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City-scale Air Quality Network of Low-cost Sensors

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City-Scale Air Quality Network of Low-Cost Sensors

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Abstract: In this paper we present a city-scale (possibly global) air pollution network made of low-cost sensors for particulate matter concentration in the air. The components of presented system are based on our research and experience from previous studies focused on air quality instruments and sensors for addressing urban air pollution. Sensor nodes are produced locally and distributed over a city of Sarajevo, Bosnia and Herzegovina. The system collects, calibrates and displays particulate metal concentrations in real-time. In comparison to the available measurements from governmental institutions, our system demonstrated good agreement of measured parameters, with several advantages including: higher resolution in space and time, lower costs, both horizontal and vertical measurements and many more. One of the capabilities of the system is the real-time air pollution city map with animations. By installing multiple sensor nodes over a slope (cable car), we receive vertical measurements of temperature, humidity and particulate matter concentration in real time, which gives a valuable insight into the dynamics of temperature inversion episodes and air pollution below the inversion layer.

Keywords: particulate matter; low-cost sensors; air pollution; temperature inversion

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1. Introduction

The city of Sarajevo, capital of Bosnia and Herzegovina, is heavily affected with air pollution with one primary component of pollution: particulate matter (PM) concentrations in the air. All other components of air pollution, for example heavy metals [1], are either acceptable or at least less problematic than PM. According to the report of World Bank [2], it is estimated that 3300 premature deaths per year can be related to the air pollution in Bosnia and Herzegovina, while the economic costs are between 1 and 1.8 billion US dollars.

As shown in Table 1, the annual average concentration of particulate matter smaller than 2.5 μm in diameter ($PM_{2.5}$) at the location of our Faculty (in the center of Sarajevo) was around 35 $\mu g/m^3$ for the years 2022 and 2023 (this was measured using the system presented in this article). One of the reasons for a such strong air pollution is the topology of the terrain. With an avearage altitude above sea level (ASL) of 550 m, Sarajevo is situated in a valley surrounded by mountains and it is affected by temperature inversions during the winter time. Our previous research on using drones for investigation of temperature inversion [3] shows that the temperature gradient in the inversion layer is very strong and the height at which temperature inversion appears is low, often just 100 m to 150 m above the ground. This prevents natural convection and pollutants emitted by households, traffic and other sources are accumulated below the inversion layer. Figure 1 shows the drone image of central part of Sarajevo, taken during a research mission.

Our system occasionally detected daily average values of $PM_{2.5}$ concentrations greater than 500 $\mu g/m^3$, which is beyond air quality index (AQI) scale [4]. In order to address this issue, we need measurements not only of air pollutants concentrations but also those related to the temperature inversion phenomenon (vertical profiles of temperature across the inversion layer). Then we can quantitatively describe the influence of temperature inversion to the air pollution in the city.

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Table 1. Annual average concentration of $PM_{2.5}$ at the location of Faculty of Mechanical Engineering in Sarajevo.

Year	$PM_{2.5}$ ($\mu g/m^3$)
2019	33.9
2020	46.1
2021	29.3
2022	35.1
2023	35.6

Governmental institutions have sparse network of stations for monitoring several components of air pollution. The spatial and temporal resolution of such measurements is low, and there is no information about vertical distribution of pollutants and temperature. Our system which is named MAQS (Mobile Air Quality System) is designed to provide high resolution measurements of air pollution components and meteorological parameters, with both horizontal and vertical variations of sensor locations.

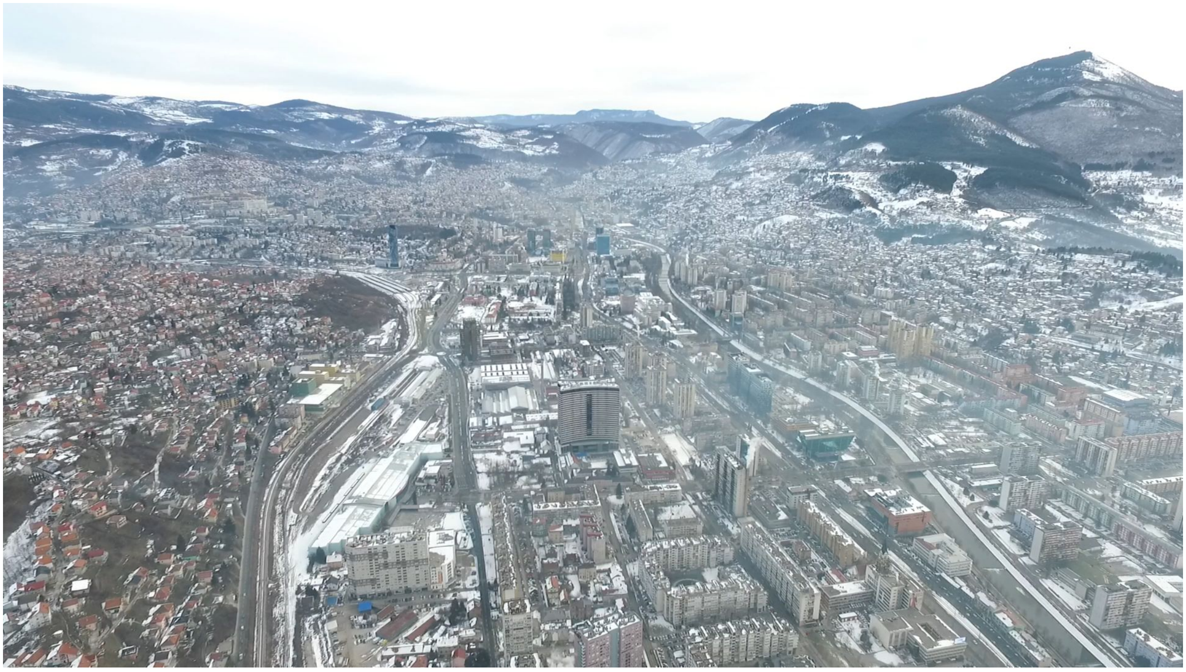

Figure 1. Central part of Sarajevo and surrounding mountains. Image taken from drone on 01/31/22.

2. About MAQS

MAQS is a system for collecting, storing and displaying measurements of air pollution and meteorological parameters in real time. It is based on internet cloud, as shown in Figure 2. The software components of MAQS are designed using open source projects. The code for server, which is responsible for direct communication with sensors, is developed in-house and written from scratch in C++ plus programming language with significant use of Boost library [5]. It is highly optimized, state-of-the-art asynchronous code designed to be flexible and scalable. In order to test the scalability of MAQS server code, a simulator was created to test the performance of MAQS server under the concurrent activity of many thousand sensors, and the results were outstanding: MAQS server worked well even on Raspberry Pi 3 single board computer (i.e. with very limited hardware resources). In reality, MAQS server uses Ubuntu Linux operating system installed on a mid-range desktop PC (Intel Core i5-4460 with 6 GB of DDR3 RAM). The measurements are stored in a database. We use open source relational database PostgreSQL [6]. Clients with appropriate permissions can access the database using SQL queries.

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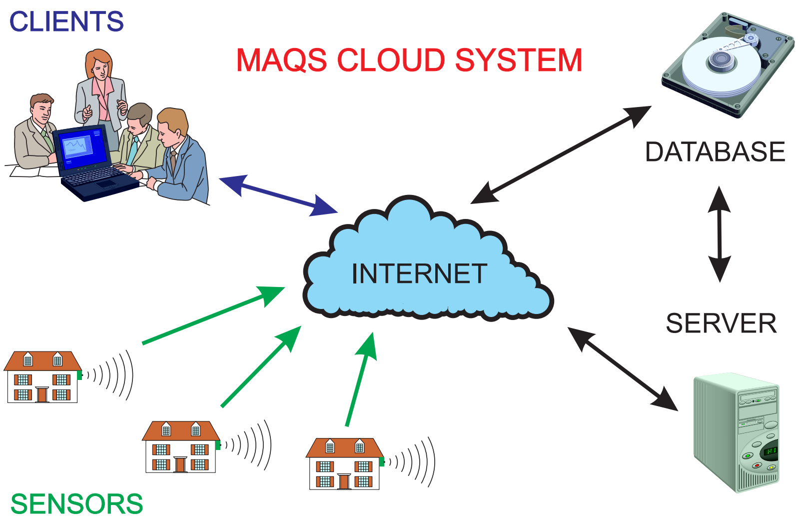

Figure 2. Components of MAQS: sensors, server with database and clients connected via internet cloud.

MAQS sensors represent the most important component of the system. We have developed two generations of sensors:

- Generation 1 – each sensor from this generation is powered by an Arduino [7] microcontroller (Mega or Due) with external ESP8266 Wi-Fi network chip.
- Generation 2 – this generation omits Arduino, and uses ESP32 for both network and processing tasks [8].

Any combination of sensors from first and second generation is supported by our server. Communication between sensors and server is implemented using our own protocol and TCP/IP connection. This choice is crucial to achieve the reliability and robustness of the system. In reality Wi-Fi connections are unstable (particularly at some of our locations of measurements) and we can't afford to lose data because of that. TCP has mechanism of retransmission: if data packet is damaged or lost it will be resent. In case of total connection loss, the measurements are stored locally in the RAM memory of the sensor microcontroller (or SD card if available). After the connection is reestablished, all stored data will be sent to the server and stored in MAQS database.

2.1. Particulate Matter Sensor

The choice of particulate matter sensor for the MAQS project was the most important decision. We previously evaluated PM sensors for mobile measurements [3], and found suitable sensor for this project: PMS5003 (Plantower, China). Apart from being the low-cost sensor, PMS5003 demonstrated surprisingly good correlations with reference measurements of $PM_{2.5}$ under conditions of strong urban pollution in Bosnia and Herzegovina, which is illustrated in Figure 3. In order to verify performance of PMS5003 sensor, we organized campaign from DEC/2/2019 until MAR/2/2020 with reference (gravimetric) measurements of $PM_{2.5}$ concentrations. Sampling was performed with a Gemini sampler (Dadolab, Italy) with air flow rate of 2.3 m^3/h. The sampling started at 12:00 (local time, CET zone) each day and ended at 11:58 the next day. Two minutes were reserved for automatic filter exchange. Particles were collected on quartz filters with diameter of 47 mm. The filters were carried out through a stabilization and weighing procedures strictly according to the requirements of the standard EN 12341:2014. In this campaign PMS5003 produced coefficient of determination $R^2 = 0.9827$ with reference measurements (for daily average concentrations of $PM_{2.5}$), and performed better than more expensive OPC-N2 (Alphasense, UK) sensor [9]. The absolute values are overpredicted by PMS5003 , mostly due to effect of the hygroscopic growth of aerosols as we explained in details [9]. However, this behavior is suitable for corrections, especially if take into account good linearity of the sensor and no observable time drift in the long-term use [9].

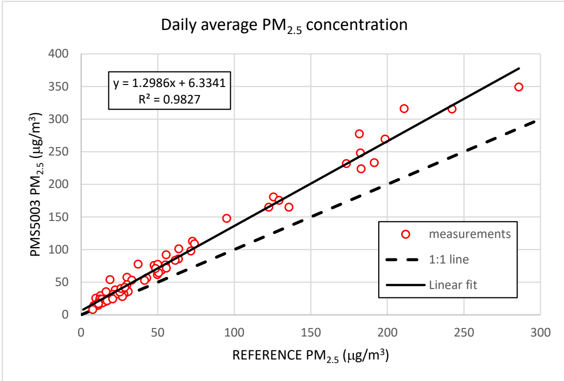

Figure 3. Evaluation of PMS5003 sensor: reference gravimetric measurements.

PMS5003 is one of the most analyzed particulate matter sensors. Numerous studies are dedicated to laboratory and field tests of PMS5003. It was tested in [10] using laboratory and field tests where high bias of PurpleAir (PMS5003) was observed. In [11] PurpleAir (PMS5003) was analysed for 16 months in Charlotte, North Carolina, USA, against BAM-1022, and high bias of PurpleAir (PMS5003) that increases with humidity was reported. High mean bias of (PMS5003) was reported in [12] as well.

The PMS5003 sensor uses Mie scattering theory to determine PM concentrations. Mie theory provides the solution of the Maxwell equations for the scattering of plane waves on spherical particles [13]. Laboratory tests of [14] and [15] are particularly important for understanding the limitations of PMS5003. According to these tests, two major limitations of PMS5003 are:

1. it can't detect properly coarse particles (especially those larger than 2.5 μm) because most particles miss the focal point of laser beam. When this happens for large particle, it is incorrectly sized,
2. strong wind can obstruct sensor's aspiration, depending on the wind direction relative to the sensor inlet.

The reason why PMS5003 works so well in Sarajevo, when urban pollution is strong, is that none of these two conditions apply: during temperature inversion periods there is no wind under inversion layer, and mass spectrometry of the particles shows that contribution of coarse particles is very small. In our campaign [9] we simultaneously measured $PM_{2.5}$ and PM_{10} concentrations using reference gravimetric method, from 12/2/2019 until 03/12/2020, and calculated that $PM_{2.5}$ makes 87% of PM_{10} mass. These are favorable conditions for the Plantower sensor. However, when spectrum of PM contained large number of coarse particles, such as the Aralkum desert sand observed in Sarajevo on 03/27/2020, the PMS5003 performed poorly (Alphasense OPC-N2 was much better in this scenario) [9]. But these desert sand episodes are not frequent in Sarajevo, while the pollution from combustion dominates most of the time, so the overall conclusion is that PMS5003 is indeed optimal sensor for this project.

Apart from these general observations of PMS5003, each sensor is additionally calibrated (Figure 4). All tested sensors show the same trends, but there is slight difference in their readings (acknowledged by the manufacturer in data sheet). As we explained in [9], we propose correction of raw readings from the sensor using steady (seasonal) calibration coefficients, determined for each sensor individually. These corrections can be linear for concentrations of $PM_{2.5}$ up to 300 $\mu g/m^3$. Above 300 $\mu g/m^3$ (which is rare situation even in Sarajevo) we observed non-linear effects, so the quadratic corrections fit better. We don't recommend calibrations using floating correction coefficients (for example based on instantaneous value of ambient air humidity), because such procedure inserts noise into results since effective hygroscopic growth coefficient depends on composition of particles. Furthermore, internal structure of the sensor and self-heating effect represent additional uncertainties in such approach [9]. It is known that PMS5003 readings show dependence on relative humidity but less than predicted by simple hygroscopic growth theory [16].

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It would be useful to test enclosures with some kind of humidity regulation, which is our future task. We already demonstrated effectiveness of in-house developed diffusion dryer, but it was applied to different class of instrument - portable aerosol spectrometer 11-D (Grimm, Germany) [9]. Promising results of development of dryers for low-cost sensors were reported in [17] and [18].

In the MAQS system calibration is implemented at the database level. When a new measurement arrives, it is stored in the main table (without corrections). At the same time, the calibration trigger calls special function which corrects the measurement based on the parameters from the calibration table. Corrections with three parameters (linear and quadratic polynomial) are supported in real time (apparently any correction can be applied in post processing). The corrected value is calculated and saved in the appropriate table. Hourly and daily averages are also recalculated. In this way, users have calibrated measurements in real time.

Figure 4. Calibration of MAQS sensors: batch of 10 sensors are being calibrated in our laboratory for particulate matter spectroscopy and gravimetry.

Each MAQS sensor has PMS5003 inside, while other sensors are optional. Table 2 shows physical quantities which have been measured using MAQS system. Enclosures for MAQS sensors are designed and produced in-house. Basic enclosure is produced using 3D printer (Figure 4), while advanced enclosure requires machining as well (Figure 8). Measurements of optional quantities can be calibrated the same way as PM concentrations (they have their own entries in the MAQS calibration table).

Table 2. Supported external sensors.

Physical quantity	Supported sensors
Position and time	All U-blox GNSS receivers
Barometric pressure	Bosch BME and BMP series
Wind speed	in-house developed cup anemometer
Carbon dioxide concentration	Amphenol Telaire 6703, Plantower DS-CO2-20
Temperature	Sensirion SHT 30 and 40 series
Relative humidity	Sensirion SHT 30 and 40 series

MAQS is not the only project of this type. For example, PurpleAir network is often discussed [19]. However, combination of sensors, vertical measurements for temperature inversion research, live pollution map (based on modified IDW algorithm) and non-linear real-time corrections make MAQS unique.

3. Results and Discussion

First MAQS sensors are installed in year 2018. Each sensor measures $PM_{2.5}$ as fast as possible (once per second) and results are averaged over a period of 60 seconds and then stored in the database. We have collected more than 60 million database records so far. This database is very valuable asset for research of air pollution. We will give two examples here.

3.1. Pollution Map

In order to generate the pollution map, we need to estimate air pollution in every single point of the city. With limited number of sensors, we have to use certain interpolation algorithm for that purpose. Inverse distance weighting (IDW) is commonly used in geosciences for such interpolations. We have adopted IDW here with some modifications. If we have N sensors accros the city, they give values of desired parameter $z_1, z_2, \ldots, z_N$ at the location of each sensor. The value of $PM_{2.5}$ at some arbitraty point M is estimated using formula

$$z_{\mathrm{M}} = \frac{\sum_{i=1}^{N} \frac{z_i}{d_i^p}}{\sum_{i=1}^{N} \frac{1}{d_i^p}}, \tag{1}$$

where d_i is the distance from sensor i to the point M, and p is the power parameter. The choice of power parameter is not trivial. For small power parameter, such as $p \leq 2$, interpolated values may be dominated by points that are far away. When p is large, the generated map looks like the mosaic of tiles with nearly constant interpolated value. Our choice for live pollution map is $p = 3$. An additional modification was implemented: only nearest neighbors within sphere of radius R were taken into account for interpolation. This is combined with our spatial search algorithm for efficient implementation, which makes the map viewable on mobile devices with limited processing speed.

The live pollution map is presented on web page https://www.maqs.info using OpenLayers library [20]. Figure 5 shows the screenshot of the live map from 12/09/19, where we can see interesting spatial variation of $PM_{2.5}$ concentration. Mild eastern wind cleared air pollution from the eastern part of Sarajevo, but it was not strong enough to reach western part of the city (this scenario was detected several times using MAQS live pollution map). Tall buildings (visible in Figure 1) are obstructing ventilation of the city in case of mild wind. This shows that MAQS can be used as a tool in urban planning, microclimate studies and future low-emission zones establishment.

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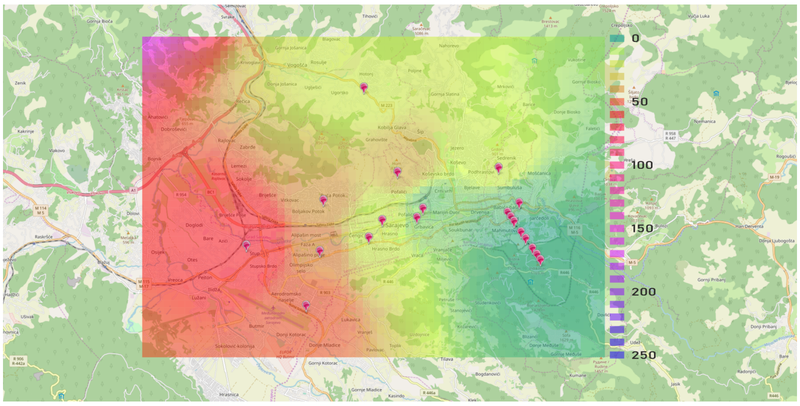

Figure 5. Live pollution map for 12/09/2019: example of spatial variation of $PM_{2.5}$ concentration across the city. Markers on the map are sensor locations.

When the mouse cursors hovers over the map (or the screen is briefly touched on a mobile device) the interpolated value in that point will be displayed as shown in Figure 6.

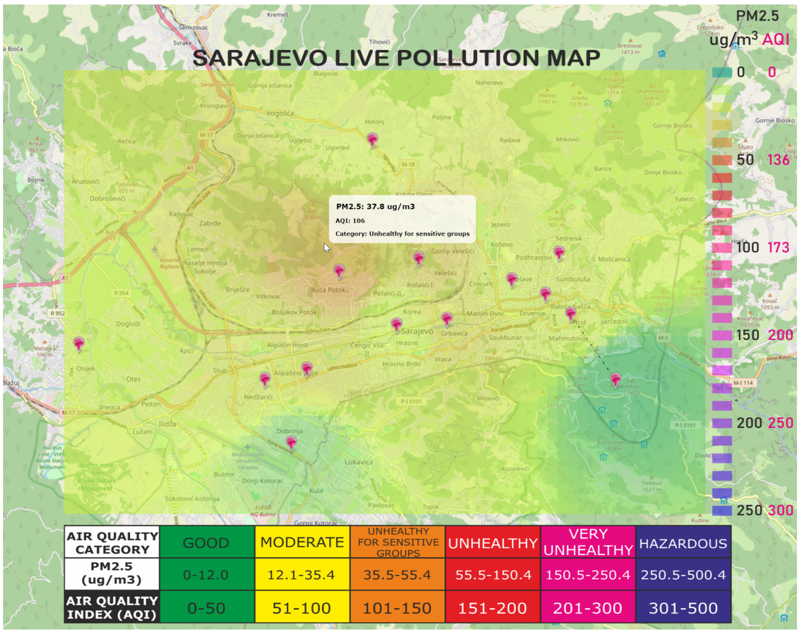

Figure 6. Live pollution map for 04/28/2024: mouse hovering for display of AQI category and $PM_{2.5}$ concentration in every point on the map.

The map can be animated in two ways: by pressing the 'H' button for hourly animations over the last 24 hours or by pressing the 'D' button for daily animations for the last 10 days.

3.2. Vertical Profiles and Temperature Inversion

Figure 7 shows hazardous air pollution in Sarajevo on 12/06/2019. Temperature inversion was strong and stable which resulted in accumulation of pollutants. Only periferal parts of the City with altitudes greater than 800 m ASL were above inversion lid.

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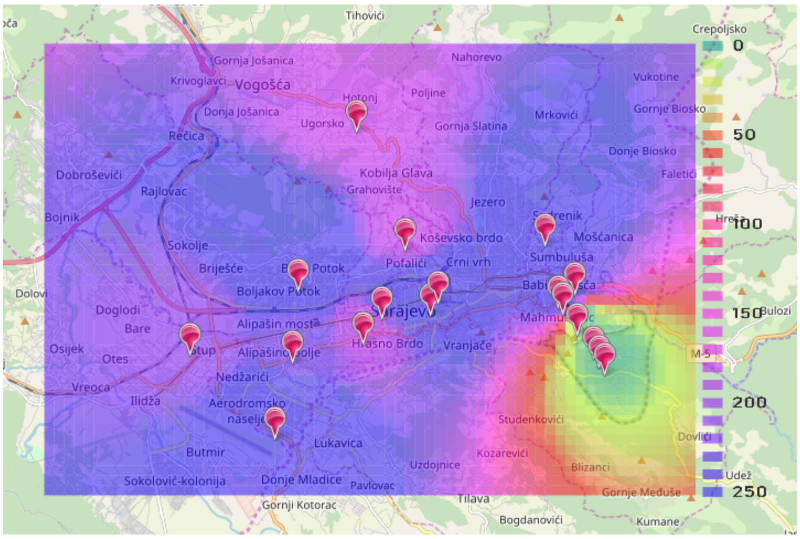

Figure 7. Live pollution map for 12/06/2019: City of Sarajevo under hazardous air pollution.

In order to test the capabilities of the MAQS system to measure vertical profiles, a special campaign was organized during the first 3 weeks of year 2020, when strong temperature inversion had been expected. We performed several preliminary measurements using drones [3] and concluded that the location of Sarajevo cable car (which spans from nearby the City Hall to Trebevic mountain, with length of 2.1 km and height difference of 580 m) would be suitable for measurements. In cooperation with City of Sarajevo, who is the owner of the cable car, we have installed batch of 8 MAQS sensors on the pillars of cable car, as shown in Figure 8. Each sensor is mounted on top of a pillar, while precise altitude of the sensor is determined using GNSS measurements and listed in Table 3.

MAQS sensors for this campaign were equipped with SHT31-D temperature and humidity sensors (Sensirion, Switzerland) together with mandatory PMS5003 PM sensors (and abovementioned GNSS receivers). Each SHT31-D sensor was calibrated in our laboratory prior to deployment. There was no Wi-Fi connection over the cable car route, so we had to use our own GSM modems and Wi-Fi repeaters in very challenging conditions. SD cards were installed in each MAQS sensor to prevent data loss in case of Internet connection problems. During this campaign, the data availability was 100% (not a single measurement was lost) which shows the reliability of MAQS system.

Table 3. Vertical positions of sensors on cable car pillars.

Pillar	Sensor altitude ASL (m)
S2	585
S3	660
S4	710
S5	810
S6	895
S7	1000
S8	1090
S9	1165

The anticipated temperature inversion in this period appeared to be very strong and stable, which made this campaign successful. Figure 9 shows six characteristic profiles of temperature and $PM_{2.5}$. When there is no temperature inversion (1/6/20 5:00), $PM_{2.5}$ concentrations were low and well distributed over the city (vertically in the range of measured altitudes). This plot shows linear decrease of temperature with altitude. Despite low ambient temperatures (well below zero degrees Celsius), wind and natural convection prevented accumulation of pollutants which resulted in excellent air quality at that time.

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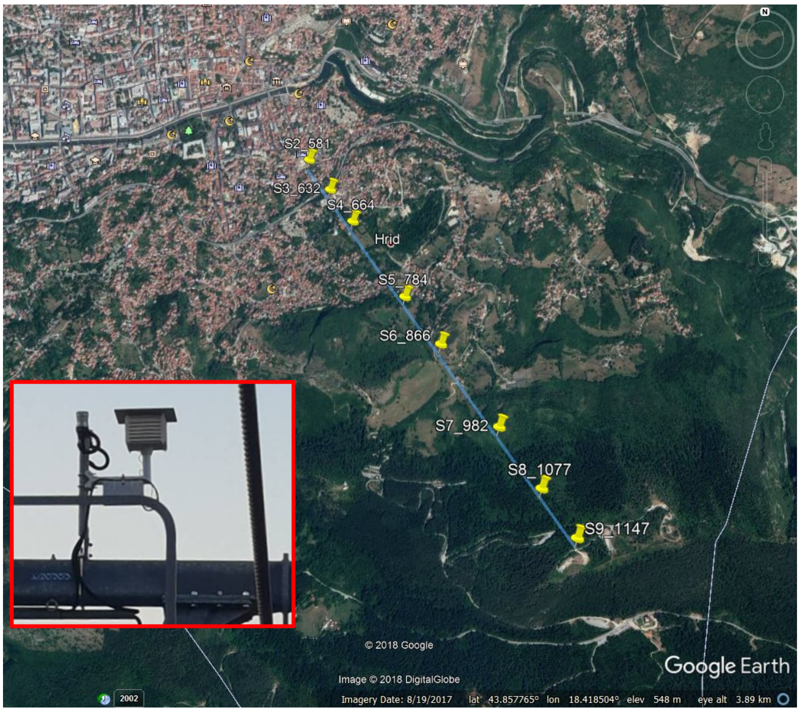

Figure 8. Sarajevo cable car pillars and terrain from Google Earth. A MAQS sensor shown as image overlay.

However, different situation happened two days earlier (1/4/20 10:00), when temperature profile had characteristic "Z" shape. That morning inversion layer started about 100 meters above ground level (AGL) and ended about 500 meters AGL, with gradient in the inversion layer of 15.5 K/km. Concentration of $PM_{2.5}$ below the inversion layer reached 250 $\mu g/m^3$. Similar profile was recorded on 1/9/20 15:00, with a difference often observed in the afternoon: inversion layer started higher, at about 250 m AGL. The gradient in the inversion layer was even greater, 33.3 K/km, which in combination with cold air in the city resulted in hazardous air pollution with $PM_{2.5}$ exceeding 300 $\mu g/m^3$.

Plot from 1/7/20 8:00 shows inversion layer starting from 150 m AGL all the way to top of the mountain, but with lower gradient of 10.8 K/km. The air temperature in the city of Sarajevo was -10 ^{0}C while $PM_{2.5}$ concentration was 120 $\mu g/m^3$.

Last two graphs (1/11/20 2:00 and 1/16/20 2:00) show similar effects: inversion layer starting from 150 m AGL with gradients around 13 K/km. Stable and lasting inversion trapped pollutants for longer periods of time, which resulted in $PM_{2.5}$ concentrations of 500 $\mu g/m^3$ even at 2AM, when most human activities were suspended.

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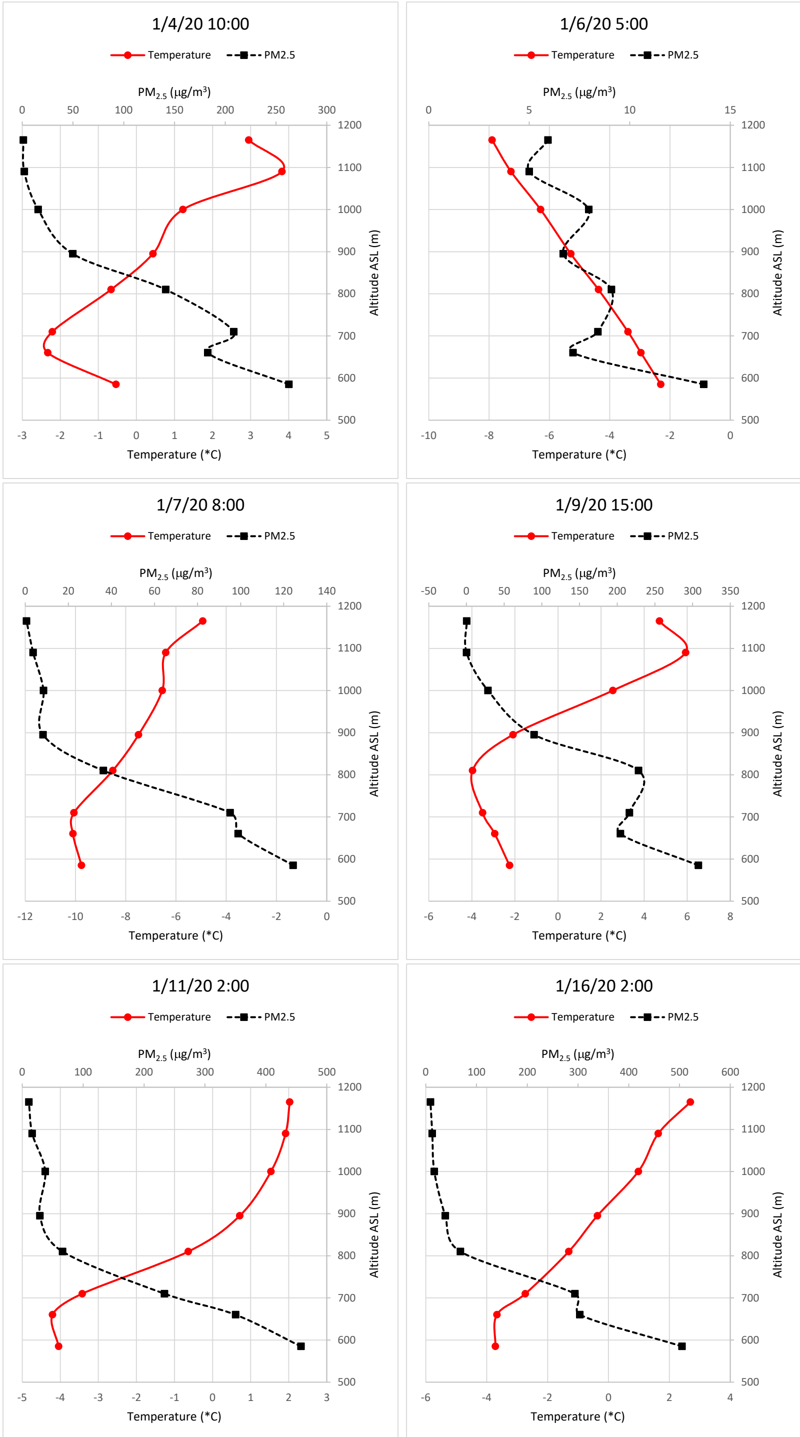

Figure 9. Temperature inversion profiles.

The relative humidity is also stratified along the inversion layer. Figure 10 shows two relative humidity profiles for morning of 1/4/20 and afternoon of 1/9/20. Below the inversion layer (inside the City) the relative humidity was very high (around 90%), while on Trebevic mountain (above inversion layer) it was around 40 %.

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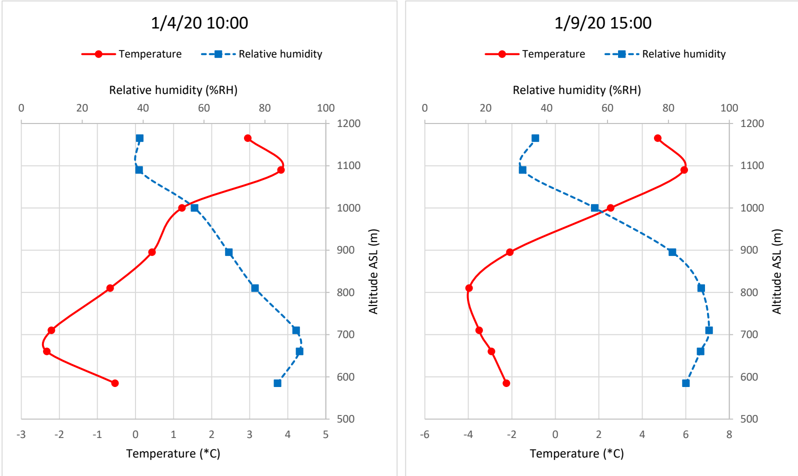

Figure 10. Relative humidity profiles.

4. Conclusions

A new system called MAQS for high resolution spatial and temporal monitoring of air pollution in urban environments has been developed and employed. After comprehensive evaluation, which included laboratory and field tests, optimal particulate matter sensor was chosen – Plantower PMS5003. The system is mostly developed in-house, while several components are being imported: particulate matter sensor, wireless network adapter and optional external sensors. Advanced code for server and sensors is written from scratch. Efficient calibration procedure is established and verified.

This system proved its capabilities to augment sparse governmental network of monitoring stations. It offers high-resolution measurements in space and time, with ability to generate live pollution map. Furthermore, it is used to measure vertical profiles of temperature, humidity and particulate matter concentration, which is very important for understanding qualitative and quantitative characteristics of temperature inversion. Using MAQS we have quantitatively shown that two major parameters of temperature inversion, in the context of air pollution, are: height above the ground where the inversion layer starts and temperature gradient in the inversion layer. Unfortunately, both of these parameters are unfavorable in Sarajevo, resulting in extreme episodes of air pollution.

MAQS can be used in future microclimate studies, urban planning projects and low-emission zones. We plan to increase number of sensors in the near future, so that we can detect hyperlocal sources of particulate matter emissions and increase the resolution of live pollution map.

Sensor modifications to include air dryers to prevent high bias of the sensors due to hygroscopic growth of aerosols will be tested in the future.

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Data Availability Statement: Live data is available at https://www.maqs.info. Access to database with all stored measurements is possible upon request.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

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The following abbreviations are used in this manuscript:

AQI	Air Quality Index
AGL	Above Ground Level
ASL	Above Sea Level
GNSS	Global Navigation Satellite System
IDW	Inverse Distance Weighting
MAQS	Mobile Air Quality System
PM	Particulate Matter
SQL	Structured Query Language
TCP/IP	Transmission Control Protocol/Internet Protocol

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