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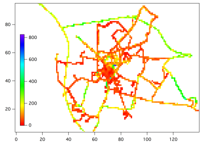
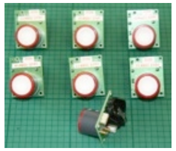
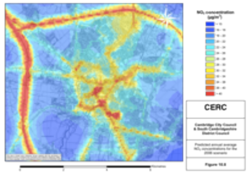
Networked Low-cost Sensors for Environmental Monitoring in Cities

Rod Jones (and team!)

rlj1001@cam.ac.uk





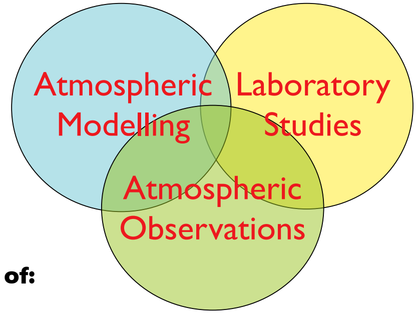


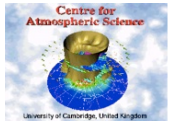
University of Cambridge Centre for Atmospheric Science:

World leading multidisciplinary research in atmospheric and environmental science

- **Fundamental science**
  - Natural environment
  - Climate Change
  - Hazards (e.g. volcanic)
- **Applied Science**
  - Air quality
  - Observational methods
  - Aviation (impacts, technologies)

Synergy in atmospheric science





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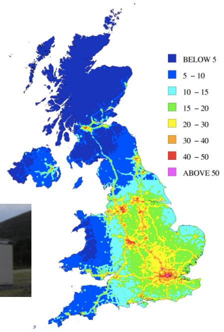
Departments of:
Chemistry
Applied Mathematics
Geography
Earth Sciences
Engineering
Architecture

20 + academics,
100 + researchers
> £10M p.a.

Motivation: granularity in urban air quality - on all scales

- Inhomogeneity in urban A/Q (sources, meteorology, chemistry)
- Non-linearity in chemical processes – main atmospheric science driver
- Precision (e.g. UK: AURN) monitoring sites costly and sparse (capture real variability?)
- Low cost solutions (e.g. NO_2 diffusion tubes) give coarse time (>bi-week) averages (precision?)

⇒ Alternative solutions?



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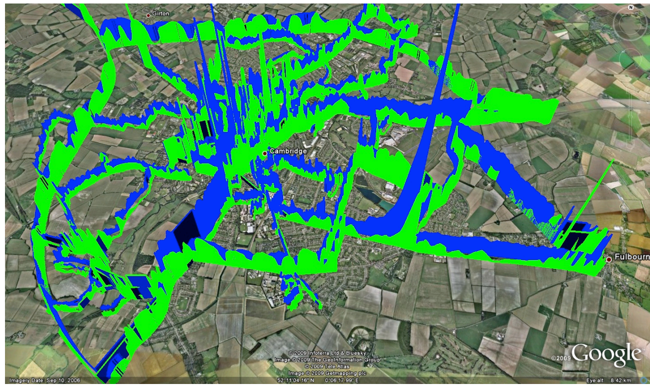
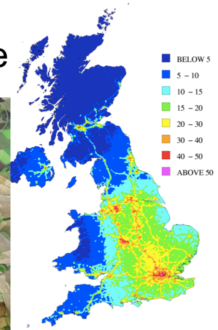
Philosophy: A 'poor' measurement in the right place may be more use than a precise measurement in the wrong place





In fact, not that much worse………

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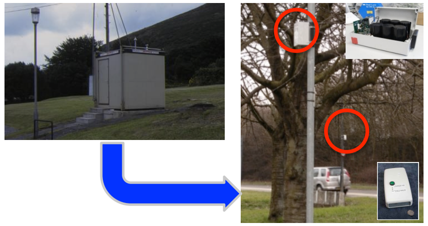
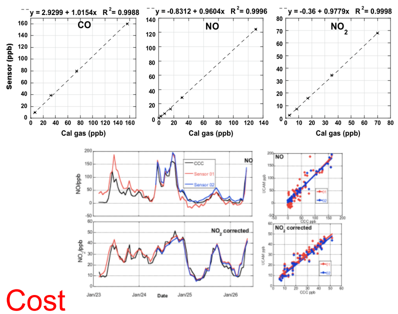
Development of *sensor networks* at the University of Cambridge*

Key Points

1). Miniaturisation/portability



2). Performance



3). Low Cost

50-100 fold reduction in cost per sensor node (also in size).

Potential new paradigm for air quality measurements
(if they can be made sensitive enough)

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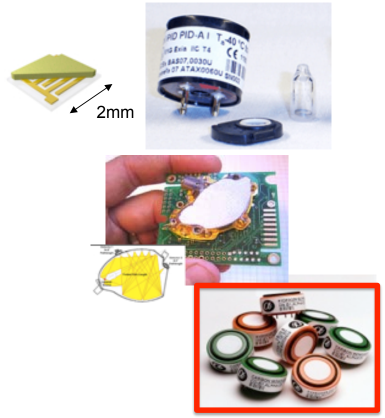
Basis for sensor network system approach:

Low cost miniature gas sensor technologies



- Electrochemical
- Non Dispersive IR
- Photo-ionisation Detection
- Metal Oxide
- SAW
- ……..

>factor of 100 cheaper (and smaller) than traditional methods
- if they can be made sensitive enough

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Miniature Sensor Methodologies

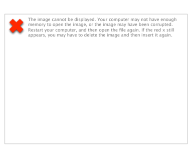
Electrochemical: e.g. NO_2, NO, CO, O_3, SO_2…

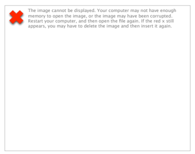
Spectroscopic: e.g. CO_2, CH_4…

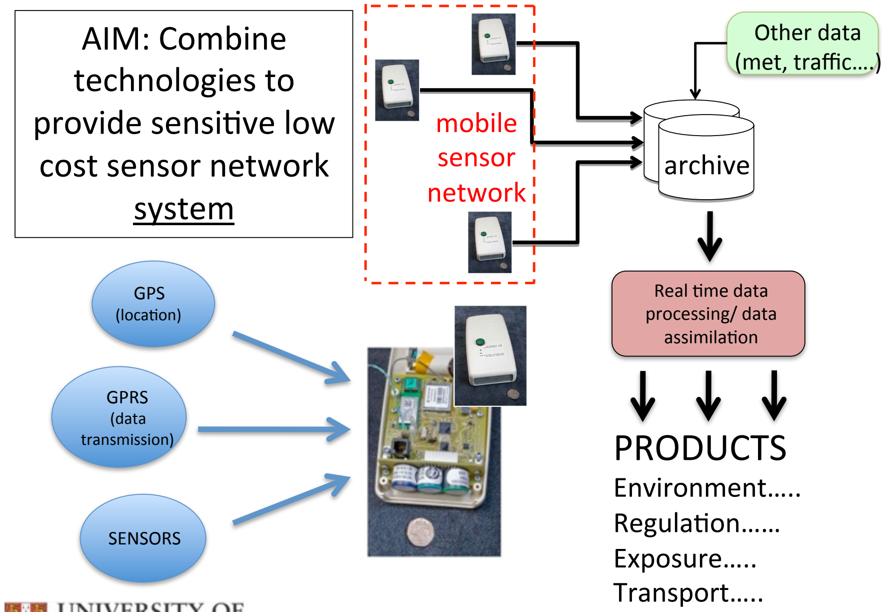
Photo-ionisation: Σ hydrocarbons

Optical: particulates PM_{10}, $PM_{2.5}$

Additional: Temperature and Relative Humidity







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Mobile Environmental Sensing System Across Grid Environments

- Collection and analysis of information from 'complex' environments (urban air quality)

Imperial College London · UNIVERSITY OF CAMBRIDGE · University of Southampton · Newcastle University

Development of low cost mobile gas sensor system for real time monitoring of urban pollution.

Cambridge role: sensors!

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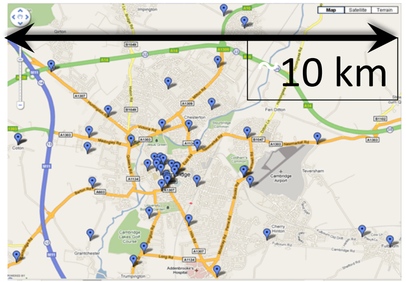
Static Sensor Deployment, Cambridge (UK)

- 2.5 month deployment
  - May-July 2010
- 46 sensors
  - CO, NO, NO_2, T, RH
- Lamp post mounted
- GPRS & GPS functionality
- Real time data transmission
- Inner city, mixed urban, rural
- >25,000,000 measurements



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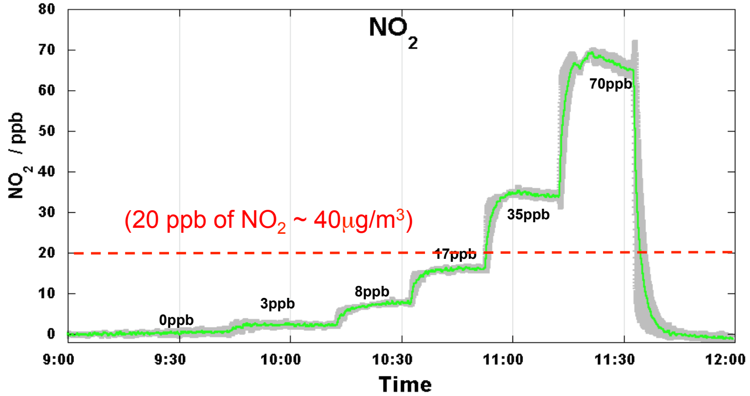
Performance of (enhanced) electrochemical sensors NO_2 sensitivity (laboratory)



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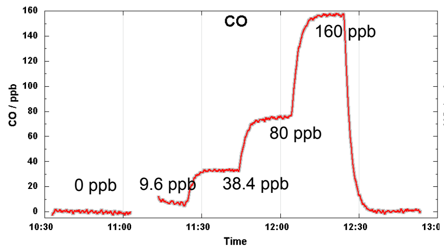
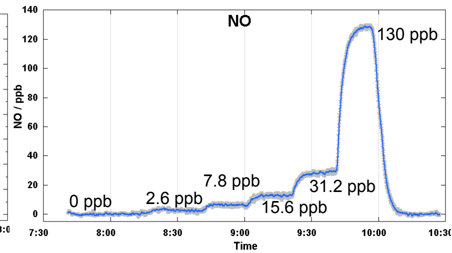
Indication of electrochemical sensor CO sensitivity (laboratory)





Improvements in: **Hardware**, control **electronics** and **analysis**

Viable tools for urban air quality monitoring.

Need to carefully consider data processing

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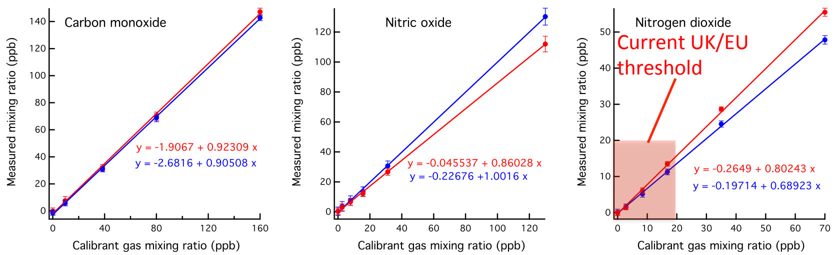
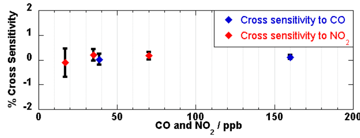
Electrochemical sensor CO/NO/NO_2 sensitivity (laboratory)



Sensitivity at the ppb level, (repeatability + selectivity*) in laboratory



* Some exceptions…

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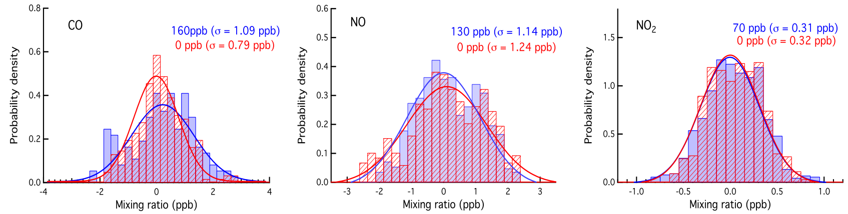
Electrochemical sensor CO/NO/NO_2 sensitivity performance (laboratory)

Noise characteristics:



- Typical sensor sensitivities/LoD are < 5ppb (< 7μg/m^3) for CO, 1-2 ppb (~2-4 μg/m^3) for NO and NO_2.
  - SO_2, O_3 have comparable performance to NO_x.
- Typical sensor T_{90} ~ 10-20s (determined by diffusion)
  - Very low power consumption (μW)

Electrochemical sensor performance:

Is laboratory performance replicated in the field?

Use *software* to account for sensor limitations

- Ambient T/RH corrections…
- Cross interferences…..
- …….
- …
- ..

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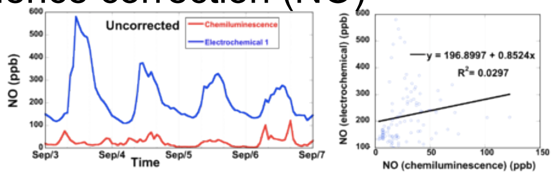
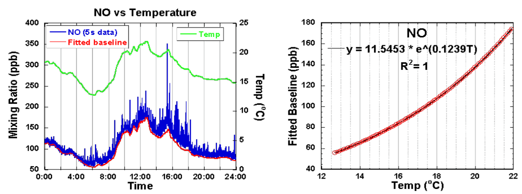
Electrochemical sensor baseline temperature/RH dependence correction (NO)

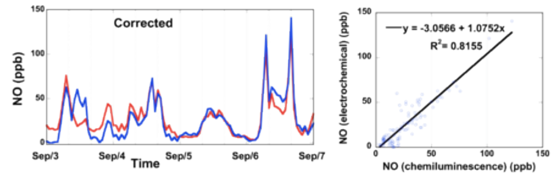
Raw data (electrochemical, chemiluminescence)



Sensor temperature and baseline correction



Baseline temperature corrected (comparison with ratified data)



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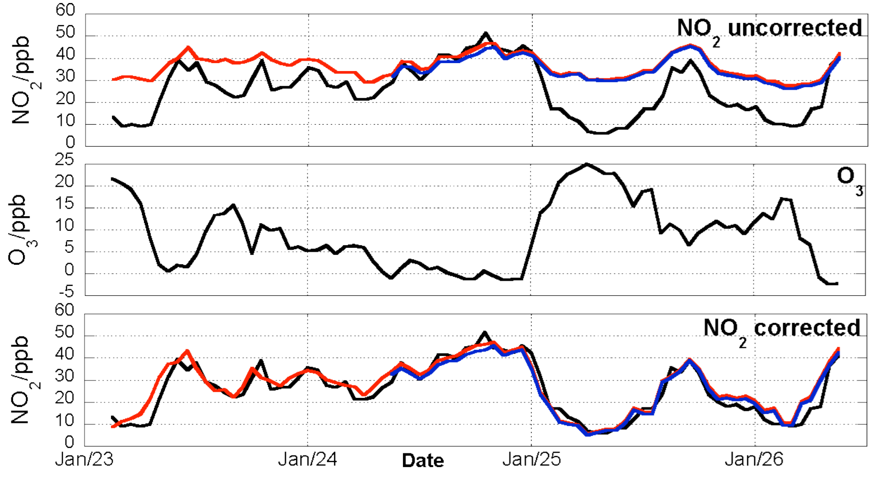
Cross interference (NO_2/O_3) + comparison with ratified site (hourly average)



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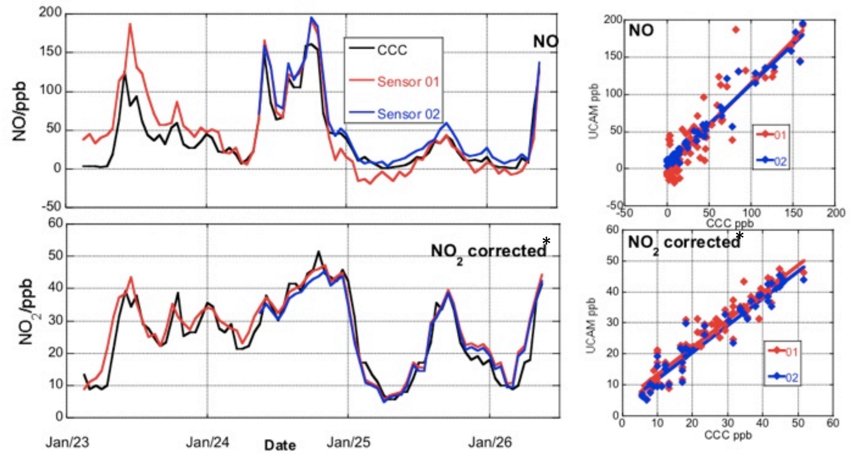
'Real world' comparison of NO_2 and NO with ratified AURN site



* Corrected for O_3 interference

Performance replicated in the field….

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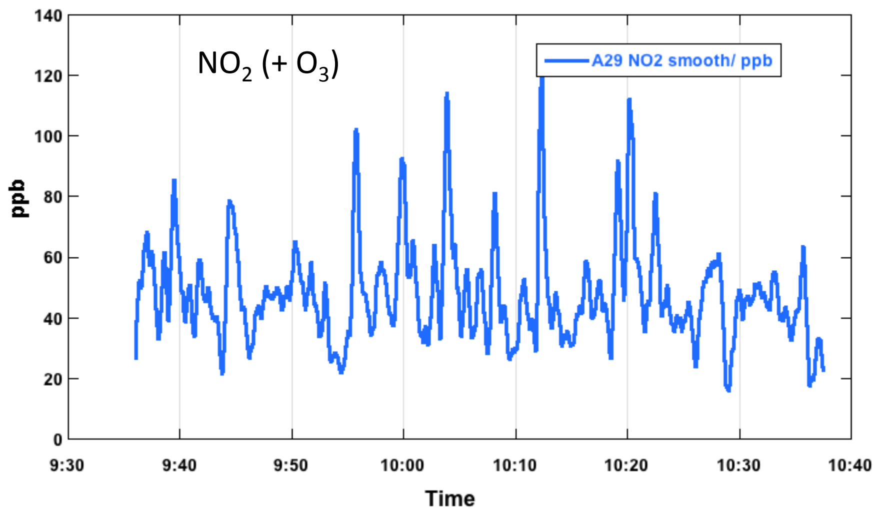
Reproduced in field? – single sensor



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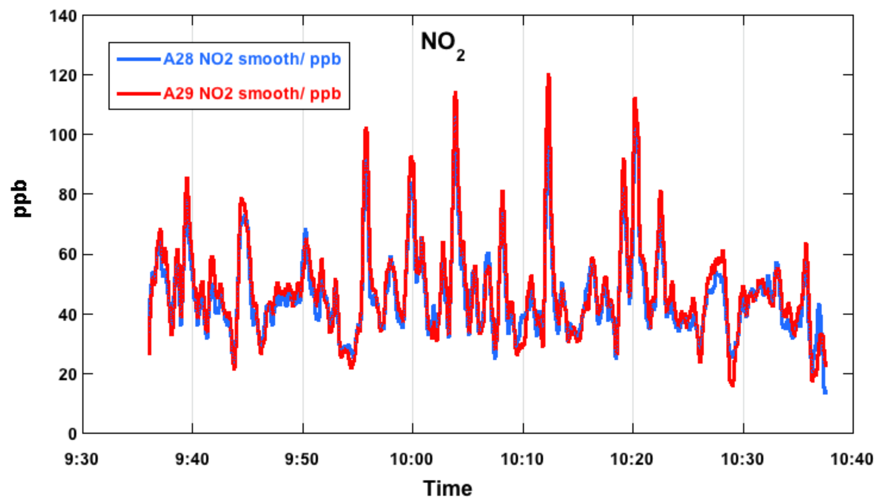
Co-located sensors (NO_2) – real structure



(Uncorrected for O_3)

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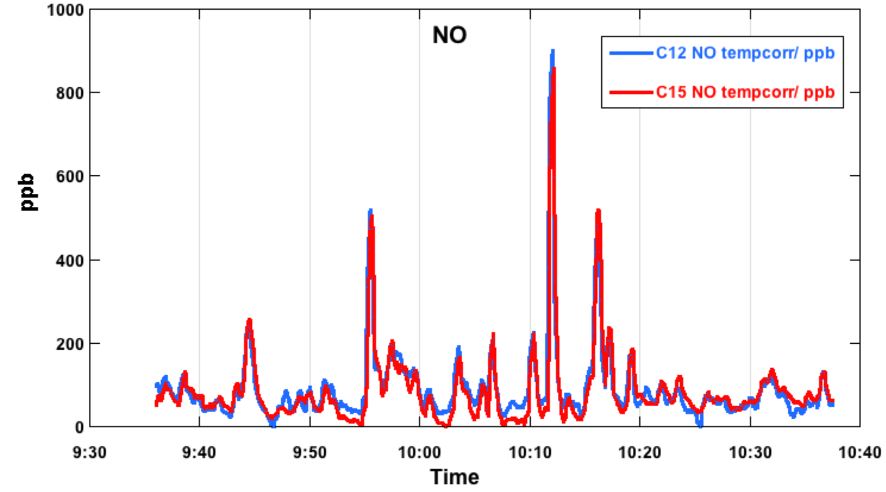
Co-located sensors (NO)



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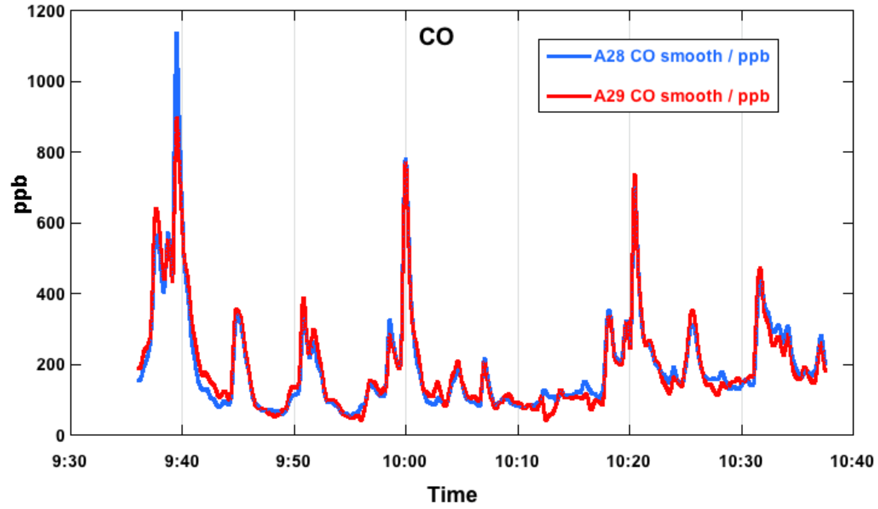
Co-located sensors (CO)



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Three-species mobile sensor node

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Multi-species real time mobile measurements of air quality in complex environments

Carbon Monoxide CO   Nitrogen Dioxide NO_2

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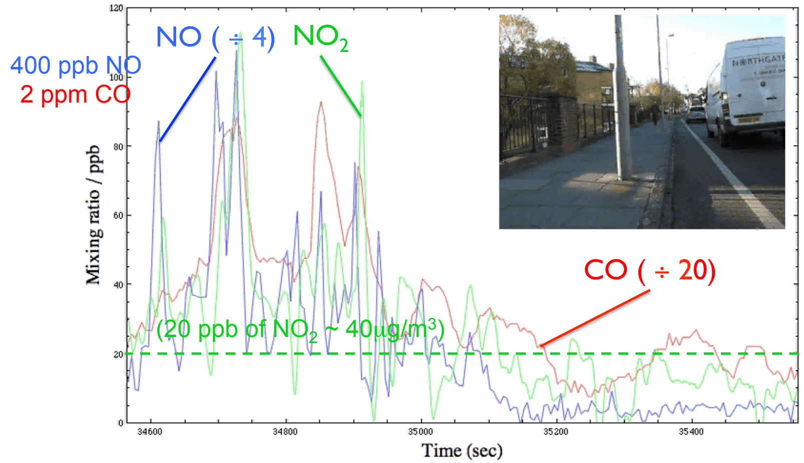
Multi-species real time mobile measurements of air quality in complex environments



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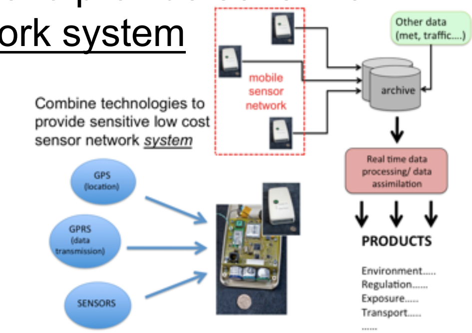
Effects of environmental exposure,
MRC, Feb 21st -22nd, 2012

Combine technologies to provide sensitive low cost sensor network system

- Real time location and data transmission by coupling sensor technology to GPS and GPRS



- Real time data processing including analysis/interpretation and visualisation (Imperial College)

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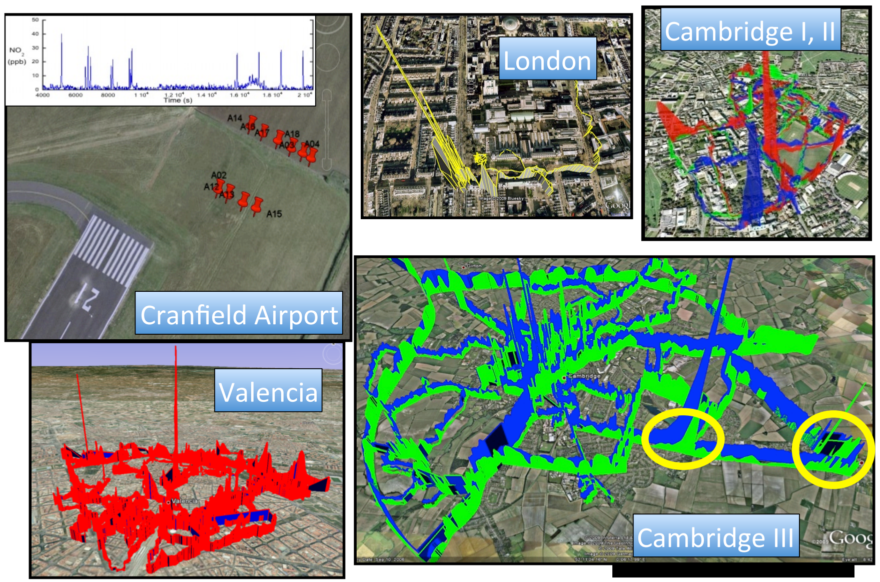
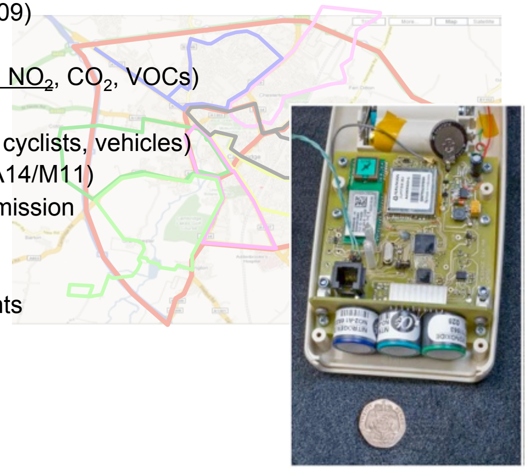
Examples of Collected data



Mobile sensor network deployment: Cambridge (UK)

- 4 hour deployment (2009)
- > 40 sensors (CO, NO, NO_2, CO_2, VOCs)
- 3 transport modes
- (walkers, cyclists, vehicles)
- Inner city, outer loop (A14/M11)
- Real time GPRS transmission
- >200,000 measurements



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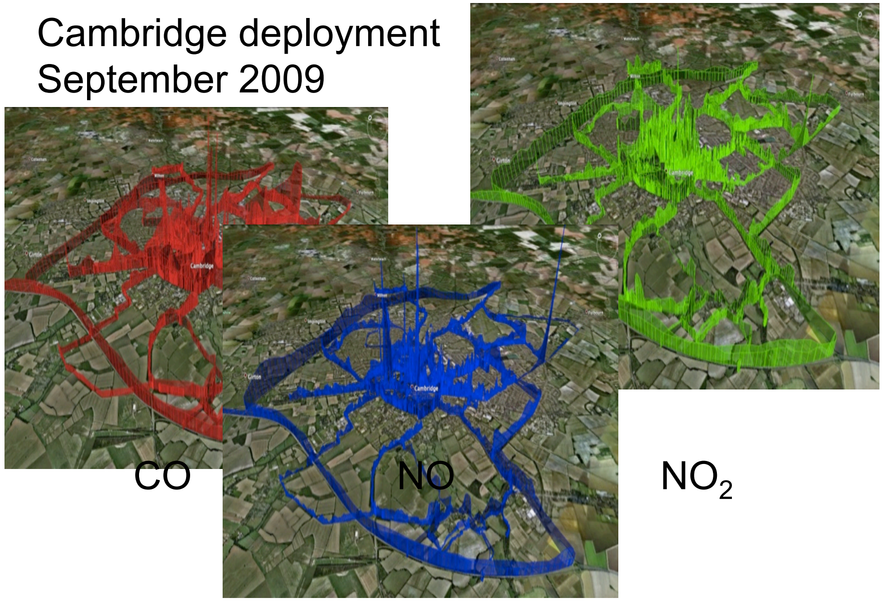
Cambridge deployment September 2009



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Cambridge deployment September 2009: NOx

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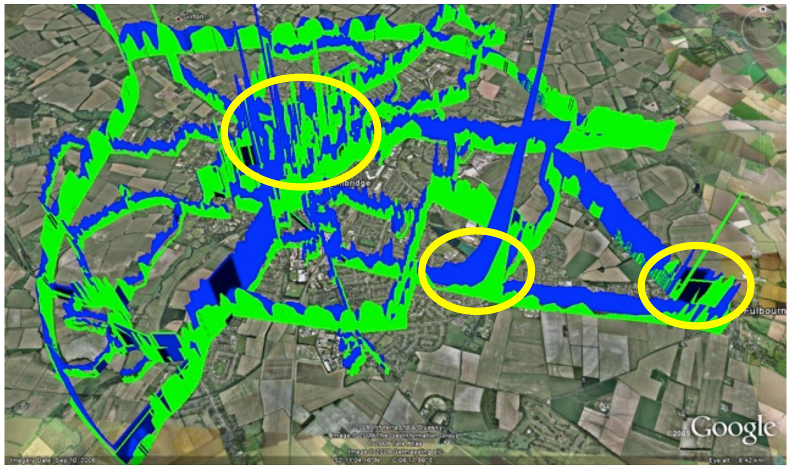
Visual determination of pollution hotspots – not possible with static sites



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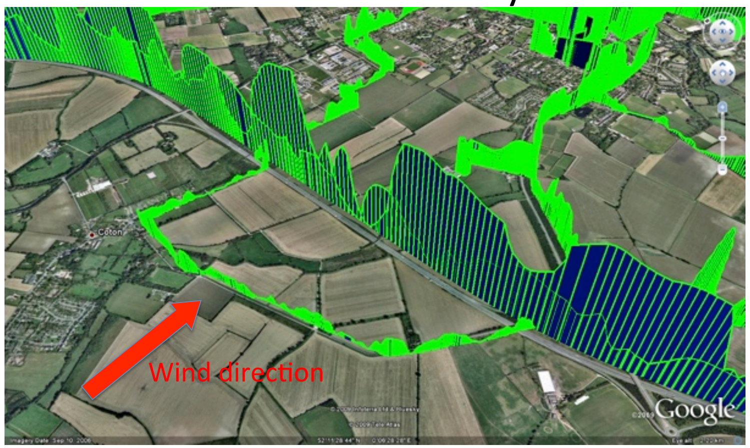
An example: NO_2: car vs bicycle – rural vs motorway



Personal exposure vs activity........

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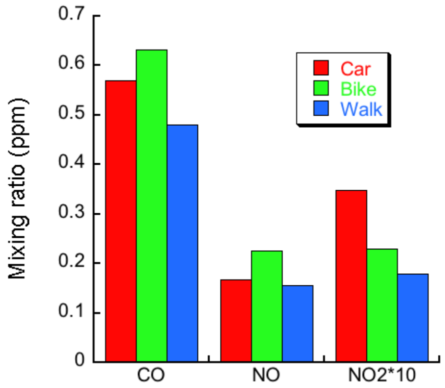
Statistical assessment of mobile A/Q data by transport mode (simplest possible!)



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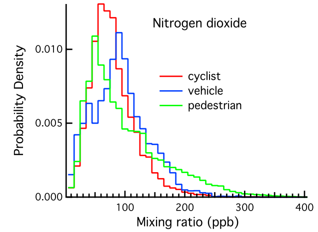
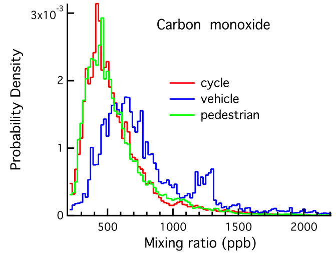
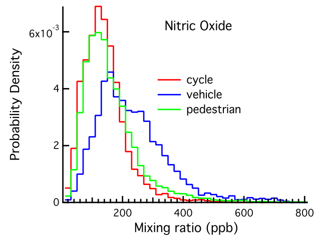
Derive ensemble averaged statistics – distinguish between transport modes:







Snapshots……….

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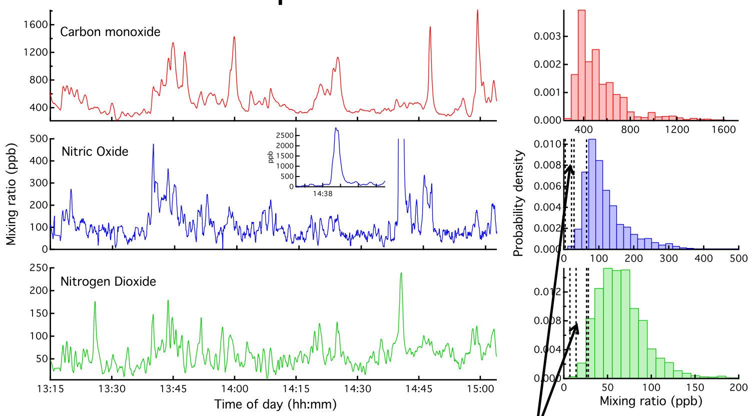
Individual exposure: are fixed site measurements representative?



Fixed site hourly averages (dashed lines)

Answer: no……

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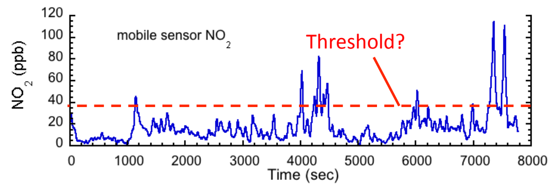
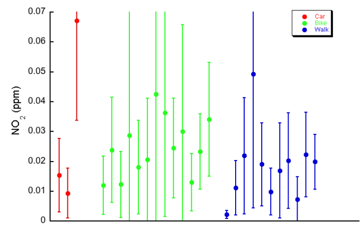
Quantification of individual exposure (not dosage – how to link to health outcomes?)



Individual high pollution events

vs



Ensemble statistics on exposure

Methodology for quantification of peak and average exposures

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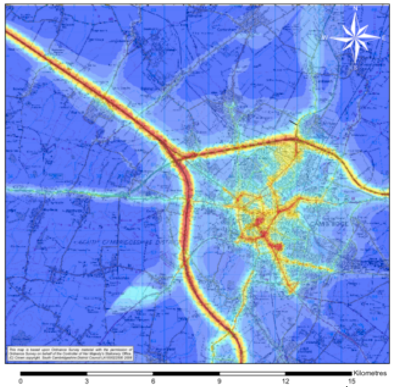
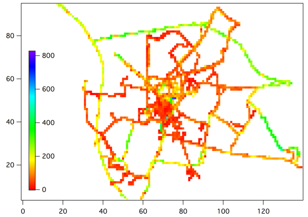
Validation of models



CERC ADMS model (David Carruthers)

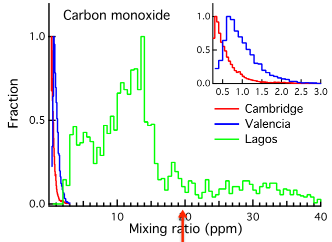
Structure within street canyons?

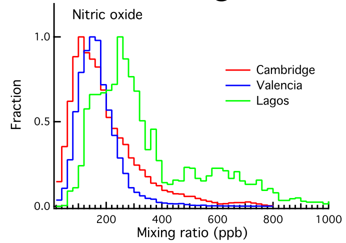
Mobile sensor network quantification of personal exposure



Determine personal exposures rather than 'simple' spatial distribution?

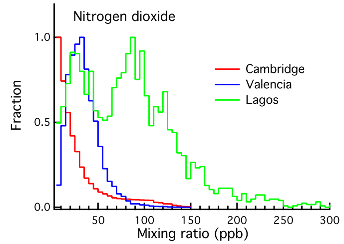
Regional air quality (snapshots): Cambridge, Valencia, Lagos





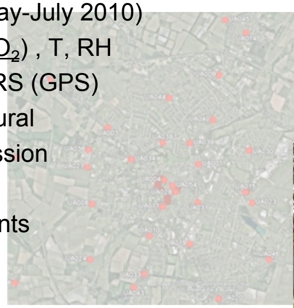
Dramatic differences……….

Flexible low cost way of characterising A/Q

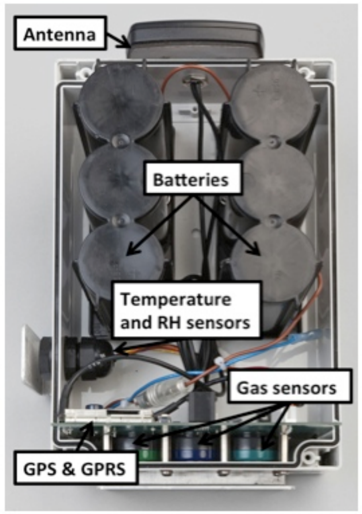


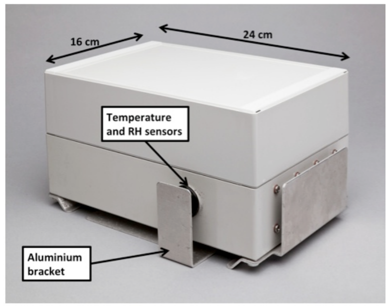
Static Sensor Deployment, Cambridge (UK)

- >2 month deployment (May-July 2010)
- >40 sensors (CO, NO, NO_2) , T, RH
- Lamp post mounted, GPRS (GPS)
- Inner city, mixed urban, rural
- Real time GPRS transmission
- >25,000,000 measurements

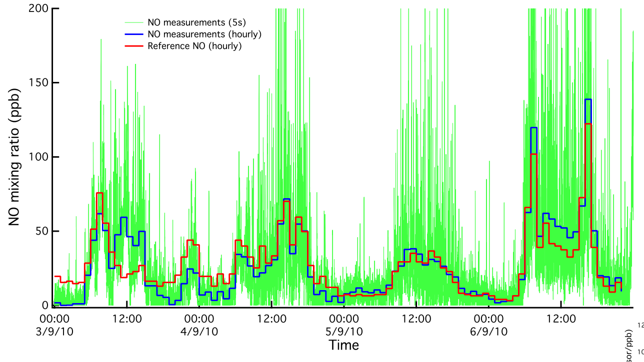


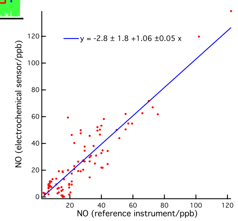
Three-species static sensor node





Hourly average *vs* fast response – near co-located instruments





Structure present on all measured scales

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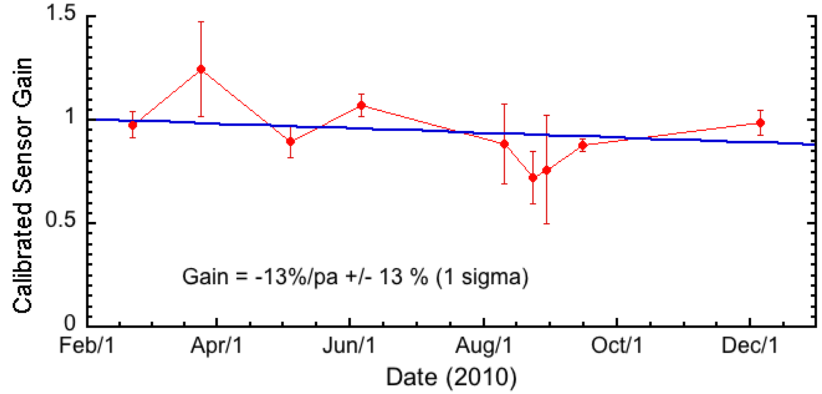
'Real world' long term stability tests (NO) with ratified AURN data



Calibration stability expected to exceed ~2 years

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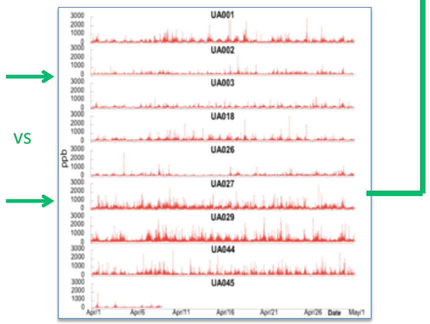
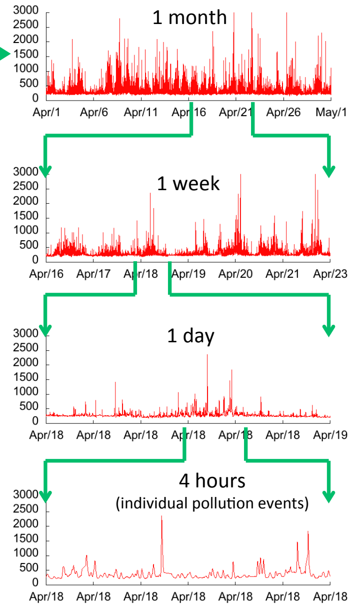
Static deployments (carbon monoxide)

Grid (46 sites)





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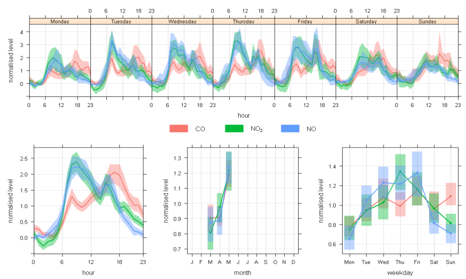
Statistical Studies

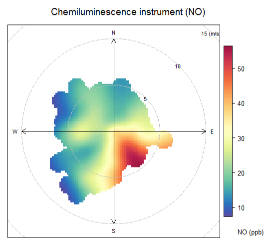


Electrochemical

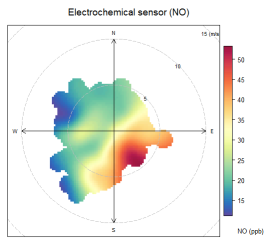
Diurnal patterns, weekend effects…

Bivariate plots (source attribution)

OpenAir open source air quality analysis tool (OpenAir 2010)),



Reference instrument



Electrochemical

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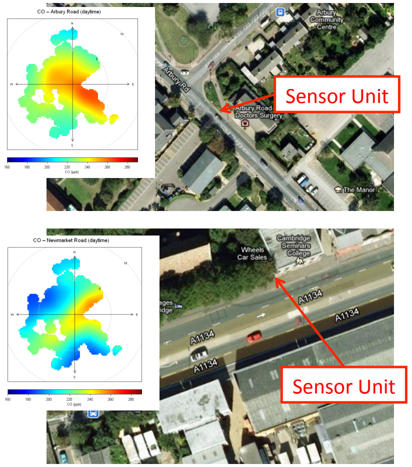
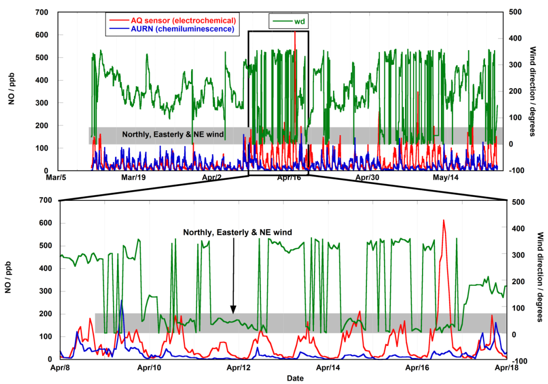
High-density mapping

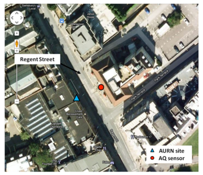
Street canyon effects: wind direction and re-circulation

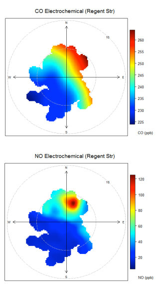


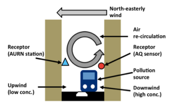
High concentrations when wind direction aligned to road

Street canyon effects: wind direction and re-circulation





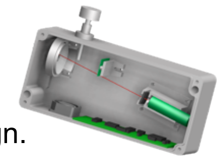




Marked canyon effects for some wind directions (perpendicular to road)

Where next?: High density sensor network system at UK Heathrow airport (2011-2013)

- 50 sensor nodes, real time data transfer (Electrochemical, NDIR, PID, Optical)
- NO, NO_2, CO, CO_2, SO_2, O_3, VOCs and size-speciated PM.
- Source attribution/model validation for area.
- Novel software tools for calibration, data-mining, visualisation/interpretation.
- Methodology for optimising sensor network design.



One key aim is to assess added information content from sensor networks…

High density sensor network system for air quality studies at Heathrow airport

Participants:

Institution	Input
University of Cambridge (PI)	sensors, a/q models
Imperial College London	traffic models, visualisation
University of Hertfordshire	aerosol measurements
University of Manchester	aerosol measurements
CERC Ltd	a/q modelling – ADMS
National Physical Lab.	metrology, calibration
Alphasense Ltd	sensor support

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UK National funded high density sensor network system at UK Heathrow airport (2010-2013)

Objectives:

- Sensor network system for a range of air quality metrics in and around Heathrow airport.
- Novel software tools for network calibration, analysis and data-mining, visualisation and interpretation.
- Evaluation against emissions inventories and dispersion models.
- Source attribution outputs for London Heathrow (area).
- Creation of a data set including NO, NO_2, CO, CO_2, SO_2, O_3, VOCs and size-speciated PM for science and policy studies.
- Optimising sensor network design for different environments.

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UK National funded high density sensor network system at UK Heathrow airport (2010-2013)

Additional comments

Network calibration

- Exploit a central reference site to allow 'non invasive' calibration across network
  - concentration correlations?
  - Lagrangian methods?
  - Kriging analysis?

Optimising sensor network design

- Evaluate 'information content' – e.g. source attribution - as a function of number of nodes in network

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Sensors and sensor networks: conclusions (and caveats)

- **Low cost mobile sensor units for real time air quality with GPS & GPRS a reality (not just this work).**
- Sensors highly reproducible with multiple species measurement.
- Urban composition is highly structured, complex, variable & interdependent.
- Ultra small low cost A/Q sensors now viable for relevant gas phase species at the ppb level – paradigm shift.
  - Quantification of air quality at high spatial resolution.
  - "Real" personal exposure.
  - Source attribution.
- COMPLEMENT existing networks, indoor/outdoor.
- Essential to combine with air quality models (exposure).
- Extend to other species (e.g. O_3, SO_2).
- Dependence on transport modes - dispersion, canyon effects.

Low cost sensor network systems have the capacity to change the urban air quality measurement paradigm

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Acknowledgements

Sensors and Sensor Networks
Iq Mead
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Robin North
Jeremy Cohen
Paul Kaye and UH team
David Carruthers (CERC)

Earlier work
Imperial College
Peter Landshoff
…….

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Wider issues

- Certification/validation
  - Do we need "equivalence"?
  - How do you integrate potentially "less good" instruments into a measurement network?
  - *Information content* rather than *instrument precision*
- Networks
  - Hybrid networks?
    - Mobile *vs* static; heterogeneous measurements
- Use of models
  - Validation (sources, canyon effects etc.)
  - Data assimilation
  - *Informed* model based assessments of air quality/ exposure (c.f. weather prediction)?

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