ACES REPORT 4

Equivalence of PM10 Instruments at a Road Traffic Site

A Study in Stockholm Spring 2012

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Foreword

This study is done by the Atmospheric Science Unit at the Department of Environmental Science, Stockholm University on behalf of the Swedish Environmental Protection Agency.

The report has been compiled by Hans Areskoug.

The companies, organisations and persons listed below contributed to the experimental part of the study and/or the review of the report and are all greatly acknowledged

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Hugo Tillquist AB, Sweden	Mikael Ramström, Peter Ramström
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Content

Summary

According to the EU-directive directive 2008/50/EC on ambient air quality and cleaner air for Europe, the assessment of the levels of PM10 in areas where PM10 is above the upper assessment level shall be made by fixed measurements with the reference method given in the directive or any method that has been shown to be equivalent with the reference method. The reference method is described in the document EN 12341.

The equivalence of a measurement method shall be tested according to procedures given in a guidance document published within EU. All decisions about equivalence of a method are made in each member state by the national competent authority. The Swedish EPA is the competent authority in Sweden and declares equivalence based on recommendations from the National Air Quality Reference Laboratory (NAQRL).

All declarations of equivalence of instruments for measuring PM10 in Sweden have been based on studies made in other European counties, mainly in Central Europe. The declarations can be regarded as provisional as they not are based on tests at the specific conditions that can occur in Sweden. Thus all declarations need to be supplemented by further testing in Sweden.

NAQRL judged that the results from the Central European tests in the urban background and at rural sites is representative also for Swedish conditions. However, most exceedances of the PM10 EU daily limit values in Sweden occur at busy roads during spring, when the PM10-fraction is dominated by coarse particles originating from abrasion of roads by studded tyres. These conditions are specific for Sweden (and other Nordic countries) and are not included in the Central European tests. Thus a supplementary equivalence study was performed at a busy street in Stockholm during spring 2012. The result from this equivalence study was combined with the results from the previous European tests to assess the equivalence of a measurement method.

Almost all instruments used for PM10-mesurements are equipped with an inlet that selectively samples PM10. Measurements to assess the PM10 air quality in Sweden according to the EU-directive are using two different types of PM10-inlet; either the one described in the standard of the European reference method or the standard inlet used in USA. Some studies have shown that the two types of inlets do not have the same properties; the US inlets giving higher concentrations in environments with a large fraction of PM10 dominated by coarse particles, i.e. the same environments where most exceedances occur in Sweden. In order to examine the difference of the two inlet types, one of the three participating EU reference samplers was modified and equipped with an US PM10 inlet. This made it possible to

1. Compare the two types of inlets
2. Evaluate the equivalence between a non-reference instrument and the reference instrument both using the same type of inlet. If the same type of inlet not had been used, any difference between the results obtained with the two instruments could have been due to inlets and not the instruments as such.

The following instruments preliminary declared as equivalent participated in the study: Opsis SM200, Thermo Scientific Sharp 5030, FAI SWAM 5A, Grimm EDM #180. A number of other instruments yet to be declared as equivalent, but which have been used frequently in Sweden also participated:

Thermo Scientific TEOM 1400AB, Thermo Scientific TEOM –FDMS, IVL PModel S10 without dynamic flow regulation and IVL PModel S10 with flow regulation based on the ambient temperature.

The result of the study of the two types of inlets, the EU type and the US type, showed that during days when the PM10 fraction is dominated by coarse particles, the US type gives higher results than the EU type of inlet.

The result of the equivalence study for the participating instrument is given in the table below.

Instrument/inlet	**Comment**
Thermo TEOM 1400AB US-EPA inlet	If the results from the instrument are corrected by the results from a regional instrument that measures the loss of volatile substances on the particles the instrument is equivalent to the reference sampler with the US-EPA inlet without any further correction.
IVL PModel S10 - old version[1]. Inlet with the same properties as the US-EPA inlet.	Equivalent to the reference sampler with the US-EPA inlet without any correction function at this site. However, results from accredited tests in other types of environments are needed to assess if the instrument is equivalent
IVL PModel S10 - new version[2]. Inlet with the same properties as the US-EPA inlet.	Equivalent to the reference sampler with the US-EPA inlet with a correction function at this site. Calibration function: x = 0.968y However, results from accredited tests in other types of environments are needed to assess if the instrument is equivalent
Thermo 1405 F. US-EPA inlet	Equivalent to the reference sampler with the US-EPA inlet without any correction function
Thermo FDMS. US-EPA inlet	Equivalent to the reference sampler with the US-EPA inlet without any correction function
Grimm EDM 180. TSP-inlet. PM10-fraction calculated by applying a theoretical cut-off curve similar to the properties of the EU inlet	Equivalent to the reference sampler with the EU-inlet without any correction function in this study. However, in the Central European studies the Swedish preliminary approval is based on, correction functions were needed. The fact that the correction function for the EDM 180 might vary in different environments, makes it important to assure the specific calibration function for the sampling site where the EDM 180 is to be used.
Thermo Sharp 5030. US-EPA inlet	Equivalent with the reference sampler with the US-EPA inlet without any correction function.
Opsis SM200. EU inlet	Equivalent to the reference sampler with the EU-inlet without any correction function
FAI Swam 5A. EU inlet	Equivalent to the reference sampler with the EU-inlet without any correction function
1. Flow corrected to seasonal average ambient temperature. Flow corrected to ambient pressure at time for flow calibration 2. Flow corrected to ambient temperature. Flow corrected to ambient pressure at time for flow calibration.	

Background

In the directive 2008/50/EC on ambient air quality and cleaner air for Europe of the European Parliament and of the Council of 21 May 2008[1], (AQD 2008), it is stated that assessment of the ambient air quality in all zones and agglomerations where the level of the regulated pollutants are above the upper assessment threshold shall be made by fixed measurements.

In order to do measurement data comparable within EU the reference measurement methods listed in the AQD 2008 shall be used. However, other methods can be used if it is shown that they are equivalent to the reference methods.

To harmonize the process of demonstrating the equivalency of a measurement method with the reference method, an EC working group has prepared a guide, "Guidance for the Demonstration of Equivalence of Ambient Air Monitoring Methods"[2], (GDE). The latest version of the GDE was published in January 2010.

In GDE equivalence of a measurement method is defined as

> *'An equivalent method to the reference method for the measurement of a specified air pollutant, is a method meeting the data quality objectives for fixed measurements specified in the relevant air quality directive'*

In AQD 2008, there are data quality objectives with minimum requirements on the time coverage, data capture and measurement uncertainty.

The evaluation of a method's equivalence thus starts with an assessment if the method is likely to fulfil the requirements on time coverage and data capture. If the method is deemed not to fulfil these data quality objectives, the assessment of the measurement uncertainty will not be done.

In the GDE procedures to test the equivalence for four different groups of methods are given:

- Manual methods for gases
- Automated measurement systems for gases
- Methods for particulate matter (PM10 and PM2.5)
- Speciated particulate matter

For many pollutants, equivalence of a measurement method that has been proven using the approach described in GDE can be assumed to be valid anywhere else in the EU member states as the test programmes described generally attempt to demonstrate equivalence for as wide a range of conditions as possible, including practical 'extremes'.

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:en:NOT
[2] http://ec.europa.eu/environment/air/quality/legislation/pdf/equivalence.pdf

However, this generalization may not hold for all pollutants. This is particularly the case for particulate matter (PM). The reason is that particles are not a uniform concept; the chemical composition and the relationship between the proportion of large and small particles can vary significantly between locations. Moreover, the semi-volatile fraction, which depends on location and ambient conditions, is not retained in the sample to the same extent by different measuring methods. In addition, current PM levels being close to the limit values, many Member States are required to perform PM measurements throughout their entire territory or in large parts of it, and thus a variety of types of conditions are usually involved.

Consequently, it may be that equivalence for PM measurements that is established under the conditions described in GDE is not valid for all sites in a Member State.

The Swedish Environmental Protection Agency, (SweEPA), is designated the task to approve a method as equivalent. Before any approval, the National Air Quality Reference Laboratory (NAQRL), at the Atmospheric Science Unit at the Department of Applied Environmental Science of Stockholm University, is consulted.

A number of measurement methods for PM (PM10 and PM2.5) have been approved as equivalent by SweEPA. However, these approvals are all based on tests performed outside Sweden and the conditions during these tests does not necessarily apply to Swedish conditions. The Swedish approvals therefore require validation that the results obtained at the equivalence test that the acceptance is based on, is also applicable at the site where the instrument will be used.

The instruments approved in Sweden have been tested in Central Europe in different environments (traffic, urban background, rural and in a gravel pit) to cover different situations. Some tests have also been made in Finland in urban background.

The results from urban background and rural areas are judged to be applicable in Sweden. The results from the traffic environments can be applied in Sweden for much of the year but not necessarily during the period in spring when the largest number of exceedances of the PM10 limit value occurs. The high concentrations during spring are due to the abrasion particles studded tires produce. On these occasions, the proportion of coarse particles greater than 2.5 µm are high. The equivalence tests in Central Europe are typically not performed in such environments.

Thus, the tests conducted in Central Europe supplemented by additional tests during spring at streets with high levels caused by wear particles from studded tires were made to assure the equivalence approvals.

The assessment of air quality in Sweden is performed by local networks, very often with only a few measurement sites. Due to the high cost to perform equivalence test, it is considered unreasonable to request each local network throughout Sweden to conduct additional equivalence tests. Therefore, NRL-M in collaboration with the local authorities in the three major cities in Sweden, Stockholm, Gothenburg and Malmö, performed a two-month equivalence study at a busy street in the Stockholm region during spring 2012. The results of this study are judged to be representative for similar conditions in Sweden.

All instruments approved in Sweden participated in the test, but also a number of instruments of older type that have yet to receive any approval. These instruments have been used for a long time,

more than 10 years, at many places in Sweden, including the networks in Stockholm, Gothenburg and Malmö.

According to AQD 2008 only approved instruments shall be used for measurements of regulated pollutants from June 2013. However, the Swedish local networks may have trouble in fulfilling that requirement in all cases due to economic constraints. The older instruments are thus likely to remain in use a number of years in the future. The aim of the study is therefore to check if these instruments meet the EU DQO, i.e. is equivalent to the reference method, in the "worst" environment in terms of PM10 exceedances in Sweden. The results of this study can also be used to evaluate the results obtained by the older type instruments during previous years. If the old instruments are found to be equivalent in the study environment, the values on exceedances of the PM10 daily limit value reported previously can be considered to be of acceptable quality, as almost all exceedances in Sweden occur in conditions similar to the ones that are likely to prevail during this study.

The claim of equivalence of an instrument for PM measurements is based on a comparison of the results of the instrument with the results from the reference method described in the European standard[3]. Among other things, the standard gives a detailed description of the inlet. A number of studies in Europe (e.g. Panteladis[4], Febo et al.[5]) have shown that this inlet (the EU-inlet) does not have the same separation properties as the PM10 inlet used in USA (US-inlet). The studies have shown that the US-inlet gives higher results than the EU-inlet in environments where the concentration of coarse particles is high compared to concentration of fine particles. Where this not is the case, the two inlet types give comparable results.

In most of the studies that the Swedish approvals are based on, the instruments manufactured in USA have used the US-inlet. As the studies mostly have been conducted at sites where PM10 mainly consist of fine particles, the use of the different inlets by the instruments that was tested and the reference has not affected the outcome.

However earlier measurements in Sweden in the same type of environments as in this study have shown that coarse particles dominates PM10. Therefore, the use of different inlets by the instruments manufactured in USA and the European reference instrument can give un-equal results that are not due to the instruments performance. In order to better be able to judge the equivalence of these instruments as such, one European reference instrument was equipped with an US-inlet during the study.

[3] EN 1234:1998. “Air quality – Determination of the PM10 fraction of suspended particulate matter – Reference method and field test procedure to demonstrate reference equivalence of measurement methods”

[4] Pavlos Panteliadis, Department of Air Quality, Municipal Health Service Amsterdam, The Netherlands, personal communication. (2012)

[5] A. Febo, P. Bruno, M. Giusto, I. Allegrini and E. De Saeger. ”PM10 Field Studies (Berlin April – November 2009)”, CNR-RAP 127, National Research Council - Institute for Atmospheric Pollution, Rome ,Italy. (2000)

Experimental

Sampling site and time period

The equivalence study was conducted near one of the busiest streets in Sweden, Essingeleden, with about 170 000 vehicles per day, see Figure 1. Two cabins were placed on a cliff about 5 meters from the street. The inlets of the instruments were about 5 – 7 meters above street level. An overview of the cabins and the placement of the instruments that took part in the study can be seen on Figure 2.

The site was rather exposed to the wind as no high buildings and trees were in the vicinity.

The campaign started 19 March and ended 27 May, in all 70 days. Some instruments did not participate during the whole campaign; see details in the equivalence evaluation.

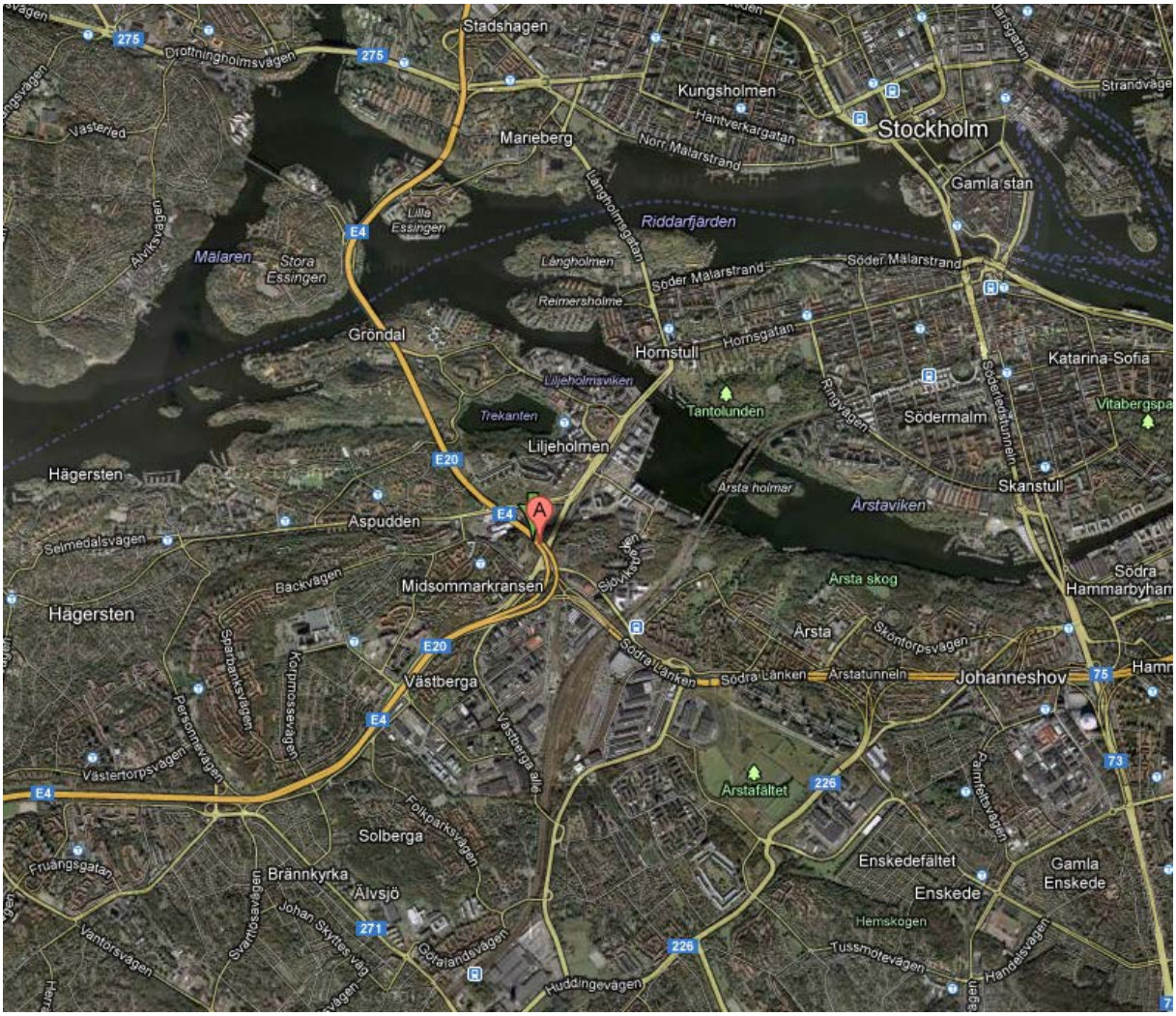


Figure 1. Location of sampling site. The site is at the A on the map. Click here (or paste the Internet adress in the footnote[6] below in a browser) to see more details of the surrondings of the sampling site.

[6] https://maps.google.se/maps?q=59.3043,+18.01815&hl=sv&ll=59.3043,18.018147&spn=0.002035,0.006968&sll=59.3043,18.018297&sspn=0.002035,0.006968&t=h&z=18

Figure 2. The measurement cabins

Meteorological conditions

During the start of the campaign, from 19th to about 30th March, the weather was very warm for the season and mainly dry. April started cooler than normal, but a warmer period in the end of the month made the monthly mean near the normal. However, the precipitation amount was more than twice the normal for the month. May started warmer than normal the first three days before a long period of unstable and significantly colder weather came to dominate the weather picture. After 20th May, there were several days with high temperatures for the season. The precipitation was lower than normal and concentrated to a number of days around the 10th May. The daily average temperature, the daily precipitation amount and the daily average relative humidity is shown in Figure 3

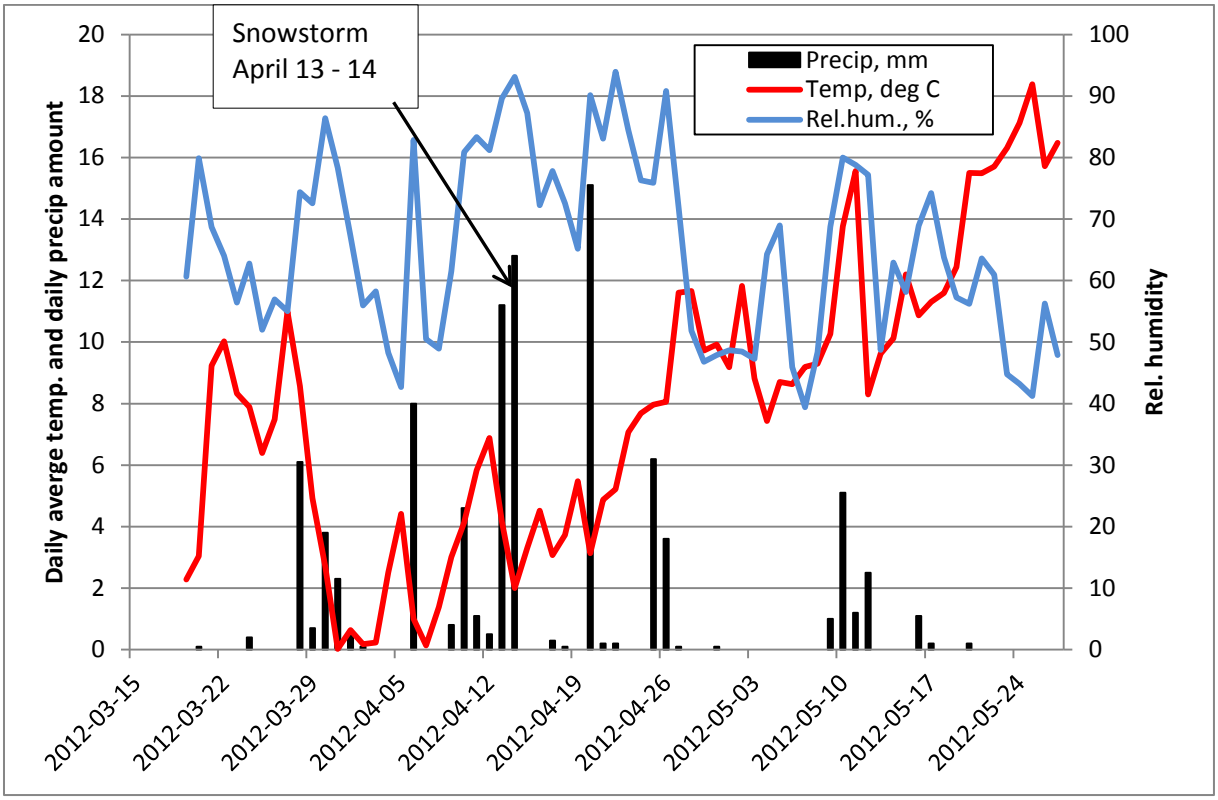


Figure 3. Meteorological conditions at the sampling site

Participating instruments

The reference method

During the campaign measurements of PM10 were made with two reference instruments:

1. Leckel SEQ 47/50.
2. Derenda PNS 16T

The two samplers are both sequential filter samplers. Ambient air is passed through a PM10 size-selective inlet at a known, constant, flow rate (2,3 m³/h). The PM10 fraction is collected on a filter for a period of 24 h. In both samplers the exposed filters were automatically changed to non-sampled ones at midnight.

The mass of the PM10 material is determined by weighing the filters at constant conditions (20 °C, 50 % RH) before and after collection of the particulate matter. The PM10 concentration is then calculated by dividing the mass increase of the filters with the sampled volume.

Teflon coated glass fibre filters (Pall Fibre film T60A20) were used. After the campaign, it was found out that this filter type do not fulfil the requirements of the filter that shall be used in the reference method. The filters used in the reference method shall have a separation efficiency of at least 99,5% at an aerodynamic diameter of 0,3 µm. The separation efficiency of the T60A20 filters is 96,4 %.

The lower separation efficiency of the used filter type might lead to an underestimation of the PM10 concentration. To investigate this, a small test after the equivalence study was conducted where the results obtained on the used filter type was compared with results obtained with a filter with the correct separation efficiency (Pall Emfab, separation efficiency 99,95%)

Two reference samplers ran in parallel during a month. PM10 was collected on each filter during 48 hours. The reason to sample 48 h rather than 24 h as during the equivalence study was to make sure that the amount of particles collected on the filters should be about the same in the two studies. The filter comparison study was conducted at urban background site with expected lower concentrations than during the equivalence study. In order to minimize the influence due to any differences between the reference samplers the sampling schedules given in the table below were used.

	Filter type used	
	Sampler 1	Sampler 2
Sample 1	Pall Fibre Film	Pall Emfab
Sample 2	Pall Emfab	Pall Fibre Film
Sample 3	Pall Fibre Film	Pall Emfab
and so on		

The comparison showed that the concentrations obtained when using the T60A20 filters were some percents too low on most of the samples. To correct for this all concentrations measured by the reference samplers during the equivalence study was recalculated according to the formula below

$$Conc_{corr} = Conc_{meas} \cdot 1.025 \qquad (1)$$

Candidate instruments

Nine different models of candidate instruments took part in the study, see Table 1

Three instruments are based on the ß-ray attenuation principle: Opsis SM200, Thermo Sharp 5030 and FAI SWAM 5A. Ambient air is passed through a PM10 size-selective inlet at a known, constant, volume flow rate. The particles are collected on a filter or a filter strip. The mass determination is based on the reduction of the intensity of β-rays that passes the filter. The radiation intensity measured before and after the sampling of particles is proportional to the mass of the particles collected on the filter. After a sampling period (usually 24 hours) the filter is replaced by a new one or the filter strip is fed forward automatically and a new sampling period can start.

Three instruments are based on the oscillating micro balance principle (Thermo TEOM 1400AB, Thermo TEOM-FDMS and Thermo 1405 F).

In the TEOM 1400 AB particle-laden air is drawn into the TEOM® (Tapered Element Oscillating Microbalance) at a constant volume flow through an air inlet followed by an exchangeable filter cartridge, where the particulate mass collects. The filtered air then proceeds through the sensor unit, which consists of a patented microbalance system. As the sample stream moves into the microbalance system (filter cartridge and oscillating hollow tapered tube), it is heated to a specified temperature (often 50 °C). This is done to minimize the deposition of water due to changes in ambient humidity. The hollow tube is attached to a platform at its wide end and is vibrated at its natural frequency. As particles gathers on the filter cartridge, i.e. the mass of the filter plus the collected particles increase, the tube's natural frequency of oscillation decreases. The electronic microbalance system continually monitors this frequency. Based upon the direct relationship between mass and frequency, the instrument's microcomputer computes the total mass accumulation on the filter, as well as the mass rate and mass concentration, in real time.

The TEOM-FDMS and the 1405 F are both based on the TEOM, but supplemented by a FDMS-unit. (FDMS = Filter Dynamics Measurement System). Many studies have shown that the original TEOM instruments gave to low concentrations in environments with a high amount of semi-volatile particulate compounds (e.g. ammonium nitrate and some hydrocarbons). This is due to the heating to 50 °C in the mass sensor. To correct for this the FDMS method was developed.

In a TEOM equipped with a FDMS the filter weight change during a six-minute period is measured when the sample air goes directly into the mass sensor as in a TEOM. In the next six-minute period, all particles are removed from the sample air before reaching the air filter on top of the glass body. The filter weight change over this period is a measure of how much that evaporates from the filter or, in some cases, the amount that is adsorbed during sampling and is used to correct the result obtained in the first six minutes. The switching between the determination of the filter mass change in air with and without particles is continuously repeated.

One instrument, the Grimm EDM 180, is based on the method of counting the number of particles by their optical properties. The physical measuring principle is orthogonal light scattering. Sample air is led into a measuring chamber and the particles are illuminated with laser light (λ = 655 nm) at 90 degrees to the direction of flow. In ambient air, the particle concentration is so low that it in general there is only one particle in the measurement volume during a measurement. The scattered light from each particle is sent via a mirror to a photo diode (detector). The intensity of the reflected light beam is proportional to the particle size. The number of counts per time unit depends on the number of particles and the volume flow. Pulse counts are transferred to a mass distribution, from which various PM values can be obtained. With appropriate software, it is possible to obtain the mass for PM10, PM2, 5 and PM1.

Unlike the other instruments in this campaign the Grimm 180 does not use a PM10 sampling head. It uses an inlet that collects almost all particles smaller than 50 – 100 µm (a TSP- inlet; TSP =Total

Suspended Particles). The instrument counts all particles in about 30 different size ranges from 0,3 - 32 µm. Specific algorithms are used to transfer the number of particles in each size range to mass. To calculate PM10 a proportion of the mass of the particles in each size fraction is included in the calculations. The proportion for each size fraction is obtained from a cut-off curve, see page 19. The cut-off curve is thus a necessary part of the algorithm to calculate the mass.

The IVL P Model S10 is an automatic manual gravimetric sampler based on the same principle as the reference sampler. However, the flow control is made in another way. In the old model, the flow is regulated by a manually set needle valve. The setting is changed now and then based on the seasonal average temperature. In the new model, the flow is regulated by a mass flow controller (MFC). The sample mass flow is regulated to a constant volume flow through the PM10-inlet by measurements of the ambient outdoor temperature and by assuming an average atmospheric pressure at the measurement site. Both models are equipped with a number of PM10-inlets, normally 8. The particles are collected on a filter that is mounted inside the PM10-inlet. Sampling is switched from one inlet to another at programmed intervals (in this study every 24 hour). When 8 PM10-inlets are used, the sampled filters in seven PM10-inlets are replaced with unexposed ones (in the case of 24 hour sampling every 7th day). The filters are weighed before and after sampling in a climate controlled weighing room.

Instrument	**Measurement principle**	**Inlet type**	**Equivalent[1]?**	**Remark**
OPSIS SM200	Beta	EU	Yes	Provided by Opsis AB
Thermo Sharp 5030	Beta	US-EPA	Yes	Provided by Hugo Tillquist AB, Swedish repr. for Thermo
FAI SWAM 5A	Beta	EU	Yes	Provided by FAI
Grimm EDM 180	Optical Particle Counter (OPC)	TSP	Yes	Two instruments. Provided by SEHPA[3]
Thermo 1405F	Osc. micro balance	US-EPA	No	Provided by Hugo Tillquist AB, Swedish repr. for Thermo
Thermo TEOM FDMS	Osc. micro balance	US-EPA	No	Two instruments. Provided by MEHPA[3]
Thermo TEOM 1400	Osc. micro balance	US-EPA	No	Two instruments. Provided by SEHPA and GEHPA[3]
IVL P Model S10 (old model)	Manual gravimetric	IVL design[2]	No	Flow controlled by a manually set needle valve. Provided by IVL[4]
IVL P Model S10 (new model)	Manual gravimetric	IVL design[2]	No	Flow regulated by a mass flow controller. Provided by IVL[4]

1. Previously declared equivalent by SweEPA
2. The separation properties are similar to the US-EPA inlet
3. SEHPA, GEHPA and MEHPA. Stockholm, Gothenburg and Malmö Environment and Health Protection Administration respectively.
4. IVL Swedish Environmental Research Institute.

Table 1. Candidate instruments participating in the equivalence study for PM10 measurements

Supplementary measurements

As mentioned on page 8 above, one reference sampler (Leckel SEQ 47/50) was used to measure PM10 with an US-EPA inlet.

In order to better assess if PM10 was dominated by fine or coarse particles, PM2.5 was measured by the FAI SWAM 5A and the Grimm EDM 180. A more detailed picture of the number of particles in 31 size ranges from 0,25 to 32 µm is given by the Grimm EDM 180.

The results from the TEOM FDMS and the 1405F can be used to assess the volatility of particles.

Data aggregation

For instruments that recorded PM10 as hourly data they were aggregated to daily values only if the number of hourly values were 22 or more. In the case of instruments that recorded daily PM10 data, the data was rejected if the sampling was interrupted due to e.g. power failures during some period of the day.

Data validation

The control of the validity of the data obtained was primarily done by the instrument providers. Data was only removed due to technical reasons. The instrument providers were not aware of the results of any other instrument when validating the results.

Evaluation method according to GDE

According to GDE, the field tests in which candidate and reference methods are compared side-by-side will serve to assess the

1. 'between-sampler/instrument' uncertainty of the candidate method through the use of two samplers or instruments
2. 'comparability' of the candidate and reference methods

In GDE it is stated that a minimum of 4 field tests at a minimum of 2 sites shall be performed preferably in different climatic seasons with particular emphasis on the following variables, if appropriate, 1) the composition of the PM fraction, notably high and low fractions of semi-volatile particles, to cover the maximum impact of losses of semi-volatiles; 2)air humidity and temperature (high and low) to cover any conditioning losses of semi-volatiles during the sampling process and 3) the wind speed (high and low) to cover any dependency of inlet performance due to deviations from ideal behaviour as dictated by mechanical design, or deviations from the designated sampling flow rate.

This study is as described on page 7 a supplementary test to the equivalence test performed earlier and the results shall thus be evaluated together with earlier equivalence studies, if available.

Suitability of datasets

Of the full dataset at least 20% of the results obtained using the standard method shall be greater than the upper assessment threshold (UAT) specified for annual limit values according to GDE. For PM10 the UAT for the annual limit value is 28 µg/m³, thus the 80-percentile of the obtained daily mean PM10 values shall be above that value.

In this study the 80-percentile of the PM10 values measured by the reference sampler was 24 µg/m³, thus this requirement was not met. It was expected that the concentrations at the site should be higher, but the wet weather in April and the fact that the site was exposed to winds gave lower concentrations.

Calculation of between sampler uncertainty

The instruments that are declared as equivalent by SweEPA have been shown to fulfil the between sampler uncertainty in other studies. This test is not therefore performed during this study, but was done for the other instruments, see Table 1. However, the test was not possible to do for the Thermo 1405F as only one instrument was available.

The between-sampler uncertainty, $u_{bs,CM}$, is calculated from the differences of all 24-hour results of the candidate samplers/instruments operated in parallel as:

$$u_{bs,CM}^2 = \frac{\sum_{i=1}^{n}(y_{i,2} - y_{i,1})^2}{2 \cdot n} \qquad (2)$$

where

$y_{i,1}$ and $y_{i,2}$ are the results of parallel measurements for a single 24-hour period i
n = number of 24-hour measurement results.

In the GDE it is stated that the between-sampler/instrument uncertainty is first determined for the complete dataset. A between-sampler/instrument uncertainty > 2,5µg/m³ is an indication of unsuitable performance of one or both samplers/instruments, and equivalence shall not be declared for the candidate method when this criterion is not satisfied.

In addition, the between-sampler/instrument uncertainty is determined for two datasets obtained by splitting the full dataset according to PM10 concentrations greater than or equal to 30 µg/m³.

The between-sampler/instrument uncertainty criterion of ≤ 2,5 µg/m³ shall be satisfied for both datasets.

In this study only four 24 h PM10 concentrations were greater than 30, thus this evaluation was only performed for the full data set.

Comparison with the reference method

First, the performance of the reference samplers/instruments is checked by calculation of the relative between-sampler/instrument uncertainty as in eq. (2). The between-sampler/instrument uncertainty for the reference method, $u_{bs,RM}$ shall be < 2 µg/m³.

For the evaluation of the uncertainty due to the 'lack of comparability' between candidate and reference methods it is assumed that the relationship between measurement results of both methods can be described by a linear relation of the form

$y_i = a + b \cdot x_i$ (3)

where y_i and x_i are the PM10 concentrations measured by the candidate and reference instrument/sampler respectively.

The relation between the results of the candidate method and the (average) results of the reference method is established for using orthogonal regression.

The procedure is applied separately to

1. the full data set

2. a data set representing PM10 concentrations greater than or equal to 30 µg/m³ provided that the subset contains 40 or more valid data pairs
3. data sets for each individual site.

Preconditions for acceptance of the full dataset are that:

- the slope b is insignificantly different from 1: $|(b-1)| \leq 2 \cdot u(b)$
- the intercept a is insignificantly different from 0: $|a| \leq 2 \cdot u(a)$

where *u(b)* and *u(a)* are the standard uncertainties of the slope and intercept, respectively, calculated as the square root of their variances.

If these preconditions are not met, the candidate method may be calibrated using the values obtained for slope and/or intercept.

Practical use of the GDE has shown that the criterion on slope and intercept discriminate candidate methods that correlate well with the reference method. Therefore, in a recent draft of the equivalence procedure for PM a significant slope and/or intercept are accepted if the slope is between 0.98 and 1.02 and/or if the intercept is between -1 and +1 µg/m³. This practice is used in this study.

The calibration shall only be applied to the full data set. To evaluate if the candidate method is equivalent after a calibration, the same statistical procedures as described below shall be used but with an extra uncertainty term added due the uncertainty of the regression terms a and b.

The uncertainty in the results of the candidate method from comparison with the reference method, u_{CR}, is calculated using a general equation describing u_{CR} as a function of PM10 concentration xi. The general relationship describing the dependence of u_{CR} on x_i is given by

$$u_{CR}^2(y_i) = \frac{RSS}{(n-2)} - u^2(x_i) + [a + (b-1) \cdot x_i]^2 \quad (4)$$

where
RSS, the sum of residuals resulting from the orthogonal regression is calculated as

$$\sum_{i=1}^{n} (y_i - a - b \cdot x_i)^2 \quad (5)$$

$u(x_i)$, the uncertainty of the results of the reference method, is calculated as

$$\frac{u_{bs,RM}}{\sqrt{2}} \quad (6)$$

The expanded uncertainty of the candidate method, U_{CR} is calculated as

$$U_{CR}(y_i) = 2 \cdot u_{CR}(y_i) \quad (7)$$

Evaluation of results of field tests

The relative expanded uncertainty, $W_{CR}(50)$, at the daily limit value for PM10 is calculated as

$$W_{CR}(50) = \frac{U_{CR}(50)}{50} \quad (8)$$

This value is calculated for all datasets, see page 15.

The candidate method is declared equivalent if the highest of all the calculated $W_{CR}(50)$ values is below 25%, the DQO objective given in AQD 2008.

The data obtained in this study at just one site and during one season (spring) was only evaluated for the full data set as only four 24 h PM10 concentrations were greater than or equal to 30 µg/m³.

Results

All results are based on calculations made by the Excel worksheet "Orthogonal regression and equivalence test utility", version 2.9, made by Ruben Beijk at RIVM (Dutch Institute for Public Health and the Environment, dep. Centre for Environment Monitoring)[7].

All daily results from the various samplers are presented in Annex C.

Evaluation of the reference method

Two reference samplers were participating in the campaign, one Leckel SEQ 47/50 and one Derenda PNS 16T. The time-sequence plot of the 24 h data of the two instruments are shown in Figure 4. The results of the two samplers are almost identical.

Due to technical problems, results for the Derenda sampler are missing for some periods. However, there are 48 days with results for both samplers. The between sampler uncertainty for the reference samplers, $u_{bs,RM}$, is 0,49 µg/m³. This is well below the allowed maximum between reference sampler uncertainty 2,0 µg/m³, see page 15.

In the comparison of the candidate samplers with reference samplers, only the results from the Leckel have been used as there are some missing data from the Derenda sampler and also as the two reference sampler gave almost identical results.

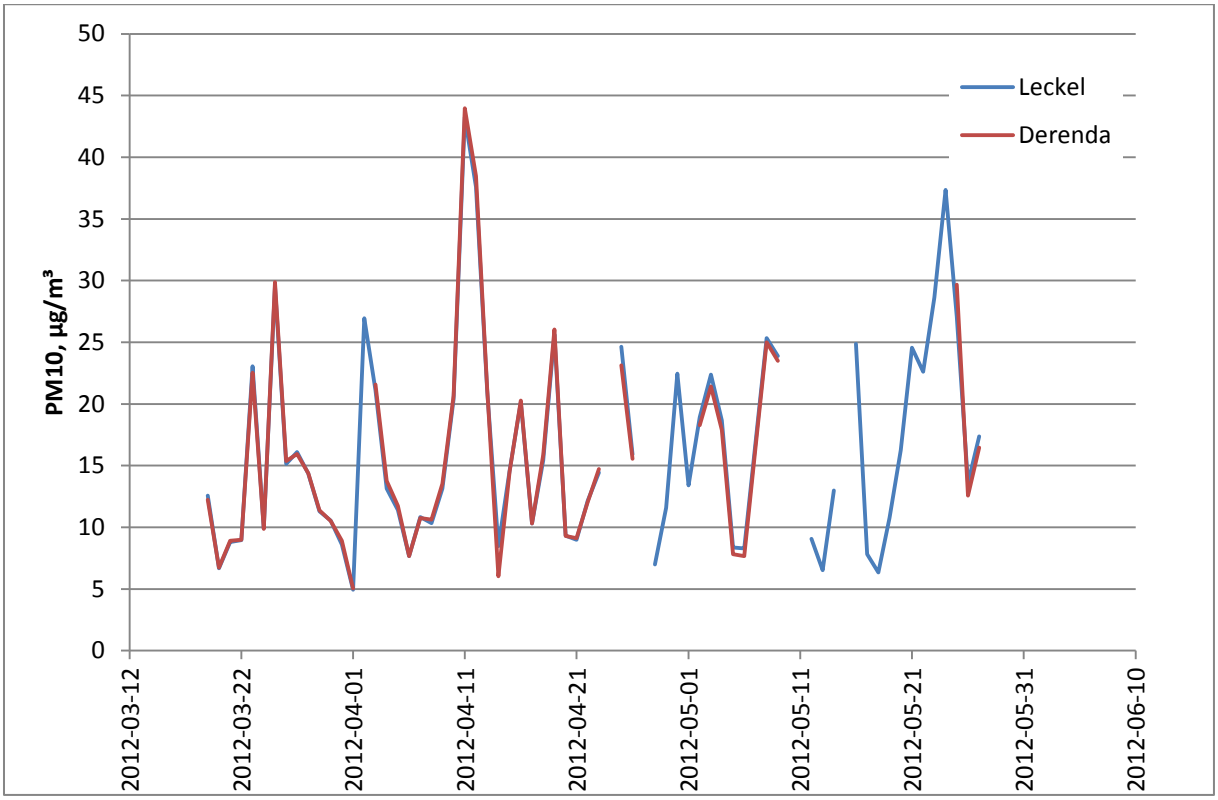


Figure 4. Daily PM10 concentrations measured by the two reference samplers during the equivalence study

[7] http://ec.europa.eu/environment/air/quality/legislation/pdf/RIVM_PM_equivalence_v2.9.xls

Comparison of the EU reference sampler with a standard EU-inlet and a reference sampler with an US-EPA inlet.

The standard inlet for PM10 used in USA and the one used in EU do not have the same separation properties, see Figure 6. According to the proposed new EU standard for PM10 the "Prallplattenabstand" (see Figure 6) shall be 8 ± 2 mm, thus the two inlets denoted " .. Kurze Düsen …" fulfils the standard. The cut-off curves for these two inlets are almost identical and the two curves are representative for the instruments with EU-inlets that participated in this study.

The EU-inlet has been constructed according to the principles described by Marple and Willeke[8] in order to get a steep cut-off curve. However, the US-EPA inlet has been designed to as much as possible mimic the thoracic convention that has a less steep cut-off curve.

The discrepancy between the two inlets might in some circumstances lead to different results. E.g. in environments where the particle size distribution in the air is such that most of the mass of the particles is greater than 10 µm, i.e. the mass median diameter is greater than 10 , the US-EPA inlet will give a higher PM10 concentration than the EU-inlet. In contrast, if the mass median diameter is around 5 – 7 µm, one can expect the EU-inlet to give the highest concentration.

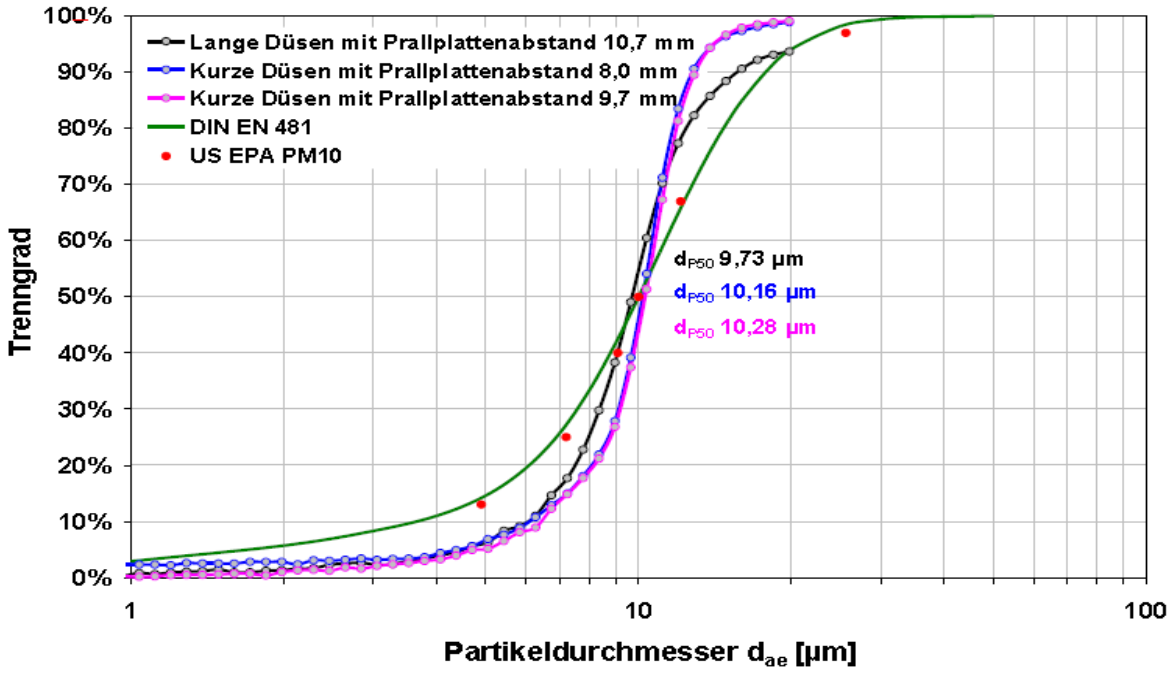


Figure 6.Cut-off curves for a number of standard inlets. The blue, black and pink curves are for different versions of the EU-inlet. Trenngrad = Separation efficiency. 100% means that collects 100% of the particles remain in the inlet, i.e. 0% reaches the PM10 instrument. DIN EN 481: Definition of the cut-off curve for the thoracic fraction. Ref: Stefan Jacobi, Hessisches Landesamt für Umwelt und Geologie. Personal communication

Earlier measurements have shown that coarse particles dominate PM10 in the same type of environments as in this study. As an example, the diurnal variation of PM10 and PM2.5 at a central street in Stockholm during spring 2009 is shown in Figure 7.

[8] Marple, V. A. and Willeke, K. Impactor design. Atmospheric Environment Vol. 10. pp. 891-896 (1976).

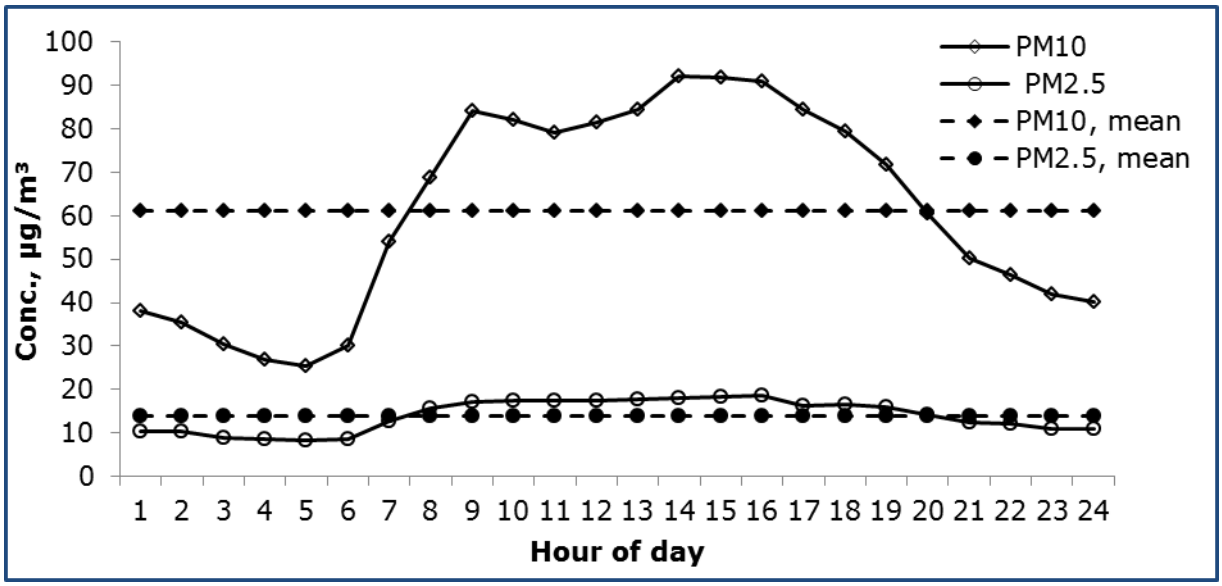
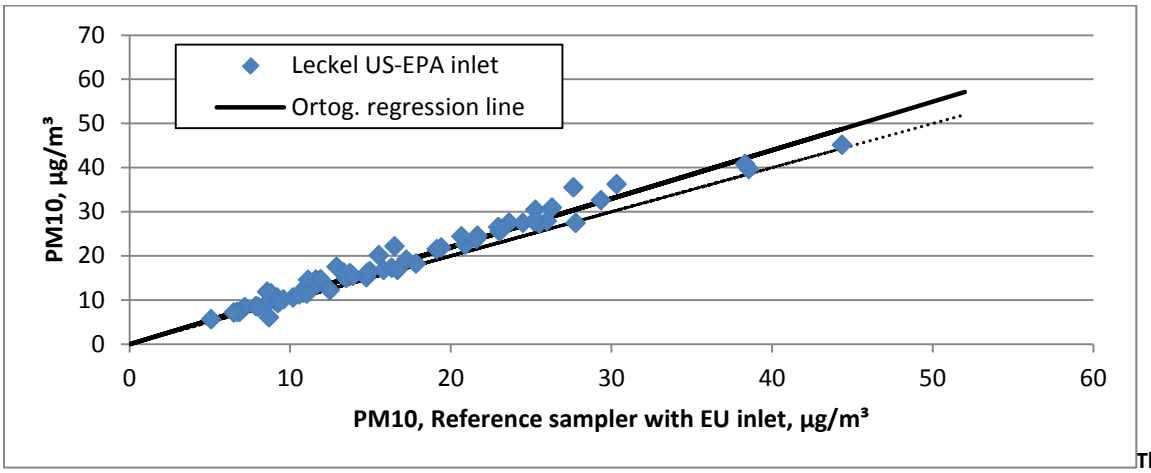


Figure 7. PM10 and PM2.5 at an 'exceedance' site in Sweden. Diurnal variation at a central street in Stockholm, March - April 2009. Data from Stockholm Environment and Health Protection Administration

The average PM10 and PM2.5 concentrations are 62 and 14 µg/m³ respectively. The highest levels, in the afternoon, is about 92 (PM10) and 18 µg/m³ (PM2.5). The ratio PM2.5/PM10 is thus in average below 25%, i.e. the coarse fraction (PM10 – PM2.5) constitutes more than 75 % of PM10.

Test of the equivalence of the US-EPA and EU inlet

In order to investigate the influence of inlets with different cut-off characteristics on the measured PM10 concentrations, one US-EPA inlet was put on an EU reference sampler. This sampler is denoted EPA-EU below. The results obtained from that sampler are compared with the results from the reference sampler with the standard EU-inlet (an EU-EU sampler) using the procedure in GDE.



The

Figure 8. Scatterplot of daily PM10 concentrations by a reference sampler with an US-EPA inlet versus a reference sampler with an EU-inlet

The EPA-EU sampler inlet fulfils the equivalence criteria without applying any calibration function, see Table 2. However, the relative expanded uncertainty decreases from 21,8% to 6,1% if the EPA-EU data is recalibrated using the data when the regression line is forced through origin (intercept = 0). The calibration function x = 0,899y means that the reference EPA-EU data is 10 percents higher than the EU-EU data. The EPA-EU data were higher than EU-EU data during almost all days during the campaign, see Figure 8.

Test of comparability	Ref. sampler with US-EPA inlet	
Number of data pairs	65	
	Ref.	Cand.
Average, µg/m³	16,7	18,7
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	21,8%	
Calibration based on	Slope and intercept	
Calib. equation	0,910y -0,256	
Rel. expanded standard uncertainty	7,6%	
Calibration based on	Intercept = 0	
Calib. equation	0,899y	
Rel. expanded standard uncertainty	6,1%	
Calibration based on	Slope = 1	
Calib. equation	y – 0,256	
Rel. expanded standard uncertainty	20,9%	

Numbers in green/red: Equivalence criteria fulfilled/not fulfilled.

Criterion

Slope. Not significant ≠ 1 or 0,98 < slope < 1,02

Intercept. Not significant ≠ 0 or -1 < intercept < +1

Rel. expanded standard uncertainty < 25%

Table 2. Equivalence study for reference sampler with US-EPA inlet vs reference sampler with EU inlet

The dependence of the difference of US-EPA and EU-inlet as a function of the particle size distribution

PM2.5 was measured during the campaign by two instruments (FAI SWAM 5A and Grimm EDM 180). The ratio PM2.5/PM10 can be used as a measure if the aerosol is dominated by fine or coarse particles. The lower the ratio, the more coarse particles there are in the aerosol.

The different cut-off curves for the US-EPA and EU-inlet will according to theory have more importance the more coarse particles there are in the aerosol.

This was tested by plotting the ratio of the ratio of PM10 measured by the reference sampler with an US-EPA inlet to the PM10 measured by a reference sampler with an EU-inlet versus the ratio of PM2.5 to PM10 as measured by the FAI SWAM 5A, see Figure 9.

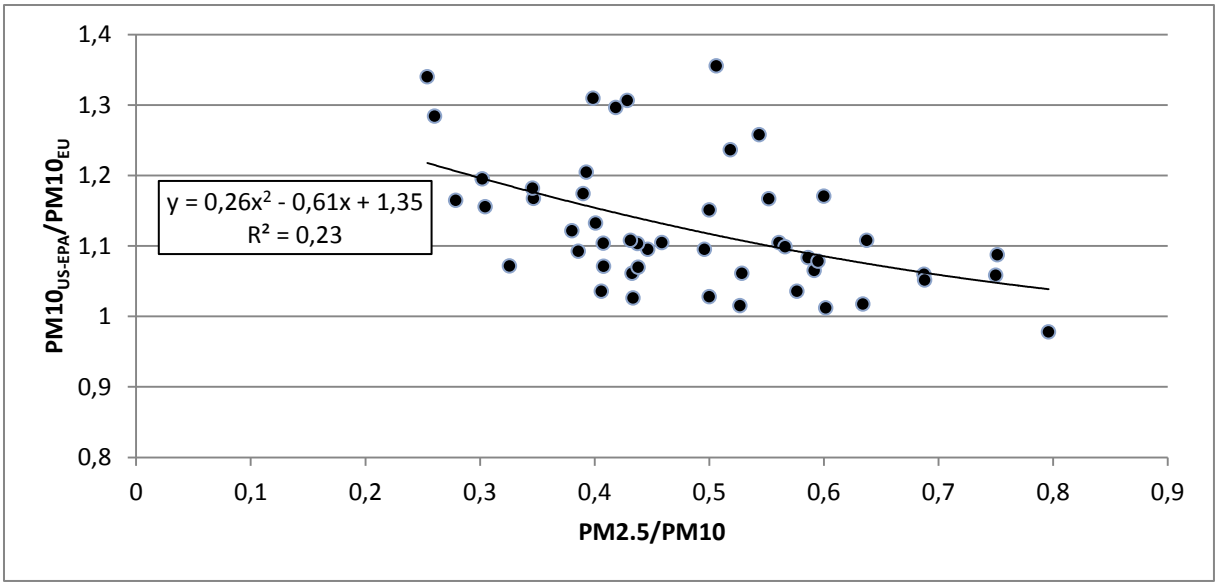


Figure 9. The ratio of the ratio of PM10 measured by a reference sampler with an US-EPA inlet to PM10 measured by a reference sampler with an EU-inlet versus the ratio of PM2.5 to PM10 measured by the FAI SWAM 5A

There is a large scatter in the data that can be explained by the large uncertainty in the data as four measurements are used for each data point. The regression curve given in the graph has thus not a strong statistical significance as seen by the R^2-value. However, it is clear from the graph that the difference between the two samplers (i.e., the inlets) increases the lower the ratio PM 2.5 to PM10 is.

This means that the difference between the two inlet types increases when the aerosol is dominated by coarse particles. That is what can be expected based on the different shapes of the separation curves for the two inlets.

Demonstration of equivalence of the candidate instruments

Thermo TEOM 1400 AB - Results

Data coverage

Two TEOM 1400 AB participated in the campaign. One of the instruments, TEOM #1, was in operation from 19 March to 27 May, the other, TEOM #2, from 24 March to 27 May. The data coverage was 98% (TEOM #1) and 100 % (TEOM #2).

Between sampler uncertainty

The TEOM instrument fulfils the criteria for the between sampler uncertainty, see Table 3.

No. of data pairs	63	Between sampler uncertainty
Avg. of daily PM10, µg/m³		$u_{bs,CM}$ = 1,07 µg/m³
TEOM #1	TEOM #2	
17,5	18,5	Fulfils criteria, $u_{bs,CM}$ < 2,5? YES

Table 3. Between sampler uncertainty for TEOM 1400 AB

This result confirms findings from a number of earlier equivalence studies in Europe[9], [10], [11].

Comparison with the reference sampler with an EU PM10 inlet

TEOM #1 fulfils the criterion for equivalence without any calibration, but the uncertainty when calibrated with slope forced through origin decreases from 13,7% to 11,7%, see Table 4

The raw data from TEOM #2 do not fulfil the equivalence criterion for slope and for uncertainty, but fulfils both criteria after recalibration with the slope forced through origin.

Thus as both instruments fulfils the criterion the TEOM 1400 AB instruments is equivalent with the reference method in this study.

However, the calibration equation obtained by the two instruments differs substantially. For TEOM #1 the raw data shall be reduced by 2,6% (1 – 0,974) to be equivalent to the reference method, for TEOM #2 the raw data shall be reduced by 8,8% (1 – 0,912). To obtain a more general calibration equation the average of the two TEOM 1400AB was calculated for each day and evaluated against the reference method.

Also in this case all criterions for equivalence are fulfilled when the raw data was recalculated by using the results when the orthogonal regression was forced through origin, see Table 4.

[9] Walden, Hilamo, Aurela, Mäkelä, Laurila. ”Demonstration of the equivalence of PM2.5 and PM10 measurement methods in Helsinki 2007–2008”. Studies No. 3. Finnish Meteorological Institute (2010)
[10] Flemish Environment Agency, Section Air. VMM (2011), “Comparative PM10 and PM2.5 Measurements in Flanders, 2010 campaign”.
[11] Harrison, D. “UK Equivalence Programme for Monitoring of Particulate Matter”. Bureau Veritas. Report BV/AQ/AD202209/DH/2396 (2006)

Test of comparability	TEOM #1		TEOM #2		Avg. TEOM 1400AB	
Number of data pairs	59		65		59	
	Ref.	Cand.	Ref.	Cand.	Ref.	Cand.
Average	17,2	17,6	16,7	18,2	17,2	18,2
Calibration based on	No calibration					
Calib. equation	y		y		y	
Rel. expanded standard uncertainty	13,7%		26,9%		19,3%	
Calibration based on	Slope and intercept					
Calib. equation	0,954y +0,424		0,883y+0,656		0,922y+0,474	
Rel. expanded standard uncertainty	14,1%		15,5%		15,1%	
Calibration based on	Intercept = 0					
Calib. equation	0,974y		0,912y		0,943y	
Rel. expanded standard uncertainty	11,7%		13,1%		12,4%	
Calibration based on	Slope = 1					
Calib. equation	y + 0,424		y + 0,656		y + 0,474	
Rel. expanded standard uncertainty	15,1%		29,5%		21,1%	

Numbers in green/red: Equivalence criteria fulfilled/not fulfilled.
Criterion
Slope. Not significant ≠ 1 or 0,98 < slope < 1,02
Intercept. Not significant ≠ 0 or -1 < intercept < +1
Rel. expanded standard uncertainty < 25%

Table 4. Equivalence results for TEOM 1400AB. Reference sampler with EU-inlet

The calibration equation for TEOM 1400 AB obtained during this study is thus

$$PM10_{ref,EU} = 0{,}943\ x\ PM10_{TEOM}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,TEOM}(50) = 12{,}4\ \%$$

Comparison with a reference sampler with an US-EPA PM10 inlet

One reference sampler (Leckel SEQ47/50) was modified and equipped with an US-EPA inlet, see page 8, in order to study the influence the use of different inlets might have on the results. Below is the results obtained when data from the modified reference sampler were used in the equivalence calculations.

The two TEOM both fulfil the equivalence criteria without applying any calibration function, see Table 5. However, the relative expanded standard uncertainty for TEOM #1 is reduced if data is calibrated. The least uncertainty is obtained when the intercept is fixed to 0. For TEOM #2, the least uncertainty is obtained without any calibration.

The difference between the two instruments is rather substantial. Data from TEOM #1 shall be multiplied with 8% to get the least uncertainty, while TEOM #2 data do not need to be corrected.

In order to generalize, the average of the two TEOM 1400AB was calculated for each day and evaluated against the reference method. This data set fulfils all equivalence criteria without application of any calibration factors, but if the sloped is fixed to 1, the relative expanded uncertainty is reduced.

The calibration equation for TEOM 1400 AB obtained during this study is thus

$$PM10_{\,ref,US-EPA} = PM10_{TEOM} + 0{,}926$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,TEOM}(50) = 8{,}2\ \%$$

Test of comparability	TEOM #1		TEOM #2		Average TEOM 1400AB	
Number of data pairs	59		65		59	
	Ref.	Cand.	Ref.	Cand.	Ref.	Cand.
Average	19,2	17,6	18,2	18,7	18,2	19,2
Calibration based on	No calibration					
Calib. equation	y		y		y	
Rel. expanded standard uncertainty	13,2%		8,4%		9,2%	
Calibration based on	Slope and intercept					
Calib. equation	1,040y + 0,897		0,976y + 0,907		1,006y + 0,926	
Rel. expanded standard uncertainty	13,2%		10,2%		10,0%	
Calibration based on	Intercept = 0					
Calib. equation	1,081 y		1,015y		1,047y	
Rel. expanded standard uncertainty	9,2%		9,9%		9,6%	
Calibration based on	Slope = 1					
Calib. equation	y + 0,897		y + 0,907		y + 0,926	
Rel. expanded standard uncertainty	10,6%		10,0%		8,2%	

Numbers in green/red: Equivalence criteria fulfilled/not fulfilled.
Criterion
Slope. Not significant ≠ 1 or 0,98 < slope < 1,02
Intercept. Not significant ≠ 0 or -1 < intercept < +1
Rel. expanded standard uncertainty < 25%

Table 5. Equivalence results for TEOM 1400AB. Reference sampler with US-EPA-inlet

Discussion on equivalence of TEOM 1400 AB

A number of comparisons between the TEOM 1400 AB instruments and reference instruments have shown that the TEOM 1400 AB instruments gives lower results than the reference instruments[12], [13].

[12] Allen, G. and R. Reiss (1997). "Evaluation of the TEOM Method for Measurement of Ambient Particulate Mass in Urban Areas." Journal of the Air & Waste Management Association **47**: 682-689.

The TEOM has the disadvantage of driving off semi-volatile material such as ammonium nitrate and organic aerosols due to heating of the mass sensor to 50 °C. An expert group in EU therefore in 2002 recommended a correction factor of 1.3 to be used for all TEOM data regardless of site and season. The factor was temporary and should be refined based on future equivalence studies.

In a Finnish study[14] in summer and autumn 2008 PM10 TEOM 1400 AB data was about 10% lower than the reference data. The concentrations were very low, thus it was not possible to judge if TEOM was equivalent.

The Swedish National Reference Laboratory summarized a number of comparative studies[15], most of them not performed according to GDE. The TEOM 1400 AB did not meet the criteria for equivalence, but an interim calibration equation that gave the best comparability was established. The calibration equation implies that the TEOM data shall be multiplied with about 1.2 at concentrations around the EU-limit values to be equivalent to the reference EU sampler.

In an extensive UK equivalence study[16] TEOM PM10 results at all eight test sites (urban background, street and rural) were lower than the results from the reference method. The TEOM 1400 AB was declared as not equivalent as it not was possible to apply any general calibration function to assure that the equivalence criteria were met at all stations.

In a one year study in Belgium, TEOM gave 29% lower results than the reference sampler at two suburban sites[17].

The correction factor of the TEOM 1400 AB can thus vary substantially depending on the amount of semi-volatile particles in the aerosol. In order to correct for the loss of semi-volatiles, the volatile correction method (VCM) were introduced in the United Kingdom and later in Belgium and France[18]. In the VCM the results from one or more FDMS instruments are used to correct TEOM results. The FDMS works in principle as a TEOM, but also measures and corrects for the loss of semi-volatile particle. As it has been shown that the volatility of the aerosol particles do not vary much within a large geographical region, this correction also can be applied for the TEOM instruments within the same region (about 200 km in diameter).

In contrast to nearly all other equivalence studies, the TEOM 1400 AB in this study gave higher results than the EU reference instrument with the European standard inlet, see page 24. When the slope is forced through zero, the TEOM 1400AB results shall be reduced by about 5% to be equivalent to the reference method.

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[13] Charron, A., R. M. Harrison, S. Moorcroft and J. Booker (2004). "Quantitative interpretation of divergence between PM10 and PM2.5 mass measurement by TEOM and gravimetric (Partisol) instruments, Atmospheric Environment, Volume 38, Issue 3, January 2004, Pages 415-423

[14] Walden et al. Demonstration of the equivalence of PM2.5 and PM10 measurement methods in Helsinki 2007 – 2008. Finnish Meteorological Institute Studies no 3. 2010

[15] Areskoug, H. Bestämning av PM10 - En jämförelse av de vanligaste mätmetoderna använda i Sverige och den europeiska referensmetoden. ITM Rapport 168. Stockholms universitet (2007). In Swedish

[16] UK Equivalence Program for Monitoring of Particulate Matter. DEFRA 2006

[17] Flemish Environment Agency, Section Air. Comparative PM Measurements in Flanders (Belgium) - 2010 campaign. VMM (2011).

[18] David C. Green, Gary W. Fuller, Timothy Baker, Development and validation of the volatile correction model for PM10 – An empirical method for adjusting TEOM measurements for their loss of volatile particulate matter, Atmospheric Environment, Volume 43, Issue 13, April 2009, Pages 2132-2141

Similar results were obtained at two small studies at a busy street, Hornsgatan, in the city centre of Stockholm in March 2007 and March – April 2010, i.e. during the period of the year when PM10 is dominated by coarse particles. The TEOM 1400AB gave on average about 10 % higher results than the EU reference sampler.

In this study (Stockholm 2012), the ratio between the average of the two TEOM instruments and the reference instrument with an EU-inlet increased (black dots in Figure 10), when PM10 was dominated by coarse particles, i.e. the ratio PM2.5/PM10 decreases. In contrast, the ratio between TEOM and the reference with an US-EPA inlet does not increase (red dots in Figure 10) when the ratio PM2.5/PM10 decreases. Thus, the difference between the two inlets increase the more the aerosol is dominated by coarse particles.

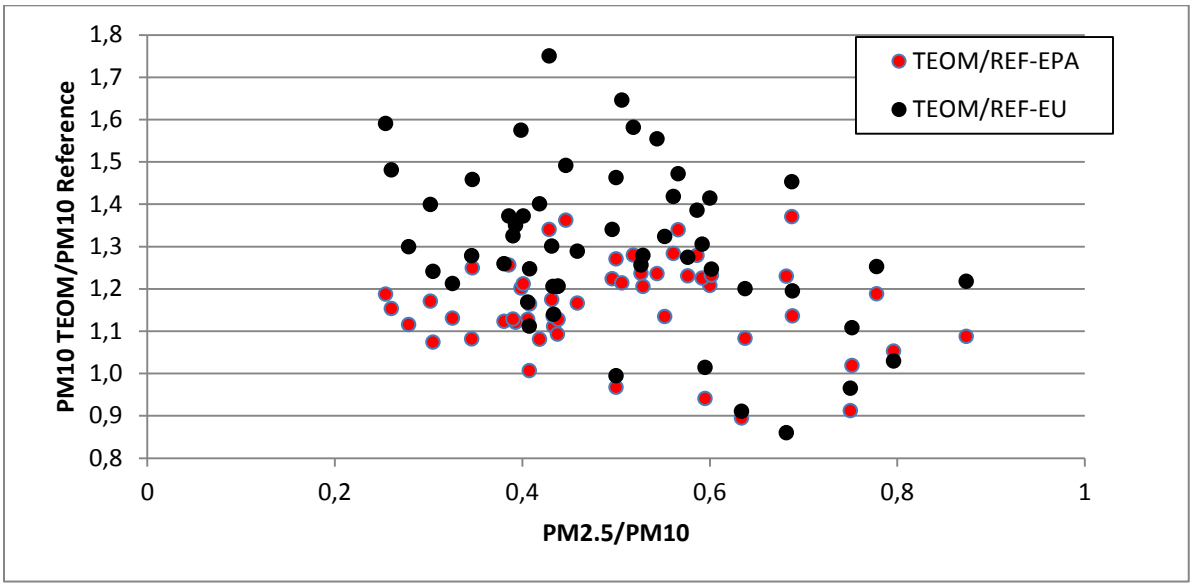

Figure 10. The ratio of the ratio of PM10 measured by TEOM 1400 AB with an US-EPA inlet to PM10 measured by a reference sampler with an EU-inlet or an US-EPA inlet versus the ratio of PM2.5 to PM10 measured by the FAI SWAM 5A. Daily averages from this study

During the comparative studies in Stockholm 2007 and 2010, PM2.5 was also measured. PM2.5 and PM10 was measured by a TEOM 1400 AB, specially equipped to alter between sampling of the two fractions. Thus it was possible to study if the difference between the TEOM 1400 AB and the EU reference is dependent on the ratio PM2.5/PM10 in the same way as during this campaign.

The results at the two comparative studies 2007 and 2010 gives the same results as during this study; the difference between the US-EPA inlet and the EU inlet increases when PM10 is dominated by coarse particles, see Figure 11.

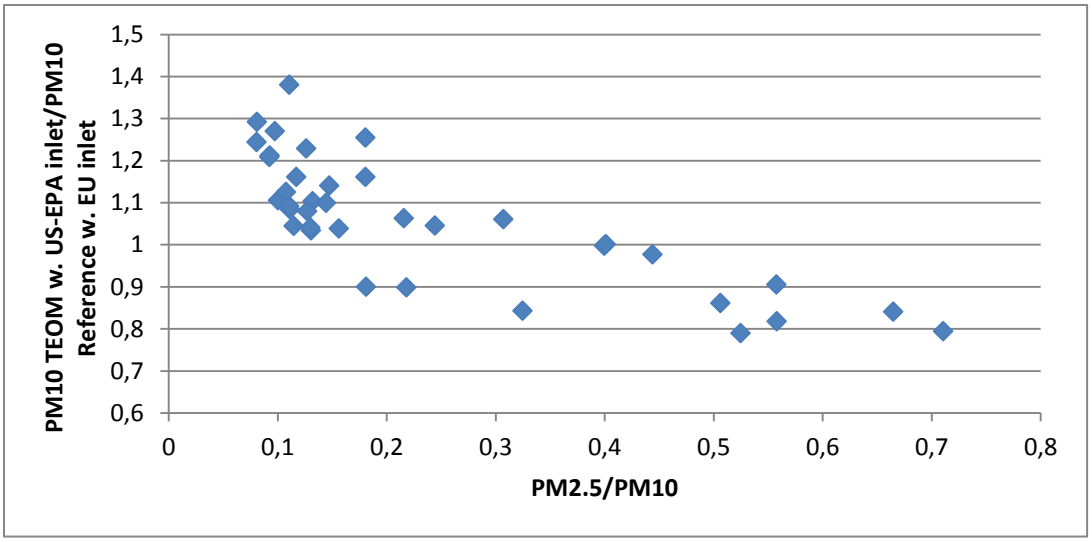

Figure 11. The ratio of the ratio of PM10 measured by TEOM 1400 AB with an US-EPA inlet to PM10 measured by a reference sampler with an EU-inlet versus the ratio of PM2.5 to PM10 measured by TEOM. Daily averages at Hornsgatan, Stockholm 2007 and 2010.

The main reason that TEOM 1400 AB have shown lower results than the EU reference instruments during the equivalence studies in Central Europe is the loss of semi-volatile particles.

During this study three instruments, the two Thermo FDMS and the Thermo 1405F, measured the volatility of the particles; see the instrument description on page 12. During the particle free cycle of the FDMS and 1405F instruments the semi volatile particles already collected on the filter evaporate and gases in the air adsorb on the particles collected on the filter. The weight change of the filter during the cycle is denoted the REF value in the FDMS and 1405F computer program. In most cases the evaporation is greater than the adsorption, thus the weight of the filter decreases and the REF value is negative. In some rare cases the adsorption is greater than the evaporation, thus the filter weight increases and the REF value is positive. Thus the more negative the REF value is the more volatile particles.

During this study the volatility of the particles was low, see Table 6. The values are close to or below the detection limit of the FDMS and 1405F (about 1,0 µg/m³). The REF values for the 1405F is somewhat lower, i.e. the volatility values higher. The reason for that is unknown.

	Instrument		
Statistics	Thermo FDMS #1	Thermo FDMS #2	Thermo 1405F
Max, µg/m³	+ 0,53	+ 0,93	- 0,65
Average, µg/m³	- 1,19	- 0,73	- 3,23
Min, µg/m³	-2,83	-2,13	- 6,26
Daily values are only given for days with more than 20 valid hourly data			

Table 6. Statistics for the daily REF value of the Thermo 1405 F and Thermo FDMS values during the equivalence study in Stockholm spring 2012. Note: The statistics for the differtent instruments are not fully comparable as they are not based on the same number of daily values.

Normally, the volatility of the aerosol particles in Sweden is low as in this study. However, occasionally and mainly during episodes with polluted air masses originating in Central Europe the volatility can increase.

At least two episodes occurred during this study. Another one occurred just a few days before the study started. As the TEOM 1400 AB and a few other instruments (but not the reference instruments) already were in operation, this episode made it possible to study how the high volatility of the aerosol particles affected the results from the TEOM 1400 AB. The two FDMS instruments at the study site was not in operation, but one was in operation at a rural site, Aspvreten, about 80 km south of Stockholm

During most of the study in Stockholm, the PM10 results from the TEOM 1400 AB was higher than the average of the instruments with EU inlets, see Figure 12.

However, during the episode 16 – 18 March, the TEOM PM10 values were 5 -15 µg/m³ lower than the average of the EU inlet PM10 values. The PM2.5 REF values at Aspvreten was significantly lower (i.e. the aerosol particles had a high fraction of volatile particles) during this episode than during the rest of the study period. As the REF measurements at the study site and Aspvreten correlates during most days during the campaign, see Figure 12, it is reasonable to assume that the aerosol particles also had a large fraction of volatile particles during the episode.

The TEOM 1400 AB PM10 values were lower than the EU PM10 instruments around 11 April and 10 – 11 May. Also during these episodes the REF values at Aspvreten and the study site were lower than during most other days during the period.

The reason that PM10 values from the TEOM 1400 AB PM10 values were lower than the average of the instruments with EU PM 10 inlets during these periods are thus very likely to be due to the increased volatility of the aerosol particles.

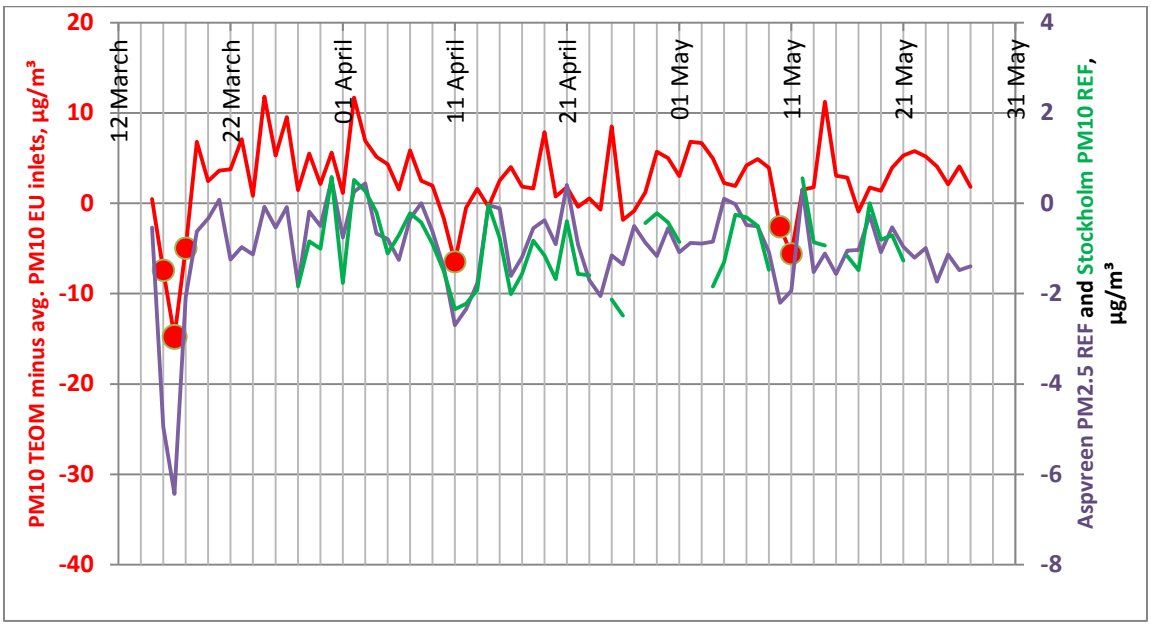

Figure 12. Daily averages of 1) difference between PM10 results from TEOM 1400AB and PM10 instruments with EU inlets, 2) the PM2.5 REF values at Aspvreten and 3) the average of PM10 REF values in Stockholm .

There are thus two reasons why the TEOM in this study gives higher results than the EU reference sampler in contrast to previous studies.

1. The TEOM 1400 AB uses an US-EPA inlet and the EU reference sampler uses the standardised EU inlet. In environments were the aerosol particle mass is dominated by coarse particles, as

in this study, the different inlet properties of the two inlets will lead to the mass of the particles collected by the US-EPA inlet being higher than the mass of the particles collected by the EU reference inlet.

2. In environments with a low amount of volatile particles, as in this study, the bias due to evaporation from the TEOM filter is low and thus the negative bias of the TEOM method as compared to the EU reference method is smaller in this study than in most other equivalence studies.

A generalised picture of how different types of aerosols in terms of if they are dominated by coarse particles or not and the volatility of the particles affect the bias of measurements with TEOM 1400 AB with an US-EPA inlet compared to the EU reference sampler is given in Table 7.

In this study the aerosol during most of the time had a high fraction of coarse particles with a rather low volatility, i.e. categorised to one of the squares in the upper left corner of Table 7. In contrast, the particles in the aerosol in most equivalence studies performed in Europe and during the episodes during this study can be categorised to one of the corners in the lower right corner in Table 7.

Fraction of mass of coarse particles in the aerosol				
	High	+ +	+	0
	Medium	+	0	-
	Small	0	-	- -
		Low	Medium	High
		Volatility of particles in the aerosol		

Table 7. A generalised picture of the bias of PM10 values obtained by TEOM 1400 AB with an US-EPA inlet compared to values obtained by the EU reference sampler depending on the nature of the aerosol. A plus sign means that the TEOM gives higher results than the EU reference, a minus sign the opposite.

To be able to make PM10 data obtained with a TEOM1400 AB instrument equivalent to the EU reference method two modifications of the method have to be implemented:

1. Exchange the US-EPA PM10 inlet to one with the same separation properties (cut-off curve) as the standardised EU PM10 inlet..
2. Correct the data from TEOM 1400 AB with an EU equivalent PM10 inlet according to the principles in the volatile correction method (VCM). VCM is described briefly on page 44.

It is not possible to use the standardised EU inlet that operates at 2,3 m^3/h with an TEOM 1400 AB as the flow in the TEOM 1400 AB is 1,0 m^3/h. However, the standardised EU inlet is manufactured according to the principles given by Marple and Willeke, see page 19. Every inlet, regardless of the flow, manufactured according to these principles will have the same separation properties. Such inlets with the flow 1,0 m^3/h are commercially available.

There are two different ways to apply the volatile correction method (VCM).

1. In the original description of the method the REF value of one FDMS instrument is used to correct the values of many TEOM instruments within a region of up to 200 km. As this approach made the method sensitive to data losses, the REF values from many FDMS instruments are weighed together to obtain a correction value. The English application of the method now uses the two nearest FDMS REF measurements and an average of all the other FDMS REF measurements within 130 km. The corrected TEOM values are then calculated as

$$TEOM_{VCM} = TEOM - 1,87\ FDMS_{REF}$$

   As the value of $FDMS_{REF}$ normally is negative, $TEOM_{VCM}$ in most cases are greater than the original TEOM values. The evaporation of volatile particles in a TEOM is greater than in a FDMS instrument as the temperature is higher in the TEOM (50 °C) than in the FDMS (30 °C). That explains the factor 1,87 that was found in the original study in United Kingdom when the method was evaluated. If the loss had been the same in the TEOM and the FDMS the factor would be 1,0. No further correction of the data is done and the data corrected in this way has been shown to be equivalent to the EU reference method.
2. Another application of the VCM is to calculate the loss directly. E.g. in the Flemish part of Belgium the lost volatile fraction of the TEOM is calculated every half hour from the average difference in absolute concentration between two FDMS monitors and three TEOM monitors. This 'lost fraction' is then added to all the TEOM data in the Flemish network. Note that all five monitors used to calculate the correction are located at different sites.
   TEOM data corrected in this way has been shown to be equivalent to the EU reference method without any further correction. It should be noted that data from any method equivalent to the reference method or the reference method itself can be used instead of the FDMS to obtain the correction factor.

None of these two applications can be used directly to correct Swedish TEOM data. The main reason is that there are too few FDMS instruments in use in Sweden. To solve this, one should consider a relocation of the existing FDMS instruments and an investment in a number of new instruments. To do that in an effective way the regional networks and national network should cooperate. It is likely that the FDMS REF values (i.e. the volatility of the particles) varies less in Sweden than in Central Europe and the UK as Sweden is situated far from the sources. Thus the VCM based on a few FDMS instruments can be applied to a larger area than in Central Europe.

Equivalence test of TEOM 1400 AB data corrected according to the Volatile Correction Method

As described above a FDMS instrument was in operation at the rural station Aspvreten about 80 km south of the study site In Stockholm. According to the VCM theory the measurements of the volatility of the particles measured Aspvreten can be applied to the TEOM measurements in Stockholm and the corrected results shall be equivalent to data from the reference method.

The evaluation according to GDE shows that PM10 data from both TEOMs corrected by data on the volatility of the particles at Aspvreten meets the equivalence criteria, see Table 8. The results obtained by the reference sampler with the US-EPA inlet were used in the calculations.

The two TEOM both fulfil the equivalence criteria without applying any calibration function. However, the relative expanded standard uncertainty for TEOM #2 is reduced if data is calibrated. The least uncertainty is obtained when the intercept is fixed to 0. For TEOM #1, the least uncertainty is obtained without any calibration.

The difference between the two instruments is rather substantial. Data from TEOM #2 shall be reduced by about 5% to get the least uncertainty, while TEOM #1 data do not need to be corrected. In order to generalize, the average of the two TEOM 1400AB was calculated for each day and evaluated against the reference method. This data set fulfils all equivalence criteria without application of any calibration factors, but if calibration curve is forced through zero, i.e. the intercept is set zero, the uncertainty is reduced to 5,0%.

The calibration equation for the VCM corrected TEOM 1400 AB obtained during this study is thus

$$PM10_{\,ref,US-EPA} = 0{,}981\, PM10_{TEOM,VCM}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,TEOM,VCM}(50) = 5{,}0\ \%$$

Test of comparability	TEOM #1, VCM		TEOM #2, VCM		Average TEOM 1400AB	
Number of data pairs	59		64		64	
	Ref.	Cand.	Ref.	Cand.	Ref.	Cand.
Average	19,2	19,1	18,7	19,5	18,7	19,1
Calibration based on	No calibration					
Calib. equation	y		y		Y	
Rel. expanded standard uncertainty	6,2%		11,8%		6,7%	
Calibration based on	Slope and intercept					
Calib. equation	1,002y + 0,070		0,945y + 0,247		0,974y + 0,151	
Rel. expanded standard uncertainty	8,0%		6,5%		6,2%	
Calibration based on	Intercept = 0					
Calib. equation	1,005y		0,955y		0,981y	
Rel. expanded standard uncertainty	6,5%		5,4%		5,0%	
Calibration based on	Slope = 1					
Calib. equation	y + 0,070		y + 0,247		y + 0,151	
Rel. expanded standard uncertainty	6,4%		12,8%		7,3%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%						

Table 8. Equivalence study for VCM corrected data from TEOM 1400AB. Reference sampler with US-EPA-inlet

However, the slope is not significantly different from 1, thus VCM corrected TEOM 1400 AB data is equivalent to data from the reference sampler with the US-EPA inlet without any calibration.

Comparison of different methods to evaluate the equivalence of TEOM 1400AB

The equivalence of the TEOM 1400 AB has been evaluated in three different ways during this campaign. A summary of the results are given in Table 9.

Reference instrument	Candidate instrument	Calibration equation that gives the least uncertainty	Relative expanded uncertainty
EU with EU-inlet	TEOM 1400	0,943y	12,4%
EU with EPA-inlet	TEOM 1400	y + 0,926	8,2%
EU with EPA-inlet	TEOM 1400, VCM corrected	0,981y	5,0%

Table 9. A summary of three different approaches to evaluate the equivalence of the TEOM 1400 AB instrument.

The best agreement (least uncertainty) is obtained when the TEOM data is corrected with VCM and the reference sampler and TEOM are using the same type of inlet. This is not surprising as this approach ascertains that the TEOM and reference sampler collects the same particles and that the loss of semi-volatiles in the TEOM is accounted for. This approach is also likely to fulfil the equivalence criteria in many different environments.

IVL PModel S10 (new version) – Results

Data coverage

Two IVL P Model S10 (new version) participated in the campaign. They were both in operation from 19 March to 27 May. The data coverage was 90% (IVL new #1) and 85% (IVL new #2). The loss of data was concentrated to the beginning of the campaign. After a modification of the sampling system, the losses were reduced substantially. Some losses of data due to operator mistakes are not included in the calculation of the data coverage.

Between sampler uncertainty

The between sampler uncertainty of the sampler IVL P Model S10 (new version) is below 2,5 µg/m³ and thus fulfils that criterion, see Table 10.

<table>
<tr><td colspan="2">No. of data pairs</td><td>49</td><td>Between sampler uncertainty</td></tr>
<tr><td colspan="3">Avg. of daily PM10, µg/m³</td><td rowspan="2">$u_{bs,CM}$ = 1,45 µg/m³</td></tr>
<tr><td>IVL new #1</td><td colspan="2">IVL new #2</td></tr>
<tr><td>17,8</td><td colspan="2">17,7</td><td>Fulfils criteria, $u_{bs,CM}$ < 2,5?
YES</td></tr>
</table>

Table 10. Between sampler uncertainty for IVL P Model S10 (new version)

Comparison with the reference sampler with an EU PM10 inlet

None of the two new IVL P Model S10 samplers fulfil the criteria for equivalence without the use of a calibration function. The reason is that the data from the IVL sampler is on average about 12% higher than results from EU reference sampler.

However both versions fulfils the equivalence criteria if data is recalculated based on a 'free' (i.e. no restrictions on slope and intercept) calibration function as well as if the calibration function is forced through zero (intercept = 0), see Table 11. The least expanded uncertainty is obtained for both versions of the instrument if the calibration function is forced through zero.

In order to generalize, the average of the two new versions of IVL P Model S10 was calculated for each day and evaluated against the reference method. This data set fulfils all equivalence criteria when a calibration equation is applied. The best agreement is obtained if the calibration function is forced through zero.

The calibration equation for the new IVL P Model S10 obtained during this study is thus

$$PM10_{\,ref,EU} = 0{,}881\; x\; PM10_{IVL\ P\ Model\ S10\ (new)}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,IVL\ PModel\ S10\ (new)}(50) = 8{,}4\ \%$$

Test of comparability	IVL new #1		IVL new #2		Average IVL new	
Number of data pairs	58		45		44	
	Ref.	Cand.	Ref.	Cand.	Ref.	Cand.
Average	16,6	18,6	15,8	17,9	15,7	17,8
Calibration based on	No calibration					
Calib. Equation	y		y		Y	
Rel. expanded standard uncertainty	30,6%		29,0%		30,7%	
Calibration based on	Slope and intercept					
Calib. equation	0,871y + 0,394		0,875y +0,094		0,866y + 0,349	
Rel. expanded standard uncertainty	15,0%		9,2%		9,4%	
Calibration based on	Intercept = 0					
Calib. equation	0,888y		0,879y		0,881y	
Rel. expanded standard uncertainty	12,0%		6,5%		8,4%	
Calibration based on	Slope = 1					
Calib. equation	y + 0,394		y +0,094		y + 0,587	
Rel. expanded standard uncertainty	32,2%		29,5%		32,1%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%						

Table 11. Equivalence results for IVL P Model S10 (new version) . Reference sampler with EU-inlet

Comparison with a reference sampler with an US-EPA PM10 inlet

When the results from the IVL sampler are compared with results from the reference sampler with the US-EPA inlet, the sampler is equivalent without the use of any calibration equation, see Table 12.

The uncertainty decreases somewhat for both instruments if the calibration function is forced through zero.

In order to generalize, the average of the two new versions of IVL P Model S10 (new version) was calculated for each day and evaluated against the reference method with the US-EPA inlet. Also this dataset are equivalent with the reference data, but the uncertainty is somewhat decreased if the calibration function is forced through zero, see Table 12 .

The calibration equation for the new IVL P Model S10 obtained during this study is thus

$$PM10_{\,ref,US-EPA} = 0{,}968 \;\; x \; PM10_{IVL\ P\ Model\ S10\ (new)}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,IVL\ PModel\ S10\ (new)}(50) = 5{,}9\ \%$$

Test of comparability	IVL new #1		IVL new #2		Average IVL new	
Number of data pairs	58		45		44	
	Ref.	Cand.	Ref	Cand.	Ref.	Cand.
Average	18,3	18,6	17,4	17,9	17,3	17,8
Calibration based on	No calibration					
Calib. Equation	y		y		Y	
Rel. expanded standard uncertainty	14,5%		6,5%		10,0%	
Calibration based on	Slope and intercept					
Calib. equation	0,945y + 0,732		0,986y - 0,255		0,953y + 0,333	
Rel. expanded standard uncertainty	14,3%		7,5%		7,6%	
Calibration based on	Intercept = 0					
Calib. equation	0,977y		0,974y		0,968y	
Rel. expanded standard uncertainty	12,5%		5,7%		5,9%	
Calibration based on	Slope = 1					
Calib. equation	y + 0,732		y – 0,255		y + 0,333	
Rel. expanded standard uncertainty	16,7%		6,2%		11,4%	

Numbers in green/red: Equivalence criteria fulfilled/not fulfilled.

Criterion

Slope. Not significant ≠ 1 or 0,98 < slope < 1,02

Intercept. Not significant ≠ 0 or -1 < intercept < +1

Rel. expanded standard uncertainty < 25%

Table 12. Equivalence results for IVL P Model S10 (new version) . Reference sampler with US-EPA inlet

IVL PModel S10 (old version) – Results

Between sampler uncertainty

As only one IVL PModel S10 (old version) participated, it was not possible to calculate the between sampler uncertainty in this study. However, in a study in Oslo 2001 – 2002[19], the between sampler uncertainty for two instruments identical to the ones that participated in this exercise was 0,68 µg/m³, i.e. the criterion (below 2,5 µg/m³) was fulfilled.

Comparison with the reference sampler with an EU PM10 inlet

The IVL sampler (old version) fulfils the equivalence criteria without any calibration, see Table 13. However, the uncertainty is reduced if data are recalculated. The uncertainty is least if the calibration based on the slope forced through zero is used for the recalculation.

The calibration equation for the new IVL P Model S10 obtained during this study is thus

$$PM10_{\,ref,EU} = 0{,}910\; x\; PM10_{IVL\;P\;Model\;S10\;(old)}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,IVL\;PModel\;S10\;(old)}(50) = 11{,}7\;\%$$

Test of comparability	IVL old	
Number of data pairs	62	
	Ref.	Cand.
Average	16,5	18,3
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	17,6%	
Calibration based on	Slope and intercept	
Calib. equation	0,950 y – 0,895	
Rel. expanded standard uncertainty	13,4%	
Calibration based on	Intercept = 0	
Calib. equation	0,910 y	
Rel. expanded standard uncertainty	11,7%	
Calibration based on	Slope = 1	
Calib. equation	y – 0,895	
Rel. expanded standard uncertainty	15,2%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 13. Equivalence results for IVL P Model S10 (old version). Reference sampler with EU inlet

[19] Marsteen, L., Schaug, J. A. 2007. PM10 intercomparison exercise in Norway. Norwegian Institute for Air Research (NILU) REPORT NO. 41/2007

On average, the IVL sampler (old version) gave about 9% higher results than the reference sampler with an EU inlet.

Comparison with a reference sampler with an US-EPA PM10 inlet

The IVL sampler (old version) fulfils the criteria for equivalence without the use of any calibration function, see Table 14. The uncertainty is only 0,1 % less when a recalculation based on a calibration with the intercept set to zero. As the slope not is significantly different from one, the data from IVL PModel S10 (old version) can be used without any correction.

The calibration equation for the old IVL P Model S10 obtained during this study is thus

$$PM10_{\,ref,US-EPA} = PM10_{IVL\ P\ Model\ S10\ (old)}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,IVL\ PModel\ S10\ (new)}(50) = 10{,}8\ \%$$

Test of comparability	IVL old	
Number of data pairs	61	
	Ref.	Cand.
Average	18,2	18,2
Calibration based on	No calibration	
Calib. equation	y	
Rel. expanded standard uncertainty	10,8%	
Calibration based on	Slope and intercept	
Calib. equation	1,038 y – 0,667	
Rel. expanded standard uncertainty	12,8%	
Calibration based on	Intercept = 0	
Calib. equation	1,008 y	
Rel. expanded standard uncertainty	10,7%	
Calibration based on	Slope = 1	
Calib. equation	y – 0,667	
Rel. expanded standard uncertainty	12,5%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 14. Equivalence results for IVL P Model S10 (old version). Reference sampler with US-EPA inlet

Discussion on the equivalence of IVL PModel S10 (old and new version)

Both versions of the IVL PModel S10 sampler fulfil the equivalence criteria with the European reference sampler with the original inlet as described in the standard EN 12341 if a calibration

function is applied. However if the equivalence is calculated against a reference sampler equipped with the US-EPA PM10 inlet, the uncertainty decreases somewhat and a much smaller correction is needed, see Table 15.

The reason for the lesser uncertainty and the smaller correction when compared with the reference sampler with an US-EPA inlet is that the inlet used by the IVL PModel S10 sampler is constructed to have the same separation properties as the US-EPA inlet.

The IVL PModel S10 sampler is a part of a manual gravimetric filter method that includes weighing of the filters before and after sampling. The quality of the data obtained with this sampler is thus not only dependent on the sampler, but also on the quality of the weighing procedure. During this study the filter weighing was made by IVL (Swedish Environmental Research Institute). IVL is accredited for weighing of filters and the weighing condition room fulfils the requirements given in the European standard for PM10 (EN 12341:1998).

		IVL PModell S10, version	
Inlet	**Statistics**	**New**	**Old**
EU	Correction[1]	-12%	-9%
	Uncertainty	8,4%	11,7%
US-EPA	Correction	-3%	+1%
	Uncertainty	5,9%	10,8%
1. Correction = How much data from the IVL sampler must be corrected to be equivalent to data from the reference sampler: Note that the correction value here are given for comparison of the two inlet types. Te calibration functions for the samplers are given above			

Table 15. Comparison of some statistics from the equivalence study for the two versions of the IVL PModell S10 sampler evaluated against 1) a reference sampler with the EU PM10 inlet and 2) a reference sampler with the US-EPA inlet.

The volume flow of the two versions of the IVL sampler varies more about the set-point than in the reference sampler as the flow control is less sophisticated.

The reference sampler controls the volume flow by measurements of the actual ambient temperature and atmospheric pressure. The new version of the IVL sampler controls the flow by measurement of the ambient temperature and assumes an average pressure for the sampling site (mostly depending on the altitude). The flow of the old version of the sampler is controlled by assuming an average seasonal temperature at the sampling site. No assumption of the pressure is made, but indirectly the sampling procedure means that the pressure is assumed to be as at the time the flow is set.

The less stringent volume control means that the uncertainty of the results increases as compared with the reference method. The uncertainty obtained during this study includes this, but does not cover all extreme situations, i.e. if the temperature and pressure varies more than during this study. However, as the atmospheric pressure and ambient temperature very rarely is more than five percent higher or lower than the average pressure/temperature at a site it can be assumed that the

uncertainty of the two samplers due to the less accurate volume control are less than the data quality objectives given in the EU directive 2008/50 at all possible sampling sites in ambient air.

However, an evaluation of the equivalence of the IVL sampler based on the results from only this site is not possible; the results from this site must be evaluated together with comparisons with the reference method at other sites carried out and evaluated according to GDE.

Thermo 1405 F – Results

The Thermo 1405 F instrument has been declared equivalent in United Kingdom and Germany based on a number of equivalence test in the two countries. The results from the tests are reported by TÜV Rheinland[20].

The Swedish representative has applied for the Thermo 1405F instrument to be declared equivalent to the reference method and supported their application with the UK/German equivalence declaration. The objective of participation of the 1405 F in this Swedish test was to assure that the German/UK declaration of equivalence also was applicable during the specific conditions that occur in Sweden during spring.

Data coverage

One Thermo 1405 F instrument participated in the campaign. Due to a delayed transport (the sampler was lost at an airport in USA) and some other problems initially the first results from the 1405 are from three weeks after the start of the campaign. After that the data coverage is 100%.

Between sampler uncertainty

As only one 1405 F participated it is not possible to evaluate the between sampler uncertainty during this campaign. However, during the UK/German equivalence tests the between sampler uncertainty was within the limits of the data quality objectives given in the EU directive 2008/50.

Comparison with the reference sampler with an EU PM10 inlet

The Thermo 1405 F fulfils the equivalence criteria without any calibration, see Table 16. However, the uncertainty is reduced if data are recalculated. The uncertainty of the calibration is least if the slope is fixed to 1.

The calibration equation for the Thermo 1405 F obtained during this study is thus

$$PM10_{\,ref,EU} = PM10_{Thermo\ 1405F} - 3{,}641$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,Thermo\ 1405\ F}\,(50) = 11{,}8\ \%$$

[20] TÜV-Report 936/21209885/B Cologne, November 25, 2011

Test of comparability	Thermo 1405 F	
Number of data pairs	39	
	Ref.	Cand.
Average	17,4	21,8
Calibration based on	No calibration	
Calib. equation	y	
Rel. expanded standard uncertainty	23,8%	
Calibration based on	Slope and intercept	
Calib. equation	0,965 y – 3,641	
Rel. expanded standard uncertainty	12,0%	
Calibration based on	Intercept = 0	
Calib. equation	0,821 y	
Rel. expanded standard uncertainty	19,9%	
Calibration based on	Slope = 1	
Calib. equation	y – 3,641	
Rel. expanded standard uncertainty	11,8%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 16. Equivalence results for Thermo 1405 F. Reference sampler with EU inlet

Comparison with a reference sampler with an US-EPA PM10 inlet

The Thermo 1405F fulfils the criteria for equivalence without any calibration, see Table 17. The uncertainty is not improved by applying any calibration function.

The calibration equation for the Thermo 1405 F obtained during this study is thus

$$PM10_{\,ref,US-EPA} = PM10_{Thermo\ 1405F}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,\ \ Thermo\ 1405\ F}\,(50) = 8{,}2\ \%$$

Test of comparability	Thermo 1405 F	
Number of data pairs	39	
	Ref.	Cand.
Average	18,9	21,8
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	8,2%	
Calibration based on	Slope and intercept	
Calib. equation	1,057 y – 4,073	
Rel. expanded standard uncertainty	10,1%	
Calibration based on	Intercept = 0	
Calib. equation	0,897 y	
Rel. expanded standard uncertainty	18,3%	
Calibration based on	Slope = 1	
Calib. equation	y – 4,073	
Rel. expanded standard uncertainty	13,8%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 17. Equivalence results for Thermo 1405 F. Reference sampler with US-EPA inlet

Discussion on the equivalence of Thermo 1405 F

The Thermo 1405F fulfils the criteria for equivalence when compared with the European reference sampler with the original inlet as described in the standard EN 12341 if a calibration function is applied. However if the equivalence is calculated against a reference sampler equipped with the US-EPA PM10 inlet, the uncertainty decreases somewhat and no correction is needed, see Table 17. The better agreement when Thermo 1405F is compared with the reference sampler with an US-EPA inlet is because the Thermo 1405F also is equipped with an US-EPA inlet.

The results from this limited study is thus in line with the results from the studies performed in Germany and United Kingdom and the Thermo 1405F is equivalent also in the environments where the largest number of exceedances of the daily PM10 limit value occurs.

Thermo FDMS – Results

The Thermo FDMS instrument has not been declared equivalent in Sweden, but fulfilled the equivalence criteria in a study in United Kingdom[21]. The instrument are used in a number of cities in Sweden and also in the national air monitoring programme in the rural background.

Data coverage

Two Thermo FDMS participated in the campaign. After some installation problems, both instruments worked without any data loss from 28 March to 22 May.

Between sampler uncertainty

The Thermo FDMS instrument fulfils the criteria for the between sampler uncertainty, see Table 18.

No. of data pairs	47	Between sampler uncertainty
Avg. of daily PM10, µg/m³		$u_{bs,CM}$ = 1,31 µg/m³
FDMS #1	FDMS #2	
17,7	16,2	Fulfils criteria, $u_{bs,CM}$ < 2,5? YES

Table 18. Between sampler uncertainty for Thermo FDMS

Comparison with the reference sampler with an EU PM10 inlet

Both FDMS instruments fulfils the criteria for equivalence without any calibration, see Table 19. For both instruments, however, the expanded uncertainty is reduced if data are recalculated based on a calibration when the intercept is zero.

The difference between the two samplers is relatively large; the results of the FDMS #1 shall be reduced by about 10% to be equivalent with the reference sampler, while the FDMS #2 only needs to be reduced by about 2%. The calibration function and the relative expanded uncertainty for Thermo FDMS is therefore based on the average of the daily results of the two instruments.

The calibration equation for the Thermo FDMS obtained during this study is thus

$$PM10_{\,ref,\ EU} = 0{,}939\ x\ PM10_{Thermo\ FDMS}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ Thermo\ FDMS}\,(50) = 6{,}7\ \%$$

[21] . Bureau Veritas. UK Equivalence Programme for Monitoring of Particulate Matter. (2006). Ref: BV/AQ/AD202209/DH/2396

Test of comparability	FDMS #1		FDMS #2		Average FDMS	
Number of data pairs	47		49		47	
	Ref.	Cand.	Ref	Cand.	Ref.	Cand.
Average	15,8	17,7	16,0	16,3	15,8	16,9
Calibration based on	No calibration					
Calib. Equation	y		y		y	
Rel. expanded standard uncertainty	17,6%		7,9%		12,4%	
Calibration based on	Slope and intercept					
Calib. equation	0,941y - 0,805		0,975y + 0,125		0,956y - 0,368	
Rel. expanded standard uncertainty	9,7%		8,8%		7,6%	
Calibration based on	Intercept = 0					
Calib. equation	0,904y		0,981y		0,939y	
Rel. expanded standard uncertainty	8,7%		6,9%		6,7%	
Calibration based on	Slope = 1					
Calib. equation	y - 0,805		y + 0,125		y - 0,368	
Rel. expanded standard uncertainty	14,9%		8,5%		11,3%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%						

Table 19. Equivalence results for Thermo FDMS. Reference sampler with EU inlet

Comparison with a reference sampler with an US-EPA PM10 inlet

Also in this case when the results of the two FDMS units was compared with the results from a reference sampler equipped with an US-EPA PM10-inlet, both FDMS instruments were equivalent with the reference sampler without any recalculation, see Table 20.

To generalize the results, the daily average of the two FDMS instruments were used in the calculation of the calibration function and the relative expanded standard uncertainty.

The calibration equation for the Thermo FDMS obtained during this study is thus

$$PM10_{\,ref,\ US-EPA} = 1{,}038\,x\,PM10_{Thermo\ FDMS}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,\ Thermo\ FDMS}\,(50) = 4{,}5\ \%$$

Test of comparability	FDMS #1		FDMS #2		Average FDMS	
Number of data pairs	47		49		47	
	Ref.	Cand.	Ref	Cand.	Ref.	Cand.
Average	17,6	17,7	17,7	16,3	17,6	16,9
Calibration based on	No calibration					
Calib. equation	y		y		y	
Rel. expanded standard uncertainty	5,8%		15,0%		9,0%	
Calibration based on	Slope and intercept					
Calib. equation	1,030y - 0,664		1,068y + 0,333		1,046y – 0,177	
Rel. expanded standard uncertainty	6,9%		7,7%		5,8%	
Calibration based on	Intercept = 0					
Calib. equation	1,000y		1,084y		1,038y	
Rel. expanded standard uncertainty	6,2%		6,5%		4,5%	
Calibration based on	Slope = 1					
Calib. equation	y - 0,664		y + 0,333		y – 0,177	
Rel. expanded standard uncertainty	14,9%		13,9%		9,8%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%						

Table 20. Equivalence results for Thermo FDMS. Reference sampler with US-EPA inlet

Discussion on equivalence of Thermo FDMS

The Thermo FDMS fulfils the criteria for equivalence when compared with the European reference sampler with the original inlet as described in the standard EN 12341 and also when compared with a reference sampler with the US-EPA inlet. There is no need to apply a calibration function. However the uncertainty decreases if the equivalence is calculated against a reference sampler equipped with the US-EPA PM10 inlet, i.e. a reference sampler equipped with the same inlet as the Thermo FDMS.

The results from this study confirms the findings from the equivalence study in United Kingdom, see page 44. In the UK study different calibration equations were found at different places. Slopes were both greater and smaller than 1 and the intercepts both negative and positive. In the report from the UK study it was concluded that “Corrections are applied where the slopes of all data sets are either all greater or all less than 1 and/or where the intercepts of all the data sets are either all greater or all less than zero”. Thus, if that not was the case, no correction should be done. Thus the conclusion was that the results obtained with the FDMS are equivalent with the reference sampler without any recalculation. The findings in this limited study confirm the results in the UK study and thus the FDMS can be declared equivalent with the reference sampler for PM10 without the application of any calibration function.

Grimm EDM 180 – Results

The Grimm EDM 180 is declared equivalent with the reference method in Sweden based on equivalence studies in Austria and Germany. In this study a control was made that the results in those studies also are applicable in the environment in Sweden where the number of exceedances is highest.

Data coverage

Two Grimm EDM 180 participated in the campaign; one during the whole campaign from 19 March to 27 May, the other from 5 April to 20 May. The data coverage was 87 and 100 percent respectively.

Between sampler uncertainty

The between sampler uncertainty is 0,49 µg/m³, less than the criteria given in GDE, see Table 21. Thus the Grimm EDM 180 instrument fulfils the criteria for the between sampler uncertainty

No. of data pairs	33	Between sampler uncertainty
Avg. of daily PM10, µg/m³		$u_{bs,CM}$ = 0,49 µg/m³
EDM #1	EDM #2	
13,6	14,0	Fulfils criteria, $u_{bs,CM}$ < 2,5? YES

Table 21. Between sampler uncertainty for Grimm EDM 180

Comparison with the reference sampler with an EU PM10 inlet

The two EDM 180 instruments both fulfil the equivalence criteria without any recalculation, see Table 22. A recalculation of the data based on the orthogonal regression does not decrease the uncertainty.

To generalize the results, the daily averages of the two EDM 180 instruments were used in the calculation of the calibration function and the relative expanded standard uncertainty.

The calibration equation for the Grimm EDM 180 obtained during this study is thus

$$PM10_{\,ref,\ EU} = PM10_{EDM\ 180}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ EDM\ 180}\,(50) = 11{,}5\ \%$$

Test of comparability	EDM #1		EDM #2		Average EDM	
Number of data pairs	55		41		31	
	Ref.	Cand.	Ref	Cand.	Ref.	Cand.
Average	16,0	14,8	16,2	15,6	14,6	13,9
Calibration based on	No calibration					
Calib. equation	y		y		Y	
Rel. expanded standard uncertainty	11,6%		11,0%		11,5%	
Calibration based on	Slope and intercept					
Calib. equation	0,937y + 2,121		1,029y + 0,129		1,022y + 0,446	
Rel. expanded standard uncertainty	14,0%		13,1%		16,4%	
Calibration based on	Intercept = 0					
Calib. equation	1,048y		1,036y		1,048y	
Rel. expanded standard uncertainty	19,0%		10,2%		12,2%	
Calibration based on	Slope = 1					
Calib. equation	y + 2,121		y + 0,129		y + 0,446	
Rel. expanded standard uncertainty	17,1%		11,1%		11,5%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%						

Table 22. Equivalence results for Grimm EDM 180. Reference sampler with EU inlet

Comparison with a reference sampler with an US-EPA PM10 inlet

When the results from the EDM 180 is compared with the results from a reference sampler with an US-EPA inlet, the two participating EDM 180 instruments are equivalent with the reference sampler without any recalculation, seeTable 23.

However, on average the EDM 180 instruments gives lower results than the reference sampler (EDM #1 17%; EDM #2 12%). Therefore calibration functions that increase the values from the EDM 180 decrease the uncertainty. In the case of EDM #1 an increase of the obtained values by 2,5 gives the lowest uncertainty (15,8%), in the case of EDM #2 an increase of the obtained values by 13% gives the lowest uncertainty (11,3%).

To generalize the results, the daily averages of the two EDM 180 instruments were used in the calculation of the calibration function and the relative expanded standard uncertainty. Also In this case the instrument is equivalent to the reference sampler without the application of any calibration function. However, the uncertainty is reduced if the results are recalculated based on the results from the orthogonal regression. The uncertainty decrease most if the calibration function based on the regression with the intercept set to zero.

The calibration equation for the Grimm EDM 180 obtained during this study is thus

$$PM10_{\,ref,\ US-EPA} = 1{,}120\ x\ PM10_{EDM\ 180}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,\ EDM\ 180}(50) = 14{,}6\ \%$$

Test of comparability	EDM #1		EDM #2		Average EDM	
Number of data pairs	55		41		31	
	Ref.	Cand.	Ref	Cand.	Ref.	Cand.
Average	17,9	14,8	17,8	15,6	15,7	13,9
Calibration based on	No calibration					
Calib. equation	y		y		y	
Rel. expanded standard uncertainty	22,1%		23,2%		18,8%	
Calibration based on	Slope and intercept					
Calib. equation	1,042 + 2,501		1,109y + 0,487		1,066y + 0,92	
Rel. expanded standard uncertainty	17,6%		13,3%		17,1%	
Calibration based on	Intercept = 0					
Calib. equation	1,175y		1,134y		1,120y	
Rel. expanded standard uncertainty	22,9%		11,3%		14,6%	
Calibration based on	Slope = 1					
Calib. equation	y + 2,501		y + 0,487		y + 0,92	
Rel. expanded standard uncertainty	15,8%		21,7%		16,4%	

Numbers in green/red: Equivalence criteria fulfilled/not fulfilled.
Criterion
Slope. Not significant ≠ 1 or 0,98 < slope < 1,02
Intercept. Not significant ≠ 0 or -1 < intercept < +1
Rel. expanded standard uncertainty < 25%

Table 23. Equivalence results for Grimm EDM 180. Reference sampler with US-EPA inlet

Discussion on equivalence of Grimm EDM 180

The Grimm EDM 180 fulfils the criteria for equivalence when compared with the European reference sampler with the original inlet as described in the standard EN 12341. It is not necessary to use any calibration function.

If the results from Grimm EDM 180 are evaluated against the reference sampler equipped with an US-EPA inlet, the sampler is still equivalent without the need of any calibration function. However, the EDM on average gives about 12% lower results than the reference in this case and the uncertainty increases.

To calculate PM10, the Grimm EDM 180 uses an assumed PM10 definition (i.e. cut-off curve) in the calculations, see page 12. It is not clear from the documentation of the instrument which PM10 definition that is used, but based on the results in this study it is likely that the used cut-off curve is close to the European definition.

That the Grimm EDM 180 fulfils the equivalence criteria in this limited study confirms the results from the equivalence studies in Austria[22] and Germany[23] on which the Swedish approval is based. However, in the Austrian and German studies a calibration function that reduced the Grimm EDM 180 data with about 15 – 20 percent was needed to obtain the equivalence. In a limited study in Finland[24], the Grimm EDM 180 also gave higher results (about 30%) than the reference.

The reason that the Grimm EDM 180 in this study does not need any correction in contrast to the other studies is unknown. The Grimm EDM 180 does not measure the mass directly; the mass calculations are based on assumptions on the physical and optical properties of the particles. The reason for the different results might thus be that the properties of the particles in the different studies not are the same.

The fact that the calibration function for the EDM 180 might vary in different environments, makes it important to assure the specific calibration function for the sampling site where the EDM 180 is to be used.

[22] Wolf, A.; Fröhlich, M. and Moosmann L. (2010) Equivalence test of optical PM monitors by order of the company Grimm at 4 measurement locations in Austria. Umweltbundesamt Austria, Vienna, January 2010.
[23] LUWB (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg) Prüf-bericht 21-18/2005 "Prüfung des Schwebstaubmessgerätes Environmental Dust Monitor - model 180 der Firma Grimm Aerosoltechnik auf gleichwertige ergebnisse wie mit der Referenzmethode der Europäischen Norm DIN EN 12341 bei der Messung von Schwebstaub der Fraktion PM10", 05. Januar 2006, 83 pp
[24] Jari Waldén et al. (2010). Demonstration of the equivalence of PM2.5 and PM10 measurement methods in Helsinki 2007–2008. Finnish Meteorological Institute Studies No. 3.

Thermo Sharp 5030 – Results

The Thermo Sharp 5030 has fulfilled all equivalence criteria in test by TÜV in Germany and have also been declared equivalent in Sweden. The participation in this study is to assure that the equivalence claim also is valid in the environment where most exceedances occur in Sweden.

Data coverage

One Thermo Sharp 5030 participated during the whole campaign, 19 March to 27 May. There were no data losses, i.e. the data coverage was 100%.

Between sampler uncertainty

As only one instrument participated, it is not possible to evaluate the between sampler uncertainty during this study. But as stated above, the criterion for between samplers uncertainty was fulfilled in the German tests.

Comparison with the reference sampler with an EU PM10 inlet

The Sharp 5030 is equivalent with the reference sampler without the application of any calibration function, see Table 24. The use of any correction does not improve the uncertainty.

The calibration equation for the Thermo Sharp 5030 obtained during this study is thus

$$PM10_{\,ref,\ EU} = PM10_{Thermo\ Sharp\ 5030}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ Thermo\ Sharp\ 5030}\,(50) = 12{,}5\ \%$$

Test of comparability	Thermo Sharp 5030	
Number of data pairs	65	
	Ref.	Cand.
Average	16,7	18,7
Calibration based on	No calibration	
Calib. equation	y	
Rel. expanded standard uncertainty	12,5%	
Calibration based on	Slope and intercept	
Calib. equation	1,038y – 2,674	
Rel. expanded standard uncertainty	15,7%	
Calibration based on	Intercept = 0	
Calib. equation	0,917 y	
Rel. expanded standard uncertainty	18,7%	
Calibration based on	Slope = 1	
Calib. equation	y – 2,674	
Rel. expanded standard uncertainty	14,7%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 24. Equivalence results for Thermo Sharp 5030. Reference sampler with EU inlet

Comparison with a reference sampler with an US-EPA PM10 inlet

The Sharp 5030 is equivalent with the reference sampler with an US-EPA inlet without the application of any calibration function see Table 25. However, the use of a correction based on the orthogonal regression reduces the uncertainty somewhat.

The calibration equation for the Thermo Sharp 5030 obtained during this study is thus

$$PM10_{\,ref,\ US-EPA} = 1{,}149\ x\ PM10_{Thermo\ Sharp\ 5030} - 2{,}821$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,\ Thermo\ Sharp\ 5030}\,(50) = 18{,}2\ \%$$

Test of comparability	Thermo Sharp 5030	
Number of data pairs	65	
	Ref.	Cand.
Average	18,7	18,7
Calibration based on	No calibration	
Calib. equation	y	
Rel. expanded standard uncertainty	20,8%	
Calibration based on	Slope and intercept	
Calib. equation	1,149y – 2,821	
Rel. expanded standard uncertainty	18,2%	
Calibration based on	Intercept = 0	
Calib. equation	1,021 y	
Rel. expanded standard uncertainty	18,5%	
Calibration based on	Slope = 1	
Calib. equation	y – 2,821	
Rel. expanded standard uncertainty	30,6%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 25. Equivalence results for Thermo Sharp 5030. Reference sampler with US-EPA inlet

Discussion on equivalence of Thermo Sharp 5030

The Thermo Sharp 5030 is declared equivalent for measurement of PM10 in Sweden based on German equivalence studies.

The Thermo Sharp 5030 was equipped with an US-EPA inlet during this study. However, the uncertainty was less a when the Thermo Sharp 5030 results were compared with the results obtained with the reference sampler with the EU inlet than when compared with the reference

sampler with the US-EPA inlet. This is surprising; one would expect that the uncertainty is smaller if the two samplers use the same inlet than if they use different inlets.

During the equivalence study in Germany, the Thermo Sharp 5030 and the reference sampler were equipped with EU-inlets, i.e. the two instruments used the same inlet. During this study the Thermo Sharp 5030 was equipped with the US-EPA inlet. To be able to compare the results from the German study with this, the results from the equivalence evaluation when the reference sampler was used with the same inlet as the Thermo Sharp 5030, i.e. US-EPA inlet should be used.

As noted above the least uncertainty when the Thermo Sharp 5030 is evaluated against the reference sampler with the US-EPA inlet is obtained when a correction for both slope and intercept is done. However, the improvement compared with the uncertainty when data not are corrected is relatively small; from 20,8% to 18,2%. Thus the result from this limited study confirms the conclusion from the German study that the Thermo Sharp 5030 is equivalent with the reference sampler and no correction of data is needed.

SM 200 – Results

The SM200 has fulfilled all equivalence criteria in tests made in Germany and United Kingdom. Based on those studies, the SM200 have been declared equivalent in Sweden. The participation in this study is to assure that the equivalence claim also is valid in the environment where most exceedances occur in Sweden.

Data coverage

One SM200 was installed at the start of the campaign, 19 March. It was running without any data losses to March 28, when the instrument was destroyed due to a leak in the roof of the measurement cabin. Another instrument was installed 11 April and was subsequently running to the end of the campaign without any data losses.

Between sampler uncertainty

As only one instrument participated, it is not possible to evaluate the between sampler uncertainty during this study, but the criterion for between samplers uncertainty was fulfilled in the German tests.

Comparison with the reference sampler with an EU PM10 inlet

The SM 200 fulfils the criteria for equivalence without the need for any recalculation based on the orthogonal regression, see Table 26. The use of any calibration function does not improve the uncertainty.

Test of comparability	SM200	
Number of data pairs	51	
	Ref.	Cand.
Average	17,6	17,6
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	5,5%	
Calibration based on	Slope and intercept	
Calib. equation	1,003y – 0,025	
Rel. expanded standard uncertainty	7,4%	
Calibration based on	Intercept = 0	
Calib. equation	1,002y	
Rel. expanded standard uncertainty	5,9%	
Calibration based on	Slope = 1	
Calib. equation	y – 0,025	
Rel. expanded standard uncertainty	5,8%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1		

Rel. expanded standard uncertainty < 25%

Table 26. Equivalence results for SM200. Reference sampler with EU inlet

The calibration equation for the SM200 obtained during this study is thus

$$PM10_{\,ref,\ EU} = PM10_{SM200}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ SM200}(50) = 5{,}5\ \%$$

Comparison with a reference sampler with an US-EPA PM10 inlet

Also when the equivalence of the SM200 is evaluated using data from the reference sampler with an US-EPA inlet, the sampler fulfils the criteria for equivalence without any correction, see Table 27.

A correction based on the orthogonal regression reduces the uncertainty. The uncertainty is least, 10,7%, when the intercept of the regression line is set to zero, i.e. the regression line is forced through origin.

Test of comparability	SM200	
Number of data pairs	51	
	Ref.	Cand.
Average	19,5	17,6
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	20,1%	
Calibration based on	Slope and intercept	
Calib. Equation	1,093y + 0,277	
Rel. expanded standard uncertainty	12,6%	
Calibration based on	Intercept = 0	
Calib. Equation	1,105y	
Rel. expanded standard uncertainty	10,7%	
Calibration based on	Slope = 1	
Calib. Equation	y + 0,277	
Rel. expanded standard uncertainty	19,4%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 27. Equivalence results for SM200. Reference sampler with US-EPA inlet

The calibration equation for the SM200 obtained during this study is thus

$$PM10_{\,ref,\ US-EPA} = 1{,}105\ x\ PM10_{SM200}$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{US-EPA,\ SM200}\,(\mathbf{50}) = \mathbf{10,7}\ \%$$

Discussion on equivalence of SM 200

The uncertainty of the SM200 is smaller when its data is compared with the reference sampler with an EU-inlet than when compared with the reference sampler with an US-EPA inlet. Moreover, no correction is needed when the uncertainty calculations are based on the comparison with the data from the reference sampler with the EU-inlet. This is to be expected as the SM200 during this study also used the EU-inlet.

In the German and United Kingdom approvals of equivalence it is stated that the uncertainty can be calculated without the need for any correction for slope and/or intercept. This study gives the same results and thus confirms the conclusion the SM200 is equivalent to the reference method and no correction of data is needed.

SWAM 5A – Results

The SWAM 5A has fulfilled all equivalence criteria in tests made by TÜV in Germany and have also been declared equivalent in Sweden. The participation in this study is to assure that the equivalence claim also is valid in the environment where most exceedances occur in Sweden.

Data coverage

One SWAM 5A was installed at the start of the campaign, 19 March and participated to 19 May; in all 62 days. There are 55 valid daily averages. At least 5 of the missing days were due to operator mistakes or problems with the air conditioning in the measurement cabin. Thus the data coverage is more than 95%.

Between sampler uncertainty

As only one instrument participated, it is not possible to evaluate the between sampler uncertainty during this study. But as stated above, the criterion for between samplers uncertainty was fulfilled in the German tests.

Comparison with the reference sampler with an EU PM10 inlet

The SWAM 5A fulfils the criterion for equivalence without any correction for slope and/or intercept, see Table 28. The relative expanded uncertainty at the daily limit value is 18,8%. However, the uncertainty is reduced to 6,9% if data is corrected for the slope and intercept; to 7,4% if data is corrected only for intercept (i.e. the slope is fixed to 1). In contrast the uncertainty increases to 20,0% if the regression line is forced to pass through origin.

Test of comparability	Swam 5A	
Number of data pairs	50	
	Ref.	Cand.
Average	15,0	18,7
Calibration based on	No calibration	
Calib. Equation	y	
Rel. expanded standard uncertainty	18,8%	
Calibration based on	Slope and intercept	
Calib. Equation	0,975y – 3,194	
Rel. expanded standard uncertainty	6,9%	
Calibration based on	Intercept = 0	
Calib. Equation	0,829y	
Rel. expanded standard uncertainty	20,0%	
Calibration based on	Slope = 1	
Calib. Equation	y – 3,194	
Rel. expanded standard uncertainty	7,4%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 28. Equivalence results for SWAM 5A. Reference sampler with EU inlet

The calibration function in this case is thus

$$PM10_{\,ref,\ EU} = 0{,}975\ x\ PM10_{SWAM\ 5A} - 3{,}194$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ SWAM\ 5A}(50) = 6{,}9\ \%$$

Comparison with a reference sampler with an US-EPA PM10 inlet

The SWAM 5A fulfils the criterion for equivalence without any correction for slope and/or intercept, see Table 29. The relative expanded uncertainty at the daily limit value is 10,9 %. If the data is corrected for the slope and intercept decreases slightly ; to 10,1 %.

Test of comparability	SWAM 5A	
Number of data pairs	50	
	Ref.	Cand.
Average	16,9	18,7
Calibration based on	No calibration	
Calib. equation	y	
Rel. expanded standard uncertainty	10,9%	
Calibration based on	Slope and intercept	
Calib. equation	1,135y – 4,134	
Rel. expanded standard uncertainty	10,1%	
Calibration based on	Intercept = 0	
Calib. equation	0,938y	
Rel. expanded standard uncertainty	21,9%	
Calibration based on	Slope = 1	
Calib. equation	y – 4,134	
Rel. expanded standard uncertainty	26,8%	
Numbers in green/red: Equivalence criteria fulfilled/not fulfilled. Criterion Slope. Not significant ≠ 1 or 0,98 < slope < 1,02 Intercept. Not significant ≠ 0 or -1 < intercept < +1 Rel. expanded standard uncertainty < 25%		

Table 29. Equivalence results for SWAM 5A. Reference sampler with US-EPA inlet

The calibration function in this case is thus

$$PM10_{\,ref,\ US-EPA} = 1{,}135\ x\ PM10_{SWAM\ 5A} - 4{,}134$$

The relative expanded uncertainty at the daily limit value (50 µg/m³) is

$$W_{EU,\ SWAM\ 5A}(50) = 10{,}1\ \%$$

Discussion on equivalence of SWAM 5A

As the SWAM 5A is equipped with an EU-inlet, the uncertainty is less when comparing the SWAM 5A results with the results from the reference sampler with the same EU-inlet than when comparing with the reference sampler with an US-EPA inlet.

The uncertainty decreases most when correcting for the intercept, from 18,8% for uncorrected data to 7,4%, see Table 28. The additional correction for slope decreases the uncertainty marginally to 6,9%.

A comparison of the SWAM 5A and the EU reference sampler results shows that the SWAM 5A are between 2 – 6 µg/m³ higher every day, with a few exceptions, see Figure 13. The difference is not dependent on the PM 10 concentration. The intercept calculated in the orthogonal regression analysis, that can be seen as a measure of the difference, is 3,28 ± 0,82 (95 % confidence level), i.e. significantly greater than zero. The reason for the difference is unknown.

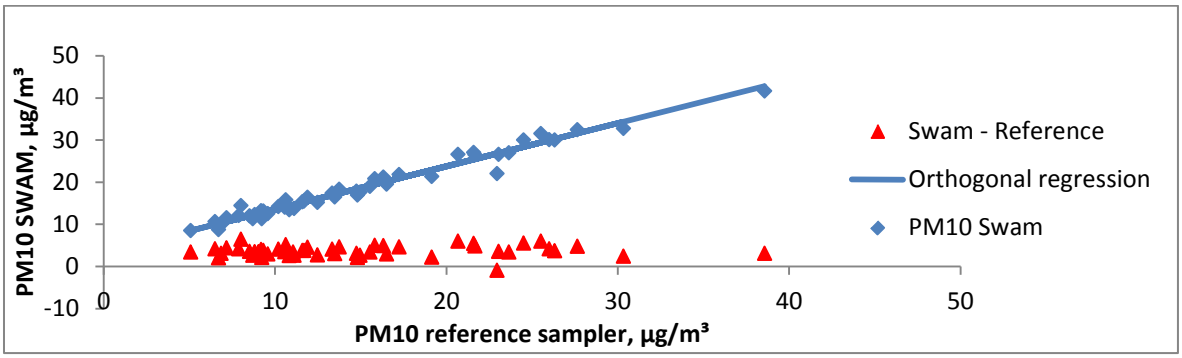

Figure 13. PM10 daily means as measured by SWAM 5A and the difference between SWAM 5A PM10 and the reference sampler PM10 versus PM10 by the reference sampler.

The Swedish approval is based on results from an equivalence test[25] performed at four sites in Germany and Great Britain. The results from the four sites as well as the results from this study is summarised in Table 30.

The slope varies from 0,96 to 1,12 and the intercept from -1,8 to 3,3. As discussed on page 46, discussion on equivalence of Thermo FDMS, a conclusion from the UK equivalence study was that if the slopes is both greater and less than 1 and the intercept is greater and less than 0, no correction of the data shall be done.

The result from this study together with the findings from the TÜV study means that the SWAM 5A can be used as an equivalent method for measuring PM10 without the application of any calibration function.

[25] TÜV Rheinland Report 936/21207522/A dated March 23, 2009

Site	Slope	Intercept	Expanded uncertainty at 50 µg/m³ (%)	Study
Stockholm, traffic	1,03	**3,28**	18,8	This
Köln, urban background	**1,10**	0,06	20,8	TÜV
Bonn, traffic	**1,12**	**-1,11**	21,7	TÜV
Teddington, urban background	0,96	**2,27**	7,7	TÜV
Bruehl, gravel pit	1,04	**-1,82**	6,5	TÜV
Numbers in bold indicates that the slope/intercept is statistically significant (95%) different from 1 respective 0				

Table 30. A summary of slope and intercept obtained from orthogonal regression analysis between PM10 daily averages measured by SWAM 5A and the EU reference sampler at five sites in Europe

Summary of equivalence discussions for the candidate instruments

Some of the instruments that were tested for equivalence used the US-EPA inlet, some the EU-inlet. As the purpose of the study was to compare the candidate instruments with the reference sampler, not to compare inlets, the equivalence results for the candidate instruments summarised here, see Table 31, are obtained when comparing with a reference sampler equipped with the same type of inlet as the candidate.

Note: The conclusions given in Table 31 are based on the results from this study and on the results from the studies in other European countries that the Swedish approval is based on.

Instrument	**Comment**
Thermo TEOM 1400, VCM corrected	Equivalent to the reference sampler with the US-EPA inlet without any correction function.
IVL PModel S10 - old version[1]	Equivalent to the reference sampler with the US-EPA inlet without any correction function at this site. However, results from more types environments are needed to declare the instrument as equivalent.
IVL PModel S10 - new version[2]	Equivalent to the reference sampler with the US-EPA inlet with a correction function at this site. Calibration function: x = 0.968y However, results from other types environments are needed to declare the instrument as equivalent
Thermo 1405 F	Equivalent to the reference sampler with the US-EPA inlet without any correction function
Thermo FDMS	Equivalent to the reference sampler with the US-EPA inlet without any correction function
Grimm EDM 180	Equivalent to the reference sampler with the EU-inlet without any correction function in this study. However, in the studies the Swedish approval is based on correction functions were needed. The fact that the correction function for the EDM 180 might vary in different environments, makes it important to assure the specific calibration function for the sampling site where the EDM 180 is to be used
Thermo Sharp 5030	Equivalent with the reference sampler with the US-EPA inlet without any correction function.
Opsis SM200	Equivalent to the reference sampler with the EU-inlet without any correction function
FAI Swam 5A	Equivalent to the reference sampler with the EU-inlet without any correction function
1. Flow corrected to seasonal average ambient temperature. Flow corrected to ambient pressure at time for flow calibration 2. Flow corrected to ambient temperature. Flow corrected to ambient pressure at time for flow calibration.	

Table 31. Summary of equivalence results

Annex A. Daily average PM10 concentrations, µg/m^3, obtained during the equivalence study in Stockholm spring 2012

Date	1405F	Derenda	FDMS no. 1	FDMS no. 2	GRIMM no. 1	GRIMM no. 2	IVL new no. 1	IVL new no. 2	IVL old	Leckel w. EPA-inlet	Leckel w. EU-inlet	Sharp	SM200	SWAM	TEOM no. 1	TEOM no. 2
2012-03-19		12,5			9,7		15,9	17,1	18,1	17,5	12,9	9,5	11,1			17,7
2012-03-20		6,9			5,6		8,0	7,9	8,2	7,3	6,8	11,4	7,7	9,9		6,7
2012-03-21		9,1			6,6		8,7	9,2	10,9	9,9	9,0	9,1	9,4	12,5		10,2
2012-03-22		9,2			7,2				10,0	10,6	9,2	9,7	9,3	13,2		10,1
2012-03-23		23,1			16,8				19,7	27,5	23,6	23,4	21,5	27,0		26,9
2012-03-24		10,1			8,8				11,9	10,5	10,2	13,8	10,1	14,2	7,8	9,4
2012-03-25		30,6			26,9				31,6	36,2	30,3	31,9	29,5	32,7	36,6	39,9
2012-03-26		15,8			17,4				16,8	20,1	15,5	20,4	16,1	18,9	16,4	20,0
2012-03-27		16,4			12,0				17,7	22,1	16,5	17,7	15,0	19,5	21,3	23,8
2012-03-28		14,8	14,5	14,3	12,3		15,9	16,1	14,9	15,1	14,7	20,1		17,8	13,2	13,6
2012-03-29		11,7	13,5	13,1	7,7		15,8	16,3	17,2	14,6	11,6	10,7		15,3	13,6	15,6
2012-03-30		10,8	10,8	10,6	4,8		10,9	11,9	19,7	11,6	10,8	12,1		13,4	9,8	10,6
2012-03-31		9,1	10,5	10,9	6,8		7,8	11,2	9,7	11,5	8,8	11,0		12,3	11,8	12,3
2012-04-01		5,2	6,4	5,8	4,4		4,1	7,2	6,9	5,6	5,1	7,0		8,4	3,9	4,3
2012-04-02			32,0	29,7	24,6		34,1	35,8	24,0	35,5	27,6	27,0		32,4	36,2	37,5
2012-04-03		22,1	25,4	21,7	20,3		23,5	24,7	24,7	24,5	21,7	25,5		26,5	24,9	27,0
2012-04-04		14,1	14,9	13,0	14,0		13,6	15,4	15,8	15,0	13,5	14,7			14,6	15,7
2012-04-05		12,0	14,0	14,2	12,3	12,7	15,1	13,9	14,2	13,6	11,7	13,4		15,4	13,5	13,8
2012-04-06		7,8	8,8	7,8	5,7	6,0	9,4	9,2	9,5	8,6	7,9	9,4		12,0	7,2	7,5
2012-04-07		11,0	12,8	11,8	8,2	8,3	13,1	11,2	11,9	14,5	11,1	10,6		13,7	13,7	14,4
2012-04-08		10,9	10,9	10,2	9,2	9,5	12,8	12,3	10,6	11,6	10,6	11,9		15,8	10,8	11,7
2012-04-09		13,9	15,0	13,9		13,0	16,2	14,8	16,2	14,9	13,5	17,1		16,5	12,7	12,9

Date	1405F	Derenda	FDMS no. 1	FDMS no. 2	GRIMM no. 1	GRIMM no. 2	IVL new no. 1	IVL new no. 2	IVL old	Leckel w. EPA-inlet	Leckel with EU-inlet	Sharp	SM200	SWAM_ PM10	TEOM no. 1	TEOM no. 2
2012-04-10		21,2	22,0	21,0		19,6	24,2	22,6	20,3	22,5	20,9	24,4			17,4	17,9
2012-04-11		45,1	43,7	43,3		40,7	49,1		31,0	45,1	44,4	42,8	45,7		35,7	36,9
2012-04-12	43,7	39,5	38,9	38,0	33,6	33,9	27,2		34,7	39,6	38,6	32,6	36,8	41,6	33,4	35,2
2012-04-13	27,8	21,8	23,4	21,2	13,5	14,5	22,7	25,3	20,3	23,8	21,6	21,0	19,2	27,0	20,2	20,6
2012-04-14	9,8	6,2	6,9	4,9		5,1	7,2	6,6	6,6	6,1	8,7	8,0	5,3	11,3		5,3
2012-04-15	17,0	14,9	17,0	13,7	17,2	15,5	16,0	16,2	16,2	16,5	15,0	19,6	14,5	17,6	14,2	15,0
2012-04-16	28,0	20,8	23,6	21,7	19,0	19,9		23,9	21,2	24,4	20,7	19,3	21,4	26,6	21,8	23,7
2012-04-17	16,4	10,6	13,6	10,6	11,8	12,0	9,2	13,0	11,8	11,2	10,6	15,9	11,4	14,0	10,0	10,4
2012-04-18	19,9	16,3	19,4	16,2	15,2	15,6	19,1	18,9	14,7	16,8	15,8	15,7	16,7	20,8	15,3	15,9
2012-04-19	31,8	26,7	31,2	28,3		24,9	31,3	32,8	31,2	30,9	26,3	26,7	24,8	30,0	29,1	32,7
2012-04-20	12,6	9,5	10,8	9,2	6,2	6,5	9,8	10,9	10,2	10,1	9,6	15,0	11,0	12,5	8,0	8,4
2012-04-21	10,4	9,4	10,8	8,8	7,8	8,4	11,5	10,5		9,3	9,2	10,1	8,9	11,3	8,0	8,5
2012-04-22	15,7	12,4	13,4	12,4	11,6	12,5	15,1			12,2	12,5	15,9	12,8	15,2	9,4	9,7
2012-04-23	17,7	15,1	17,0	15,8		17,3	17,0	15,8	15,3	16,1	14,8	16,4	16,5	16,9	12,9	13,1
2012-04-24	29,6					25,9	30,7	29,5	25,3			23,2	25,6	28,0	22,9	23,5
2012-04-25	32,8	23,7	34,7	28,9		26,3	35,5		32,3	30,4	25,3	28,1	22,5		28,6	31,8
2012-04-26	20,8	16,0		17,6	18,0	19,5	17,7	17,3	15,9	17,3	16,3	28,2	16,7	21,2	12,3	12,5
2012-04-27							12,1	12,0	12,8			9,8	10,2	17,3		
2012-04-28	10,2		8,8	7,5	6,3	7,2	6,7		9,7	8,4	7,2	9,7	7,9	11,5	6,6	6,9
2012-04-29	15,1		12,7	12,3	8,8	9,6	15,0		16,2	14,7	11,9	12,0	10,7	16,4	14,6	16,0
2012-04-30	26,8		23,7	22,8		22,0	26,6		24,1	25,4	23,0	26,2	23,7	26,6	26,4	27,4
2012-05-01	19,7		16,5	15,0		13,5	16,4		14,9	16,0	13,7	16,7	13,1	18,3	11,6	15,3
2012-05-02		18,7				19,9	18,3		22,2	21,9	19,4	19,6	20,8		22,4	23,3
2012-05-03		22,0			21,2	21,7	19,6		27,5	26,5	22,9	23,3	20,2	22,0	23,6	25,9

2012-05-04	22,2	18,4	20,6	18,2	16,2	16,8	23,7		18,2	21,5	19,1	24,3	17,6	21,3	19,5	21,5
2012-05-05	15,5	8,0	14,2	12,9	12,1	12,7	13,6		13,4	11,8	8,6	16,4	9,3		9,7	10,1
2012-05-06	12,3	7,9	8,1	6,8	6,3	6,5	8,4		9,7	9,1	8,5	8,0	8,3	12,0	7,8	8,0

Date	1405F	Derenda	FDMS no. 1	FDMS no. 2	GRIMM no. 1	GRIMM no. 2	IVL new no. 1	IVL new no. 2	IVL old	Leckel w. EPA-inlet	Leckel with EU-inlet	Sharp	SM200	SWAM_ PM10	TEOM no. 1	TEOM no. 2
2012-05-07	21,6	16,8	18,3	16,8	16,3	16,8	22,0		19,4	19,1	17,2	15,8	16,9	21,8	18,5	19,2
2012-05-08	32,4	25,6	27,2	25,3	29,6	29,5	27,0	25,7	26,5	27,9	26,0	25,7	24,5	30,1	27,4	27,9
2012-05-09	31,7	24,1	28,2	26,2	25,3	26,3	29,2	25,3	26,7	27,4	24,5	32,8	24,7	30,0	25,7	26,4
2012-05-10	18,5				15,3	15,8	14,2	13,5	13,0			25,6	12,4	19,5	10,3	10,5
2012-05-11	11,7				9,0	9,5	9,4	8,6	9,1			9,6	9,6	15,3	4,1	3,9
2012-05-12	15,8		8,8	7,2	6,6	7,1	9,4	9,1	8,8	9,5	9,3	9,9	7,9	13,1	8,5	8,4
2012-05-13	12,4		7,2	5,3	5,5	5,5	7,3	6,8	7,1	7,3	6,7	6,7	6,9	8,7	5,9	6,3
2012-05-14	18,5		15,5	14,5	14,3	14,5	10,3	14,8	15,7	16,2	13,3	16,9	13,5	17,4	20,5	24,4
2012-05-15	27,4					24,8	25,2	23,0	24,2			21,2	21,6	25,6	23,3	23,8
2012-05-16	30,0		27,1	26,2	21,8	23,1	29,1	29,2	24,6	27,3	25,5	30,5	25,9	31,5	26,6	27,3
2012-05-17	15,6		11,7	10,6	11,9	12,2	10,4	10,5	10,6	8,4	8,0	18,5	10,0	14,4	7,0	6,6
2012-05-18	12,1		8,1	6,0	5,7	5,9	6,0	8,0	7,1	7,1	6,5	7,9	6,1	10,6	6,4	6,4
2012-05-19	15,6		12,1	11,2	9,5	9,9	10,9	13,5	13,4	11,4	11,0	13,0	12,2	14,4	10,7	10,8
2012-05-20	20,3		17,9	17,2	16,9	17,4	19,5	20,2	16,8	16,8	16,7	19,8	18,4		18,0	18,5
2012-05-21	32,8		28,9	28,7	24,5		27,6	29,3	28,2	27,8	25,2	31,1	26,5		27,1	28,3
2012-05-22	29,3			18,4	22,5		26,4	27,4	28,9	26,1	23,2	25,0	22,6		24,9	25,6
2012-05-23	30,4				27,8		36,8	30,2	35,4	32,6	29,4	25,6	28,9		29,6	32,1
2012-05-24	41,1				45,8		45,4	44,6	44,8	40,8	38,3	37,5	39,0		38,2	40,2
2012-05-25	27,7	30,4			29,1		31,0	28,0	30,1	27,5	27,8	29,1	30,1		26,7	28,9
2012-05-26	17,1	12,9			13,7		21,6	17,6	20,4	15,4	13,9	18,7	15,4		15,1	14,5
2012-05-27	18,1	16,9			18,8		21,9	18,9	21,8	18,2	17,8	17,8	21,7		17,0	17,4

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