Particulate matter measurement with low-cost sensors - investigation of data quality and the benefit of data correction approaches

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Abstract

The transmission and analysis of data is one of the challenges of the 21st century. In the field of environmental measurement technology, existing broadband and wireless technologies have not been able to transmit data reliably and cost-effectively over long distances and in hard-to-reach places. LoRaWAN, an IoT technology, could be an energy-efficient, cost-effective and secure alternative as a narrowband technology in combination with battery-powered sensors and thus make an important contribution to the intelligent, largely wireless networking of objects, plants and machines (IoT), for example in the municipal sector. In addition to ecological and economic benefits, the quality of life in modern, intelligently networked cities can be enhanced by real time data acquisition. However, the prerequisite is that the quality of the data acquired via this method is sufficiently good. This paper therefore addresses the question of the quality of particulate matter data collected by low-cost sensors. To determine this, an SDS011 particulate matter sensor from Nova Fitness was ported to LoRaWAN. The sensor was installed next to a governmental measurement station. In a test that lasted five weeks, data from the SDS011 sensor were compared with those from the governmental station. Differences were identified and a correction approach was developed and applied. The efficiency of the approach was verified. Based on the results, it can be seen that the use of the low cost sensors has weaknesses. Problems can only be partially reduced. Nevertheless, the use of the low-cost sensors can be helpful for a flexible and cost effective collection of environmental data.

JEL-Classification:
Keywords: Fine dust measurement ($PM_{2.5}$, PM_{10}), LoRaWAN, Internet of Things, low-cost sensors, SDS011, level-indication measurements, sustainability.

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1 Introduction

Data collection, data transmission and data persistence in and from areas that are difficult to access, such as forest and agricultural areas, but also in municipal and rural areas, could not be obtained in an economically or ecologically way until now. So far it was only possible to collect data in a cumbersome way, for a limited time or a topic-specific project. Up to now, scientific measurement data from the forest and environmental area have been realised using cellular radio technologies (e.g. GSM, UMTS, LTE, 4G, 5G) or WLAN technology. None of the existing data transmission technologies has been satisfactory in terms of range, energy consumption and data bandwidth. This is because, with the current state of knowledge, it is not possible for these transmission technologies to implement all three conditions equally well. WLAN technology, for example, is characterised by a good energy balance and a very good bandwidth with which the data is processed. However, WLAN technology does not have a high range, so that measurements in the forest and environmental area always depend on the good availability of a WLAN. The radius in which measurement results can be obtained is also limited and the choice of valid, reliable and objective comparative measurements is severely restricted. For the cellular technologies in the mobile radio sector currently on the market, on the other hand, efforts can be seen to be able to implement the range, the energy consumption and the data bandwidth equally well. However, this is partly based on open standards or proprietary rights.

The Internet of Things (IoT) can be a solution to this problem, especially the LoRaWAN technology, which was developed in 2015. Using LoRaWAN, data collected by sensors or actions performed by actuators can be collected, transmitted and stored by radio over a distance of several kilometres in an energy saving and at the same time cost effective manner. LoRaWAN is an open LPWAN system architecture that operates in the non licensed radio spectrum and thus has the potential to collect data from areas that could not be accessed before. This makes this technology suitable for industrial (e.g. smart metering in the energy sector) and municipal (smart parking in France and Dubai) examples of applications, as well as for the individual technology enthusiastic for private use (e.g. beekeeper's scales to transmit the weight of a beehive as a measured value). This technology also offers many advantages for scientific research due to the low energy consumption, the measuring ranges for the transmission of data, as well as the cost savings due to the royalty-free radio technology. The constant technical development of the hardware and software, also with regard to the costs for these, enables further future application examples that can be implemented with and through LoRaWAN.

One area of application that has become more significant for humans and nature in recent years is the particulate matter (PM) pollution at the respective place of residence. Not only because recent research is showing an interaction of air pollution and COVID-19 mortality (Wu et al. 2020), but also due to the recently established scoreboard on air quality in European cities and diverse discussions about summer driving bans in case of high PM pollution, it must be the common goal of all municipalities and cities to reduce PM pollution to protect humans and nature. Due to the far reaching health effects, air quality is monitored by state institutions with a network of air monitoring stations. But due to the high costs per air monitoring station, these are spatially distributed in small numbers. However, particulate pollutants are mobile and subject to spatial and temporal variance. Citizens' initiatives and individual projects are trying to determine the environmental pollution of individual areas more adequately with the help of digital tools and citizen science communities. It is their aim to shape their own city with this additional information in a healthier and more livable way. If and to what extent these measurement results are credible, reliable and objective has not yet been scientifically determined in a larger study. Indeed, only a view comparative measurements of state measuring stations for $PM_{2,5}$, PM_{10} and PM measurement on LoRaWAN basis exists so far in the German-speaking area which takes place under conditions comparable in time and space. Benabbas et al. 2019 provide one of the few studies available.

This study presents further analysis on this issue. It demonstrates a pragmatic way of collecting scientific data using LoRaWAN which makes it possible to collect, store and evaluate data in municipal sectors (and others) economically, efficiently and in an energy-saving manner.

This is examined within the framework of this elaboration using the example of PM measurement in Eberswalde (Brandenburg, Germany) at a comparative measuring station with a reference source from the "Landesamt für Umwelt Brandenburg" (LfU). For this purpose, the PM sensor including the necessary infrastructure was designed, built and installed to enable the transmission of the data using the LoRaWAN technology.

A limiting factor of the sensors currently available on the market is the inaccuracy of the measurement results in certain situations (e.g. weather). Within the framework, approaches to overcome problems of inaccuracy will be presented. The approaches will be statistically evaluated.

The following questions will be answered: Are the PM data measured using low-cost sensor technology comparable with those of the LfU? Can data adjustments contribute to comparability?

To answer the questions the paper is organized as follow: Chapter two describes the current state of the art with regard to environmental measurement techniques, the governmental measurement system and non-governmental initiatives. Chapter three deals with the methods and the materials used like the workflow, the hardware and software, the study area, the monitoring as well as the case study for the particulate matter measurement. The results are statistically evaluated and summarised in the fourth chapter. Approaches to deal with inaccuracies are presented and discussed. In chapter five, a summary is made and an outlook on further possible research is given.

2 Environmental measurement and particulate matter measurements

2.1 Health protection against particulate matter as a state task

Maintaining air quality where it is good and improving it where it is not - this is the basic idea of the EU Directive on ambient Air Quality and cleaner Air for Europe (Air Quality Directive, see EUR-Lex 2008), which was implemented in Germany with the 39th statutory order on the Implementation of the Federal Immission Control Act (BlmSchG, see ELAW 2002). It is the aim of the BlmSchG to achieve levels of air quality that do not have negative significant impacts on human health and the environment. Further measures and guideline values have been defined, which are intended to protect citizens from exposure to particles and ozone in the air, as well as ecosystems from acid disposition, excessive nitrogen accumulation and ozone (EUR-Lex 2005). The WHO estimates that approximately seven million people die each year due to air pollution (WHO 2021a). A particular dangerous and harmful emission for humans and the environment is PM. PM, also known as aerosol particles, are solid particles that exist as suspended dust in the atmosphere (MLUK 2021a). The chemical composition of PM is diverse and depends on the respective emission source. For example, PM can have a natural origin through forest and bush fires, sandstorms and volcanic eruptions. However, the following anthropogenic causes are responsible to a considerable extent for the formation of PM: motorised road traffic, agriculture, the energy sector, industrial facilities and processes, as well as private and commercial heating systems (see WHO 2021b; UBA 2020; MLUK 2021a). In addition to the emission source, the size of the particles is a decisive differentiating factor. A distinction is made between coarse particles with an aerodynamic diameter smaller than 10 µm (PM_{10}), fine particles with a diameter smaller than 2.5 µm ($PM_{2.5}$) and ultrafine particles with a diameter of less than 0.1 µm. The smaller the particles, the further they can penetrate into the respiratory tract. Particles with a diameter of more than 10 µm only reach the throat and nasal mucous membranes, also called inhalable airborne dust, and are usually coughed up again. Particles smaller than 2.5 µm, on the other hand, can reach the lungs and bronchi. They are referred to as respirable airborne dust (see UBA 2009; MLUK 2021a; MLUK 2021f). Particles smaller than 0.1 µm can pass through the lungs into the bloodstream, the tissue and the entire body. According to current knowledge, they are also of health significance. Due to a lack of reliable standardised measurement methods suitable for measuring ultrafine particles, and thus a sufficient number of studies on the exposure-impact relationship for ultrafine particles is missing, no guideline and limit values for ultrafine particles exist to date (see MLUK 2021a; UBA 2018). That´s why these particles will not be considered here further. Diseases caused by PM are multifaceted (e.g. asthma, cardiovascular diseases) and can lead to an increase in mortality and morbidity (WHO 2018). A concentration threshold in the ambient air below which no harmful effect is to be expected does not exist for PM. PM is therefore fundamentally different from other pollutants, such as nitrogen dioxide, and is always harmful. Local and time-limited actions against PM, such as imposing driving bans, is not very effective in the long term, since air currents transport PM over greater distances and the PM itself can remain in the atmosphere for a certain time until it sinks to the ground (see UBA 2009; UBA 2021c, p. 22). In order to improve the air quality in the long term, the relevant authorities in the EU countries therefore jointly measure, monitor and assess air pollutants and compliance with the specified limit and target values in accordance with the Air Quality Directive (UBA 2019a).

2.2 Official air quality measurement systems

The monitoring and assessment of pollutants present in the air has been measured by hundreds of air quality measuring stations in Germany for several decades (UBA 2021b). In addition to PM_{10} and $PM_{2.5}$, the most important air pollutants monitored are carbon monoxide (CO), ozone (O3), sulphur dioxide (SO2) and nitrogen dioxide (NO2), which are measured by the measuring stations of the ministries of environment of the respective German federal states and by the German Federal Environment Agency (UBA 2021a). There are legal requirements for the location, number of measuring stations and the measuring methods used (see EUR-Lex 2008; MacDonnell et al. 2013, ES-1). An example of this is the requirement to set up measuring stations where the population is exposed to the highest concentration (UBA 2019b). This type of data collection results in expensive, large, stationary measuring stations that, apart from being purchased, need to be regularly maintained as well as calibrated and this is partly done by technical staff stationed on site (see Williams et al. 2014, p. 50f.; UBA 2013, p. 50f.; Eickelpasch and Eickelpasch 2004, p. 61).

The location and number of air quality measuring stations in Germany corresponds to the European requirement that the territory of a Member State is to be divided and assessed into agglomerations, i.e. cities with more than 250,000 inhabitants, and other assessment areas (MLUK 2021b). Area-wide coverage is not envisaged and a measurement obligation for individual cities and municipalities cannot be derived (UBA 2019b). The combination of the number of inhabitants and the pollution situation in each assessment area determines the number and location, i.e. type of monitoring station, to be operated for each pollutant in the respective monitoring area. The pollution situation is the place where the population is most exposed to a certain pollutant, e.g. nitrogen dioxide is mainly caused by traffic. In addition, concentration data is collected, i.e. representative data for the exposure of the population to (certain) pollutants. This is done by measuring stations in typical urban residential areas, also referred to as station type background (UBA 2021c, p. 7). In addition to the two station types traffic and background, there is a third measuring station type in industrial areas industry. Furthermore, the surroundings of a monitoring station are classified as urban, suburban and rural / regional (MLUK 2021f). The combination of environment, number of inhabitants and station type thus determines the number of monitoring station locations. The exact location of a monitoring station depends on various local conditions and legal requirements. As a general rule, the measuring stations should never be located in the direct vicinity of strong emission sources such as traffic routes or industrial facilities (see EUR-Lex 2008, Annex III, IV). For the sampling point, both large-scale and small-scale local regulations must be observed. Large-scale means that the measurement of very small-scale environmental conditions in the immediate vicinity should be avoided. Air samples from road sections, for example, are only representative if the road section is at least 100m long (EUR-Lex 2008, Annex III, B). In the case of measuring stations close to traffic, it should be noted in the sense of small scale that the measuring stations should be set up no further than 10m from the edge of the carriageway, at least 25m from a busy intersection and that interference factors such as safety, power supply, accessibility and visibility of the measuring station should be taken into account (see MLUK 2021b; EUR-Lex 2008, Annex III, C).

Although this classification and scientific categorisation of the measuring stations appears to make it possible to compare the types of measuring stations, unfortunately observation data can hardly be combined and compared with each other (Snyder et al. 2013). The respective environment of the measuring stations (Helbig et al. 2013, p. 208), weather data, geographical location and technical equipment used, which is often also manufacturer-specific, are too different. In comparison with other national air quality measuring stations, these are usually country-dependent and difficult to assess and reproduce. Combining air quality data from heterogeneous sources is therefore a major challenge, especially in urban and suburban areas (see Kotsev et al. 2016, p. 2; MacDonnell et al. 2013, ES-1).

The measurement technology used to measure PM is an essential instrument for assessing air quality (Eickelpasch and Eickelpasch 2004, p. 1). The performance of immission studies in Germany is regulated by state provisions and is carried out on the basis of state-recognised standards and guidelines. Part of these regulations concerns quality assurance, which is ensured, among other things, by the use of standardised measurement procedures according to VDI (Verein Deutscher Ingenieure) guidelines and standards, suitability-tested measuring instruments, and reference, equivalence and calibration procedures (see Williams et al. 2014, p. 2; UBA 2021d; Eickelpasch and Eickelpasch 2004, p. 97; UBA 2021d). The measurement procedures are to be divided into discontinuous and continuous. During discontinuous measurement methods, sampling usually takes place in the field and analysis in the laboratory, and thus in two separate processes. This method is advantageous for sample measurements, when many measuring points in the field, different substances and also substances for which there are no automated measuring methods yet, are to be investigated. In contrast, sampling and analysis take place in one procedure in continuous procedures by means of automatically operating measuring instruments, whereby a measurement without time gaps can be carried out. This measurement procedure offers the possibility of stationary air monitoring without gaps in time and can thus reveal air pollutants that only arise due to higher temporal rather than spatial fluctuations (Eickelpasch and Eickelpasch 2004, p. 61). This procedure is mainly used for the implementation of government regulations (Eickelpasch and Eickelpasch 2004, p. 62). The procedural distinction does not apply without restriction, as individual measurement procedures may possibly include components of both measurement procedures. For example, discontinuous measurements can be automated both in sampling by automatic sampling devices and in laboratory analysis by laboratory automates (Eickelpasch and Eickelpasch 2004, p. 61).

In order to meet a certain data quality, minimum requirements for data collection apply with regard to duration and possible acceptable uncertainties in the measurement methods. For both fixed and indicative measurements, for example, 90% of the time of a calendar year data per pollutant must be determined. Further parameters for high-quality data collection are hourly and 8-hour averages, as well as daily (24-hour average) and annual averages (see see ELAW 2002 - BlmSchV, A in Annex 1; Eickelpasch and Eickelpasch

2004, p. 50). If a method other than the reference method is used, the measuring station operators must prove the equivalence of the method used (UBA 2021d). The purpose of these quality requirements is the equivalence measurement of the occurring pollutants and an equivalence of the measurement results in order to comply with the applicable limit and target values. Table 1 lists the EU and World Health Organisation (WHO) limit and target values for $PM_{2.5}$ and PM_{10} currently in force to protect human health. It is noticeable that the WHO specifies stricter target values in its air quality guideline. There are binding limit values and so-called target and guideline values. It should be the aim to fall below as far as possible and therefore these value are only strong recommendations (LfU 2021a). “But these limit values are more than 20 years old.” emphasised the UBA president in spring 2021. “As the WHO is planning to develop new recommendations in 2021, the EU would also have to develop new limit and target values following the WHO values”, he further stated (ÄrzteZeitung 2021).

Table 1: EU and WHO limit values for $PM_{2.5}$ and PM_{10}

Pollutant	**Organisation**	**Measuring time**	**Max. value**	**Liability**
$PM_{2.5}$	EU	Annual mean value	25 $\mu g/m^3$	Limit value
			20 $\mu g/m^3$	Target value
	WHO	Annual mean value	10 $\mu g/m^3$	Target value
		Daily average	25 $\mu g/m^3$	Target value
PM_{10}	EU	Annual mean value	40 $\mu g/m^3$	Limit value
		Daily average	50 $\mu g/m^3$	Limit value*
	WHO	Annual mean value	20 $\mu g/m^3$	Target value
		Daily average	50 $\mu g/m^3$	Target value**

Notes: * May be exceeded on max. 35 days / year; ** Must not be exceeded more than 3 times according to the recommendation.
Source: own presentation; see EUR-Lex 2008; ELAW 2002; EEA 2017, p. 30; WHO 2005: 175; LfU 2021a; LfU 2021b.

When assessing the long-term development of PM, the respective weather conditions must be taken into account in addition to changing environmental conditions, as weather-related fluctuations have a considerable influence on the level of pollution. In cold weather, for example, the pollutants released increase because more heating takes place. In wintry high-pressure weather, pollutants tend to accumulate in the lower air layers due to low wind speeds and limited vertical air exchange. And ground-level ozone is favoured above all by intense solar radiation and high temperatures. But wind speeds also have a high influence on the level of pollutant load. High wind speeds and generally

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good mixing conditions reduce the pollutant load. Interannual fluctuations and also annual fluctuations during extreme weather phenomena are thus possible (UBA 2021c). In Brandenburg, for example, so-called PM episodes occur in late autumn or winter, during which the PM concentration is elevated for several days in a row. This is caused by weather conditions in which cold, pollutant-enriched air masses are not exchanged due to a weak flow (MLUK 2021e).

The current air pollution situation is made available to every citizen by each federal state within the framework of an area-wide presentation. These actual data, which are mostly published online, are data that are determined by means of the interpolation method. With the method of optimal interpolation, hourly measurement and model results are linked. The measurement results obtained represent the ambient air quality of a measuring station without prior quality assurance of the measured values (see UBA 2021b; MLUK 2021c). This is because quality assurance can only take place retrospectively by means of the necessary laboratory tests. Final, validated and quality-assured measurement data are published in the annual reports of the Federal Environment Agency and in the annual reports of each ministry of environment of the respective German federal states.

After these final, validated measured values are available, those areas are identified in which the applicable limit values for the protection of human health and the environment have been exceeded. Clean air plans must be developed for these areas within 2 years. The aim and purpose of an air pollution control plan is to ensure, by means of suitable measures, that air pollution is permanently improved by complying with limit values and / or reducing the period during which they are exceeded (see ELAW 2002). The respective federal and local authorities cooperate with the public in an appropriate manner when drawing up the clean air plans (MLUK 2021d). The main cause of localised limit value exceedings is road traffic, especially in urban areas (VM 2021). The primary goal of many clean air plans is therefore to reduce private motorised transport and to encourage citizens to choose more sustainable forms of mobility, for example cycling, car sharing, electric mobility and local public transport. The establishment of an environmental zone and the introduction of bans on lorries passing through are further measures. But conceivable measures are also possible in the field of urban development and urban land use planning.

2.3 Citizen science and air pollution measurements

Anyone and everyone can do research - this approach illustrates the idea of the citizen science movement. The participation of citizens in acquiring knowledge and gaining insights is itself not a new invention. Passionate amateur researchers who experimentally investigated natural phenomena and took part e.g. in bird counts existed already centuries ago (Leibnitz 2021). Nowadays, advancing digitisation and new technical developments enable interested citizens to participate more actively in all steps of the research process. Research questions are formulated, observations reported, measurements taken, data analysed and findings published. This increasingly creates a dialogue between science and society (ACS 2021), because without the support of active citizens, science would no longer be able to collect or evaluate large amounts of data itself (Leibnitz 2021). The term citizen science itself is not clearly definable, as it is dynamic and changes over time (ACS 2021). The potential of citizen participation has recently been recognised by science and different European states and, for example, the European Citizen Science Association (ECSA) has been founded.

Research into air pollution control is one of the areas that the citizen science movement supports and develops through the collection of data. For a few years now, low-cost air pollution sensors that can be used with technical understanding have made it possible for citizens to monitor air quality themselves. Citizens collect data, recognise correlations and can thus influence municipal strategies for cleaner air (Snyder et al. 2013). Various pollutants are measured by different citizen science projects such as the Air Quality Egg or the sensor.community, formerly "luftdaten.info". The latter is the best known in German-speaking countries in the field of PM measurement. Furthermore, the HackAir initiative of the German government, which has been in existence since 2018, supports the citizens' desire for cleaner air.

The various sensor-based citizen science projects differ mostly in terms of data transmission technologies, measurement accuracy, prices for the components and whether mobile or stationary measurement methods are used. The advantage of all projects is that large amounts of data can be collected. Critically, however, laypersons collect measurement data that does not adequately meet scientific standards of comparability, accuracy and reliability. Many of the sensors used in the citizen science projects were tested by the United States Environmental Protection Agency (EPA) in 2017 to assess the quality of the measurement data. The SDS011 sensor used here was also tested by LUBW 2017 or Benabbas et al. 2019, with the result of a satisfactory correlation at humidity levels of 50-70% and response to climatic variations (LUBW 2017, p. 20). As the market for sensor measurement systems is subject to constant further developments, there are also constant further developments with regard to measurement accuracy and more up-to-date comparative studies, such as the one by the LUBW 2017 or from Benabbas et al. 2019, would be desirable.

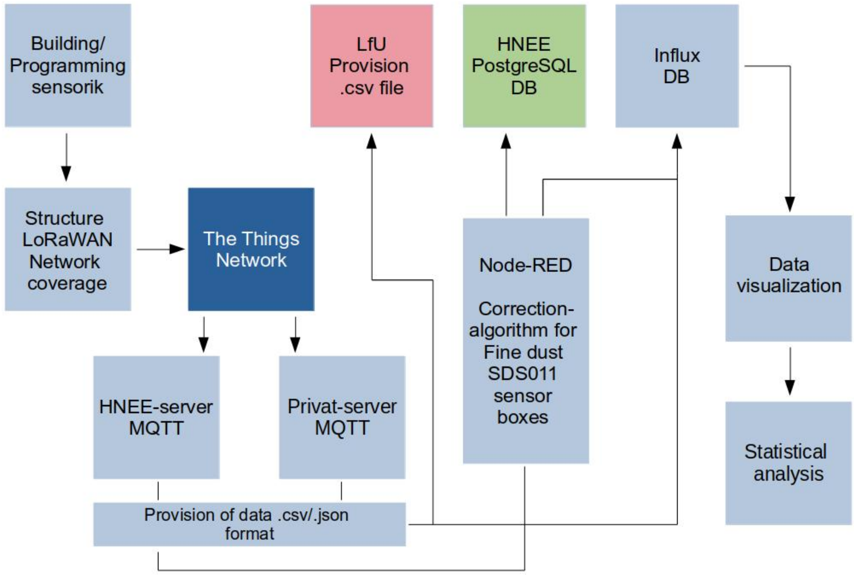
3 Materials and methods

3.1 Workflow and software

Data transmission by means of IoT low-cost microprocessors and sensors based on LoRaWAN basically consists of four topics: (1) Building the local gateway infrastructure, (2) Construction and programming of the sensors, (3) Data storage and visualization of the transmitted data, and (4) Statistical analysis of the transmitted data.

All these four topics contain different hardware and software components. They are not structurally based on each other, but can be worked on in parallel. Figure 1 shows schematically these four topics and the entire hardware and software included. First, a PM sensor box was built, programmed, tested and then inserted into the created LoRaWAN network. Thus, the sensor box could now send it's collected data, which refers to $PM_{2.5}$, PM_{10}, air temperature, air humidity, as well as air pressure, to the databroker TTN (The Things Network, see TTN 2021) every three minutes. Since TTN does not offer visualisation and permanent persistence of the data, a way had to be found to take care of this. Using the MQTT protocol, it was possible to build up the data stream, which was provided in .csv/.json format, from TTN to a server of the Eberswalde University for Sustainable Development (Hochschule für nachhaltige Entwicklung Eberswalde - HNEE), as well as an alternative private server. The LfU was able to retrieve this data independently from the private server as a .csv file. In order to test measurement adjustment approaches, a function was built into the data flow with the help of NodeRed to make this possible. From this point on, the rest of the process was double-tracked. The data for the HNEE is provided in .csv and .json format so that the HNEE can implement it in its PostgreSQL DB. In the private database, the data was transferred to InfluxDB for subsequent visualisation and evaluation. Every 180 seconds, the sensor send the measured values in a data packet of approx. 33 bytes to the next reachable gateway. From this gateway, the measurement information is sent to the TTN data broker via an internet connection. The information is kept there for up to seven days and must be actively retrieved, otherwise it will be lost. The information is actively retrieved via machine-to-machine communication using an MQTT network protocol and persisted on a server. The data packets from the database are then visualised.

Figure 1: Workflow



Source: own presentation.

3.2 Hardware

The used SDS011 sensor box is a further development of a former system, which was initially operated with an SDS011, DHT11 ESP8266. Its use was limited to a few hours, as it was powered by a power bank. By porting it to the LoRaWAN technology, it was possible to use the complete sensor box with a 5V/1A power supply (e.g. smartphone power supply) at any location within the existing LoRaWAN network in Eberswalde. In order to connect all components of the sensor box (see table 2) with each other in a modular way, an extension board was constructed and printed as a circuit board. This enables a modular construction without soldering. Should it be necessary to replace components, this is done in a sustainable way. A printed 3D housing made of PLA, called a Stevenson Screen, enables the electronics to be enclosed and thus allows free air exchange (see figure 2). At the same time, this housing prevents the penetration of adverse weather conditions (e.g. heavy rain, heavy hail) and protects the entire electronics. The air intake is via a 5cm long flexible, transparent hose. The total material costs for an SDS011 sensor box are approx. 70 - 80 EUR.

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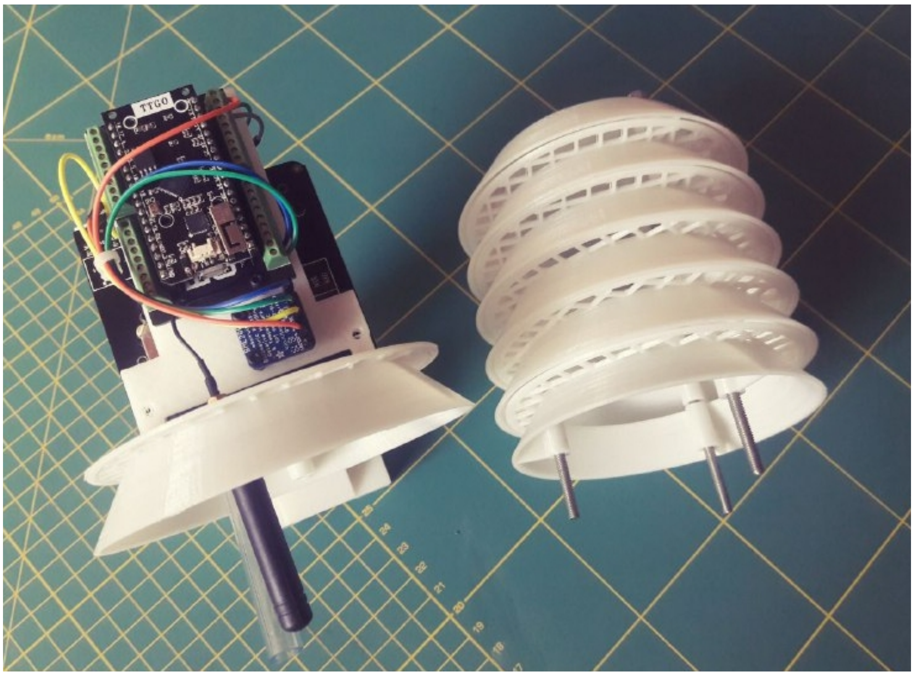
Table 2: Description of the PM sensor parts

	Hardware used for the sensor box
1x	MCU ESP32 SX1276 LoRa 868 MHz
1x	Sensor SDS011
1x	Sensor BME280
1x	DIY Backplane connector for MCU and wires
1x	Koaxial Pigtail, U.FL male to N female
1x	LoRaWAN Antenna 868 MHz
1x	DIY 3D Print Enclosure
1x	Set of M2.5 screws and nuts
1x	USB microcable
1x	Power supply 5V-1A

Source: own presentation.

Figure 2: DIY PM sensor box based on SDS011 and BME280



Source: own presentation.

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3.3 Comparison measurement sites and methods for PM measurements

The study area “Breite Straße” is located in the eastern part of Eberswalde (north-east of Germany in the federal state of Brandenburg) 20m above sea level. It is an urban main traffic road, on which the Bundesstraße 167 runs. It is built up on both sides within the urban boundary, partly the buildings are located directly at the edge of the roadway with a narrow pavement in between. It has a traffic volume of 14,225 vehicles per day on average (MLUK 2021c). The LfU measuring station is located in front of house number 22 in the Breite Straße. It is located between the pavement and a narrow bicycle lane runs to the side of the street. The air inlet of the LfU measuring station for sampling is at a height of 3.50 m and that of the SDS011 sensor box at a height of 3.15m. In 2020, an average annual mean value for $PM_{2.5}$ of $10\mu g/m^3$ and an average annual mean value for PM_{10} of $14\mu g/m^3$ were measured in the year-end report of the LfU. In 2020, the daily mean value of $50\mu g/m^3$ for PM_{10} was exceeded only once (MLUK 2020, p. 13f.).

Three measurement methods are used by the LfU: (1) the continuous measurement with beta absorption, (2) gravimetric measurement with a low-volume sampler for sampling and (3) a continuous scattered light measurement with the EDM 180 (LfU 2021c, p. 53f.).

According to the annual report 2019, the latter measurement method is used for air quality in Breite Straße and, according to LUBW 2017 testing, determines equivalent measurement results as the reference method of DIN EN 12341 (see LUBW 2005, p. 36; Grimm 2011, p. 5). The stationary dust measuring device EDM 180 from Grimm is used for continuous measurement of dusts in the air and their aerosol distribution. The particle rate is measured as a function of diameter according to the principle of scattered light measurement and the mass concentration is calculated via a calculation factor. The device can measure $PM_{2.5}$ and PM_{10} simultaneously (LUBW 2005, p. 15).

The actual data of this measurement are made available hourly approx. 20 minutes after the measurement at: https://luftdaten.brandenburg.de/home/-/bereich/aktuell. However, these are only pre-tested, preliminary measurement data that still have to be compared with the reference procedure (daily filter sampling and subsequent gravimetric determination in the laboratory according to DIN EN 12341: 2014). This takes place retroactively for the complete calendar year, so that final quality-assured measurement results of the Brandenburg air quality measurement network can only be taken from the respective annual reports on air quality of the LfU (see LfU 2021d).

However, the measurement method used here by means of the IoT low-cost sensor

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technology uses the laser scattering method, which is a variant of multiscan technology. It can evaluate surface features with the help of laser triangulation, which is created by the scattering of laser light when it hits a material surface. Scattering here basically refers to anything that deflects the incident laser light from its original direction. The particles detected in this way, which fall within the detection range, are converted into electrical signals, amplified and further processed into information. The SDS011 sensor from Nova Fitness sucks in air containing particles (e.g. PM particles) via a 5cm long flexible, transparent tube. The measurement parameters of the sensor include the values $PM_{2.5}$ and PM_{10}.

The particle measurement parameters have a range of 0.0-999.9 $\mu g/m^3$. The temperature operating range of the sensor is -10 to +50°C. According to the manufacturer, the relative error of the sensor is ± 15%, which corresponds to ± 10$\mu g/m^3$. The power requirement is 5V (Nova Fitness 2015). The air sampling has a temporal resolution of 180 seconds, which corresponds to approx. 500 measuring points per day. The data is forwarded to the MCU via a serial interface and transmitted to a gateway via LoRaWAN.

3.4 Data and statistical methods

The statistical data evaluation covers the period from 19.04.2021 to 24.05.2021 (12:00 to 12:00 CET). The possibility of installing a sensor box (SDS011) in the immediate vicinity of the air inlet of the LfU measuring station in Breite Straße made it possible to generate measured values under real conditions and to compare them with those of the reference measuring station of the LfU.

The main objective of this paper is the statistical evaluation of the particulate matter measurement values in Breite Straße with and without correction algorithm in comparison with the measurement values of the reference data of the LfU. This allows also to measure the efficency of the correction algorithm for the low-cost sensor (SDS011). Besides visual comparisons, the following formulas are used to describe and evaluate the data:

The mean absolute error (MAE) measures the average absolute deviation between the values of the reference source of the LfU station (x) and the values of the low-cost sensor (y) while (n) indicates the number of measurements:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i|$$

The BIAS, on the other hand, indicates the systematic error, i.e. it indicates how strongly the measurement is biased in a certain direction (sign) (Sachs and Hedderich

2006: 87f.):

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)$$

The Root Mean Square Error (RMSE), i.e. the root of the mean square error, is a measure of the spread of the data. It shows the average of the deviance between the measured values and its mean (expected value). The formula for this is:

$$RSME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$$

Thus, the RSME measures the average strength of an error. In this work, it is a measure of how much the values of the SDS011 sensor with its uncorrected as well as corrected measured values deviate from the reference values.

The RE (relative error) shows the percentage of all SDS011 observations with a deviation of less than 15% from LfU. Thus, the ratio, which is based on the manufacturer's value for the relative error, provides additional information on the distribution and comparability of the data.

$$RE = \frac{\text{number of observations with a deviation less then 15\%}}{\text{number of all observations}} \times 100$$

4 Results

4.1 Results before correction

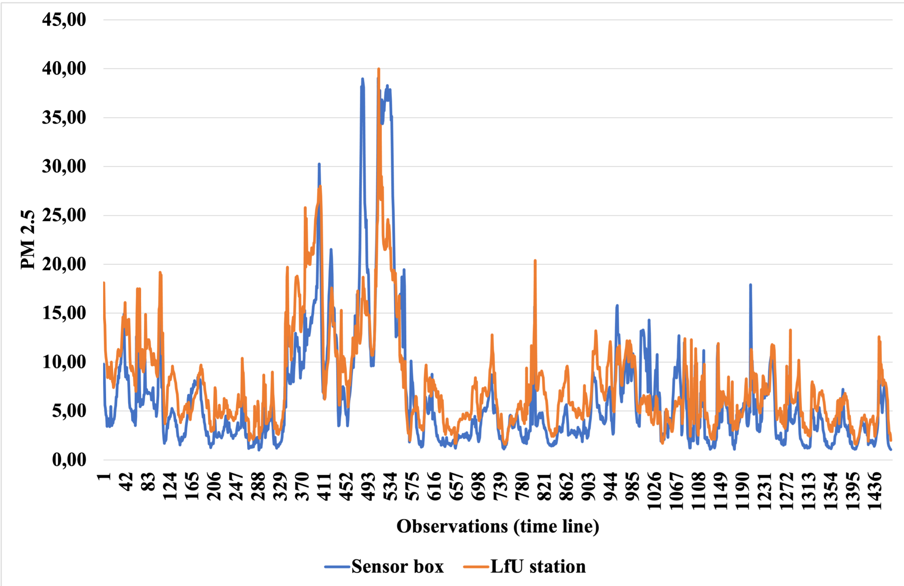
During the period mentioned, sensor box (SDS011) transmitted 17,551 data packets (one data packet contains several measured values) with a time resolution of approx. 180 seconds via LoRaWAN. The LfU made its measured values available with a temporal resolution of 30min and comprise 1,681 data packets. To make the data comparable, average values were determined for the time span of 30 minutes (30min mean and 30min median). After adjusting and merging the result is a data set with 1,466 observations.

Figure 3 and 4 presents a visual comparison of the captured data and table 3 shows some descriptive results using the formula for MAE, BIAS, RSME and RE.

The statistical analysis shows the following results: Both $PM_{2.5}$ and PM_{10} show deviations from the reference values. However, the deviations for $PM_{2.5}$ are comparatively small, and those for PM_{10} are about 2 times larger than those for $PM_{2.5}$. With regard to the BIAS indicator, it can be seen that on average the LfU values are higher than those of the sensor box. The sign of BIAS is positive in each case. For PM_{10} the expected value for the deviation is closer to zero. However, the value for RMSE also shows that the values for PM_{10} are generally larger, i.e. that the LfU values and the sensor box values generally show larger differences. Finally, the values for the indicator RE show that for $PM_{2.5}$ about 80% of all observations the deviation between the LfU and the sensor box values is bigger than 15%. For PM_{10} the indicator shows a slightly better rate.

The statistics clearly show that the sensor box covers the $PM_{2.5}$ values comparatively well. With regard to PM_{10}, however, there are more significant deviations. The next section deals with the reasons for these and presents approaches for adjustments.

Figure 3: $PM_{2.5}$ LfU reference values from 19.04.-24.05.2021 to uncorrected SDS011 values



Source: own calculation and presentation.

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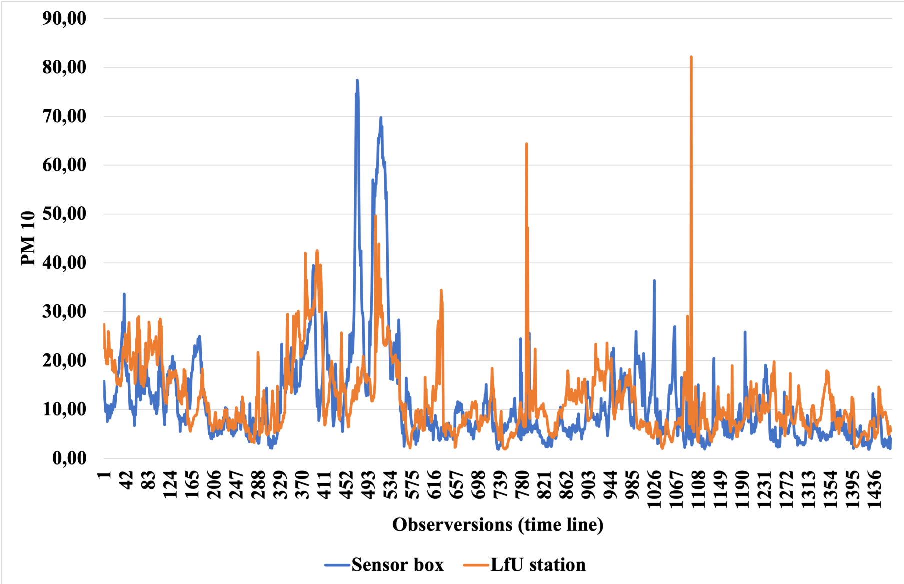
Figure 4: PM_{10} LfU reference values from 19.04.-24.05.2021 to uncorrected SDS011 values



Source: own calculation and presentation.

Table 3: Descriptive statistics - uncorrected vaules

	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
MAE	2.88	6.24
BIAS	1.40	0.61
RMSE	3.94	9.88
RE	18.35%	22.37%

Source: own calculation and presentation.

4.2 Error correction method

The statistical evaluation shows that relevant deviations exist especially for PM_{10}. The values of $PM_{2.5}$, on the other hand, can rather considered as robust. The visual inspection (but also the value for MAE and so on) (see Figure 3 and 4) suggests that in the range of low values the sensor box underestimates the PM exposure. On the other hand, in the range of high values, the deviation from the reference value often seems to be quite high. This means that the inaccuracies increases with the PM exposure. This could be a

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starting point for a correction approach.

Two papers (see LUBW 2017, Benabbas et al. 2019) give further starting points. The papers show that certain weather conditions can influence the results of the sensor box. Especially humidity seems to have an influence. However, both studies could not determine a systematic correlation between the measured deviations and air humidity. LUBW lists further points. Thus, deviations in the measurements of sensors of different batches are shown. Anyway, the aim of this paper is not to find a way to achieve 100 percent agreement of LfU values and sensor box values. This seems rather unachievable in view of the results from the LUBW paper. Therefore, the aim is to work out whether there are generally adaptation approaches and how efficient they are.

For this purpose, linear regression analyses are used in a first step. The above mentioned assumption that high deviations are associated with high measured values (and vice versa) should be shown by a significant positive correlation between the MAE value and the PM_{10} (respectively $PM_{2.5}$) value measured by the sensor box. If this is the case, the determined regression coefficients can be used to correct the sensor box values.

In addition to the PM_{10} ($PM_{2.5}$) value as an influencing factor, the air humidity must also be included. The study of LUBW suggests a positive influence of humidity on the MAE values. Since other weather data were determined in addition to humidity (temperature, air pressure), these can be included as control variables in the regression analysis.

Table 4 and 5 show the correlation between the addressed factors. The values support the assumption that the deviations between the values of the sensor box and LfU station become stronger when the PM values are high (and vice versa). With regard to the influence of the weather data, a relevant correlation is only shown for the humidity. This is more pronounced with regard to the PM_{10} values. It is particularly evident with regard to the BIAS indicator.

Table 4: Correlation matrix for $PM_{2.5}$

	$PM_{2.5}$	MAE	BIAS	temp	press	hum
$PM_{2.5}$	-	0.62	-0.62	-0.07	-0.03	0.29
MAE	0.62	-	-0.25	0.07	-0.03	-0.01
BIAS	-0.62	-0.25	-	0.15	-0.01	-0.35
temp	-0.07	0.07	0.15	-	-0.20	-0.35
press	-0.03	-0.03	-0.01	-0.20	-	-0.12
hum	0.29	-0.00	-0.35	-0.35	-0.12	-

Note: temp = Air temperature, press = Air pressure, hum = Air humidity; Source: own calculation and presentation.
Source: own calculation and presentation.

Table 5: Correlation matrix for PM_{10}

	PM_{10}	MAE	BIAS	temp	press	hum
PM_{10}	-	0.63	-0.73	-0.16	0.04	0.37
MAE	0.63	-	-0.28	-0.00	-0.06	0.14
BIAS	-0.73	-0.28	-	0.24	-0.11	-0.44
temp	-0.16	-0.00	0.24	-	-0.20	-0.35
press	0.04	-0.06	-0.11	-0.20	-	-0.12
hum	0.37	0.14	-0.44	-0.35	-0.12	-

Note: temp = Air temperature, press = Air pressure, hum = Air humidity; Source: own calculation and presentation.
Source: own calculation and presentation.

Considering the results of correlation analysis, the following two regression models are tested:

$$\text{(M1) } MAE_{PM_{i,n}} = b0 + PM_{i,n}b1 + hum_n b2 + u_n$$

$$\text{and (M2) } BIAS_{PM_{i,n}} = b0 + PM_{i,n}b1 + hum_n b2 + u_n$$

With PM = measured PM value from sensor box, hum = humidity, $i \in (2.5, 10)$ and $n \in (1, ..., N)$ observations. Table 6 and 7 present the results.

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Table 6: Regression results for $PM_{2.5}$

	$M1$	$M2$
	$n = 1466$	
$Intercept$	***2.96	***5.88
$PM_{2.5}$	***0.28	***-0.32
hum	***-0.02	***-0.03
R^2	0.43	0.42
$F - stat$	***552.6	***530.7

Source: own calculation and presentation.

Table 7: Regression results for PM_{10}

	$M1$	$M2$
	$n = 1466$	
$Intercept$	**3.45	***14.83
PM_{10}	***0.50	***-0.62
hum	***-0.04	***-0.10
R^2	0.41	0.57
$F - stat$	***518.6	***975.7

Source: own calculation and presentation.

In order to check the robustness of the results, various tests can be performed. These are tests related to the efficiency of the calculated estimators (best linear unbiased estimators). These are also tests that ask how much the calculated results depend on how many data and which data (which time period) are considered. The bootstrap method is used for this purpose.

Examination of the efficiency of the estimated parameters indicates problems. An important requirement is that there must be a linear relationship between dependent and independent variables. There is little empirical evidence for this. A transformation of data could not eliminate this problem. As a result, the estimated parameters have limited explanatory power.

Tests that examine structural breaks in the data show that there are some approaches for adjustment: There is an indication of limited homogeneity with regard to a certain range of PM-values. Clusters can also be identified with regard to weather data especi-

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ally to the humidity level (as expected with regard to LUBW 2017). But the number of observations shrinks very quickly when corresponding models are set up and as a consequence, the robustness of the results decreases. It is as LUBW 2017 already shows: there are influences (especially with regard to humidity), but the correlations are not sufficiently systematic. Therefore, the results of the first regression models can be used, taken into account, that the results are of limited reliability.

Beside the efficiency of the regression models, it is of interest how strong the value of the estimation parameters varies with the amount of data. Two methods were used to test this. First, bootstrap procedures were performed. Here, a subsample of the data set is randomly produced. Subsequently, the regression analysis is carried out with this subsample. This procedure is repeated a sufficient number of times. Here, with a number of 2.000 repetitions, there is hardly any relevant deviation from the original estimation result (see table 8).

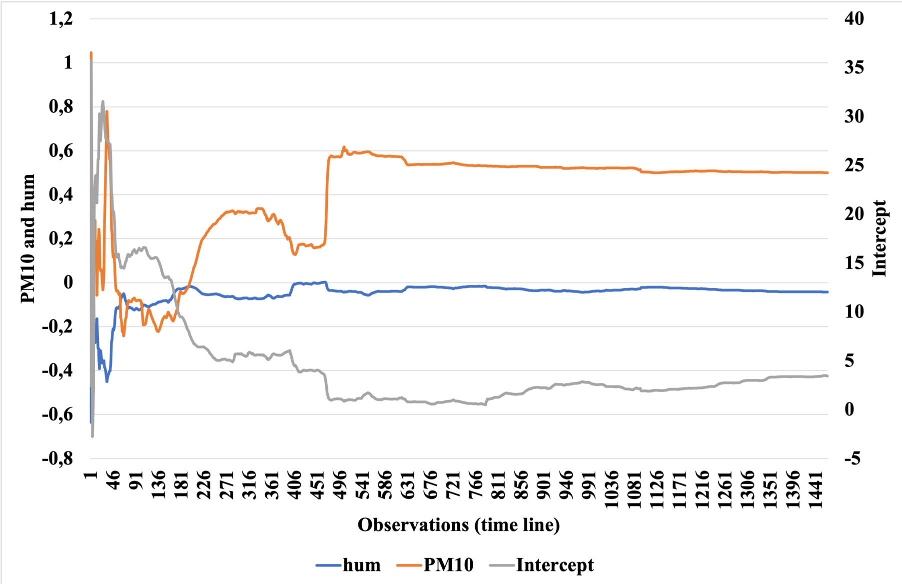
Table 8: Example for bootstrap statistic for PM_{10} (M1)

	Original	**Bias**	**Std. error**
Intercept	3.45	0.015	0.502
PM_{10}	0.50	-0.001	0.029
hum	-0.04	-0.000	0.007

Note: Bias = difference between the original estimate and the bootstrap estimate; Std. error is the standard error of the bootstrap estimate; Source: own calculation and presentation.
Source: own calculation and presentation.

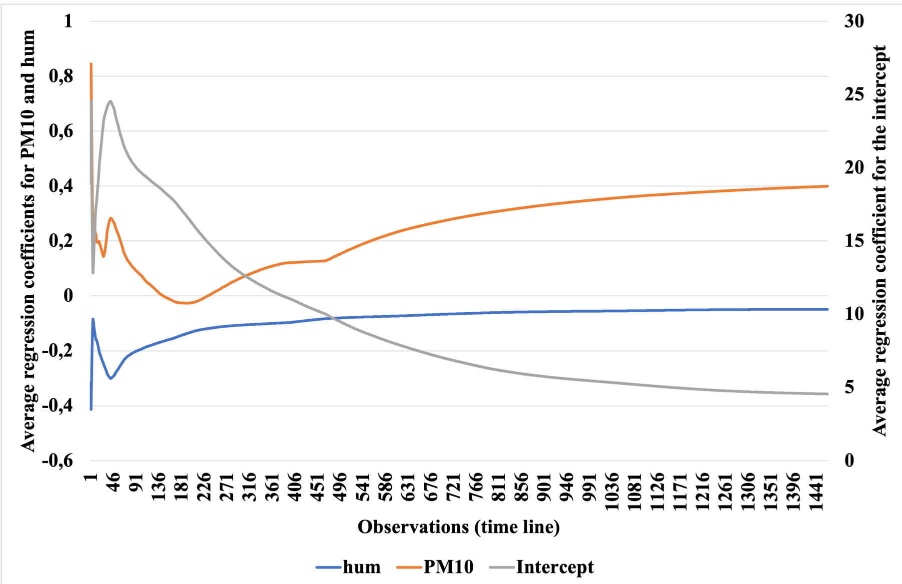
Second, the data set is increased by one observation at a time (starting with $n = 1$). The idea is to determine how much data is needed to get useful results from the regression. Usefulness can then be judged by the results of the regression for the entire data set. So, figure 5 and 6 show how the regression parameters develop. It turns out that reasonably useful results can be derived only after about the first 500 observations. This is an important result: It gives an indication of how many observations or how much time is needed to calculate reasonably robust correction values.

Figure 5: Regression results for M1 (PM_{10}) with stepwise data set enlargement



Source: own calculation and presentation.

Figure 6: Development of the average regression coefficients for M1 (PM_{10})



Source: own calculation and presentation.

In summary, the correction approach is as follows: It is possible to estimate LfU values by using the regression results and measured value of the sensor box (for PM_i and hum). Finally the comparison of the real and the estimated $LfU^\star$ values show the efficiency of the method. Therefore, the correction algorithm is (for M1): Because of $MAE_{PM_i,n} = |LfU_{PM_i,n} - PM_{i,n}|$, for $PM_{2.5}$ if

$$LfU_{PM_{2.5},n} > PM_{2.5,n} \text{ then } LfU^\star_{PM2.5,n} = 2.96 + 1.28PM_{2.5,n} - 0.02hum_n$$

$$\text{otherwise } LfU^\star_{PM_{2.5},n} = -2.96 + 0.72PM_{2.5,n} + 0.02hum_n$$

furthermore for PM_{10}, if

$$LfU_{PM_{10},n} > PM_{10,n} \text{ then } LfU^\star_{PM10,n} = 3.45 + 1.5PM_{10,n} - 0.04hum_n$$

$$\text{and otherwise } LfU^\star_{PM_{10},n} = -3.45 + 0.5PM_{10,n} + 0.04hum_n$$

4.3 Results after correction

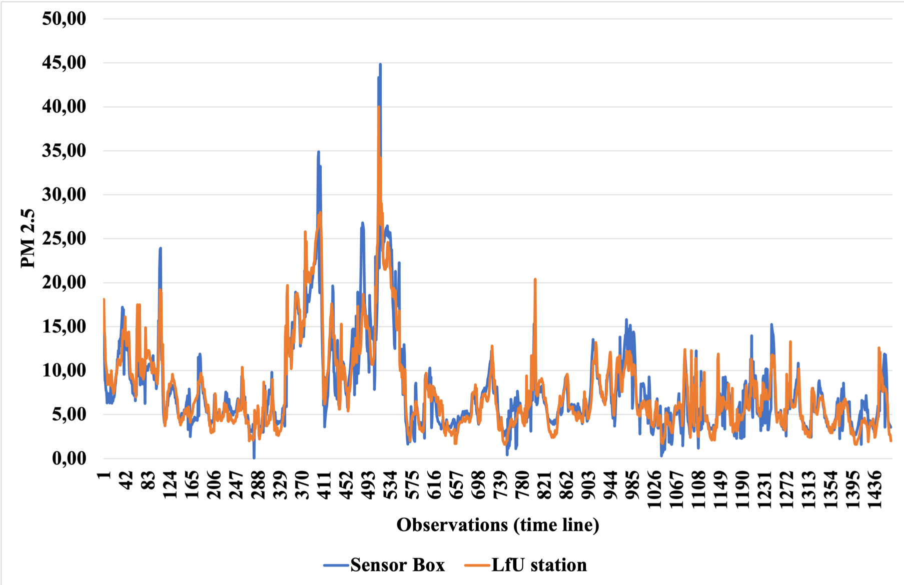
Figure 7 and 8 presents the visual comparison of the corrected sensor box data and the LfU data. Table 9 shows corresponding descriptive results using the formula for MAE, BIAS, RSME and RE.

The results show that adjusting the values using the correction approach significantly reduces the discrepancies between the LfU and sensor box data. This result is stronger in the case of $PM_{2.5}$ values. While before the adjustment only about 20% of the sensor box data show small deviations ($< 15\%$), after the correction more then 50% (25%) of the values for $PM_{2.5}$ (PM_{19}) deviate by less than 15%.

With regard to the key figure MAE, the average absolute deviation between the LfU and sensor box data could be reduced by 50% (40%) in the case of $PM_{2.5}$ (PM_{10}).

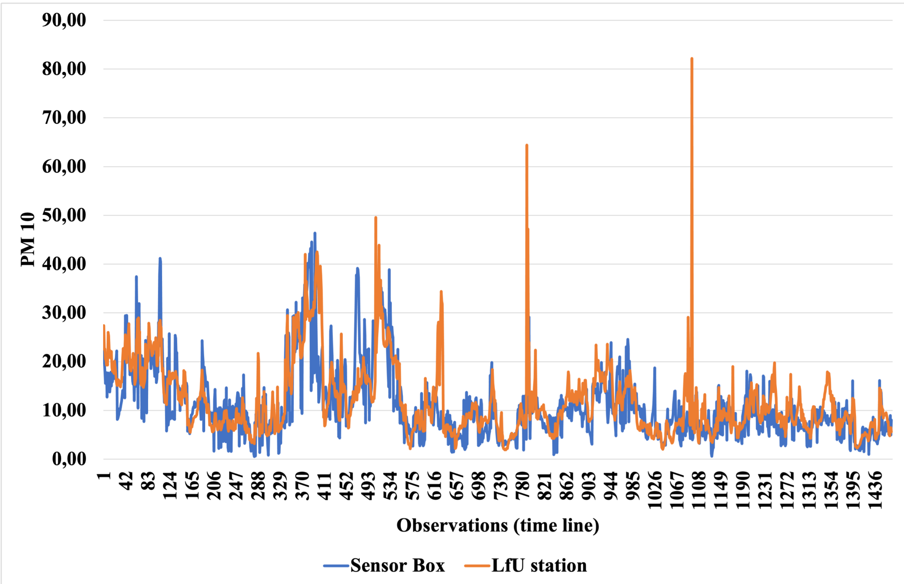
The visualization also illustrates that the adjustment works very well, especially in the data range that shows low fluctuations or low PM values. This effect is particularly clear for PM_{10}. The sensor box overemphasis high PM values.

Figure 7: $PM_{2.5}$ LfU reference values and corrected Sensor Box (SDS011) values



Source: own calculation and presentation.

Figure 8: PM_{10} LfU reference values and corrected Sensor Box (SDS011) values



Source: own calculation and presentation.

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Table 9: Descriptive statistics

	uncorrected		corrected	
	$PM_{2.5}$	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**
MAE	2.88	6.24	1.51	3.88
BIAS	1.40	0.61	-0.03	1.00
RMSE	3.94	9.88	2.08	5.86
RE	18.35%	22.37%	50.64%	27.01%

Source: own calculation and presentation.

5 Conclusions

Are the particulate matter data measured using low-cost sensor technology comparable with those of the LfU? Can data adjustments contribute to comparability? The results show that the low-cost sensor is quite capable of imaging particulate matter data with some accuracy. Especially for PM_{25}, useful results are obtained in sum. For PM_{10} there are clear deviations. The deviations become stronger when high concentrations of PM are detected. Here, the sensor shows weaknesses.

But: With statistical methods, this weakness can be dampened. The analysis has shown that efficient correction approaches can be found. They contribute to the fact that the data of the sensor box can be adapted to those of the LfU station. It must be taken into account that the correction approaches require a sufficient number of sample measurements and reference data at the same time. I.e. an adjustment process is possible, but needs access to official measuring stations. To what extent the correction approaches can be transferred could not be determined. The investigation only referred to one specific sensor. However, looking at other studies (LUBW 2017), it can be assumed that the adjustment should be checked with regard to its effect if it is applied to other sensors of type SDS011.

In sum, it can be stated that the low-cost sensor can be used very well as a kind of warning system. As long as PM values are low, the sensor measures sufficiently accurately. As soon as the PM values increase, the sensor produces significant deviations and fluctuations. In this case, it is no longer possible to say exactly how the PM values turn out. However, it can be said that there is a fairly high probability of high PM concentration. This warning can be taken into account by the public. After all, this result is interesting. Combined with the fact that a favorable sensor is considered here, this results in a sufficiently good instrument for the public to monitor PM levels at arbitrary locations and to detect high levels of pollution. This is the prerequisite for further discussion, for example in the field of traffic planning or urban greening.

Next studies could develop further correction approaches. They could also investigate the reliability and transferability of the correction approaches through larger test series.

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