Ambient air quality measurements in a large city: existing solutions, new opportunities and challenges

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Abstract. The city of Moscow has been actively introducing advanced technologies in the field of pollution control in real time. At the same time, Russian legislation often lags behind modern trends. The article discusses the issues of introducing reference and equivalent measurement methods and the problem of introducing small-sized instruments (low-cost sensors) for monitoring atmospheric air pollution. The article presents preliminary results of large-scale tests of low-cost sensors in comparison with traditional measurement methods, which were carried out by the State Environmental Protection Institution "Mosecomonitoring".

Life in a city is shaped by its environment in which air quality is a major contributor. Ambient air quality monitoring and management are important aspects of urban governance.

In the city of Moscow, the local ambient air quality monitoring system has been in operation for over 25 years. At present, the air monitoring network in Moscow comprises over 70 stationary automatic air quality monitoring stations (AQMS), 3 mobile environmental labs and an analytical laboratory. The system is aimed at the application of automatic continuous control methods in accordance with international recommendations [1]. Over 20 parameters, including particulate matter 10 micrometers or less in diameter (PM10) and particulate matter 2.5 micrometers or less in diameter (PM2.5) are being automatically measured at the AQMSs and mobile labs in the city.

Similar air monitoring networks, but on a much smaller scale, exist in other regions of Russia. On the one hand, the number of stations that are currently operating in the city is sufficient to determine the overall level of pollution in the city. On the other hand, the use of small-sized devices or low-cost sensors could complement the general picture of the air quality in the city, determine point sources of emissions, facts of unauthorized waste incineration, etc. It is possible if low-cost sensors in Russia would have a separate status and undergo a corresponding accuracy assessment.

It should be noted that modern and high-precision monitoring systems based on reference and equivalent measurement methods are resource-intensive and require regular maintenance. Only government agencies could afford operation of such systems. Despite these "disadvantages", these systems are able to measure even the smallest levels of pollution, their readings are very little dependent on weather conditions and the presence of other pollutants.

Technological development does not stand still, and the market has offered solutions that can be used not only by government agencies, but also by residents of the city - it has created low-cost sensors that assess air quality in real time, in addition to traditional high-precision measurement methods.

More and more companies offer small-sized devices/sensors with wide-ranging applications. Private companies and initiative groups of citizens create entire networks using such sensors.

Such instruments (sensors) are still at an early stage of technology development, significantly inferior in accuracy to instruments using reference or equivalent measurement methods and have not been properly evaluated to determine the accuracy of their measurements.
Everyone knows and does not dispute the importance of monitoring air pollutants for the health and well-being of the population. But even when using reference and equivalent methods, there are certain issues that need to be addressed.

In Moscow measurements of PM10 and PM2.5 are carried out at 42 stations by 4 different methods: gravimetric, tapered element oscillating microbalance (TEOM), beta absorption and nephelometry. Each of the methods used has its own advantages and disadvantages, reacting differently to changes in meteorological parameters and conditions in the controlled area. The difference in PM readings when using different methods at one point can reach 20 μg/m³ depending on changing meteorological parameters and conditions in the monitored area.

Currently, when applying various measurement methods, it is necessary to introduce correction factors to bring the measured values to the globally recognized reference method – gravimetry.

At the same time, gravimetry in Russia is still not a reference method for measuring particulate matter. The situation is similar for other pollutants.

Among the unsolved problems, it is worth noting the problem of the absence in the legislation of the concept of equivalent measurement methods.

In the European Union (EU) legislation the terms of a reference method (RM) and an equivalent method (EM) are clearly separated [2]. Despite the fact that the Russian Federal Law "On ensuring the uniformity of measurements"[3] includes the term of the reference method of measurement, until now there is no RM for the control of air pollutants, and the Russian legislation does not provide for the term of EM as well.

At the same time, in international practice, for most pollutants, RM methods are officially established at the legislative level, and in some cases EM methods are also established.

Against this background, and taking to account unresolved problems in the field of pollutant control, small-sized devices began to be actively introduced. Their readings were increasingly used not to inform about the real state of the environment, but to create tension between society and authorities.

Low-cost sensors which still have unstable metrological characteristics, are often offered as an alternative to the generally accepted RM and EM measurement methods.

The main disadvantages of low-cost sensors which even the leading manufacturers could not completely overcome are their short service life, significant influence of humidity on readings, low selectivity and cross-sensitivity, daily zero drift, and the possibility of "poisoning".

As for the use of RM and EM and low-cost sensors as well, the Russian legislation also lags behind European one.

Thus, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (Ambient Air Quality Directive) [2] states that Member States shall apply the reference methods. Other measuring methods may be used by Member States if they can prove that the method being used give the same results as the reference one, that is to confirm the equivalence of the method.

The Ambient Air Quality Directive defines the use of some "indicative measurements" that meet data quality objectives that are less strict than those required for fixed measurements. At the same time, the Directive also states that ambient air quality information could be supplemented by means of indicative measurements for interpretation of the monitoring data in a particular area. Thus, the Directive does not define any indicative methods, but requires them to comply with an expanded uncertainty that is half that of the reference methods.

Therefore, low-cost sensors fall under definition "indicative measurement" in accordance with the European legislation. And EU certification bodies have already been conducting similar testing of low-cost sensors or indicators since 2019.

It is worth mentioning that some devices, which according to the Directive 2008/50 / EC [2] are recognized as indicators in European countries can not be used in the state regulation area. As distinct from EU, in the Russian Federation such devices are able to be tested for type approval as measuring instruments. It gives them the possibility to be used in the state regulation area. However, in this case,
their data can be used as basis for governmental decision-making in the areas that are vital for the citizens. Such approach is indubitably incorrect and can increase health risks.

Actually, low-cost sensors are a compromise between reference and equivalent measuring methods in cases when application of RM and EM could be complemented by indicative measurements. On the side of small-sized devices are the price, size, weight, mobility and the amount of consumed electricity, and on the side of reference measurement methods: measurement accuracy, low detection limits for pollutants, very low dependence on environmental factors and high reliability.

Disadvantages of low-cost sensors do not prevent them from applying for overall assessment of air quality. And it is possible for such devices to be the future, if their accuracy approaches the accuracy of RM and EM measurement methods. In any case, they are the basis for a concept of “Smart Cities” and the Internet of Things (IoT).

These technologies have inevitably aroused great public interest as people can monitor the air around them and understand the level of the actual impact of pollution on themselves and their families. It is a powerful tool to engage citizens and help city authorities make faster decisions to improve urban environment. This approach not only complements the existing state monitoring systems, but also engages city residents in solving environmental problems.

Moreover, State Environmental Protection Institution "Mosecomonitoring" (SEPI "Mosecomonitoring") does not support any restrictions or barriers for the use of small-sized devices or low-cost sensors at all. The areas of their application (see Table 1) is really huge and to some extent even wider than that of standard air quality monitoring equipment starting with their use in educational programs to identification of the source and characteristics of emissions without obtaining true numerical values.

| №  | Application area                                      | Brief description                                                                 | Examples                                                                 |
|----|-------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 1  | Informing scientific research or popular science programs | New or supplementary information on air pollution in real time by increasing the number of control points and receiving information from more sites. | Sensors network can help to evaluate A network of low-cost sensors can be used to estimate the dispersion of particulate matter concentrations over a city, localize the main sources of PM, and indicate where PM10 dispersion is minimal. |
| 2  | Individual exposure assessments                        | Personal monitoring of air quality in course of a routine daily activity of a sensor owner. | A person who is sensitive to higher levels of air pollution can use a sensor to determine when and where he is exposed to pollutants potentially affecting his health. |
| 3  | Getting an overall picture of traffic in real time without installing expensive video surveillance systems | Sensors can provide information on road congestion, including the identification of major vehicle types. | Sensors could help studying traffic flows and their redistribution in order to improve the environmental situation. |
| 4  | Complementing to the existing monitoring network        | Sensors can supplement data of an existing monitoring network and increase the coverage area of the measurement devices. | Sensors can be installed in the area between fixed monitoring stations in order to better characterize the concentration gradient between different points. |
| 5  | Identification of source and                           | Identification of an actual emission source by placing                            | Sensors can be placed on the leeward side of an industrial facility     |
In this regard the problem of the quality of these low-cost sensors has become especially relevant. Comparative tests of small-sized devices and EM and RM methods are carried out in various countries constantly and numerous. In the Russian Federation, a single similar test was also carried out.

SEPI "Mosecomonitoring" became the first institution in Russia to conduct large-scale and long-term comparative tests of low-cost sensors and the EM and RM devices that allows us to draw certain conclusions. These conclusions will be published later on and we believe that this paper to be only the beginning.

It should be noticed that SEPI "Mosecomonitoring" have no financial interests or personal relationships with the cited authors that could affect the tests. The paper does not specify any manufacturers or brands of the devices being tested.

Comparison with EM and RM methods was carried out simultaneously with 7 types of different small-sized devices from different manufacturers at three points in the city of Moscow in different territories. The instruments measured various environmental indicators, including PM.

Some of the sensors being tested showed good measurement results in comparison with the EM and RM devices. Measurement error and variations in the data obtained were often significant and depended on the specific measured substance, environmental conditions such as temperature, pressure, humidity, atmospheric precipitation, etc., and temperature control in the device if any.

At the same time, it should be noted that if changes in readings are similar then measurement error is within the range of ± 50%. Thus, such devices are still just indicative ones.

In most cases, the influence of weather conditions led to absolutely unpredictable measurement results.

Thus, such devices should still be considered as indicative ones that can give a general description of the state of the environment under certain conditions.

Differences in the readings of the two low-cost sensors (SS1 and SS2) and RM and EM devices are given in the Table 2 and on the Figures 1 and 2.

But somehow commenting on these graphs is not the topic of this article. It might be only mentioned that presented data clearly show “accuracy” and selectivity of sensors’ readings.

At the same time, graphs and tables require a brief explanation.

### Table 2 Differences in the readings of low-cost sensors (SS1 and SS1)

| Correlation, SS1       | Correlation, SS2       | Determinant |
|------------------------|------------------------|-------------|
| y = 0.0592x + 0.0252   | y = 0.2135x + 0.0217   | R² = 0.0034  |

| PM10 | PM10_SS1 | Mode | Median | Mean | PM10 | PM10_SS2 | Mode | Median | Mean |
|------|----------|------|--------|------|------|----------|------|--------|------|
| 0.032| 0.011    | 0.032| 0.026  | 0.028| 0.032| 0.026    | 0.032| 0.028  | 0.029|
Table 2 shows that the values of the correlation coefficients are close to "0", therefore, the readings
of the sensors are not related to each other.

Determination coefficients, in their turn, are also close or tends to "0", that means a low significance
of the model, when the input variable poorly "explains" the behavior of the output, i.e. there is no linear
relationship between the readings of the two sensors.

Figures 1-2 also demonstrate the difference in readings of the two low-cost small-sized PM10 sensors
(SS1 and SS2) in comparison with the TEOM method.

![Fig. 1 Difference in readings of a low-cost small-sized PM10 sensor (SS1) in comparison with the TEOM method](image1)

![Fig. 2 Difference in readings of a low-cost small-sized PM10 sensor (SS2) in comparison with the TEOM method](image2)

The Figures 3-6 characterize typical dependences in readings of low-cost sensors on weather
conditions or, in other word, on operational conditions. This article provides comparative graphs of
readings of small-sized sensors that measure particulate matter in comparison with the TEOM method.
Data on testing of the sensors that measure particulate matter are given here for the reason that such devices are most common among city residents due to their low price and availability.

Fig. 3 Influence of temperature on PM10 concentration in the air according to readings of low-cost small-sized sensors (SS1, SS2) and TEOM

Fig. 4 Influence of humidity on PM10 concentration in the air according to readings of low-cost small-sized sensors (SS1, SS2) and TEOM
Fig. 5 Influence of pressure on PM10 concentration in the air according to readings of low-cost small-sized sensors (SS1, SS2) and TEOM on particle concentration in the air.

Fig. 6 Influence of atmospheric fog on PM10 concentration in the air according to readings of low-cost small-sized sensor (SS) and TEOM, December 2020.

At the same time, at temperatures within the range 10 - 25 °C and at a relative humidity of 70% or below and in the absence of precipitation low-cost sensors show almost identical dynamics with the RM and EM devices and are close in terms of the concentrations of pollutants. In some cases, for small-sized devices with temperature control and temperature compensation, the temperature range at which the devices show stable characteristics expands significantly and covers the region of negative temperatures.
Manufacturers of low-cost sensors have not yet been able to completely eliminate the influence of atmospheric humidity on the readings, and at a humidity above 80% readings can be either overestimated or underestimated by significant values, reaching tens and hundreds of micrograms per cubic meter. Those facts were known before and were described in detail in the articles [4] and [5], for example. So, this is far from saying that SEPI "Mosecomonitoring" made a discovery in this field.

For instance, in the course of the studies of small-sized (indicative) devices that measure PM concentration in the ambient air our experts have confirmed what various researchers in Western countries have seen previously including the fact that the size, density and composition of aerosols play a potentially important role in linearity and the overall sensitivity of the PM sensors.

The size and composition of aerosols (i.e., refractive index) inherently alters particle dispersion and absorption, and are supposed to impact significantly on any light-based measurements. Likewise, for the same reasons differences in particle density also affect light-based measurements and complicate the relationship between particle size and mass. Our research has also shown that low-cost sensors appear to respond differently to aerosols with different physical and chemical properties.

In fact, experts of SEPI "Mosecomonitoring" have confirmed that such devices must be calibrated "in place" according to the actual time of year and real weather conditions in order to be used in the same way as the EM and RM devices are used.

Based on the above it should be concluded that nowadays in the Russian Federation the problem of introducing the terms of equivalence of measurements and indicative measurements into the legislative norms regarding the uniformity of measurements has become very urgent.

Conclusions
The existing practice of introducing reference measurement methods (techniques) in the field of environmental protection is not perfect and is too cumbersome. It is proposed to Federal agency for technical regulation and metrology of the Russian Federation (Rosstandart) to recognize international and EU standard reference measurement methods (such as, for example, EN 14212: 2012 Ambient air - Standard method for the measurement of the concentration of sulphur dioxide by ultraviolet fluorescence) as standard reference measurement methods in Russian Federation by issuing an order.

The results of our tests presented in this paper are preliminary and we are planning to publish a detailed report in the nearest future.

Based on the tests results it could be concluded that testing of devices intended for use in the field of continuous monitoring of the environment should be carried out not only in laboratory conditions, but also in real-life conditions, and clear criteria should be established for testing equipment intended for use in the field of environmental protection.

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