Low-cost Gas Sensors for Air Quality Monitoring: Overview in Europe and New Trends

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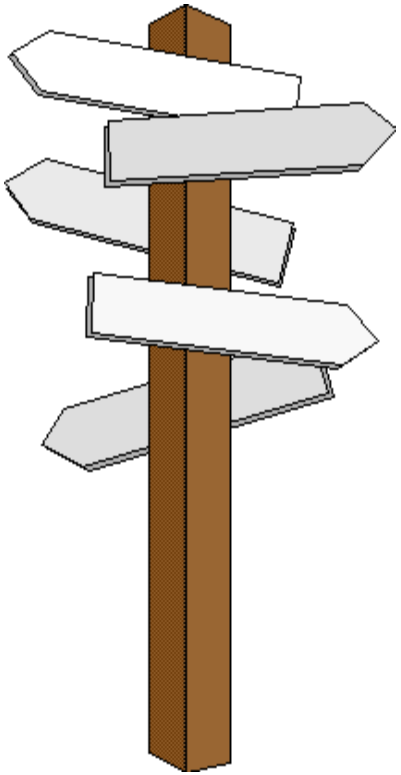
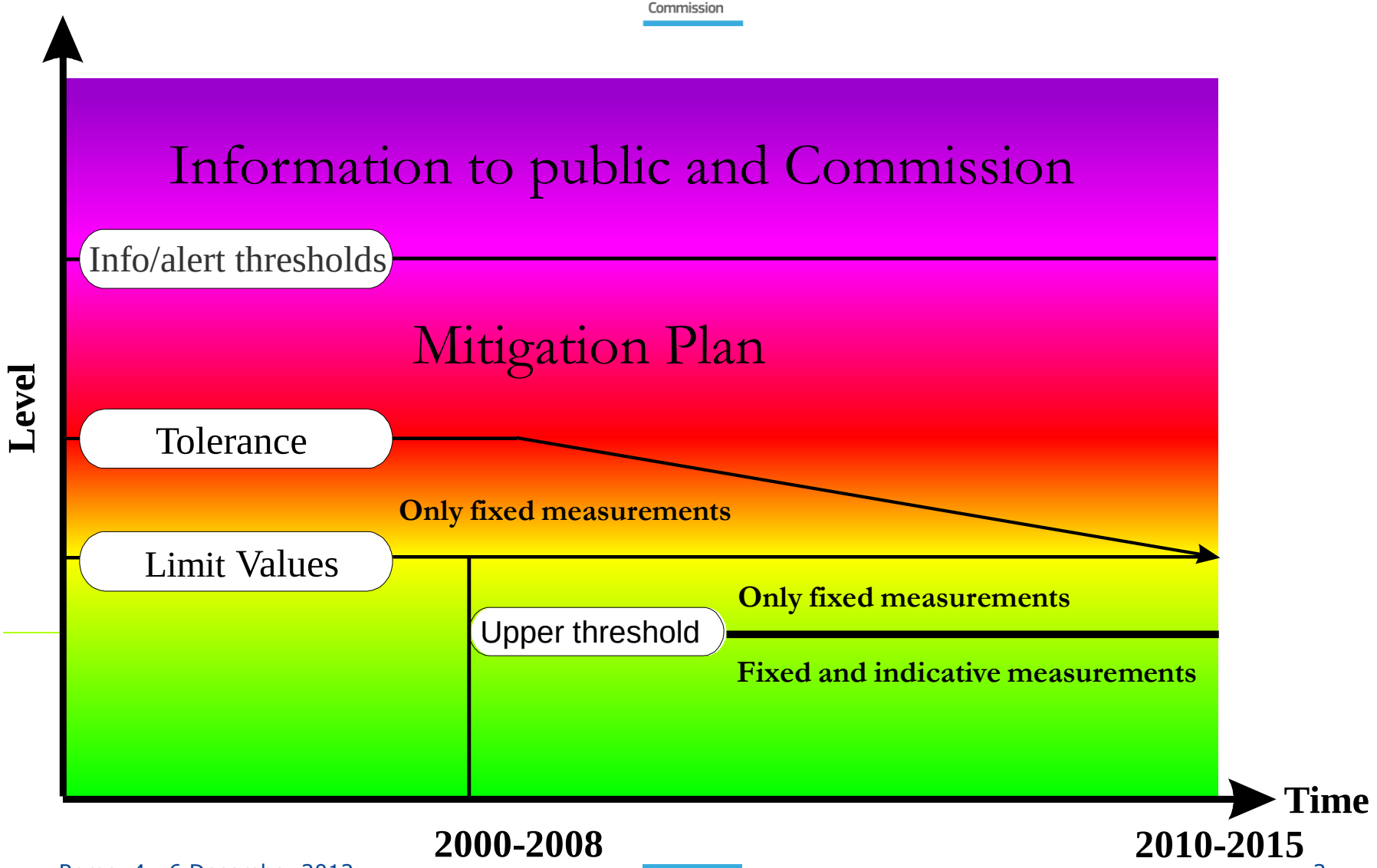
COST Action TD1105, European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability – EuNetAir
FIRST SCIENTIFIC MEETING
Working Groups and Management Committee
Rome, 4 - 6 December 2012



Road map: Monitoring Air Pollution with Sensors for Regulatory Purposes

- Low cost sensor systems: the fixed/indicative methods concept
- Availability of sensors for ambient air monitoring
- Systematic evaluations of gas phase sensors
- On-going validation of sensors


Information to public and Commission
Info/alert thresholds
Mitigation Plan
Tolerance
Only fixed measurements
Limit Values
Only fixed measurements
Upper threshold
Fixed and indicative measurements
Level
Time
2000-2008
2010-2015

Fixed measurements: definition

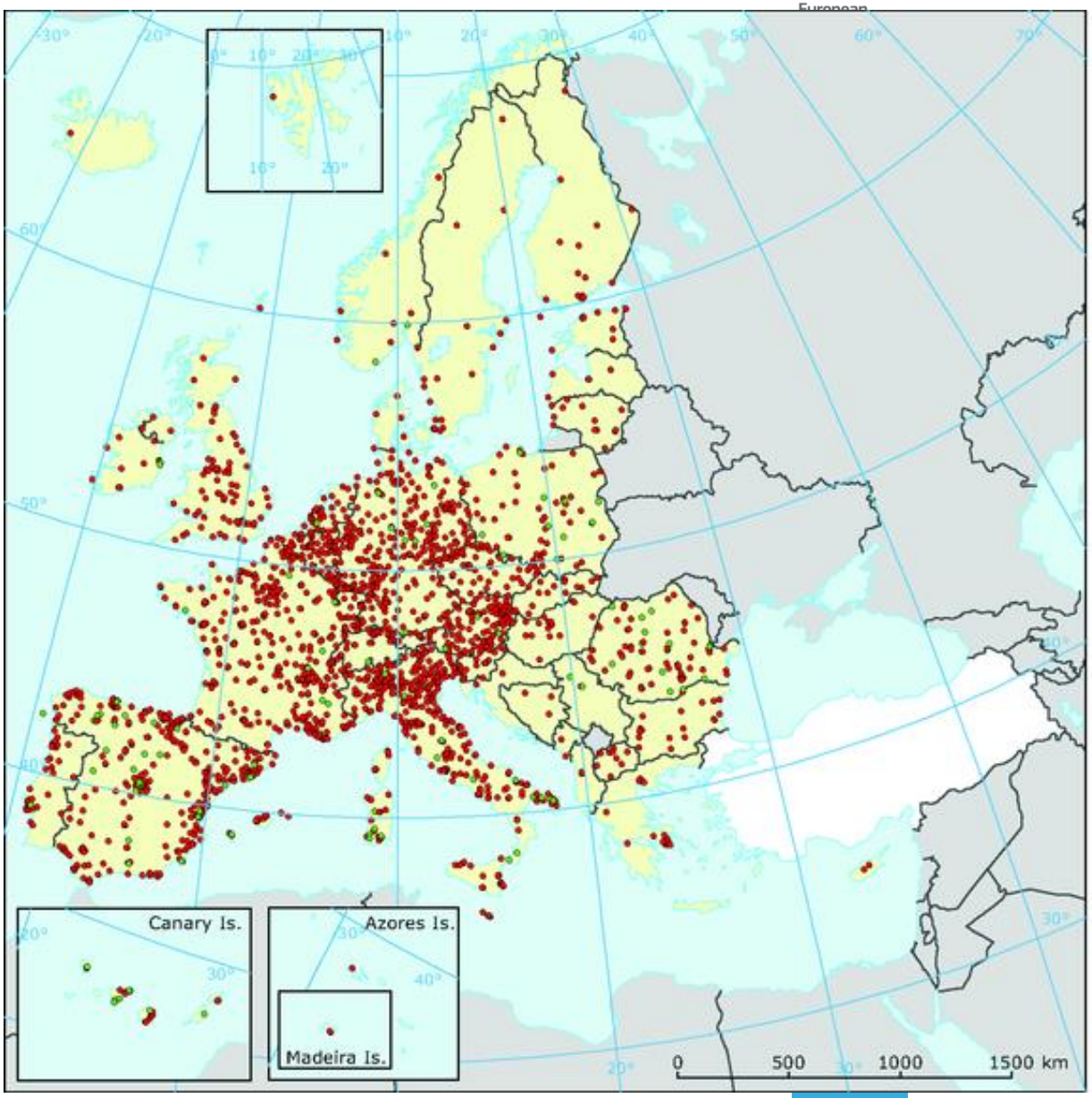
'fixed measurements' means measurements taken at fixed sites to determine the levels in accordance with the relevant *Data Quality Objectives* (DQO);

Fixed measurements are mandatory in zones and agglomerations where the upper assessment thresholds are exceeded.

AQD: European DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe, art. 2

AQD: Data Quality Objectives (DQO)

	SO_2, NO_2/NOx, CO	Benzene	O_3
Uncertainty for **fixed measurements**	15 %	25 %	15 %
	Fluoresc., chemil., NDIR	automatic GC or pumped sampling	UV photometry
	demonstration of equivalence would be mandatory to use micro-sensors		



About 6000 monitoring stations in AirBase

Location of ozone monitoring stations as reported by Member States and other European countries in 2010

European Environment Agency

Fixed measurements: cost per station

Tasks	Estimated cost k€
Purchase/installation of multi-pollutant station including O_3, CO, NOx, SO_2, PM_{10}, power and phone connections, calibration gases, data collection software	**62.5 – 100**
Staff (12 months)	**25 - 62.5**
Annual data management and QA/QC costs	**6.25 - 12.5**
Annual staff costs for site visits	**6.25 - 12.5**
Annual cost of electricity/phone	2.5 – 3.75
Web site, annual software and web site maintenance fees	3.75 – 12.5

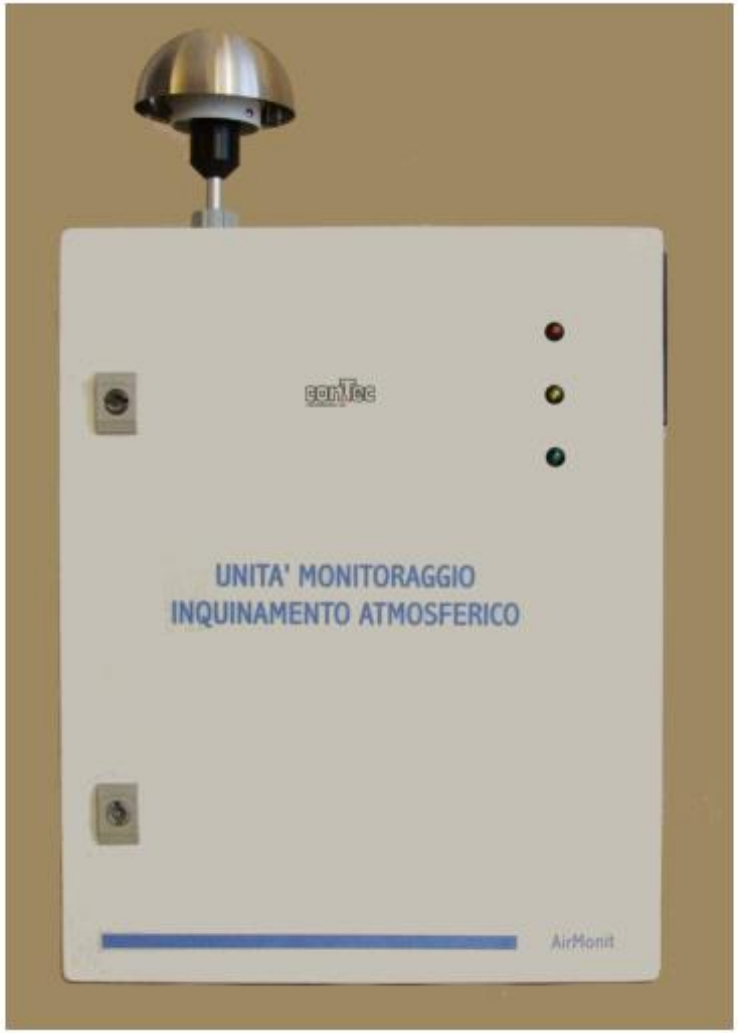
A Guide for Local Authorities, Purchasing Air Quality Monitoring Equipment, AEAT/ENV/R/2088 Issue 2, August 2006, UK

- **UNITEC srl**, ETL3000 multi-component outdoor air quality monitor
- using CO, NO2, O3 thick film sensors, optional C6H6
- built-in data logger (Flash memory)
- 15’ minutes or hourly averages
- GSM modem for remote data handling

AEROQUAL, AQM 60 Air Quality Station
With 6 sensors including:

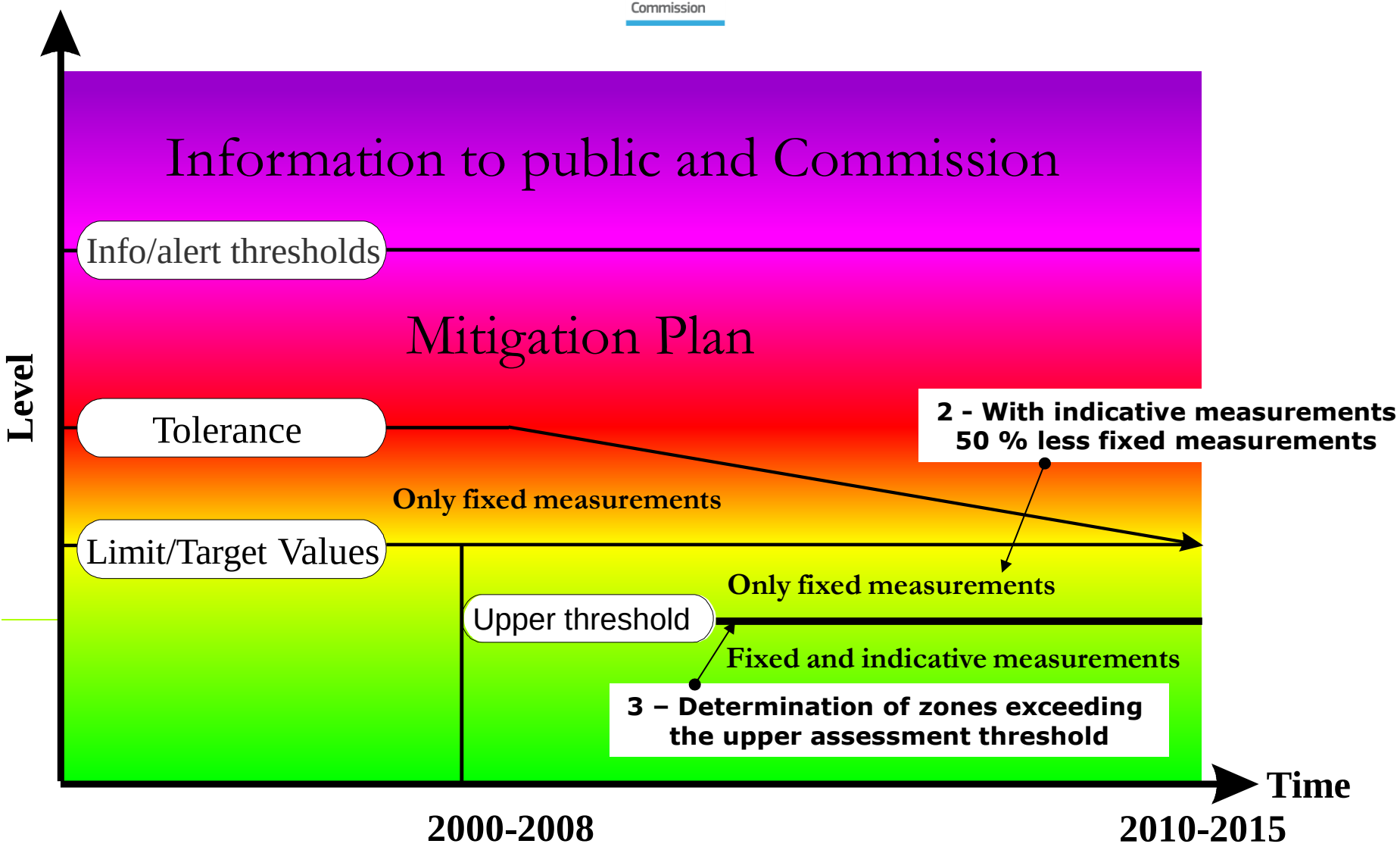
- ozone (O3),
- nitrogen dioxide (NO2),
- nitrogen oxides (NOx),
- carbon monoxide (CO),
- sulphur dioxide (SO2),
- volatile organic compounds (VOC),
- hydrogen sulphide (H2S),
- non-methane hydrocarbons (NMHC),
- carbon dioxide (CO2),
- particulate matter (PM10, PM2.5, PM1)

http://www.conteng.it/Bollettini/AirMonit.pdf



UNITA' DI MONITORAGGIO INQUINAMENTO ATMOSFERICO AirMonit/Contec

- **PM10 – PM2,5 – PM1**
- **CO**
- **NO2**


Information to public and Commission
Info/alert thresholds
Mitigation Plan
Level
Tolerance
2 - With indicative measurements
50 % less fixed measurements
Only fixed measurements
Limit/Target Values
Only fixed measurements
Upper threshold
Fixed and indicative measurements
3 – Determination of zones exceeding
the upper assessment threshold
Time
2000-2008
2010-2015

Indicative methods
upper assessment threshold: definition

'upper assessment threshold' shall mean a level below which a combination of fixed measurements and/or indicative measurements may be used to assess ambient air quality;
Generally, upper thresholds are 60-70 % of limits values (health effect related and requiring a plan for mitigation)

European DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe, art. 2

Indicative methods: definition

'indicative measurements' means measurements which meet *data quality objectives* that are less strict than those required for *fixed measurements*;

AQD: European Directive 2008/50/EC on ambient air quality and cleaner air for Europe, art. 2

AQD: Data Quality Objectives (DQO)

	SO_2, NO_2/NO /NOx, CO	Benzene	O_3
Uncertainty for **fixed measurements**	15 %	25 %	15 %
Uncertainty for **indicative measurements**	**25 %**	**30 %**	**30 %**
	diffusive samplers, ***micro-sensors***		

Indicative method: what for ?

The use of indicative measurements allows for reduction of 50 % of the required minimum number of fixed sampling points.

European DIRECTIVE 2008/50/EC on ambient air quality and cleaner air for Europe, art. 6

Sensor improvement in recent years

- New technologies
- Improvement of existing technologies
- New evaluation studies

New technologies

- Miniaturisation of MOX: huge number of publications on nano particles, nano-wire, carbon nanotubes: no commercial sensors yet
- Graphene sensors (material with low resistance able to enhance sensitivity) – no commercial sensors yet
- Chemical filter directly coated on the sensing layer to avoid cross-sensitivity (NO_2 and O_3)
- Sensors in integrated stations (Unitec, Aeroqual, contec, Libelium …) , light badge

Improvement of existing sensors

- Pulsed-temperature mode (improve sensitivity/selectivity), not commercially available
- Cycles measurement-zero (e, g. AEROQUAL, R/R0)
- Electrochemical sensors with 4 electrodes (Alphasense B4 series, CityTech A3OZ and C3OZ) to subtract baseline drift to signals
- New corrections of temperature/humidity effects on sensor responses (Ingenieros Asesores)

New evaluation studies

- CO, NO_2, O_3 commercial sensors exist in the suitable range of concentrations*

- Little number studies are published for full validation of commercial sensors, mainly some field and laboratory evaluations:
  - USEPA, Characterization of Low-Cost NO_2 Sensors (for Intel Berkeley and Aeroqual sensors), USEPA: Sensoric 3E50 possible NO2 sensor

*** http://www.airmontech.eu/fileadmin/airmontech/user/AAMG_2010-Presentations/MGerboles.pdf**

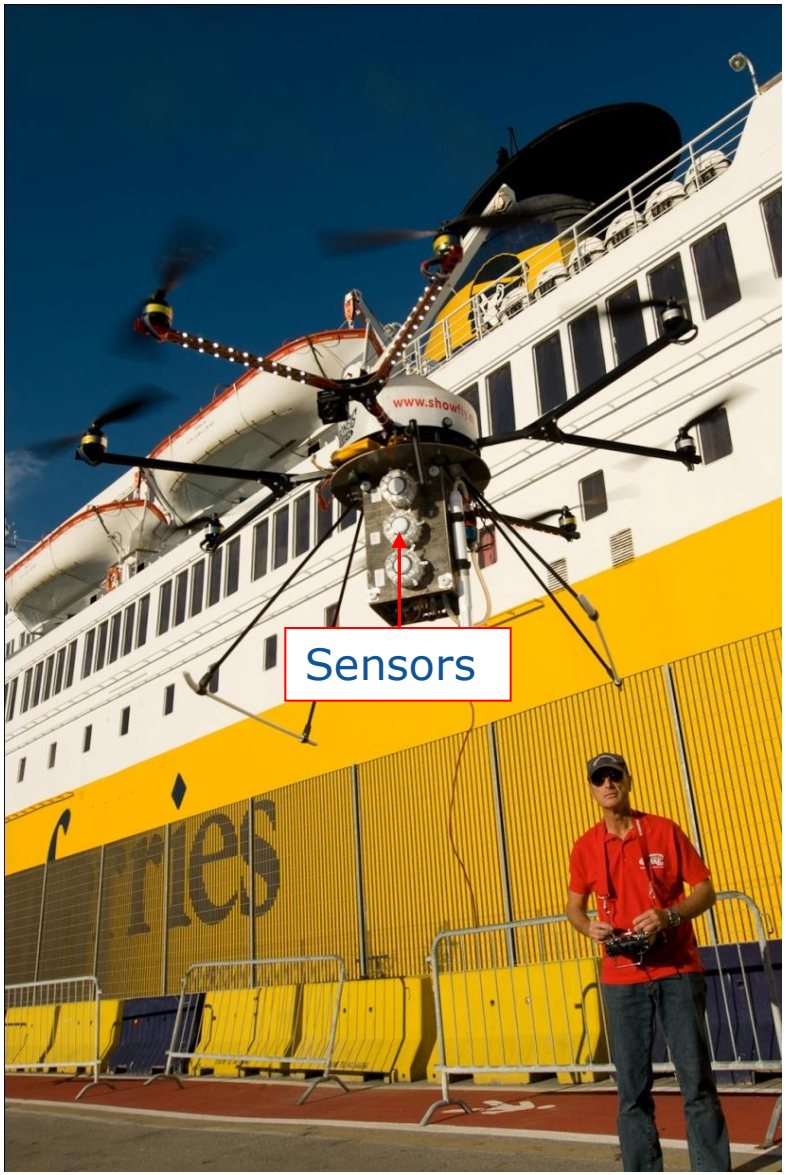
RECENT OR ON-GOING PROJECTS / APPLICATIONS

Recent project (JRC):

Monitoring of ship emissions with high levels of CO, NO, NO_2 and SO_2 using an unmanned Aerial Vehicle (UAV) (i)

The payload (up to 1.5 kg) is carried with a remotely controlled Oktokopter (autonomy: 7 minutes), the measurement signals are sent directly to the ground. A live videocamera was installed to allow better positioning.

FINAL REPORT ON SIRENAS project: Remote Sensing of Ship's Emissions of Sulphur Dioxide, B. Alfoldy, J. Balzani, F. Lagler, J. Hjorth and A. Borowiak, 21.06.2011



Exhaust plume measurement from unmanned flying platform (ppm concentration range):

CONFIGURATION 1:

- Real time measurements by electrochemical sensors:

  -NDIR CO_2 GASCARD (0-3000 ppm),

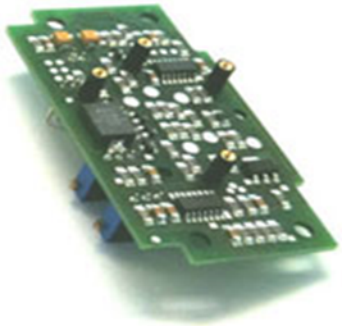
  -NO, NO_2, SO_2 membrapor electrochemical sensors (0-100,0-20,0-20 ppm),

- Temperature.

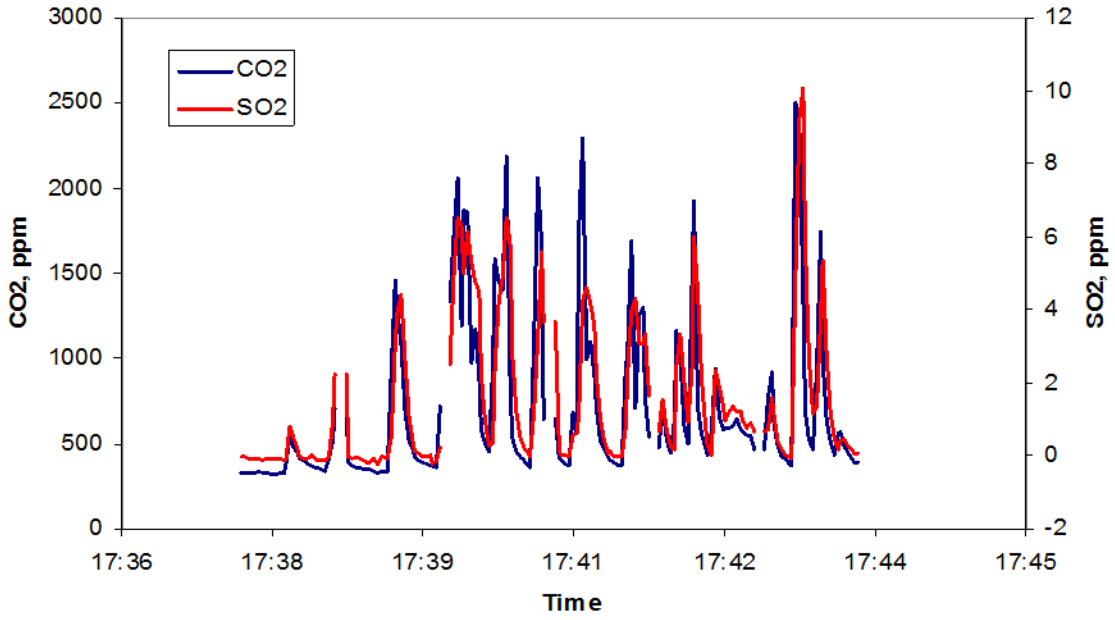
CONFIGURATION 2

- Sampling by under-pressurized canister with a remotely controlled valve,
- Measurement in laboratory by traditional gas analyzers.

Sensor unit



Transmitter unit



Simultaneous SO_2, CO_2 concentration plots

- SO_2/CO_2 ratio: 4.13 ppb/ppm,
- Measurement of canister sample by gas analyzers gives: 3.84 ppb/ppm,
- Difference < 8%.

NETWORK OF SENSORS AT FIXED SITES

Life Rescatame – EC DG Env.

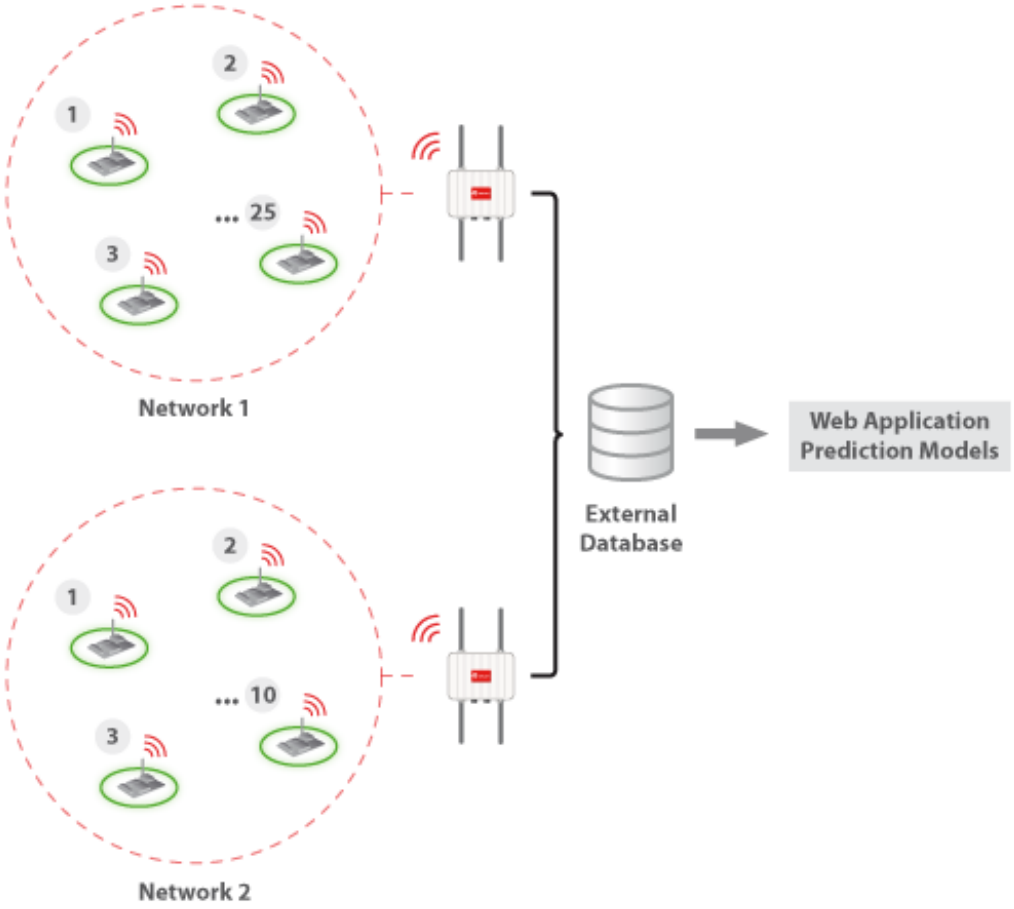
http://www.rescatame.eu

- Prevention of high urban pollution from traffic
- Promote the sustainable management of urban traffic using air-quality sensors + prediction models.

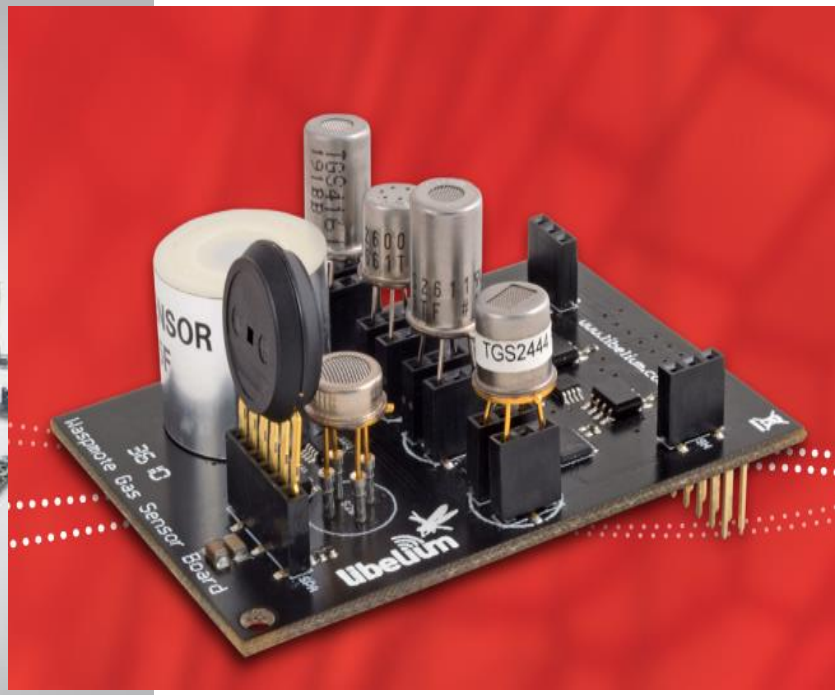
  *The Spanish city of **Salamanca** will be the scenario for this project although the proposed model can easily be implemented in other locations.*

35 Waspmotes were deployed in two different locations; measuring 7 parameters:

Temperature
Relative humidity
Carbon monoxide (CO)
Nitrogen Dioxide (NO2)
Ozone (O3)
Noise
Particle



European Commission

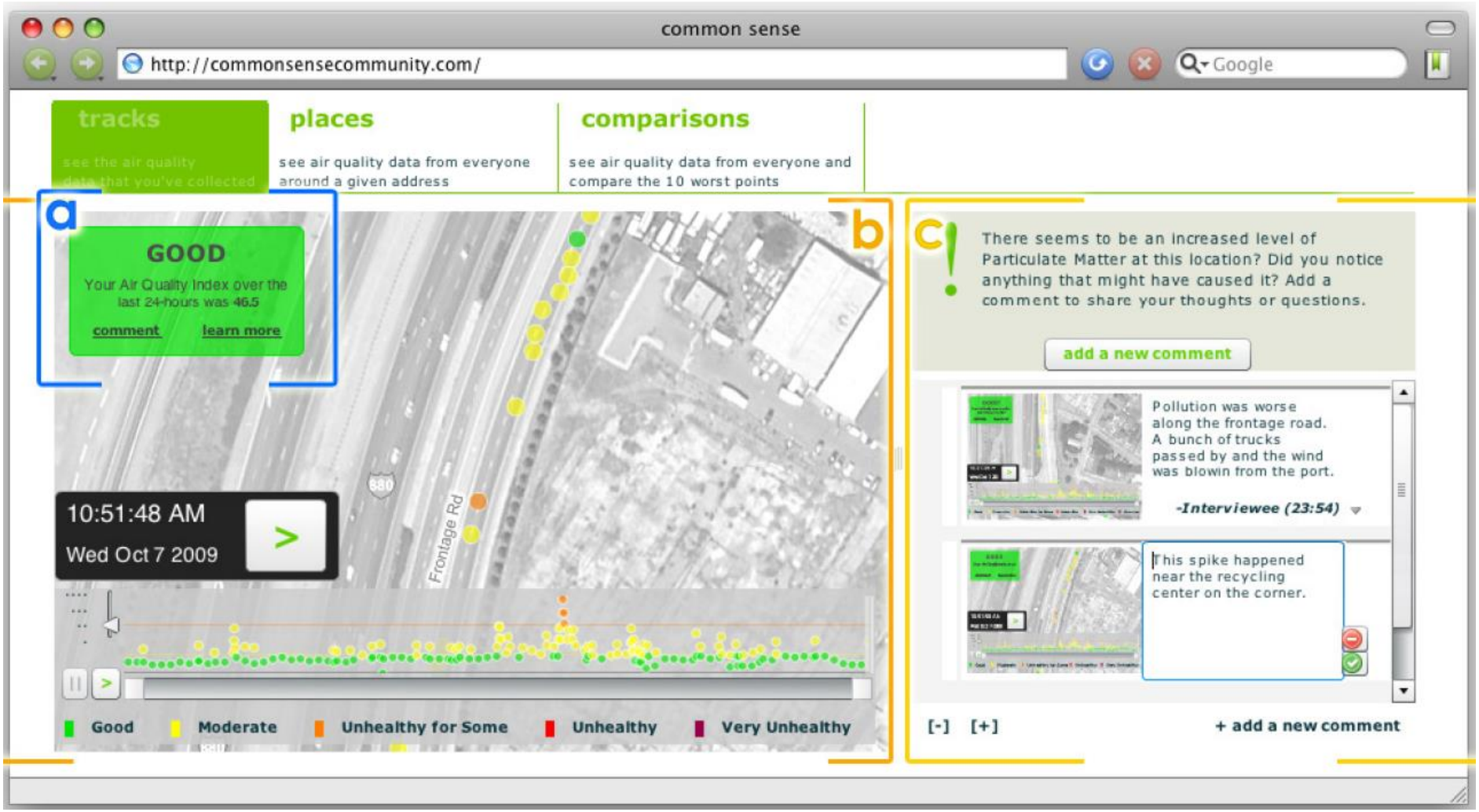


NETWORK OF MOBILE SENSORS

Common sense, INTEL Lab Berkley - USA

- Web-based and mobile applications
- provide live and historical data
- visualization tools
- online community features to allow people to explore and discuss the data and develop strategies for practical action.

European Commission



Sensor units components

Satellite navigation

Mobile phone

Gas sensors

Simple operation!

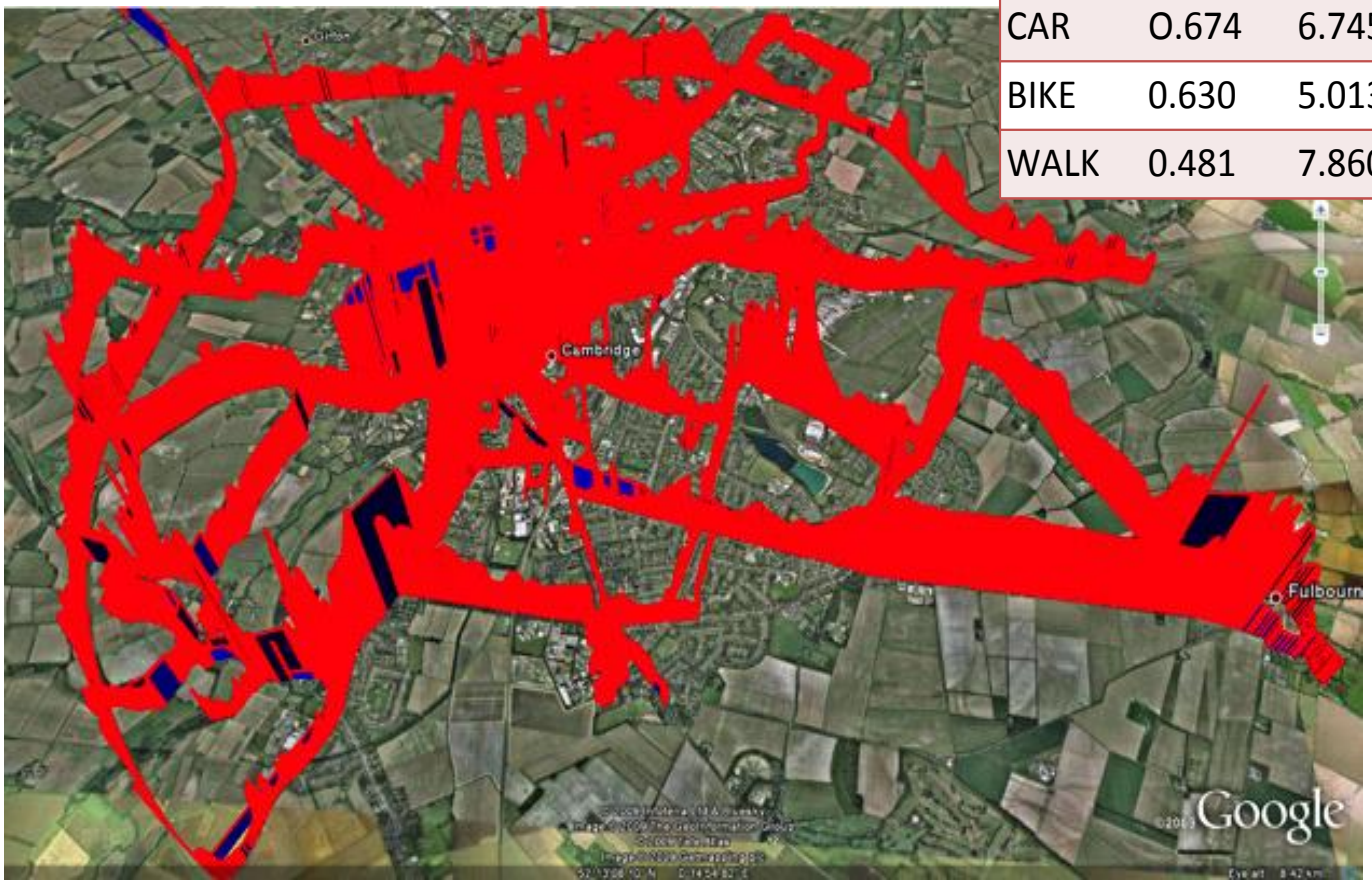
400 gm (incl. batteries)

Rod Jones

rlj1001@cam.ac.uk

Statistical evaluation CO

CO	MEAN	MAX
CAR	O.674	6.745
BIKE	0.630	5.013
WALK	0.481	7.860



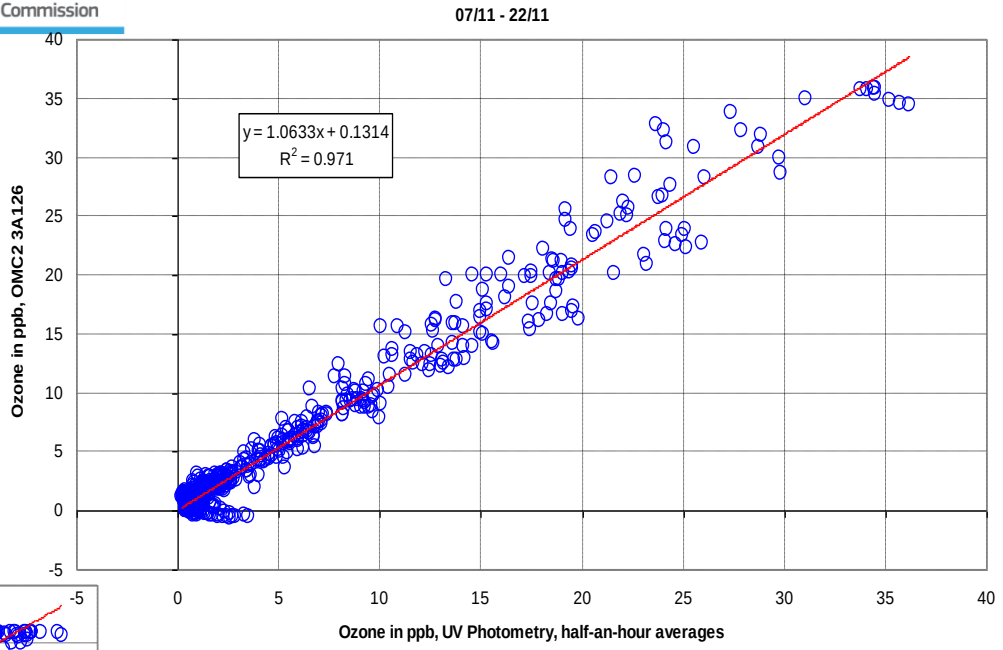
Systematic evaluation of sensors:

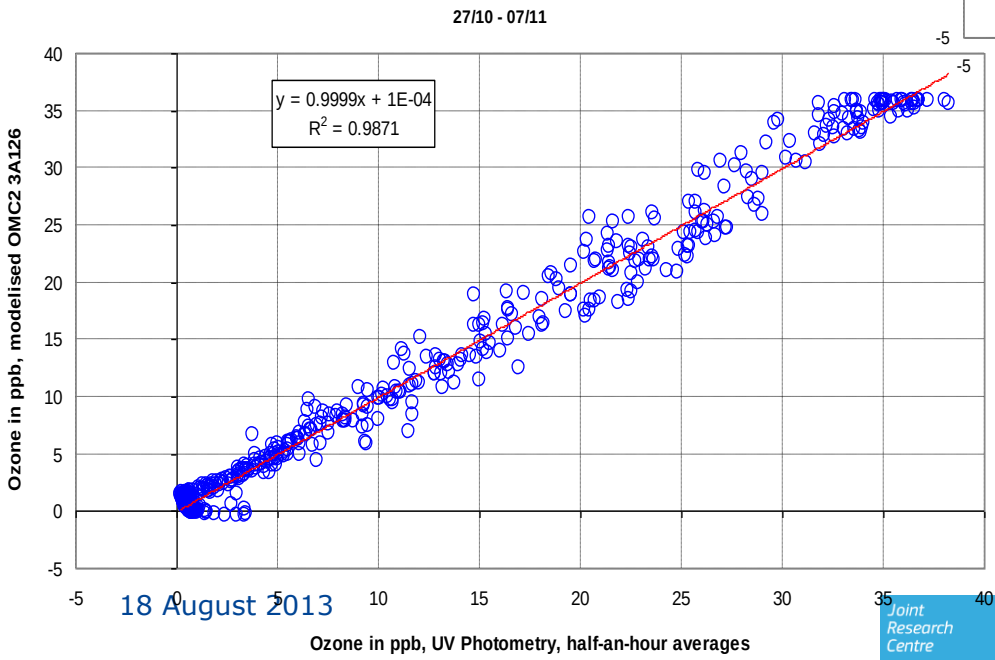
Protocol of validation

for sensors

Two-week field calibration, MICS 2610 sensors

$$O_3 = \sum_{n=0}^{3} x_n \left(R e^{KT} \right)^n$$





Subsequent 2-week implementation of the calibration function

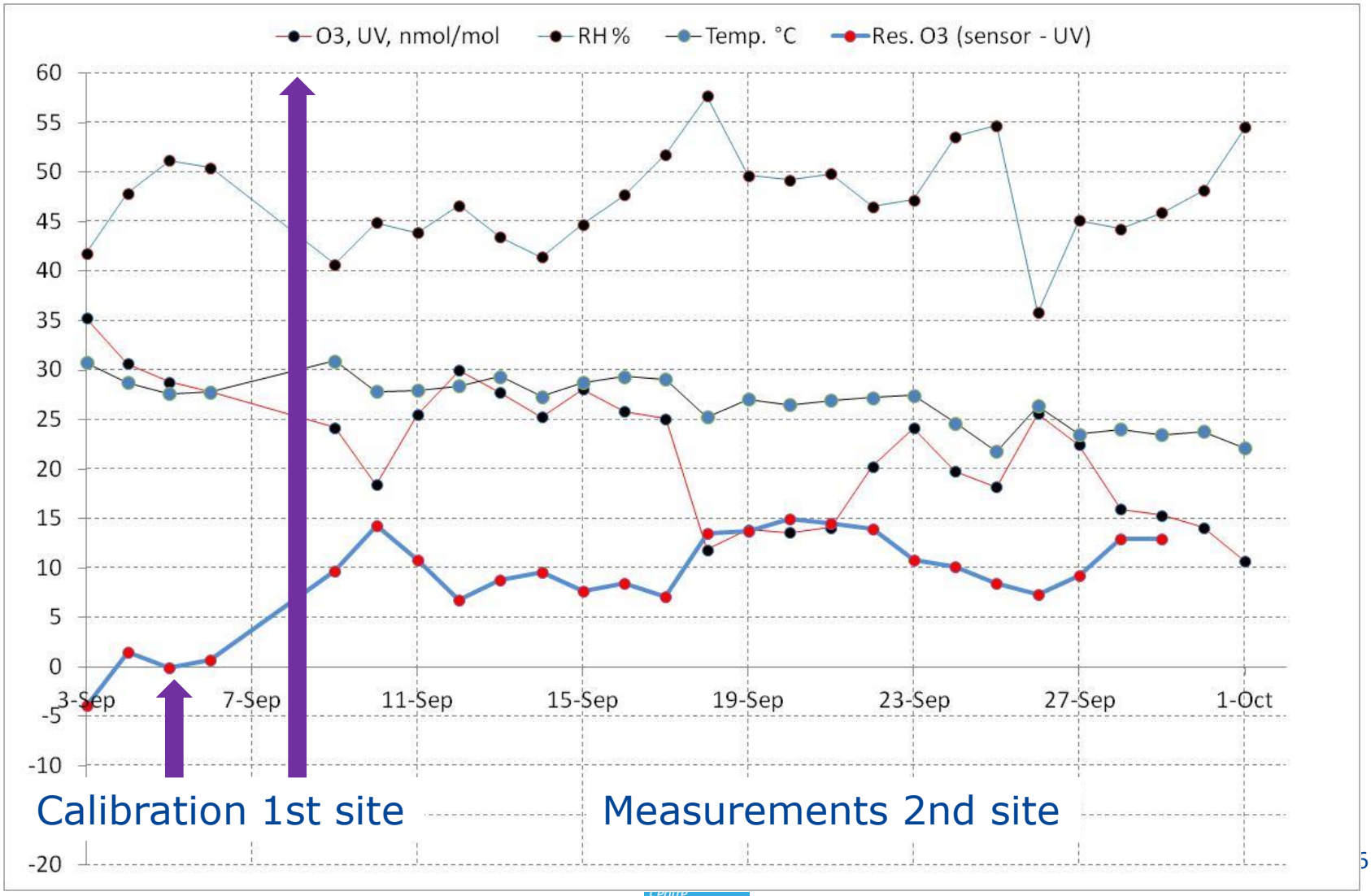
At O_3 = 30 ppb

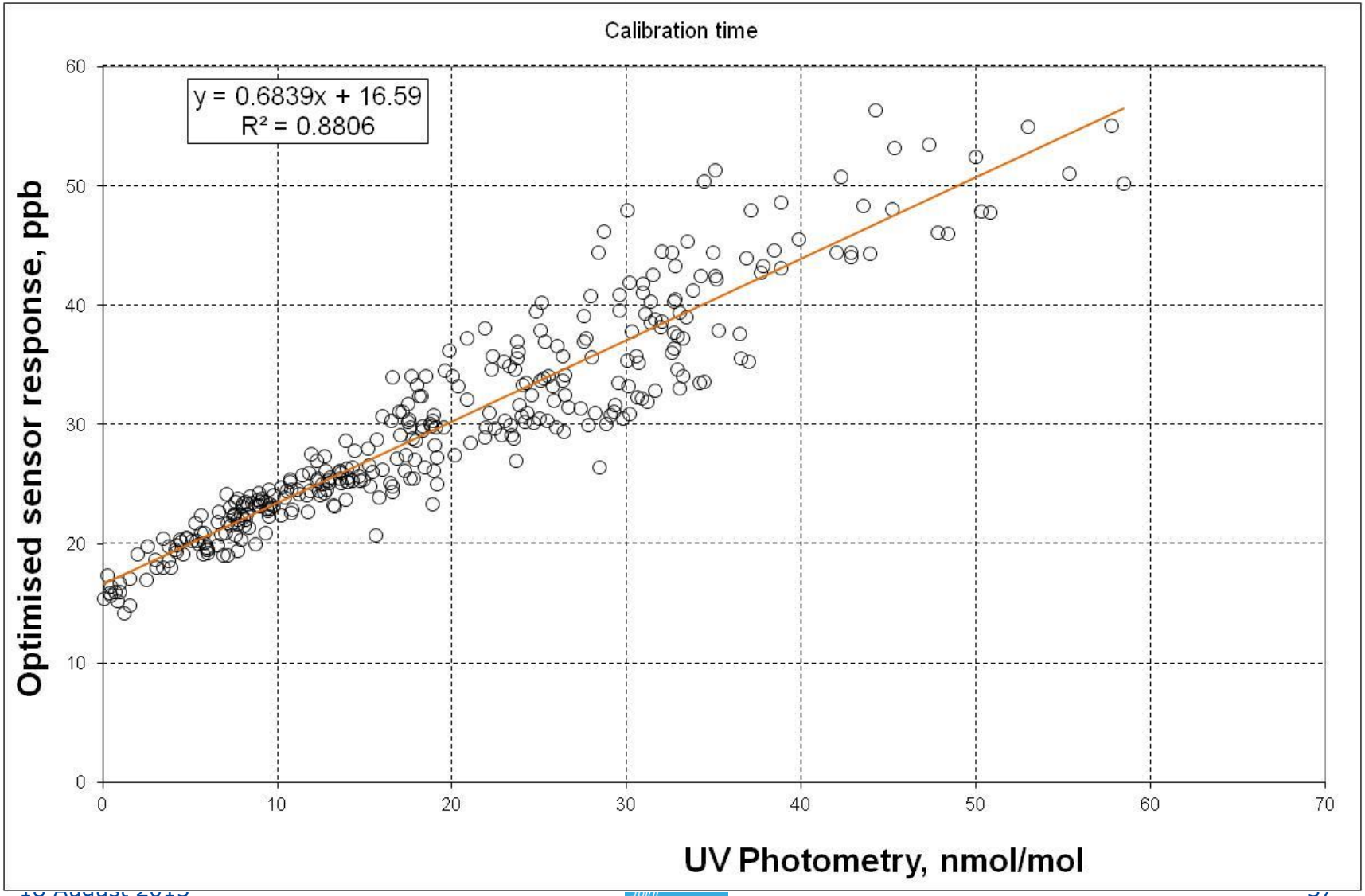
$Ur = 2\ (s^2_{lof} + s_r^2 + s^2_{bias})$

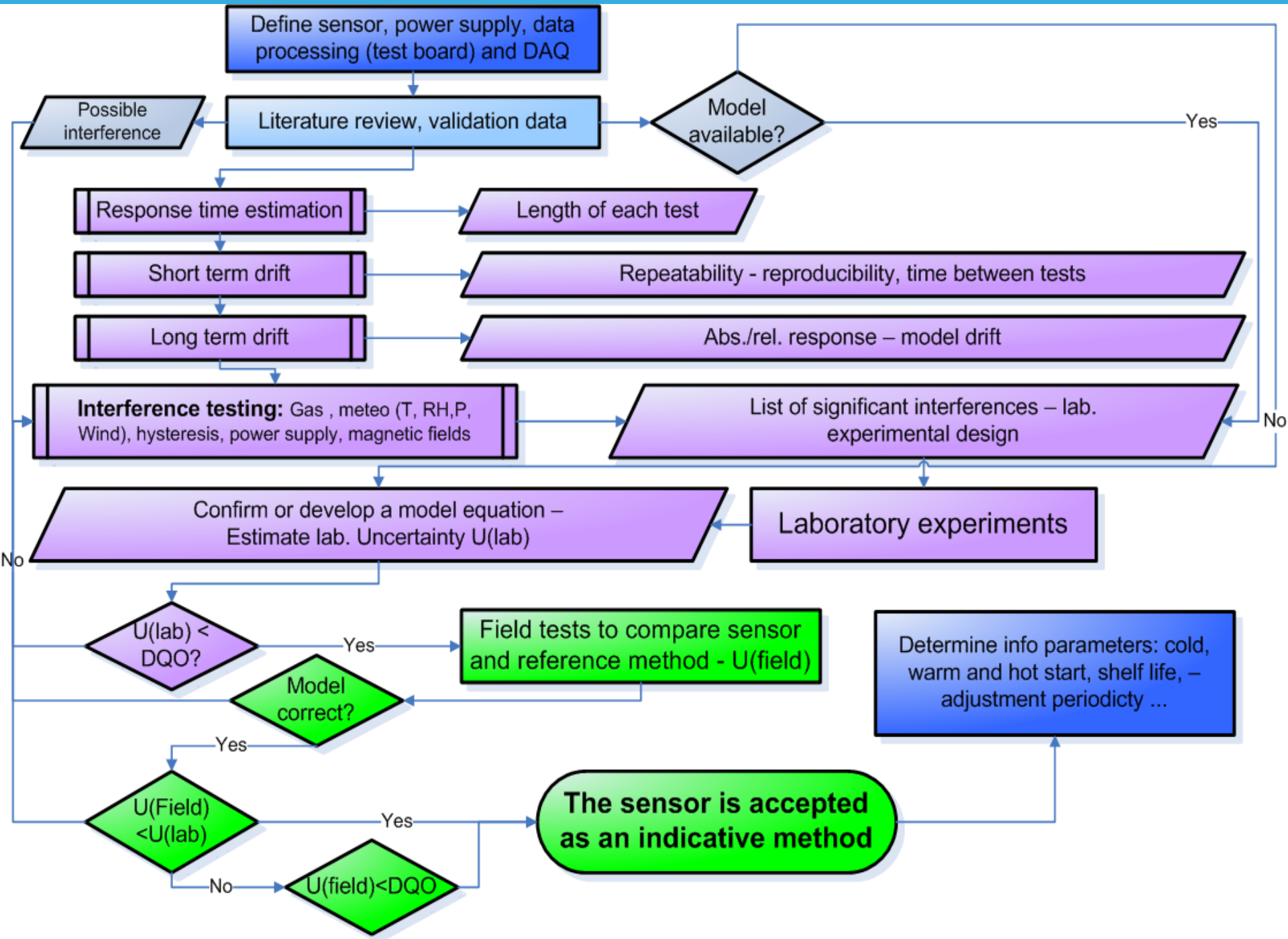
= 15 %

For hourly values

NanoEnvi Sensor – UV photometry (nmol/mol)




Calibration time
y = 0.6839x + 16.59
R² = 0.8806
Optimised sensor response, ppb
UV Photometry, nmol/mol
0
10
20
30
40
50
60
70


Define sensor, power supply, data processing (test board) and DAQ
Literature review, validation data
Possible interference
Model available?
Yes
No
Response time estimation
Length of each test
Short term drift
Repeatability - reproducibility, time between tests
Long term drift
Abs./rel. response – model drift
Interference testing: Gas , meteo (T, RH,P, Wind), hysteresis, power supply, magnetic fields
List of significant interferences – lab. experimental design
Laboratory experiments
Confirm or develop a model equation – Estimate lab. Uncertainty U(lab)
No
U(lab) < DQO?
Yes
Field tests to compare sensor and reference method - U(field)
Model correct?
Yes
Determine info parameters: cold, warm and hot start, shelf life, – adjustment periodicty ...
U(Field) <U(lab)
Yes
The sensor is accepted as an indicative method
No
U(field)<DQO

O_3 Lab tests

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

		12ºC	17ºC	22ºC	27ºC	32ºC	40% HR	60% HR	80% HR
1-1	Short term Drift	x		x		x		x	
2-1	Interferent			NO2 / NO / CO / CO2 / NH3 / SO2				NO2 / NO / CO / CO2 / NH3 /SO2	
2-2	Air Matrix			Laboratory air Outside air				Laboratory air Outside air	
2-3	Pressure			Atmospheric Surpressure 10 mbar Depressure 5 mbar			/	Atmospheric Surpressure 10 mbar Depressure 5 mbar (avg of 50% HR)	/
2-4	Wind			from 1 to 5 m/s				from 1 to 5 m/s	
2-5	Long term term Drift	x		x		x		x	
3-1	Linear Variation	x	/	x	/	x	x	x	x
3-2	Linear Fit	x	x	x	x	x	x	x	x
3-3	Hysteresis	/		x		/		x	
3-4	Variation of Temperature			/			12ºC 22ºC 32ºC	12ºC - 22ºC - 32ºC Mean concentration from 12 to 32ºC by step of 5ºC	12ºC 22ºC 32ºC
3-5	Variation of Humidity	40% 60% 80%		40% - 60% - 80% Mean concentration from 40 to 80% by step of 10 %		40% 60% 80%	/	/	/
4-1	Response Time			x				x	
4-2	Cold start, warm start, hot start			x				x	
4-3	Power suply effect			x				x	

O_3 Sensors

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Manufacturer	Model	Type
Unitec s.r.l – IT	O_3 Sens 3000	Resistive
Ingenieros Assessores – SP	NanoENvi mote and MicroSAD datalogger, with Oz-47 sensor	
αSense - UK	O_3 sensors (O3B4)	
Citytech – G	Sensoric 4-20 mA Transmitter Board with O3E1 sensor	
Citytech – G	Sensoric 4-20 mA Transmitter Board with O3E1F sensor	
CairPol – F	CairClip O3	
e2V – CH	MiCS-2610 sensor and OMC2 datalogger,	
e2V – CH	MiCS Oz-47 sensor and OMC3 datalogger	
IMN2P – FR	Prototype WO3 sensor with MICS-EK1 Sensor Evaluation Kit	
FIS - J	SP-61 sensor and evaluation test board	Resistive

NO_2 Sensors

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Manufacturer	Model
Unitec s.r.l – IT	Sens 3000
Ingenieros Assessores – SP	NanoENvi mote and MicroSAD datalogger, unidentified sensor probably e2v-MICS sensor
αSense – UK	NO_2 sensors (B4)
Citytech – G	Sensoric 4-20 mA Transmitter Board with 3E50/3E100 sensor
Citytech – UK	A3OZ EnviroceL (for now without test board?)
MIKES – FI	Prototype graphene sensors
InRim – IT	Prototype graphene sensors
CairPol – F	CairClip NO2/O3 - filtered

MACPoll

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Data treatment is finishing for O_3 – NO_2 tests Are starting

For ozone some nice field results

European Policy for the use of sensors

Micro-sensors:

- - for now: not mentioned, not foreseen in European legislation for regulatory purposes
- - European Members States shall demonstrate that the Data Quality Objective for Indicative Methods is met

For now, the European Commission mainly observes the results of some Research projects related to micro-sensors: MACPoll, AIRMONTEC, FP7- ENV.2012.6.5-1 (air quality monitoring in a "Smart City" context with community involvement, SSS …)

Some lessons learned – what is needed

- Sophisticated applications that combine sensors with WEB based system, GPS and GPRS system are now available. However, we miss validated sensors for monitoring at ambient air levels (ppb)

- A few lab. and field comparisons of sensors with reference methods are carried out. However, results are hardly repeatable. We need model equations that better describe the sensing processes to reach the DQO of indicative methods

My guess

- Better fixed than mobile sensors for data quality and the time response of sensors

- Develop methods:
  - for correcting of cross-sensitivities and temperature/humidity effect
  - for calibration (lab, field) linked with aging and baseline / span drift of sensors