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The summary of results of the comparative analysis of low-cost devices used to measure particulate matter concentration

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The study presented below is an introduction to more extensive reports that have been mentioned in the bibliography. We encourage readers to check the above-mentioned studies in full. Due to the limited nature of this study, its authors were not able to include all the results available in the listed reports.

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Chapter 1

Introduction

The growing popularity of low-cost particulate matter sensors and a simultaneous lack of method for verifying the quality of measurement results led to an agreement concluded in 2017 and 2018 between the authorities of the Małopolska Voivodship, the Chief Inspectorate for Environmental Protection, the AGH University of Science and Technology in Kraków, the municipality of Rabka-Zdrój, the municipality of Dobczyce and the Kraków Smog Alert association. The agreement resulted in two series of measurements conducted with the use of low-cost sensors in comparison with a reference method. The measurements aimed at verifying and evaluating the reliability of available low-cost measuring instruments. The study presented below is a summary of two reports drawn up on completion of the comparative measurements. It should be noted that this is another presentation of results included in the reports on both series of measurements [1] and [2]. This study should be treated as an introduction and a summary of the above-mentioned reports. The results of the measurements have been analysed according to the methodology used while proving the equivalence to a reference method. Yet, the above-mentioned reports do not aim at proving the equivalence to a reference method. The study main objectives include:

- evaluation of low-cost sensors reliability,
- determination of their usefulness for indicating the quality of air,
- determination of their usefulness for information or education purposes,
- presentation of instructions for potential buyers.

Chapter 2

Analysis methodology

2.1 The course of comparative measurements

The comparative measurements were conducted in two series. The first series was carried out in the period between 15 February 2017 and 20 June 2017 in Rabka-Zdrój, and the other one between 1 December 2017 and 15 March 2018 in Dobczyce. The participation in the measurements was voluntary. Each of the participants provided two sensors to the measurement site. The sensors were installed by the participants under the supervision of a person employed at the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (the Laboratory). Every hour, the participants were obliged to send an average value of PM10 and PM2.5 concentration (if it was measured). Furthermore, once a day, the participants sent average concentration levels for a given day, with no possibility to correct them. At the measurement site, the Laboratory employees installed low-volume particulate matter samplers to determine with the use of a reference method[1] average daily concentrations of PM10 and PM2.5[2]. They also installed a BAM-1020[3] analyser of particulate matter concentration to measure the concentration levels at a resolution of 1h. No reference devices or reference devices equivalents were located in the immediate vicinity of the measurement sites apart from the devices installed by the Laboratory employees but the data thus obtained were not available to the participants.

In the course of the analysis, each of the participants installed a set of two sensors at the measurement site, with the exception of the company Airly that provided two sets of two sensors in the second series of measurements, hereinafter marked with letters „A" and „B".

5 entities participated in the first series of measurements (alphabetical order):

- **Elkomp Jacek Kędzioła**,
- **Envimet Services sp. z o.o.**,
- **Warsaw University of Technology (Artur Badyda, Bogdan Dziadak, Mariusz Rogulski)**,
- **Solutions for Technology sp. z o.o.**,

[1] A reference method consists in measuring the difference in mass between the filter before and after exposure. Exposure is a forced flow of air through the filter. The concentration value is determined by dividing the mass of particulate matter deposited on the filter by the total volume of air that was pumped through the filter. The measurement of mass is conducted in laboratory conditions, in accordance with PN-EN 12341 standard.

[2] The PM2.5 concentration was measured only in the second series of measurements.

[3] The concentration measurement based on the beta radiation absorption. The device with proven equivalence to a reference method.

- **Tetatbit sp. z o.o.**

7 entities participated in the second series of measurements (alphabetical order):

- **Airly Sp. z o.o.**,
- **OMC Envag Sp. z o.o.** ,
- **Far Data Sp. z o.o. Spółka Komandytowa**,
- **Warsaw University of Technology (Artur Badyda, Bogdan Dziadak, Mariusz Rogulski)**,
- **Tetatbit sp. z o.o.**,
- **Zakład Elektroniki Vidiaq**,
- **Xorbit**.

Full contact details can be found in the reports on both series of measurements [1] and [2].

2.2 Reference devices used in the course of measurements

The results of the measurements conducted by means of low-cost sensors that were provided for the analysis were compared with the results obtained with the use of devices installed in the same place. In the course of the measurements, the companies participating in the analysis had no access to the results obtained with the use of reference devices and their equivalents. The average daily concentrations of PM10 and PM2.5 were provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection as a result of the measurement based on a gravimetric analysis that is a reference method of measuring PM10 and PM2.5 concentrations. The average hourly PM10 concentrations were compared with the results obtained with the use of the BAM-1020 device. The results of the measurements conducted with the use of the BAM-1020 device were verified on completion of the analysis on the basis of a reference method.

In the first series of measurements, a comparison was made as regards PM10 concentrations. In the second series, a reference measurement of the average daily concentration of PM2.5 was additionally introduced.

Chapter 3

Analysis of the measurement results

Ze względu na różne warunki w jaDue to different conditions in which both series of measurements were conducted, it is impossible to directly compare their results. The first series began at the end of the winter season and was characterised by significantly lower average concentrations in relation to the second series. Therefore, the participants in the first series were in a privileged measurement position in comparison with those participating in the second series. Thanks to more diverse conditions as regards concentrations and a considerable number of days with average daily concentrations above 30 μg/m^3 the second series of measurements enabled us to check the devices in the conditions typical of the autumn and winter season in Poland.

Information on the calibration of measuring data will often appear in this part of the report and in the reports [1] and [2]. The data provided by the measurement participants were directly compared to a reference method and a calibration in relation to a reference method was carried out by the reports' authors. Such a procedure is followed by laboratories operating as part of the State Environmental Monitoring (SEM) to verify indications of the devices used in monitoring to determine the particulate matter concentration at a resolution of 1h. However, to enable such a procedure, a gravimetric method should be used simultaneously in the immediate vicinity of the device that is subject to calibration. A lack of a sampler at the verified device excludes the possibility to conduct a proper calibration. It should also be noted that the verification of results through calibration in relation to the SEM station, on the basis of the results obtained with the use of a device installed in its vicinity gives no 100% certainty that the producer's remaining sensors will operate in the same way. Even if initially the devices were appropriately calibrated against each other by their producers, one cannot guarantee that particular devices will maintain their parameters in time when they become dirty or when their components wear out. Taking the above into account, the reader should first pay attention to the results obtained by the devices that were not calibrated by the reports' authors because in most cases these are the values provided by the producers. Data presented after a calibration provide information on how much can be obtained from the given device by applying the calibration. Readers should realise that a calibration in relation to a reference method does not mean that the calibrated device will indicate values consistent with the reference method. In the case of some participants, the values generated by the sensors indicated a complete lack of correlation with the actual concentration level, which made a proper calibration impossible.

Several parameters proving the quality of the sensors were analysed in the reports. First, an analysis of data completeness (see subsection 3.1) and discrepancy of results between the sensors provided by the same supplier was conducted (each producer provided 2 sensors), see subsection 3.2.

Section 3.3 was dedicated to the consistency of measurement data provided by the producers with reference data. The average values obtained in the entire measurement period with the use of the tested sensors were first compared with a reference device. Uncertainty of the measurement conducted with the use of particular sensors before and after a calibration was presented in subsection 3.3.2. This parameter is crucial in terms of evaluation of the measurement results' reliability.

In section 3.4 , the calibration coefficients were presented to which data were to be subject to obtain the best possible adaptation to the reference data for the entire period analysed. The results of the average daily measurements before and after a calibration can be visually compared in appendices B and C.

Section 3.5 analyses the stability of the calibration coefficients in the course of the second series of measurements. In the first series, it was impossible to follow this procedure as the analysed period was too short and particulate matter concentration was too low.

Section 3.6 presents the results of the analyses concerning the influence of air humidity on the concentration measurement conducted with the use of low-cost sensors.

3.1 Data completeness

Table 3.1 illustrates the number of days on which the participants reported the average daily values to a database. The values presented in the table indicate whether the data were actually sent to the database. The values specified below do not prove that a device has made a measurement. If a participant did not send data within a deadline set in the rules and regulations, he/she could not have sent them later.

Table 3.1: Number of days on which a participant sent the average daily concentration values obtained with the use of both sensors to the database. P – means the total time of the measurement duration (the first day on which a participant made his/her first transfer of data was taken into account). N – number of average daily values from the participant's both devices. Prepared on the basis of the reports [1] and [2].

Participant	P_{PM10}	N_{PM10}	$P_{PM2.5}$	$N_{PM2.5}$
First series				
Elkomp	123	123	-	-
Envimet	121	62	-	-
PW	121	112	-	-
S4Tech	122	110	-	-
Tetabit	121	61	-	-
Second series				
Airly_A	99	86	99	86
Airly_B	99	86	99	86
Envag	99	93	99	93
Far Data	94	90	94	90
PW	84	76	-	-
Tetabit	99	68	99	69
Vidiaq	99	76	99	76
Xorbit	99	60	99	60

3.2 Discrepancy between the results obtained with the use of two sensors held by the given participant

In this part of the report, uncertainty values were determined for two sensors produced by the same company on the basis of raw data provided by the producers (in this process, no calibration of data was conducted by the authors in relation to a reference method). The parameters of uncertainty of the values indicated by two sensors held by a given participant provide information on the consistency of results between two devices produced by a given company. The comparison presented below takes into account the uncertainty for an average daily value. Momentary and average hourly values are more uncertain. We would like to draw the reader's attention to the fact that this parameter does not show how the device operates against the real (reference) value. This parameter only illustrates the consistency of the measurement results between two identical sensors produced by a given company.

Fig. 3.1 presents a list of participants in the first series of measurements in terms of the measurement uncertainty for the PM10 average daily values between two devices held by the same participant, for the entire measurement period. In order to illustrate how the devices operate in the case of higher concentration levels, a similar list has been made for a set of data excluding[1] average daily values below 30 μg/m^3. The results for this measuring range were presented in Fig. 3.2. The corresponding data for the second series of measurements were presented in Fig. 3.3 and Fig. 3.4. Fig. 3.5 anf Fig. 3.6 present data for the PM2.5 measurement.

The value of the presented parameters shows how the given participant calibrated both devices against each other. The lower the value, the higher the degree of device calibration. A significant increase in this parameter for high concentration levels means that the devices differ more and more from each other as the measured values increase.

In the first series of measurements, the lowest value of uncertainty between devices was obtained by the company Envimet. The uncertainty between the devices amounted to $2,1$ μg/m^3. For a subset of data with average daily values above 30 μg/m^3 the lowest value was obtained by the company Tetabit ($2,4$ μg/m^3).

In the second series of measurements, the best result of the PM10 concentration measurement was obtained by the company Xorbit ($4,3$ μg/m^3). For the high concentration range, the lowest value was obtained also by Xorbit ($4,3$ μg/m^3). Similarly, in the case of PM2.5, the best result was obtained by Airly with its „A" set of sensors[2], where the value of uncertainty amounted to ($2,4$ μg/m^3). For a high concentration range, the best result was obtained also by Airly with its „A" set ($2,7$ μg/m^3).

[1] It was not the reference value but the value measured by a participant that determined the exclusion of measurement data in this part. Both devices had to record the value above 30 μg/m^3 to be taken into account while determining uncertainty for high concentration levels.

[2] The „B" set held by this company obtained a much worse result

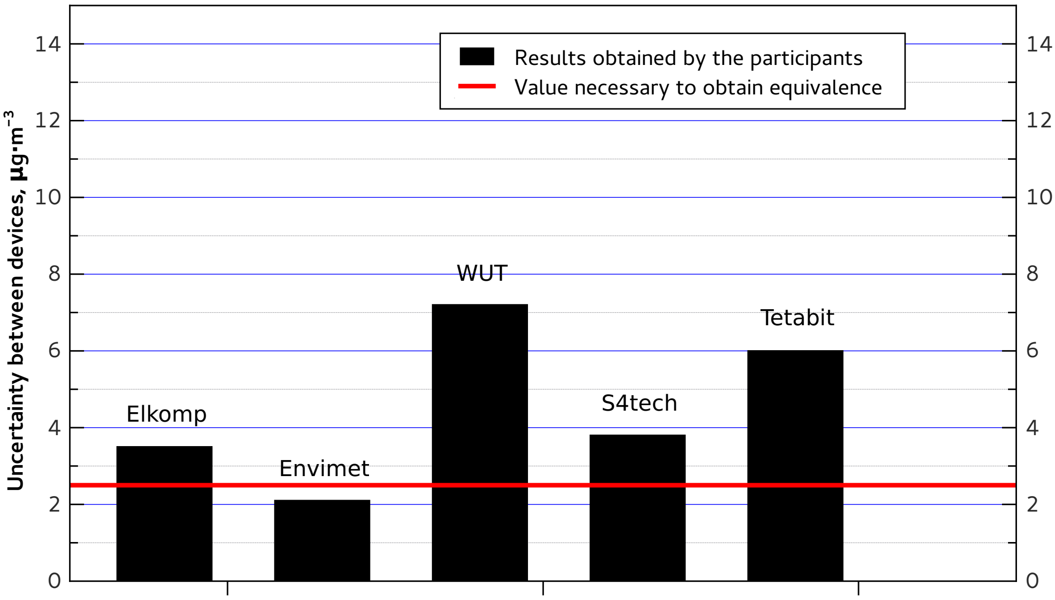

Figure 3.1: I series of measurements: uncertainty of average daily indications of **PM10** concentration between two devices held by a given participant in the entire period analysed. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. Prepared on the basis of the report [1].

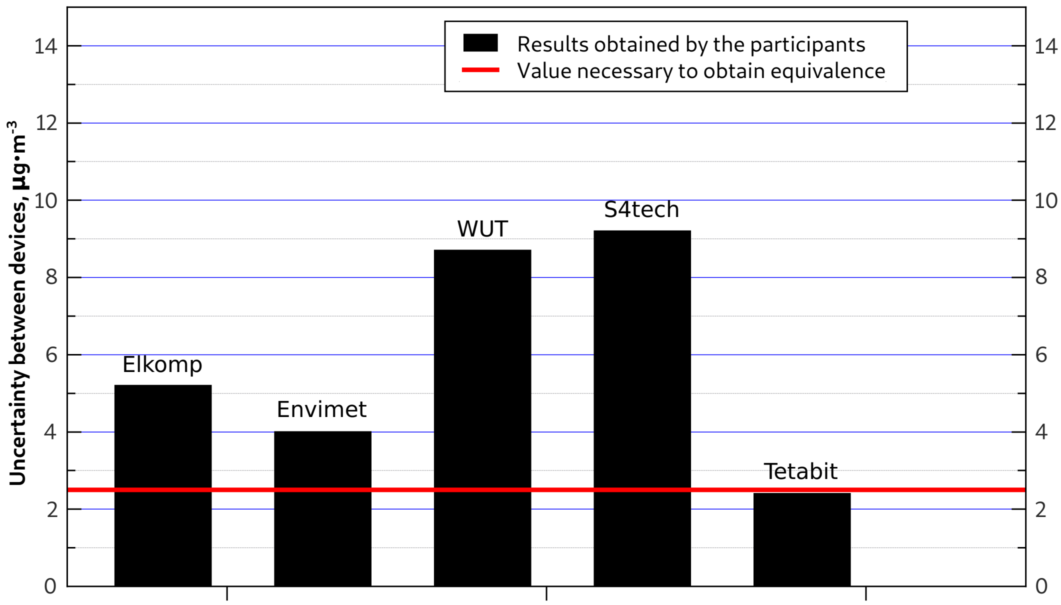

Figure 3.2: I series of measurements: uncertainty of average daily indications of **PM10** concentration between two devices held by a given participant in the entire period analysed excluding average daily values below 30 $\mu g/m^3$. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. Prepared on the basis of the report [1].

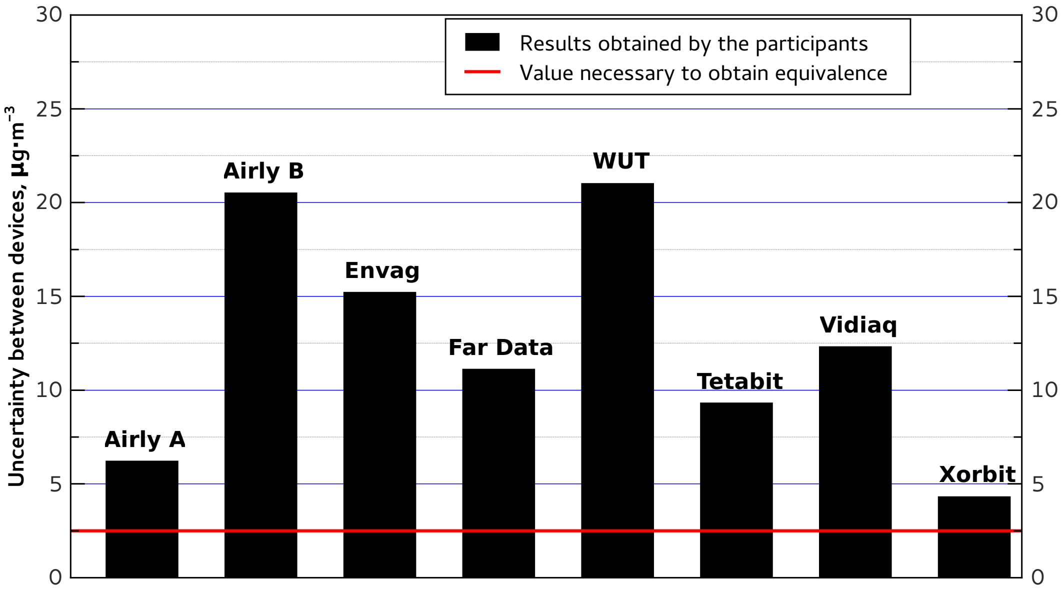

Figure 3.3: II series of measurements: uncertainty of average daily indications of **PM10** concentration between two devices held by a given participant in the entire period analysed. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. Prepared on the basis of the report [2].

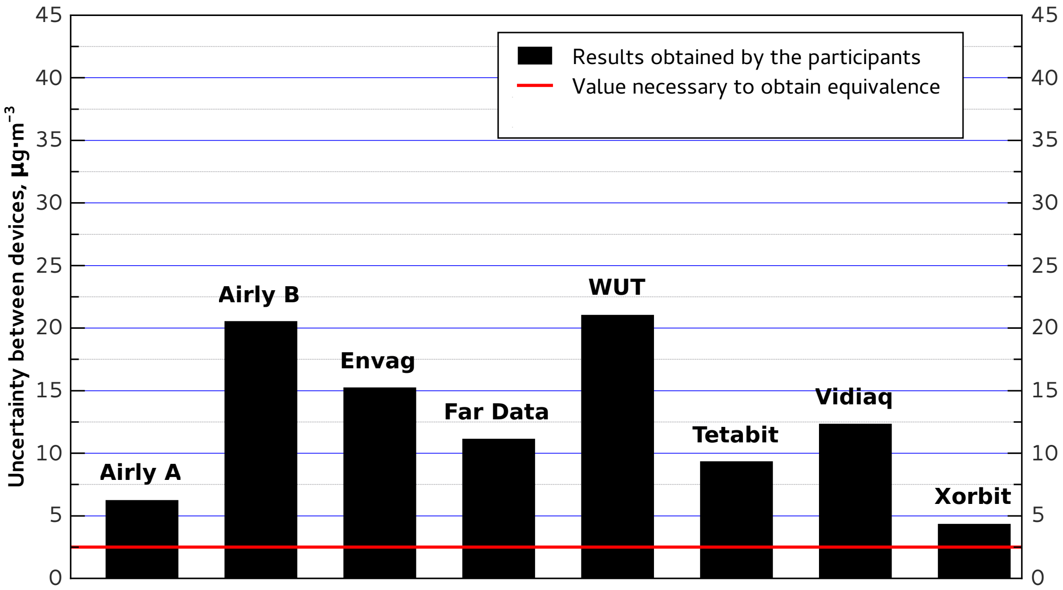

Figure 3.4: II series of measurements: uncertainty of average daily indications of **PM10**concentration between two devices held by a given participant in the entire period analysed excluding average daily values below 30 $\mu g/m^3$. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. Prepared on the basis of the report [2].

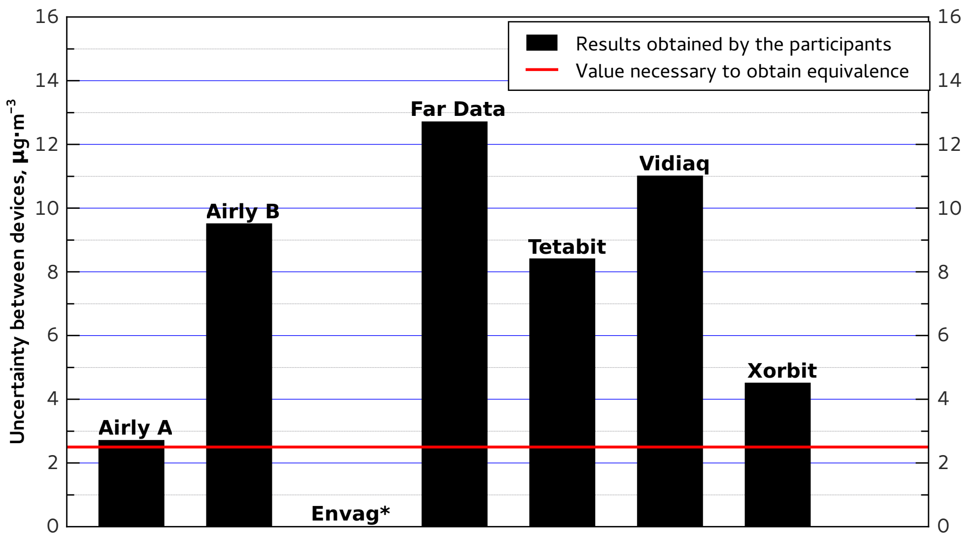

Figure 3.5: II series of measurements: uncertainty of average daily indications of **PM2.5** concentration between two devices held by a given participant in the entire period analysed. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. The Warsaw University of Technology was not included in this comparison due to the lack of results for PM2.5 obtained with the use of this participant's devices. Prepared on the basis of the report [2].

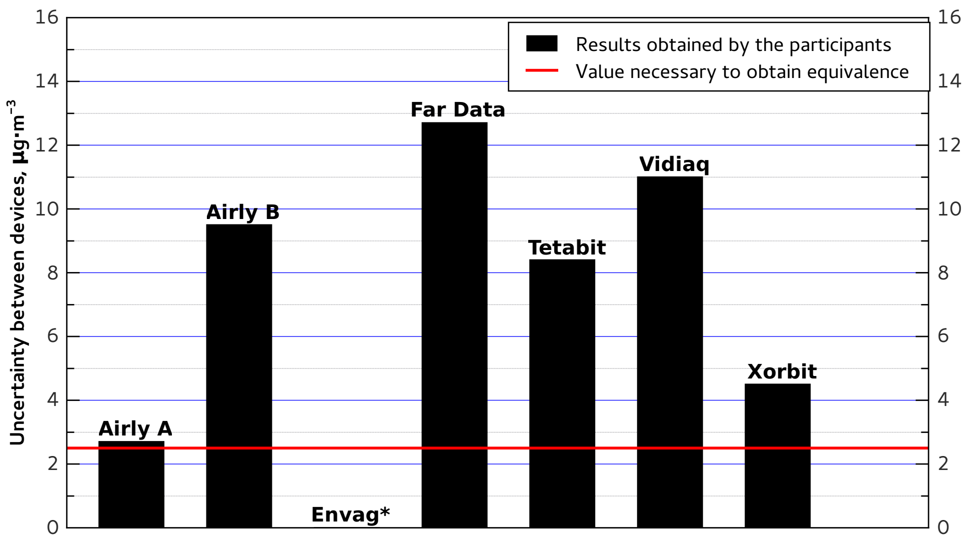

Figure 3.6: II series of measurements: uncertainty of average daily indications of **PM2.5** concentration between two devices held by a given participant in the entire period analysed excluding average daily values below 30 μg/m^3. The red line marks the level that cannot be crossed by the devices which are to be recognised as equivalent. The Warsaw University of Technology was not included in this comparison due to the lack of results for PM2.5 obtained with the use of this participant's devices. *) The "0" value for the company Envag results from the fact that this participant's devices did not report the values above 30 μg/m^3. Prepared on the basis of the report [2].

3.3 Compliance of the tested devices with a reference method

3.3.1 Average concentration level

Average indications of the devices in the analysed period have been presented below. The average results for the tested devices have been calculated on the basis of the values provided by the producers. As it can be observed, in the first series of measurements, the differences between the reference value and the value measured by the device are smaller than in the second series. It is most probably related to the fact that in the case of incorrectly calibrated or poor quality devices the differences are bigger for higher concentration levels. The results presented in this section show only an averaged result of the measurement for the entire period analysed. This result should not be interpreted as a calibration coefficient. A doubled average value does not mean that the device will double the measurement result in any conditions. This parameter can be interpreted as evaluating the correctness of the device operation and of the calibration conducted by its producer.

Fig. 3.7 compares the average values recorded by particular devices during the first series of measurements with the average values obtained with the use of a reference device for the entire measurement period[3] Fig. 3.8 shows the results obtained in the second series of measurements by the devices measuring PM10 concentration. Fig. 3.9 presents the corresponding data for PM2.5.

In the first series of measurements, the smallest difference in relation to the reference method was obtained by S4Tech. In the second series, Vidiaq obtained the best result as regards the average concentration of PM10 in the entire period; the best result for PM2.5 was obtained by Airly.

It should be noted that the average value coverage does not always translate into the measurement uncertainty. The devices used by Vidiaq (both devices, PM10 measurement) and by Airly, set B (device I, PM2.5 measurement) indicated the average values that are very close to the value obtained with the use of a reference method, whereas the expanded relative uncertainty was in their case greater than in the case of devices that indicated average values with lesser accuracy (compare subsection 3.3.2).

3.3.2 Relative expanded uncertainty of the measurement

In nature, each measurement of physical quantity is burdened with measurement uncertainty. In most cases, it is useless to specify a measurement value without determining its uncertainty. The measurement uncertainty constitutes basic information that should be provided by a measuring device vendor. It cannot be confused with the measurement resolution, measurement stability or average difference between the real and measured value.

In order to simply explain the term of uncertainty and expanded uncertainty, let us use the following example[4]. We use a device to make 1000 measurements of a certain physical quantity the value of which we know. Let us assume that for each measurement we have calculated a difference between the real value and the measurement result. The standard uncertainty (shortly: uncertainty) is the value of the above-mentioned difference that was not exceeded in

[3]The measurement period means the time in which the given device reported data to a database. Particular devices may have different levels of reference due to the lack of coverage of the set of days on which they reported data.

[4]For the sake of simplicity, mathematical dependence relations were given up. The example aims to explain the meaning of this parameter to a person who has encountered the term 'uncertainty' for the first time.

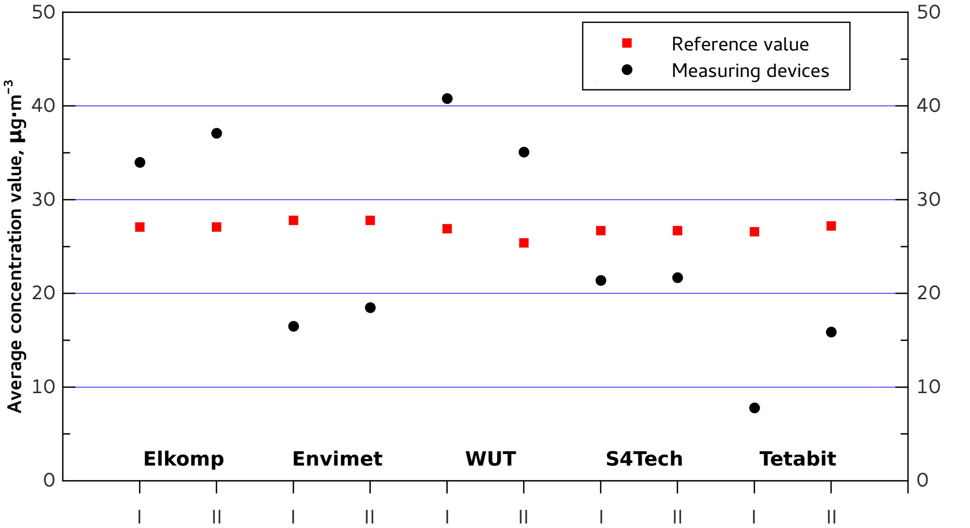

Figure 3.7: I series of measurements: comparison of the **PM10** average concentration values obtained with the use of the tested devices with a reference method. The average values were calculated for each device before a calibration and compared with the average value obtained in the period in which the device reported data. Prepared on the basis of the report [1].

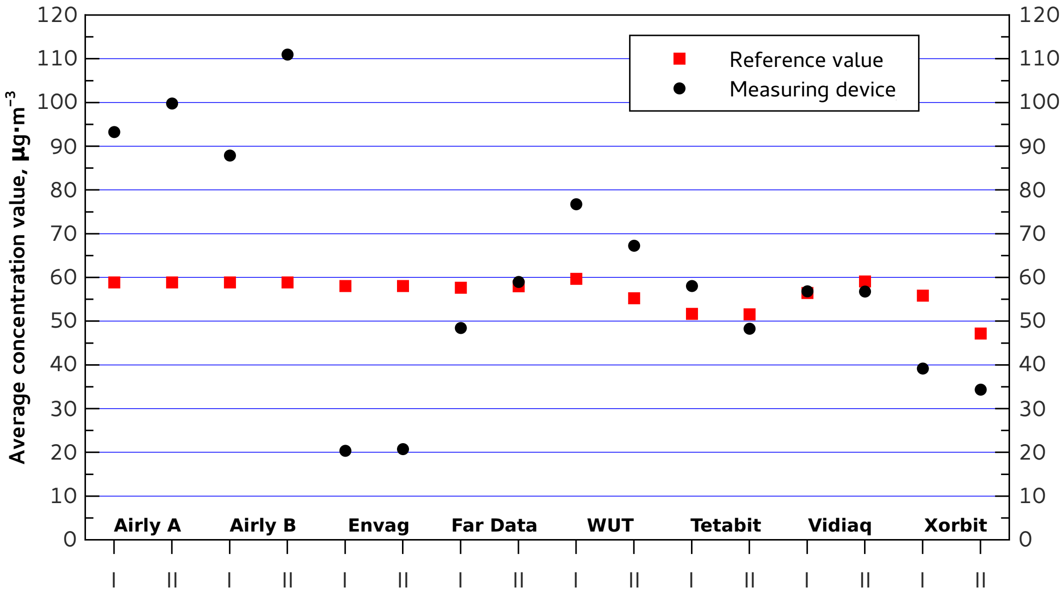

Figure 3.8: II series of measurements: comparison of the **PM10** average concentration values obtained with the use of the tested devices with a reference method. The average values were calculated for each device before a calibration and compared with the average value obtained in the period in which the device reported data. Prepared on the basis of the report [2].

case of 68 % of measurements. Expanded uncertainty (for k=2)[5] is the value of difference that was not exceeded in case of 95 % of measurements. A considerable number of measurements does not differ so much from the real value as the uncertainty value. However, without knowing the real value, we should be aware of the fact that each measurement is burdened with such uncertainty. By providing us with the value of expanded uncertainty, a device producer somehow

[5] The 'k' factor determines the degree of expanding standard uncertainty. The value of expanded uncertainty is obtained by multiplying the value of standard uncertainty by the 'k' factor.

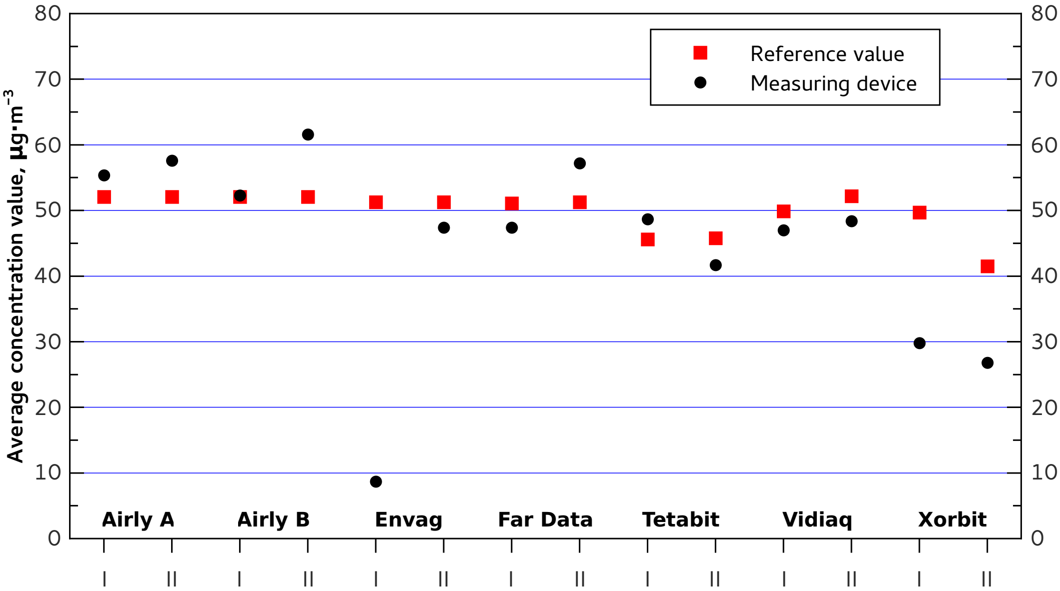

Figure 3.9: II series of measurements: comparison of the **PM2.5** average concentration values obtained with the use of the tested devices with a reference method. The average values were calculated for each device before a calibration and compared with the average value obtained in the period in which the device reported data. Prepared on the basis of the report [2].

guarantees that in most cases the value measured with the use of the device will not differ from the real value by more than the indicated expanded uncertainty.

In a later section of the report, there appears a term of relative expanded uncertainty. This parameter is obtained through dividing expanded uncertainty of a given device by an admissible value. In the case of PM10, the admissible value is $50\mu g/m^3$, whereas for PM2.5 the admissible value assumed in the report [2] amounts to $25\mu g/m^3$.

To ensure a good quality measurement of particulate matter concentration, it was assumed that relative expanded uncertainty should not exceed 25 %.It means that the results shown by the devices recognised as equivalent to the reference method in most cases will not deviate from the actual value of average daily concentration by more than$25\% \cdot 50\mu g/m^3 = 12,5\mu g/m^3$. The above reasoning means that expanded uncertainty of the measurement of PM10 daily average concentration for the method equivalent to a reference method is not worse than $12,5\mu g/m^3$. In the case of PM2.5, expanded uncertainty should not exceed $6,25\mu g/m^3$ (these differences result from different levels admissible for particular fractions).Correspondingly, the relative expanded uncertainty equal to 100 % for PM10 means expanded uncertainty of an average daily concentration measurement equal to $50\mu g/m^3$. It does not mean that each measurement result will differ from the real value by $50\mu g/m^3$. Measurement data may include days on which a device records a value different from the real value only by a few $\mu g/m^3$. However, without knowing the real value, we are not able to identify such days.

The further section of the report presents a comparison of the value of relative expanded uncertainty for the tested devices with the value that is imposed on the measuring method consistent with a reference method. The majority of methods consistent with a reference method may obtain a much better result than the level of 25 %. shown in the figures. In the case of periodic measurements, it is allowed to increase the value of relative expanded uncertainty up to the level of 50% of the target value, which was also marked in the charts.

Fig. 3.10 presents a comparison of relative expanded uncertainty of PM10 concentration for the tested devices before and after a calibration in the first series of measurements. For the second series, a comparison concerning the devices measuring PM10 was illustrated in Fig. 3.11, and concerning PM2.5 in Fig. 3.12. The comparisons present relative uncertainty of the measurement before and after a calibration has been conducted by the report authors. A significant improvement of this parameter for calibrated data means that the given device was initially calibrated in an incorrect manner. The value of uncertainty after a calibration additionally takes into account the uncertainty related to adapting data obtained with the use of low-cost sensors to reference data. For the devices that showed a weak linear relation to the reference method or in the case of variable calibration coefficients in time[2], uncertainty after a calibration was sometimes higher.

In the first series of measurements, the lowest value of relative expanded uncertainty for initial data was obtained by the device produced by Envimet (50,4 %). In the case of calibrated data, the best result (16,8 %) was obtained by Tetabit.

In the second series of measurements, the best result in the case of PM10 concentration measurement for the initial data was obtained by Tetabit (value 29,3 %). For calibrated data, the best value was also obtained by Tetabit (value 29,7 %). For PM2.5, a device produced by Tetabit had the lowest relative expanded uncertainty for the initial data (44,4%). For the calibrated data, the best result was obtained also by Tetabit (the value of relative expanded uncertainty amounted to 32,6 %).

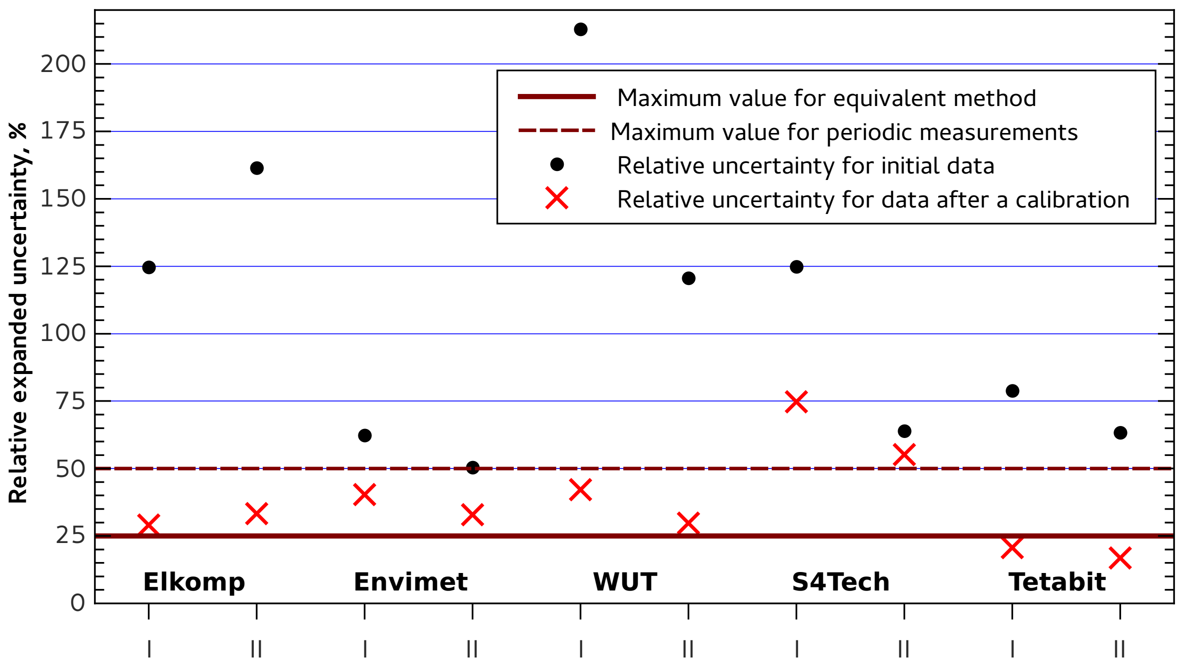

Figure 3.10: I Edycja: relative expanded uncertainty of the **PM10** daily average concentration measurement for particular devices before and after a calibration. Prepared on the basis of the report [1].

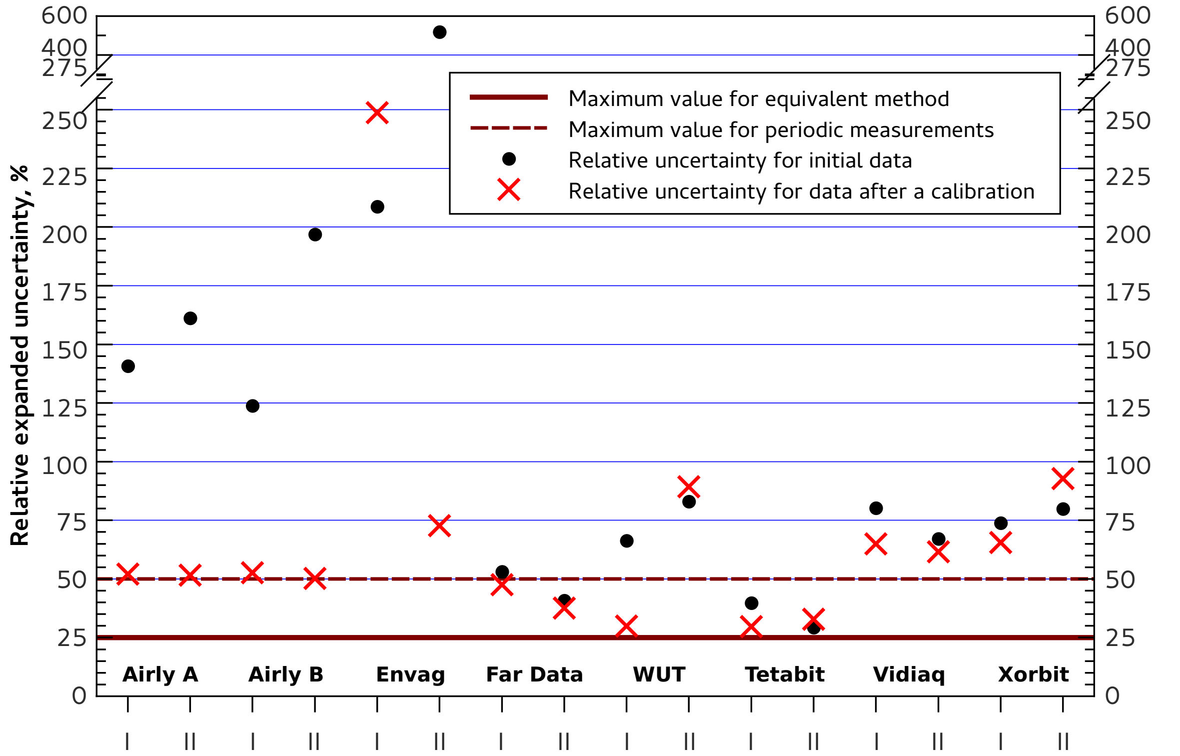

Figure 3.11: II Edycja: relative expanded uncertainty of the **PM10**daily average concentration measurement for particular devices before and after a calibration. Due to considerable differences between the participants, intercepts and various scales were used for a chart divided in this way. Prepared on the basis of the report [2].

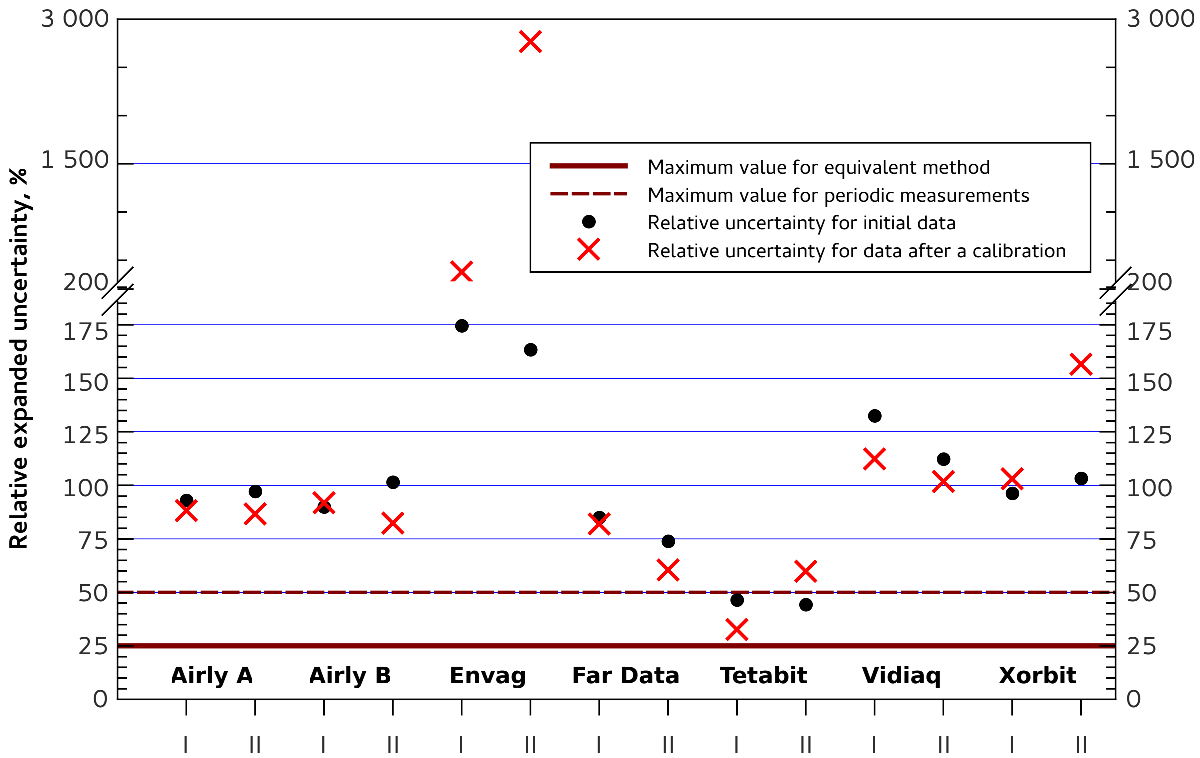

Figure 3.12: II Edycja: relative expanded uncertainty of the **PM2.5** daily average concentration measurement for particular devices before and after a calibration. Due to considerable differences between the participants, intercepts and various scales were used for a chart divided in this way. Prepared on the basis of the report [2].

3.4 Calibration coefficients

For each low-cost device, the authors of the reports [1] and [2]
have conducted a calibration with the use of the compliance sheet Órthogonal regression and equivalence test utility, version 2.9,"provided by the RVIM (Dutch Institute for Public Health and the Environment, dep. Centre for Environment Monitoring) and their own studies. The level of concentration after a calibration has been conducted results from the following interrelation[6]:

$$C_{cal} = a \cdot C_{initial} - b$$

gdzie: C_{cal} – concentration after a calibration, $C_{initial}$ – concentration before a calibration, a – calibration curve slope coefficient, b – calibration curve shift coefficient.

The calibration coefficients for the first and second series of measurements have been presented in table 3.2. The value of slope coefficient (a) that is close to 1 and accompanied by the parameter (b) close to 0 implies that the initial calibration conducted by a given participant was correct. Despite a calibration, some devices still had a high value of uncertainty (compare section 3.3.2). It is related to a weak correlation of the results obtained with the use of a given device with the results obtained by means of a reference method.

Table 3.2: Calibration coefficients for the I and II series of measurements. Prepared on the basis of the reports [1] and [2].

I series of measurements

Provider	Device	PM10 a	PM10 b
Elkomp	I	0,51	-9,73
	II	0,45	-10,26
Envimet	I	1,08	-9,48
	II	1,05	-8,42
PW	I	0,40	-10,68
	II	0,57	-5,31
S4Tech	I	0,50	-15,97
	II	0,81	-8,97
Tetabit	I	1,02	-18,69
	II	1,23	-7,64

II series of measurements

Provider	Device	PM10 a	PM10 b	PM2.5 a	PM2.5 b
Airly$_A$	I	0,650	1,78	0,933	-0,39
	II	0,589	-0,09	0,879	-1,46
Airly$_B$	I	0,700	2,62	0,998	0,1
	II	0,520	-1,12	0,819	-1,68
Envag	I	1,225	-33,07	3,704	-5,44
	II	0,309	-51,68	11,14	45,26
Far Data	I	1,124	-3,23	1,000	-3,53
	II	0,891	-5,46	0,797	-5,68
PW	I	0,731	-3,62	-	-
	II	1,347	35,34	-	-
Tetabit	I	0,905	0,87	1,074	6,70
	II	1,193	6,01	1,363	10,98
Vidiaq	I	0,785	-11,81	0,890	-8,10
	II	0,905	-7,71	0,951	-6,10
Xorbit	I	1,449	0,89	1,714	1,45
	II	1,483	3,85	1,756	5,52

[6] The marking of coefficients (a) and (b) was used to simplify the record. The sheet [3] uses other markings. The exact interrelations between the coefficients assumed in the study and in the sheet have been presented in the reports [1] and [2].

3.5 Stability of devices' indications in time

A set of data obtained during the second series of measurements enabled us to evaluate the stability of sensors' operation. In the course of the tests, the report authors have analysed the stability of calibration coefficients. The entire set of results was divided into weekly periods. For each subset of measurements, a calibration of measuring devices was conducted in relation to a reference method, on the basis of average hourly data. For each of the weeks, the report authors determined the Pearson correlation coefficient (R^2), calibration curve slope coefficients (a) and calibration curve shift values (b). On the basis of these data, the coefficients obtained were analysed in terms of their stability in the course of the entire measurement. The exact values for particular devices along with the charts are included in the study [2].

On the basis of the calculations made, a considerable drift of the calibration curve shift coefficient (b) was recorded (in terms of the measurement uncertainty) only in the case of two devices. The devices that showed the considerable drift included: device n° 2 produced by the Warsaw University of Technology and device n° 1 produced by Far Data. This parameter's drift could have been related to the increased soiling of the measuring chamber. In the course of the measurements, no significant drift of the straight line slope coefficient (a) was recorded for the tested devices in terms of the measurement uncertainty.

For the device n° 2 produced by Airly (set B) and the device n° 2 produced by Envag, a statistically significant decline in the adaptation correctness parameter was recorded (Pearson correlation coefficient - R^2). For both devices, the correlation coefficient value decreased in time. It may imply an increase in the noise made by the devices.

3.6 Influence of humidity on the device indications

Numerous devices that are used to measure particulate matter concentration overestimate the measurement result since they recognise small drops of water in the air as particulates. It takes place because the method of concentration measurement is based on the principle of diffusing a laser light on particulates. The detector installed in the device is not able to distinguish whether the light that reached it is a result of diffusion on a particulate or on a drop of water. Moreover, condensation of water vapour on particulates may lead to changing their size. Therefore, it is recommended to condition the air[7]before analysing the particulate matter concentration. If the conditioning is not very efficient or has not been conducted at all, we can observe a correlation between particulate matter concentration and humidity of the air for high values of humidity. In the case of a high level of humidity of the air, water vapour is easily condensed.

For both series of comparative measurements, an analysis was carried out in terms of correlation with humidity. Calculations were made for two ranges of humidity: 0-90% and 90-100%.

The report [1] contains detailed calculations along with the adaptation parameters for the devices tested in the first series of measurements. The devices produced by Solutions for Technology and Envimet recorded a significant influence of humidity on their indications of particulate matter concentration. It was particularly noticeable for humidity values close to 100%. The report points out an increasing influence of humidity in the case of the devices produced by the Warsaw University of Technology and by Elkomp. No influence of air humidity was recorded on the operation of the devices produced by Tetabit.

[7] Air conditioning – a process of preparing the air so that it has specific physicochemical parameters. In the case of concentration measurement, it is about heating the air to a temperature that enables the transformation of condensed water vapour into gas without influencing the concentration of the analysed substance – in this case particulate matter.

In the second series of measurements, the influence of humidity on measurement results was also analysed. In the case of the devices tested in this series of measurements, no obvious influence of humidity on particulate matter concentration was recorded. More detailed information on the correlation of results can be found in the report [2].

Chapter 4

Summary

1. Low-cost sensors that have been tested in both series of measurements show a significant diversity in terms of measurement uncertainty.

2. In the majority of tested sensors, significant discrepancies were observed in the measurement results obtained by two sensors produced by a given company. In the first series of measurements, only Envimet met the criterion of equivalence to the reference method (it should be noted though that during the first series of measurements, the levels of average daily concentration were low). In the second series of measurements, only one set of sensors produced by Airly obtained such a consistency for PM2.5. When choosing a sensor for measuring particulate matter concentration, it is advisable to ask its producer about the consistency of measurement results indicated by the producer's devices. This value should be included in the product specification and should constitute the basis for complaints. The value of this parameter can be easily checked by locating two sensors produced by a given company in the immediate vicinity. A lack of consistency between the producer's devices (e.g. for the average daily value) should be determined at the moment of purchase and should be the basis for a complaint.

3. Taking into account the measurement uncertainty for the tested sensors (on the basis of data provided by participants without an additional calibration), none of them met the criterion imposed for the method consistent with a reference method. In the case of data calibrated by the reports' authors, the criterion of relative expanded uncertainty for the method consistent with the reference method was met by two sensors produced by Tetabit and tested in the first series of measurements (concentration levels in the first series were considerably lower than those obtained in the second series). Some participants fulfilled the criterion of uncertainty for periodic tests, which equals 50% of the target value. In this case, the criterion for raw data in relation to PM10 was met by one sensor produced by Far Data and two sensors produced by Tetabit. For PM2.5, this criterion was met only by two sensors produced by Tetabit.

   The calibration of raw data made it possible to fulfil the criterion of 50% of the target value in the case of PM10 for two sensors produced by Elkomp (the first series of measurements), two sensors produced by Envimet (the first series), two sensors produced by the Warsaw University of Technology (the first series), two sensors produced by Tetabit and analysed in the first series of measurements (they also met a more stringent criterion), two sensors produced by Far Data (the second series), one sensor produced by the Warsaw University of Technology (the second series) and two sensors produced by Tetabit (the second series).

In the case of PM2.5, a less stringent criterion was met only by one sensor produced by Tetabit.

Taking this parameter into consideration, it is advisable to ask the given sensor's producer about the uncertainty of the average daily measurement. A lack of such information in the product specification should be alarming as it suggests that the producer does not know this parameter. While purchasing the device, the manner of verifying this parameter should also be determined to enable a complaint. The simplest way of verifying the data obtained with the use of the purchased device is to place it in the immediate vicinity of a reference device[1]. The complaint procedure should however be discussed with the producer already at the purchase stage.

4. The majority of the tested sensors indicated incorrect values of calibration coefficients. In the case of most sensors, the calibration conducted by the reports' authors increased their compliance with a reference method.

   When planning a purchase, it is advisable to ask the sensor's producer about its calibration procedure and to obtain a documentation that confirms the calibration process. As it was emphasised in the report [2] the devices used to measure particulate matter concentration should be calibrated in the conditions that ensure a wide range of concentration levels (at least in the range of $0 - 100\,\mu g/m^3$).

5. The calibration of measuring devices does not guarantee that calibration coefficients will be maintained in time. In particular, the calibration coefficient (b) may be subject to a drift due to soiling of a detection chamber. In particular items, this process may have different pace and consequently it is impossible to use the same drift coefficients for all the items.

   No drift of calibration coefficient (a) was recorded in the report. It should however be noted that the efficiency of a laser may decrease in time, thus leading to a change in this parameter in the case of a period longer than a few months.

   Taking the above into consideration, it is advisable to calibrate each sensor separately in relation to a reference device, at least once a year[2]. Naturally, more frequent calibrations will have a favourable influence on the quality of measurements. When negotiating a purchase, it is advisable to agree such a calibration after one year of use with the sensor's producer at the purchase price. It should however be noted that the calibration should be made for a wide range of concentration levels.

6. In the first series of measurements, the influence of air humidity on the measurement result was recorded. Condensed water vapour may lead to an overestimated result of the measurement. When choosing a measuring device, it is advisable to make sure if in the device structure the producer provided an element that conditions an air sample before a measurement to heat it above the dew point. This feature is particularly important in the autumn-winter-spring season.

7. None of the tested sensors met all the criteria that would enable the use of data generated by a sensor to evaluate the quality of air as defined in the Polish and European Union

[1] Such devices are installed at the measurement stations held by the Regional Environmental Protection Inspectorates. The access to data obtained in this way is open.

[2] According to PN-EN 16450 standard, the period between calibrations should not exceed 3 months.

laws. The results obtained cannot be used as part of the official procedures of announcing information or alert thresholds for the concentration of PM10. Taking the above into consideration, despite the presence of low-cost sensors in the immediate vicinity of one's place of residence, attention should be paid to the results presented by the official SEM stations and to announcements made by the Regional Centre for Crisis Management concerning the quality of air.

8. Some sensors, despite their significant uncertainty, can be used for education or information purposes. However, we should be aware of the fact that the difference in measured and real average daily value (for the best low-cost sensors that have been tested) may reach $25\mu g/m^3$. in the case of PM10 concentration. For average hourly values, these differences may be much bigger.

9. In the course of the measurements (due to their limited duration of up to several months), it was impossible to evaluate the period after which sensors should be replaced.

10. In order to determine particulate matter concentration in a representative manner, it is advisable to appropriately install the sensor. More details on this subject can be found in Appendix A.

References

[1] Bartyzel Jakub, Frączkowski Tomasz, Pindel Andrzej, Łyczko Piotr, Dąbrowska Ewa, Dworakowska Anna, *Sprawozdanie z badań porównawczych urządzeń do pomiarów pyłu zawieszonego PM10 (urządzenia niereferencyjne i bez wykazanej równoważności do urządzeń referencyjnych)*, Kraków styczeń 2018

[2] Bartyzel Jakub, Frączkowski Tomasz, Pindel Andrzej, Łyczko Piotr, Musielok Małgorzata, Zięba Damian, Dworakowska Anna, *Sprawozdanie z drugiej serii badań porównawczych urządzeń do pomiarów pyłu zawieszonego PM10 (urządzenia niereferencyjne i bez wykazanej równoważności do urządzeń referencyjnych)*, Kraków sierpień 2018

[3] *Orthogonal regression and equivalence test utility, version 2.9, RIVM (Dutch Institute for Public Health and the Environment, dep. Centre for Environment Monitoring)*

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Appendix A

Recommendations concerning the location of low-cost sensors

The appendix presents the recommendations that should be taken into account while locating the sensors. Depending on the device location, we can obtain a different picture of air quality for a given town/city. Detailed requirements concerning the methods and scope of evaluating substances levels in the air as well as information on the location of sampling points can be found in 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 (EU Official Journal L 152 of 11 June 2008, p. 1) and the Commission Directive (EU) 2015/1480 of 28 August 2015 amending several annexes to Directives 2004/107/EC and 2008/50/EC of the European Parliament and of the Council laying down the rules concerning reference methods, data validation and location of sampling points for the assessment of ambient air quality.

The report presents only a few remarks concerning the selection of place on a macro scale and recommendations related to the location of a measuring device on a micro scale. A measurement station may be used to determine the quality of air for different areas and it may take into account other sources of emissions. When choosing a place for a device installation, we should decide on what information we want to obtain as a result of the measurement. The location criteria adopted for a station that measures the urban background will differ from the criteria imposed on a station that measures the influence of transport or industry. Detailed information on this subject can be found in the regulation. The location of a sampling point should definitely take into account the representative character of the measurement for the entire population in a given area. Emission should also be distinguished from immission. Locating a sensor too close to the source of pollution will provide information on the pollutant emission. If it is possible, a spatial analysis of concentration distribution should be conducted and places that best represent the average value for the analysed area should be selected.

As regards the sensor installation, the sensor immediate surroundings should be taken into account. The regulation presents detailed guidelines concerning the location of a measurement station. The guidelines concerning low-cost sensors (measuring PM10 and PM2.5 concentration) are as follows:

1. No obstacles should reduce the airflow around the sensor (at least within 270° or 180° in the case of measurements at the building line).

2. In general, the sensor should be located at a distance of several metres from buildings, balconies, trees and other obstacles.

3. In the case of measuring the quality of air at the building line, the sensor should be installed at a distance of at least 0.5 m from the nearest building.

4. The general rule is that the sensor should be located from 1.5 m (the breathing zone) to 4 m above ground level. In some cases, it is allowed to locate the sensor at a height exceeding 4 m, especially when the measurement is to be representative for a bigger area.

5. In order to avoid a direct suction of substances before they are sufficiently mixed with the air, sensors should not be located in the immediate vicinity of pollution emission sources.

6. As regards the measurement of transport influence, low-cost sensors should be located at a distance of at least 25 m from the boundary of the main intersections (on which the heavy traffic roads cross and which interrupt the traffic flow and cause emissions other than in the remaining part of the road). Simultaneously, this point should not be located at a distance of more than 10 m from the kerb. Its location too close to the intersection could create an unrepresentative picture of the given road (stopping and starting cars increase emissions but do not correspond to the value typical of the entire road).

Appendix B

Average daily values in relation to a reference method – I series of measurements

The appendix presents the figures that compare average daily values with the values determined by a reference method before and after a calibration has been conducted by the report authors. The figures were taken directly from the report [1].

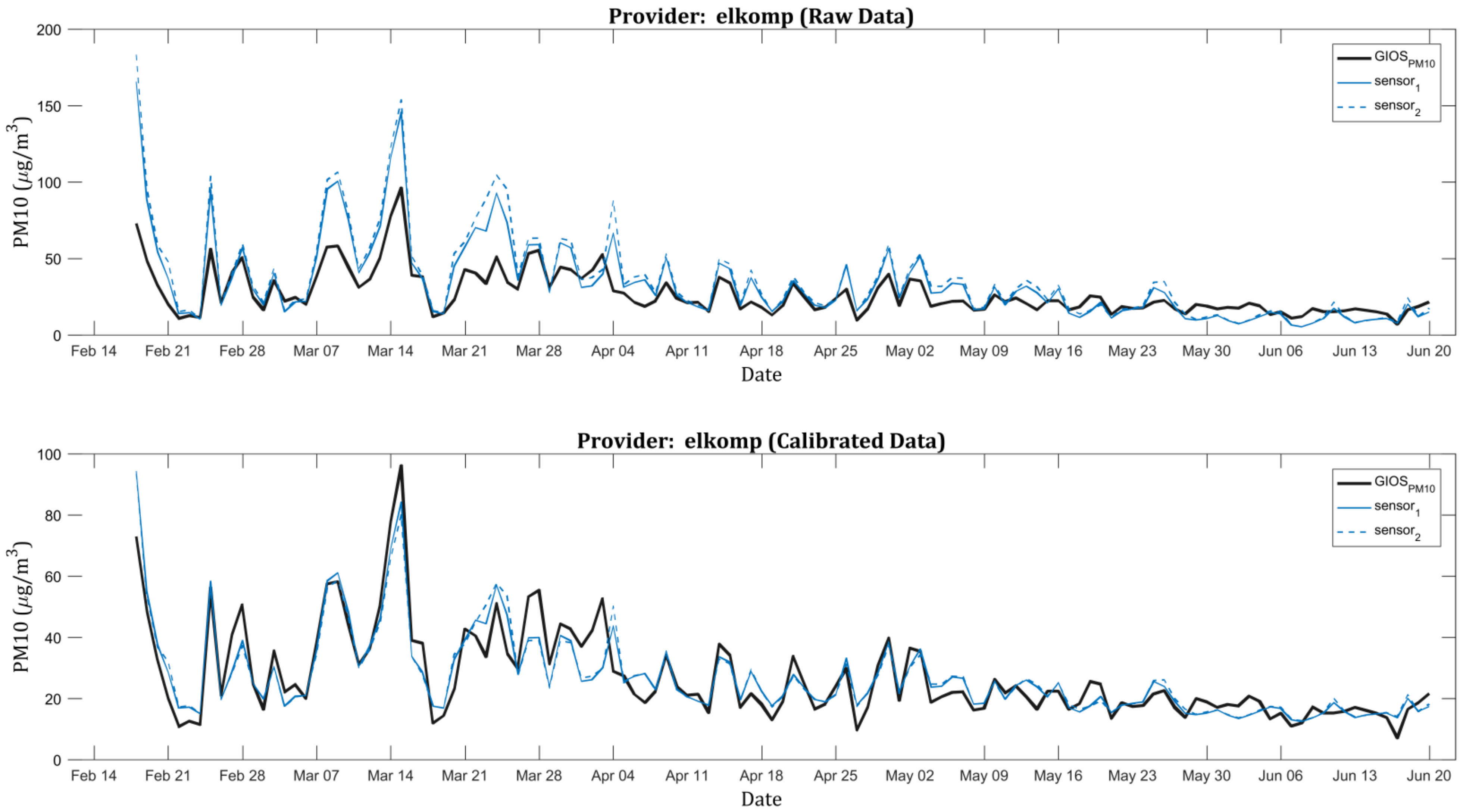


Figure B.1: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Elkomp (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [1].

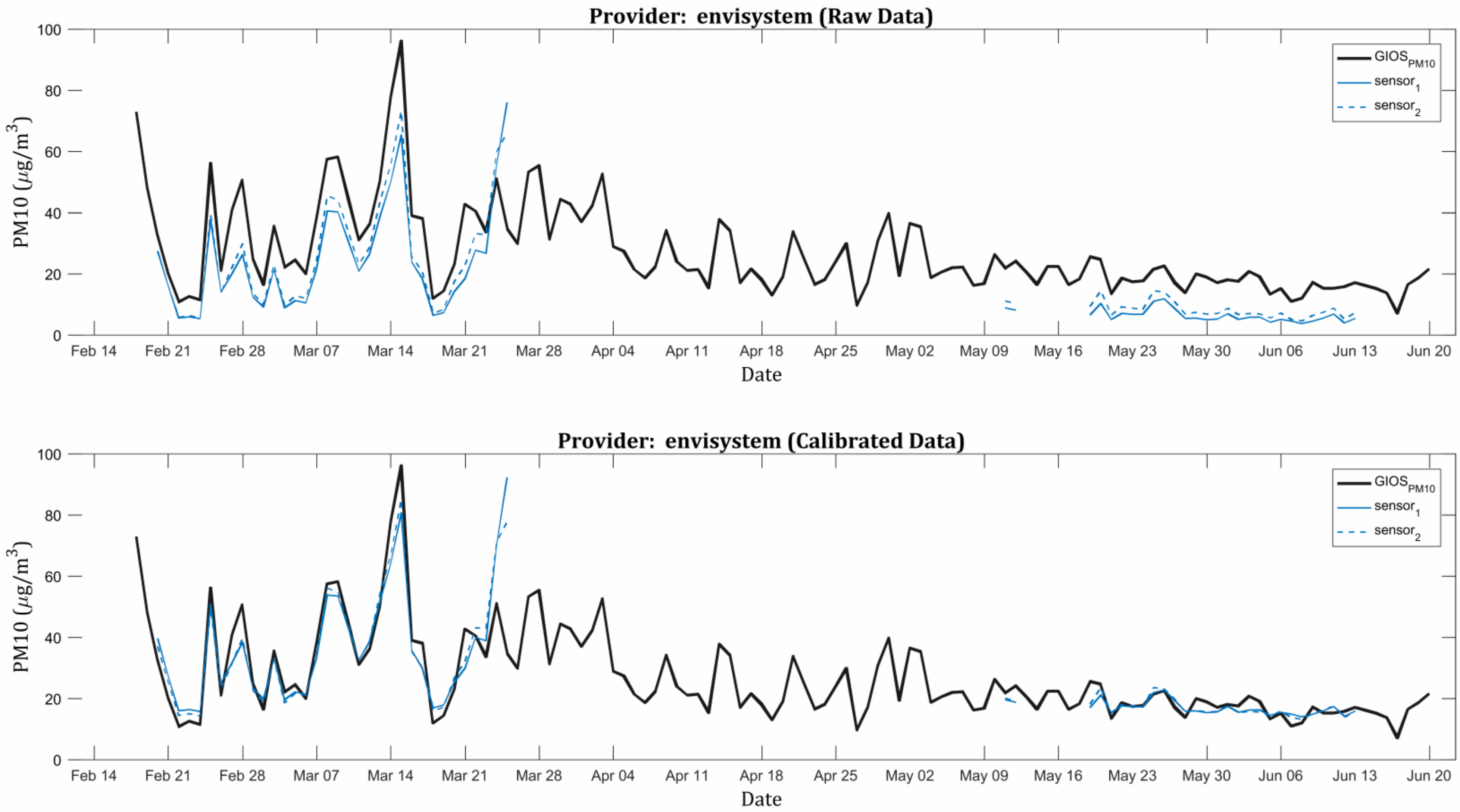
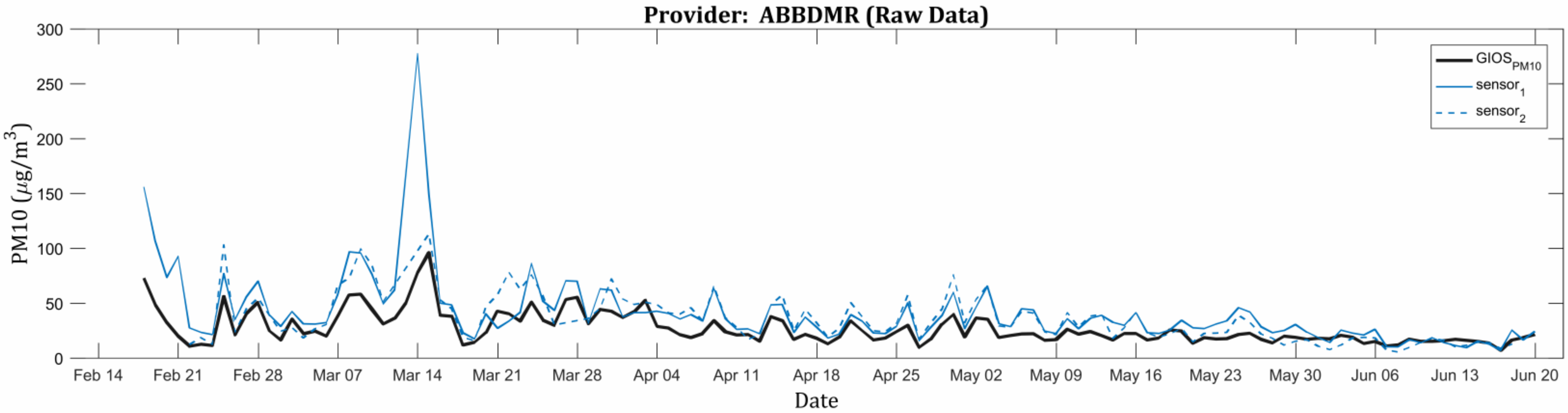


Figure B.2: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Envimet (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [1].



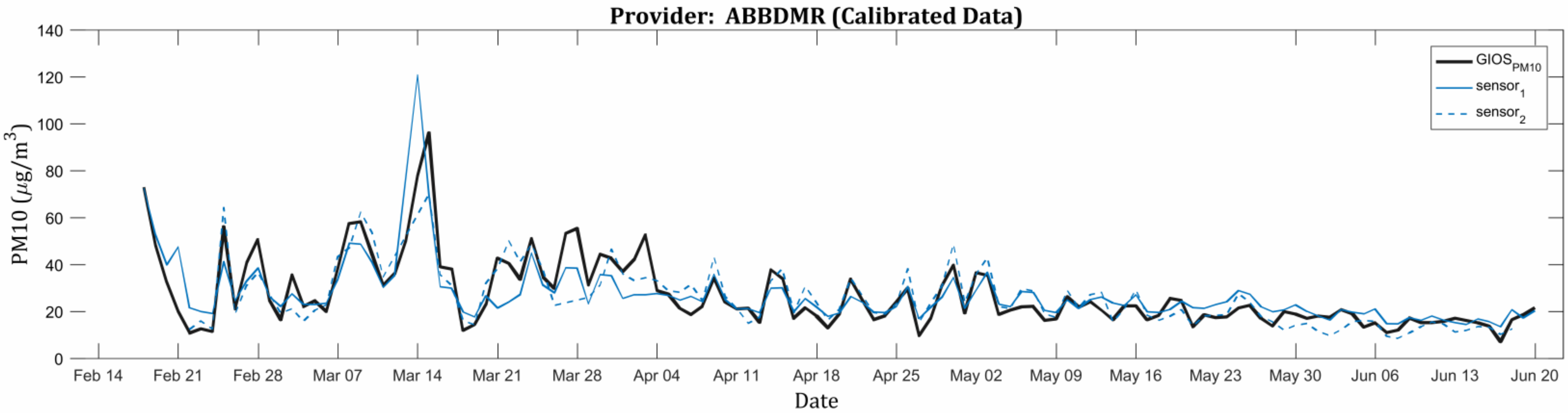


Figure B.3: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Warsaw University of Technology (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [1].

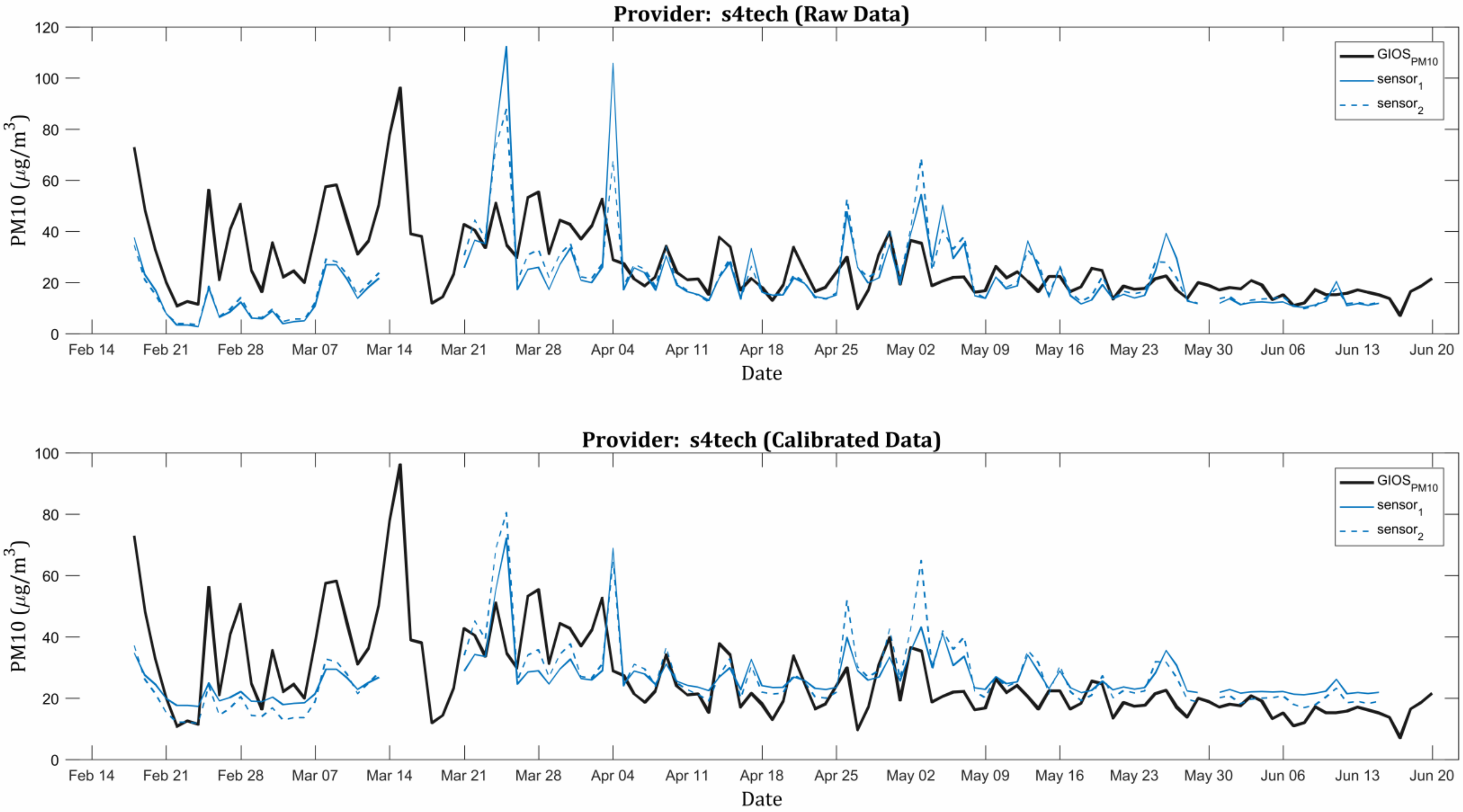


Figure B.4: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by S4Tech (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [1].

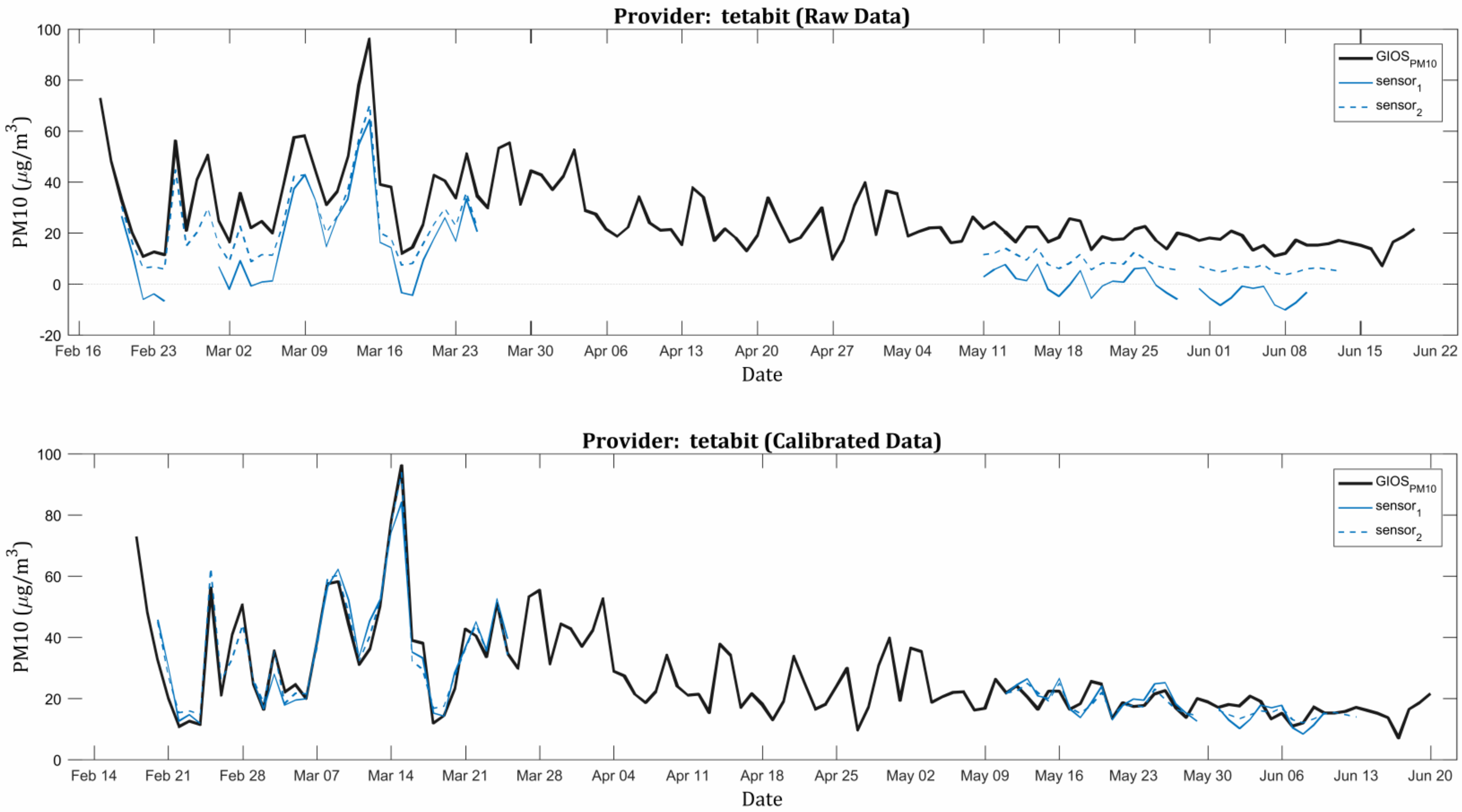


Figure B.5: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Tetabit (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [1].

Appendix C

Average daily values in relation to a reference method – II series of measurements

The appendix presents the figures that compare average daily values with the values determined by a reference method before and after a calibration has been conducted by the report authors. The figures were taken directly from the report [2]. The data presented below concerning some participants were subject to certain corrections. The corrections made were presented in subsection 2.1 of the report [2].

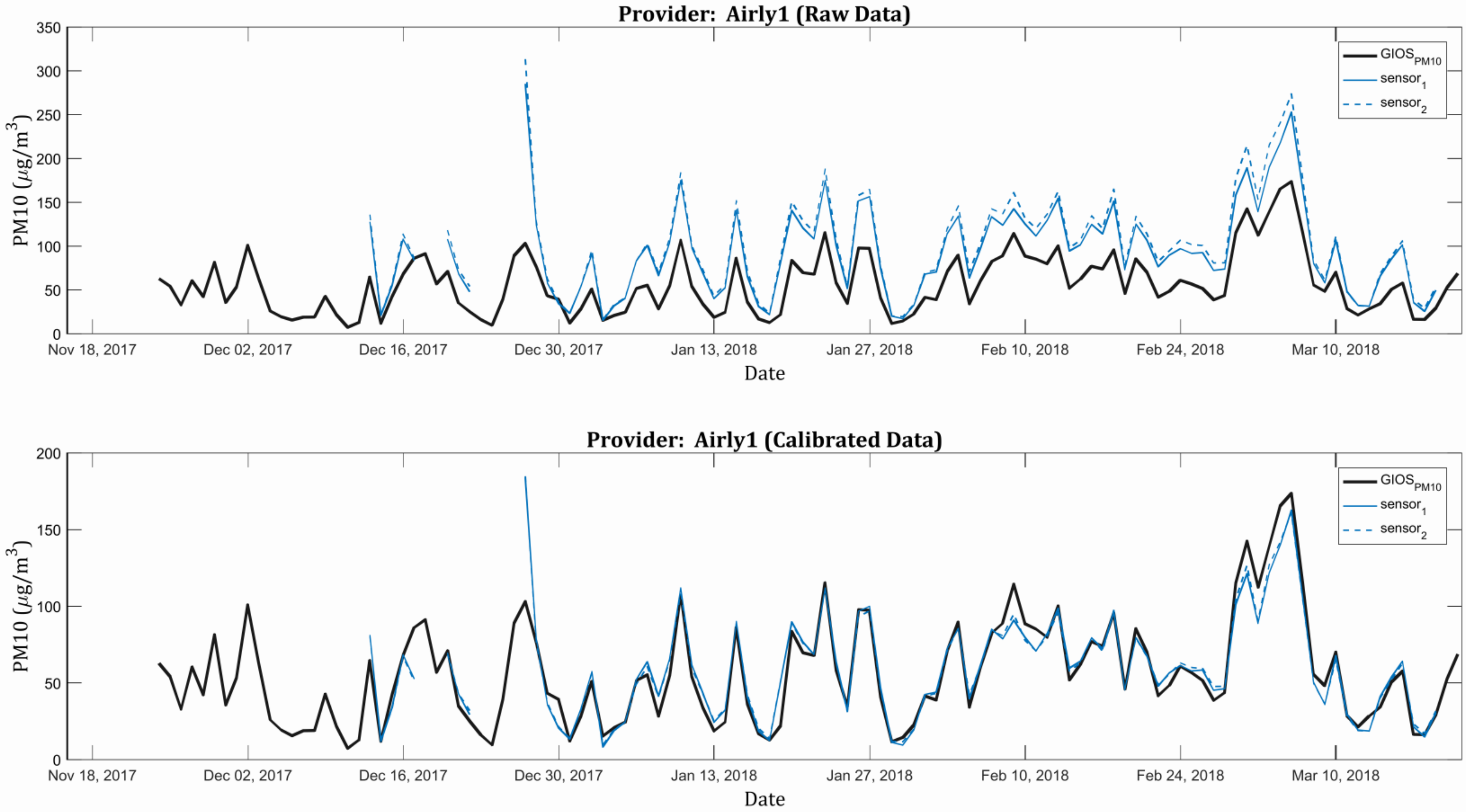


Figure C.1: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Airly set A (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

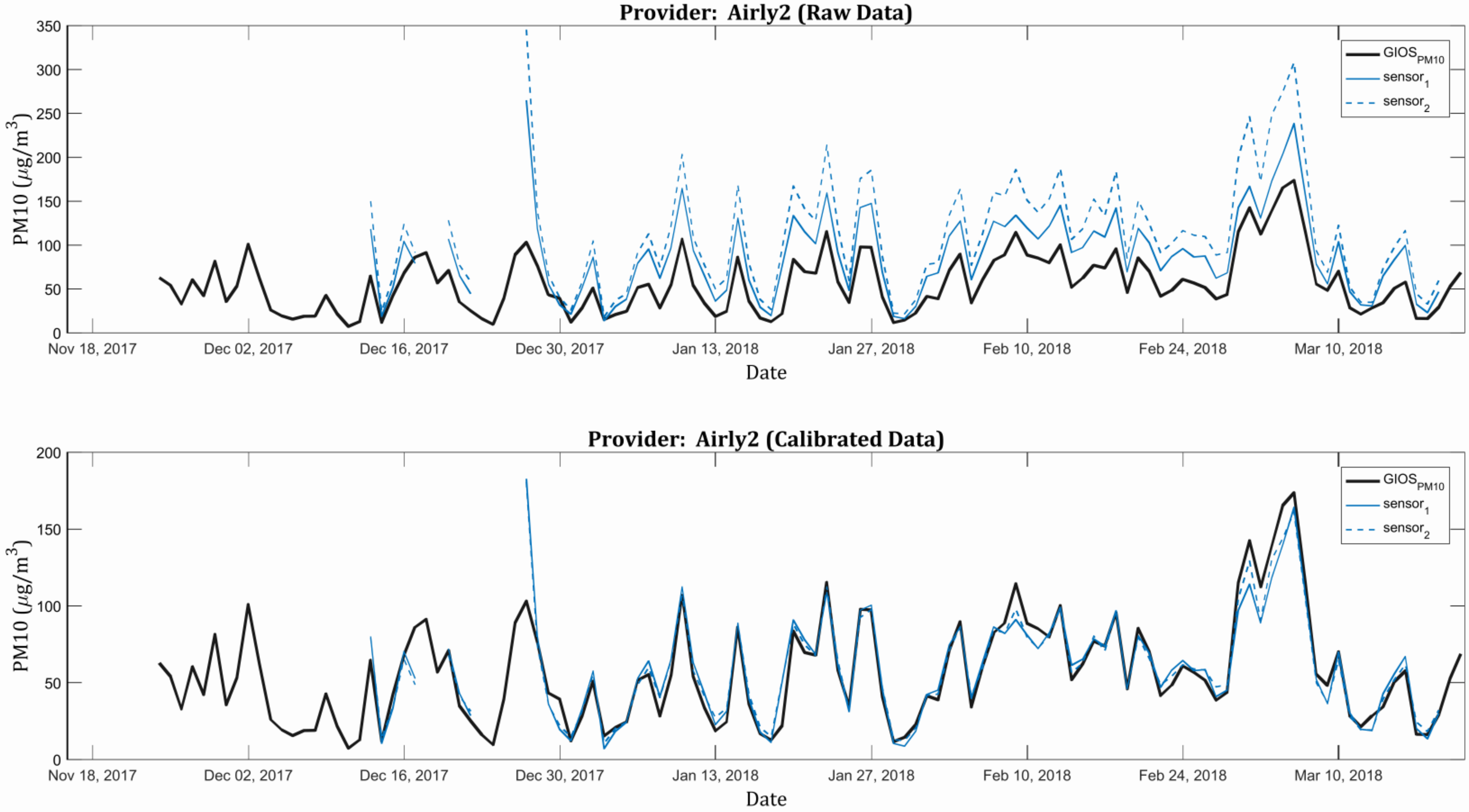


Figure C.2: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Airly set B (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

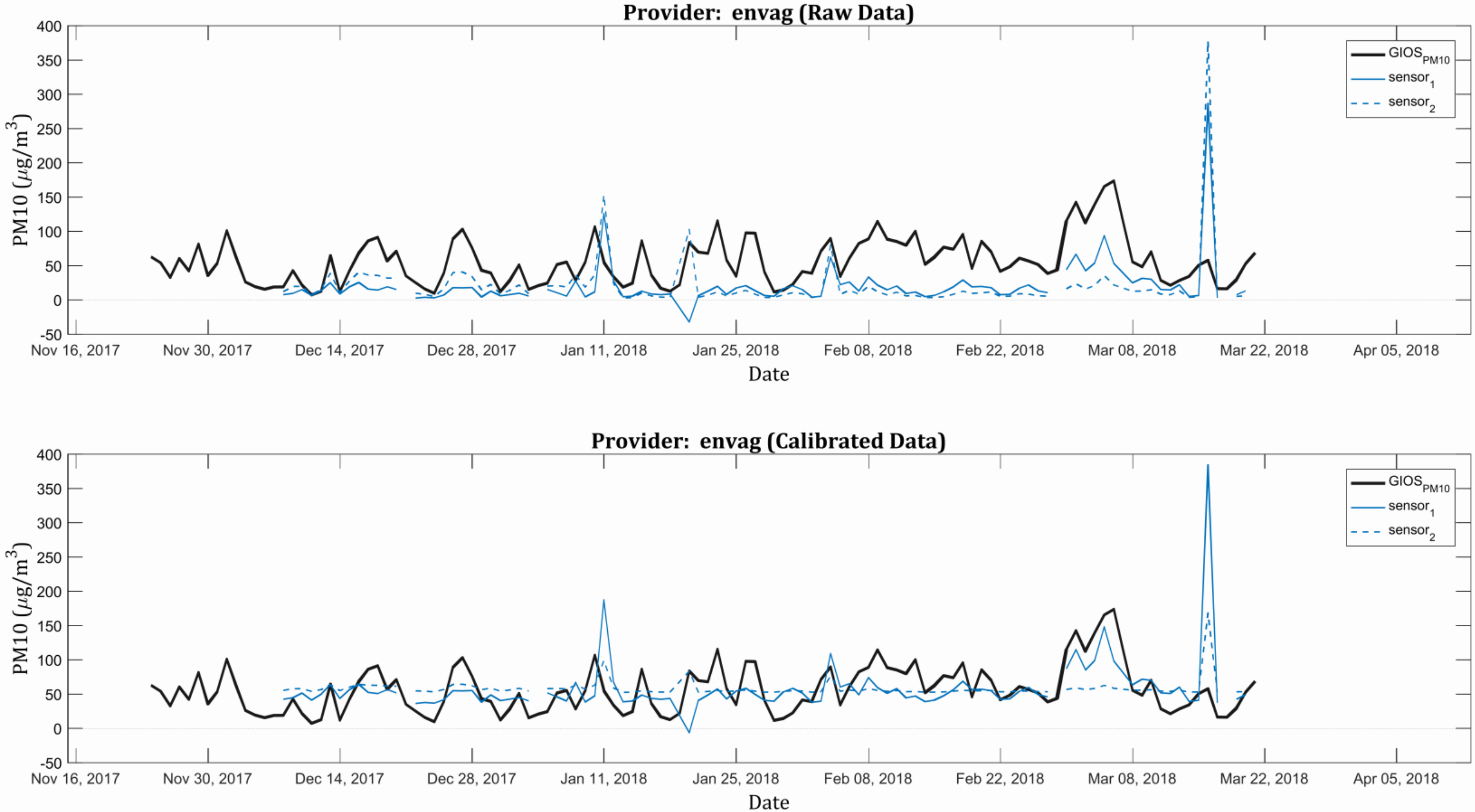
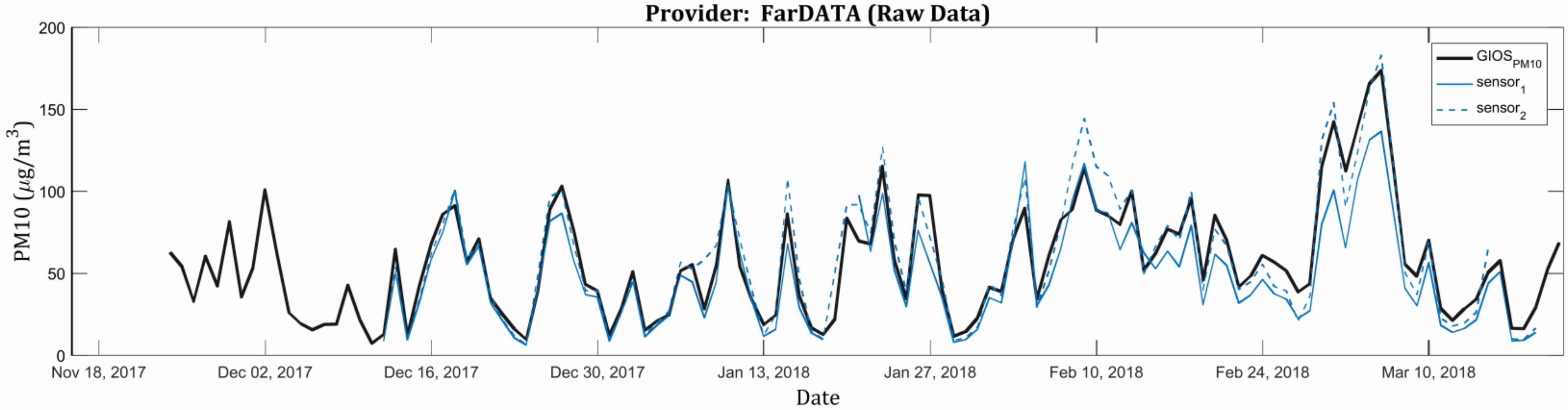


Figure C.3: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Envag (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].



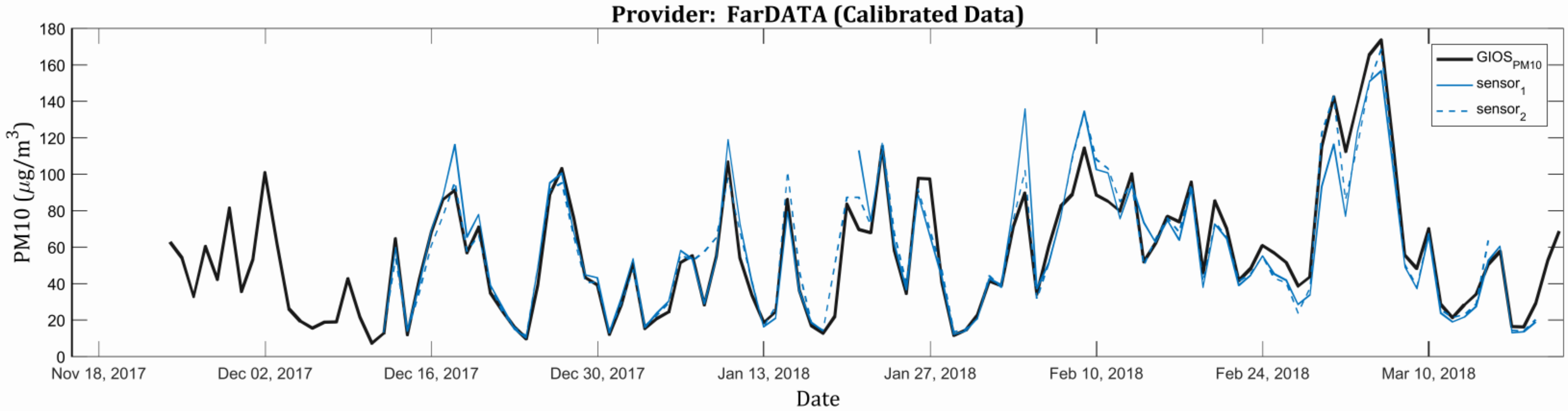


Figure C.4: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Far Data (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

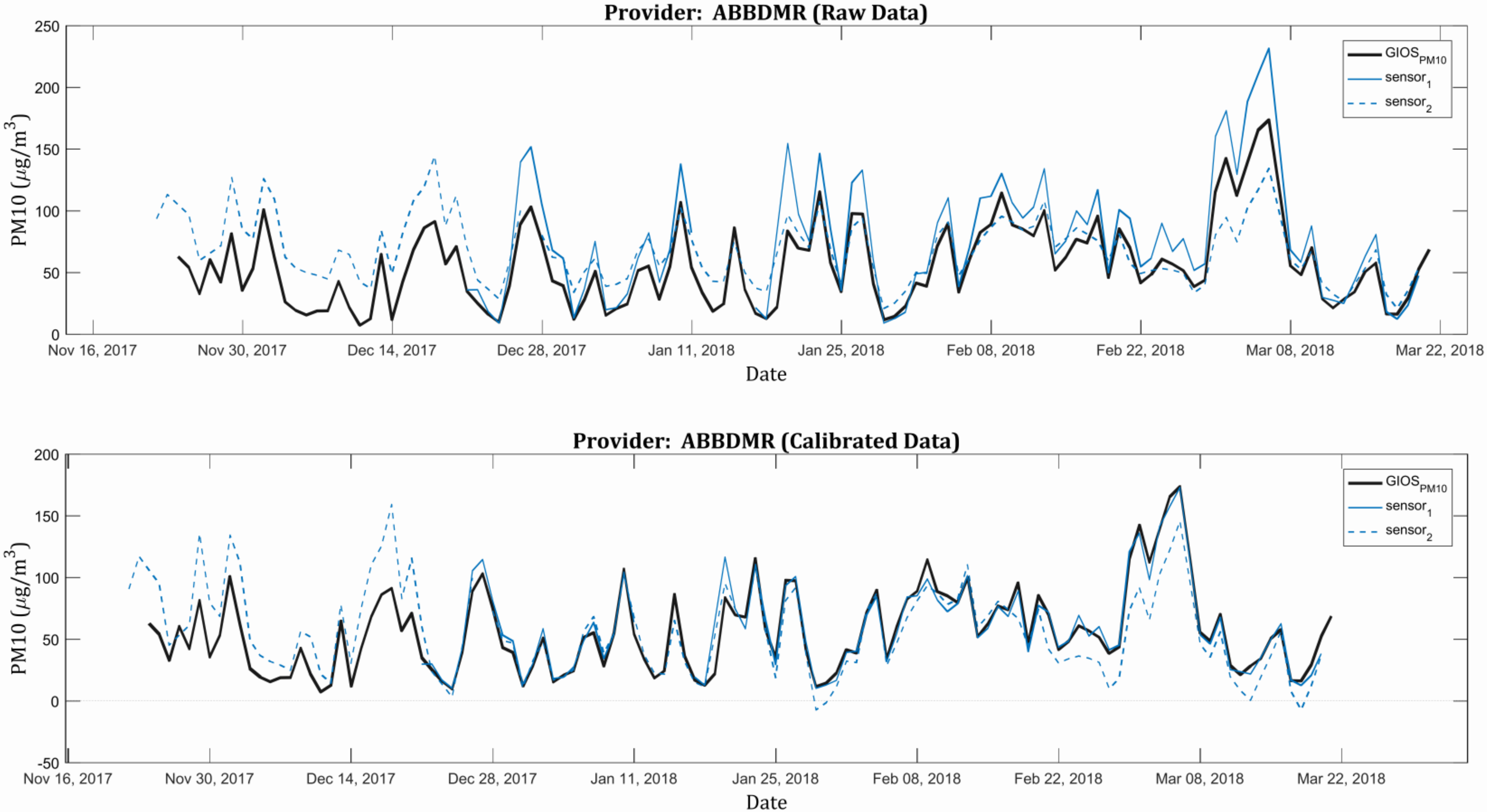


Figure C.5: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Warsaw University of Technology (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

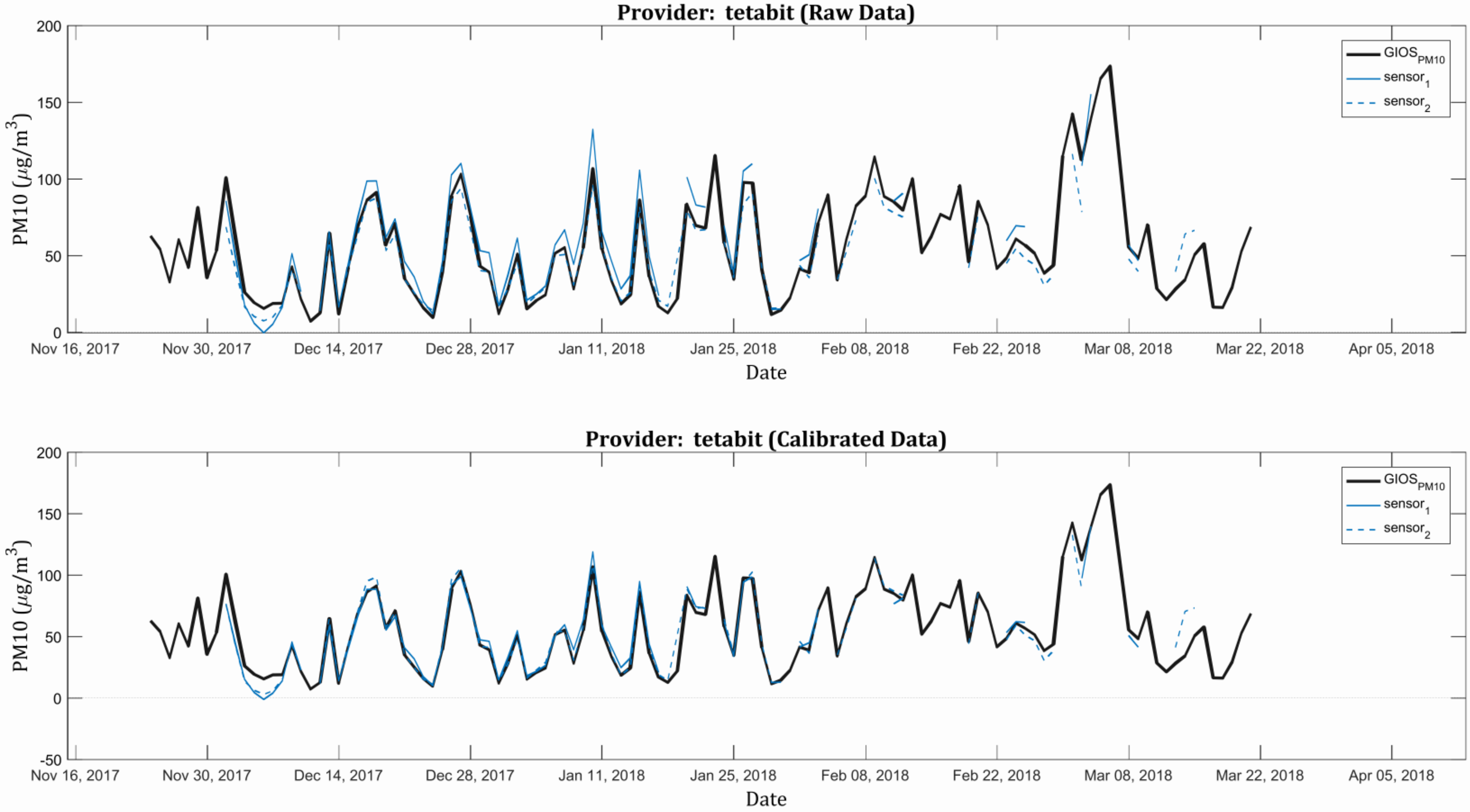
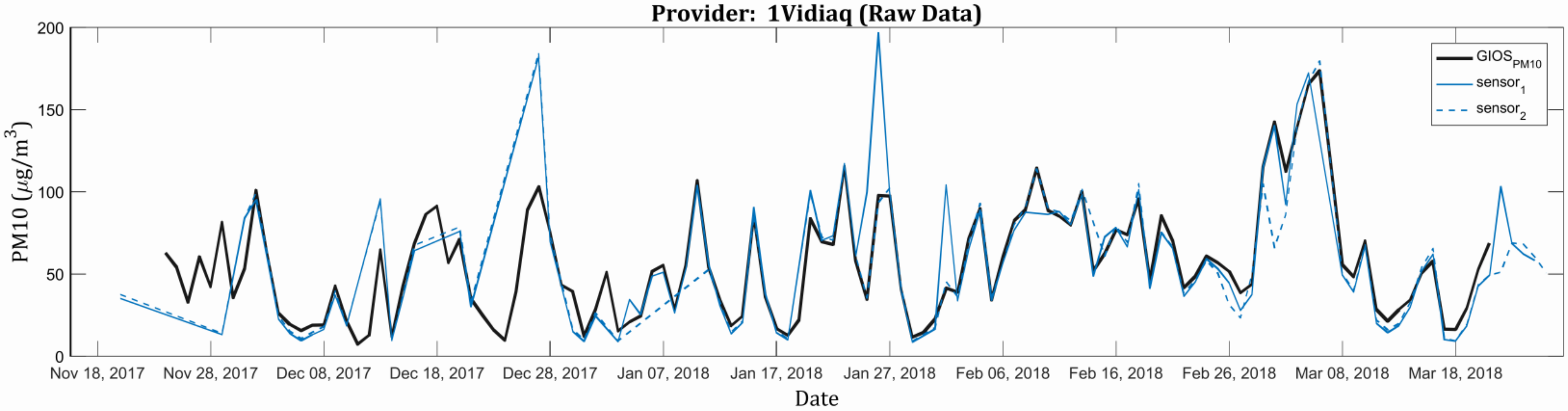


Figure C.6: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Tetabit (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].



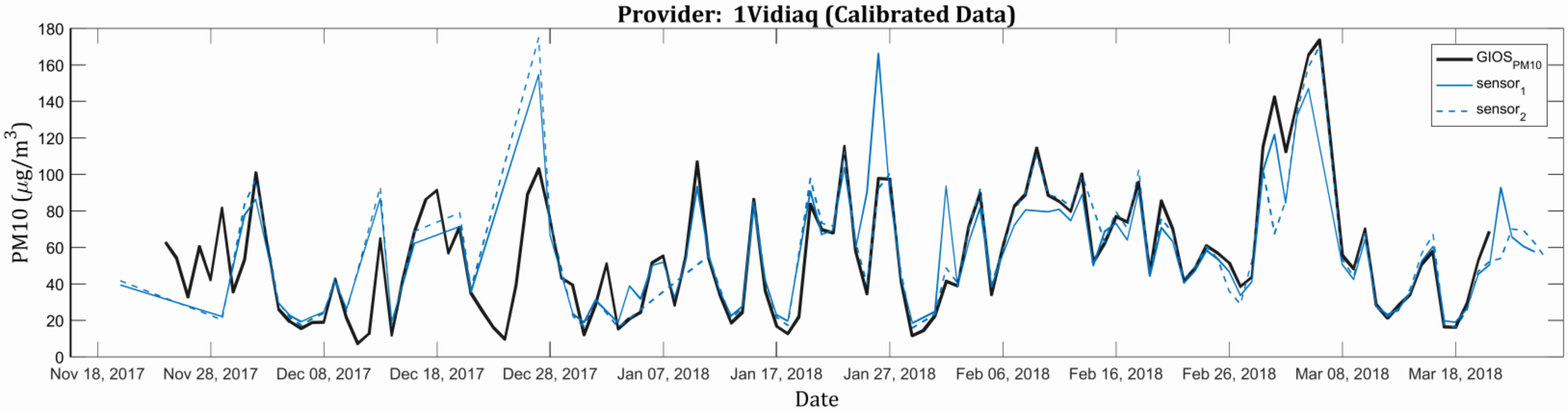


Figure C.7: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Vidiaq (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

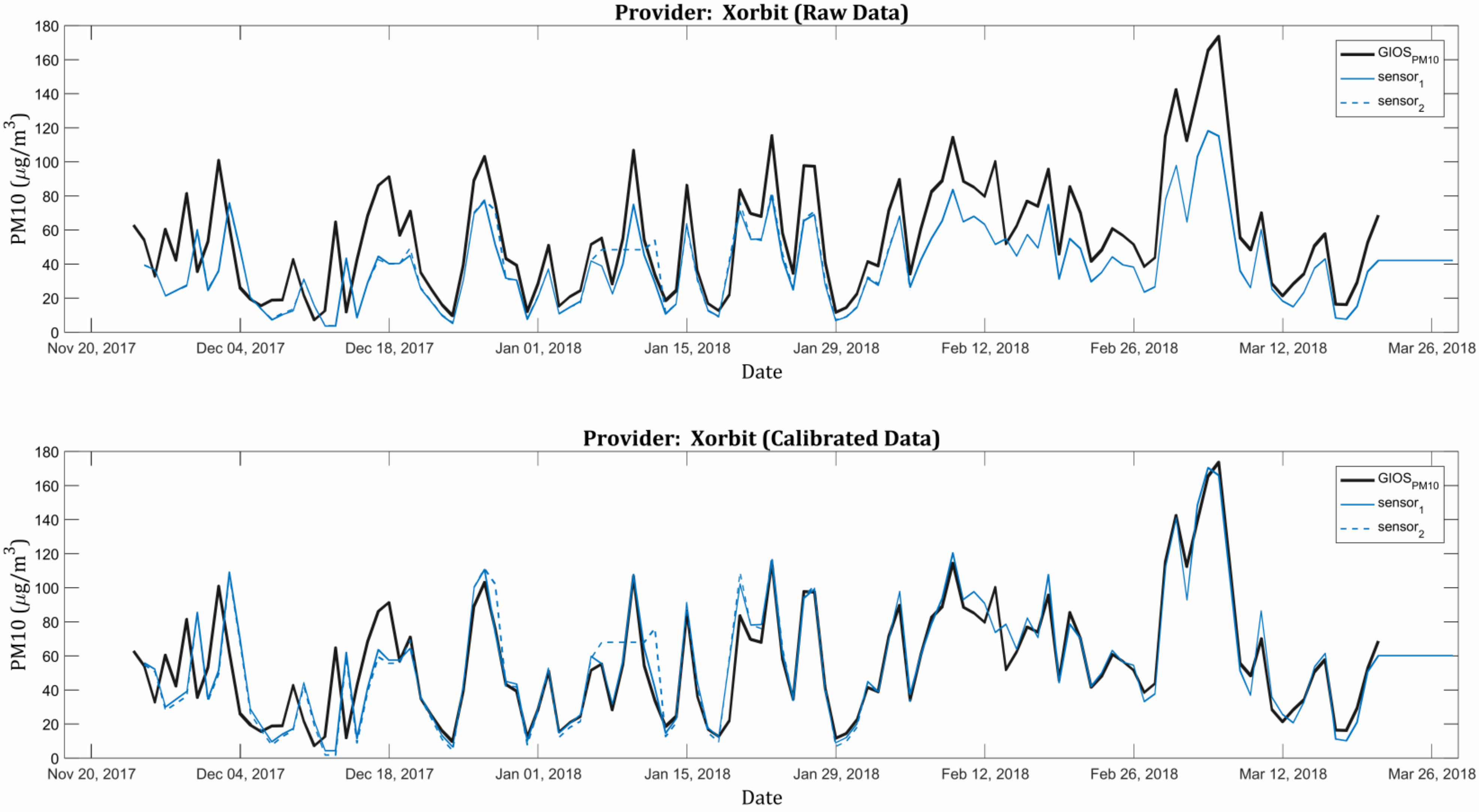


Figure C.8: Comparison of the results of the PM10 average daily concentration measurements for the sensors produced by Xorbit (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

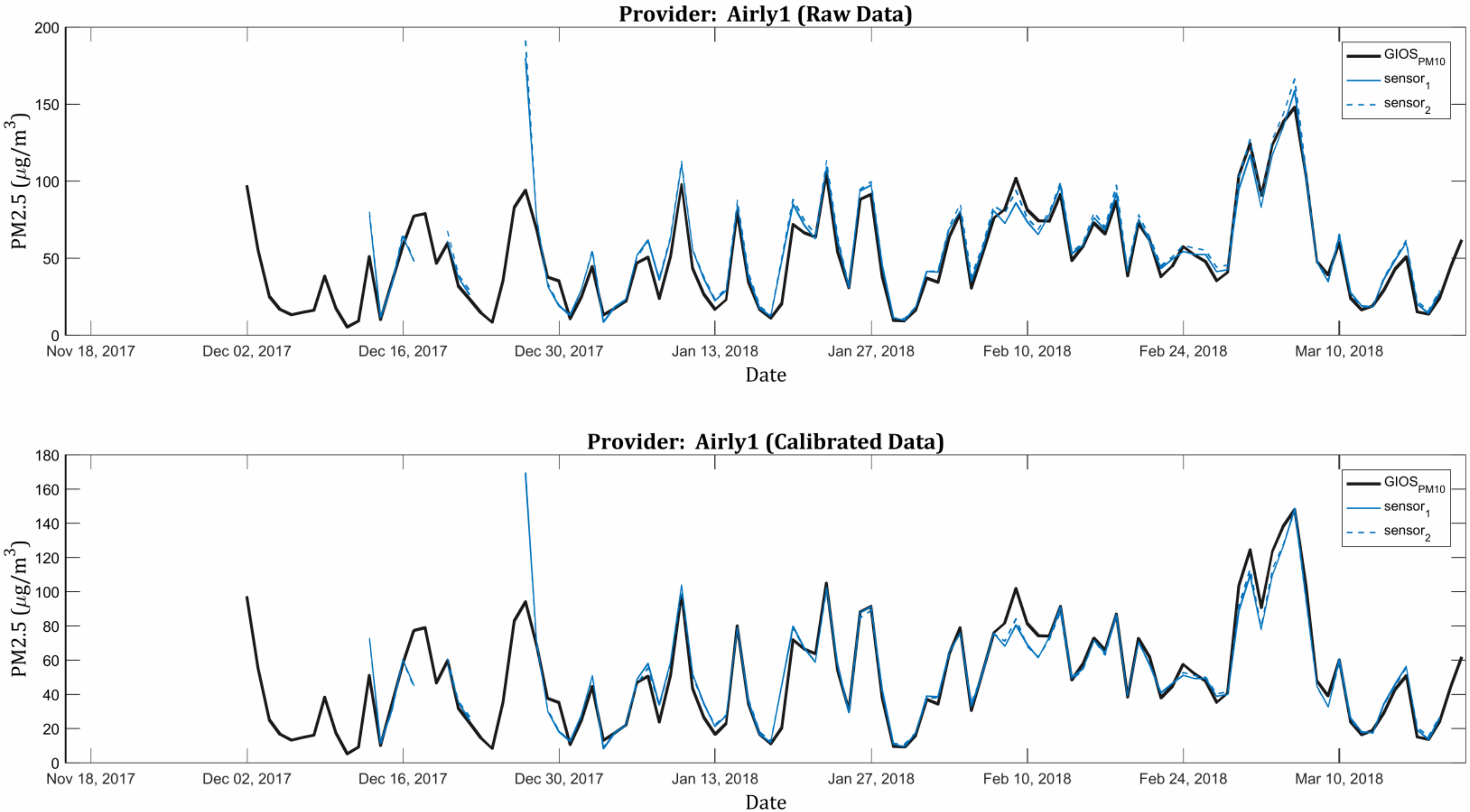


Figure C.9: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Airly set A (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

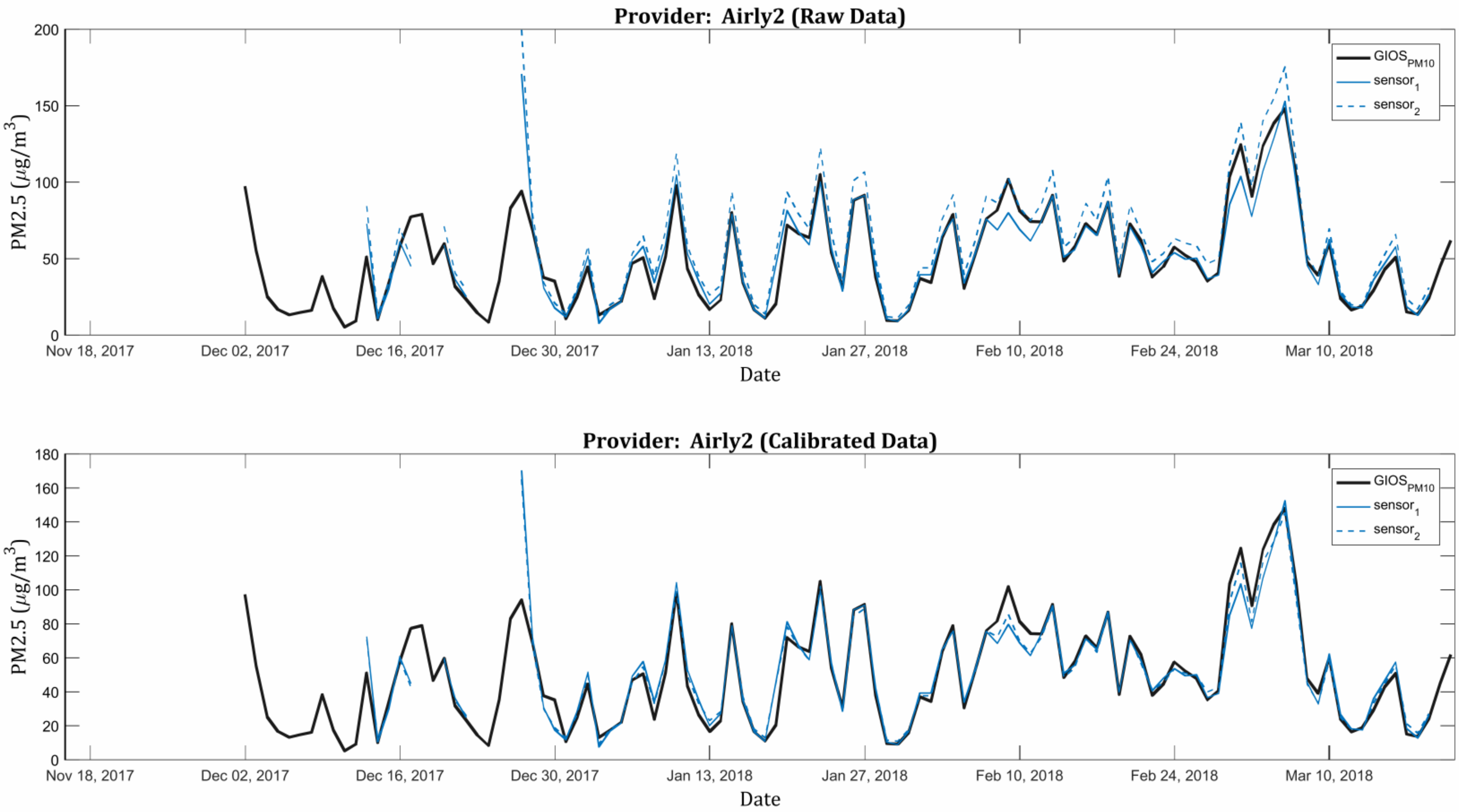


Figure C.10: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Airly set B (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

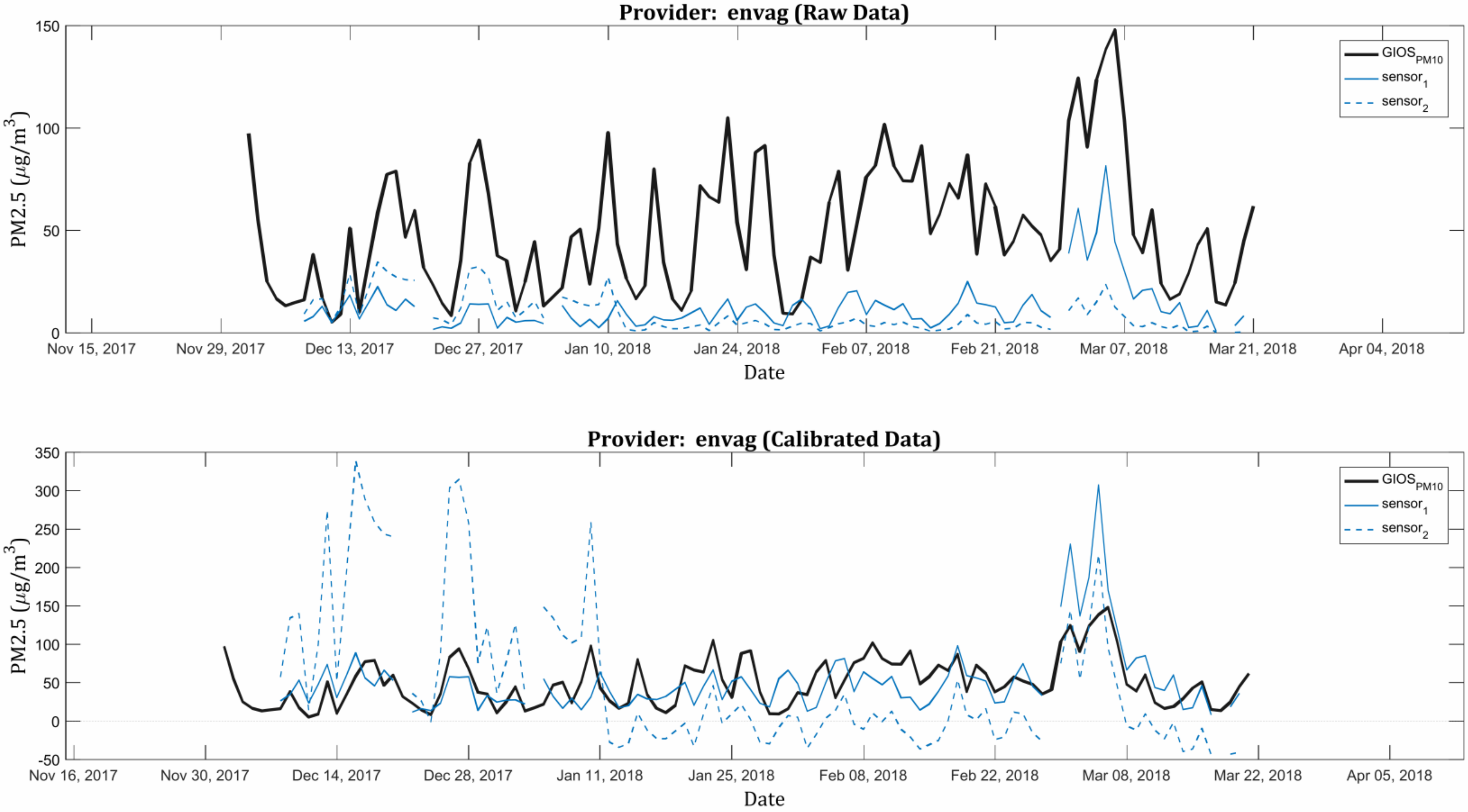


Figure C.11: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Envag (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

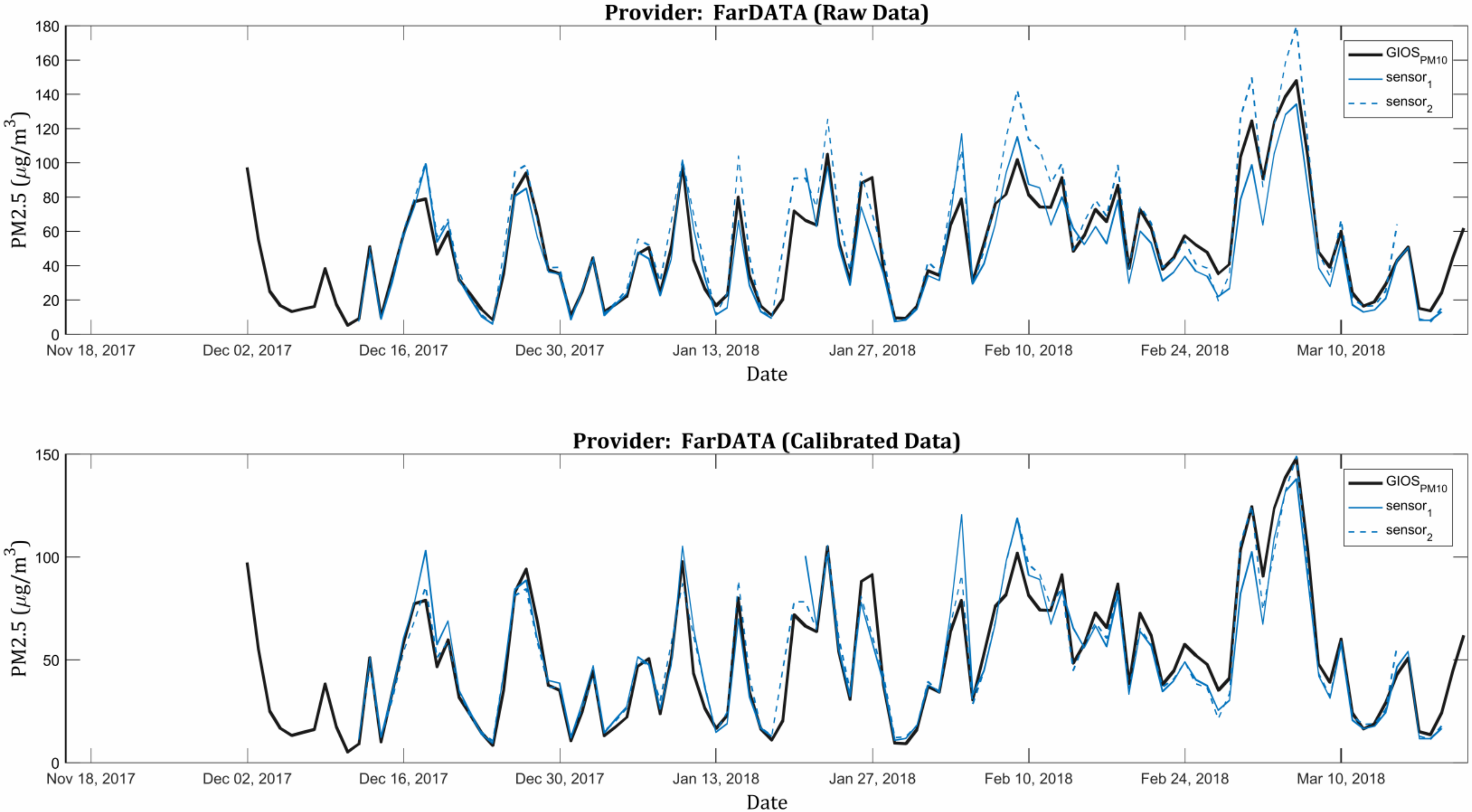


Figure C.12: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Far Data (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].

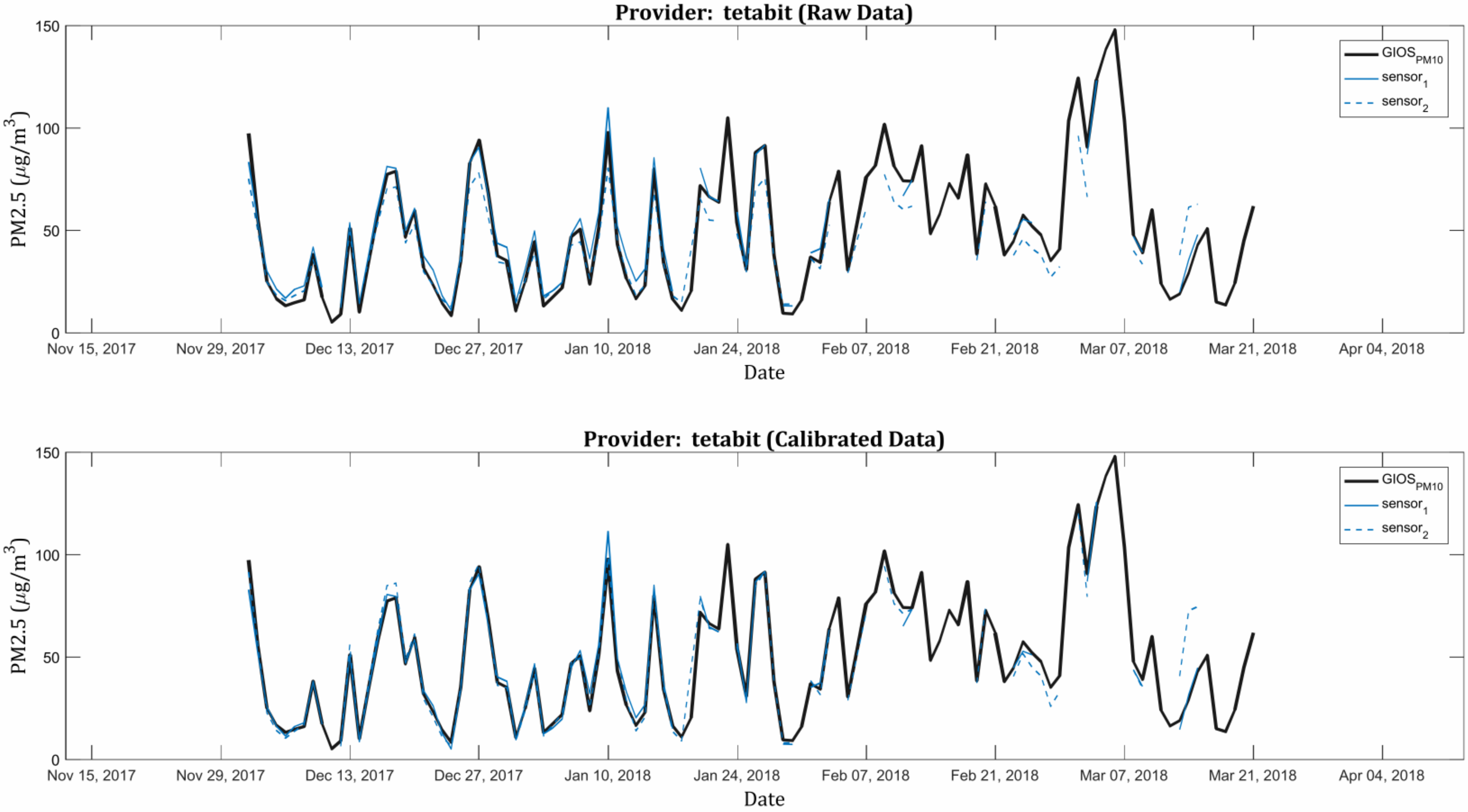
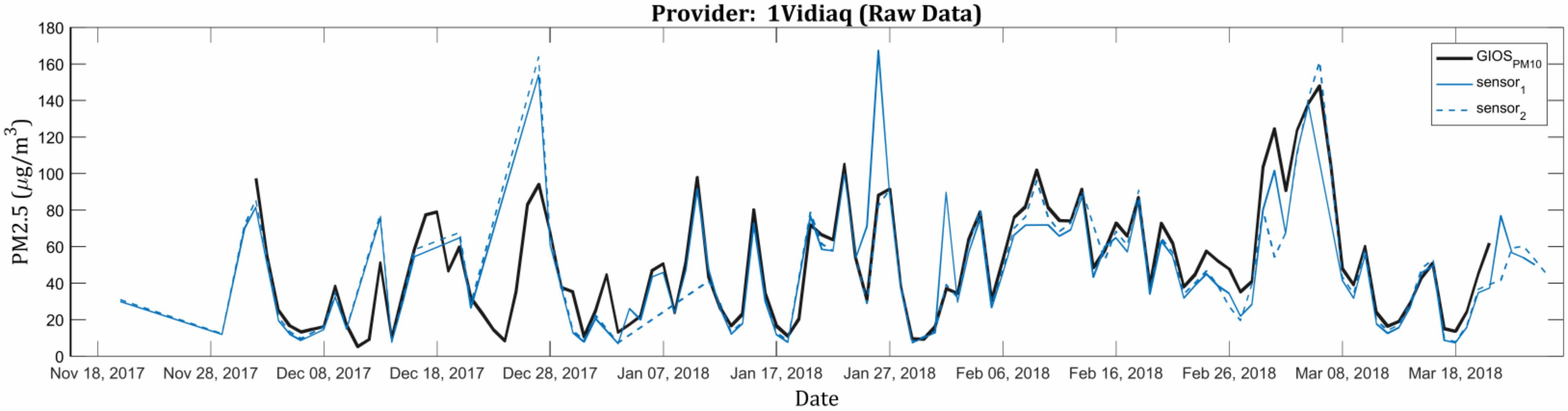


Figure C.13: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Tetabit (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].



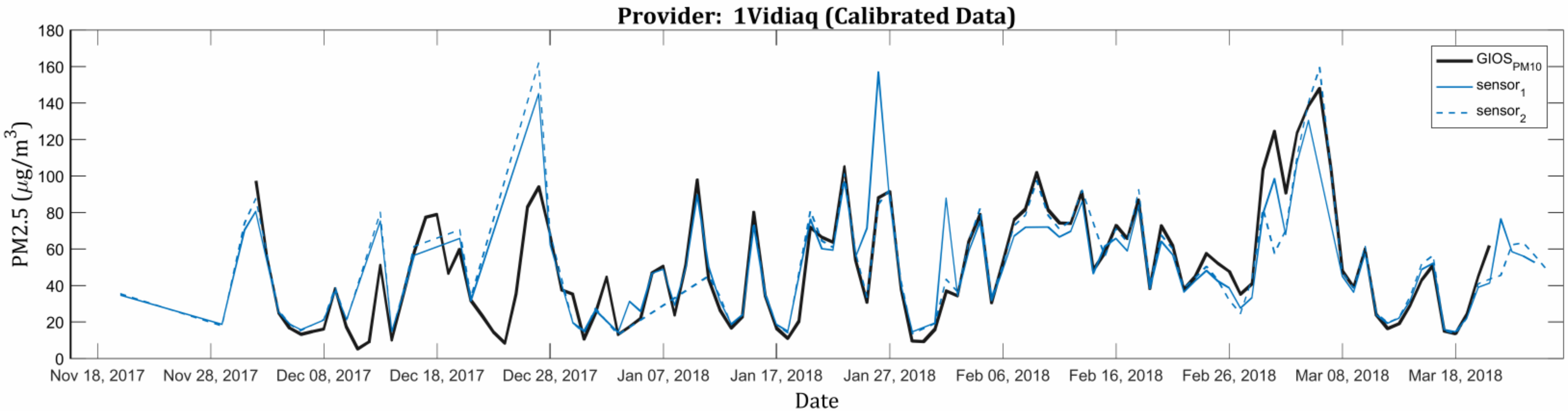
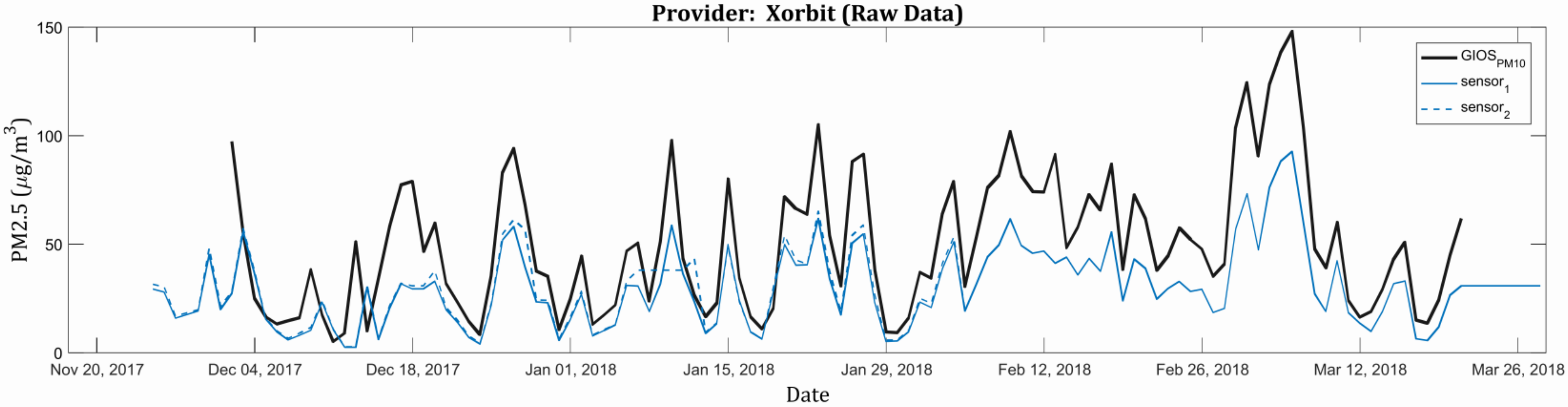


Figure C.14: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Vidiaq (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].



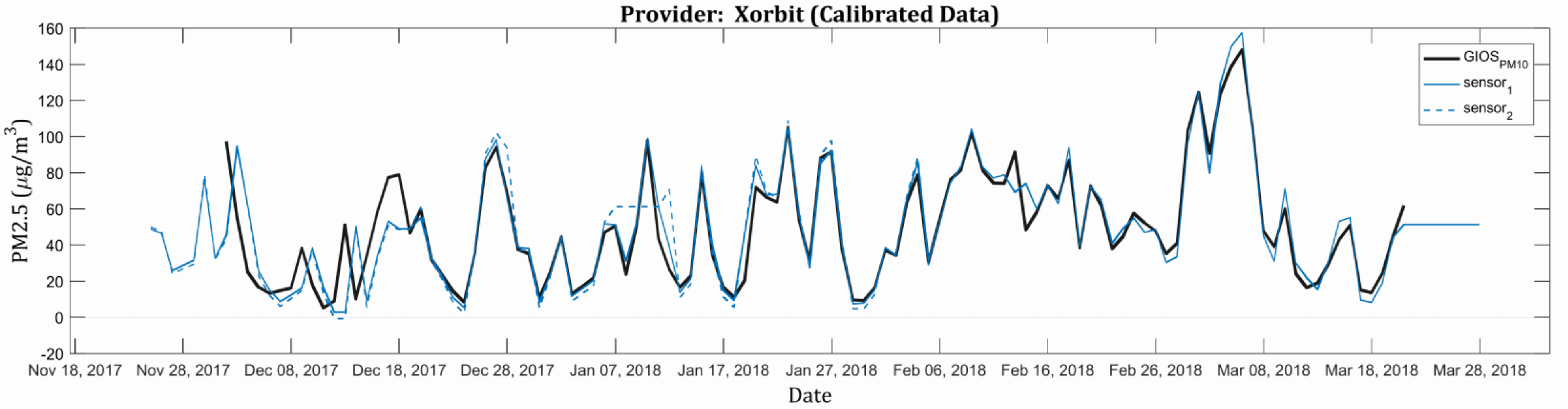


Figure C.15: Comparison of the results of the PM2.5 average daily concentration measurements for the sensors produced by Xorbit (blue lines) with the values provided by the National Reference and Calibration Laboratory of the Chief Inspectorate for Environmental Protection (black line). The first chart presents the data provided by the participants. The lower chart presents the data after a recalibration has been conducted by the report authors [2].