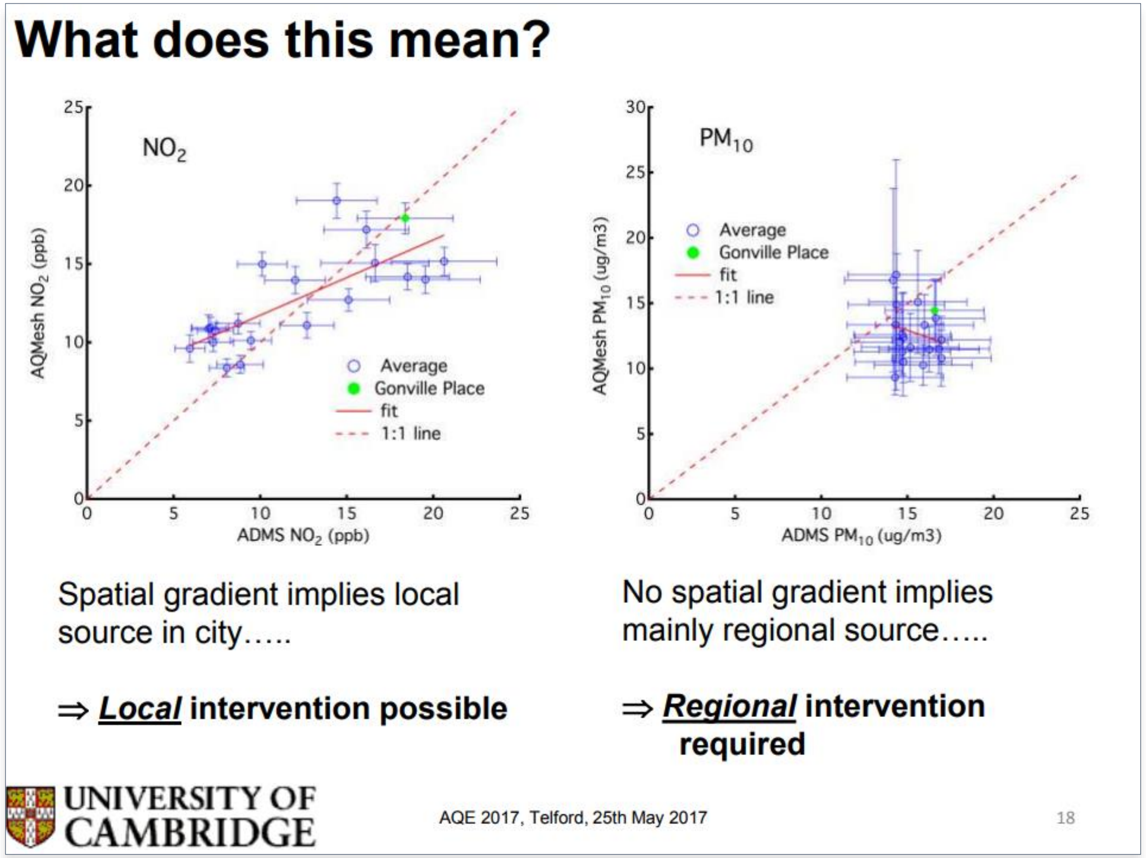
AQMesh

www.aqmesh.com/cambridge

"We're seeing very encouraging results, with correspondences in excess of 0.7 and 0 .8 for R2, and that's very good for something straight out of the box."

says Professor Rod Jones of the University of Cambridge

Read more »



AQMesh

Applications

- Outdoor-indoor
  - Office buildings / HVAC management
  - Air flow management
    - Car dealer, Sweden
    - Industrial process impact
  - Inside vehicles
- Employee exposure
  - Unregulated generator emission
  - H2S in sewage plant
  - Diesel fumes classified as grade 1 carcinogen
- Mobile
  - Walking
    - Glasgow ‘trolley’ study looking at exposure close to ground; BBC study
  - On a bicycle
    - BBC Newsnight, (Cambridge University prototype)

AQMesh

Achievements and remaining challenges

- Achievements
  - Precision and accuracy of gas readings
    - Best performance from gas sensors
  - Understanding and managing limitations
    - Sensor destabilisation
    - Sensor failure
  - Optimising performance by application
    - 'Out of the box'
    - Local scaling and 'gold pod'
  - A practical monitoring tool
  - Wide usage – global / applications
    - Also brings challenges…

- Remaining challenges primarily around QA/QC

AQMesh

Opportunities

- Continued refinement: sensors, processing and QA/QC
  - Metadata, remote diagnostics
- What information AQMesh offers right now, eg:
  - Identifying, understanding and managing sources of pollution
  - Measuring impact of mitigation measures
  - Integration of wider spatial networks
    - Through managed data validation
    - In combination with modelling
- Engagement with general discussion about data validity for local air quality networks

AQMesh

Questions?

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