Air quality sensors: potential & challenges AirSensEUR: An Open-source Multi-Sensor Platform for Air Quality Monitoring

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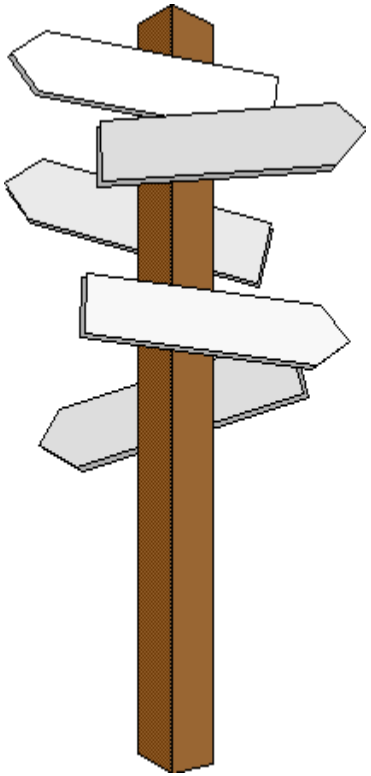
LiberaIntenio s.r.l, Malnate, Italy

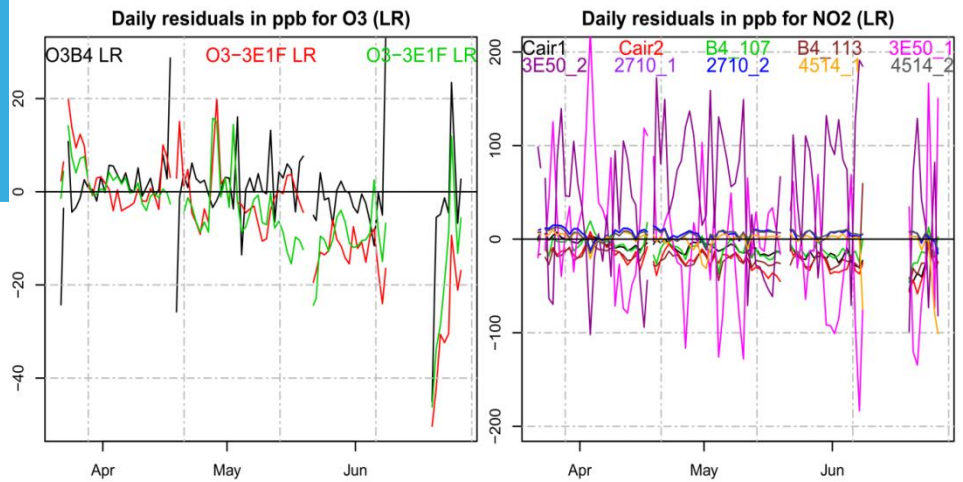
4th International Workshop EuNetAir on Innovations and Challenges for Air Quality Control Sensors
2526 February 2016
Vienna - Austria

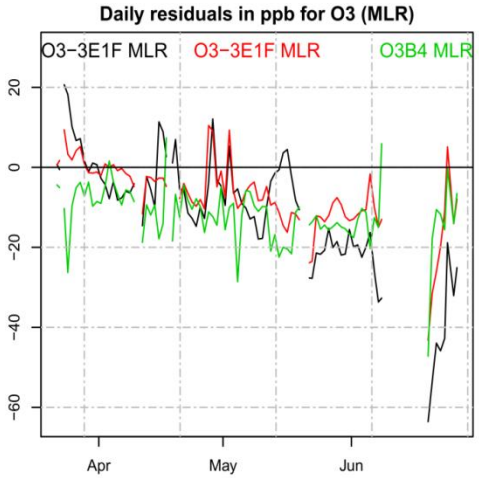
Roadmap of presentation

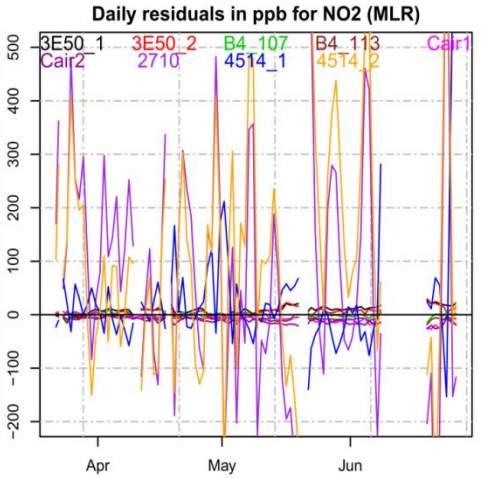


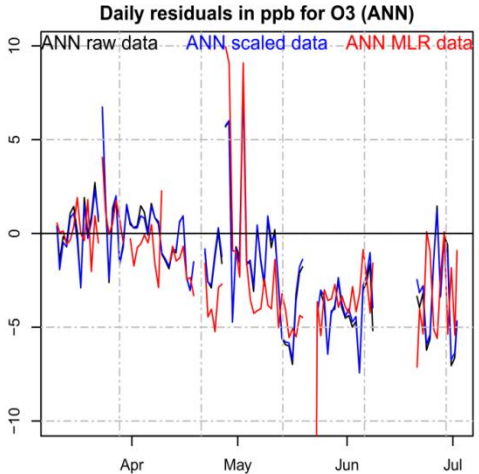
1. Previous sensor evaluation
2. Key-VOCS project
3. Legislative framework
4. Independent, open sensor evaluation
5. CEN standardisation work
6. Aquila-Fairmode sensor intercomparison exercise
7. AirSensEUR platform

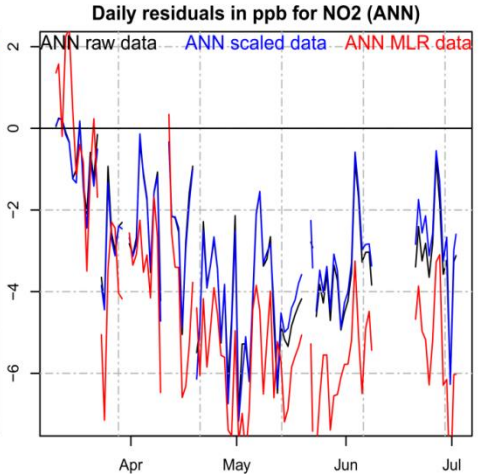
MACPoll, EMRP, 2011-2014











Spinelle et al., S&S-B, 2015

MACPOll: evaluation of single sensors, rural site

Ozone:

- Amperometric: Good: precise, linear, long term stability(not all), little matrix effect, hysteresis and temperature effect

  Less good: interference NO_2, humidity effect

- MOx: Good: low gaseous interference, precise, sensitive, humidity and temperature effect can be corrected

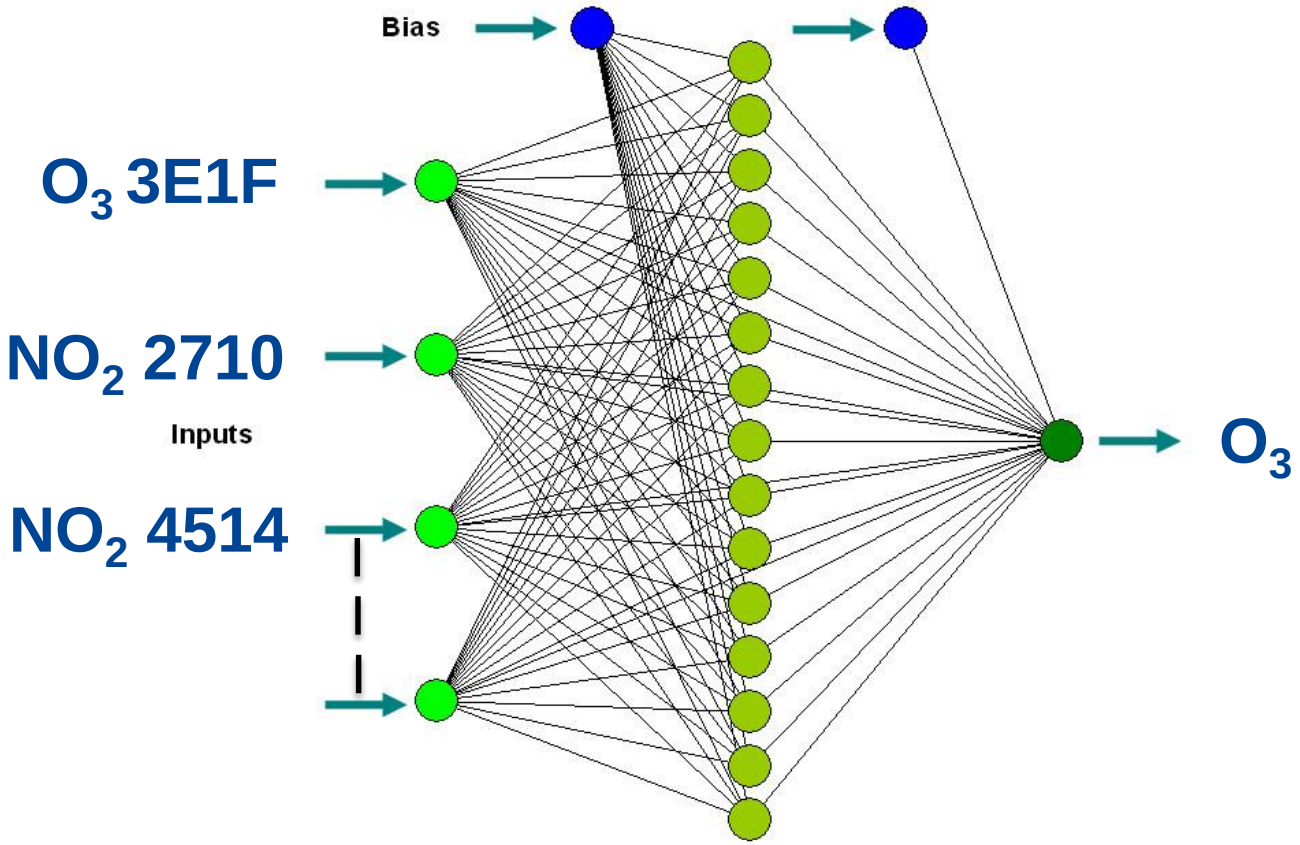
  Less good: calibration, lack of linearity, long term stability, matrix effect, response time

- DQO: Found Ok for one chemical sensor (NO2 interference and humidity effect solved)

- Calibration: field calibration better as lab calibration is not reproducible

Nitrogen dioxide: O_3 interference for amperometric sensors, matrix effect and humidity, gaseous interference on res. sensors – no good field results with chemical sensors (sensitive to O_3)

Artificial Neural network

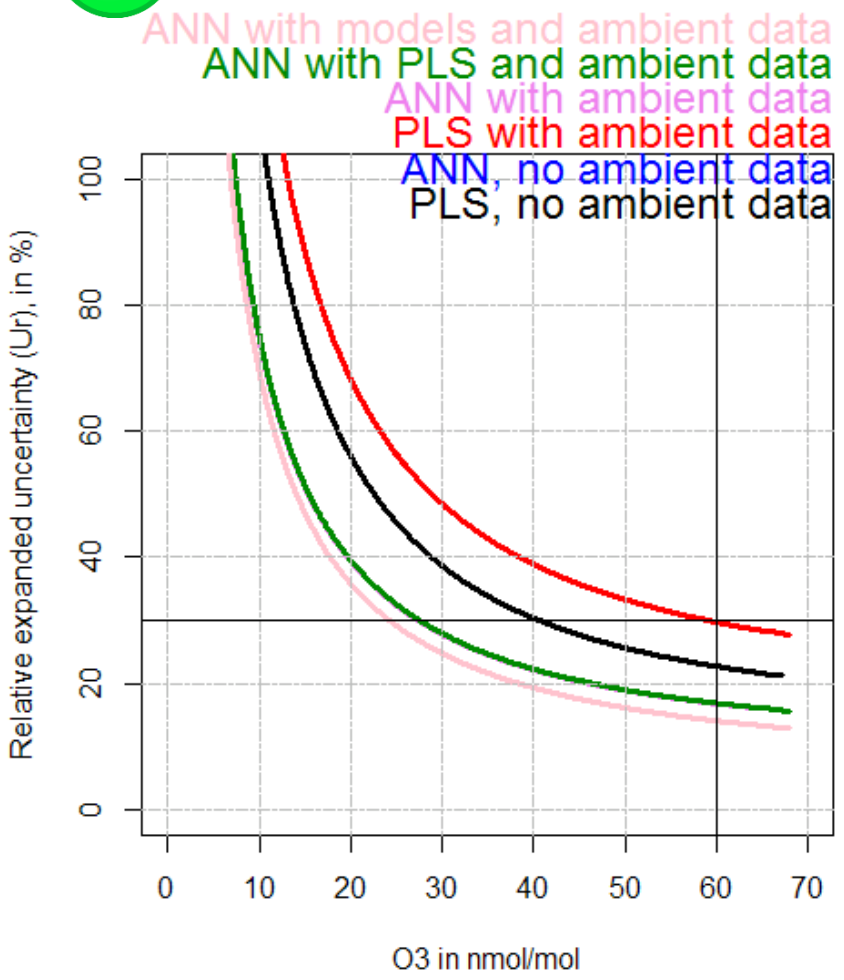


Model Uncertainty

Algorithms	Ambient parameters	Inputs
Phys. Model (PLS)	No	Sensors
~~ANN~~	~~No~~	~~Sensors~~
PLS + Ambient	Yes	Sensors + Ambient
ANN + Ambient	Yes	Sensors + Ambient
ANN + PLS	Yes	Sensors + Ambient
ANN + MLR	Yes	Sensors + Ambient+ Model

$$U_r(y_i) = 2\left(\sqrt{\frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1)\cdot x_i]^2}\right) / y_i$$

O_3 NO_2 NO CO CO_2



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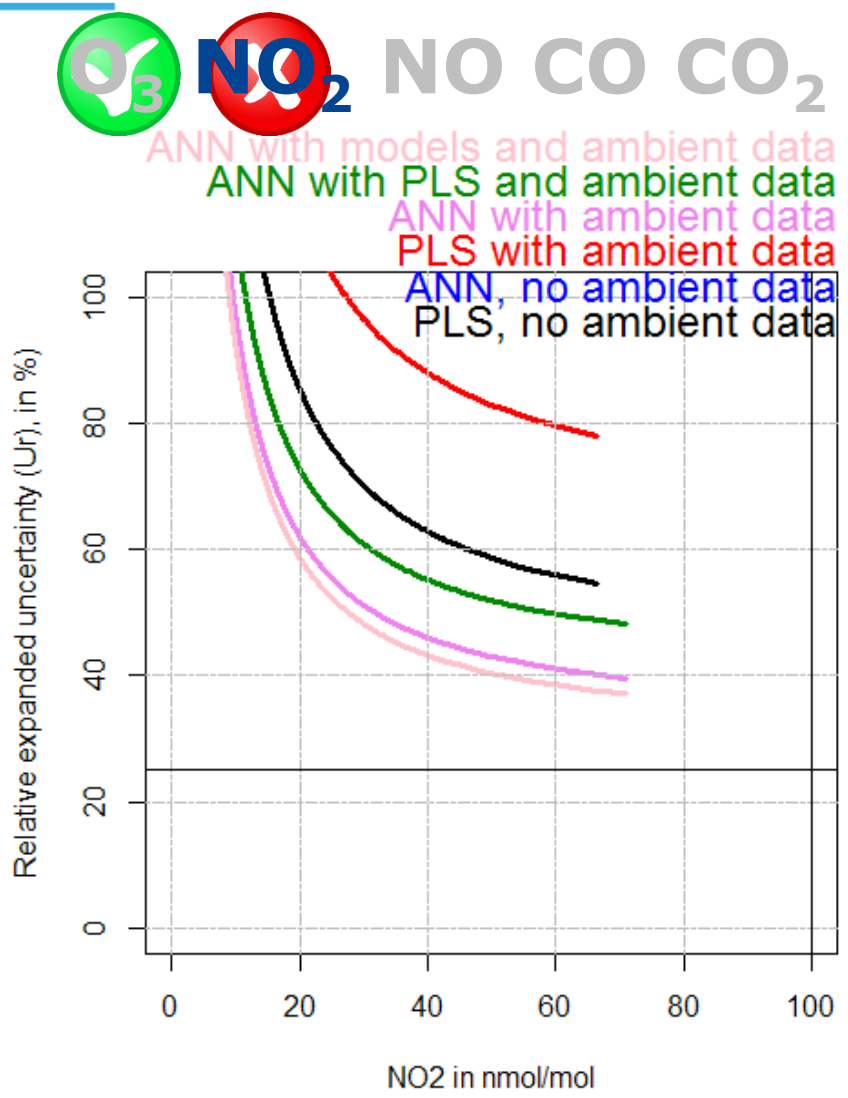

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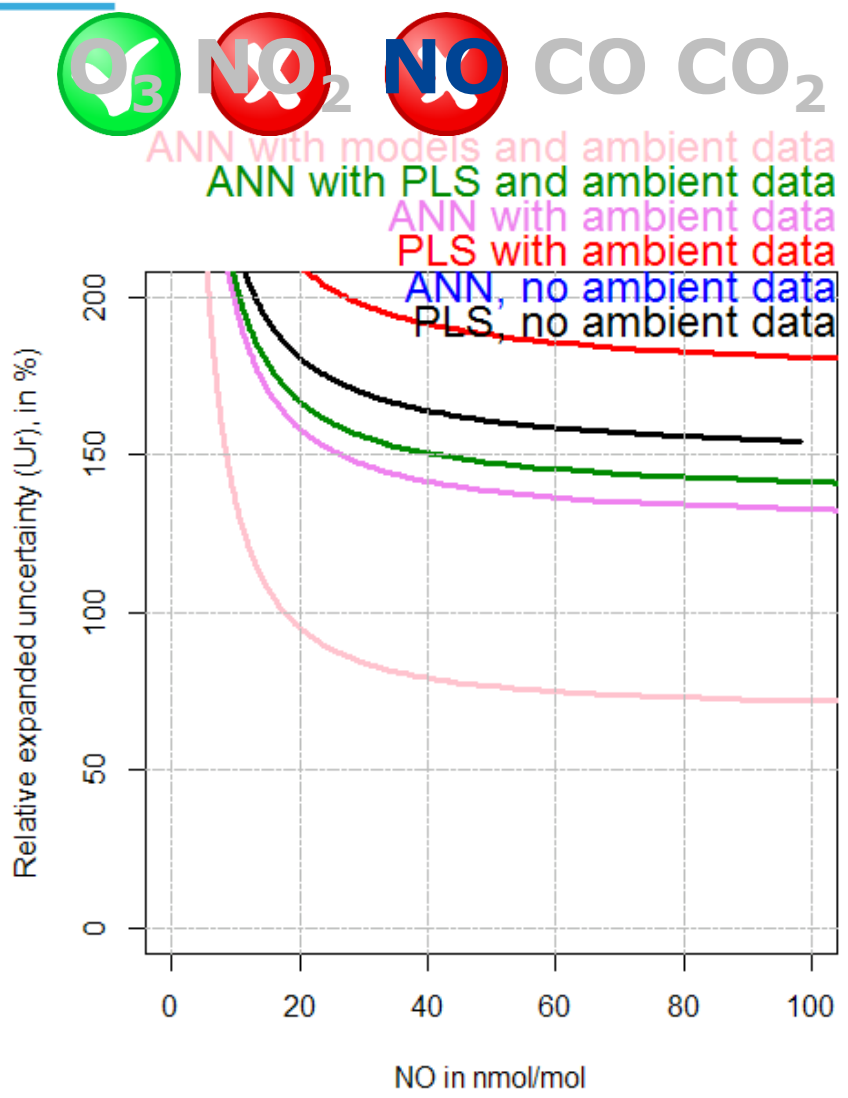

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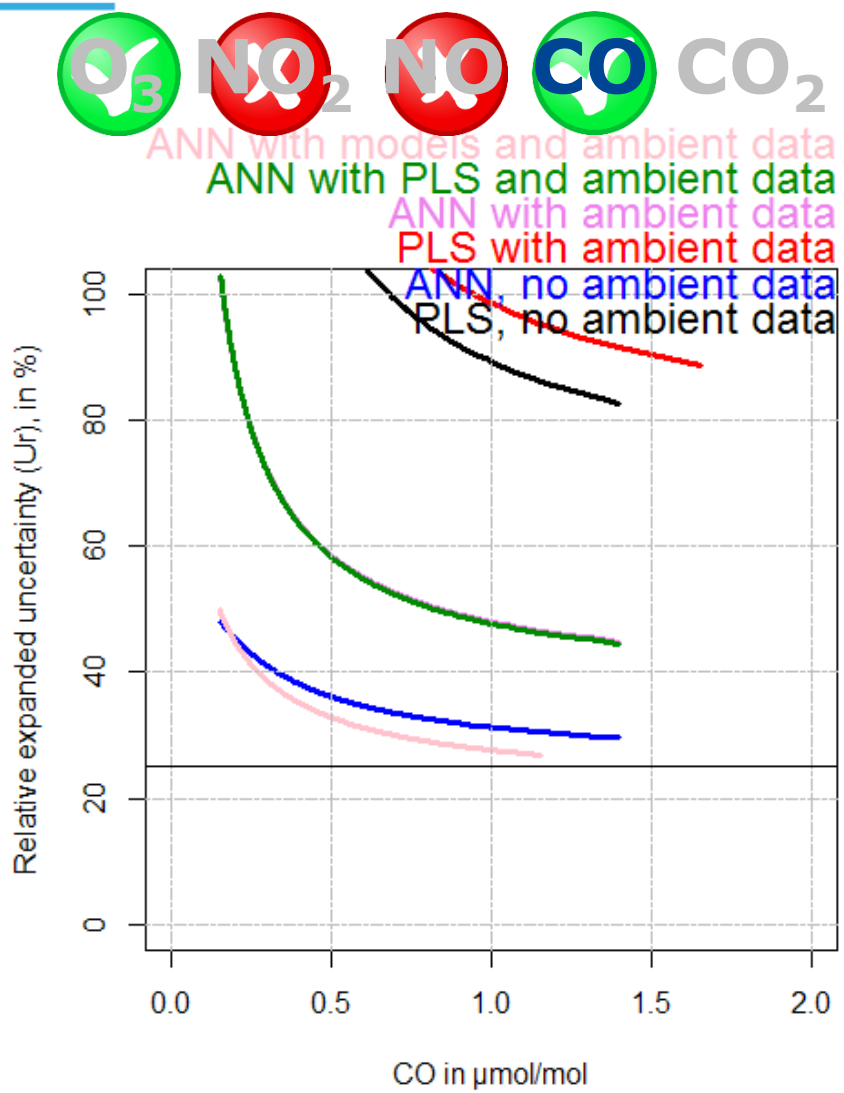

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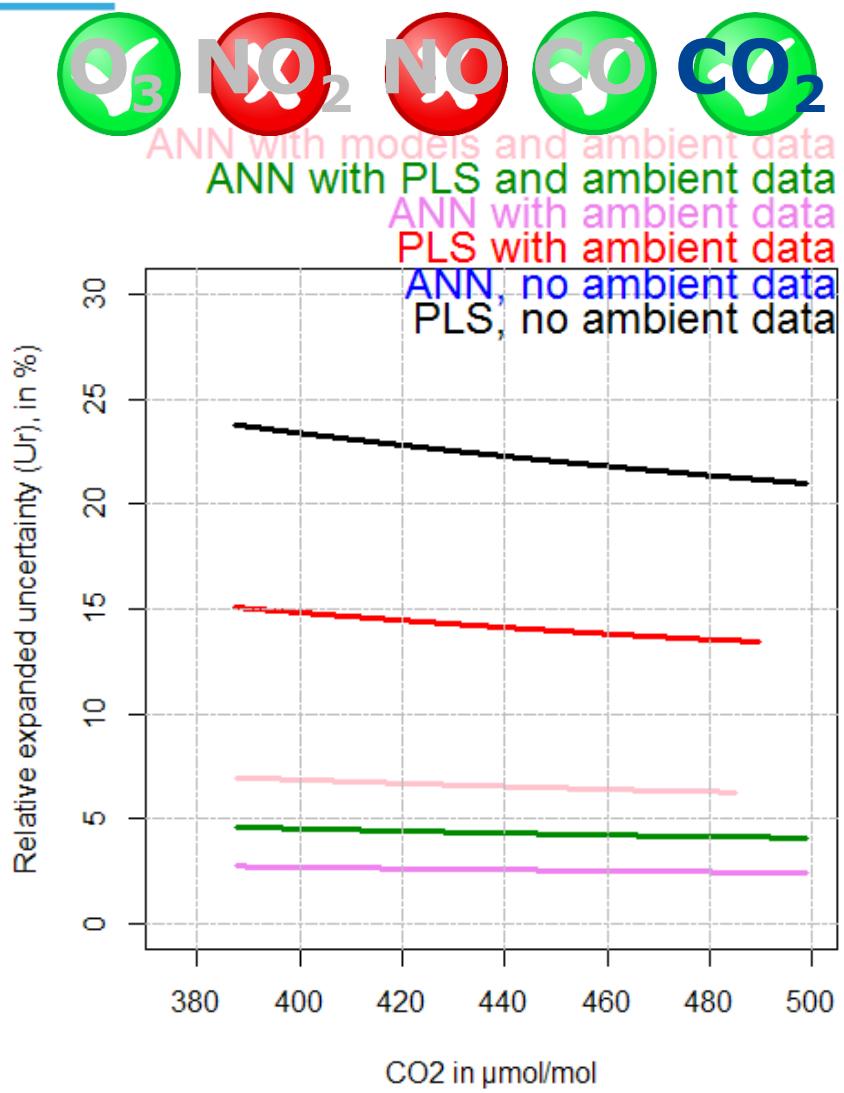
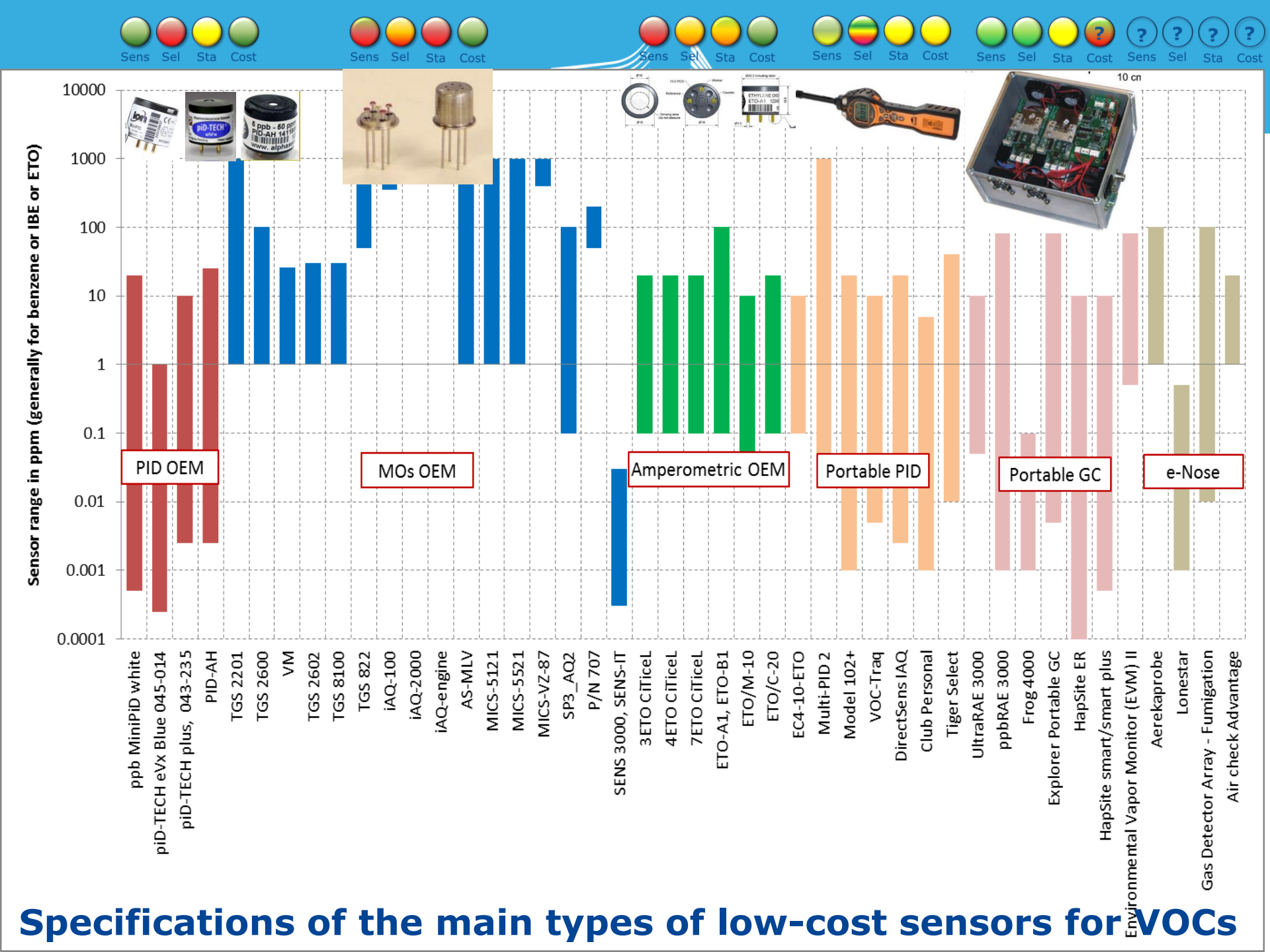


MACPoll conclusions calibration methods for the cluster of sensors (AT A RURAL SITE)

- The DQO for indicative methods can be met for O_3, likely for CO , not for NO_2 (DQO of 35% > 25%). SO2 too low to be evaluated. High uncertainty for NO (> 75 %). For CO_2, low uncertainty down to about 3%.
- Multivariate PLS regression gives thee highest U (with or without meteo)
- Meteo data does decrease measurement uncertainty for the ANN methods.
- ANN methods: higher R^2 and lower RSS -> lower U
  ANN methods: lower bias to reference data (slopes and intercept nearer to 1 and 0, respectively)
- ANN method with input from the physical model and meteo is the best. The inclusion of the PLS as an input for the ANN does not improve the estimation.

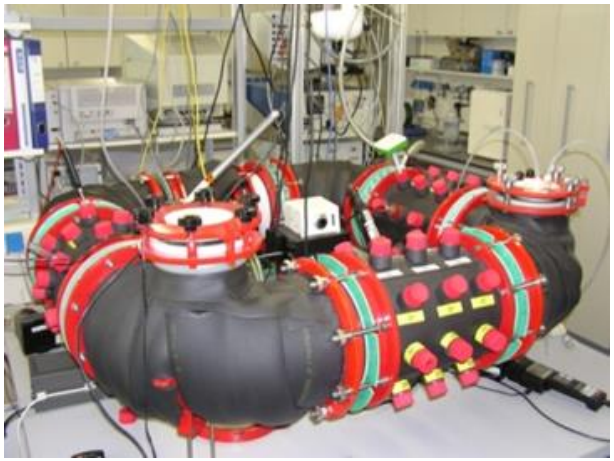


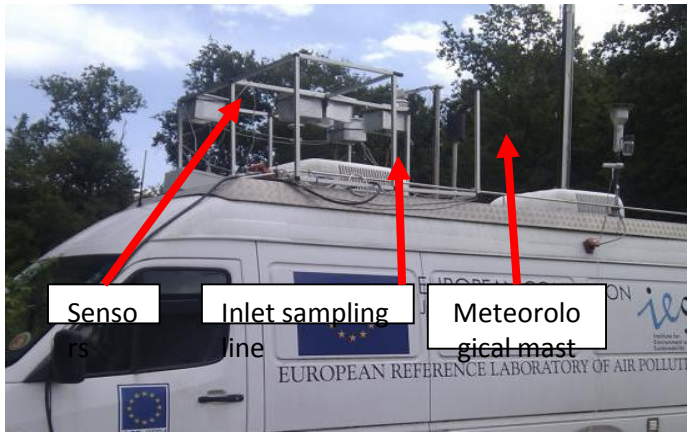
Specifications of the main types of low-cost sensors for VOCs

Key VOCs tests

- Benzene (1.5 ppb) and other BTEXs
- Sensors: MiniGC (ENEA-Recordnum), IonScience Tiger Select, Aeropqual, NanoSence TCO, SiC-FET (Linkoping),
- Tests: laboratory tests 6 months (linearity, drifts, gaseous interference, T, RH … -MACPoll) and 6 months in field conditions

Field test	Lab tests





3 The legal framework and sensor evaluations

- No defined EC policy for the use of low-cost sensors for ambient air monitoring
- The legal framework is the one of the air quality Directive: DQO for indicative measurements and objectives estimations. Really adapted for low-cost sensors?
- Research on sensors is mainly financed with public call for projects: FP7, H2020, life projects (many projects > 30, e. g. Castell et al., 2013). Mainly about sensor material research or sensor applications. Data quality is not generally the main focus.
- Little information is publically available about independent sensor evaluation, correction algorithms and software/electronic design of sensor platforms (a few exceptions as EveryAware …)
- EURAMET projects MACPoll and Key-VOCs focus on protocols and sensor evaluations
- In the CEN TC264 (Air Quality), Working Group 42 (Sensors), a protocol of evaluation of sensor is being developed.
- Looking for independent evaluation of sensors ….

4 Independent evaluation of sensors-USERS

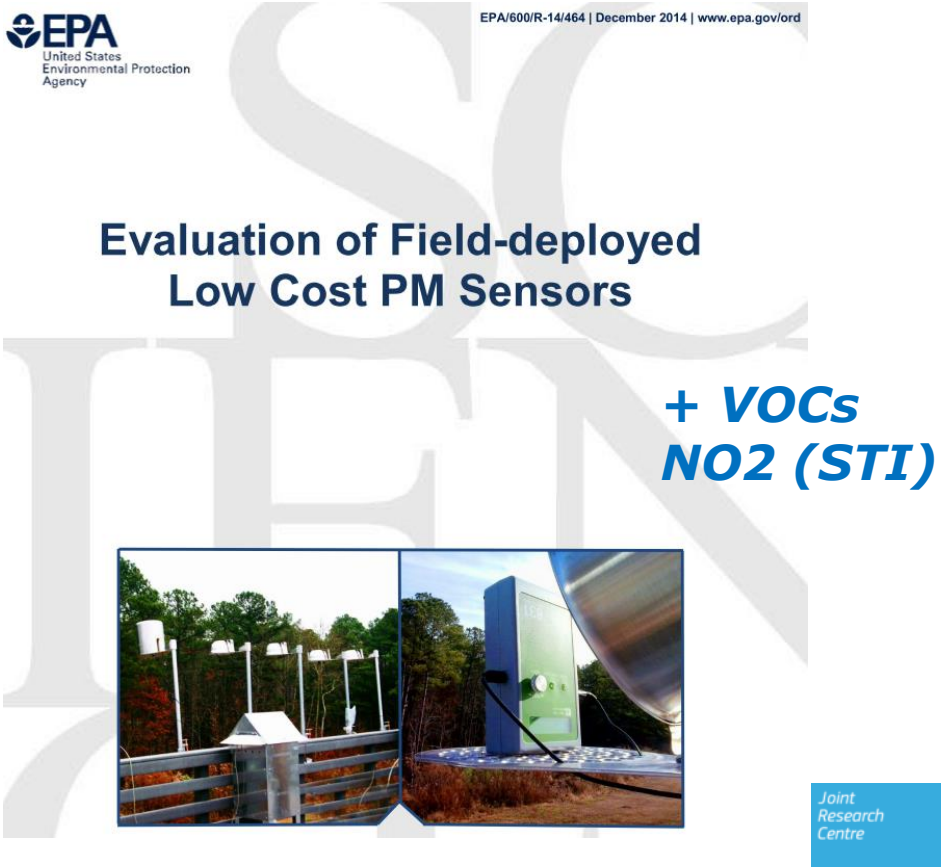
	Manufacturer (Model)	Type	Pollutant(s)	Approximate Cost	Time Resolution	Sensor *vs* FRM/FEM Method[1]
	**Dylos** (DC1100)	Optical	$PM_{(0.5-2.5)}$	~$300	1 min	R^2 ~ 0.65 to 0.85
	**Shinyei** (PM Evaluation Kit)	Optical	$PM_{2.5}$	~$1,000	1 min	R^2 ~ 0.80 to 0.90
	**RTI** (MicroPEM)	Optical	$PM_{2.5}$	~$2,000	10 sec	R^2 ~ 0.65 to 0.90
	**HabitatMap** (AirBeam)	Optical	$PM_{2.5}$	~$200	1 min	R^2 ~ 0.65 to 0.70
	**Met One** (Neighborhood Monitor)	Optical	$PM_{2.5}$	~$1,900	15 min	R^2 ~ 0.53 to 0.67
	**Speck**	Optical	$PM_{2.5}$	~$200	1 min	R^2 ~ 0
	**Naneos** (Partector)	Electrical	PM (LDSA: Lung-Deposited Surface Area)	~$7,000	1 min	$PM_{1.0}$: R^2 ~ 0.1 $PM_{2.5}$: R^2 ~ 0.2
	**AethLabs** (microAeth)	Optical	BC (Black Carbon)	~$6,500	1-300 sec	R^2 ~ 0.79 to 0.94
	**Air Quality Egg** (Version 1)	Optical, Metal oxide	PM, CO, NO_2 and O_3	~$200	1 min	PM: R^2 ~ 0 CO: R^2 ~ 0 NO_2: R^2 ~ 0.40 O_3: R^2 ~ 0.85
	**Perkin Elmer** (ELM)	Optical, Metal oxide	PM, NO, NO_2 and O_3	~$5,200	1 min	PM: R^2 ~ 0 NO: n/a NO_2: R^2 ~ 0 O_3: R^2 ~ 0.89 to 0.96
	**2B Technologies** (PO_3M)	UV absorption (FEM Method)	O_3	~$4,500	10 sec	R^2 ~ 1.00
	**Aeroqual** (S-500)	Metal oxide	O_3	~$500	1 min	R^2 ~ 0.85
	**Smart Citizen Kit**	Metal oxide	CO, NO_2	~$200	1 min	CO: R^2 ~ 0.50 to 0.85 NO_2: R^2 ~ 0
	**AQMesh** (v.3.0)	Electrochem	CO, NO, NO_2, SO_2, and O_3	~$10,000	1-15 min	CO: R^2 ~ 0.75 to 0.90 NO: R^2 ~ 0.75 to 0.90 NO_2: R^2 ~ 0 SO_2: R^2 ~ 0 O_3: R^2 ~ 0.25 to 0.55
	**AQMesh** (v.4.0)	Electrochem	CO, NO, NO_2 and O_3	~$10,000	1-15 min	CO: R^2 ~ 0.42 to 0.80 NO: R^2 ~ 0.0 to 0.44 NO_2: R^2 ~ 0.0 to 0.46 O_3: R^2 ~ 0.46 to 0.83
	**UNI-TEC** (SENS-IT)	Metal oxide	CO, NO_2 and O_3	~$2,200	1 min	CO: R^2 ~ 0.33 to 0.43 NO_2: R^2 ~ 0.60 to 0.65 O_3: R^2 ~ 0.72 to 0.83

Air Quality Sensors Performance Evaluation Center, South Coast AQMD

http://www.aqmd.gov/aq-spec/evaluations#&MainContent_C001_Col00=2

4 Independent evaluation of sensors US –EPA: Air Sensor Toolbox for Citizen Scientists: Resources

http://www.epa.gov/air-research/air-sensor-toolbox-citizen-scientists-resources



Sensor	R^2	Response	RH Limit	Major temp effects
AirBase CanarIT ($\mu g/m^3$)	0.004	-0.101	100%	None
CairClip PM ($\mu g/m^3$)	0.064	-0.229	95%	0.657
Carnegie Mellon Speck (particle counts)	0	0.06	90%	None
Dylos DC1100 (particle counts)	0.548	21368	95%	None
Met One 831 ($\mu g/m^3$)	0.773	0.049	90%	None
RTI MicroPEM ($\mu g/m^3$)	0.720	1.35 ± 0.12	95%	0.588
Sensaris Eco PM ($\mu g/m^3$)	0.315	0.034	100%	0.313
Shinyei PMS-SYS-1 ($\mu g/m^3$)	0.152	0.292	95%	None

4 Air quality – Performance evaluation of sensors for the determination of concentrations of gaseous pollutants and particulate matter in ambient air (Doc. N 2274)

Scope of the proposed deliverable :

Description of specific performance requirements and test methods under prescribed laboratory and field conditions for low-cost sensors and sensor arrays that may include a sensor holder and auxiliary systems for sampling, data treatment and/or power supply

Aims of the protocol (request 2364)

- meet the Data Quality Objective (DQO) for "indicative measurements" – Added: "objective estimation" and a new category call "informative method" without DQO

- O_3, NO_2/NO, CO, SO_2, PM10, $PM_{2.5}$, CO_2 and benzene. Avoid VOCs because of cross sensitivities

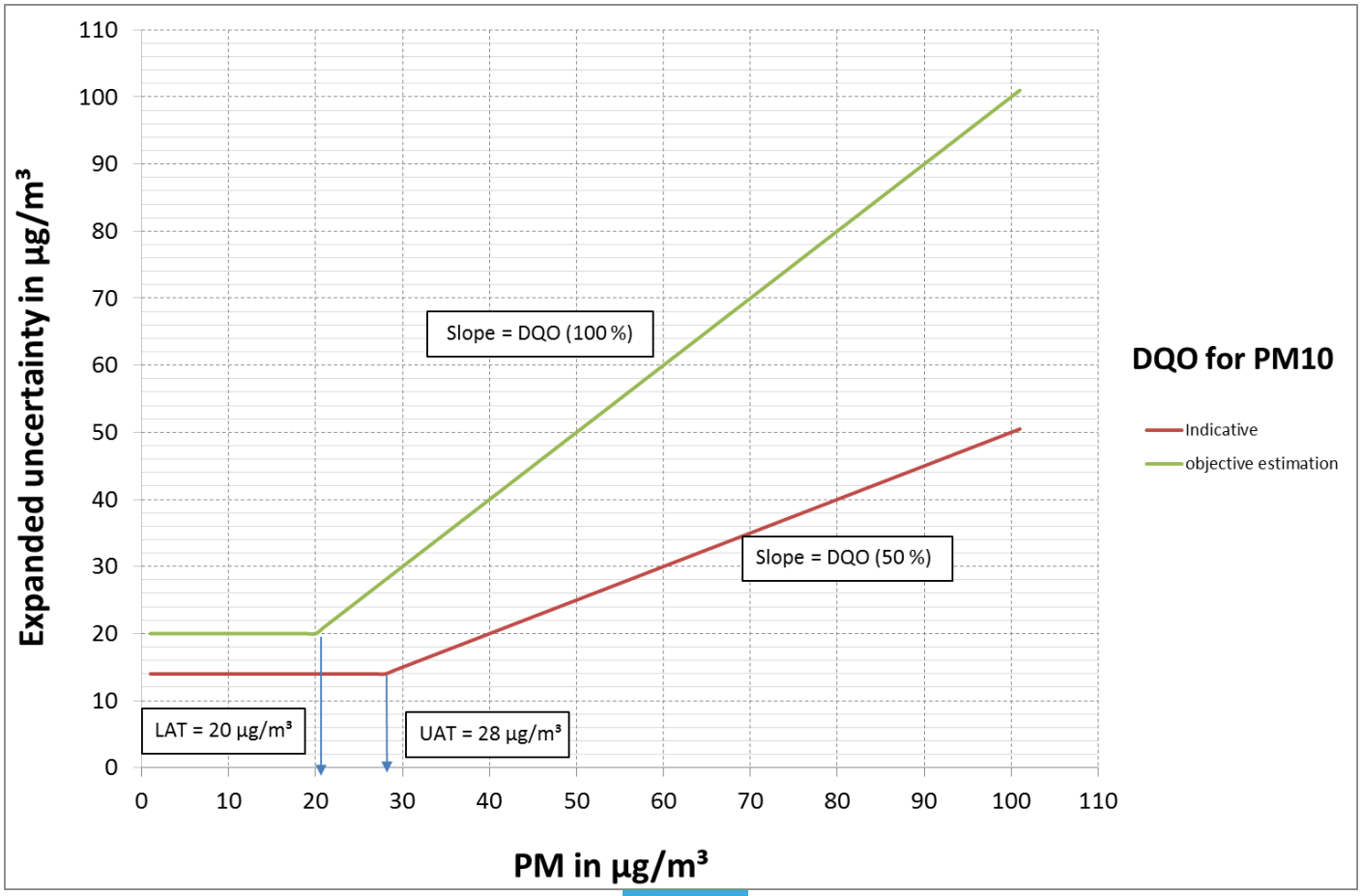
Applications

➢ Fixed measurements	yes for outdoor
➢ Mobile measurements	Only for outdoor monitoring and if we can find supporting data
➢ Indoor	No
➢ Networks of sensors	(not for this standard)

Data Quality Objective (2008/50/EC)

	Indicative	Objective estimation
SO_2, NO_2/NOx, CO	25 %	75 %
Benzene	30 %	100 %
PM_{10}/$PM_{2.5}$	50 %	100 %
O3	30 %	100 %
	LAT<[]<UAT	[]<LAT

Data quality objectives



Parameters to be evaluated (E), corrected (C)

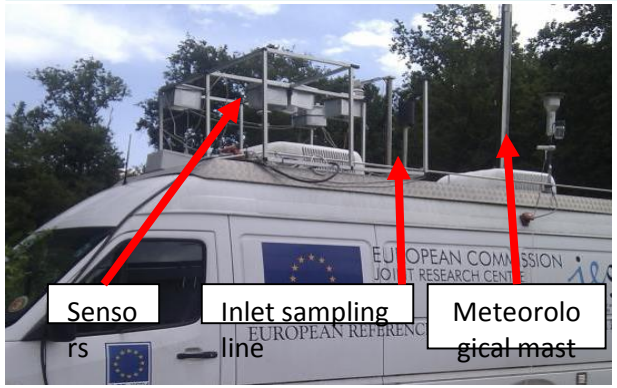
Parameters to be tested (significant ones: in bold)	Indicative method	Objective estimation	Informative method (~~dqo~~)
Response time (at controlled conditions)	E (in lab.)	E (lab.)	E (in lab.)
Calibration at constant Temp. and RH	E/C (in lab.)	E/C (lab.)	E/C (in lab.)
Repeatability for 0 and span at constant Temp. and RH	E (in lab.)	E (lab.)	E (in lab.)
Short and **long term** drifts	E/C (in lab. or field)	E (lab or field)	E (only long term drift) (in field)
Cross sensitivities	E/C (in lab.)	E (in lab.)	E (in field)
Temperature (Temp.) and humidity (RH)	E/C (in lab.)	E (in lab.)	E (in field)
Hysteresis (concentration levels, Temp., RH), transient effects of humidity	E/C (in lab.)	E (in lab) (temp., RH), not transient	E (in field)
Wind velocity	E/C (in lab.)	E (in lab.)	E (in field)
Power supply	E/C (in lab.)	E (in lab.)	
Active sampling, loses … only for some sensors	E/C (in lab.)	E (in lab.)	
Electromagnetic fields …	E/C (in lab.)	E (in lab.)	
Pressure effect	E/C (in lab.)	E (in lab.)	E (in field)
Solar heating	E (in field)	E (in field)	

5 Call for interest, IE with low-cost sensors

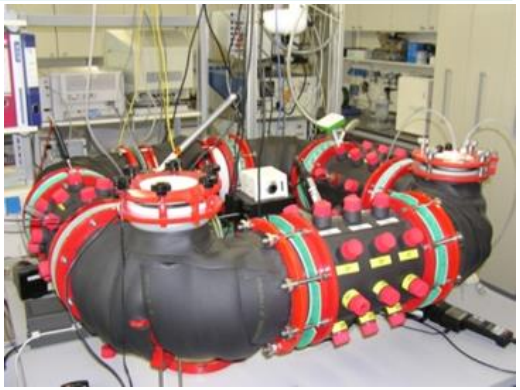
1 Selection

Field test	Lab tests

2 Centralized tests



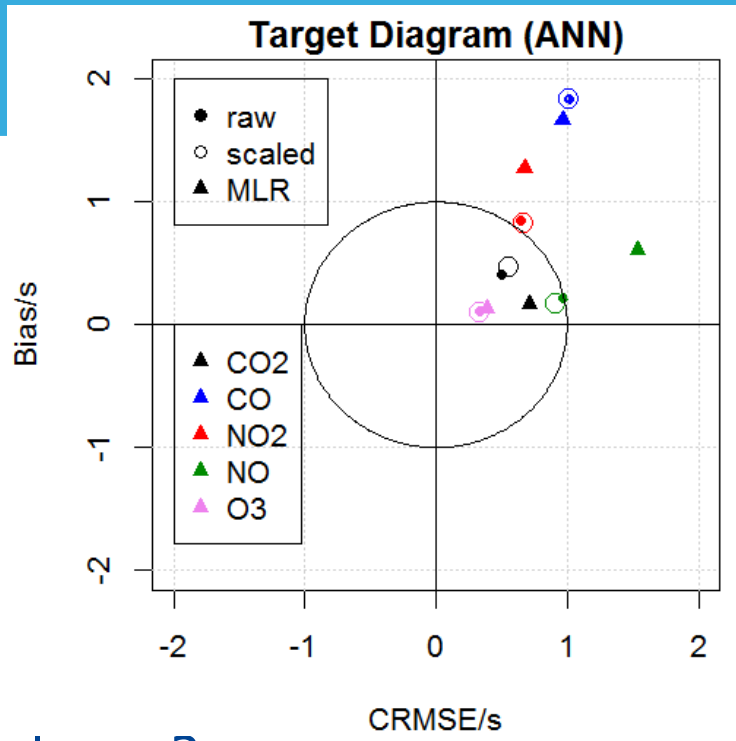
and/or



3 Dispatch to National Reference Labs.

To be discussed

- Pollutants to be included: O_3, NO_2, PM
- Possible evaluation of results:
  - Aquila N37 document, Z_{score} and σ_p?
  - Target diagram ?
  - Guide for the demonstration of equivalence?
- Duration of tests?
- Proposed time table: > Nov 2016
- (winter, likely no O_3)
- Participants responsible for the maintenance and data acquisition
- Synergy with EuNetAir?

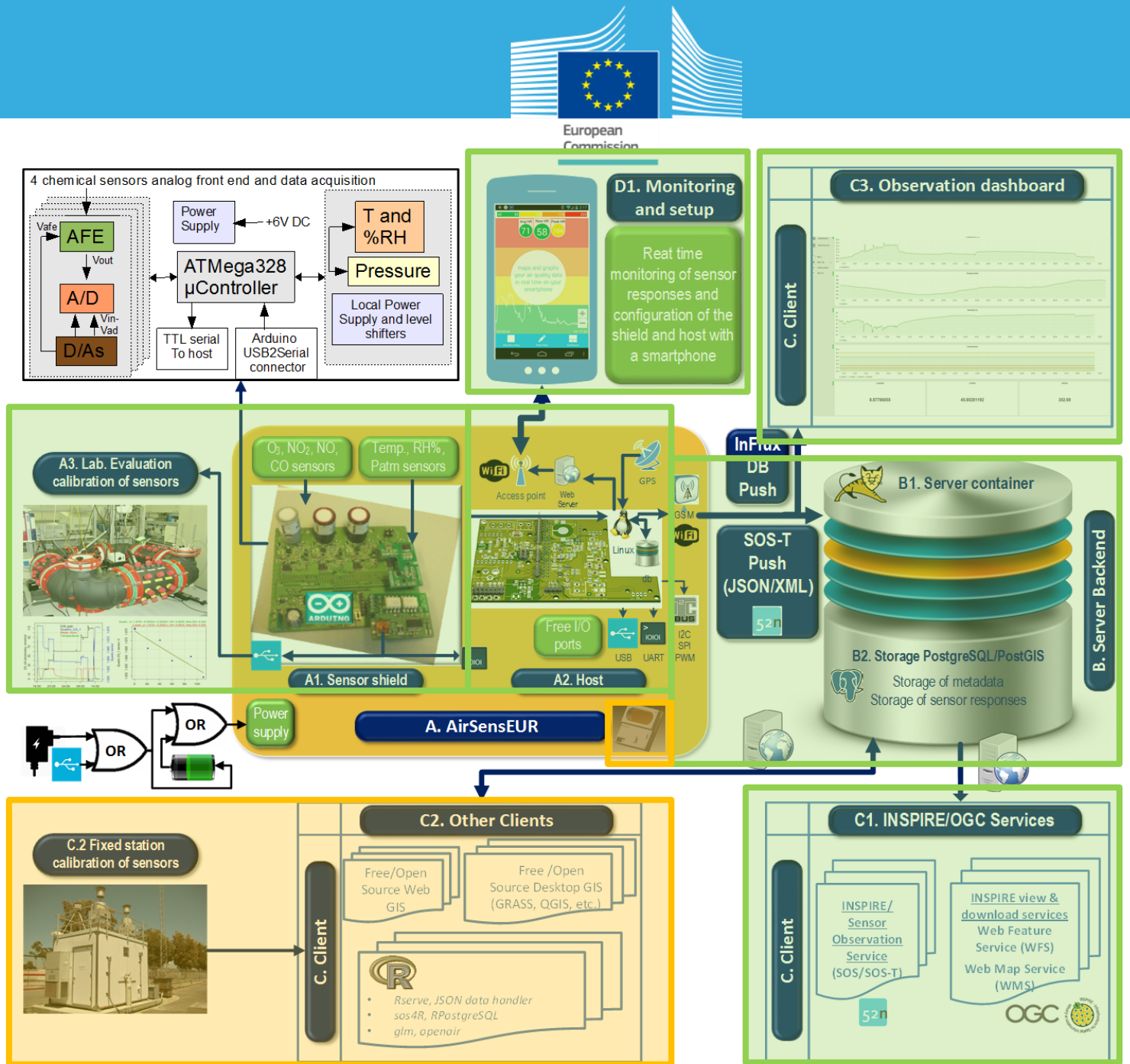


6 AirSensEUR: An open source sensor platform

JRC & partners are working on the AirSensEUR project since spring 2014: 4 amperometric sensors, T, RH, P, GPS

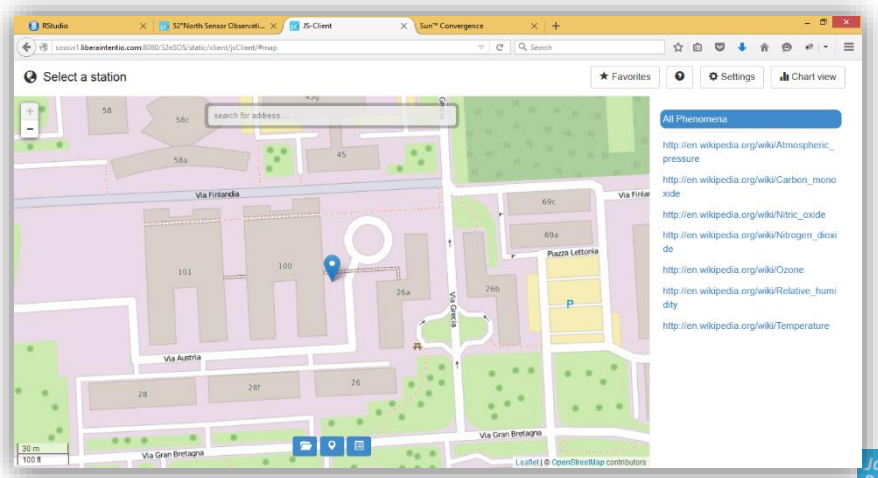
- Accepts about 230 amperometric sensors (main companies…)
- User configurable: JAVA AFE (sensor voltage, DAC control ADC, gain, load resistance, bias, IIR filtering, DAQ periodicity and averaging time)/channel- resolution of 15 µV without ampl.:
- Create open and interoperable sensor nodes which provide observation data", and meet the requirements of INSPIRE Directive

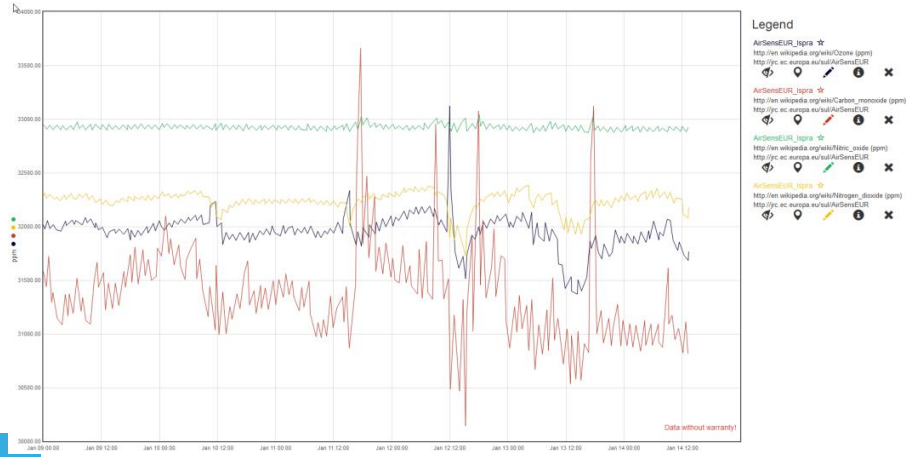
- **Specifications, data quality and calibration:** JRC Air and Climate Unit (ERLAP, Michel Gerboles, Laurent Spinelle)
- **Data management:** JRC Digital Earth Unit (Sven Schade, Max Craglia, Alex Kotsev)
- **Platform design and software:** Liberaintentio srl (Marco Signorini)
- **Growing community of sensor testers**: RIVM-NL, NILU-NO, AIRPARIF-FR, AEA Ricardo-UK (?), EMPA-CH (?), VMM (?)


European Commission
4 chemical sensors analog front end and data acquisition
Vafe
AFE
Vout
A/D
Vin-
Vad
D/As
Power Supply
+6V DC
ATMega328 µController
TTL serial To host
Arduino USB2Serial connector
T and %RH
Pressure
Local Power Supply and level shifters
D1. Monitoring and setup
Reat time monitoring of sensor responses and configuration of the shield and host with a smartphone
C3. Observation dashboard
C. Client
A3. Lab. Evaluation calibration of sensors
O3, NO2, NO, CO sensors
Temp., RH%, Patm sensors
Access point
Web Server
GPS
GSM
WiFi
Linux
db
Free I/O ports
USB
UART
I2C
SPI
PWM
A1. Sensor shield
A2. Host
InFlux DB Push
SOS-T Push (JSON/XML)
52n
B1. Server container
B2. Storage PostgreSQL/PostGIS
Storage of metadata
Storage of sensor responses
B. Server Backend
OR
OR
Power supply
A. AirSensEUR
C.2 Fixed station calibration of sensors
C2. Other Clients
C. Client
Free/Open Source Web GIS
Free /Open Source Desktop GIS (GRASS, QGIS, etc.)
Rserve, JSON data handler
sos4R, RPostgreSQL
glm, openair
C1. INSPIRE/OGC Services
C. Client
INSPIRE/ Sensor Observation Service (SOS/SOS-T)
INSPIRE view & download services
Web Feature Service (WFS)
Web Map Service (WMS)
52n
OGC

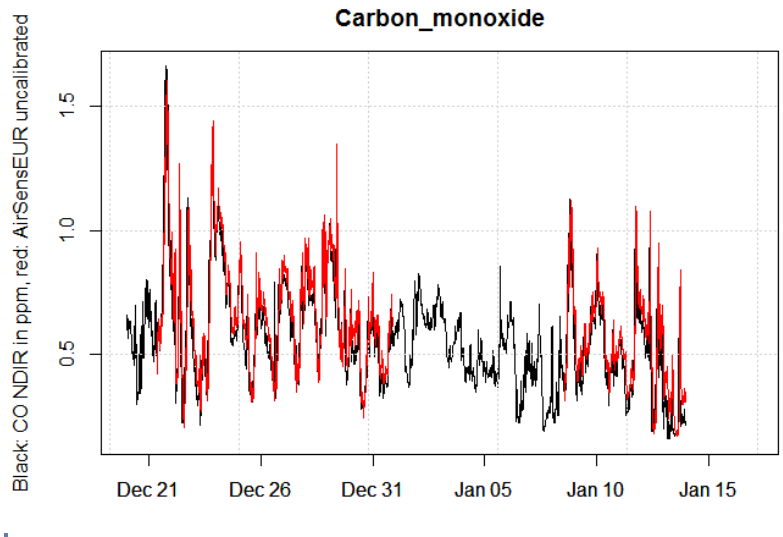
AirSensEUR uses Public licenses

- low cost open source sensor platform, battery operated, for air quality monitoring
- 4 chemical sensors (e.g O3, NO, NO2, CO or SO2) from several manufacturers including AlphaSense, City technology, Membrapor and SGX SensorTech
- auxiliary sensors for temperature, pressure and relative humidity
- Aggregate samples with GPS information, periodically update an external server through WiFi or GPRS channels
- Own SOS-T Java client (open source, EUPL) – consistent with the Inspire Directive





Joint Research Centre


Carbon_monoxide
Black: CO NDIR in ppm, red: AirSensEUR uncalibrated
0.5
1.0
1.5
Dec 21
Dec 26
Dec 31
Jan 05
Jan 10
Jan 15


EUROPEAN COMMISSION
JOINT RESEARCH CENTRE
EUROPEAN REFERENCE LABORATORY OF AIR POLLUTION
JRC
Ispra

Thank you

AirSensEUR: an open data/software /hardware multi-sensor platform for air quality monitoring. Part A: sensor shield, doi: 10.2788/30927, http://publications.jrc.ec.europa.eu/repository/handle/JRC97581

Sensitivity of VOC Sensors for Air Quality Monitoring within the EURAMET Key-VOC project, http://dx.doi.org/10.5162/4EuNetAir2015/02

Performance Evaluation of Amperometric Sensors for the Monitoring of O3 and NO2 in Ambient Air at ppb level, Procedia Engineering, Vol. 120, pp 480-483 (2015). ftp://ftp_erlap_ro:3rlapsyst3m@s-jrciprvm-ftp-ext.jrc.it/ORAPRO_eurosensors2015_O3_NO2_Amperometric.pdf

Field calibration of a cluster of low-cost available sensors for air quality monitoring. Part A: Ozone and nitrogen dioxide, Sensors and Actuators B, http://www.sciencedirect.com/science/article/pii/S092540051500355X

AirSensEUR: An Open-Designed Multi-Sensor Platform for Air Quality Monitoring." http://dx.doi.org/10.5162/4EuNetAir2015/03

Calibration of a cluster of low-cost sensors for the measurement of air pollution in ambient air. In *2014 IEEE SENSORS*. pp. 21–24. DOI: 10.1109/ICSENS.2014.6984922, http://ieeexplore.ieee.org/search/searchresult.jsp?queryText=Calibration%20of%20a%20cluster%20of%20low-cost%20sensors%20for%20the%20measurement%20of%20air%20pollution%20in%20ambient%20air&newsearch=true

Calibration of small resistive commercial sensors to measure ozone with the interference of temperature and humidity. In *2013 IEEE Sensors*. 2013 IEEE Sensors. pp. 1–4. http://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=%20Calibration%20of%20small%20resistive%20commercial%20sensors%20to%20measure%20ozone%20with%20the%20interference%20of%20temperature%20and%20humidity

Evaluation of a portable nephelometer against the Tapered Element Oscillating Microbalance method for monitoring PM 2.5, J. Environ. Monit., 2012, 14, 2145, http://dx.doi.org/10.1039/c2em30099k

Review of Small Commercial Sensors for Indicative Monitoring of Ambient Gas, VOL. 30, 2012, Chemical Engineering Transactions, http://www.aidic.it/cet/12/30/029.pdf

Report of laboratory and in-situ validation of micro-sensor for monitoring ambient air - Ozone micro-sensors, AlphaSense, model B4-O3 sensors (UK), http://publications.jrc.ec.europa.eu/repository/handle/JRC90463

Report of laboratory and in-situ validation of micro-sensor for monitoring ambient air pollution - NO9: CairclipNO2 sensor of CairPol (F), Spinelle et al., http://publications.jrc.ec.europa.eu/repository/handle/JRC86499

Report of the laboratory and in-situ validation of micro-sensors for monitoring ambient air pollution - O12: CairClipO3/NO2 of CAIRPOL (F), Spinelle et al., http://publications.jrc.ec.europa.eu/repository/handle/JRC86479

Protocol of evaluation and calibration of low-cost gas sensors for the monitoring of air pollution, http://publications.jrc.ec.europa.eu/repository/handle/JRC83791

Field evaluation of NanoEnvi microsensors for O3 monitoring, http://publications.jrc.ec.europa.eu/repository/handle/JRC68169

Evaluation of Micro-Sensors to monitor Ozone in Ambient Air, http://publications.jrc.ec.europa.eu/repository/handle/JRC48905

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