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An evaluation tool kit of air quality micro-sensing units

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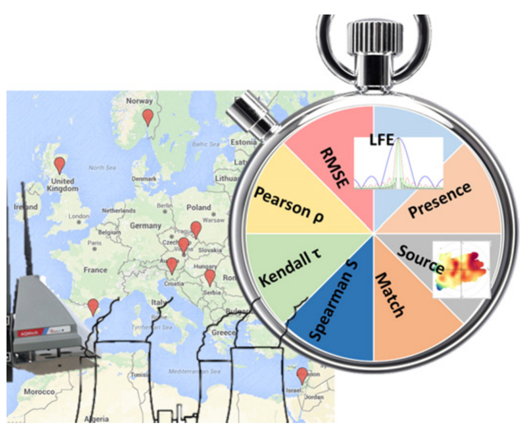
HIGHLIGHTS

- A comprehensive evaluation of modern approach to air-quality (AQ) monitoring
- AQ micro sensing units (MSUs) performance assessment in a range of applications
- Four new assessment measures that highlight new sensors' performance aspects
- Comprehensive assessment of AQ MSU network across Europe
- In-depth understating of MSU functionality via large scale comparative analysis

GRAPHICAL ABSTRACT



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ABSTRACT

Recent developments in sensory and communication technologies have made the development of portable air-quality (AQ) micro-sensing units (MSUs) feasible. These MSUs allow AQ measurements in many new applications, such as ambulatory exposure analyses and citizen science. Typically, the performance of these devices is

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assessed using the mean error or correlation coefficients with respect to a laboratory equipment. However, these criteria do not represent how such sensors perform outside of laboratory conditions in large-scale field applications, and do not cover all aspects of possible differences in performance between the sensor-based and standardized equipment, or changes in performance over time. This paper presents a comprehensive Sensor Evaluation Toolbox (SET) for evaluating AQ MSUs by a range of criteria, to better assess their performance in varied applications and environments. Within the SET are included four new schemes for evaluating sensors' capability to: locate pollution sources; represent the pollution level on a coarse scale; capture the high temporal variability of the observed pollutant and their reliability. Each of the evaluation criteria allows for assessing sensors' performance in a different way, together constituting a holistic evaluation of the suitability and usability of the sensors in a wide range of applications. Application of the SET on measurements acquired by 25 MSUs deployed in eight cities across Europe showed that the suggested schemes facilitates a comprehensive cross platform analysis that can be used to determine and compare the sensors' performance. The SET was implemented in R and the code is available on the first author's website.

1. Introduction

Air pollution is recognized as a contributing factor to various health outcomes, and has been associated with public health risks (International Agency for Research on Cancer (IARC), 2013; Sarnat et al., 2000). Accurately assessing ambient concentrations of different air pollutants is necessary in any study on the impact of air quality (AQ) on different health endpoints. To date, ambient pollutant concentrations are obtained from either short time-period measurement campaigns using a large number of sensing devices (e.g. (Crouse et al., 2009)), or from measurements reported by standard Air Quality Monitoring (AQM) stations over extended time periods (e.g. (Pope et al., 2002)). While the former is limited in temporal representativeness (e.g. due to inter-seasonal variation), the latter is limited in spatial representativeness (e.g. due to dispersion patterns) and typically measures only a limited number of criteria pollutants (Bishoi and Prakash, 2009). Further, regulatory AQM stations require certified instrumentation meeting measurement accuracy requirements, and an extensive set of procedures to ensure that data quality remains satisfactory. These requirements, typically required by laws and regulations, ensure that measurements are comparable across all networks with similar requirements, but limit the AQM spatial deployment due to their high investment and operational cost. As a result, the AQM network has limited ability to account for spatial variability of pollution levels in heterogeneous regions such as urban areas, which in return, renders exposure assessment a very difficult task (Rao et al., 2012). Moreover, the air-inlets of AQM stations are typically located on rooftops or way above the ground (European Environment Agency, 1998), thus misrepresenting the true exposure of any individual at head height.

Recent developments in sensory and communication technologies have made the deployment of portable and relatively low-cost micro sensing units (MSUs) possible. These MSUs can operate as a set of individual nodes, or may be interconnected to form a Wireless Distributed Environmental Sensor Network (WDESN) to measure air pollution over large spatial scales. WDESNs gather high-resolution spatial and temporal data from numerous individual nodes allowing for a better interpolation and the generation of dense pollution maps, which are closer to real-life pollution dispersion scenarios (Kanaroglou et al., 2005). The gaseous sensors mounted on these MSUs are low-power and low-cost, and are based on widely understood amperometric sensor methodologies designed for sensing selected gases at the parts-per-million (ppm) level (Bard and Faulkner, 2001; Mead et al., 2013; Stetter and Li, 2008). Electronic circuitry, which applies signal processing, allows for the detection at the part-per-billion level (Mead et al., 2013). Recent miniaturization of Optical Particles Counters (OPCs) (Gao et al., 2016; Ulanowski et al., 2013) and solid state (Carminati et al., 2014, 2015) sensors allows to extend the MSUs capabilities to measure particulate matter (PM) as well.

The small size and low power-consumption of MSUs lay the path for many new applications that require AQ data, such as exposure analyses (Jerret et al., 2005; Lebret, 1990), education (Ballantyne et al., 2010), hot-spot identification and characterization (Ma et al., 2008), supplementary network monitoring (Molchanov et al., 2015; The European Parliament and the Council of the European Union, 2008), and citizen science (Bonney et al., 2009; Shirk et al., 2012; Williams et al., 2014). In particular, the essence of citizen science requires active participation of citizens in the scientific research process (Bonney et al., 2009). Within the context of air-quality research, MSUs may be deployed at citizen's homes, monitoring either ambient or indoor air quality in their local environment. An example is the CITI-SENSE project, which aims at developing sensor- based citizen observatories for improving the quality of life in cities (CITI-SENSE Project, 2015).

Seminal studies that evaluate MSUs in pre-field and field trials show that these units indeed can capture air pollution spatio-temporal variation (Becker et al., 2000; Lee and Lee, 2001; Lerner et al., 2015; Mead et al., 2013; Molchanov et al., 2015; Piedrahita et al., 2014; Williams et al., 2013). However, these studies have shown that the MSUs' main limitation is their low accuracy relative to laboratory equipment (Becker et al., 2000; Lee and Lee, 2001; Mead et al., 2013; Piedrahita et al., 2014; Williams et al., 2013) or an AQM station (Mead et al., 2013; Molchanov et al., 2015; Williams et al., 2013).

Previously-used MSU calibration and evaluation measures, i.e., sensitivity (Becker et al., 2000; Lee and Lee, 2001; Mead et al., 2013; Williams et al., 2013), correlation coefficient, ρ, coefficient of determination, R^2 (Lerner et al., 2015; Mead et al., 2013; Molchanov et al., 2015), and the Root Mean Squared Error, RMSE (Lerner et al., 2015; Molchanov et al., 2015) aim at assessing the MSUs' accuracy and capability to capture trends and values of the pollutants' true ambient levels. While these criteria evaluate some aspects of the sensors' performance in many fields, for some applications different criteria covering additional performance aspects may be more adequate (Williams et al., 2014).

Personal exposure studies have supplied participants with MSUs that measured various air pollutants of exposure during daily routines (e.g., (Rabinovitch et al., 2006; Sarnat et al., 2000)). However, exposure is affected by many factors, and thus the variance of the dose response function is typically high and dominates the attributed relative risks/hazard ratios results, regardless of sensors' accuracy (Jerret et al., 2005; Lebret, 1990). Therefore, one common practice for estimating individual exposure is to use a coarse scale (Bishoi and Prakash, 2009; CITI-SENSE Project, 2015; Kyrkilis et al., 2007), rather than the sensors' actual measurement. Educational and citizen science applications typically aim at fostering informal and qualitative awareness. The measuring range in such applications is typically quantized into a binary scale, indicating the presence or absence of a pollutant. These scales and measures, although quantized, can still be used for relational comparison of air-pollution levels among different locations and times. This