

Workshop on Use of Sensors in Air Quality Measurements

Brussels, 22 January 2019

Summarised by Federico Karagulian, Michel Gerboles, Annette Borowiak, Alexander Kotsev

2019

This publication is a Conference and Workshop report by the Joint Research Centre (JRC), the European Commission’s science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

**Contact information**

Name: Federico Karagulian

Address: Via E. Fermi 2479, 21027 Ispra (VA)

Email: federico.karagulian@ec.europa.eu

Tel.: +39 0332 78

**EU Science Hub**

https://ec.europa.eu/jrc

JRCXXXXXX

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
|  |  |  |  |

Ispra: European Commission, 2019

© European Union, 2019

The reuse policy of the European Commission is implemented by Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Reuse is authorised, provided the source of the document is acknowledged and its original meaning or message is not distorted. The European Commission shall not be liable for any consequence stemming from the reuse. For any use or reproduction of photos or other material that is not owned by the EU, permission must be sought directly from the copyright holders.

All content © European Union, 2019

How to cite this report: Author(s), *Title*, Publisher, Publisher City, Year of Publication, JRCXXXXXX.

Acknowledgements

We thank all participants and contributors of the workshop.

**Disclaimer**

The report represents the understanding of the authors of presentations and discussions taking place during the workshop.

Workshop Summary

Within the AQSens Administrative Arrangement (AA) between the DG Environment and the DG Joint Research Centre, a first workshop took place at DG ENV premises in Brussels on 22 January 2019. The overall objective was to share experiences about the performance and deployment of low-cost sensor systems to monitor air pollution within Aquila, the network of National Reference Laboratories (NRL) of the EU, and key EU partners.

In the report “Investigating the Feasibility of Innovative Technologies to Improve Air Quality Monitoring over the Medium to Long Term” (2015)1, the use of low-cost sensors was targeted as the first disruptive technology in the future of air quality monitoring. Second to this, there is the use of satellite remote sensing data from the Copernicus products delivered by the Sentinel constellation of high spatial resolution satellites. A growing number of companies started commercializing Sensor Systems able to give a “best guess” for the concentration of indoor and outdoor pollutants. The benefit about the use of low-cost sensor is the increase spatial coverage when monitoring air quality in cities and remote locations.

Today, there are more than 250 low-cost sensor systems commercially available on the market with a cost ranging from a few hundreds to a few thousand euro. At the same time, independent information about the performance of sensor systems against reference measurements is only available for about 70 sensor systems in literature. In fact, the behaviour of commercial low-cost sensors is unstable and often affected by atmospheric condition, pollutants concentration range and, by the site location where the measurements are carried out.

Members of AQUILA and key European institutes experienced in sensor based measurements from the Netherlands (RIVM), Norway (NILU), Switzerland (EMPA), United Kingdom (Ricardo, NPL), Belgium (VMM, ISSEP), France (INERIS, EMD), Hungary (Met.hu), Czech republic (CHMI), the Joint Research Centre, Germany (LANUV), presented their results about the calibration and evaluation of sensor performances. For some of the NRLs, this workshop was the first opportunity to present their results about field and laboratory tests performed with low-cost sensors. The presented field tests consisted of comparisons of sensors against reference measurements according to limit values, and uncertainty required by the Air Quality Directive.

List of oral presentations:

1. Air Policy background, V. Franco (DG ENV) and A. Borowiak (EC-JRC)

V. Franco emphasised that in Europe the main health effects of air pollution on populations comes from high levels of PM, NO2 and O3, and that mitigation of these pollutants is high on the EC agenda. He acknowledged the possible future role and importance of networks of low-cost sensors to monitor air quality in Europe and their role in citizen science. However, in many situations the data quality of sensor measurements has shown to be questionable. Therefore, DG ENV’s main message is «validate low-cost sensors, in order to understand the measurement uncertainties». Finally, V. Franco presented the new AA AQSens whose main objective is to develop open calibration procedures for sensors, to get experience including sensors in AQ monitoring networks by deploying sensors in three European cities and to provide guidance on sensor deployment to all stakeholders.

*Question: Will the European NO2 limit value be decreased in the future?*

*Answer: It is likely that the NO2 will not be changed in the near future because this Limit Value is in line with the current recommendation and Limit Value of WHO.*

1. Literature review sensor- and system performance, F. Karagulian (EC-JRC)

F. Karagulian presented the new repository recently setup in which quantitative data about the performance of tested low-cost sensors against reference measurement are collected. This information was gathered using reports published by the EC-JRC, US-EPA and relevant testing laboratory. Other information was drawn from peer-reviewed journals that tested different types of sensors in research studies. Finally, the repository has been then linked with scripts able to perform a statistical analysis in the form of an electronic report. This work represents an important review to classify all commercial sensors based on their comparison with reference systems. In conclusion, there are only a few sensor systems that are consistent with all requirements set in the AA AQSens consisting of: transparent data treatment, commercial availability, able to monitor several pollutants, good agreement with reference measurements (R² > 0.75 and slope with 1±0.5) and total price < 3 k€.

*Question: what is the validity of the observation of such a repository and derived conclusions?*

*Answer: the conclusion is that in peer review articles only positive findings seems to be published. Conversely, technical reports that are published by independent laboratories seems to be more trustable with positive and negative evaluations.*

1. The VAQUUMS project & early findings lab tests for gas sensors, E. Elst, C. Mattheeussen (VMM) and E. Weijers (RIVM)

E. Elst presented the first results of the Life-VAQUUMS project including the process of selection of sensors for laboratory and field tests and the first laboratory tests showing the influence of humidity and O3 on the AlphaSense sensor NO2-B43F during lab tests. Field tests at monitoring stations are now starting. E. Elst also highlighted the objective of creating a Data Quality Index for sensor measurements, which would be useful for having more trust in the validity of data produced by sensors. VAQUUMS welcomes the collaboration with other AQUILA members for the elaboration of such Data Quality Index.

*Synergies were identified between the VAQQUMS selection of sensors based on literature review and the JRC repository of performance of sensors (currently under* [*http://db-airmontech.jrc.ec.europa.eu/*](http://db-airmontech.jrc.ec.europa.eu/) *). Both groups are willing to collaborate on this topic.*

1. French validation tests, L. Spinelle (INERIS) and F. Mathe (EMD)

L. Spinelle and F. Mathe presented the partial results of a pilot study carried out during 6 weeks in January/February and 6 weeks in July/August 2018 at an urban site in Lille (FR) for the evaluation of a long list of low cost sensors (44 sensors). The organisers have developed a multi-composite indicator for measuring the performance of sensor that take into consideration both quantitative parameters (R², slope …). A few examples of anonymised results were given. For organising field evaluation, INERIS intends to use an in-house developed prototype for spiking air pollutants at field site.

*Question: will the result of this pilot study be available and brand sensor names be disclosed?*

*Answer: it is likely that the brand names will be disclosed and that the results will be open (pending confirmation of some of the participating sensors).*

1. The Swiss Carbosense CO2 sensor network and applications of sensor systems for NO and NO2, C. Hueglin (EMPA)

C. Hueglin presented the work performed by EMPA in Switzerland with the deployment of one hundred CO2 sensors. The aim of CarboSense is to determine CO2 emissions of the city of Zurich over multiple years, to enhance understanding of biospheric CO2 fluxes over Switzerland and to describe accurately the 4-D evolution of CO2 over Switzerland. EMPA carries out the calibration of CO2 sensor in laboratory climatic chamber using the effect of temperature, pressure and the sensor response to known CO2 mixtures. Applying the laboratory calibrations to field was initially very successful. However, after one year an important long-term drift of calibration was observed making the sensor data unusable. It was decided to correct the sensor long-term drift by re-calibrating the sensor using a period of time when wind velocity is > 2 m/s corresponding to CO2 being constant everywhere. C. Hueglin also presented findings of the efficiency of the calibration of the AirCube Sensor System using the Radom Forrest method and sensor collocated with reference method at field sites. This method was found to perform very well when the calibration and deployment consider the same field site and poorly when deployment is carried out at sites different than the one used for calibration. Finally, C. Hueglin concluded that the initial purchase of low cost sensors is counterbalanced by higher QA/QC cost. The QA/QC procedure includes initial calibration and recalibration of sensors, outlier detection and data correction, and replacement of malfunctioning sensors plus the need for required expertise.

1. RIVM efforts: testing/calibration/comparison at field sites, J. Vonk and E. Weijers (RIVM)

J. Vonk presented the RIVM vision of the future of monitoring air pollution, expecting that sensors will be increasingly present and that citizens will play an active role for the collection of ambient air observations. RIVM has developed a climatic chamber for testing sensors in laboratory under controlled conditions and J. Vonk presented some lab results for NO2 sensors. J. Vonk presented the results of field tests of the AirBox ECN, AirSensEUR and Mushroom sensor systems. For AirBox, although the strength of relationship between sensor and reference measurements is satisfactory (R² > 0.73), the AirBox sensor system needs field re-calibration is order to decrease systematic errors. For AirSensEUR, the Alphasense NO2-B43F raw sensor results had to be corrected using multivariate algorithm to reach meaningful agreement with reference measurements and additional treatment is still needed for considering the long-term drift of these sensors. Good reproducibility of the sensor measurements was observed for 5 Mushrooms placed at the same site.

1. Hungarian experience testing sensor & Vaisala, V. Deszi (Met.hu)

V. Deszi presented the results of field comparison of Vaisala O3, SO2, CO, NO2, PM10 and PM2.5 sensors with reference measurements at a field site (György Marczell Observatory Gilice square Budapest) equipped with reference methods. The performance of Vaisala sensor was generally not satisfactory except for CO. He reported coefficient of determination, R², 0.143 for O3, 0 for SO2, 0.884 for CO, 0.55 for NO2, 0.123 for PM10 and 0.062 for PM2.5. It is likely that the high relative humidity observed during the tests disturbed the PM sensor measurements and the SO2 levels were low, likely under the limit of quantification of the SO2 sensor.

1. Real world application of low-cost sensors, B. Stacey (RICARDO)

B. Stacey presented an evaluation of the “Electronic Diffusion Tube” (EDT) from AlphaSense. Initially, the reproducibility of 10 EDT was evaluated by co-locating sensors at the same field site. The raw data of all EDT showed four sensors perfectly correlated among themselves while the others showed large discrepancies. The good correlation of one pair of sensor could still be observed after one month of sampling. At the same time, this pair of sensors showed good agreement with reference measurements (R2 > 0.83, Slope ~ 1 and Offset – 0.5 for 15-minute averages) after sensor data processing including scaling and baseline adjustment. EDT sensors were deployed around a school at three locations including a Roadside (mean 22 ppb), a School Entrance (17 ppb) and School Playground (12 ppb) compared to the local reference monitoring station showing 9 ppb over the sampling time. In another sensor deployment with triplicate EDT at 5 sites along a street canyon and two background sites, a few high sensor data peaks were recorded with values up to 1200 ppb. Out of these peaks, all sampling sites showed good correlation when considering minute data. This study showed that EDT sensors are very “temperamental” with issues for timekeeping, logging data and data treatment that also require substantial human intervention. B. Stacey concluded that provided all shortcoming are correctly solved, the data are good, both intra sensor and comparison to conventional analysers and that they can be used for spatial and temporal distribution information.

1. Czech experience with Vaisala, S. Rychlik (CHMI)

S. Rychlik presented the results of field tests of CairPol and Vaisala O3, SO2, NO2, CO, PM10 and PM2.5 sensors with reference measurements at a field site (Tušimice) equipped with reference methods. Good agreement between the NO2/O3 CairClip sensor measurement and the sum of NO2 and O3 reference were observed during the whole month of July 2015. Conversely, the test of the Vaisala sensor for showed poor agreement with coefficient of determination of 0.0038, 0.0272, 0.0845, 0.139 for NO2, O3, SO2 and PM2.5, respectively while PM10 did not show any relationship at all. In conclusion. S. Rychlik found difficult to handle with sensors that are not particularly user friendly, that sensor measurements shall be handled with extreme care, that differences could be observed within the measurement of the same brand model types and that using artificial intelligence, it is likely that the data quality of sensor measurements could be improved.

1. Sensor use within the Outdoor and Indoor Exposure project, F. Lenartz (ISSEP)

F. Lenartz presented some finding about the in-house developed sensor system called Antilope that accommodates AlphaSense NO, NO2 and O3 sensors, Honeywell PM2.5 sensor and humidity, temperature and pressure sensors. The Antilope sensor system includes a data filtering module to decrease the noise level created by the AlphaSense analogic front end. Calibration is performed in laboratory. It is planned to use the Antilope sensor system to estimate population exposure to air pollution. With the development of version 2.3 of Antilope the system did not work reliable anymore (negative values, etc.). He asked for support from the community to find the faults in the system.

1. AirSensEUR deployment in NL, calibration results & interoperability, M. Gerboles/A.Kotsev (EC-JRC)

M. Gerboles presented the AirSensEUR open sensor system. AirSensEUR is designed by a community of developers and users. The aim is that AirSensEUR behaves as a sensor node within a sensor network satisfying the requirements of the Inspire and Air Quality Directives. The design of AirSensEUR is released under the European Public Licence to allow free re-use. Its design simplifies the addition of new sensor model type. In its standard version AirSensEUR can accommodate 4 electrochemical sensors (typically, NO2, CO, O3 and NO), PM, CO2 sensors and an optional radon sensor. Sensor data together with GPS data are pushed to the cloud either by WIFI or GSM. During a deployment of 5 AirSensEUR units at a traffic site station in the Netherlands, the AirSensEUR Shiny App has been used for the filtering and calibration of sensor data. The App is a friendly tool for sensor and reference data transfer, time synchronisation, outliers discarding and fitting of several types of calibration models. Rather than using artificial intelligence, simple deterministic models based of multivariate equations using temperature, humidity and cross-sensitivities were used for sensor calibration. The calibration was performed over one week of sampling in Sep. 2018. Nearly identical calibration functions were fitted for the 5 AirSensEURs. The calibration functions were effective with R² > 0.88 for CO, NO, NO2 and O3. The application of the calibration function for 2 months in Aug.–Oct. 2018 also resulted in agreement with reference measurements (R² ≥ 0.82 for minute data and R² ≥ 0.90 for hourly averages and all slopes between 0.9 and 1.1). The least good agreement being the one for the NO2 sensor.

1. Deployment and data integration inside the IFLINK project, N. Castell (NILU)

N. Castell presented the results of CitySense, a previous project, highlighting the use of a network of sensor combined with annual reference measurements or output of AQ model for mapping air pollutant distribution. The aggregation method is designed to take into consideration sensor measurement uncertainty. N. Castell also presented a study, Citi-Sense-Mob, that used sensor worn by bikers in order to estimate personal exposure to air pollution. The iFLINK project aims at developing open and scalable network of sensors in 5 Norwegian cities providing real-time accurate air quality information with high spatial and temporal resolution at an affordable cost. iFLINK is designed around 4 modules: the sensor network infrastructure, the data processing infrastructure, the design of information solution and the 4 pilot studies. NILU also runs several actions activities including ”Clean air for all” in several high schools in Oslo and surroundings in which students build their own sensors and carry out measurements

1. C40 project, N. Martin (NPL)

N. Martin presented “Breathe London”, a pilot study carried out within the C40 (a network of cities committed to bold action on climate change and air pollution) whose objective is to improve understanding of exposure to air pollution by Londoners using state-of-the-art technology. Breathe London will use about 100 AQMesh sensor systems at fixed sites. 30 % of sensor systems could be moved in order to identify sources of pollution. The study will evaluate the suitability of several parameters of sensors including their sensitivity, selectivity, stability, accuracy and comparability between each other’s. Two GOOGLE street views cars equipped with state of the art measuring instruments for regulated pollutants, CO2, BC and ultrafine particles will also be operated. The street view car will be used for mapping purpose, for determining emission indexes and the distance of sources using CO2 sensors. By assimilating the sensor measurements and modelling outputs, it will be possible to map air quality ‘everywhere’ and to make predictions. Results will be coupled with emission inventories to perform source apportionment and to evaluate the effect of the future London “Ultra Low Emission Zone”.

1. LANUV sensor projects, C. Ehlers (LANUV)

C. Ehlers presented the results of sensor evaluation at field sites including AirSensEUR, Laser Egg and Nova SDS 011 at an urban background station. Two AirSensEURs were operated at the field site and showed nearly identical measurements for NO2-B43F sensors. As with other presentation, LANUV found poor agreement between the raw NO2-B43F sensor and reference measurement. Conversely, multivariate calibration allowed reaching better agreement (R² ~ 0.8, slope of 1). The reproducibility of two OX-A431 sensors was less satisfying than for NO2 (R² ~ 0.7). As for NO2, multivariate calibration was necessary in order to reach good agreement (R² ~ 0.8). The reproducibility of two NO-B4 sensors was less acceptable (R² ~ 0.6), so was the multivariate calibration. The test of Nova SDS 011 PM sensor showed that the agreement was depending on relative humidity. An acceptable agreement was found when relative humidity ranged between 40 and 70 %. Higher humidity was responsible to high overestimation of PM measured by sensors because of particle growth. Two PM Laser Egg sensors showed very good reproducibility while as for the Nova SDS 011 sensor, the agreement between sensor and reference data was rather poor. C. Ehlers concluded that raw gas sensor data shall be corrected using multivariate calibration taking into consideration meteorological parameters and cross-sensitivities. A lot of low-cost commercial sensors are commercially available but they are mainly developed for indoor measurements at nearly constant humidity. LANUV did not find obvious method for correcting humidity changes. The performance of a commercial system using correction by proprietary algorithm (LaserEgg) did not show better agreement with reference measurements than the tested low-cost PM sensor (Nova System).

*F. Lenartz reported about a recent paper about humidity correction for PM sensors (Developing a Relative Humidity Correction for Low-Cost Sensors Measuring Ambient Particulate Matter, sSensors, 2018, 18, 2790; doi: 10.3390/s18092790)*

1. Data fusion: integrating sensors in AQ Assessment, J. Wesseling (RIVM)

J. Wesseling presented the RIVM vison of the future of monitoring air pollution, expecting that AQ model outputs and reference plus sensor measurements will be more embedded, a process called “data fusion”. In particular, it is expected that sensor measurements will be officially integrated into air pollution distribution maps even though such a claim seems currently unrealistic because of the data quality of sensor measurements. RIVM carries out PM distribution maps by combining PM sensor data that assess local sources together with the output of the RIO Model to predict background PM levels. Another method consists in estimating differences between sensors and model outputs to be able to interpolate corrections in wider areas.

RIVM has been looking for the possibility to automatically re-calibrate a network of PM sensors using reference measurements. For NO2-B43F sensors, a multilinear regression function is fitted with initial field co-location of sensor and reference instrument. Periodically the parameters of the calibration equation are adjusted using the reference measurements of the nearest reference station. Another correction can be set in order to correct for the long-term drift that affects NO2 sensors (loss of sensitivity). Assuming that the true distribution of NO2 concentration levels is uniform over wide areas at night time when local emission are close to naught, it is possible to re-set the sensitivity of NO2-B43F sensors.

*Questions: What is the validity of the assumption of NO2 homogeneity at night time. Is there a risk that the assumption of uniform NO2 distribution and following sensor re-calibration will trigger wrong NO2 sensor measurements?*

*Answer: it is likely that this assumption needs some verification to check its validity.*

1. Discussion & Outlook: (Joining efforts, sustainable repository with quantitative metrics, setting rules on access, remain independent, calibration strategies, synergies & deployment strategies, regular meetings)Final session

The above initiatives show the growing interest of National labs to explore the possible deployment of low-cost sensors to monitor air quality. The great advance of having these sensors in operation is the increase in spatial coverage at low cost, the possibility to assimilate sensor data with reference measurements, air quality modelling and emission inventories.

All the interventions from the different participants focused on the necessity to target reliable sensor systems that must meet the following requirements:

1. Validity and stability of the sensor upon calibration with a reference system. This would mean that the sensor could be used in different location after calibration at a reference monitoring station.
2. Possibility to use the sensor at different locations over different pollution concentration ranges and meteorological conditions and micro-environments.
3. Open source sensor systems that give the possibility to develop correction algorithm and calibration methods, still ensuring transparency of data treatment in particular that black box sensor system do not use modelled data. Participants were reluctant and expresses doubts about the sensor measurements obtained from black boxes. In fact, some participants emphasized their interest in the AirSensEUR project as a unique sensor system completely open design and with transparent Shiny interface for data treatment.

As final outcome, the participants at this workshop recognised the necessity to define rules about the choice and operability of low-cost sensors. It was agreed that, under the supervision of the JRC, National Reference Laboratories involved in testing low-cost sensors will:

1. share their results with the JRC in order to populate a global repository of quantitative metrics. A report about performance of commercially available sensors will be released soon by the JRC. This will represent a documented European Knowledge Base that until now is absent.
2. Participants claimed that there is an urgent need for a harmonised protocol for sensor testing with associated quantitative metrics. Within Working Group 42 of the CEN Technical Committee 264, several AQUILA members are working to prepare Technical Specification that describe a unified protocol for the evaluation of the performances of sensors.
3. have regular meetings. Due to the fast growing sector of the business of low-cost sensors, we agreed to have meetings on AQ sensor every 6 months). The workshop participants want to remain independent from commercial interest and therefore would like to exclude manufactures from these meetings.
4. Additionally to sensor system, there is a growing interest into using data from networks of sensors.
5. Develop brochures addressing measurement performance and reliability for citizens, politicians and more technical people.

A dedicated CIRCABC site with all presentations has been set up by JRC and is managed by JRC:

<https://circabc.europa.eu/ui/group/4b8644cc-53cd-48ac-91f8-89806a697737>

Participating speakers and the AQUILA community were informed an invited to join the CIRCA BC forum (applications will be confirmed by JRC).

**GETTING IN TOUCH WITH THE EU**

**In person**

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: <https://europa.eu/european-union/contact_en>

**On the phone or by email**

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: <https://europa.eu/european-union/contact_en>

**FINDING INFORMATION ABOUT THE EU**

**Online**

Information about the European Union in all the official languages of the EU is available on the Europa website at: <https://europa.eu/european-union/index_en>

**EU publications**

You can download or order free and priced EU publications from EU Bookshop at: <https://publications.europa.eu/en/publications>. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see <https://europa.eu/european-union/contact_en>).



XX-NA-XXXXX-EN-N