2024

Evidence Synthesis Report

$PM_{2.5}$ EQUIVALENCE WORKING GROUP
MARCH 2024

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LIST OF ABBREVIATIONS/TERMS

Abbreviation/ Term	Meaning
ALN	Automatic London Network
AMCT	Annual Mean Concentration Target
AMS	Automatic Monitoring System
AQUILA	The European Network of National Air Quality Reference Laboratories
AURN	Automatic Urban and Rural Network
BAM	Beta Attenuation Monitor
BC	Black Carbon
BS EN 16450	European Standard for the type approval of particulate matter measurement systems
BS EN 12341	Standard gravimetric measurement method for the determination of the PM_{10} or $PM_{2.5}$ mass concentration of suspended particulate matter
C	Celsius
DA	Devolved Administration
Digitel DPA14	Reference Method
EA	Environment Agency
EC	Elemental Carbon
ESU	Equipment Support Unit
EU	European Union
FDMS	Filter Dynamic Measurement System
FIDAS	Fine dust measurement device
HEPA	Highly Efficient Particulate Air
LSO	Local Site Operator
MCERTS	Environment Agency monitoring certification scheme
MCZ	Reference Method
NERC	Natural Environment Research Council
OC	Organic Carbon
PERT	Population Exposure Reduction Target
PM	Particulate Matter
PM_{10}	Inhalable particles, with diameters that are generally 10 micrometres and smaller
$PM_{2.5}$	Fine inhalable particles, with diameters that are generally 2.5 micrometres and smaller.
PNC	Particle Number Count
PSD	Particle Size Distribution
rH	Relative Humidity
QA/QC	Quality Assurance / Quality Control
SEQ47/50	Reference Method
TC	Total Carbon
TEOM	Tapered Element Oscillating Micro-balance
UB	Urban Background
UK	United Kingdom
UT	Urban Traffic
UVPM	Ultra-violet particulate matter
WCM	Expanded uncertainty
$\mu g\ m^{-3}$	Micrometre cubed

EXECUTIVE SUMMARY

This report provides a synthesis of findings and outputs from a programme of works related to fine particulate monitoring instrument performance as evaluated by comparisons with the European Reference Method. This process of comparing performance of instruments chosen with that of the EU Reference Method is known as "particulate matter equivalence".

The programme of works is focused on instrument performance and identification of influencing factors that could provide plausible explanations to differences in $PM_{2.5}$ mass reported between the instruments when compared to each other. The drivers behind the works are the adoption (in England) of $PM_{2.5}$ targets under the Environment Act 2021 and the science and evidence required to report progress in England against these targets where confidence in data can be achieved. Whilst the work addresses the new $PM_{2.5}$ regulations in England, the outcomes consider the wider needs within the UK, as new targets are established and levels of $PM_{2.5}$ reduce. The terms of reference for the programme were on instrument performance only. As such, the work and its findings does not consider other elements of the Regulations such as the number of sites required, siting locations and criteria, etc.

A series of fourteen Deliverables is presented, each of which interprets the relevant evidence required to help inform decisions for the future operational needs of the $PM_{2.5}$ monitoring network with respect to ongoing assessment of instrument performance. These Deliverables have been developed in the context of the network currently being expanded to provide the further scientific evidence required for reporting progress against the new targets. Moreover, given the complexities of monitoring $PM_{2.5}$ through continuous methods, consideration is made to a programme of works that sets out the proposed approach to "ongoing equivalence" of methods adopted, and the extent to which the current Environment Agency's MCERTS for UK Particulate Matter may need to be adapted or modified to remain relevant.

Changes in Instrumentation

$PM_{2.5}$ monitoring is currently undertaken as part of the Automatic Urban and Rural Network (AURN) and Automatic London Network (ALN): collectively making up the UK's $PM_{2.5}$ air quality compliance network. Methods for monitoring have been established through a programme of Particulate Matter Equivalence testing (a programme of comparing $PM_{2.5}$ methods with the EU Reference Method).

Initially, the Thermo Fisher Filter Dynamic Measurement Systems 8500 ("FDMS") instruments were used for $PM_{2.5}$ monitoring, but as these reached the end of their operating life, and were no longer supported by the manufacturer, a competitive procurement exercise to source alternatives was undertaken in 2017. This resulted in the Palas Fidas 200 ("Fidas"), and the Met One Smart Heated BAM (Beta Attenuation Monitor) 1020 ("BAM") being selected to replace the FDMS instruments and installed across the network in the following years. All instruments were adopted into the network on the basis of achieving compliance with the acceptable bounds of uncertainty and certified under the UK MCERTS for Particulate Matter programme.

Deliverable 7 (Section 3.5) indicates that there was a reduction in concentrations when the new instruments were introduced around 2019 and this change does not coincide with Covid 19 restrictions. The move from FDMS to Fidas resulted in more of a decrease in reported $PM_{2.5}$ compared with when instruments changed from FDMS to BAM. This Deliverable also discusses how it is thought that the reduction is in part due to the FDMSs having over-read both through high baselines and a 7% slope overestimation of the European Reference Method against which they were originally tested. Slope correction was not mandated for the $PM_{2.5}$ FDMS whereas a similar slope correction is now mandatory for the $PM_{2.5}$ Fidas. BAMs were also shown to have an above zero response on average across all instruments tested.

Performance of Current Instrumentation

The present report seeks to collect and interpret additional evidence as to the accuracy of the current instruments used in the UK networks through comparison of UK-adopted instruments with the EU Reference Method. Four existing cross comparison sites were complimented by seven temporary ‘mini-equivalence’ sites, each with either a European Reference Method (or pseudo-Reference Method), Fidas and BAM. Deliverables 1 and 2 (Section 3.1) shows that when considering the period average concentration there is no obvious systematic difference between either the Fidas or BAM and the Reference (or pseudo reference) Method, regardless of whether the site is in a background or traffic location. The Fidas is shown to be more repeatable than the BAM, with the BAM being prone to an unstable baseline which gives lower confidence over measured concentrations. Deliverable 6 (Section 3.4) suggests that both the Fidas and the BAM may not respond to all particulate matter types equally leading to some occasions where the concentration is either over or underestimated relative to the Reference Method. This can affect the linear regression of the results, which using traditional comparison methodologies could lead to misinterpretation of the relationship between the Reference Method, Fidas and BAM. $PM_{2.5}$ monitoring is set against an annual average target and as such changing the assessment approach to one comparing the annual average is more appropriate than the current methodology of plotting the line of best fit between candidate and reference. The Fidas performs very well against a revised assessment methodology considering annual averages. Averaged over many sites the BAM performs well, but for any given site the lower confidence in the baseline directly translates to lower confidence in the annual average. Baseline correction of BAM data does improve the relationship, and Deliverable 5 (Section 3.3) discusses future potential improvements to the baseline correction procedures by comparison to similar Fidas locations within a defined distance radius. BAM instruments had traditionally been used with tapes manufactured by Sibata. Deliverable 4 (Section 3.2) shows that improved results can be achieved when Whatman tapes are used instead. This change has been implemented.

The Fidas operates by counting and sizing particles to which it applies an algorithm to calculate mass concentrations. Deliverable 3 (Section 3.1) compares the data from an additional eleven algorithms that could potentially be used in place of the existing one. None of the alternative algorithms were shown to offer a significant improvement over the current methodology, particularly when set against the very considerable effort to approve a new algorithm and reprocess all historic data.

Deliverable 5 (Section 3.3) shows that concentrations of $PM_{2.5}$, for traffic, urban background and rural environments, are remarkably similar across significant distances.

Deliverable 6 (Section 3.4) compares the BAM and Fidas measurements to the Reference (and pseudo reference) Methods at sites where additional particulate matter speciation data exists. The results show that performance of instruments can be affected by the occurrence of certain air mass compositions: the BAM was seen to under-read during ammonium nitrate episodes, whereas the Fidas was seen to under-read when black carbon concentrations were high. The influence of other metrics was less clearly defined.

The manufacturers of the Fidas (Palas) and BAM (Met One) were consulted as to whether the operation of their instruments could be improved (Deliverables 8 and 9, Section 4.1). Palas noted that additional algorithms are available, and these are discussed in Deliverable 3 (Section 3.1).

Six instruments not currently installed in the UK compliance network were tested next to the Birmingham A4540 urban traffic monitoring station. The results showed that all tracked the rise and fall of $PM_{2.5}$ concentrations as measured by the Reference Methods, but with variable performance on accuracy and data capture set against the Reference Method. It is not possible to give detailed results due to confidentiality requests of the manufacturers.

Revisions to European Standards and MCERTS for UK Particulate Matter

Deliverable 10 (Section 5.1) discusses improvements that could be made to guide the future iteration of the relevant British and European Standard (BS EN 16450) particularly with regards to the implications of falling concentrations upon the effectiveness of the maths on which equivalence is assessed. Deliverable 10 also discusses the implications of falling concentrations on the UK's MCERTS for UK Particulate Matter scheme. In both cases, switching to a system of assessing the $PM_{2.5}$ annual average would be of benefit, which continues to align to the principle of assessing uncertainty at the "limit value". However, for PM_{10} there remains a requirement to assess and report daily average data, therefore switching solely to an annual assessment system for PM_{10} would not be appropriate. Deliverable 11 (Section 5.2) considers the requirement that instruments deployed in the UK networks shall have been certified with field test data collected in the UK. Any data from outside the UK should meet UK pollution climate requirements. When certifying instruments, if the requirement to collect data with higher PM concentrations is leading to tests being undertaken in locations not consistent with the UK pollution climate this would suggest either reducing the requirement for higher concentration data, or consideration to relaxing the UK pollution climate recommendations, though this would require further work and consideration.

Deliverable 12 (Section 5.3) discusses how the UK is well placed to influence the development of documentation for type testing and demonstration of equivalence, and it is recommended that we continue to use our data, expertise, and leverage to ensure the development of the revised BS EN 16450 meets the needs of the UK.

Deliverable 13 (Section 6.1) reprocesses the original data collected when the instruments were first approved. This shows that as the concentration at which equivalence is assessed reduces then the uncertainty expressed as a percentage increases. However, when expressing the uncertainty as a concentration is largely independent of the concentration at which equivalence is assessed. When the data are reprocessed as a period average (as less than a year of data were originally collected), then the instruments are shown to be more likely to pass at the current annual target value of 10 µg m^{-3} than they would be by using the existing mathematics assessed at 10 µg m^{-3}.

Future Ongoing Equivalence Testing

Deliverable 14 (Section 7.1) discusses the future of equivalence monitoring. Consideration has been given to moving the Reference Methods around all sites on an annual basis, but this is impractical due to space limitations at the majority of sites and any increase in footprint would require planning consent. Instead, an approach of maintaining a small number of permanent monitoring sites is recommended. For urban background and urban traffic sites three groupings of areas have been identified across the UK that are sufficiently different from each other, but cover the ranges of low, medium and high key factors likely to impact instrument performance including Ammonium Nitrate, Black Carbon and $PM_{2.5}$ concentration. As such, a minimum of three urban traffic and urban background sites is recommended to provide a geographical spread that also includes variance in ammonium nitrate and black carbon. At least one of the urban background and urban traffic equivalence sites should be large enough to fit in both PM_{10} and $PM_{2.5}$ monitoring equipment as well as space for the future type testing of instrumentation under UK conditions. It is further recommended that urban background and urban traffic sites are paired in close geographic proximity. Collocated continuous black carbon and daily ammonium nitrate measurements would be beneficial to understand differences in concentrations as measured across different instruments. However, no improved correction methodology could be implemented without measuring these at many more locations across England. Each site should have Reference Methods as opposed to pseudo-Reference Methods as this would remove the possibility that the results are affected by the different characteristics of the $PM_{2.5}$ inlets of the two methods.

London Teddington and London Marylebone Road should both continue as paired London sites. There is a strong preference to increase the footprint of Birmingham A4540 to allow for the installation of PM_{10} instrumentation and space to test new instruments. This is subject to planning permission, but data from the existing $PM_{2.5}$ instrumentation is of significant interest. To create a paired site, the pseudo-reference Method at Birmingham University should be swapped for a Reference Method. The third set of paired sites should be in a location with lower ammonium nitrate concentrations, such as the North East.

For rural background locations, 2 rural background sites provide suitable geographical coverage of any composition variance as secondary aerosols are similar over far greater distances. Chilbolton and Auchencorth Moss are recommended as they provide a north south transect of the UK.

1. INTRODUCTION

Particulate Matter in ambient air is of concern to health[1] [2]. Traditionally, two size fractions have been monitored – $PM_{2.5}$ – the mass concentration of particulate Matter below 2.5 microns in diameter, and PM_{10} – the mass concentration of particulate Metter below 10 microns in diameter. In the last decade, health concern has focused primarily on $PM_{2.5}$ as it penetrates further into the body than PM_{10} and there is thought to be no safe $PM_{2.5}$ limit[3].

The European Reference Methods for measurement of both $PM_{2.5}$ and PM_{10} are covered by British and European Standard BS EN 12341:2023[4]. Ambient air is passed through a size selective inlet then through a filter for a period of 24 hours. The filter is weighed both before and after sampling, and the mass gain is divided by the volume of air sampled to give the concentration of $PM_{2.5}$ or PM_{10} (dependent upon the size selective inlet used). Multiple manufacturers make versions of the Reference Method – three of which have been used in the current project (SEQ 47/50, Digitel DPA14 and MCZ).

European Directive 2008/50/EC[5] was promulgated into UK law in 2010. It still forms a part of UK law. It requires that countries monitor PM_{10} and $PM_{2.5}$ using the Reference Method, or an instrument proven to be "equivalent" to the Reference Method. Like most countries, the UK have chosen to use equivalent methods rather than the Reference Method, due to the need for high frequency real time data for the purposes of rapid information to the public on air pollution, particularly during pollution episodes. The laboratory analysis delay in the Reference Method means that this immediate public information feed cannot be achieved by Reference Methods alone.

The methodology for proving instruments equivalent to the Reference Method is described in the Guide to Demonstration of Equivalence 2010[6]. This has been refined primarily through the inclusion of mandatory laboratory testing to standard BS EN 16450:2017[7]. The requirements are:

i) field tests are undertaken where two identical Reference Methods are operated in parallel with two identical Candidate Methods.
ii) There shall be at least four field tests covering a variety of location types and seasons a period of at least 40 days each.

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[1] assets.publishing.service.gov.uk/media/64fadfdea78c5f0014265847/COMEAP_Quantification_recommendations.pdf

[2] https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf

[3] https://assets.publishing.service.gov.uk/media/623075a3d3bf7f5a89aecec3/COMEAP_WHO_AQG_-_Defra_PM2.5_targets_advice__2_.pdf

[4] https://knowledge.bsigroup.com/products/ambient-air-standard-gravimetric-measurement-method-for-the-determination-of-the-pm10-or-pm2-5-mass-concentration-of-suspended-particulate-matter?version=tracked

[5] https://eur-lex.europa.eu/eli/dir/2008/50/oj

[6] https://circabc.europa.eu/ui/group/cd69a4b9-1a68-4d6c-9c48-77c0399f225d/library/17ef508b-3aab-450e-b511-72f8a9892d48/details

[7] https://knowledge.bsigroup.com/products/ambient-air-automated-measuring-systems-for-the-measurement-of-the-concentration-of-particulate-matter-pm10-pm2-5?version=tracked

iii) There shall be at least 32 days where the $PM_{2.5}$ concentration is above 18 µg m^{-3} and the PM_{10} concentration is above 30 µg m^{-3}.

The mathematics is based upon plotting the Reference Method on the x axis and the Candidate Method on the y axis and drawing a straight line of best fit. The expanded relative uncertainty shall be less than 25% is calculated at a daily limit value of 50 µg m^{-3} for PM_{10} and a pseudo daily limit value of 30 µg m^{-3} for $PM_{2.5}$.

The uncertainty is a combination of the "random component" and the difference between the limit value and the concentration estimated by the line of best fit at the limit value. Should slope and/or intercept correction be required, then it is mandatory for the same correction factor to be used across all field tests.

Historically, most instruments certified in Europe have been tested by TÜV Rheinland around Cologne. BS EN 16450:2017 is being rewritten as a part of the continual review and renewal processes that all European Standards undertake. The present project seeks to gain evidence on current equivalence challenges to help both inform and influence the revision of the Standard so that it remains suitable for the UK, both for now and over the lifetime of the Environment Act targets duration (*i.e.*, out to 2040), and in the event that new and emerging national $PM_{2.5}$ ambitions arise.

In 2012 the UK set up the MCERTS for UK Particulate Matter Scheme[8]. This required that instruments have at least two UK field tests and that field test data from outside the UK are of a comparable pollution climate to the UK (based upon UK measurements from 2007 to 2010). There was no requirement for the comprehensive lab tests required in BS EN 16450:2017 as the UK scheme predated this. In 2020 the MCERTS for UK Particulate Matter scheme was modified primarily to make the laboratory testing mandatory and to change the year range of the definition of UK pollution climate measurements to 2012 to 2020[9]. A list of instruments approved in the UK is provided on UK-AIR[10]. The present project seeks to help understand whether further modifications to the MCERTS for UK Particulate Matter are required.

The Ambient Air Quality Directive (2008/50/EC) requires that the annual average $PM_{2.5}$ concentration is below 20 µg m^{-3} and the annual mean PM_{10} concentration is below 50 µg m^{-3}. Legislation has recently been introduced in England that requires the $PM_{2.5}$ concentration to be below 10 µg m^{-3} by 2040 as an Annual Mean Concentration Target (AMCT)[11]. There is the additional requirement to see a reduction in $PM_{2.5}$ concentrations through the Population Exposure Reduction Target (PERT). The Reference Method is defined as BS EN 12341:2014[12] (BS EN 12341:2023 primarily differs from BS EN 12341:2014 by requiring that instruments manufactured in accordance with the Standard have undergone independent accredited testing new

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[8] https://uk-air.defra.gov.uk/assets/documents/MCERTS_for%20UK_Particulate_Matter_final.pdf

[9] https://www.gov.uk/government/publications/mcerts-performance-standards-for-ambient-monitoring-equipment/mcerts-performance-standards-for-ambient-monitoring-equipment

[10] https://uk-air.defra.gov.uk/networks/monitoring-methods?view=mcerts-scheme

[11] https://www.legislation.gov.uk/uksi/2023/96/contents/made

[12] https://knowledge.bsigroup.com/products/ambient-air-standard-gravimetric-measurement-method-for-the-determination-of-the-pm-sub-10-sub-or-pm-sub-2-sub-d-sub-5-sub-mass-concentration-of-suspended-particulate-matter?version=standard

legislation. The present project seeks to help define the methodology of proving equivalence in England for $PM_{2.5}$.

$PM_{2.5}$ concentrations across Europe are falling. As concentrations fall the existing mathematical approach to declaring equivalence has become more challenging (*i.e.,* drawing a straight line of best fit becomes less effective). The requirement for at least 32 “high” concentration points become increasingly difficult, and in order to certify instrumentation, TÜV Rheinland are now needing to collect field data in locations away from Cologne. These locations are potentially different in pollution climate to the UK. The present project seeks to help understand the implications of the challenges of responding to equivalence studies in an increasingly lower $PM_{2.5}$ climate.

In the UK, PM monitoring is undertaken through the AURN (Automatic Urban and Rural Network). $PM_{2.5}$ and PM_{10} monitoring is currently undertaken with two instrument types: the Palas Fidas 200 and the Met One Smart Heated BAM 1020. Both have been proven equivalent to the European Reference Methods both through BS EN 16450:2017[13] and the 2012 iteration of MCERTS for UK Particulate Matter[14]. The present project deals primarily with the operation of the Palas Fidas 200 (“Fidas”) and the Met One Smart Heated BAM 1020 (“BAM”). Previously the UK utilised 8500 series FDMS instruments and the implications of changing instrumentation are discussed herein. These had reached end of life and were no longer supported by the manufacturer, necessitating replacement. The evidence of this is further outlined in Appendix A: Principle of operation of instruments used to monitor PM2.5.

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[13] https://www.qal1.de/en/main-navigation/components/

[14] https://www.csagroup.org/en-gb/services/mcerts/mcerts-product-certification/mcerts-certified-products/mcertscertified-productscontinuous-ambient-air-monitoring-system-mcerts-for-uk-particulate-matter/

2. $PM_{2.5}$ EQUIVALENCE RESEARCH PROGRAM OVERVIEW

The present project primarily focuses on $PM_{2.5}$. Work Packages and Deliverables were instigated to help guide the future of the UK's $PM_{2.5}$ monitoring. These are in turn:

Work Package 1 – Reviewing/Assessing the Data from existing 'ongoing equivalence sites' and the 'mini-equivalence programme. There are seven Deliverables:

> ***Deliverable 1:*** *Interpreting the data from the seven additional 1-year 'Mini Equivalence' sites.*
>
> ***Deliverable 2:*** *Interpreting the data from the four 'Ongoing Equivalence' sites.*
>
> ***Deliverable 3:*** *Processing data from the additional Fidas algorithms at the equivalence sites.*
>
> ***Deliverable 4:*** *Interpreting the data from the trial of running 50% of AURN BAM sites with Whatman tapes as compared with Sibata tapes as well as the data from two BAMs running as a HEPA zero for a year.*
>
> ***Deliverable 5:*** *Interpreting the BAM data with an aim of improving the baseline and to understand what additional QA/QC could be put in place.*
>
> ***Deliverable 6:*** *Interpreting the data from the sites with speciation data with regards to what speciation occurs on the days that there is deviation seen for* $PM_{2.5}$.
>
> ***Deliverable 7:*** *Interpreting the data from the updated analysis of PM instrument change effects over time.*

Deliverables 1, 2 and 3 have been combined into a single Deliverable.

Work Package 2 – Equivalence testing of other 'in-scope' Analysers. There are two Deliverables:

> ***Deliverable 8:*** *A summary of discussions with Palas - the manufacturer of Fidas 200 - as to whether there are improvements that can be made to the operation of the instrument.*
>
> ***Deliverable 9:*** *A summary of discussions with Met One - the manufacturer of BAM 1020 - as to whether there are improvements that can be made to the operation of the instrument.*

Due to the confidentiality requests of the manufacturers, these Deliverables are only very briefly discussed herein.

Subsequent to Work Package 2, six instruments that are not currently in the UK networks were each installed in an enclosure next to the Birmingham A4540 monitoring station. Confidentiality arrangements are in place with the instrument suppliers which restrict the sharing of data collected.

Work Package 3 – Identification of how the current requirements from UK MCERTS for Particulate Matter and BS EN 16450 may need to change with lower UK $PM_{2.5}$ readings. There are three Deliverables:

> ***Deliverable 10:*** *Identification of how MCERTS for UK Particulate Matter and BS EN 16450 may need to change with lower UK* $PM_{2.5}$ *readings.*
>
> ***Deliverable 11:*** *Assessment of the UK Pollution Climate requirements.*
>
> ***Deliverable 12:*** *Providing an understanding of the current EU / DA's / AQUILA / US EPA position on equivalence and an assessment on how to best align options with others to minimise risk and cost of deviating from other potential EU manufacturer standards.*

Work Package 4 – Identification of new uncertainty thresholds. There is one Deliverable.

> ***Deliverable 13:*** *Reassessment of data from equivalence certification at a range of different daily and annual limit values.*

Work Package 5 – Assessment of continuation of mini-equivalence programme. There is one Deliverable.

> ***Deliverable 14:*** *Interpreting the data from the programme of work to consider the merits of continuing the mini-equivalence sites and the existing equivalence sites.*

Work Package 6 – Synthesis of evidence from all the above work packages into this report.

The following Sections give the findings of each Deliverable in turn.

3. ASSESSING THE DATA FROM EXISTING ‘ONGOING EQUIVALENCE SITES’ AND THE ‘MINI-EQUIVALENCE PROGRAMME’.

3.1 Deliverables 1, 2 and 3: Data Assessment from the equivalence monitoring study

As stated in the introduction, the UK AURN network measures $PM_{2.5}$ and PM_{10} using Palas Fidas 200 and Met One Smart Heated BAM 1020 instruments. These were certified by comparison against the European Reference methods which comprise of 24-hour filter (gravimetric) samples. After the initial certification of instruments, it is required by BS EN 16450 to have ongoing equivalence sites to prove that the data from certified instruments (in this case the Fidas and BAM) are still comparable to the Reference Methods.

The UK has three sites with $PM_{2.5}$ and PM_{10} measurements from each of the Fidas, BAM and European Reference Methods (SEQ 47/50), which provide for evidence regarding “ongoing equivalence’[15]:

- London Teddington Urban Background (since 2013).
- Manchester Piccadilly Urban Background (since 2017).
- London Marylebone Road Urban traffic (since 2022).

In addition, data from a semi-permanent site in Glasgow have been included where the European Reference Method was the MCZ. Whilst the Reference Method and Fidas were operational throughout, the BAM was only operational at this site from 9/12/2022.

A further seven temporary ‘mini-equivalence’ sites were set up each containing a Fidas, $PM_{2.5}$ BAM and $PM_{2.5}$ Reference Method or $PM_{2.5}$ Partisol (a ‘pseudo’ Reference Method) for the purposes of this work:

- London Honor Oak Park Urban Background. Operated from 20/05/2022 to 24/05/2023.
- Birmingham University Urban Background. Operated from 24/05/2022 to 20/05/2023.
- Manchester University Urban Background. Operated from 25/05/2022 to 27/05/2023.
- Chilbolton Rural Background. Operated from 27/05/2022 to 24/05/2023.
- Birmingham A4540 Urban Traffic. Operated from 14/07/2022 to 04/10/2023.

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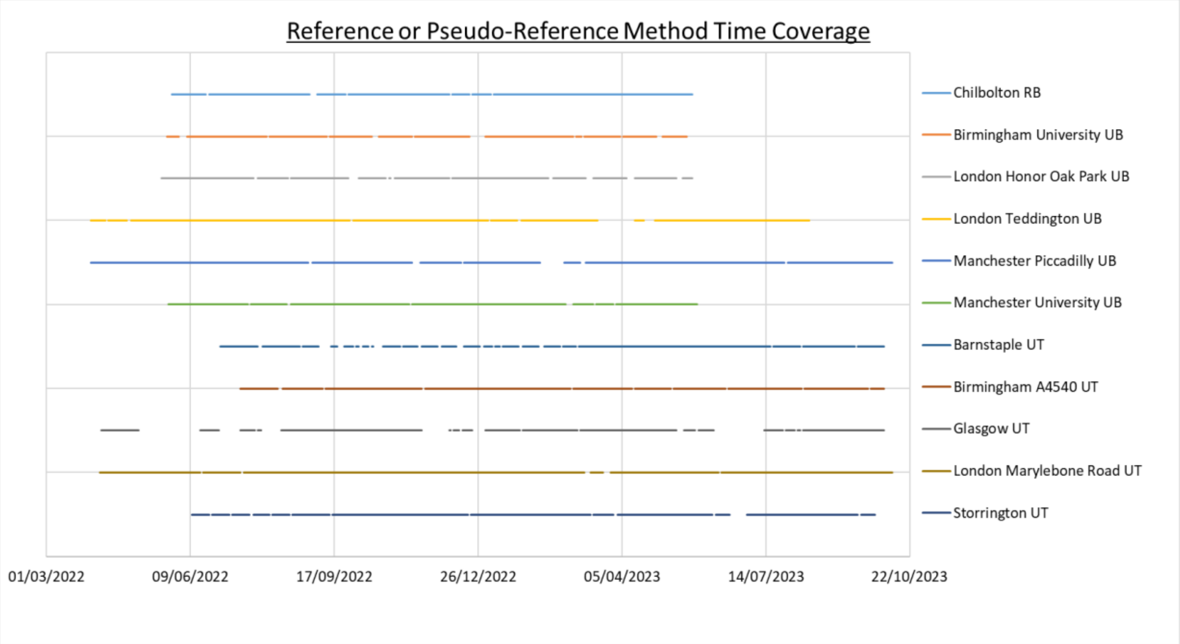
[15] uk-air.defra.gov.uk/assets/documents/reports/cat09/2309281149_On-going_Particulate_Matter_(PM_{10}_and_$PM_{2.5}$)_Equivalence_2022.pdf

- Storrington Urban Traffic. Operated from 10/06/2022 to 28/09/2023.
- Barnstaple A39 Urban Traffic. Operated from 30/06/2022 to 04/10/2023.

The Urban Background sites were selected as there was space to accommodate additional equivalence instruments co-located with other instrumentation that could be used to help understand the relationship between the pseudo-Reference Method and the Fidas and BAM. The Urban Traffic sites were selected as they had large enclosures with space to install equivalence instruments. All sites selected had to meet the Health and Safety requirements for the operation of the additional equipment, and this limited the selection of some Urban Traffic sites where it was not deemed to be safe to clean the additional sampling heads.

Figure 3.1 shows the time coverage of the Reference and pseudo-Reference Methods at each of the eleven sites. Note that at Glasgow the BAM was not operational until December 2022.

Figure 3.1 Reference or pseudo-Reference Method Time Coverage



A European Reference Method (a Digitel DPA14) was installed at each of Chilbolton, Birmingham A4540, Storrington and Barnstaple A39. Towards the end of the study, the Digitel from Chilbolton was relocated to Birmingham A4540 to provide two identical reference instruments at that site. A gravimetric sampler that has previously been shown to be equivalent to the European Reference Method (a Partisol 2025) was installed at each of London Honor Oak Park, Birmingham University and Manchester University. The reference method data has therefore been acquired from a combination of reference (SEQ 47/50, Digitel or MCZ) and pseudo-reference instruments (Partisol 2025) for the purposes of this project.

Deliverables 1 and 2 seek to better understand the uncertainties at lower concentrations of $PM_{2.5}$ from existing instruments on the network and to provide a wider dataset for examination as part of the on-going equivalence programme.

The principle of operation of the Fidas instrument is based on optical measurements of particle size, The Fidas counts and sizes particles and applies an algorithm to calculate $PM_{2.5}$ and PM_{10} concentrations. The manufacturer has developed many algorithms of which an additional eleven have been installed on the Fidas at the above sites. Deliverable 3 discusses whether these algorithms provide an improvement over the one certified and operated in the UK networks.

3.1.1 Repeatability of Measurements

Figure B.1 in the Appendix shows the 1-hour data from two Fidas that are around 50 metres apart at Chilbolton Rural Background site where the air is well mixed and free of local pollution sources. It shows that there is very little difference between the two instruments and that data from the Fidas are highly repeatable.

Two identical BAMs were not installed at any of the sites covered by this study and so it is not possible to definitively state the repeatability, but the example at Manchester Piccadilly highlights the propensity for the baseline to jump in a way that is not linked to the air mass, and as such it can be inferred that the BAM is less repeatable. This observation of baseline change is also observed at other sites.

Figure B.2 shows 1-hour data from a Fidas and BAM side by side at the Manchester Piccadilly Urban Background site. There is a gap in the BAM data attributed to when a QAQC audit was carried out at the site, with a HEPA filter installed over several days to calculate the instrument zero. Prior to the audit the two instruments were agreeing relatively well, though the BAM is consistently negative towards the beginning of the time series and is overall much noisier than the Fidas. Following the removal of the HEPA filter, the BAM read consistently around 5 µg m^{-3} lower than the Fidas.

3.1.2 BAM 1020 and Fidas Method 11.

The comparison results between each instrument and the Reference Method / pseudo-Reference Method are shown in **Figure B.3** to **Figure B.13** in the Appendix. These show the Reference Method on the x axis and the uncorrected BAM, baseline corrected BAM and Fidas Method 11 / 1.06 on the y axis:

The parameters shown are:

- W_{CM} – the expanded uncertainty at a pseudo daily limit value of 30 µg m^{-3}. Under the existing system, this should be below 25%. Following this, P = pass and F = fail;
- RCDW – a newly constructed parameter that is four results in one.
    - R is the average reference method concentration.
    - C is the average candidate method concentration.
    - D is the difference calculated as candidate minus reference.
    - W is the expanded uncertainty (multiplied by k = 2) expressed at the reference method average.

- n – the number of datapoints;
- b – the slope followed by S(ignificant) or N(ot) S(ignificant) dependent on whether it is within 2 standard deviations of 1;
- a – the intercept followed by S(ignificant) or N(ot) S(ignificant) dependent on whether it is within 2 standard deviations of 0;
- Bias at 30 µg m^{-3} – the difference between the slope of the distribution and 30 µg m^{-3} at a reference method concentration of 30 µg m^{-3};
- RT – the random term, which the noise component to the uncertainty.

3.1.3 Results

Table 3.1 summarises the minimum, mean and maximum Reference or pseudo-Reference Method concentrations measured at each site. All available data from 1st April 2022 to the 9th October 2023 are included. As sites operated for different periods during this window, direct comparison between sites cannot be made – as shown in **Figure 3.1**. For example, whilst Barnstaple A39 Urban Traffic site had lower concentrations than Chilbolton Rural Background site, Chilbolton operated for a twelve-month period, whereas Barnstaple operated for a sixteen month period including two Summers (when concentrations are lower).

Table 3.1 Minimum, mean, and maximum Reference or pseudo-Reference Method concentrations measured at each site. All available data from 1st April 2022 to the 9th October 2023 are included. As sites operated for different periods during this window, direct comparison between sites cannot be made – as shown in Figure 3.1.

	Reference or Pseudo-Reference Method Concentration / µg m^{-3}		
	Minimum	**Mean**	**Maximum**
Chilbolton RB	1.6	6.4	24.2
Birmingham University UB	1.4	6.5	25.0
London Honor Oak Park UB	2.5	7.8	47.9
London Teddington UB	2.1	7.1	50.9
Manchester Piccadilly UB	2.5	9.4	35.5
Manchester University UB	1.9	7.5	39.5
Barnstaple UT	1.1	5.8	19.6
Birmingham A4540 UT	2.0	9.0	30.5
Glasgow UT	2.4	7.7	24.6
London Marylebone Road UT	2.8	9.0	40.6
Storrington UT	1.6	7.9	30.0

As all reference method concentration averages were below 10 µg m^{-3},

Table 3.2 summarises the values of W_{CM} and D (as opposed to W) for each of the datasets as well as the average for all urban background sites, all urban traffic sites, and all sites. All available data from 1st April 2022 to the 9th October 2023 are included. As sites operated for different periods during this window, direct comparison between sites cannot be made – as shown in **Figure 3.1**.

One potential option being discussed is that it would be required for when R is less than 10 µg m^{-3} that D should be between - 1.5 µg m^{-3} and + 1.5 µg m^{-3} but W is not considered. Conversely, when R is greater than 10 µg m^{-3}, W should be less than 30% but D is not considered. This would require relaxation of the current uncertainty requirement from 25 to 30% as is being proposed by a revised European Air Quality Directive[16].

Table 3.2 Summary of the uncertainty calculations and difference in period mean for the Fidas Method 11 / 1.06, baseline corrected BAM and non-baseline corrected BAM and the difference relative to the Reference or pseudo-Reference Method. All available data from 1st April 2022 to the 9th October 2023 are included. As sites operated for different periods during this window, direct comparison between sites cannot be made – as shown in Figure 3.1.

	W_{CM} / %			D / µg m^{-3}		
	Fidas M11 / 1.06	**BAM Corrected**	**BAM Uncorrected**	**Fidas M11 / 1.06**	**BAM Corrected**	**BAM Uncorrected**
Chilbolton RB	10.68	21.72	16.56	0.32	1.12	-1.59
Birmingham University UB	27.65	6.89	20.39	0.38	-0.47	-3.15
London Honor Oak Park UB	15.57	11.12	30.28	-0.62	-0.91	-4.11
London Teddington UB	17.37	18.02	18.02	0.74	0.85	0.85
Manchester Piccadilly UB	28.26	13.69	21.97	-0.99	-0.39	-3.33
Manchester University UB	18.19	9.21	22.00	-0.70	0.09	-2.11
Barnstaple UT	15.96	21.78	27.56	0.65	2.09	2.10
Birmingham A4540 UT	17.32	18.79	18.79	-1.09	-1.25	-1.25
Glasgow UT	45.55	34.27	17.64	-1.35	-1.59	1.41
London Marylebone Road UT	11.98	19.09	19.09	-0.10	2.34	2.34
Storrington UT	16.92	12.33	20.99	-0.04	-0.86	-2.23
Number Passing	8/11	10/11	9/11	10/11	7/11	1/11
Average All Sites	20.50	16.99	21.21	-0.25	0.09	-1.01
Average Urban Background	21.41	11.79	22.53	-0.24	-0.17	-2.37
Average Urban Traffic	21.55	21.25	20.81	-0.39	0.15	0.47

Considering the current approach of requiring W_{CM} to be below 25% at 30 µg m^{-3}, over this assessment period three sites would fail for the Fidas Method 11/1.06 and two for the uncorrected BAM 1020. Baseline correcting the BAM results in both of these two sites being below 25% at 30 µg m^{-3}, though it also results in another site going from below 25 % to above, giving a total of one failing.

Considering one of the potential options currently under discussion, taking that the current expanded uncertainty requirements are 25% and that these are calculated using a 95% confidence interval of k=2, the period average would need to be within 1.25 µg m^{-3}. Ten of the eleven Fidas datasets would pass, and if the requirement could be increased to 1.5 µg m^{-3} then all eleven would pass. For the uncorrected

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[16] https://data.consilium.europa.eu/doc/document/ST-7335-2024-INIT/en/pdf

BAM 1020 data, ten of the eleven datasets would fail a 1.25 µg m^{-3} requirement and eight would fail a 1.5 µg m^{-3} requirement. Baseline correcting the BAM, four of the eleven datasets would fail a 1.25 µg m^{-3}, requirement and three would fail a 1.5 µg m^{-3} requirement.

The reasons for exceedances of the uncertainty requirements are not fully understood and therefore require further investigation. Considering **Table 3.2**, there is no obvious systematic difference between Urban Background and Urban Traffic sites (as conveyed through the consideration of averages shown at the bottom of the table), though more significant differences are observed considering each site in turn.

3.1.4 Influence of High Concentrations

Figure B.14 in the Appendix shows the 2022 $PM_{2.5}$ Fidas data at London Marylebone Road for two different periods: from March 2022 when the instruments were installed and from June 2022 when the other urban traffic sites came online. June to December 2022 data are shown in red and March to December 2022 data are shown in red and blue with the blue dots being from March, April and May 2022. The blue text relates to the equivalence calculations for March to December whereas the red text relates to the equivalence calculations for June to December. When considering the data from June onwards the Fidas instrument appears to underestimate with a slope of 0.864 and an expanded uncertainty of 25.56%, but the inclusion of data from March, April and May contains a few higher concentration points which forces the line of best fit higher to 0.975 and an expanded uncertainty of 12.99%. The calculation of D is much less affected, rising from -0.75 to -0.45 µg m^{-3}. These results are an example of how the traditional approach of W_{CM} is much more susceptible to high concentration points than the D approach would be, such that a pass or fail could be due to the spread of data, and not necessarily a feature of the performance of the instrument in that location.

Figure B.15 repeats these calculations for the BAM. At this site no correction was made to the BAM data. The results show that the BAM did not underestimate on high concentration days in March, April or May 2022 with both sets of data looking highly comparable. However, whilst showing less affect upon high concentrations than the Fidas, the calculation of D is further from 0 µg m^{-3} than for the Fidas 1.16 µg m^{-3} for March to December 2022 and 1.40 µg m^{-3} for June to December 2022.

For London Teddington (**Figure B.6**) and London Marylebone Road (**Figure B.12**) there was a pollution episode in early September 2023. On this day the Fidas and BAM both significantly overestimated the Reference Method. As this occurred across multiple $PM_{2.5}$ and PM_{10} instruments across both sites, it is considered that these results are real. These results would further strengthen the argument that considering the period average concentration is more appropriate than the traditional approach of W_{CM}.

3.1.5 Alternate Fidas Algorithms

The comparison results for different Fidas algorithms are shown in **Figure B.16** to **Figure B.26** in the Appendix and are summarised in **Table 3.3** and **Table 3.4** below. At the permanent sites of London Teddington, Manchester Piccadilly, and London

Marylebone Road there are a greater number of data points for the current algorithm Method 11 than for any of the alternative algorithms. This is because the Fidas at these sites were upgraded to report the additional algorithms after the first date in the comparison spreadsheet (1st April 2022). When considering the current approach of requiring W_{CM} to be below 25% at 30 µg m^{-3}, two of the algorithms (11d04 and 231) appear to offer an advantage over the current approach of Method 11/1.06. Considering a revised approach of D, results in four of the algorithms (11d04, 225, 227 and 73) being potentially better than Method 11/1.06. Only algorithm 11d04 appears to offer an improvement by both metrics. Given the very significant effort required to certify a new algorithm and reprocess historic data, set against the minimal benefit demonstrated, it is recommended to continue using Method 11/1.06.

Table 3.3 Summary of the W_{CM} / % uncertainty calculations for the twelve Fidas algorithms.

W_{CM} / %	Algorithm											
	11/1.06	**11d04**	**206**	**215**	**223**	**225**	**227**	**228**	**231**	**43**	**73**	**73d03**
Chilbolton RB	10.68	14.18	13.44	21.91	17.90	13.86	11.53	10.71	10.02	25.73	15.98	21.45
Birmingham University UB	27.65	34.99	31.29	37.87	34.78	32.19	28.88	27.67	23.43	47.66	33.03	40.67
London Honor Oak Park UB	15.57	12.68	13.49	10.30	10.69	13.96	14.06	18.57	14.76	10.41	9.07	10.32
London Teddington UB	17.37	23.21	21.39	31.62	28.49	19.76	19.64	17.04	14.68	28.08	25.68	30.51
Manchester Piccadilly UB	28.26	22.88	27.88	18.05	18.58	29.12	27.24	31.81	29.45	14.01	22.81	15.43
Manchester University UB	18.19	14.60	16.99	9.09	11.76	17.35	16.91	22.02	17.89	12.37	9.35	9.11
Barnstaple UT	15.96	21.94	16.70	28.96	36.90	12.50	16.81	16.77	19.97	47.66	15.77	19.69
Birmingham A4540 UT	17.32	13.60	17.77	13.03	13.24	18.06	16.34	18.73	21.15	13.73	16.64	13.05
Glasgow UT	45.55	39.45	46.54	35.68	32.22	48.29	44.14	47.66	39.90	47.66	43.29	37.48
London Marylebone Road UT	11.98	11.64	13.11	12.35	12.04	13.45	12.79	16.04	16.10	19.21	11.11	12.45
Storrington UT	16.92	20.57	19.25	26.26	25.75	17.26	17.84	17.70	13.72	26.31	25.94	28.86
Number Passing	8/11	9/11	8/11	6/11	6/11	8/11	8/11	8/11	9/11	5/11	7/11	7/11
Average All Sites	20.50	20.89	21.62	22.28	22.03	21.44	20.56	22.25	20.10	26.62	20.79	21.73
Average Urban Background	21.41	21.67	22.21	21.39	20.86	22.48	21.35	23.42	20.04	22.50	19.99	21.21
Average Urban Traffic	21.55	21.44	22.67	23.26	24.03	21.91	21.58	23.38	22.17	30.91	22.55	22.31

Table 3.4 Summary of the D / µg m^{-3} uncertainty calculations for the twelve Fidas algorithms.

D / µg m^{-3}	Algorithm											
	11/1.06	**11d04**	**206**	**215**	**223**	**225**	**227**	**228**	**231**	**43**	**73**	**73d03**
Chilbolton RB	0.32	0.58	0.31	0.87	1.20	0.79	0.52	0.27	0.92	1.36	0.68	1.00
Birmingham University UB	0.38	0.70	0.35	0.89	1.21	0.82	0.59	0.32	0.94	1.26	0.74	1.11
London Honor Oak Park UB	-0.62	-0.26	-0.58	0.09	0.44	-0.17	-0.33	-0.62	0.12	0.30	-0.16	0.21
London Teddington UB	0.74	1.11	0.72	1.39	1.76	1.12	1.01	0.72	1.39	1.47	1.03	1.34
Manchester Piccadilly UB	-0.99	-0.57	-1.08	-0.39	0.09	-0.69	-0.76	-1.07	-0.35	0.25	-0.69	-0.22
Manchester University UB	-0.70	-0.43	-0.75	-0.12	0.17	-0.27	-0.49	-0.80	-0.08	0.40	-0.25	0.13
Barnstaple UT	0.65	0.93	0.49	1.10	1.67	0.89	0.86	0.65	1.23	2.00	0.77	0.95
Birmingham A4540 UT	-1.09	-0.71	-1.29	-0.63	-0.13	-0.87	-0.89	-1.18	-0.63	-0.13	-1.00	-0.64
Glasgow UT	-1.35	-1.08	-1.48	-0.97	-0.46	-0.96	-1.15	-1.38	-0.77	-1.38	-1.15	-0.95
London Marylebone Road UT	-0.10	0.18	-0.32	0.42	0.84	0.03	-0.01	-0.35	0.42	1.23	0.06	0.52
Storrington UT	-0.04	0.29	-0.17	0.48	1.00	0.19	0.16	-0.06	0.51	1.23	0.16	0.46
Number Passing	10/11	11/11	9/11	10/11	9/11	11/11	11/11	10/11	10/11	6/11	11/11	10/11
Average All Sites	-0.25	0.07	-0.34	0.28	0.71	0.08	-0.04	-0.32	0.34	0.73	0.02	0.36
Average Urban Background	-0.24	0.11	-0.27	0.37	0.73	0.16	0.00	-0.29	0.40	0.73	0.13	0.51
Average Urban Traffic	-0.39	-0.08	-0.55	0.08	0.58	-0.14	-0.20	-0.46	0.15	0.59	-0.23	0.07

3.1.6 Variation in Filter Weights

Filters were weighed by three different laboratories. All filters were of the same type, a form of Teflon coated Glass Fibre called Emfab. This filter type was chosen by the UK from the list of allowed filter materials in BS EN 12341 as it had previously been shown to change in mass less in high humidities than quartz fibre and glass fibre, and further does not have the problems of high static and a reduced ability to retain volatile components associated with Teflon.

To test the inter-comparability of using three different weighing laboratories, a combination of field blank, travel blank and sampled filters were sent between the laboratories. Overall, filters were weighed seventeen times. The results showed that the blanks gained mass whereas the sampled filters lost mass by a variable amount. As filters would not normally be weighed or transported repeatedly, these findings are not thought to be significant, though it does highlight the need to weigh filters quickly – as is already undertaken in the UK. When moving between laboratories, changes were observed with the overall calibration of each facility. As each laboratory pre-weighs and post-weighs the same filters then this is not expected to impact the results. Taken together, these results highlight an advantage of continuous instruments (like the Fidas and BAM) in that the concentrations are calculated very soon after sampling and samples do not need to be transported prior to analysis.

As the sample volume of the pseudo-Reference Method Partisol is 2.3 times lower than that of the Reference Method, the above effects are magnified for a constant filter mass. This effect can be minimised by discontinuing the use of the Partisol in favour of the Reference Method. This would also ensure that any differences observed to the Fidas or BAM are not due to the differences in $PM_{2.5}$ cut characteristics of the Reference Methods and Partisols.

3.1.7 Conclusions

The following conclusions can be made from the above analysis in respect of Deliverables 1 and 2 (relating to the Fidas Method 11/1.06 and Smart Heated BAM at temporary and existing sites respectively):

- When looking at data for the entire monitoring period there is no obvious systematic difference between Urban Background and Urban Traffic sites.
- Instrument performance has been shown to vary with particle composition as described in Deliverable 6 (Section 3.4).
- Baseline correction of BAM data does lead to an improvement, but this is not consistent.
- Data from the Fidas are highly repeatable and therefore it is possible to see changes in concentration. Conversely, data from the BAM 1020 were prone to jumps in the baseline and it is more difficult to see changes in concentration.
- The current mathematics of requiring W_{CM} to be below 25% at 30 µg m^{-3} is affected by the high concentration points dominating the slope of the graph and hence the calculated uncertainty. Switching to an approach of

comparing period averages reduces the dominance of the high concentration data upon the uncertainty.

- The results of these deliverables would suggest changing the requirement from the current approach of requiring W_{CM} to be below 25% at 30 µg m^{-3}, to one related to the annual average. This is not true of PM_{10} as there is a legal requirement on the daily average data.
- When considering equivalence by the current approach of requiring W_{CM} to be below 25% at 30 µg m^{-3} then both the BAM and Fidas perform similarly. When considering a revised approach based on the annual average, the Fidas performs significantly better than the BAM for any given site, though on average across many sites it performs comparably.

The following conclusions can be made from the above analysis in respect of Deliverable 3 (relating to alternate Fidas algorithms):

- None of the alternative algorithms give a significant advantage over Method 11/1.06, particularly given the very significant effort required to certify a new algorithm and reprocess historic data. It is recommended to continue using Method 11/1.06.

The following conclusions can be made with respect to the inter-laboratory weighing comparison:

- Filters should be pre and post weighed by the same laboratory to minimise differences between weighing facilities.
- Filters should be transported with care and weighed as quickly as possible.
- Future test should use the Reference Method rather than pseudo-Reference-Method Partisols
- An advantage of continuous instruments like the Fidas and BAM is that the concentrations are calculated very soon after sampling and samples do not need to be transported prior to analysis.

3.2 Deliverable 4: Analysis of the data from the trial of running 50% of AURN BAM sites with Whatman tapes (PM_{10} and $PM_{2.5}$) as compared with Sibata tapes.

3.2.1 Background

The Met One BAM has its origins in Japan. Historically the glass fibre tape used in the instruments was provided by a Japanese company called Sibata. Sibata tapes were installed in the instruments when both the PM_{10} and $PM_{2.5}$ Smart Heated variants of the BAM undertook their equivalence certification. After the field equivalence tests had been undertaken, but before completion of certification, Met One issued a document relating to tape type. This stated that users had noticed inconsistency in the quality of the Sibata tape and that in response to this, Met One had tested multiple other tape types. Of these, their preferred option was Whatman which is also made of glass fibre. The use of Whatman tapes was included alongside Sibata in the official certifications for the PM_{10} and $PM_{2.5}$ Smart Heated BAMs.

BAMs have a user programmable background value that is subtracted from every single hourly measurement of particulate matter (PM_{10} or $PM_{2.5}$) produced by the instrument. This correction is to account for the change in beta attenuation characteristics of the tape as it is compressed by the filter tape gripping mechanism during the course of continually moving the tape between the initial beta count, PM, sampling and the final beta count. The background value is not consistent between individual instruments. At their test facility in Grants Pass Oregon, USA, Met One evaluate this background value for each instrument independently in a test chamber alongside the original Japanese instrument, or one directly traceable to it (i.e., a transfer standard). Historically these tests were undertaken using Sibata tapes. Following Met One's decision to use Whatman tape, both tape types continued to be sold, and instruments were tested with either Sibata or Whatman tapes. Subsequently instruments were tested with Whatman tapes only. Met One did not keep detailed records of the serial numbers of those instruments that were tested with which tape type. As these tests are undertaken without a size selective inlet and with a HEPA filter on the inlet instead, the results are largely unaffected by whether the instrument is to be used for monitoring PM_{10} or $PM_{2.5}$.

In the UK, the purchase of new Smart Heated BAMs to replace old unheated BAMs and ageing 8500 series FDMSs began in 2017. At this stage, the background setting programmed in the instrument at the time of purchase was retained. Our records indicate that nine AURN instruments relate to this period.

As the number of Smart Heated BAMs purchased increased dramatically, at the end of 2017 Bureau Veritas (in its role as Central Management and Coordination Unit for the AURN) instructed the supplier (Enviro Technology (ET)) to test every instrument prior to deployment. Each instrument had Sibata tape installed and the HEPA zero was undertaken for three days on ambient air: no size selective inlet was applied to the instruments. The average zero was calculated for the period for which the HEPA filter was applied. If a zero value was more than +/- 1 µg m^{-3} from a "true zero" the background setting was revised in the instrument and the instrument tested for a further 3 days. If, during the further HEPA zero period, the average was within +/- 1

$\mu g\ m^{-3}$ of zero, the result was deemed acceptable. If not, the test was repeated as many times as necessary until, the average was within +/- 1 $\mu g\ m^{-3}$ of zero. There was no obvious pattern to the changes made with some instruments requiring larger background setting amends than others, whilst for some instruments no changes were necessary. Most BAMs currently in operation in the UK network relate to this period.

In 2022, the decision was made to create seven short-term $PM_{2.5}$ equivalence test sites. For these tests it was necessary to procure six new Smart Heated BAMs. These were each tested at ET using Whatman tape to set the background settings rather than Sibata tape.

3.2.2 Continuous HEPA Zeroes

Two instruments have been set up to measure HEPA zero continuously. One of these is installed at London Teddington, and the other at Manchester Piccadilly. **Figure C.1** and **Figure C.2** in the Appendix show the time series of the hourly data and 24-hour averages in turn. Both instruments were from the period when the background setting of instruments were checked using Sibata tape at ET. Tapes were alternated between both Whatman and Sibata at both sites.

The ideal distribution would be if each were a straight line at zero: the data show that this is not the case and are considered to be significantly noisy around the zero irrespective of the tape type. Some of the higher readings at Manchester may indicate a leak around the tape, though even accounting for these there are significant jumps in the average HEPA zero.

If a baseline for an instrument is not zero but provides for a stable “off-set”, then over time this can be identified and reliably corrected for through the audit findings and a ratification process. Arguably the most problematic issue is if there is a jump in zero offset as tapes are routinely changed or the site is audited or serviced (i.e., interventions to the instruments appear to create changes in the baseline). Evidence has been seen of this for both tape types, though more clearly with Sibata.

3.2.3 Changing Tape Types at Network Sites

All Smart Heated BAMs in the UK network have historically operated with Sibata tape. In early 2022, enough tapes were procured to operate half of the sites with Whatman and half with Sibata.

To get a significant amount of data which aimed to reduce the impact of further artefacts through possible external factors, all the UK instruments were split as equally as possible between the tape types according to the following variables:

- Site type (Urban Background, Urban Industrial, Urban Traffic)
- PM_{10} and $PM_{2.5}$ (in order to avoid potential errors a site was provided with only one tape type if it measured both size fractions)
- Area of the UK
- Coastal or inland

In April 2022, those sites for which Whatman tapes were allocated began collecting data using Whatman tapes. There was effectively no change for those sites using Sibata tapes.

Figure C.3 in the Appendix shows the average HEPA zero for FDMSs (blue); BAMs with Sibata tape (orange) and BAMs with Whatman tape (green). Focusing on the last three audit rounds where both Whatman and Sibata tapes were used, the distribution is relatively similar, but Whatman does not have as many highly negative zeroes as observed with Sibata.

HEPA zero concentrations are given in **Table 3.5.** The last six rows (shaded blue) compare the results for Sibata and Whatman for the period both were running. Whilst for the Summer 2022 and Winter 2023 audit rounds Sibata were on average closer to zero than Whatman, the reverse is true for the Summer 2023 audit round.

Table 3.5 Variation of average HEPA BAM zero concentrations and Detection Limits. Winter is taken as 1st October to 31st March the following year, whereas Summer is taken as 1st April to 30th September.

Period	Concentration / µg m^{-3}	Detection Limit / µg m^{-3}
Sibata Winter 2017	1.80	6.94
Sibata Summer 2017	2.38	7.72
Sibata Winter 2018	1.74	6.78
Sibata Summer 2018	1.64	7.52
Sibata Winter 2019	0.69	6.57
Sibata Summer 2019	1.26	7.54
Sibata Winter 2020	0.68	6.37
Sibata Summer 2020	0.55	7.12
Sibata Winter 2021	0.55	6.16
Sibata Summer 2021	0.51	7.00
Sibata Winter 2022	0.45	6.56
Sibata Summer 2022	-0.07	7.50
Whatman Summer 2022	0.65	6.82
Sibata Winter 2023	0.23	6.70
Whatman Winter 2023	1.68	6.83
Sibata Summer 2023	0.88	8.06
Whatman Summer 2023	0.57	7.08

Figure C.4 in the Appendix shows the results of each site going through four audit rounds each with Sibata filter tape. When sticking with Sibata tape there is evidence of an increase in the spread of zeroes in the summer audits.

Figure C.5 in the Appendix shows the results of each site going from the Winter 2022 audit with Sibata tape to the subsequent three audits with Whatman tape. When switching to Whatman tape, the summer spread seen with Sibata is less evident. There is evidence of a slight overall increase in the average zero across the first two audit rounds with Whatman tape, but this is not observed for the third audit round with Whatman tape.

Figure C.6 in the Appendix shows the hourly detection limit of instruments as calculated as 3.3 times the standard deviation of the hourly data (3.3 being a multiplier historically used by QAQC). The lower the detection limits the more aligned the instrument is for measuring lower concentrations. Whilst for the FDMS a detection limit below 5 µg m^{-3} was achievable for many of the instruments, the BAM is shown to be noisier than the FDMS was, but there is no obvious difference between the two BAM tape types. **Table 3.5** shows the averages across all sites for the BAMs. The detection limit is on average around 7 µg m^{-3} for hourly data.

3.2.4 The new BAMs at the new equivalence sites

The new BAMs at the new equivalence sites were all HEPA zero tested at ET with Whatman tape and are all being operated with Whatman tape during the temporary study. Instruments are being audited more frequently than the usual six months, which is our preferred approach for equivalence sites. The results from the HEPA zeros periods are summarised in **Table 3.6**. They are nearly all negative. This is different to the distribution of the zeroes for those instruments operating on Whatman tape, but for which pre-set zeros set prior to operation were tested on Sibata tape. The reason for this is not known.

At some sites the repeatability of the routine HEPA zeroes is consistent, for example, at London Honor Oak Park where the routine HEPA zero was consistently between -3 and -4 µg m^{-3}. Whilst highly negative it does make the correction of data through the QAQC ratification process more straightforward, due to its consistent nature. At other sites the repeatability of the routine HEPA zeroes is more variable.

Table 3.6 Summary of HEPA zeroes for the six new BAMs that were zero tested using Whatman tape and are being operated using Whatman tapes.

Instrument	Date	Concentration / µg m^{-3}	Detection Limit / µg m^{-3}
Birmingham A4540	01/08/2022	1.01	5.34
Birmingham A4540	10/10/2022	-1.24	7.71
Birmingham A4540	26/01/2023	-0.70	5.77
Birmingham A4540	13/04/2023	-0.69	6.04
Birmingham A4540	31/07/2023	-1.36	5.35
Birmingham A4540	27/09/2023	-0.76	7.39
Birmingham University	02/08/2022	-2.55	6.00
Birmingham University	11/10/2022	-3.20	4.82
Birmingham University	24/01/2023	-2.07	6.37
Birmingham University	13/04/2023	-2.99	5.90
Chilbolton	22/07/2022	-2.86	6.97
Chilbolton	18/10/2022	-3.49	6.02
Chilbolton	11/01/2023	0.16	7.38
Chilbolton	27/04/2023	-3.14	6.95
London HOP	19/07/2022	-3.49	4.92
London HOP	14/11/2022	-3.74	4.44
London HOP	26/01/2023	-3.16	4.83
London HOP	17/05/2023	-3.82	5.48
Manchester University	02/09/2022	-0.82	4.90
Manchester University	27/10/2022	-1.29	5.08
Manchester University	23/02/2023	-0.30	6.11
Manchester University	18/05/2023	-2.20	6.21
Storrington	09/08/2022	-1.63	7.92
Storrington	25/10/2022	-1.62	5.97
Storrington	06/02/2023	-1.43	6.29
Storrington	25/04/2023	-2.58	6.26
Storrington	30/08/2023	-2.13	5.80
Storrington	26/09/2023	-1.34	5.66

3.2.5 Decisions

A meeting was held on the 26th of April 2023 with all relevant stakeholders related to the operation of the AURN and ALN contracts in attendance. At this time, only two sets of audit results with Whatman tape were available. Prior to this meeting, both QAQC units (AURN and ALN) were asked to look back through the last years' worth of data paying particular attention to the following:

- Has either type shown more tape breakages?
- Has either type resulted in more loss of data due to tape related reasons than the other?

- Has either type shown more evidence of jumping when tapes were changed (excluding when initially swapped from Sibata to Whatman)?
- Has either type required offset correction as part of the ratification process more than the other?

Both QAQC units have responded that here is no clear evidence of either being better and that they have no clear preference. Notwithstanding this, the decision was made to switch all sites to Whatman as this is the tape type supported by the manufacturer and overall seems more stable and repeatable. It was noted that this might lead to an overall slight increase in the average zero. It was decided that the switch to Whatman from Sibata tapes could take place over time and when the Sibata tape ran out on the instruments.

Following the meeting, all Sibata sites were issued Whatman tape and instructed to begin using these after the Sibata tapes at site have been fully utilised. Prior to the switch to Whatman tape, the third set of audit results with Whatman tape became available (as presented above), and these appeared to validate the decision to move from Sibata to Whatman.

3.3 Deliverable 5: Improving baseline performance of automatic PM analysers.

Establishing a robust baseline for air quality instruments is fundamental in building high quality datasets. This becomes especially important if large errors in the baseline measurements exist, which could represent a significant uncertainty contribution at lower measured concentrations. This would also be the case when Limit/Target values are set for lower concentrations.

The current procedures for ongoing quality control within EN16540 require co-location tests to be undertaken for all automatic measurement systems (AMS) at least annually, and recommends action be taken only if the baseline is outside an action criterion of ±3 µg m^{-3}. UK baseline tests are performed at least every six months, using high efficiency HEPA particle scrubbers. If an individual test falls outside of the ±3 µg m^{-3}, the measurement data is assessed during the ratification process, using the zero test evidence as well as reviewing baseline performance of analysers at other sites, to determine if a baseline correction is justified. This evaluation process is based on expert human judgement.

At a concentration of 10 µg m^{-3}, a 3 µg m^{-3} baseline would contribute a non-expanded relative uncertainty of 30% to the total uncertainty budget, clearly exceeding the required data quality objectives before any other contributions are even considered. If it were possible to improve confidence in baseline performance, and reduce the 3 µg m^{-3} tolerance, this would significantly improve the measurement uncertainty for $PM_{2.5}$ measurements.

PM measurements in the UK are currently undertaken with two types of analyser; Fidas 200 and BAM 1020.

The design of the optical technique used for the Fidas means that it reports zero when there are no particles in the detection chamber. With regular baseline testing, it has been demonstrated that this particular analyser gives a high level of confidence that the baseline particulate concentration is consistently very close to zero. In addition, because the analyser responds very quickly to changes in concentrations, the zero test can be undertaken in approximately an hour. There is very little signal noise associated with the measurement, so the limit of detection of the technique is also extremely close to zero.

Zero testing of the BAM analyser is less successful. The baseline response of the analyser depends on many different parameters all coming together successfully: leak tightness, filter tape quality, temperature and humidity can all contribute to the quality of the final test result. The analyser responds very slowly to the introduction of a HEPA filter to the sample line, the test typically takes 36 hours to complete. The output from the analysers during this test is typically noisy, often leading to a limit of detection in the region of 7-10 µg m^{-3}.

Table 3.7 shows a selection of BAM zero tests undertaken at the summer 2023 audit exercise.

Table 3.7 BAM zero tests, summer 2023. All results in µg m^{-3}.

Site	Baseline	Limit of Detection	Site	Baseline	Limit of Detection
Barnstaple A39 PM2.5	2.2	8	London Teddington EQ PM2.5	1.8	6.8
Barnstaple A39 PM2.5	1.9	7.4	London Teddington EQ PM2.5	-0.3	8.5
Barnstaple A39 PM2.5	2.7	8.5	Manchester Piccadilly PM2.5	-3.2	8.9
Birmingham A4540 Roadside EQ PM2.5	-1.4	5.3	Middlesbrough PM2.5	-3.2	5.7
Birmingham A4540 Roadside EQ PM2.5	-0.8	7.4	Newcastle Centre PM2.5	1.1	8.1
Bournemouth PM2.5	1.5	5.3	Northampton Spring Park PM2.5	5.5	5.9
Brighton Preston Park PM2.5	0.2	13.2	Port Talbot Margam PM2.5	0.2	6.5
Bristol St Pauls PM2.5	0.8	8.1	Saltash Callington Road PM2.5	-2.1	5.7
Carlisle Morton PM2.5	4.9	6.9	Sheffield Barnsley Road PM2.5	1.1	7.2
Chatham Centre Roadside PM2.5	-2	10.6	Stockton On Tees A1305 Roadside PM2.5	-2.1	6.3
Chepstow A48 PM2.5	-1.2	5.9	Stockton On Tees Eaglescliffe PM2.5	-1.5	8.6
Christchurch Barrack Road PM2.5	1.3	7.3	Storrington PM2.5	-2.1	5.8
Derry Rosemount PM2.5	1.1	7.5	Storrington PM2.5	-1.3	5.7
Glasgow Kerbside EQ PM2.5	0.7	7.3	University Manchester EQ PM2.5	-2.2	6.2
Glasgow Kerbside EQ PM2.5	1.6	5.2	Warrington PM2.5	-3.5	5.4
Glasgow Kerbside EQ PM2.5	3.2	6.4	Worthing A27 PM2.5	-2.3	6.7
Grangemouth PM2.5	-0.4	5.5	York Bootham PM2.5	1.3	6.1
Leeds Headingley Kerbside PM2.5	0.4	5.6	York Fishergate PM2.5	6.1	6.9
Liverpool Speke PM2.5	3.2	7.5			

Table 3.7 shows that 8 of the 37 $PM_{2.5}$ BAMs tested had baseline responses outside of the current ±3 µg m^{-3} acceptance criteria. Only 8 of the analysers gave baseline responses of less than ±1 µg m^{-3}. For measurements where comparisons will be made against a limit of 10 µg m^{-3}, the majority of these uncorrected baselines would yield ratified data that fall outside of the required data quality objectives.

When assessing the possibility to improve confidence in the baseline performance of automatic $PM_{2.5}$ analysers, it's important to note that concentrations of $PM_{2.5}$, at least for traffic, urban background and rural environments, are remarkably similar across significant distances. These local similarities mean that it may be possible to use this property to confirm "true" baselines for poorly performing analysers. The timeseries plot below shows the close agreement of $PM_{2.5}$ Fidas data at a selection of sites in the South East:

Figure 3.2 Plot of Fidas $PM_{2.5}$ measurements, SE England Oct-Dec 2023

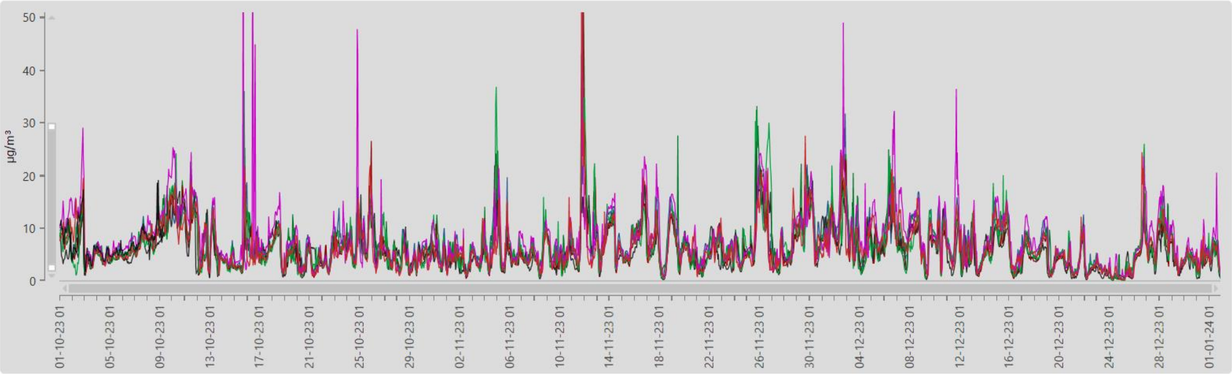


Figure 3.2 shows a high degree of commonality between measurements, across a wide range of different site types (roadside, urban background and rural), within a 50-mile radius of London Bloomsbury. Most importantly, the baseline for all analysers show strong agreement, mostly well within 1 µg m^{-3} of each other. If we can safely assume that this baseline performance is a true reflection of baseline $PM_{2.5}$ concentrations across a region, we can use this information to correct instruments

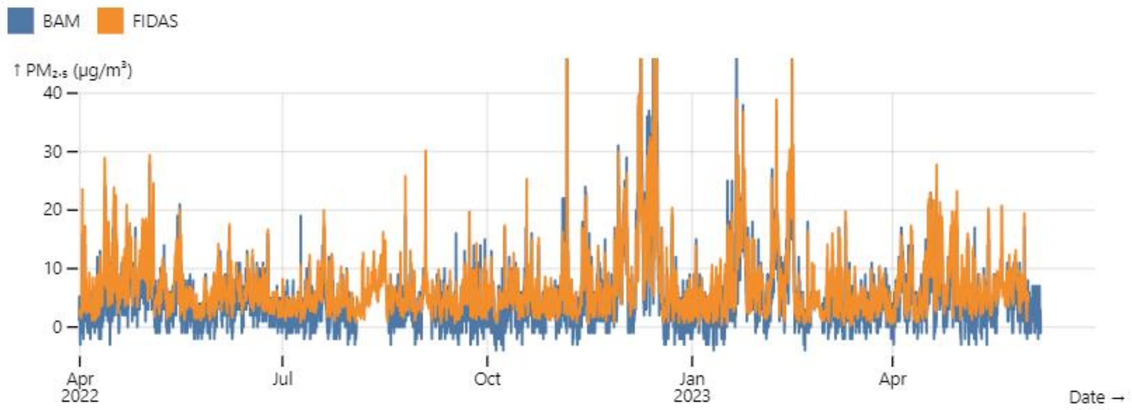
with poor baseline performance. This assumption forms the basis for the analysis presented below.

The philosophy of the baseline correction protocol is reasonably straightforward:

- Select BAM analyser to baseline check
- Select Fidas analysers in similar locations in the region of the test BAM analyser (within a 100 km radius)
- Calculate a 7-day rolling 0.1 percentile for the BAM and Fidas analysers (assumes the quantile values represent the background measurements for each analyser)
- Compare these values to determine the required baseline adjustment for the BAM
- Compare each BAM vs Fidas result to determine the robustness of the comparisons
- Review the quantile corrected baselines against HEPA zero tests to assess the reliability of the six-monthly checks
- Assess the relative reliabilities of correcting BAM data using HEPA results, co-located Fidas data and non-co-located Fidas data

The methodology was tested on data from the co-located BAM and Fidas at Manchester Fallowfield, from April 2022 to May 2023. The plot below shows the timeseries data for the period:

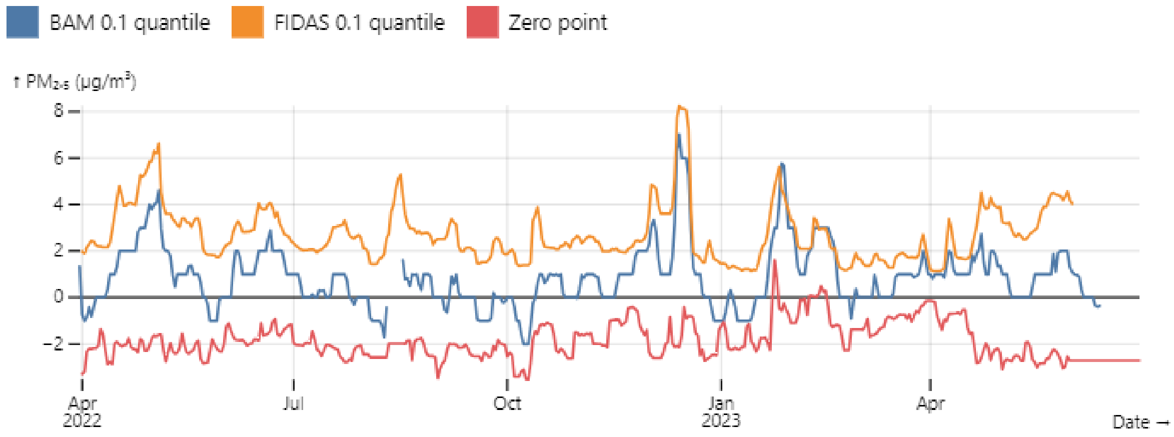
Figure 3.3 Timeseries Plot, Manchester Fallowfield



Visual assessment of this data confirms that, while the trends between datasets are strongly correlated as expected, the BAM analyser appears to be reporting lower concentrations than the Fidas. Currently, the data ratification process reviews the HEPA baseline tests and decides, by expert consensus, what the most appropriate baseline should be. Typically, this might involve a small number of “best estimate” step changes in baseline processing over a six-month review. For this particular example, as the HEPA tests and timeseries data are mostly within ±3 µg m^{-3}, it is unlikely that any corrective action would have been taken.

The following plot shows the rolling 7-day quantile plot for the BAM and Fidas at Manchester Fallowfield:

Figure 3.4 Quantile plot and evaluated baseline correction, Manchester Fallowfield

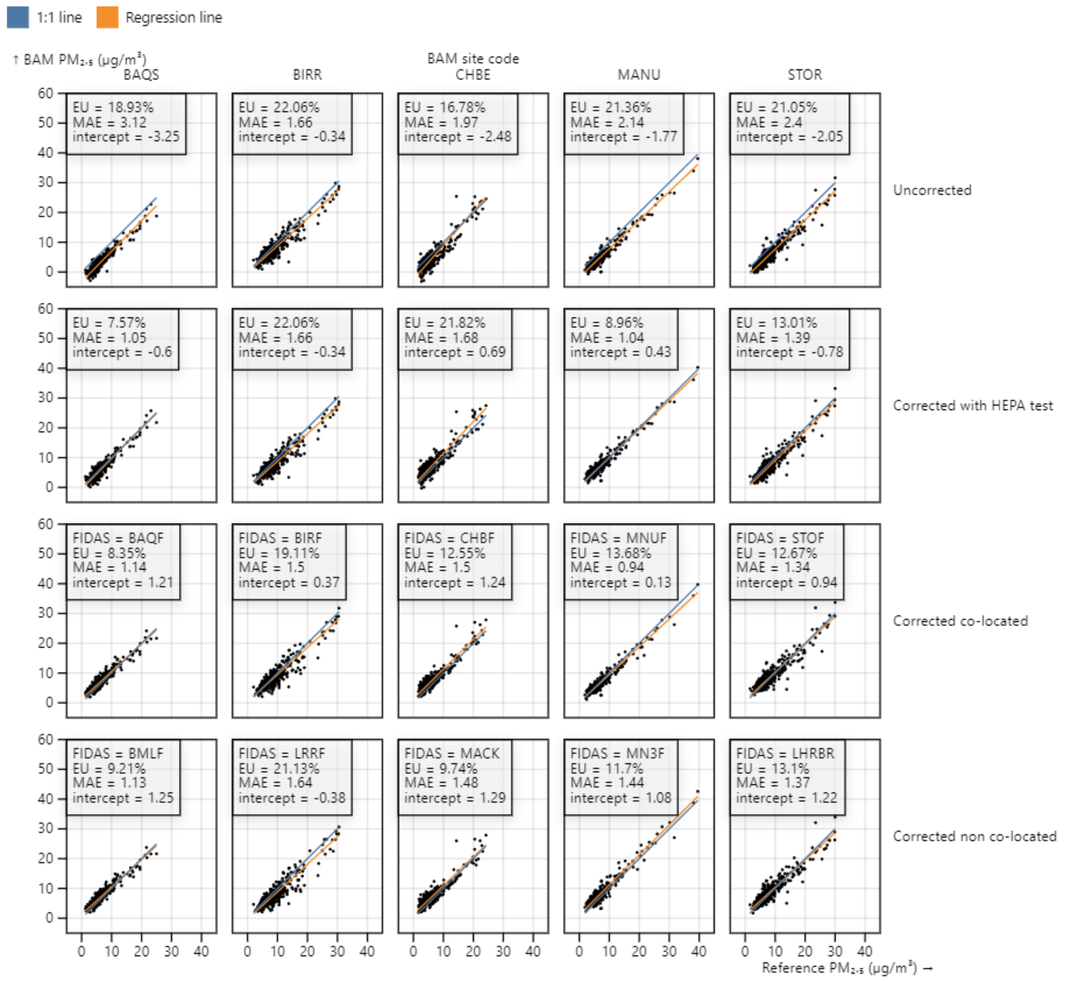


The plot shows the difference between Fidas and BAM baseline responses much more clearly than the timeseries plot in **Figure 3.3**. Additionally, the plot provides a robust evaluated daily correction suggestion to reprocess the BAM data for improved agreement with the Fidas. This also clearly shows that the suggested correction is always less than 3 µg m^{-3} but is also not constant with time. The initial comparison with co-located analysers at Manchester Fallowfield demonstrates that this mathematical approach to baseline assessment has potential for use in the wider network operation. To test this further, the method was applied to a number of other sites where co-locations of Fidas, BAM and gravimetric samplers were deployed for this equivalence exercise:

- Birmingham University
- Birmingham A4540 Roadside
- Chilbolton
- Storrington Roadside

For this test, the calculated baseline correction from the co-located Fidas was applied to each BAM dataset, and the BAM data compared against the reference method data. The scatter plots as follows show how the BAM data are affected when corrected with HEPA test results and also with co-located Fidas baseline data.

Figure 3.5 Scatter plots of reprocessed BAM data using HEPA filters and Fidas correction



Looking down the columns of scatter plots, where there was originally an offset between BAM (y axis) and gravimetric (x axis), the BAM data quality – for uncertainty, Mean Average Error (MAE) and intercept (baseline) correction – can be improved by correction using HEPA and co-located Fidas datasets (Rows 2 and 3).

Additionally, Fidas data from a nearby site to each of the stations was used to determine whether correction using a remote Fidas location was possible. Initially, this test selected the nearest site, but best performance was observed when comparing data matched by site type, especially for rural stations. Row 4 shows the BAM data scatter, using remote Fidas measurements for the baseline correction. It can be seen that the measurement uncertainty and baseline are dramatically improved, with the exception of BIRR, where no baseline correction was required. In all cases, the baseline correction improves the scatter plot offset to less than 1.25 μg m^{-3} compared to the reference method dataset.

The plots above show that correction of BAM baselines is possible using nearby Fidas data. The final aspect of our evaluation was to assess how far away the comparison site could be before the relationship starts to break down. To achieve this, the five equivalence sites were corrected with comparable site locations at varying distances, up to 100km from the stations. The plots below show how uncertainty and baseline are affected by distance from the BAM analyser location:

Figure 3.6 BAM correction as a function of distance – measurement uncertainty

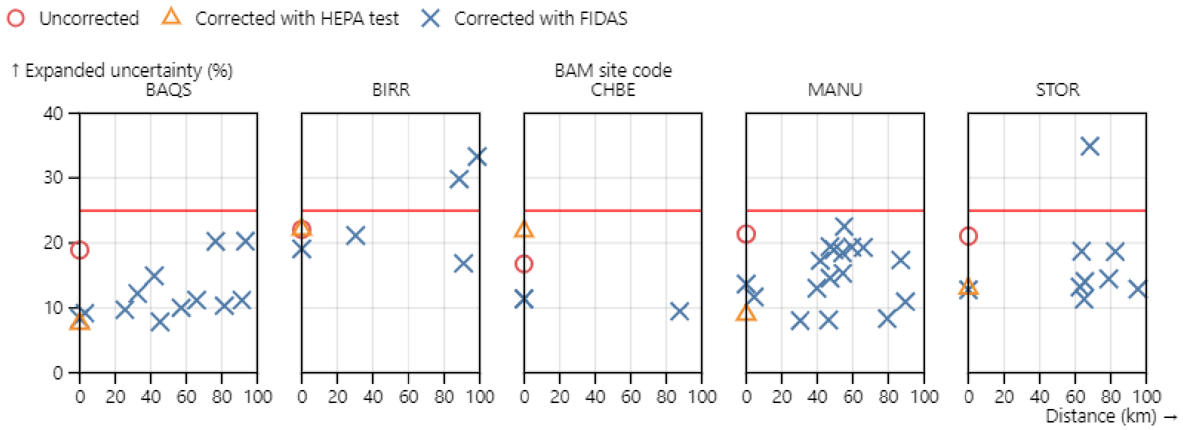
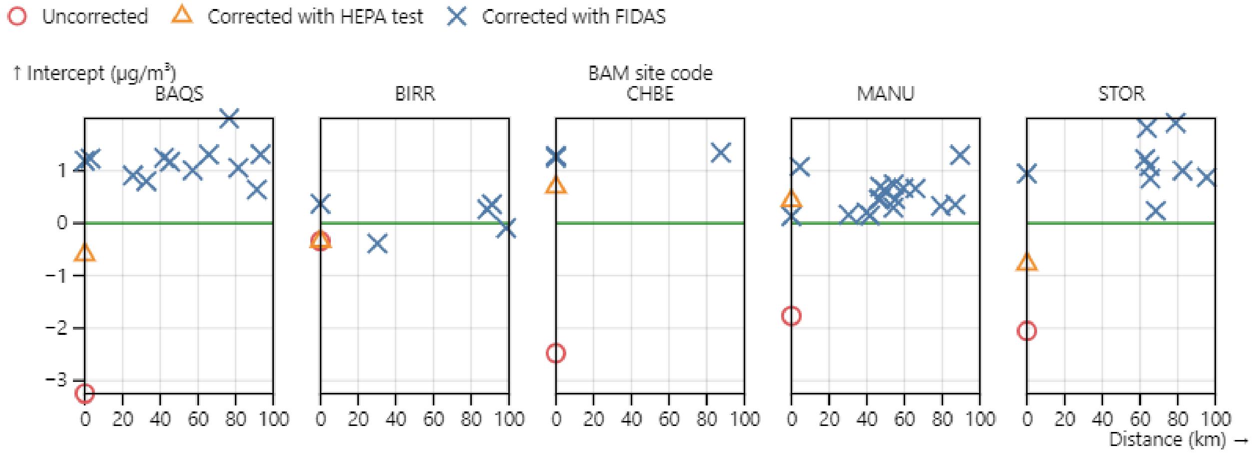


Figure 3.7 BAM correction as a function of distance – baseline



These plots show that, where baseline correction is required, measurement uncertainty continues to meet the requirements of the data quality objective, even when comparator sites are 100km from the BAM location.

In virtually all cases, baseline correction can be undertaken using Fidas data, to bring the BAM baseline to within approximately 1 μg m^{-3} of the gravimetric dataset.

Observations:

The study to assess the potential for baseline correction of BAM $PM_{2.5}$ measurements has shown that BAM data can be reliably adjusted using Fidas data from similar locations up to 100km distance from the BAM station. It is clear from the analysis that this correction can be undertaken without the need for HEPA tests, reducing data loss and the need for return visits to remove the HEPA filter.

The baseline correction improves the BAM baseline to within approximately ±1 μg m^{-3} of the gravimetric zero, which would represent a significant improvement in measurement uncertainty calculations. This improved uncertainty contribution should be fed into future ongoing equivalence assessments, if it is adopted into data processing and ratification protocols, which would significantly benefit assessment of compliance with data quality objectives at lower concentrations.

The calculation process is not dependent upon expert judgement, meaning that a consistent mathematical approach to evaluating BAM baselines is obtained. These results would then provide valuable information to inform the ratification and expert judgement processes and improve confidence in baseline processing.

The correction protocol should be evaluated and refined, for both $PM_{2.5}$ and PM_{10} measurements using BAM data and Fidas comparison sites in the AURN. If successful, this methodology could be incorporated into existing QA/QC procedures, which would result in more consistent and harmonised BAM PM datasets throughout the entire network.

3.4 Deliverable 6: Investigation of the effect of speciation on PM measurements

Particulate matter in the ambient atmosphere is a complex mixture of different components. Depending on the location, the composition of PM may include:

- Internal combustion engine (ICE) emissions from transport,
- Brake dust
- Tyre wear particles
- resuspended road dust,
- secondary aerosols (e.g., ammonium nitrate, ammonium sulphate, organic aerosols),
- condensable and semi-volatile aerosols
- combustion products from domestic and commercial heating / cooking,
- emissions from industrial processes,
- agricultural dust,
- mineral dust from quarrying,
- Saharan dust,
- wildfires,
- sea salt,
- bonfires / fireworks
- Bioaerosols

Unlike measurements of ambient gas concentrations, where the measurement technique is specific for the pollutant of interest, the mass concentration reported by PM analysers and gravimetric samplers is not composition specific. The PM measurement techniques for the instruments and samplers presently in common use in the UK are described in Appendix A: PRINCIPLE OF OPERATION OF INSTRUMENTS USED TO MONITOR $PM_{2.5}$.

These three techniques are sufficiently different (Fidas, BAM and Reference Method) that all changes in PM composition could have an effect on reported concentrations. Some of the potential limitations of each technique are presented below:

- Gravimetric sampler. Differences in filter materials could impact on PM collected. Changes in ambient temperature during the day could cause losses in any semi volatile PM collected. Filter conditioning regime (20C, 45%rH) may not completely remove particle bound water from the PM collected.

- BAM1020. Variability of filter material could impact on measurement results. Relative Humidity affects absorption and reports. Sample collection and analysis processes are prone to leaks. Sample inlet heating, to keep water in gas phase, might also impact other semi volatile components.
- Fidas 200. The analyser is only able to count and size particles larger than 0.18 µm – it makes an extrapolation for mass concentration of smaller particles. The analyser calculation protocol assumes a density profile matrix for different particle sizes which may not be valid in different environments.

In addition to the detailed comparison of measurement methodologies examined in this report, an investigation of particle speciation will offer some insight into whether variations in PM composition have any impact on reported concentrations from the different analysers.

During this investigation, speciated PM measurements were made at a number of locations across the UK:

Table 3.8 UK PM speciation 2022-23

Monitoring Station	Gases	Anions/Cations	Carbon	Particles	Elemental analysis
Manchester Fallowfields	O3, NO, NO2, NOy, SO2, CO, VOC, H2O, NH3, CH4, CO2	Ammonium, Nitrate, Sulphate	Black Carbon, UV Particulate Matter, Elemetal Carbon, Organic Carbon, Total Carbon	Particle Number Concentration, Particle Size Distribution	Yes
Birmingham University	O3, NO, NO2, NOy, SO2, H2O, NH3	not available	Black Carbon, UV Particulate Matter	not available	Yes
London Honor Oak Park	O3, NO, NO2, NOy, CO, H2O, CH4, CO2	Ammonium, Nitrate, Sulphate	Black Carbon, UV Particulate Matter, Elemetal Carbon, Organic Carbon	Particle Number Concentration, Particle Size Distribution	Yes
London Marylebone Road	O3, NO, NO2, NOy, SO2, CO, VOC, H2O	Ammonium, Nitrate, Sulphate	Black Carbon, UV Particulate Matter, Elemetal Carbon, Organic Carbon, Total Carbon	Particle Number Concentration, Particle Size Distribution	Yes

Processed data from Honor Oak Park, Birmingham University and Manchester Fallowfield were provided by Imperial College London, University of Birmingham and University of Manchester respectively, as part of their National Environmental Research Council-funded research programmes. Processed data from London Marylebone Road were obtained from the Defra Particles Research Network.

Data quality was largely accepted as supplied by the site owners. Marylebone Road data have been processed in accordance with accredited national network procedures, but details of how the NERC sites data have been processed is not available. Data capture was variable throughout the period of interest (1 Jan 2022 to 31 May 2023) and large portions of data were missing, presumably rejected by the data owners, due to poor performance, instrument malfunction or on data quality grounds.

For the purposes of the speciation study, it is assumed (by convention) that the gravimetric reference data are correct. Provided the reference sampler is in compliance with the design specifications, and clean filters are conditioned, weighed, exposed, reconditioned and reweighed in accordance with the standard method, the calculated mass concentrations from the filters and volume of air sampled for each 24-hour period are "correct". It is acknowledged that this assumption carries a number of uncertainties, this will be investigated in future iterations of BS EN12341 and BS EN 16450.

The timeseries plots below show the $PM_{2.5}$ measurements at each site:

Figure 3.8 Manchester Fallowfield daily timeseries plot

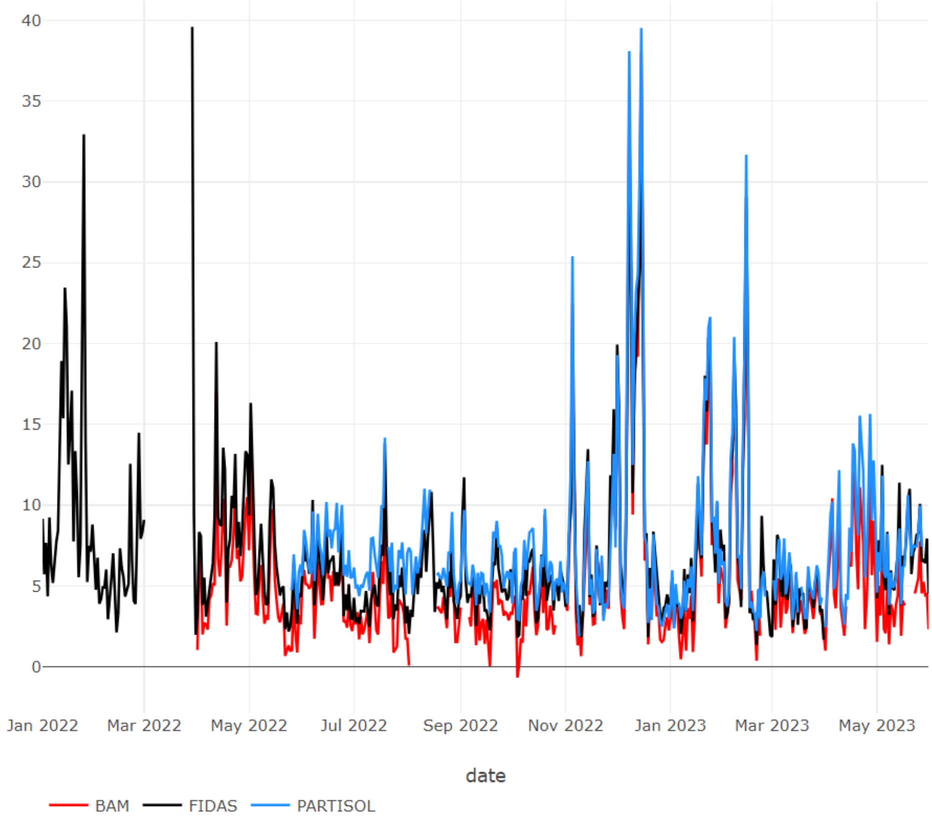


Figure 3.9 Birmingham University daily timeseries plot

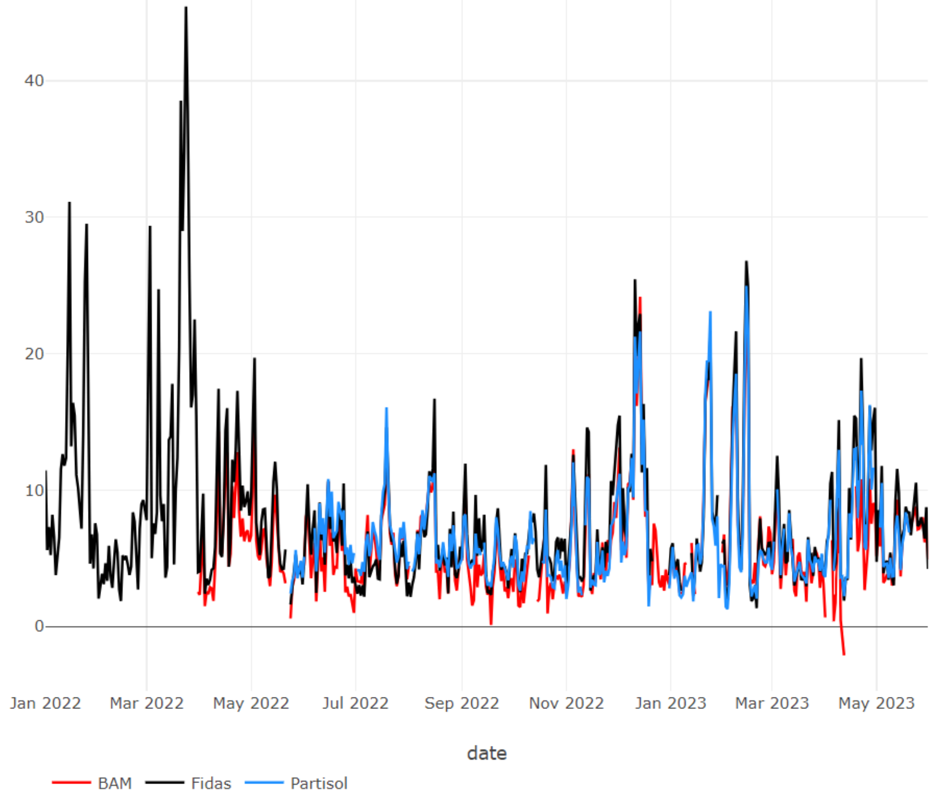


Figure 3.10 London Honor Oak Park daily timeseries plot

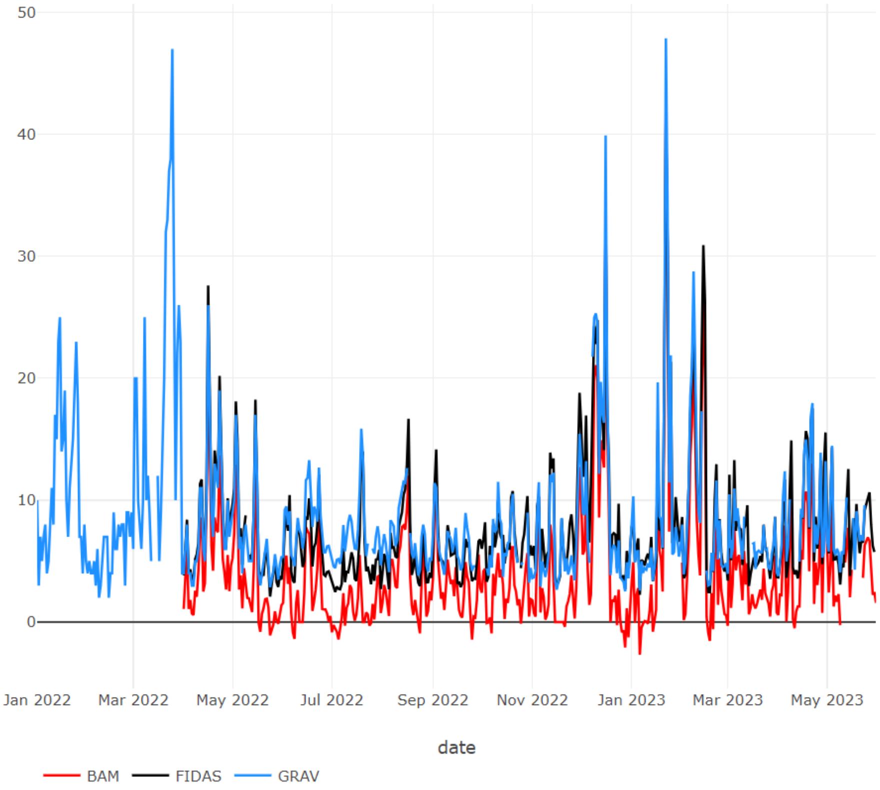
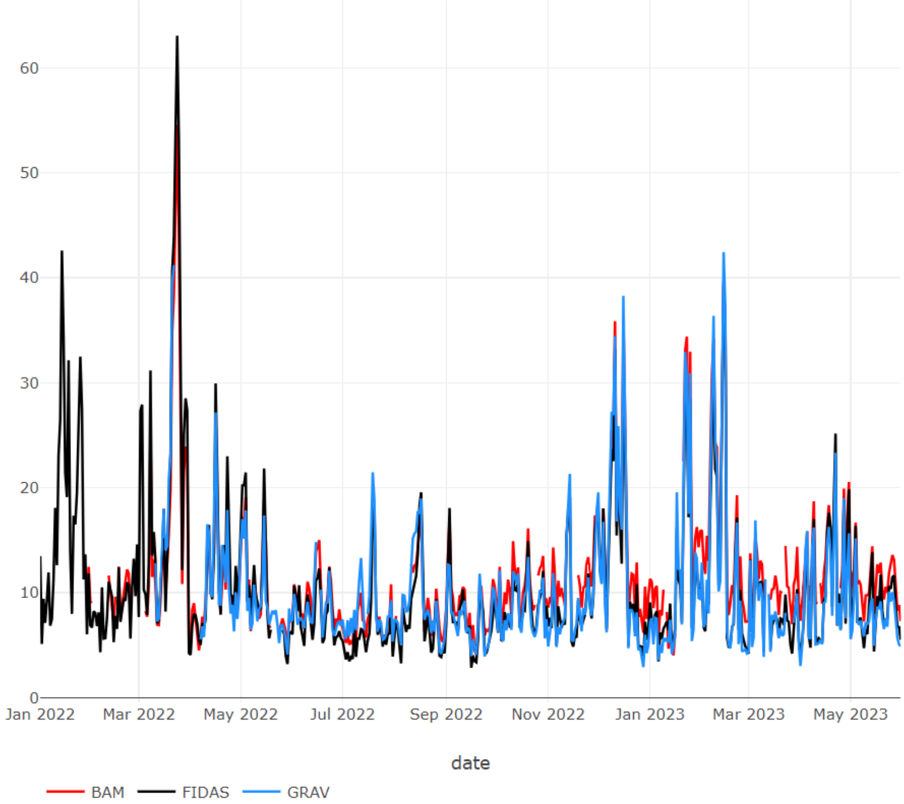


Figure 3.11 London Marylebone Road daily timeseries plot



Trend analysis at all four locations is encouraging, but some systematic biases in BAM baselines are apparent, especially at Honor Oak Park and Fallowfield. Additionally, there are a number of periods where differences between Fidas and BAM are visible, notably during the elevated data periods in November and December 2022. To investigate these further, at each site, the difference between Fidas and BAM was compared to speciation data to identify any possible correlations.

Differences between (Reference-Fidas) or (Reference-BAM) and the various speciation components were examined to see if any trends could be observed. By way of example of the analysis undertaken, the following plots show how the difference between Fidas and BAM data correlates with a selection of other pollutants at Manchester Fallowfield:

Figure 3.12 Manchester Fallowfield speciation correlation with (Fidas-BAM) measurements

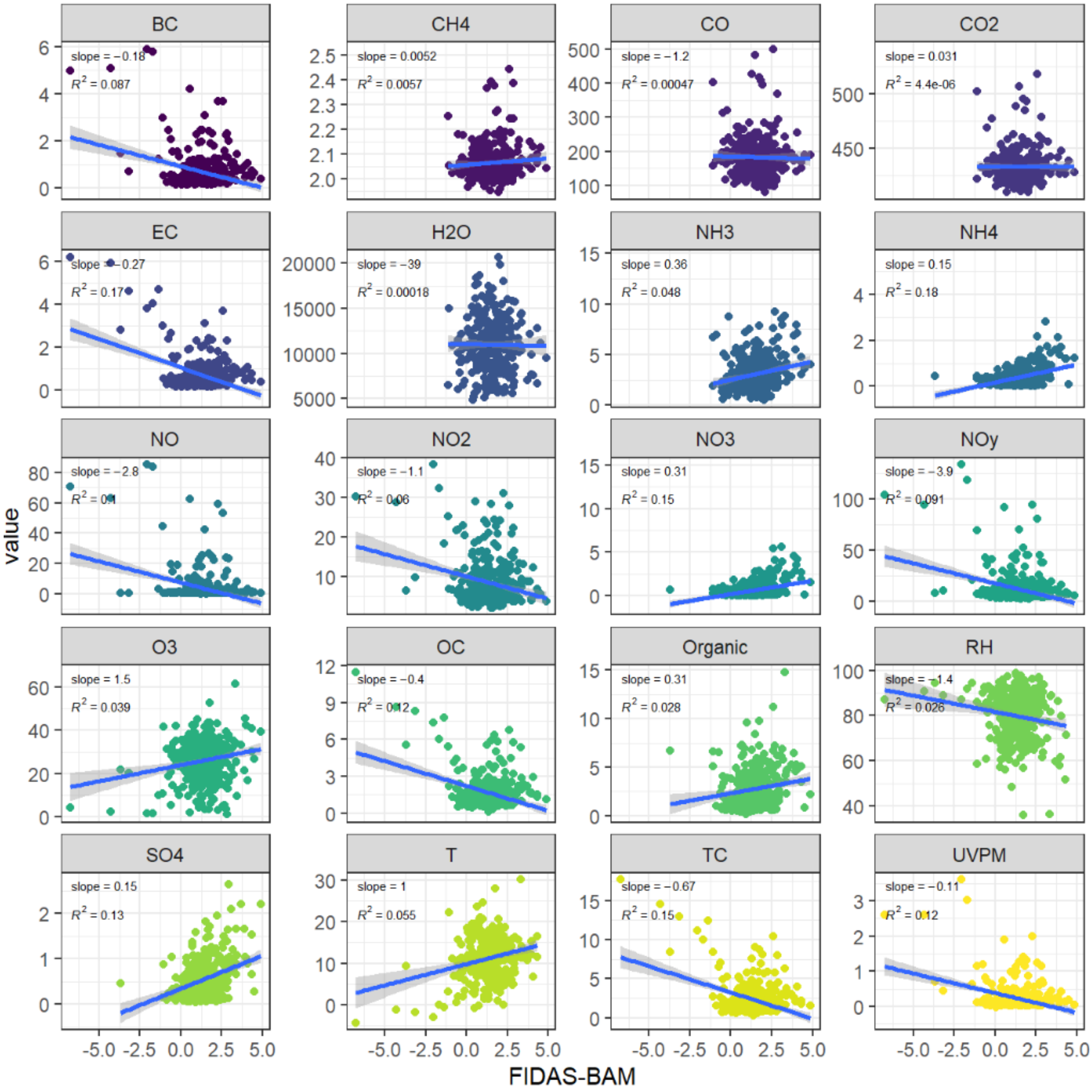
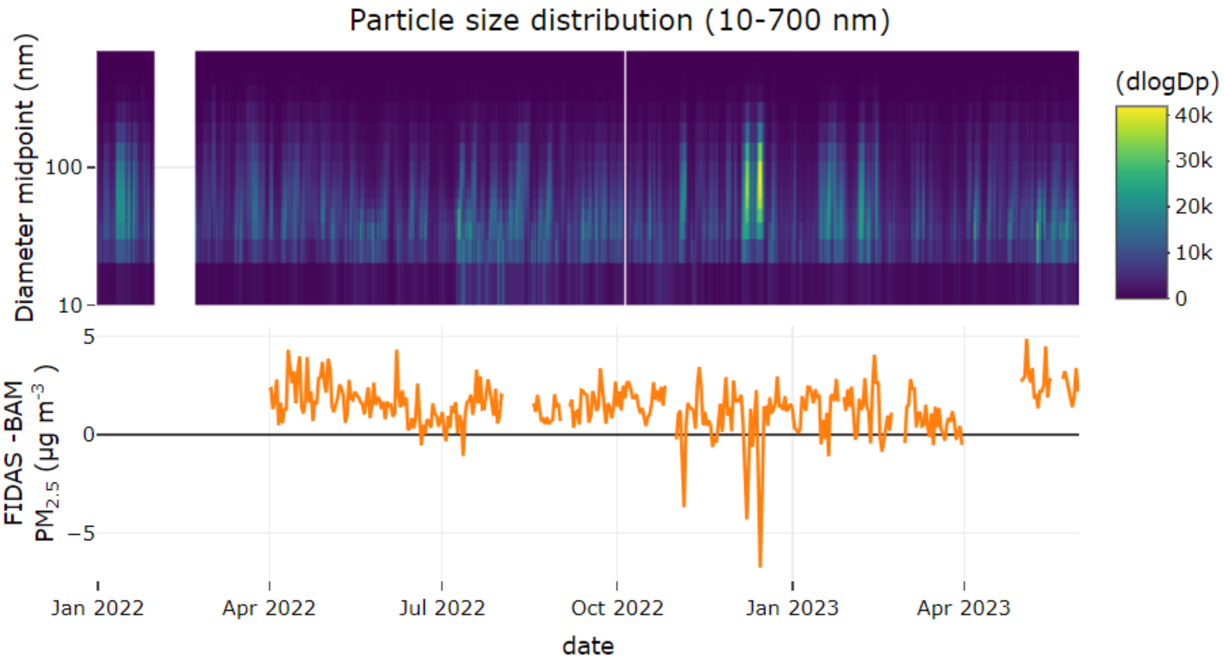


Figure 3.13 Manchester Fallowfield correlation of particle size distribution concentrations with (Fidas-BAM) measurements.



Data shown in **Figure 3.12** show two clear trends:

- The (Fidas-BAM) relationship with EC, OC, TC, BC and UVPM (listed in **Table 3.8**) shows that when "carbon" concentrations are highest, the (Fidas-BAM) calculation is negative, suggesting that the Fidas does not detect these particles as effectively as the BAM. It is known that a significant proportion of these carbon particles are usually very small, thus the Fidas may have difficulty in detecting and reporting them. The trend is also observed in the NOx and NOy data, suggesting that these pollutants might also be a useful surrogate for identifying periods where the Fidas might underreport $PM_{2.5}$.

- The (Fidas-BAM) relationship with NH_4^+, NO_3^- and SO_4^{2-} shows that when the concentrations of these particles are highest, the (Fidas-BAM) calculation is positive, suggesting that the BAM does not detect these semi volatile particles as effectively as the Fidas. It is possible that the inlet heating and unpredictable behaviour of these particles on the BAM filter tape may impact on the BAM measurements.

Figure 3.13 shows that BAM measurements are higher than Fidas measurements, when very fine particles are present in high concentrations, suggesting that the Fidas does not detect these particles as effectively as the BAM. The particle size distribution plot in **Figure 3.12** shows a large number of particles smaller than 100 nm (0.1 µm), with a number of significant episodes. This observation will have an impact on the calculation methodology used by the Fidas when estimating the mass of particles smaller than it's 0.18 µm detection limit.

There are no further clear trends in the (Fidas-BAM) vs other species analysis at Manchester Fallowfield.

Analysis of the correlations against speciation data is less obvious at the other locations. This is partially due to data gaps either for repair of instrumentation or rejection of data of unknown quality. In addition, PSD and PNC data from Honor Oak Park and Marylebone Road for 2023 were not available at the time of investigation (September 2023). However, where data analysis was possible, the following observations could be made or confirmed:

- There are no obvious relevant correlations with any of the measured elements at any site
- Ammonium and nitrate ion correlations at Honor Oak Park followed a similar trend to Manchester Fallowfield. The correlation was not quite so obvious at Marylebone Road, while no ion data was available from Birmingham University.
- The EC, OC, TC, BC, UVPM correlations at Honor Oak Park followed a similar trend to Manchester Fallowfield. The correlation was not quite so obvious at Marylebone Road, and weaker still at Birmingham University
- The Particle Size Distribution correlation at Marylebone Road followed a similar trend to Manchester Fallowfield. Data gaps in the PSD data at Honor Oak Park prevent a conclusive analysis, whilst all PSD and PNC data from Birmingham University were rejected following QA/QC checks.

Observations:

The study to assess whether particle speciation has an impact on measurements has shown that the BAM and Fidas methods can be sensitive to the presence of a number of components.

Fidas analysers appear to under report results when carbon particles and UFP are present in high concentrations. Knowledge of the Fidas calculation methodology and the nature of these particles, helps to understand this observation during pollution episodes. The nature of this relationship is highly variable between sites and temporally: while the information would be informative, it would not be possible to use co-located carbon particle or UFP measurements to apply any correction to Fidas data.

BAM analysers appear to under report results when concentrations of ammonium, nitrate and sulphate ions are present in high concentrations. It is likely that the inlet heating and filter tape conditioning have an impact on how these ions behave during the capture and analysis. The nature of this relationship is highly variable between sites and temporally: while the information would be informative, it would not be possible to use co-located ion measurements to apply any correction to BAM data.

3.5 Deliverable 7: Analysis of $PM_{2.5}$ Instrument changes

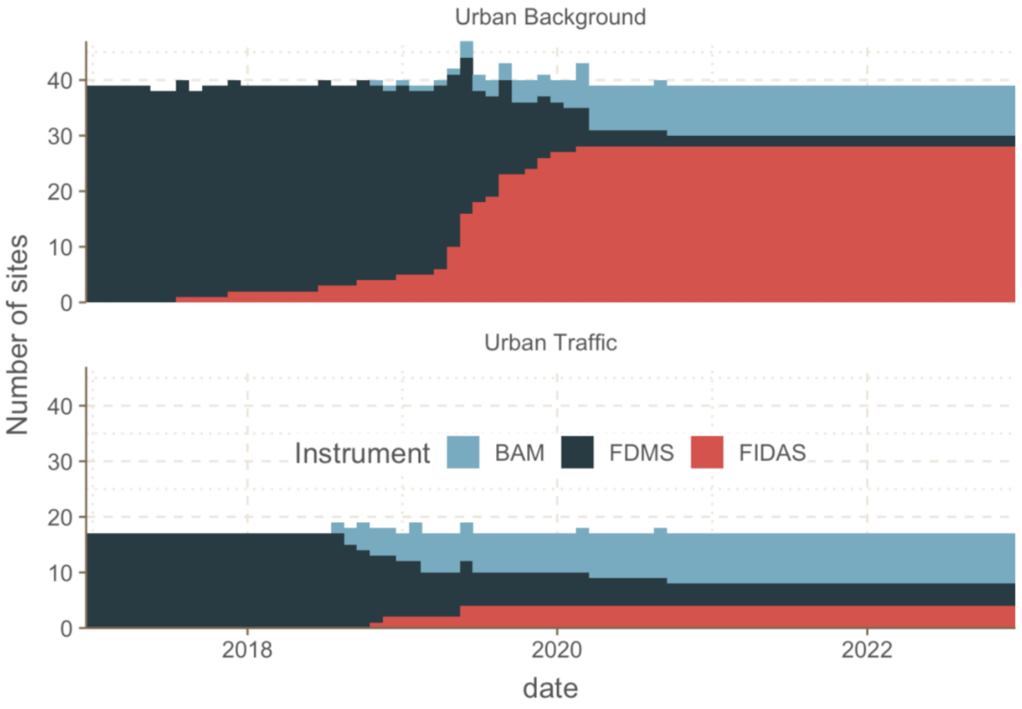
A potentially important issue with respect to measurements of $PM_{2.5}$ is whether changes in the instruments used in the UK network(s) affect the reported $PM_{2.5}$ concentrations. If changes in instrument type result in systematic changes in reported $PM_{2.5}$ or PM_{10} concentrations, then there could be important implications for assessing compliance with air quality limits and new targets as well as in the analysis of particle concentrations in general. Analysis of $PM_{2.5}$ measurements, might for example, seek to understand roadside increments in concentration where the $PM_{2.5}$ from a background site is subtracted from the $PM_{2.5}$ from a roadside site. If, as is now the case, there are different instrument types that dominate at background (Fidas) compared with roadside (BAM), it is important to establish there are no systematic differences in reported $PM_{2.5}$ concentrations by instrument type.

To answer such questions, detailed, co-located intercomparisons of instrument types provide the most comprehensive way of understanding this issue. However, there is also merit in considering at an air quality network level whether there is evidence from measured concentrations of changes when one instrument type is replaced by another instrument type. The main purpose of the present analysis is to determine whether there is evidence of differences in reported $PM_{2.5}$ concentrations by instrument type rather than focusing on quantifying absolute values.

The approach focuses on considering the AURN network as a whole and specifically considers changes in instruments from FDMS → BAM and FDMS → Fidas. These instrument changes mostly occurred during 2019 with most of the changes to BAM at traffic sites and most changes to Fidas at urban background sites. The principal approach of the analysis is to consider a before-after study to the instrument changes and focus on the evidence for any systematic changes in $PM_{2.5}$ concentrations that could be attributed to a change in instrument type. The other focus of the analysis is to consider any timings of changes in the difference in concentrations between BAM and Fidas, both from a network perspective and at an individual site. The analysis solely focuses on whether there are differences between instruments and not which is more ‘correct’. Notwithstanding this, all instruments have shown to be compliant with the UK MCERTS for Particulate Matter criteria.

Figure 3.14 shows the time series of instrument types split by urban background and urban traffic sites.

Figure 3.14 Number of instruments measuring $PM_{2.5}$ by instrument type for urban background and traffic locations.



Network-wide analysis

This analysis considers periods two years before and after each individual instrument change in the network, in order to explore whether (when averaged across the network) there is evidence of any systematic difference in changes in $PM_{2.5}$ concentrations when considered by instrument and location type. A challenge with the analysis is that many ‘after’ periods coincided with changes in activity due to Covid-19 lockdowns, which potentially frustrated the analysis in terms of attributing change. However, as described above, it is not the magnitude or direction of any underlying trend which is important here, merely consideration of whether any changes are systematically and observably different according to the instrument type deployed.

Figure 3.15 shows the aggregate effect on trends in $PM_{2.5}$ by instrument and site type. For these trends, the BAM and Fidas trends shown were based on original FDMS instruments before being changed to either BAM or Fidas. At urban background locations the trends are largely consistent by instrument type, especially when accounting for uncertainties (shown in the square brackets); although at sites that moved from FDMS to Fidas there is more of a downward trend (-0.56 µg m^{-3} per year), than for FDMS to BAM (-0.38 µg m^{-3} per year).

At traffic sites there is a clearer divergence in behaviour by instrument type. For sites changing from FDMS to BAMs there is a slight downward trend (although not statistically significant), whereas for instruments that changed from FDMS to Fidas there is a strong downward trend that is statistically significant (-0.56 µg m^{-3} per year). A move to using Fidas tends therefore to lead to greater decreases in $PM_{2.5}$ compared with moving to using a BAM.

Figure 3.15 Trends in $PM_{2.5}$ by instrument and site type. Note that in the case of both BAM and FIDAS, the earlier measurements were made by FDMS.

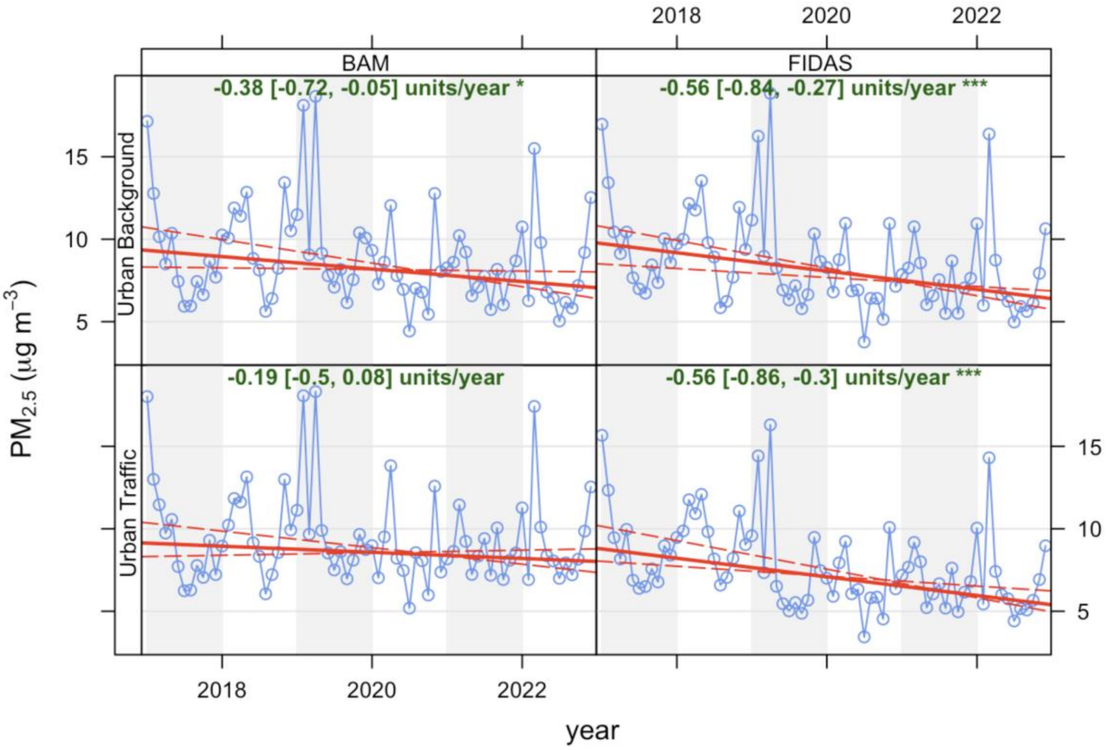
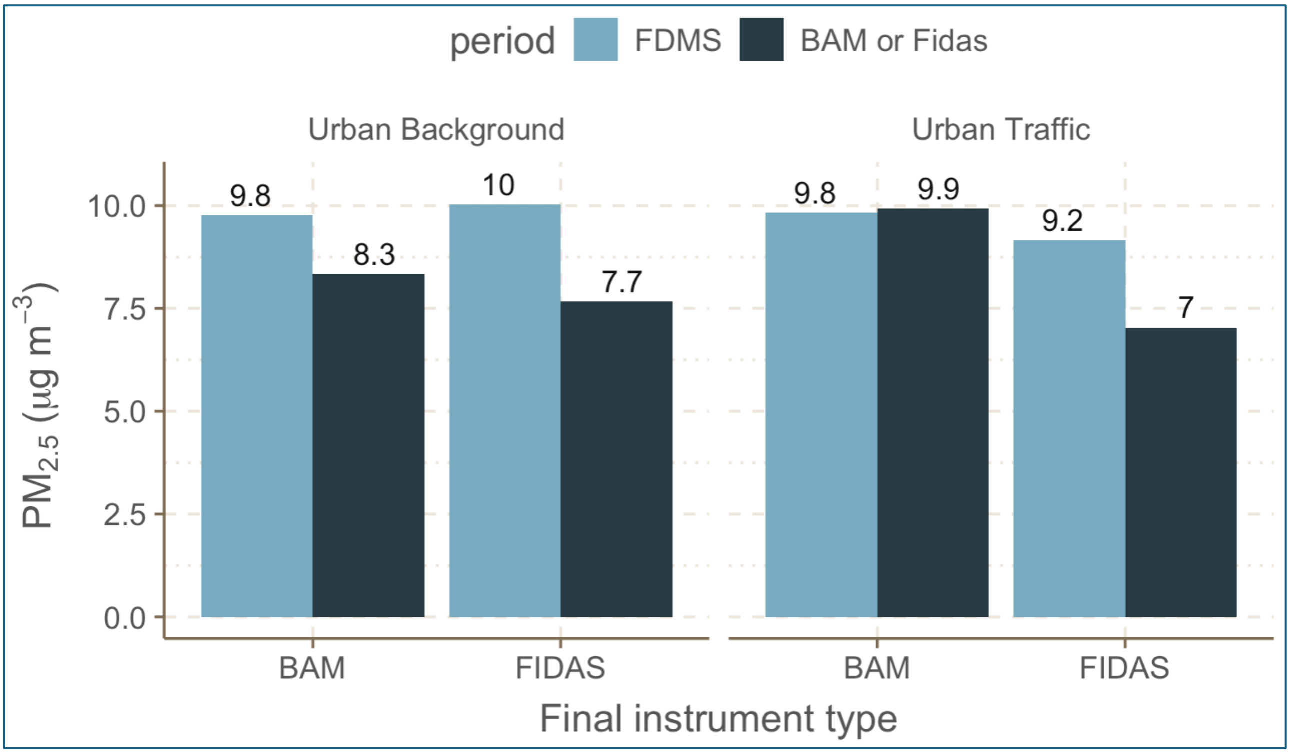


Figure 3.16 shows the mean concentrations across the AURN network for two years before and two years after an instrument was changed (from FDMS) for urban background and traffic sites. It highlights at both site types, the change from FDMS to Fidas results in a greater reduction in concentrations than instruments going from FDMS to BAM. At urban background sites on average, converting from FDMS to Fidas results in an additional reduction of 0.8 µg m^{-3}, whereas at traffic sites the additional reduction in 2.3 µg m^{-3} compared with BAM instruments. Furthermore, the analysis does not suggest a difference in going to a Fidas at urban background or urban traffic sites, as they both show a similar change; although it should be noted there are fewer FIDAS instruments at traffic sites. The main point overall is that in moving to use the Fidas, there was a greater reduction in $PM_{2.5}$ compared with moving to use a BAM.

Figure 3.16 Mean change in average $PM_{2.5}$ concentration two years before an instrument change from FDMS compared with two years after. *The x-axis labels show the replacement instrument type. The numbers show the average concentrations.*



Another way to consider whether changes in instruments affect concentrations of $PM_{2.5}$ is to consider the difference between BAM and Fidas instruments over time and accumulate these differences to help highlight the timing of any changes using a Cusum plot. If the two instrument types report the same concentration on average, then a Cusum line will be horizontal. **Figure 3.17 (A)** shows an example of a simple cusum with a time series of some random noise where there is a step change of 0.5 units in values halfway through the time series. The change is not immediately apparent in (A) but by plotting the cumulative sum of the differences from the mean (B) the changes are emphasised.

Figure 3.17 (A) Example time series with some random noise and a small change in the value of x of 0.5 units halfway through the time series. By considering the cumulative sum of the difference from the mean **(B)** it becomes much more apparent that a consistent change in x occurred.

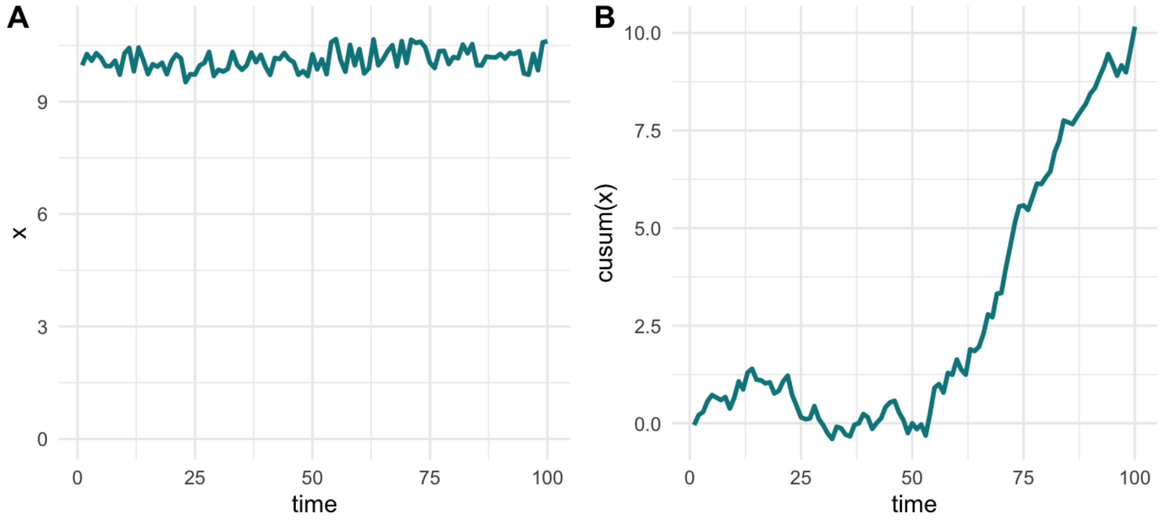
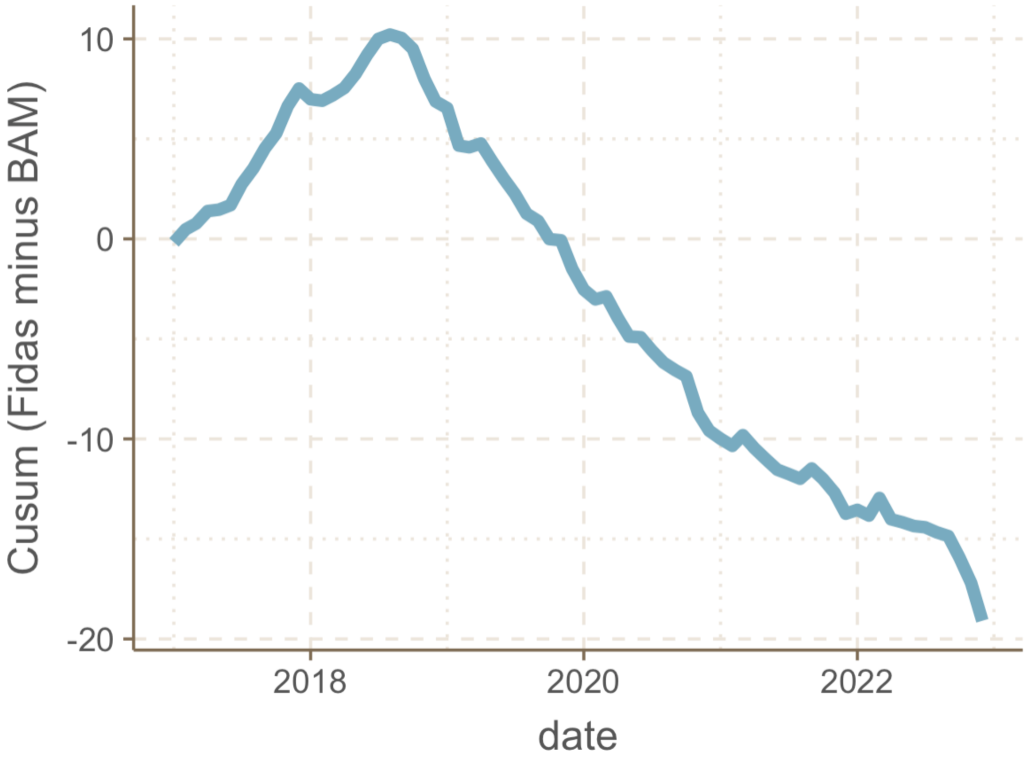


Figure 3.18 shows that there was a clear change in the Cusum differences between BAM and Fidas at urban background sites in 2019, and the Cusum line decreases in a linear way after that time. The 2019 date coincides with when most instruments were changed. This plot indicates that a move to Fidas tended to decrease the reported $PM_{2.5}$ concentration compared with BAM instruments. The average difference between the instruments from 2019 onwards corresponds to a reduction in concentration of 0.6 µg m^{-3}.

Early in the time series shown in **Figure 3.18**, the Cusum line tends to increase, which means that on average FDMS sites that were later changed to Fidas had higher concentrations than those converted to a BAM. The fact there is a clear inflexion point ~ 2019 where this trend is reversed, provides a strong indication of a change in behaviour.

Figure 3.18 Cusum of the difference in $PM_{2.5}$ between sites that change from FDMS to Fidas or BAM instruments (Fidas minus BAM) at urban background sites.

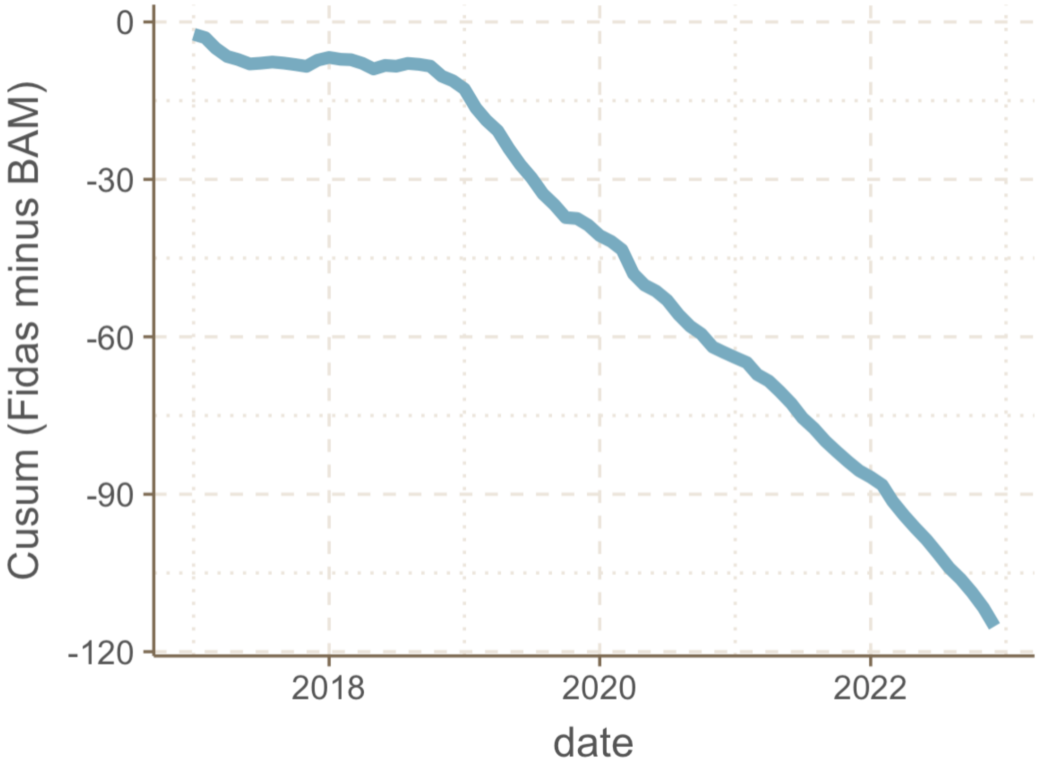


At traffic sites the changes are clearer as shown in **Figure 3.19**, where there is a much larger decrease in the Cusum value compared with urban background sites. Again, the change point is around 2019 when most instruments were changed. These results show that a change of instrument to BAM or Fidas had different effects on the reported $PM_{2.5}$ concentration, with Fidas reporting a greater decrease in $PM_{2.5}$ compared with BAMs at traffic sites i.e., consistent with the trend analysis in **Figure 3.15**. The first part of the Cusum plot is broadly level (when all instruments were FDMS), which means there was no significant difference in reported concentrations of $PM_{2.5}$ between sites which were later converted to BAM or Fidas.

It should be noted that in moving from FDMS to BAM concentrations did not change much at Urban Traffic (**Figure 3.16**), but there is nevertheless a clear change in the *difference* between BAM and Fidas sites, and a change that corresponds to instrument change dates. The average difference between the instruments from 2019 onwards corresponds to a concentration of 2.5 µg m^{-3}.

The difference at urban background and urban traffic sites is consistent with the before-after analysis even though they do not consider the exact same time periods. The Cusum analysis does however provide additional information on the timing of the change, which is close to the average date instruments were changed and not, for example, related to actions taken due to Covid-19.

Figure 3.19 Cusum of the difference in $PM_{2.5}$ between sites that change from FDMS to Fidas or BAM instruments (Fidas minus BAM) at urban traffic sites.



Single site analysis

Plotting $PM_{2.5}$ time series directly and trying to identify changes in concentrations is challenging given the large variation in $PM_{2.5}$ concentrations and the effects of meteorology. Removing the effects of meteorology does not necessarily help because only a small fraction of $PM_{2.5}$ concentrations is affected by local meteorology.

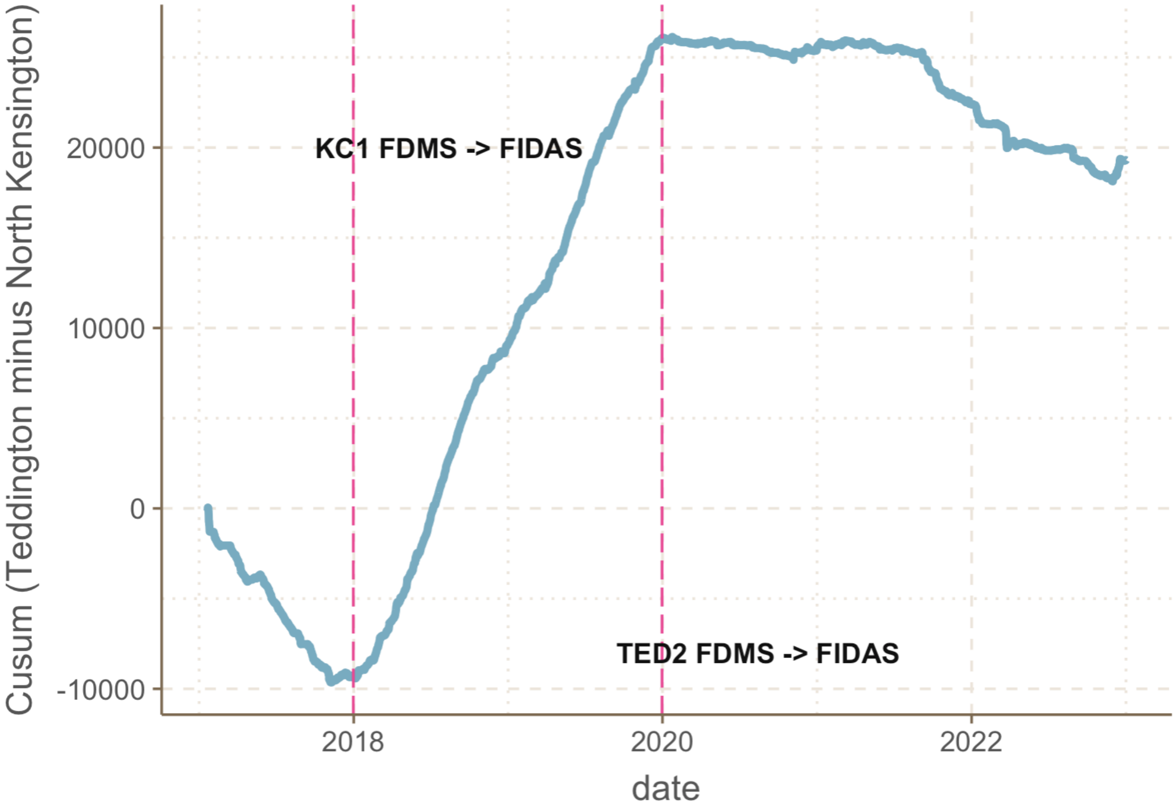
However, by considering the difference in $PM_{2.5}$ concentrations between two reasonably close sites (to avoid significant differences due to regional contributions) does have the potential to provide clearer indications of any changes in concentrations at particular times. As an example, concentrations have been considered at two London sites where instruments change from FDMS to Fidas at different times. At North Kensington the instrument was changed at the end of December 2017 and at Teddington at the end of December 2019.

Additionally, by calculating the Cusum of the differences in $PM_{2.5}$ concentrations, the timing of any shifts in concentration can potentially be identified. **Figure 3.20** shows the Cusum of the differences in $PM_{2.5}$ concentrations (Teddington minus North Kensington $PM_{2.5}$ concentrations), which does indicate shifts in concentration that are timed close to the actual instrument change dates.

The interpretation of **Figure 3.20** is as follows. The Cusum line initially decreases, which means that Teddington has lower concentrations than North Kensington on average. At this point they both have FDMS instruments, and lower concentrations would be expected at the less urban Teddington site. The Cusum line increases at the end of 2017 when the North Kensington site changes to an Fidas instrument.

From the end of 2017 to the end of 2019, the Teddington site had higher $PM_{2.5}$ concentrations than North Kensington. At the end of 2019, the Teddington site changes from using a FDMS to a Fidas and the Cusum line shows another change. There is some evidence of a further change in autumn 2021 but currently no explanation as to the cause.

Figure 3.20 Cusum of difference in hourly $PM_{2.5}$ concentrations between the Teddington and North Kensington sites (i.e., Teddington minus North Kensington). *The red dashed line show the dates when the instruments changed from FDMS to Fidas*



It should be stressed that the analysis above is focused on determining whether there are changes in concentrations of $PM_{2.5}$ when instruments are changed from one type to another and not whether one instrument is better than another. Similar analysis could be carried out with gravimetric instruments.

Overall, this analysis concludes that:

- The change from FDMS to Fidas instruments on average across the AURN network resulted in a larger decrease in reported $PM_{2.5}$ concentrations compared with those sites where instruments changed from FDMS to BAM.
- Changing from FDMS to BAM appears to result in a larger decrease in reported $PM_{2.5}$ concentrations at background sites compared to traffic sites.

- Cusum analysis shows that the timing of changes in concentrations across the network are consistent with when instruments changed and not, for example associated with the start of Covid-19 lockdown on the 23rd March 2020.
- Considering the difference in $PM_{2.5}$ concentrations at two urban background sites in London, shows clear changes in $PM_{2.5}$ concentrations consistent with the finding above and which have clear inflexion points corresponding to known instrument changes.
- When analysing trends at individual sites, or the difference between pairs of sites (for modelling or other scientific analysis) it may be important to consider how changes in instrument type affect these measurements. This is explored further in the next section.

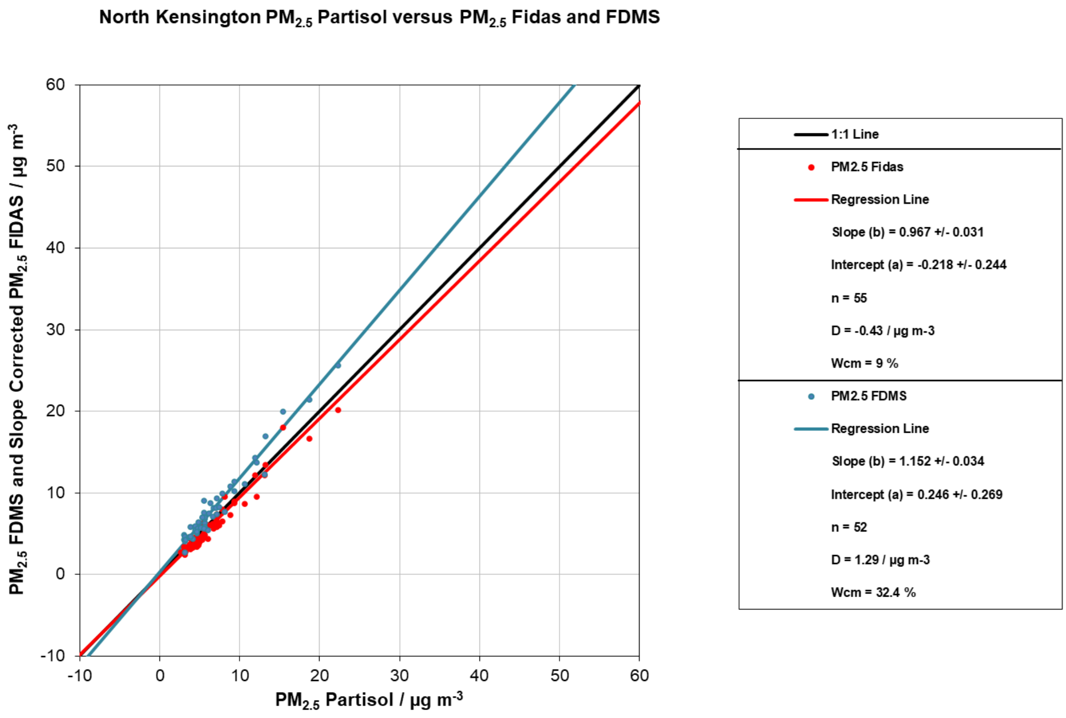
3.6 Additional analysis of $PM_{2.5}$ Instrument changes

The previous section (Section 3.5) shows the effect of changing instrumentation based on the assessment of publicly available data. It highlights that on average across the AURN network there are different changes in reported $PM_{2.5}$ concentrations associated with the different types of new instrumentation deployed. It also shows that the difference between $PM_{2.5}$ concentrations measured at nearby monitoring locations can also be seen to be affected by changing instrumentation.

In this section we attempt to provide some explanation of why these differences can be observed, including the analysis of some gravimetric $PM_{2.5}$ measurements which are not reported as part of the AURN but made for ongoing equivalence studies.

During the period when the FDMS 8500 was swapped for a Fidas at London North Kensington (2017), there was also a Partisol 2025 pseudo-Reference Method operating, the Fidas, Partisol and FDMS were all operated at the same time. The results for this period are shown in **Figure 3.21**. The data shows that the Fidas read lower than the FDMS 8500 but that it agreed much more closely with the Partisol than did the FDMS.

Figure 3.21 $PM_{2.5}$ Equivalence calculations for London North Kensington. X Axis Partisol. Y Axis Fidas and FDMS.



At London Teddington the Reference Method (SEQ 47/50), FDMS, Fidas and BAM were all operating at the same time throughout 2018, 19, 20 and 21. The equivalence calculations are shown in **Table 3.9** along with calculations for 2016 and 2017 for the FDMS and BAM. The column 'D / µg m^{-3}' shows by how much each instrument reported greater than the Reference Method on average over that particular year. These show that whilst the FDMS read higher than the Fidas, the Fidas consistently read closer to the Reference Method.

Table 3.9 Equivalence Calculations for 2016-21 at London Teddington for the PM$_{2.5}$ Fidas, BAM and FDMS.

X axis	Y axis	Year	Slope	Intercept / µg m^{-3}	W_{CM} / %	D / µg m^{-3}
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2016	1.05	-0.56	10.1	-0.10
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2017	0.99	1.24	9.2	1.10
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2018	1.10	1.18	28.5	2.14
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2019	1.07	2.15	29.8	2.90
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2020	1.07	-0.24	14.0	0.37
PM$_{2.5}$ SEQ	PM$_{2.5}$ FDMS	2021	1.09	1.17	27.8	1.87
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2016	1.01	-0.61	9.2	-0.52
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2017	1.08	-0.41	14.0	0.28
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2018	1.09	-0.32	21.2	0.67
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2019	1.05	1.12	17.4	1.58
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2020	1.02	-0.04	7.6	0.12
PM$_{2.5}$ SEQ	PM$_{2.5}$ Heated BAM	2021	1.03	0.83	14.2	1.08
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2016	Not installed			
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2017	Installed November 2017			
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2018	1.01	0.35	9.4	0.47
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2019	1.01	0.16	8.0	0.31
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2020	0.95	0.30	10.3	-0.13
PM$_{2.5}$ SEQ	PM$_{2.5}$ Fidas M11 / 1.06	2021	1.04	0.24	12.3	0.55

Taken together, the results at North Kensington and London Teddington indicate that the step change in concentrations can more than likely be attributed to the FDMS over-reading than to the Fidas under-reading; particularly given that both sites are Urban Background where any influence of smaller particles below the limit of detection of the Fidas is less pronounced.

Figure C.3 in the Appendix shows the average HEPA zeroes for the FDMSs and BAMs. On average (over all 830 measurements) the FDMS off-set at zero was 1.34 µg m^{-3}. In contrast, over all 641 measurements for the BAM (with Sibata tapes) the offset was less at 0.69 µg m^{-3}. On average over all 102 measurements the BAM with Whatman tape was 0.98 µg m^{-3}. All of these are greater than zero which shows that on average the BAM and FDMS do over-estimate assuming that the HEPA zero is a true representation of the instrument in particle free air. For any given instrument the HEPA zero could be much higher or lower than this average. For the FDMS at London

Teddington it was believed that the Nafion drier was ageing. When this was replaced in early 2020 after switching the AURN dissemination of data to the Fidas for this site, the reported concentrations were shown to drop and this can be observed in column 'D / µg m^{-3}' of **Table 3.9**. Across the AURN network replacement of driers was not systematic but undertaken as needed throughout the life cycle of the FDMSs. Due to instrument failure, the FDMS was replaced in early 2021 and so 2021 data are from a combination of two FDMSs. Following this the FDMS was removed as all FDMSs in the AURN had been removed by the end of 2021.

When the Fidas is HEPA tested the concentration is always 0.00 µg m^{-3}. As such, there is anticipated to be a reduction in concentrations measured when using the Fidas. It is however also possible that the Fidas is not correctly attributing the mass to those particles below its minimum detection limit of 180 nm when there are a greater number of particles than it is anticipating. This would be most evident at busy Urban Traffic sites.

The $PM_{2.5}$ FDMS was shown to overestimate with a slope of 1.067 during the initial equivalence testing[17]. Slope correction at the time was not deemed mandatory or felt necessary because slope correction did not change the number of equivalent datasets. This decision was made in 2006 when the mathematical procedures now followed were in the process of being developed. It is not felt appropriate to back correct the FDMS data to account for the 6.7 % over estimation found during the initial equivalence testing.

Conclusions

The additional evidence presented here on $PM_{2.5}$ instrument performance suggests that:

- The FDMS 8500 units in the AURN were likely over-reading $PM_{2.5}$ concentrations due to a combination of on average positive HEPA zero measurements and a 7% slope over estimation found during initial equivalence testing. As such, the change in FDMS to Fidas should be viewed in the context of the FDMS over-reading.
- The BAM units in the AURN may also be over-reading $PM_{2.5}$ concentrations due to on average positive HEPA zero measurements. This over-reading is expected to be to a lesser extent than the FDMS 8500 though could in part explain why replacing 8500 FDMSs with BAMs gave rise to less significant change than replacing 8500 FDMSs with Fidas.
- Based a short study at North Kensington, and 5 years of $PM_{2.5}$ measurements compared to the pseudo reference method at London Teddington, the Fidas limitations relating to the 180nm cut off of particles are unlikely to be leading to a significant under estimation at Urban Background sites.

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[17] https://uk-air.defra.gov.uk/assets/documents/reports/cat05/0606130952_UKPMEquivalence.pdf

4. EQUIVALENCE TESTING OF OTHER POTENTIAL ‘IN-SCOPE’ ANALYSERS.

4.1 Deliverables 8 & 9: Consideration of other instruments.

As part of the programme, engagement with instrument manufacturers was undertaken. This engagement covered manufacturers of instruments that were currently being used in the AURN and formed part of the current ongoing equivalence programme, in addition to a number of suppliers that supply particulate matter instruments in development.

Existing instrument manufacturers:

The manufacturer of the BAM is Met One. Engagement with the manufacturer of the BAM highlighted that there were no suggestions for operational improvements of the BAM units within the ongoing equivalence programme or AURN-wide operations.

The manufacturer of the Fidas is Palas. Discussions with Palas highlighted that available further algorithms on which the calculation of particle mass was based, could be made available. These are discussed in Deliverable 3 (Section 3.1). No suggestions were made to improve the operation of the UK’s Fidas instruments.

New or emerging instrument manufacturers

Wider available particulate matter instruments were considered as part of the programme, covering a broader range of instruments that may otherwise be available, although not formally certified through the UK MCERTS for Particulate Matter process. Engagement with manufacturers led to a number of different instruments (six in total) being tested at Birmingham A4540. Due to confidentiality agreements with the suppliers, the data cannot be discussed in detail herein. However, some general observations can be provided.

All instruments appear to track the reference method well providing an initial indication that they have potential for use in the UK. In general, data capture was low however, this is in a large part due to the project being operated as a research project rather than as a network with continual data checks, and cover provided by Local Site Operator (LSO) and Equipment Support Unit (ESU) call out contracts, and a stock of hot spare instruments. Notwithstanding this, the Birmingham A4540 site appears to provide a good site location for comparison of performance of instruments for particulate matter in the context of traffic emissions. The site has clear access arrangements in place and has shown itself to be a suitable working environment for such a study.

5. UK CERTIFICATION AND ON-GOING EQUIVALENCE ASSESSMENT OPTIONS SCOPING.

5.1 Deliverable 10: Identification of how the current requirements from UK MCERTS for Particulate Matter and BS EN 16450 may need to change with lower $PM_{2.5}$ readings.

Potential changes to BS EN 16450

Standard BS EN 16450 has reached the point in its continual life cycle where it requires review and reissue. The most significant issue at the moment relates to falling PM concentrations and the limitations of the current mathematics at these lower concentrations. Several issues have been identified both by the UK and other countries and have been presented at CEN TC264 WG15 meetings.

There are three ways in which WG15 are currently working towards a revision of the current requirements:

A. Investigation as to whether a corrigendum to the existing standard is possible to provide guidance on how minor modifications could aid the certification and ongoing QAQC processes. The timescales for this are estimated to be 1 year. Likely modifications include:
    i. Allowance for fewer than 32 high concentration points (18 µg m^{-3} for $PM_{2.5}$ and 30 µg m^{-3} for PM_{10}) if evidence shows the relationship is acceptable with fewer points.
    ii. Suggestion that co-location studies between Reference Method and Candidate instruments should primarily be undertaken in winter and at locations where PM concentrations should fulfil the required range. This would require relaxation of the requirement that the same instruments (i.e. instruments with the same serial numbers) should be used consistently at every site. This would allow all tests to occur in winter at multiple sites but may have a significant cost burden.
    iii. Allowance to force through the origin of data acquired through co-locations studies if HEPA zero testing is within +/- 1 µg m^{-3} of the 0 µg m^{-3}.
B. Set up of a subgroup to investigate if any other statistical techniques are more appropriate than those currently employed. The timescales for this are estimated to be 1 year.
C. Authorship of a revised standard fully implementing all required changes. The timescales for this are estimated to be 5 years.

Potential changes to MCERTS for UK Particulate Matter

MCERTS for UK Particulate Matter was published in 2012 at a time when PM concentrations were higher. It requires that at least two field tests are conducted in the UK and that tests from other areas of Europe are suitable for use in the UK if they are of a similar pollution climate to the UK.

As with BS EN 16450, as concentrations are now lower than when the scheme was initiated, the mathematics has limitations due to the low confidence in the line of best fit and the effect of a limited number of outliers upon the distribution. Taking the findings from the other Deliverables together, the evidence would suggest that for $PM_{2.5}$ the requirement should change to calculating the difference in period average rather than the requiring W_{CM} to be below 25% at 30 μg m^{-3}.

No calculations have been made for period average PM_{10}; however, there is a legal requirement on the daily average data for PM_{10}, which would suggest that the current approach should be maintained.

Deliverable 11 (Section 5.2) discusses the changing pollution climates and the impact upon MCERTS for UK Particulate Matter and as such these findings are not repeated here.

Three commercially led certification tests are ongoing under the existing scheme and a procurement round is imminent that requires MCERTS for UK Particulate Matter as a prerequisite. As such, any transition to a revised scheme should have a transitional period and any risks should be carefully managed. Dependent upon the magnitude of changes they could either be itemised on the performance standard webpage[18] or may require a complete set of new documentation. The process would need to be managed by the EA as owners of the MCERTS programmes.

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[18] https://www.gov.uk/government/publications/mcerts-performance-standards-for-ambient-monitoring-equipment/mcerts-performance-standards-for-ambient-monitoring-equipment

5.2 Deliverable 11: Assessment of the UK Pollution climate requirements against our current datasets and predicted datasets, establishing whether different requirements are needed.

Introduction

In 2012 a report was published that compared the pollution climate of the UK with other European countries and set out a series of rules for the certification of instruments in the UK where data were collected elsewhere in Europe[19]. The report defines a UK pollution climate and gives tables of the range of PM concentrations, semi-volatile particulates, PM Concentrations, temperature, ambient dew point and wind speed. Further, the report stated that there needed to be at least two tests in the UK and that each test must have two collocated reference and candidate methods.

The tables of data ranges in the report were calculated from data collected between 2007 and 2010. The document predates BS EN 16450:2017 and so is somewhat out of date. It requires only very straightforward laboratory tests and so falls well short of BS EN 16450:2017 in this regard.

In 2020, it was decided that the performance standard for MCERTS for UK Particulate Matter needed updating. However, it was agreed by the Environment Agency that this would be simply through a government web page listing how instruments certified after the meeting date would need to follow the 2012 document, but with changes. Specifically, the document says the following[20].

Tests commissioned after 27 August 2020 must apply the following modifications:

- your CAMS (Continuous Ambient Monitoring System) must meet all the laboratory test requirements specified in BS EN 16450:2017
- you must conduct at least 2 of the field tests in the UK – CAMS with European Union approval with at least 4 field tests can reduce the reference methods from 2 to 1 for the UK tests.
- the pollution climate of all your other field tests should be within the range of those monitored in the UK between 2012 and 2020
- you are no longer required to assess the pollution climate in relation to the concentrations of volatile particulate matter.

The rationale behind these changes was to reduce the cost burden to new instruments entering the UK market in recognition that there may be other instruments better suited to the UK than those we are currently aware of.

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[19] Annex to the MCERTS Performance Standards for Ambient Air Quality Monitoring Systems: Requirements of the UK Competent Authority for the Equivalence Testing and Certification of Automated Continuous and Manual Discontinuous Methods that Monitor Particulate Matter in Ambient Air https://uk-air.defra.gov.uk/assets/documents/MCERTS_for%20UK_Particulate_Matter_final.pdf

[20] https://www.gov.uk/government/publications/mcerts-performance-standards-for-ambient-monitoring-equipment/mcerts-performance-standards-for-ambient-monitoring-equipment

Pollution Climate Calculations

Through this work package, the tables of the 2012 document were reprocessed for 2012 to 2020 data. Additionally, data from 2021 and 2022 have been processed. The results are shown below.

Approach

All ratified hourly mean PM_{10} and $PM_{2.5}$ data measured on the AURN between 1st January 2012 and 1st January 2023 was accessed via the openair R package. The range of geometric mean concentrations for each site type in the UK calculated and is shown in **Table 5.1**.

Table 5.1 Range of geometric mean concentrations for each site type in the UK

Date Range	Site Type	Geometric Mean PM_{10} Range (µg m^{-3})	Geometric Mean $PM_{2.5}$ Range (µg m-^{3})
1st Jan 12 - 31st Dec 20	Rural Background	5.3 - 13.1	3.1 - 8.5
	Urban & Suburban Background	8.9 - 18.5	5.1 - 13.5
	Urban Industrial	9.1 - 17.3	6.1 - 8.6
	Urban Traffic	8.4 - 22.6	3.3 - 16.2
1st Jan 21 - 31st Dec 21	Rural Background	4.1 - 12.1	2.5 - 7.8
	Urban & Suburban Background	6.6 - 14.2	3.4 - 9.8
	Urban Industrial	7.8 - 17.5	4.7 - 6.8
	Urban Traffic	8.5 - 22.0	3.6 - 10.6
1st Jan 22 – 31st Dec 22	Rural Background	4.6 - 13.1	2.7 – 8.0
	Urban & Suburban Background	7.4 - 14.6	3.9 - 9.4
	Urban Industrial	8.5 - 18.8	6.0 - 6.6
	Urban Traffic	8.8 - 25.2	3.3 - 9.6

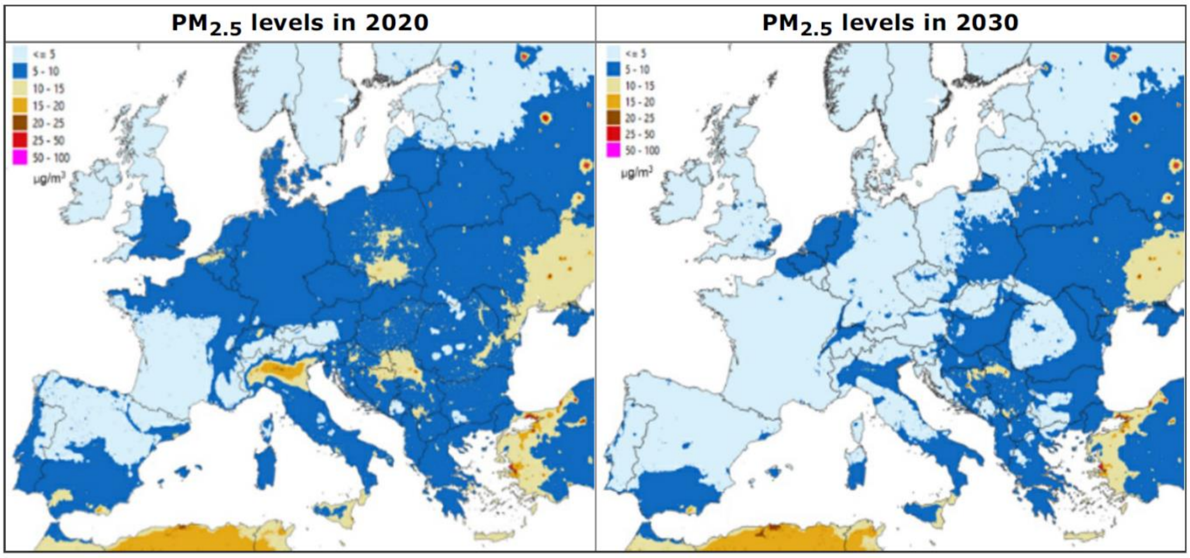
All hourly mean meteorological data (wind speed (at 10 metres), ambient temperature, ambient dew point) from the British Isles between 1st January 2012 and 1st January 2023 was accessed via the worldmet R package. 211 measurement stations were used and over 18 million hourly data points summarised. The 25th and 75th percentiles of the daily mean wind speed, ambient temperature and dew point are shown in **Table 5.2.**

Table 5.2 Low and high thresholds and the requisite number of daily means for PM_{10} and $PM_{2.5}$ equivalence tests to be carried out outside these thresholds, whichever is appropriate (as a percentage of the number of measurements within one comparison) for selected meteorological conditions.

Date Range	Threshold	Wind Speed		Ambient Temperature		Dew Point	
		Value	%	Value	%	Value	%
1st Jan 12 - 31st Dec 20	**Low**	3.1	10	6.4	10	3.4	10
	High	6.6	10	13.6	10	10.4	10
1st Jan 21 - 31st Dec 21	**Low**	2.8	10	6.8	10	2.9	10
	High	6.2	10	14.4	10	11.3	10
1st Jan 22 – 31st Dec 22	**Low**	3.0	10	7.1	10	4.1	10
	High	6.4	10	14.3	10	10.6	10

BS EN 16450:2017 requires that there are at least 32 points where daily mean PM_{10} is above 30 µg m^{-3} and 32 points where daily mean $PM_{2.5}$ is above 18 µg m^{-3}. It was agreed in the 2020 meeting that the total number of these higher concentration points should remain at a minimum of 32. As instruments tested in the UK have typically been certified in mainland Europe prior to testing in the UK, there are already at least 32 higher concentration points and so there is no requirement to have additional high concentration points within the UK data. However, during the current UK tests the concentrations have been low which reduces confidence over the linear regression used to assess equivalence. As concentrations are reducing throughout Europe, there are few areas where concentrations are still high enough to give enough high data to achieve certification. This is shown in the following diagram as published by the EU, which shows true $PM_{2.5}$ concentrations in 2020 alongside aspirational $PM_{2.5}$ concentrations in 2030.

Figure 5.1 2020 & 2030 $PM_{2.5}$ levels



To collect enough high points, TÜV Rheinland have undertaken tests in Northern Italy. Whilst this is very effective for collecting relatively high concentration data, it is then possible that the data do not meet the UK pollution climate requirements as the concentrations are higher than those typically found in the UK in recent years. However, if the Italian data cannot be used then there will not be 32 higher concentration points.

It is felt that the makeup of the particulate matter in Northern Italy is similar to the UK, even though the concentrations are higher. Whereas in Southern Poland (another area considered for monitoring high concentrations) it is felt that the make-up of the pollution is somewhat different to that in the UK due to a large amount of industrial activity[21].

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[21] **Bressi, et al., 2021**, *“European aerosol phenomenology - 7: High-time resolution chemical characteristics of submicron particulate matter across Europe”* & **Chen, et al., 2022**, *“European aerosol phenomenology − 8: Harmonised source apportionment of organic aerosol using 22 Year-long ACSM/AMS datasets.”*

5.3 Deliverable 12: Alignment of certification methodologies

The methodologies currently used to assess equivalence of automatic analysers is increasingly challenged by the lower PM concentrations typically experienced throughout the UK and Europe. The current tests require a proportion of data points to be above a threshold value, in order for the calculation of measurement uncertainty to be reported with confidence.

The UK procedures for operation of gravimetric samplers and demonstration of equivalence of automatic measurement systems (AMS) follow BS EN 12341:2023 and BS EN 16450:2017 respectively. These procedures are employed throughout Europe and ensure that measurements are harmonised and meet the current data quality objectives. BS EN 16450 is currently being reviewed by the European Committee for Standardisation (CEN), to account for the challenges of demonstrating equivalence at lower measured concentrations.

The operating procedures used in the UK and Europe differ from those employed in other countries. As part of this evaluation exercise, a wider international assessment of procedures, calculations and development plans was undertaken, to evaluate the potential benefits of these differences and whether they could be adopted into the current UK procedures. The most commonly used alternative operation strategy comes from the USEPA Federal Register 40 CFR Part 58. **Table 5.3** lists the key aspects of the US/European operating methodologies.

Table 5.3 Key US/European operating procedures

Metric	Europe	US
Gravimetric sampling methodology	24 hours, midnight to midnight, 2.3m³/hr flow rate, no restriction on filter type	24 hours, 1m³/hr, PTFE filters
Filter conditioning	At least 48hr, 20-23C, 45-50%rH, before and after exposure	24hr, 20C, 35%rH, followed by 24hr, 20C, 40%rH, followed by 48hr, 40C.
Type approval	BS EN 12341:2023 requires type testing	Type tested by USEPA (FEM or FRM designation afterwards)
AMS equivalence strategy	4 sampling locations, 40 days minimum at each, two seasons, requirement for secondary aerosol to be assessed	
AMS type test requirements	Slope 0.9 – 1.1, offset not significantly different from zero, uncertainty <25% for individual campaigns and combined dataset	Coefficient of Variance within 10% (at 90% confidence interval), slope 0.9 – 1.1. Network bias less than 3 µg m^{-3}
Ongoing QC	Co-location of reference samplers with AMS in field operations to confirm ongoing relationship. No guidance provided if this is not the case	Evaluated from measurements at all FRM and FEM sites.

The differences in European and US sampling protocols and filter conditioning are significant.

- Samplers operating at the US flow rate (1m³/hr) have been tested in Europe and found to be equivalent to the samplers operating at 2.3m³/hr, but the measurement uncertainties were found to be higher than the European reference method.
- The sole use of PTFE filters in the US is problematical for European operation, where the higher flow rate of the reference method raises an increased risk of blocked filters during PM episodes.
- The US filter conditioning regime will drive off a larger proportion of semi volatile aerosol and particle bound water than the European regime. Studies undertaken for the validation of BS EN 16450:2017 suggest that these particles could account for up to 5 µg m^{-3} of the total deposited mass

on a filter during periods where secondary aerosol concentrations are elevated.

- It is not clear what requirements are placed on end users for ongoing quality control (QC) in the US. It appears that buying an approved FEM or FRM device and operating in accordance with 40 CFR is required. The European ongoing QC procedures are clearly documented, but no definitive guidance is provided if the results fall outside of requirements.

The European and US sampler and operation protocols are markedly different. The US protocols may be more robust from a metrology perspective, as the impact of water and semi volatile aerosol is minimised by the collection and conditioning procedures, it may not be as representative of the actual ambient PM composition as the European protocol.

It would not be advisable for the UK to adopt the US protocol, as this would introduce a step change in measurements away from historic datasets (with no possibility to adjust historic data) and would mark a deviation from European measurements, removing harmonisation and traceability with these data.

UK experts are active within CEN TC/264 WG15 and AQUILA. Both these groups are working collaboratively to revise BS EN 16450, specifically to address the challenges of demonstrating equivalence at lower concentrations. UK data from the $PM_{2.5}$ equivalence studies will provide valuable input and aid the views of UK in the discussions.

Recommendations

- Continue to follow the protocols in BS EN 12341 and BS EN 16450
- Use the UK $PM_{2.5}$ equivalence data to input into the development of the revised BS EN 16450 standard.

6. IDENTIFICATION OF NEW UNCERTAINTY THRESHOLDS.

6.1 Deliverable 13 Identification of New Uncertainty Thresholds

Introduction

A total of four continuous instruments are both certified for use in the UK and commercially still available[22]:

- Fidas 200 M11 / 1.06
- BAM 1020
- FDMS 1405F
- FAI SWAM DC Hourly

The original certification data for these instruments have been reevaluated for current purposes.

Period Average Data

As these tests were conducted for short periods (typically 40 to 80 days per site per season) the number of data points is significantly less than 1 year and as such represent a period average rather than an annual average.

Legislative changes have been made in the UK to reduce the target $PM_{2.5}$ concentration to 10 µg m^{-3} as an annual average by 2040 and it looks likely that the EU will also do so. The EU are also considering increasing the allowed uncertainty requirement (W_{CM}) from 25% to 30%, though this is still in discussion. As such, the present analysis focuses only on calculations at 10 µg m^{-3},

Table 6.1 lists each dataset for each of the four instruments currently certified and available. The subsequent columns are in order:

- W_{CM} D %: The expanded uncertainty at 10 µg m^{-3} as calculated for the daily average data using the current mathematics of BS EN 16450 but with a target value of 10 µg m^{-3} rather than 30 µg m^{-3}. Values are shaded green where the uncertainty is below 25%, orange for between 25 and 30%, and red for above 30%. These are calculated as the average percentage for both collocated instruments. As most values are red, this shows that simply reducing the limit value and making no modifications to the mathematics would result in many instruments failing at 10 µg m^{-3}.
- W_{CM} A %: As W_{CM} D % except that the random component of the uncertainty has been reduced by 50% in line with empirical calculations and as presented in the previous iteration of this deliverable. This was undertaken

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[22] https://uk-air.defra.gov.uk/networks/monitoring-methods?view=mcerts-scheme

as any uncertainty due to noise reduces the more measurements are averaged. This shows that reducing the random component of the uncertainty increases the number of datasets that pass at 10 µg m^{-3}.

- R / µg m^{-3}: The average of all the reference method data.
- C / µg m^{-3}: The average of all the candidate method data.
- D / µg m^{-3}: The difference between the average reference method and average candidate method. Where the average reference method concentration is below 10 µg m^{-3}, D is shaded green if below 1.25 / µg m^{-3}. (and would be shaded orange if between 1.25 and 1.5 µg m^{-3} or red if above 1.5 µg m^{-3}).
- W %: The expanded uncertainty calculated as the difference (D) expressed at the reference method average (R). In line with current EU thinking on how to calculate uncertainties of annual averages, where the average reference method concentration is above 10 µg m^{-3}, W is shaded green if below 25%, shaded orange if between 25 and 30% or red if above 30%.

Using the D and W methodology results in all datasets being shaded either green or orange and represents an improved situation to that previously reported in the version of this Deliverable included with the interim position statement (W_{CM} A %).

Table 6.1 Assessment of original certification data at 10 µg m^{-3}.

Instrument	Dataset	W_{CM} D / %	W_{CM} A / %	R / µg m^{-3}	C / µg m^{-3}	D / µg m^{-3}	W / %
Fidas 200 M11 / 1.06	Cologne Summer	30.35	16.22	9.34	8.97	-0.37	7.99
	Cologne Winter	26.71	15.23	18.42	18.58	0.15	1.68
	Bonn Winter	36.44	19.08	20.14	20.13	-0.01	0.15
	Bornheim Summer	34.94	17.99	10.88	10.85	-0.03	0.49
	Teddington Winter	20.04	12.68	14.29	13.70	-0.59	8.29
	Teddington Summer	17.33	10.00	9.84	9.58	-0.26	5.24
	≥ 18 µg m^{-3}	38.79	19.54				
	All Data	29.12	15.07	13.47	13.28	-0.20	2.94
BAM 1020	Teddington Summer	46.59	34.54	10.01	11.48	1.48	29.50
	Cologne Winter	38.70	24.94	19.47	20.56	1.09	11.16
	Bornheim Summer	42.90	22.36	13.33	13.37	0.04	0.56
	Teddington Winter	24.03	14.96	17.37	17.23	-0.14	1.60
	≥ 18 µg m^{-3}	47.94	24.61				
	All Data	40.69	24.02	14.86	15.63	0.77	10.37
FDMS 1405F	Teddington Summer	36.70	28.07	16.85	18.41	1.56	18.55
	Cologne Winter	42.15	29.61	21.83	23.53	1.70	15.60
	Bornheim Summer	45.56	36.90	12.13	13.84	1.71	28.18
	Teddington Winter	49.38	41.65	12.69	14.45	1.76	27.77
	≥ 18 µg m^{-3}	40.16	24.15				
	All Data	46.46	36.60	15.30	17.00	1.70	22.20
FAI SWAM DC Hourly	≥ 18 µg m^{-3}	36.04	20.96				
	All Data (Cologne 2011)	36.05	21.77	21.22	21.87	0.65	6.11
Number Passing		3/22	16/22			2/2	13/16

W is effectively independent of the target value as it is reported at the period average concentration of the Reference Method; however, the lower the average Reference Method concentration the harder it is to pass. Conversely, as D is assessed for all average Reference Method concentrations below 10 / µg m^{-3}, it is equally possible to pass irrespective of the average Reference Method concentration.

Daily Average Data

Currently both in the UK and the EU, the requirement is that for $PM_{2.5}$ the expanded uncertainty (W_{CM}) to be below 25% at a pseudo daily average limit value of 30 µg m^{-3}. **Table 6.2** shows the effect of repeating this calculation at reduced limit or target values using all paired data. **Table 6.2** also gives the combined standard uncertainty (u) expressed in µg m^{-3}. This is calculated as the root mean square of the bias at the limit/target value under consideration and the random component of the distribution. For each of the four certified available instruments, the combined standard uncertainty remains relatively constant whereas the expanded uncertainty increases as the limit or target value reduces. This is because the expanded uncertainty is calculated by dividing the combined standard uncertainty by the target or limit value and so results in a higher uncertainty as concentration target reduces.

As the slope of the data for the four instruments is close to 1, there is very little difference in the combined standard uncertainty irrespective of the limit/target value. An example is also shown in the table of one of the constituent datasets (from the BAM 1020) where there was a high slope and a low intercept. This shows that the combined standard uncertainty was lowest around 10 µg m^{-3} where the slope of the distribution crosses the y=x line.

Table 6.2 Assessment of original certification data at varying limit/target values.

Instrument	Slope	Intercept / µg m^{-3}	RT / µg m^{-3}	Uncertainty	30 µg m^{-3}	25 µg m^{-3}	20 µg m^{-3}	15 µg m^{-3}	10 µg m^{-3}	5 µg m^{-3}
Fidas 200 M11 / 1.06	0.999	-0.19	1.44	**W_{CM} / %**	9.67	11.61	14.50	19.33	28.99	57.96
				u / µg m^{-3}	1.45	1.45	1.45	1.45	1.45	1.45
BAM 1020	1.000	0.76	1.74	**W_{CM} / %**	12.70	15.23	19.03	25.36	38.02	76.00
				u / µg m^{-3}	1.90	1.90	1.90	1.90	1.90	1.90
FDMS 1405F	1.016	1.45	1.58	**W_{CM} / %**	16.64	19.48	23.74	30.87	45.15	88.04
				u / µg m^{-3}	2.50	2.43	2.37	2.32	2.26	2.20
FAI SWAM DC Hourly	0.998	0.69	1.47	**W_{CM} / %**	10.68	12.85	16.09	21.51	32.33	64.82
				u / µg m^{-3}	1.60	1.61	1.61	1.61	1.62	1.62
Example	1.134	-1.50	0.00	**W_{CM} / %**	16.72	14.73	11.73	6.74	3.25	33.20
				u / µg m^{-3}	2.51	1.84	1.17	0.51	0.16	0.83

Recommendations

In conclusion the following recommendations are made:

- As $PM_{2.5}$ reporting targets are based upon annual rather than daily average data, it is recommended to calculate the uncertainty as a function of closeness of the reference and candidate method averages (D or W),
- For daily average data reducing the limit or target value from 30 µg m^{-3} would result in the W_{CM} uncertainty increasing. Switching to the combined standard uncertainty – u has more potential as a metric as this is more constant at different limit or target values as it is expressed in units of µg m^{-3}. It is however recommended to retain the current methodology of calculating the expanded uncertainty (W_{CM}) at a pseudo daily average limit value of 30 µg m^{-3}.
- The UK should continue to attend WG15 meetings to make sure the findings and recommendations of the UK EWG are presented for consideration.

7. MERITS OF CONTINUING MINI EQUIVALENCE AND ASSESSMENT OF CURRENT EQUIVALENCE SITES.

7.1 Deliverable 14 The future of equivalence testing in the UK.

Introduction and an overview of requirements

Ongoing equivalence monitoring is essential to ensure that the type tested automatic analysers deployed throughout the UK continue to be equivalent to a reference method in recognition that environments change over time. This section discusses how this reassurance can be achieved across the range of conditions in the UK.

BS EN 16450:2017 states that end users “may move the Reference Method between sites”. As with other countries, the UK’s approach has historically been to have a small number of sites with permanent measurements (due to commercial, practical, and planning limitations). Carrying out equivalence monitoring assessments at every site on the network is an alternative approach, however there is insufficient evidence to date that this approach provides any added value. Therefore, there is merit in continuing the current approach of carrying out equivalence assessments at a number of representative sites. However, to provide further reassurance and resilience in our assessments it is recommended that the number and range of location types is increased and that this should cover traffic, urban and rural environments as further explained below.

$PM_{2.5}$ composition is complex including both transboundary and secondary aerosols, which all need to be considered in the context of an instrument’s ability to be equivalent with the Reference Method. Deliverable 6 (Section 3.4), looked to increase our understanding of how differences in atmospheric speciation and environmental conditions could influence the current network instrument performance. Of twenty metrics reviewed as part of the study, two were shown to have the greater influence on instrument deviations from the reference method and form the evidence base for identifying representative locations for assessing future ongoing equivalence. These were ammonium nitrate and black carbon which were also assessed alongside $PM_{2.5}$ concentration as a third helpful consideration.

Figure D.1 in the Appendix shows a map of modelled ammonium nitrate concentrations across the UK for 2021. These are based on modelled averages over one year, but in reality, there would be differences on an hourly, daily and yearly basis as the meteorology changes and therefore this acts as a guide only. Concentrations are influenced by long range transport from continental Europe, moving through the UK starting around East Anglia. Ammonium nitrate is further generated through secondary aerosol processes within the UK, with concentrations remaining high across London and the West Midlands but reducing further northwards. Concentrations drop more rapidly approaching the far Southwest of England, with concentrations being similar to the far north of Scotland. This would suggest that a distribution of equivalence sites is needed across the varying ranges.

Figure D.2 in the appendix shows a map of Black Carbon emissions for 2021. This shows that Black Carbon emissions are highest closest to areas of high traffic density, this would suggest that monitoring is required at every Urban Background and Urban Traffic equivalence site. Black Carbon emissions are primarily driven by vehicle tail pipe emissions and would include factors such as traffic flow and vehicle fleet type. Within the UK, different cities are undertaking different strategies to reduce PM concentrations, and these can lead to differences in the vehicle fleet make-up and therefore emissions of black carbon. This should be taken into consideration when choosing a distribution of traffic sites to ensure a range is covered. In addition, fuel burning also contributes to black carbon emissions, further supporting the need for equivalence sites in both urban background and urban traffic locations.

Figure D.3 in the appendix shows a map of modelled background $PM_{2.5}$ concentrations across the UK for 2021. In general, concentrations reduce the further away from the southeast of England, again supporting the need for a geographical distribution of equivalence sites.

From this information, it is proposed that representative information for the whole UK can be achieved by grouping areas into three groups that cover the ranges of low, moderate and high within the three key factors identified likely to impact equivalence readings. There are no precise exact boundaries within each grouped area instead the colourations found in **Figure D.1**, as described in **Table 7.1**, has been used as a guide. These groupings can roughly be summarised to cover the following areas:

- **Group 1**: an area predominantly covered by the South-East of England; this area is characterised by “high” levels of ammonium nitrate across the region with localised Black Carbon arising from road traffic emissions in urban areas. Annual mean concentrations of $PM_{2.5}$ are within the range of 6 – 10 µg m^{-3} (annual mean 2021) with additional increments of 1 – 3 µg m^{-3} within the London area (annual mean of 11- 13 µg m^{-3}). The geographic area is subject to imports of $PM_{2.5}$ from Europe through transboundary secondary aerosol formation.
- **Group 2**: an area extending to the west of Group 1 predominantly covering the West of England, the Midlands and extending to the North-West of England and down to South Wales. This area is characterised by “moderate” levels of ammonium nitrate with localised black carbon arising from road traffic. Annual mean (2021) $PM_{2.5}$ concentrations are typically 6 – 10 µg m^{-3}. The influence of long-range transport is less in the area than that of Group 1 geography but remains a “moderate” influence.
- **Group 3**: the geographic extent of everything within the UK not linked and defined by Groups 1 and 2. This area extends from the far South-West of England in an arc to North Wales, up to North East England, Scotland and Northern Ireland. The area is characterised by low ammonium nitrate concentrations with localised black carbon arising from road traffic, and annual mean concentrations of $PM_{2.5}$ within the range of 0 – 5 µg m^{-3} (2021). Long-range transport of secondary aerosol is a low influencing factor on $PM_{2.5}$ within the area.

Long range secondary aerosol transport has also been added to the table to further support rationale of the identified following three groupings.

Table 7.1 Key factors that show appropriate coverage within the three groupings.

Key factors for representation	**Group 1**	**Group 2**	**Group 3**	***Reference***
Ammonium Nitrate (concentration colour bands from **Figure D.1**)	High (red)	Moderate (orange/green)	Low (blue/purple)	**Figure D.1**
	Black Carbon emissions are usually closely related to traffic flow. Therefore, assessing their impact on PM measurements can be assessed within each group.			**Figure D.2**
$PM_{2.5}$ concentrations ($\mu g\ m^{-3}$)	6-10	6-10	0-5	**Figure D.3**
EU long range secondary aerosol transport influences	High	Moderate	Low	**Ailish M. Graham, et al.**[23]

These areas are sufficiently different from each other, that it should be possible to infer performance of analysers at non-co-located stations throughout the UK. A fourth grouping was considered to capture the very lowest concentrations of particulates including Black Carbon and ammonium nitrate, such as in North Scotland and the far South West. The reason for not pursuing this separate grouping is that we don't expect the interferences / effects in the table to have a significant effect on equivalence. However, it is recognised special cases may arise where the existing groupings does not fully represent the emissions characteristics or $PM_{2.5}$ composition of an area and this unique situation would then warrant further investigation to confirm equivalence, such as in Northern Ireland, that has greater domestic heating sources and therefore different PM emissions that could warrant further investigation to confirm equivalence.

For each grouping, it is recommended that equivalence monitoring is undertaken at a traffic and urban background site, and ideally these would be paired to further support any investigations into any differences in equivalence. Pairing means that the regional secondary aerosol influences are similar, such that you could help identify if the roadside increment caused an effect.

Monitoring equivalence at rural background sites should also be added due to the differences in particulate mix at these locations compared to urban background and traffic locations. They also typically measure lower concentrations and could provide insight into how a future network may perform as concentrations change. Due to PM

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[23] *Impact of weather types on UK ambient particulate matter concentrations - ScienceDirect*

composition for rural background being similar over much larger distances, a minimum of two sites is recommended; one in the south to capture any long-range secondary aerosols due to long range transport from continental Europe and one in the north where these influences are less prevalent. If it was possible to locate a site to pair with an urban background site, it could also be used to determine any increments from urban background sources.

All equivalence sites should use the Reference Method rather than a pseudo-Reference Method such as a Partisol 2025. To further enhance any investigations of failures, if space at a location allows, two $PM_{2.5}$ Reference Methods should be installed and daily nitrate and continuous Black Carbon measurements should be monitored at all sites. However, for ammonium nitrate due to its transboundary distribution, if it is not possible to measure at all sites, then monitoring must be at one of the paired urban traffic or background sites. For Ammonium Nitrate the reference method filters could be analysed by ion chromatography. Additional ion concentrations, such as sulphate would also benefit further understanding. For Black Carbon, near real time instruments such as the Aethalometer should be used. Some models give multiple channels relating to different forms of organic carbon, and this would be of use particularly in areas of high solid fuel burning.

Whilst this report focuses primarily on $PM_{2.5}$, space is required for PM_{10} instrumentation at least some of the sites.

At least one of the urban background and at least one of the urban traffic equivalence sites should have sufficient space to install additional instrumentation should new instruments require certification (both for $PM_{2.5}$ and PM_{10}) or to run bespoke tests.

Additional equivalence sites per grouping could add further resilience to assessments. However, any increase in equivalence sites should follow an evidence need to either further investigate if any equivalence failure is unique or more widespread, or to provide additional geographical coverage following identification of any new conditions not currently being tested. It should not simply increase as the national $PM_{2.5}$ network numbers increase.

It is worth noting that current ongoing equivalence sites only house those instruments used in the AURN; the BAM 1020 and the Fidas 200. Future procurement rounds might result in other instruments entering the networks and space would be required to house these. In addition, although this report focuses primarily on $PM_{2.5}$, space would also be required for PM_{10} instrumentation for some of the sites.

All equivalence sites should capture data every day of the year to further increase our understanding of the equivalence relationship.

Based on the above an initial possible suggestion for each group is summarised as follows.

Urban Background and Traffic Sites

Group 1

It is recommended that the existing equivalence site at London Teddington be retained. It has sufficient space to install additional instrumentation and can be paired with the existing traffic equivalence site at London Marylebone Road.

London Marylebone Road provides a site with a high traffic flow, however, there is insufficient space to accommodate testing of any new instruments, therefore this should be captured in another site.

Both sites are located within London's Ultra Low Emission Zone so will be able to assess the impact of a lower emission vehicle fleet.

This means that the mini equivalence site at London Honor Oak Park and Storrington should be decommissioned, and the additional instrumentation removed.

Group 2

The traffic site at Birmingham A4540 is one of the very few traffic sites in the UK that could be expanded to provide testing of new instruments (for both PM_{10} and $PM_{2.5}$). This is subject to planning permission. If successful, then the Birmingham University Supersite could provide a geographically paired site. However, if this were to be used as a future ongoing equivalence site it is recommended that the existing Partisol 2025 should be replaced with a Reference Method. Currently, ammonium nitrate and Black Carbon are already monitored at this site.

Manchester as a future location for equivalence sites was considered, however there are doubts about the current Urban Background classification of Manchester Piccadilly due to the localised sources, and the square in which it sites is being redeveloped. Therefore, it is recommended that the equivalence instrumentation should be removed but only after finding a suitable replacement site for this grouping (such as in Birmingham). A possible alternative could be the Manchester University supersite, as it has existing speciation monitoring, however it is recommended that the Partisol 2025 should be replaced by the Reference Method. There is limited additional space for more instrumentation. If Manchester is taken forward for this group instead of Birmingham, then a suitable traffic site should be found.

Group 3

Urban Background and Urban Traffic sites would need to be identified.

The preferred location would possibly be in the Newcastle, Gateshead or Sunderland greater urban area if suitable sites could be found.

Depending on locations chosen, this means that the mini equivalence sites of Barnstaple A39 and Glasgow Hope Street should be decommissioned. Space is heavily limited at these sites to add additional instrumentation.

Rural Background Sites

Chilbolton (near Winchester) and Auchencorth Moss (near Edinburgh) would represent an initial north to south transect though would require additional cabins to be installed.

APPENDIX A: PRINCIPLE OF OPERATION OF INSTRUMENTS USED TO MONITOR $PM_{2.5}$

A.1: Reference Methods and Pseudo-Refence Method Partisols

These methods are filter-based “gravimetric” methods for the measurement of daily mean mass concentrations of $PM_{2.5}$. Sampled air is drawn through a size-selective inlet onto a pre-weighed filter. The change in mass on the filter at the end of the sampling period is converted to a mass per volume of air sampled through post processing of mass and volume measurements. Specialist laboratories are required to condition filters to specific environmental conditions around temperature and humidity in pre-and post-exposure measurements of filter mass. The necessity for laboratory processing for gravimetric methods means that results are unable to be provided in real-time which gives rise to delays in reporting and dissemination to the public information feeds. As a consequence of these delays the UK has adopted a number of continuous monitoring methods for $PM_{2.5}$ which provide for almost real-time data into UK-AIR (the public information website for air quality in the UK).

The EU Reference Method (EN12341) can be manufactured by a number of different companies, may or may not cool the filters after sampling, and, for mass measurements of PM, can be operated with filters made from any of glass fibre, PTFE (Teflon), Quartz Fibre and PTFE coated glass fibre. There is therefore significant variation in official permutations of the Reference Method and although ‘Reference Method’ is used as a catch-all term, it can lead to a large variation in reported concentrations.

A.2: Thermo Fisher Filter Dynamic Measurement System (FDMS)

The FDMS is based on a Tapered Element Oscillating Microbalance (TEOM). TEOMs work on the principle that the frequency of oscillation of a tapered glass tube (element) is highly sensitive to the mass attached to the end of the tube, so that small changes to the mass of a filter mounted on the end of the tube can be quantified by accurate measurements of the tube’s resonant frequency. The FDMS is a modified form of TEOM that accounts for semi-volatile PM that would not be detected by earlier TEOM models. The system’s basic output consists of one-hour average mass concentrations (in $\mu g\ m^{-3}$) of PM updated every six minutes, together with corresponding “non-volatile” (“base”) and “volatile” (“reference”) concentrations. The analyser constantly samples ambient air using a switch valve to change the path of the main flow every six minutes. The sampling process consists of alternate sample and reference (filtered) airstreams passing through the exchangeable filter in the TEOM mass sensor. During the original equivalence testing it was shown that the $PM_{2.5}$ data need to be corrected by dividing by 1.067 prior to reporting. As the measurement uncertainty of the uncorrected data fell within the uncertainty requirements of the data quality objective, the decision was taken not to routinely correct the data. This was made in 2006 when the concept of equivalence testing was in development at the EU level and early adoption of the programme results were being made. It is important to note that we do not recommend retrospective post processing of any of the data on UK-AIR based upon these findings.

Between 2008 and 2018, most monitoring of PM in the AURN was carried out using FDMS. However, these instruments are reaching the end of their working lives and the constituent TEOM 1400AB component of the FDMS ceased to be supported by its manufacturer in 2019. A programme of replacement has been under way since 2018, with the FDMS being replaced by the Palas Fidas 200 and the Met One BAM.

A.3: Palas Fidas 200

The Fidas is an aerosol spectrometer which continuously analyses dust particles present in the ambient air size range 180 nm to 18 µm. The spectrometer reading sizes particles according to different size bins within the overall particle size range and an algorithm then converts the particle counts to mass based on empirical data sets previously collated in formulating the method. During the equivalence testing for the instrument, it was shown that the $PM_{2.5}$ data need to be corrected by dividing by 1.06 prior to reporting. No correction was required in order for PM_{10} data to be considered equivalent. The instrument was tested with algorithm Method 11. Therefore, in order to be deemed equivalent to the UK Reference Method, the Fidas needs to be operated with algorithm Method 11, and $PM_{2.5}$ data need to be divided by 1.06. Unless stated to the contrary herein, all Fidas data within this report fulfil these requirements.

A.4: Met One Beta Attenuation Monitor (BAM)

The BAM instrument employs an absorption technique of beta radiation by solid particles extracted from the sampling air flow. Many different versions exist, but that adopted by the UK is manufactured by Met One. A filter tape moves through the sampling point of the analyser, with the instrument cycling through a period of sampling on a “blank” tape prior to sampling on the tape which captures the particles in the air. A size selective cut-off provides for sampling of the $PM_{2.5}$ size fraction. During the equivalence testing it was shown that the $PM_{2.5}$ data do not need to be corrected prior to reporting.

APPENDIX B: DELIVERABLES 1 - 3

Figure B.1 Two Fidas operating about 50 metres apart in Chilbolton Rural Background site.

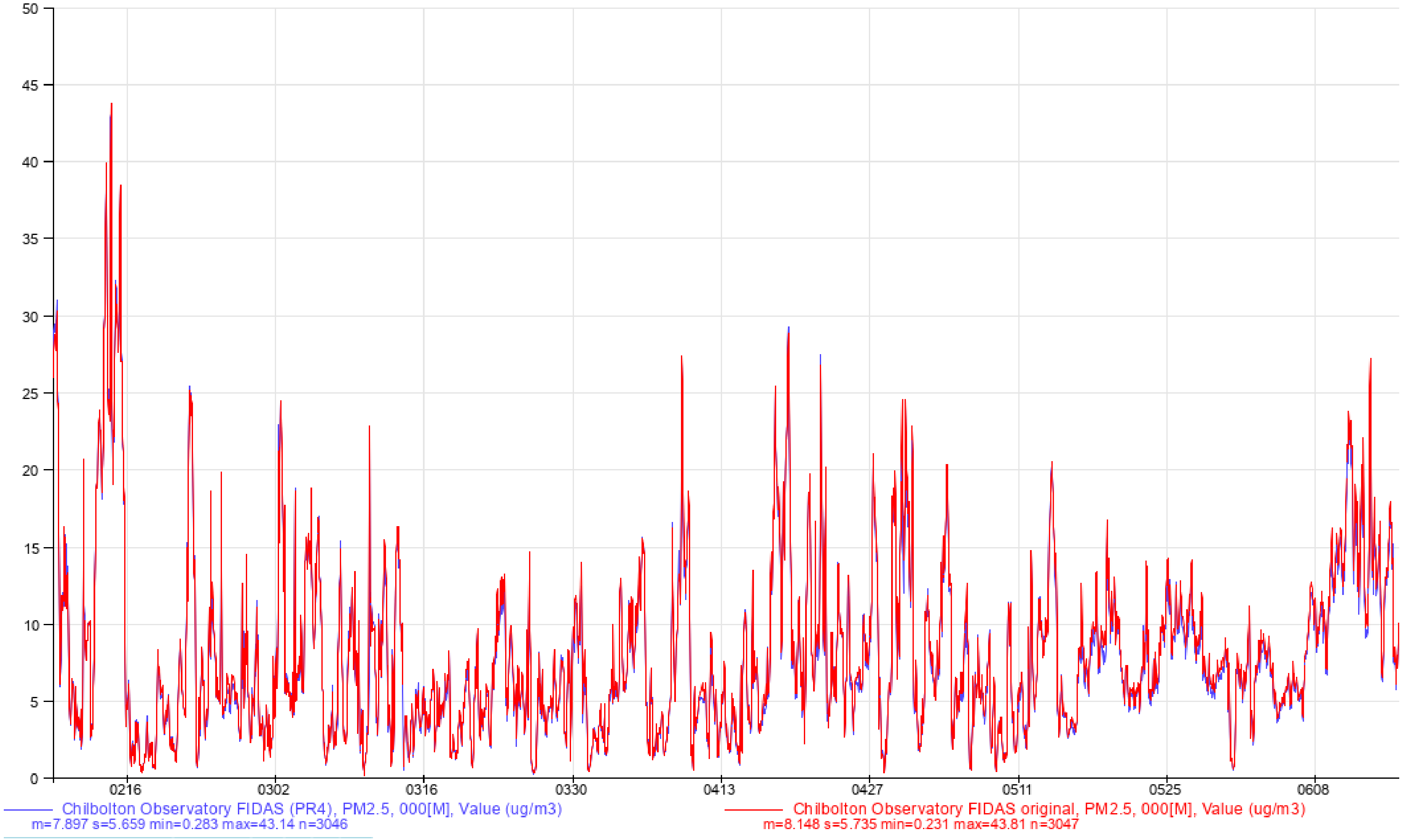


Figure B.2 Fidas and BAM operating side by side in Manchester Piccadilly Urban Background site.

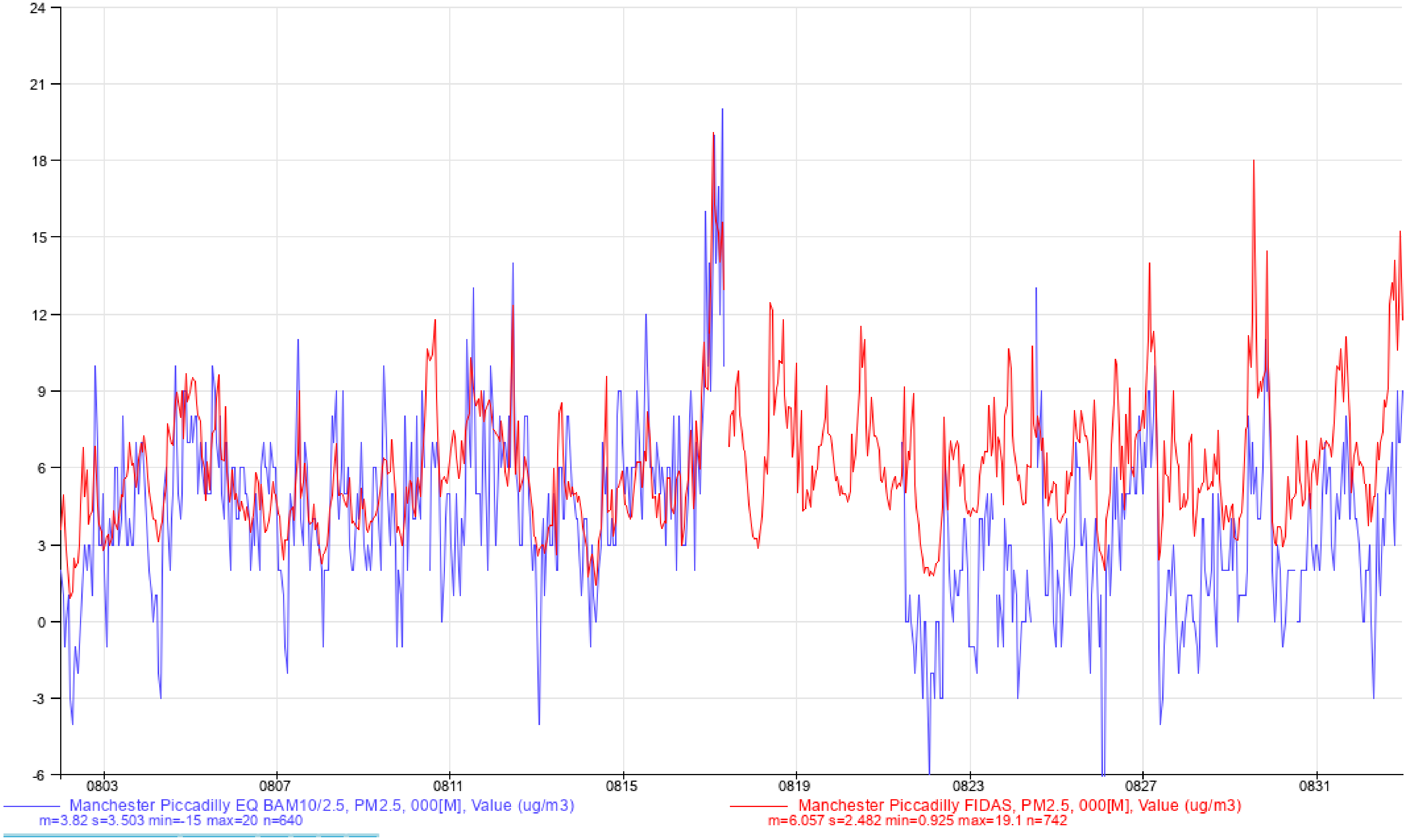
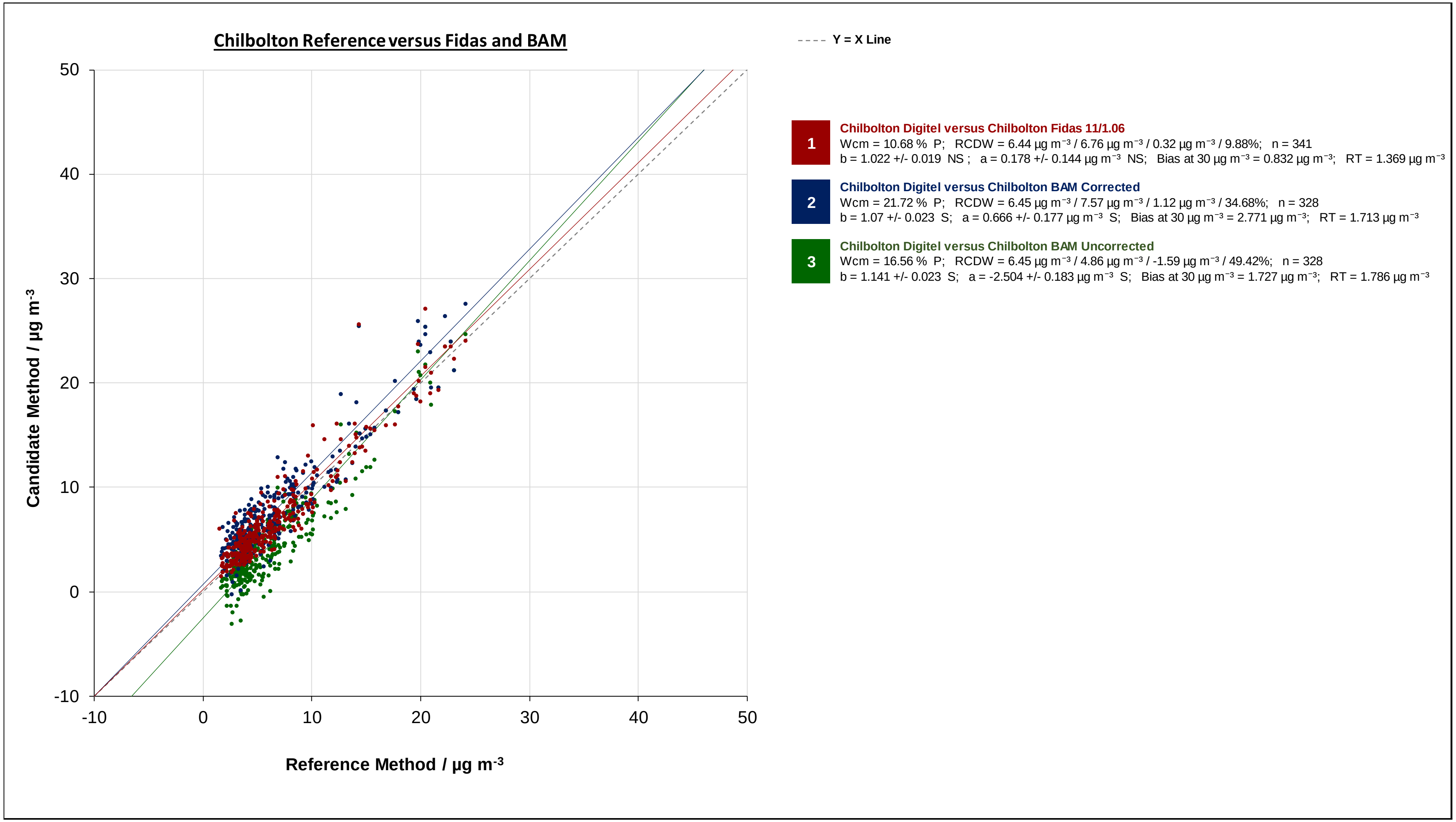


Figure B.3 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Chilbolton

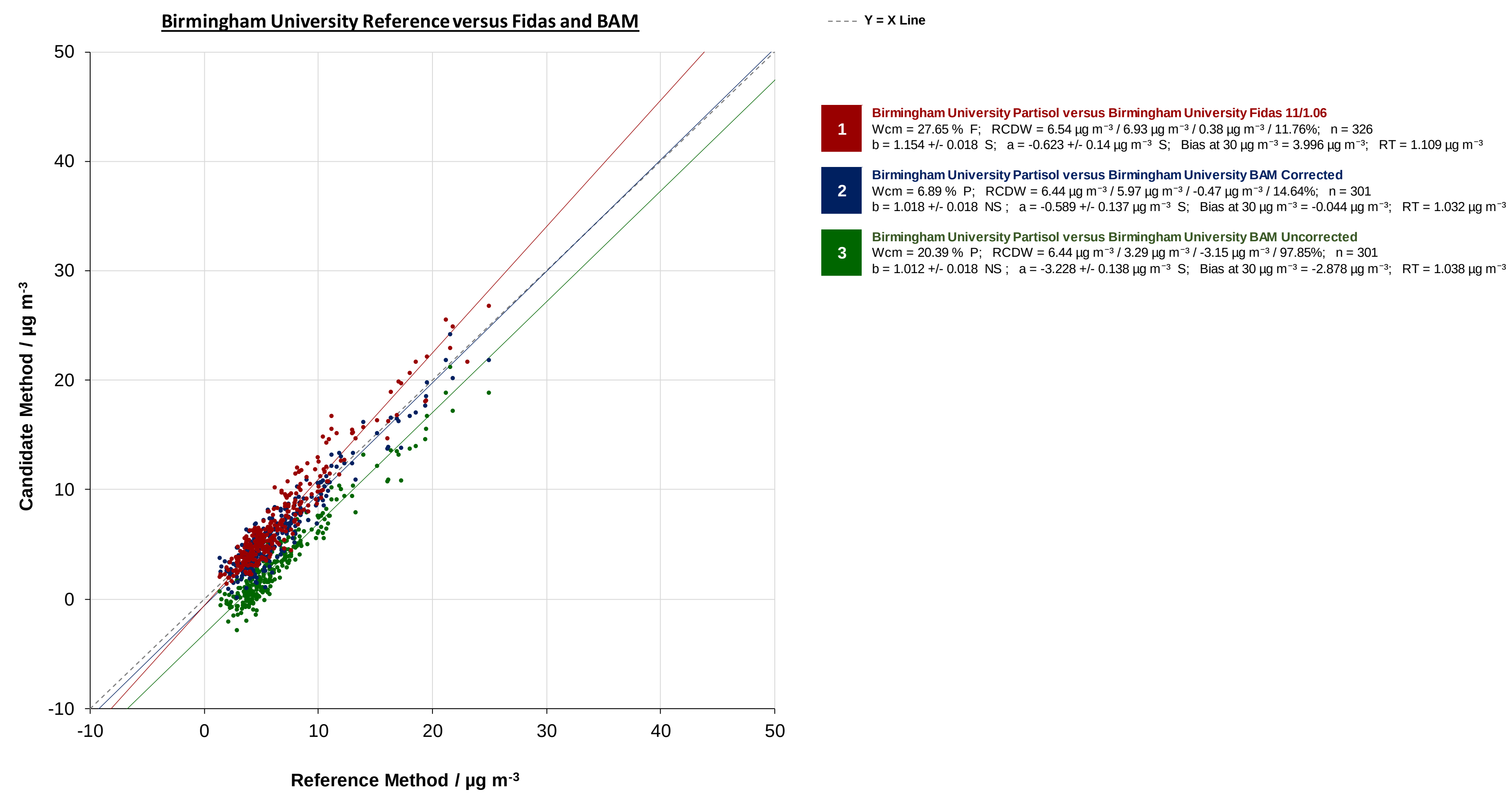


Chilbolton Digitel versus Chilbolton Fidas 11/1.06
Wcm = 10.68 % P; RCDW = 6.44 µg m^{-3} / 6.76 µg m^{-3} / 0.32 µg m^{-3} / 9.88%; n = 341
b = 1.022 +/- 0.019 NS ; a = 0.178 +/- 0.144 µg m^{-3} NS; Bias at 30 µg m^{-3} = 0.832 µg m^{-3}; RT = 1.369 µg m^{-3}

Chilbolton Digitel versus Chilbolton BAM Corrected
Wcm = 21.72 % P; RCDW = 6.45 µg m^{-3} / 7.57 µg m^{-3} / 1.12 µg m^{-3} / 34.68%; n = 328
b = 1.07 +/- 0.023 S; a = 0.666 +/- 0.177 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.771 µg m^{-3}; RT = 1.713 µg m^{-3}

Chilbolton Digitel versus Chilbolton BAM Uncorrected
Wcm = 16.56 % P; RCDW = 6.45 µg m^{-3} / 4.86 µg m^{-3} / -1.59 µg m^{-3} / 49.42%; n = 328
b = 1.141 +/- 0.023 S; a = -2.504 +/- 0.183 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.727 µg m^{-3}; RT = 1.786 µg m^{-3}

Figure B.4 $PM_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Birmingham University



Birmingham University Partisol versus Birmingham University Fidas 11/1.06
Wcm = 27.65 % F; RCDW = 6.54 µg m^{-3} / 6.93 µg m^{-3} / 0.38 µg m^{-3} / 11.76%; n = 326
b = 1.154 +/- 0.018 S; a = -0.623 +/- 0.14 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.996 µg m^{-3}; RT = 1.109 µg m^{-3}

Birmingham University Partisol versus Birmingham University BAM Corrected
Wcm = 6.89 % P; RCDW = 6.44 µg m^{-3} / 5.97 µg m^{-3} / -0.47 µg m^{-3} / 14.64%; n = 301
b = 1.018 +/- 0.018 NS ; a = -0.589 +/- 0.137 µg m^{-3} S; Bias at 30 µg m^{-3} = -0.044 µg m^{-3}; RT = 1.032 µg m^{-3}

Birmingham University Partisol versus Birmingham University BAM Uncorrected
Wcm = 20.39 % P; RCDW = 6.44 µg m^{-3} / 3.29 µg m^{-3} / -3.15 µg m^{-3} / 97.85%; n = 301
b = 1.012 +/- 0.018 NS ; a = -3.228 +/- 0.138 µg m^{-3} S; Bias at 30 µg m^{-3} = -2.878 µg m^{-3}; RT = 1.038 µg m^{-3}

Figure B.5 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for London Honor Oak Park

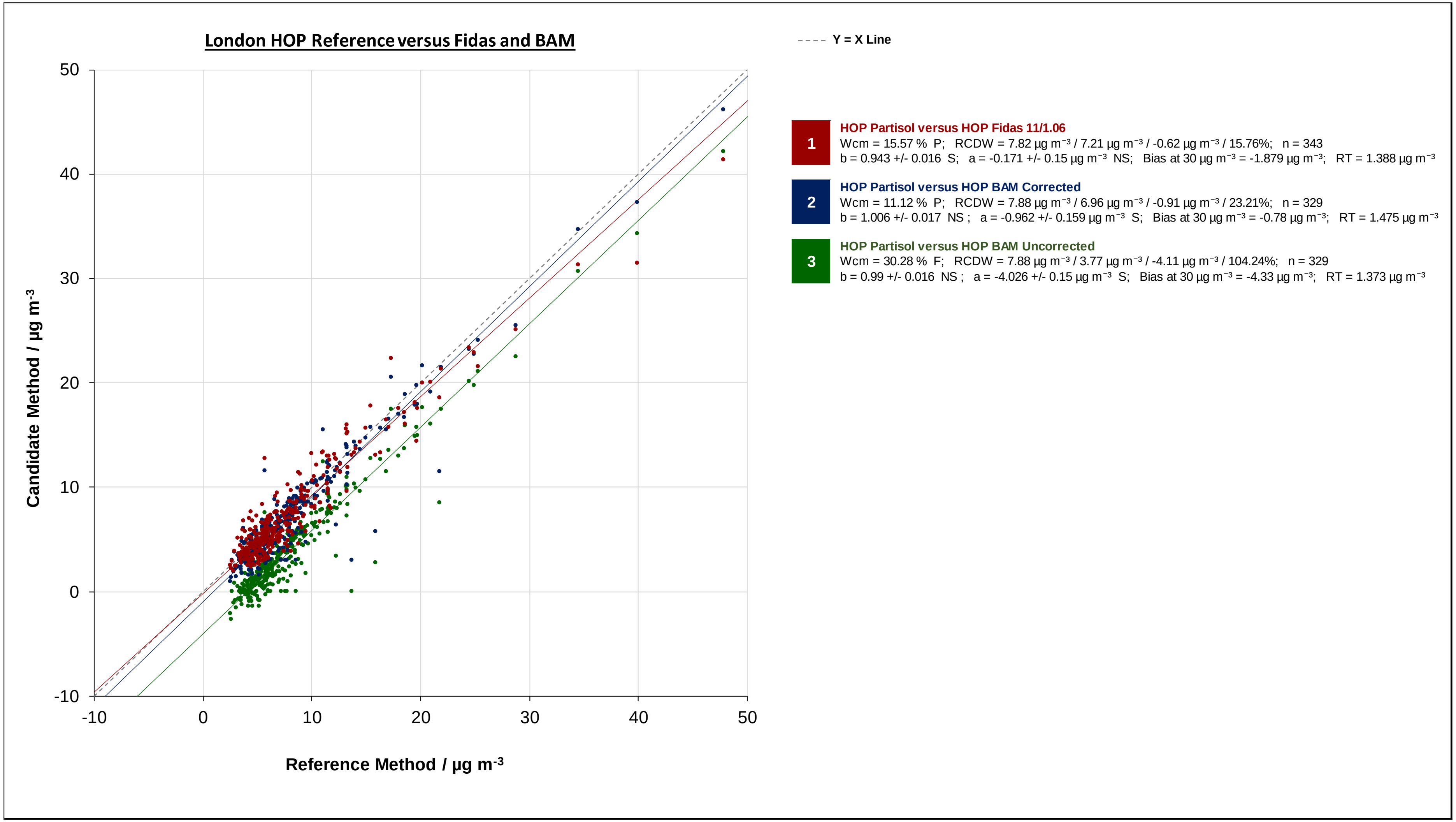


Figure B.6 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for London Teddington

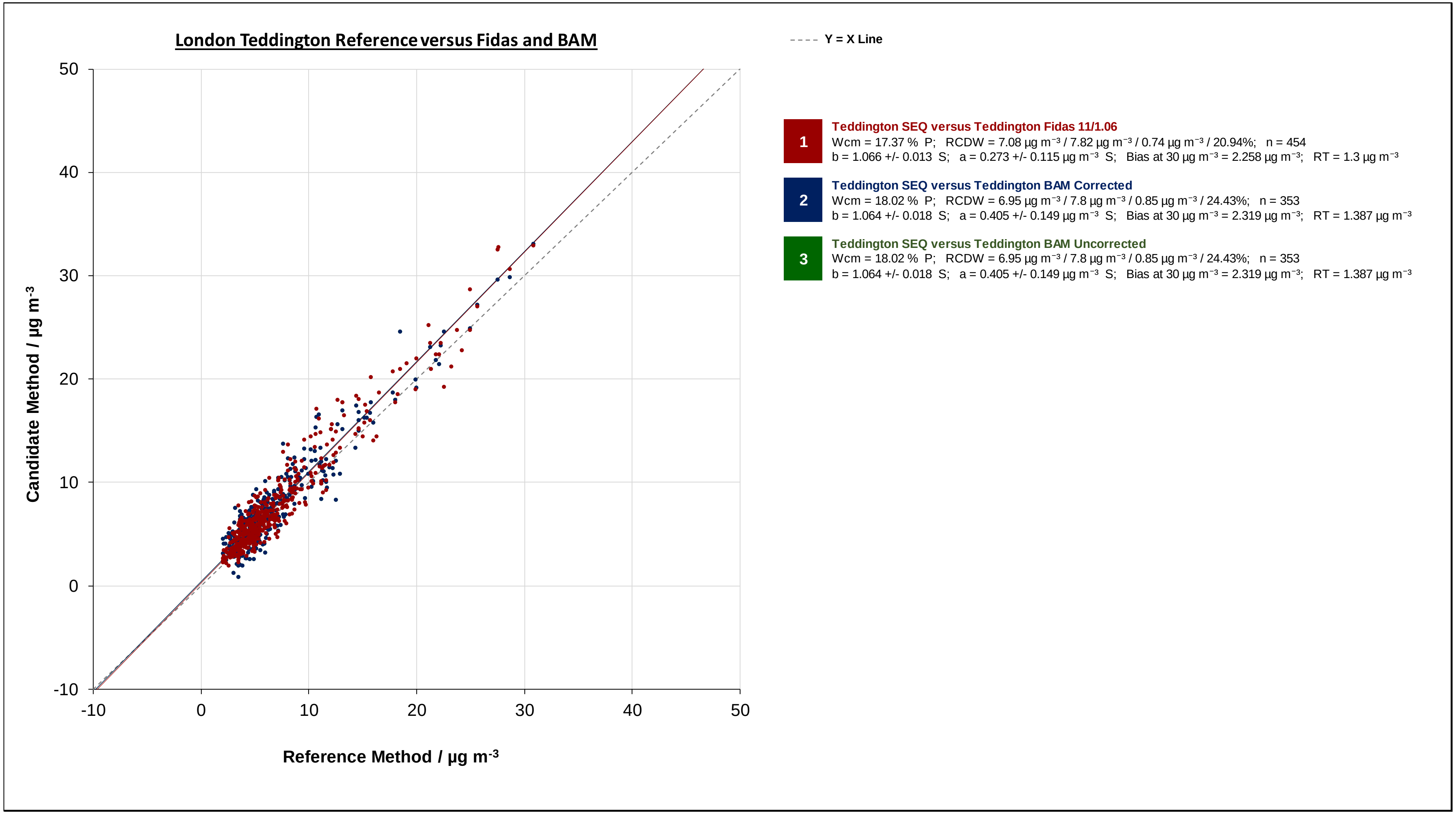


Figure B.7 $PM_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Manchester Piccadilly

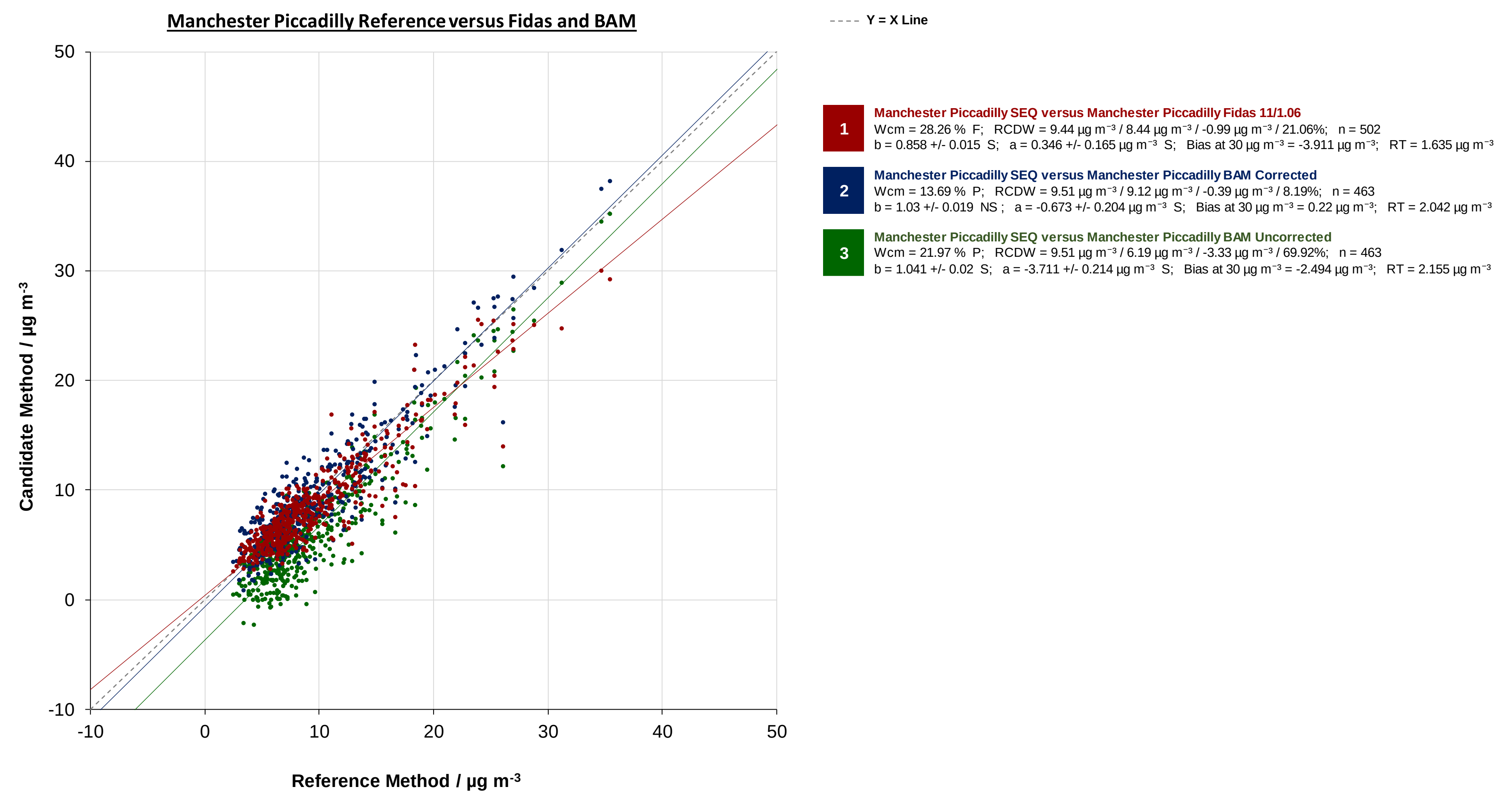


Figure B.8 $PM_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Manchester University

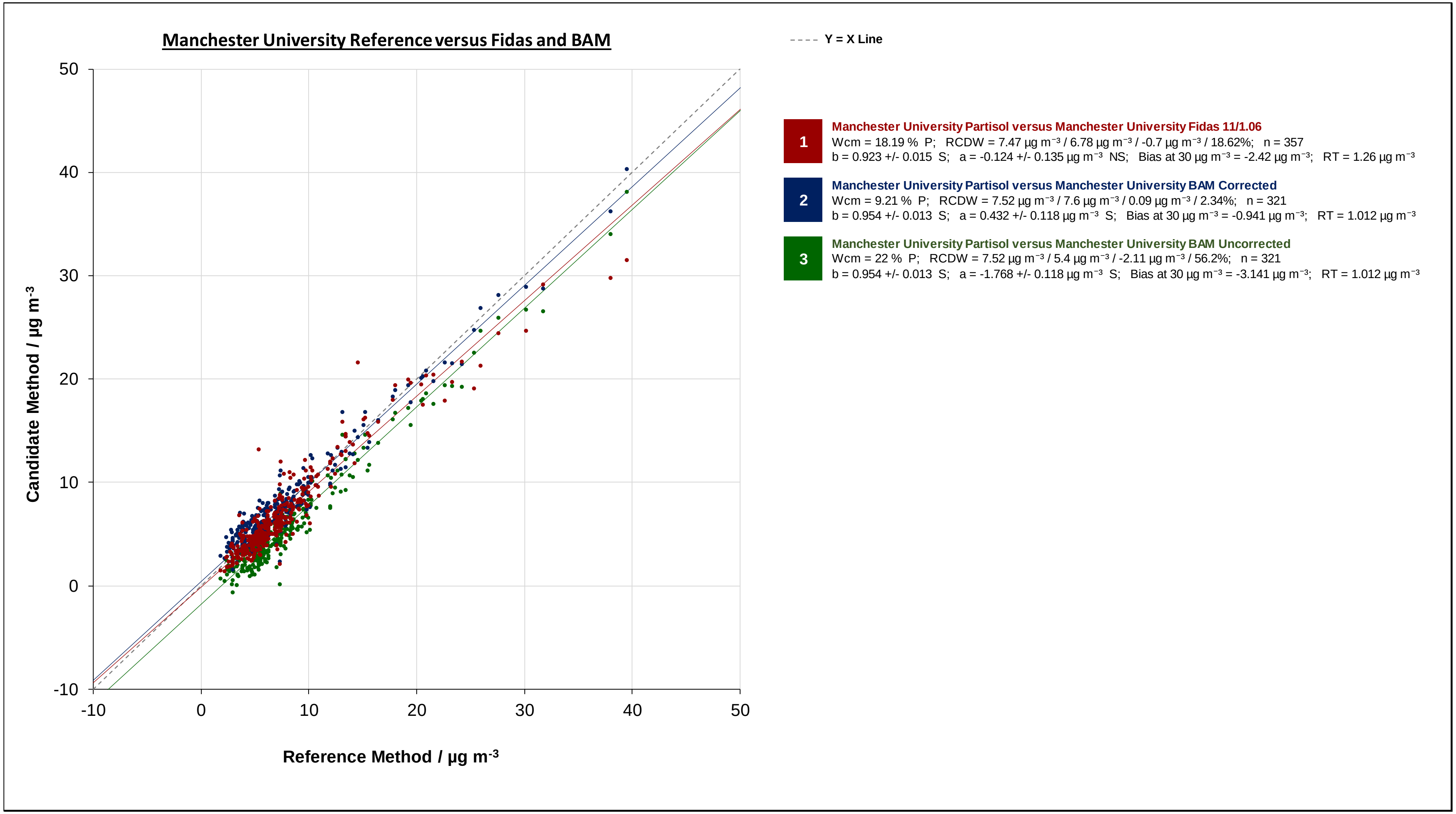


Figure B.9 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Barnstaple A39

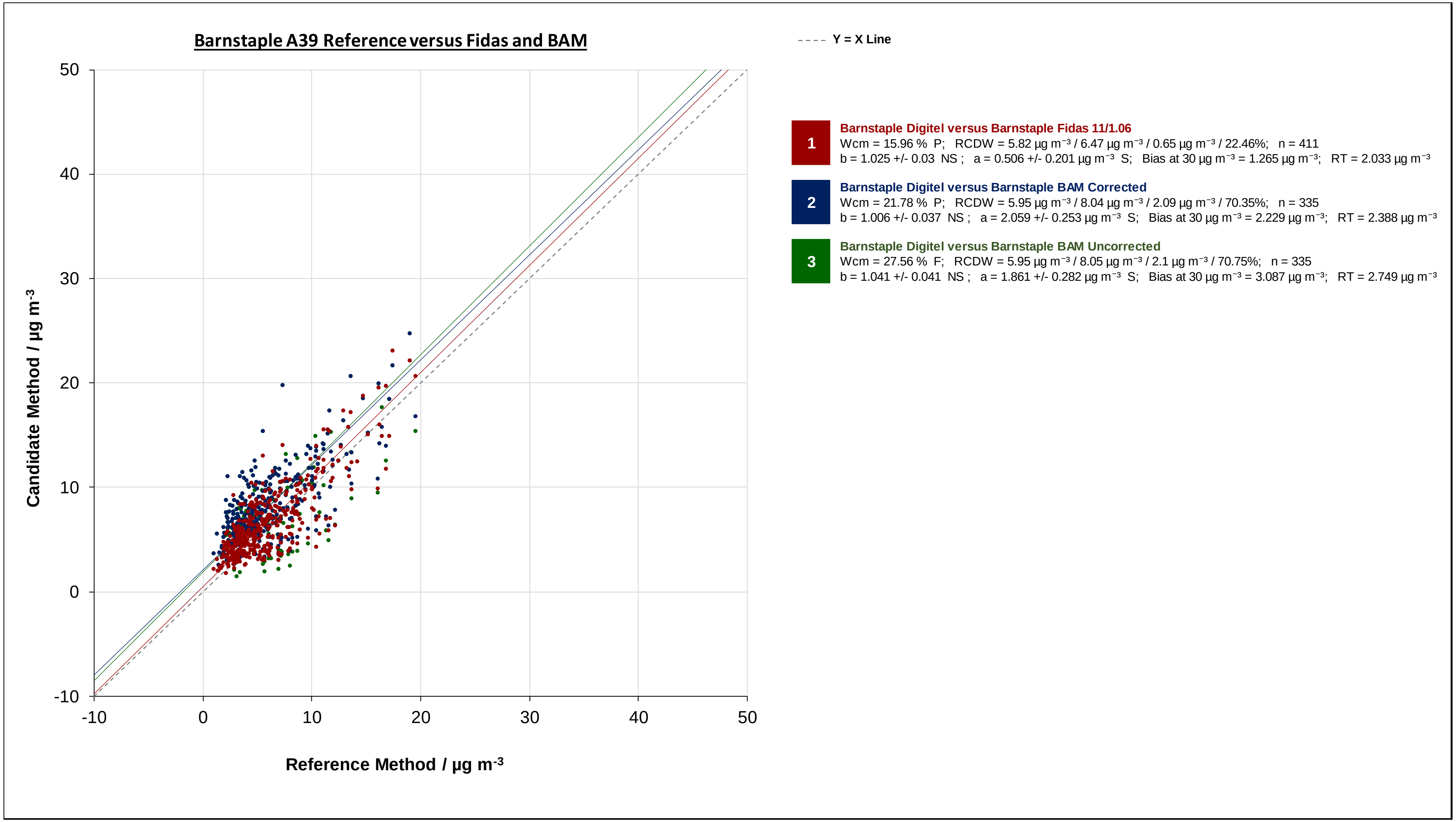


Figure B.10 $PM_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Birmingham A4540

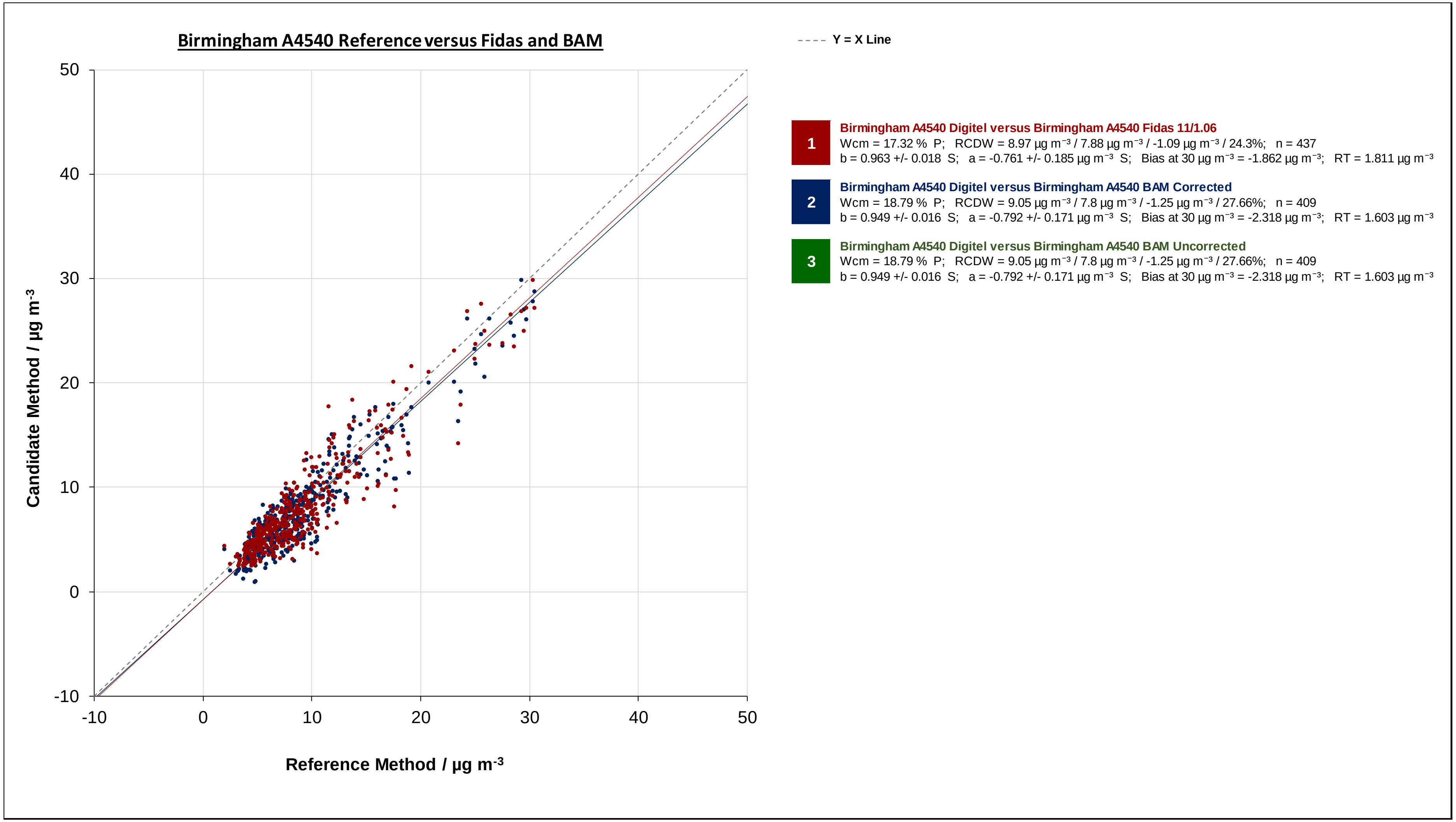


Figure B.11 $PM_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Glasgow

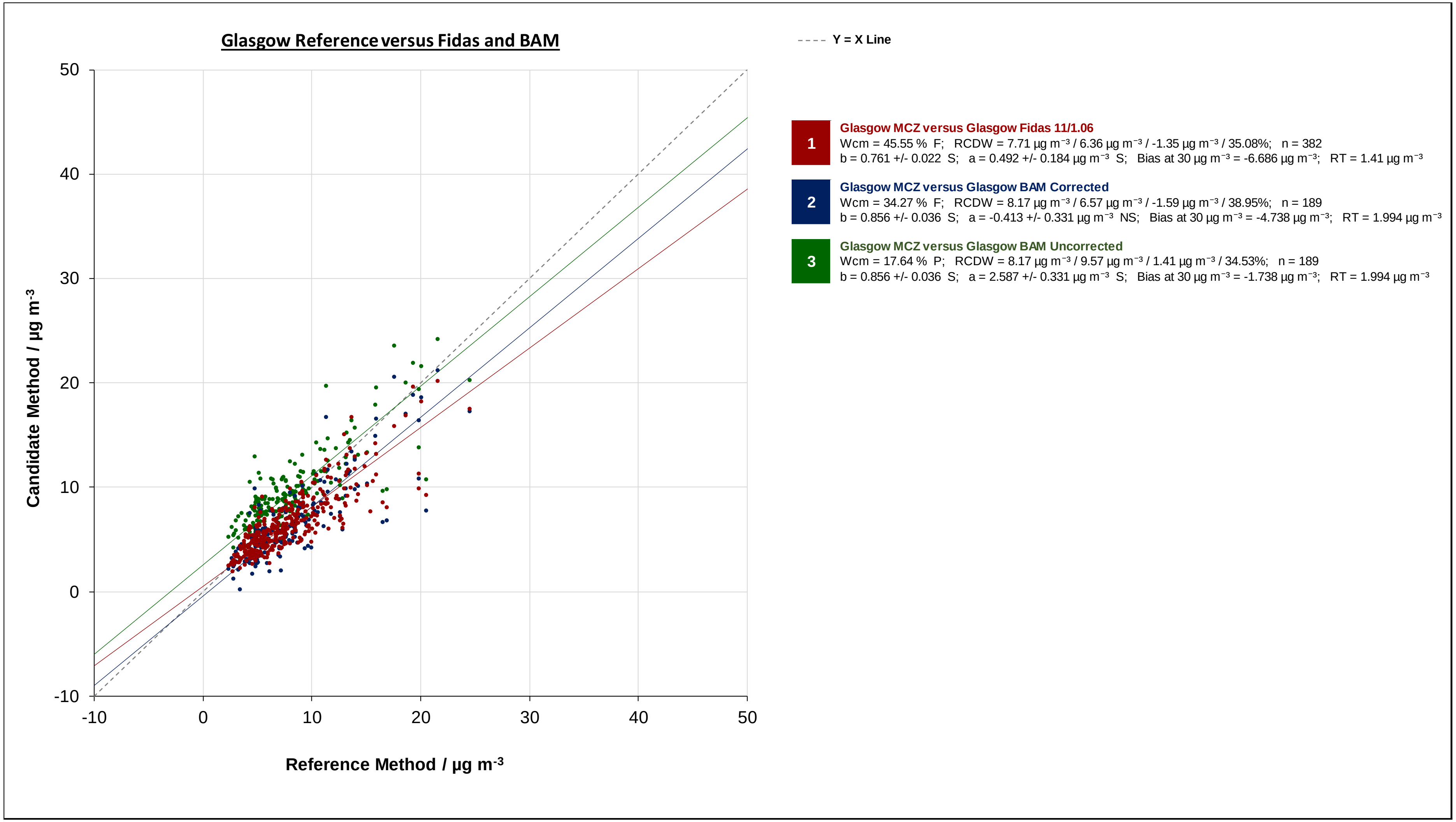


Figure B.12 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for London Marylebone Road

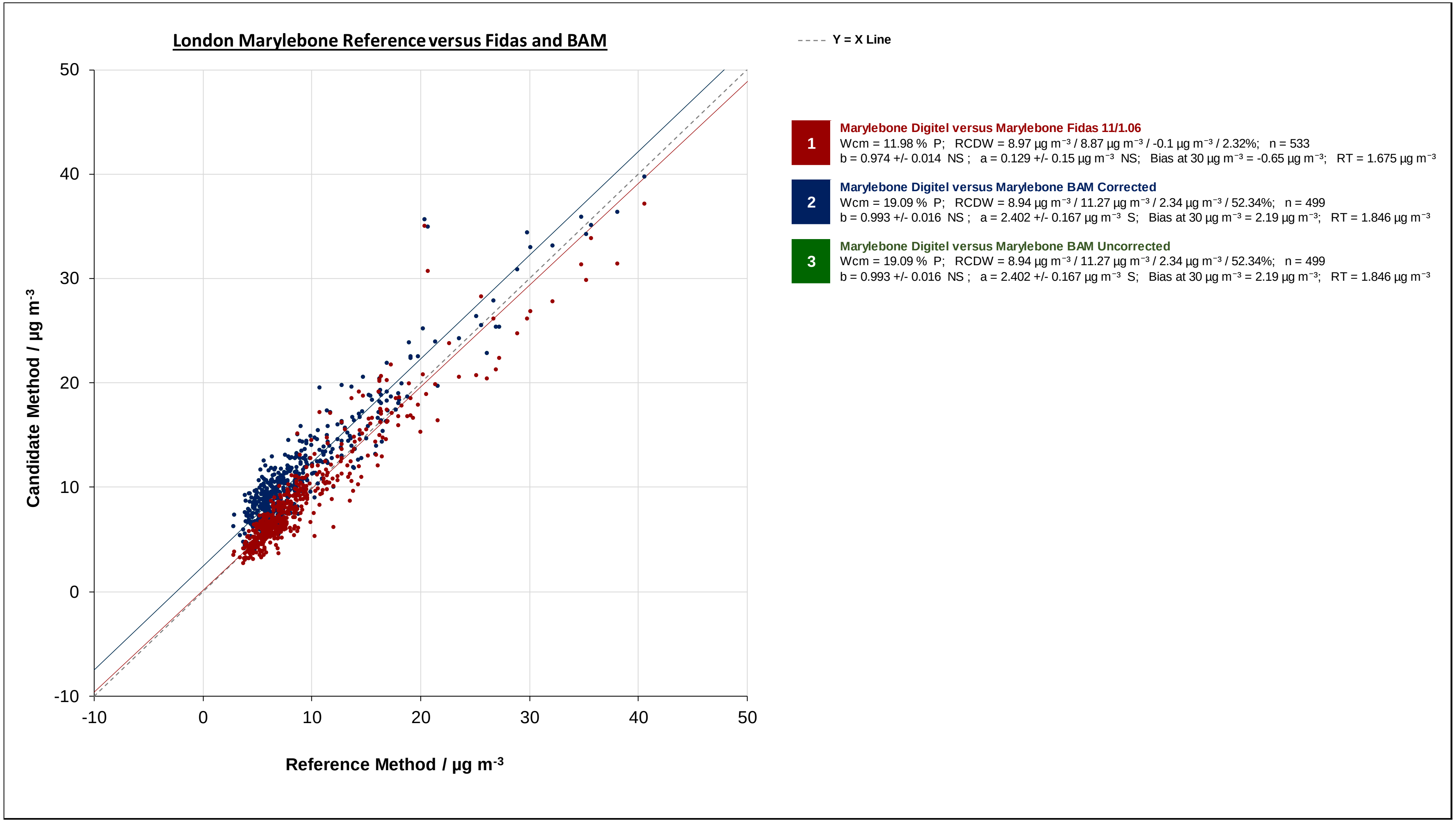


Figure B.13 PM$_{2.5}$ Fidas M11 / 1.06, BAM Corrected and BAM Uncorrected equivalence calculations for Storrington

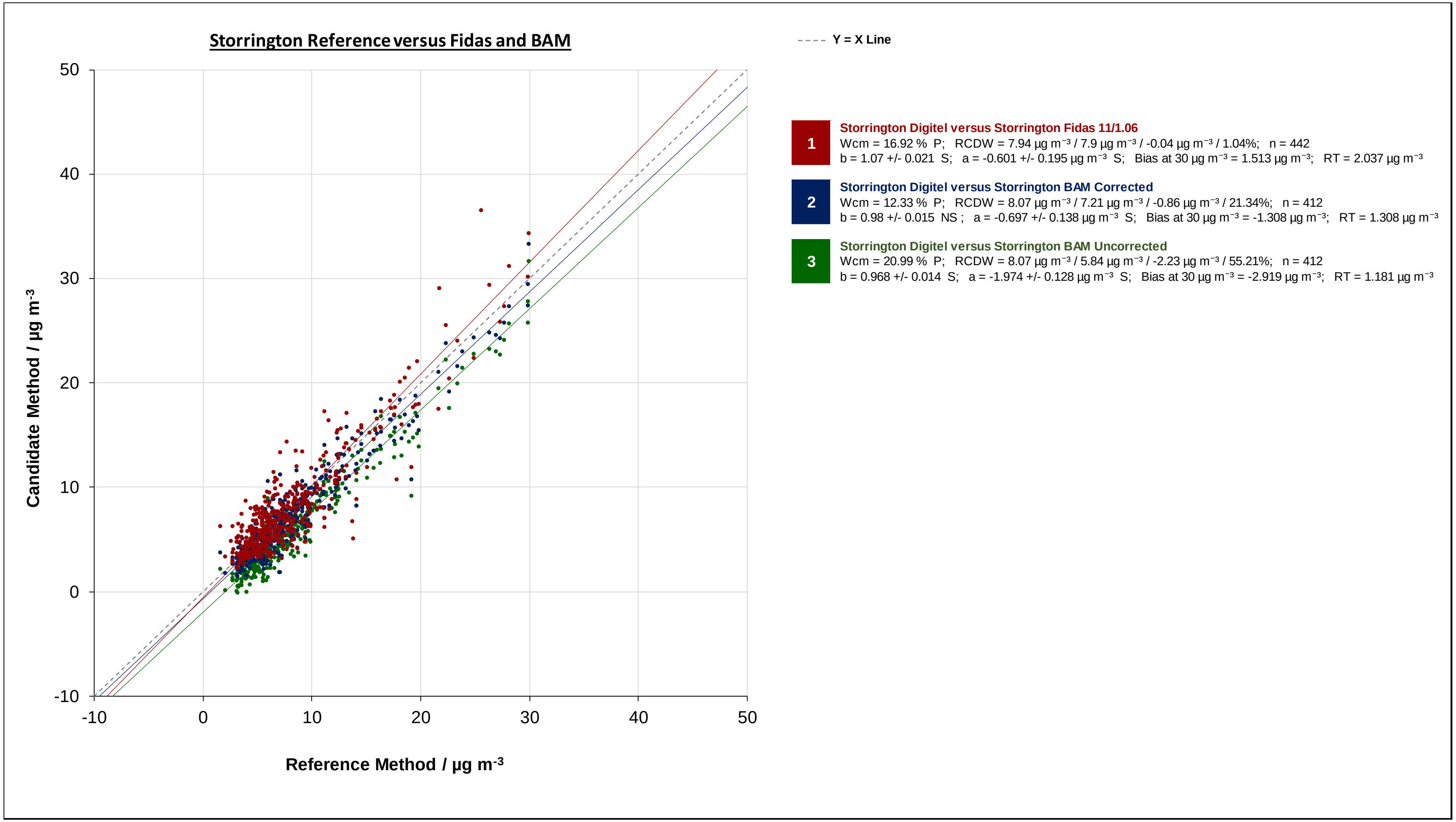


Figure B.14 PM2.5 Fidas M11 / 1.06 equivalence calculations for London Marylebone Road for June to December 2022 (red) and March to December 2022 (blue and red)

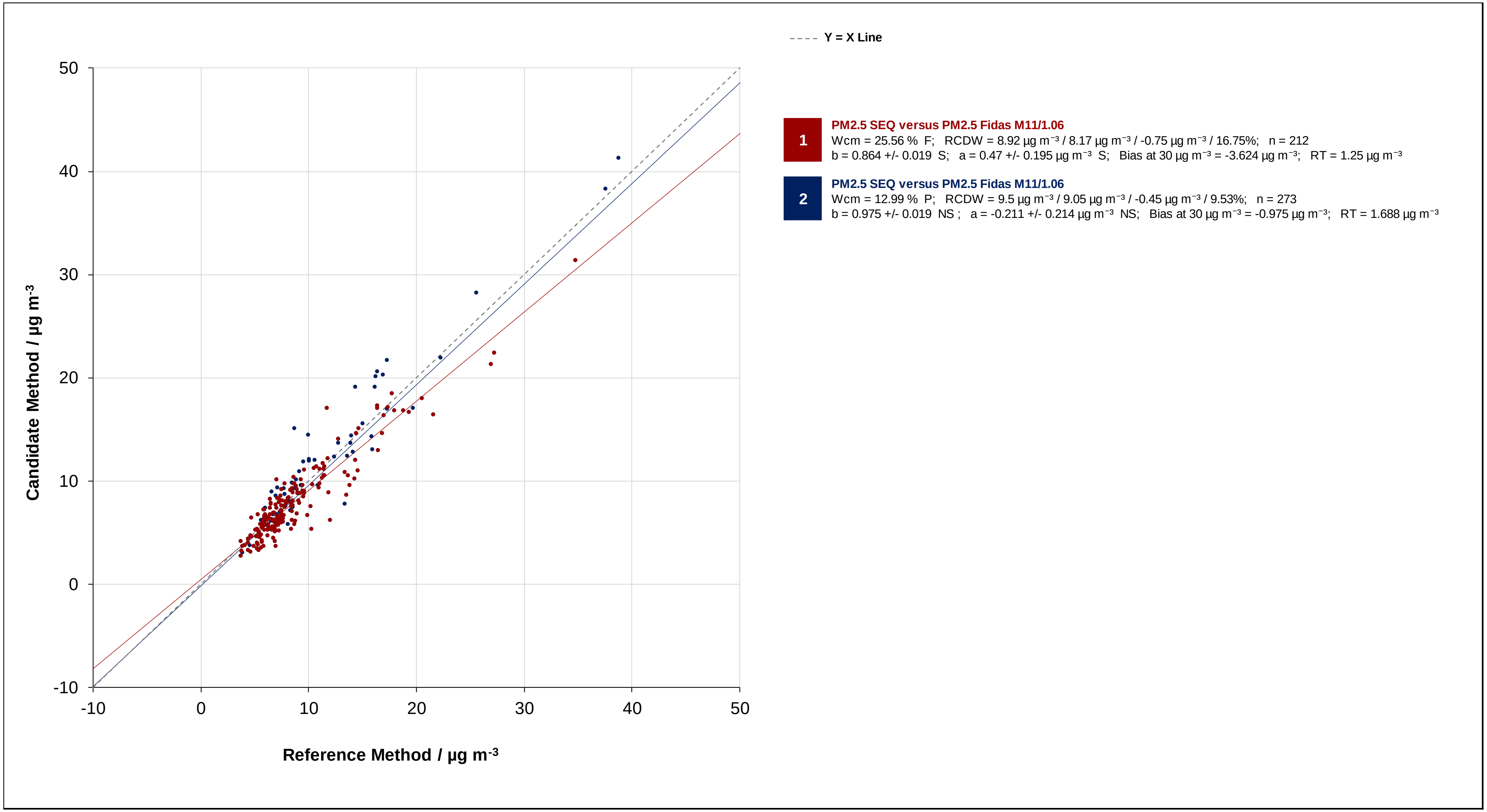


Figure B.15 PM$_{2.5}$ BAM equivalence calculations for London Marylebone Road for June to December 2022 (red) and March to December 2022 (blue and red)

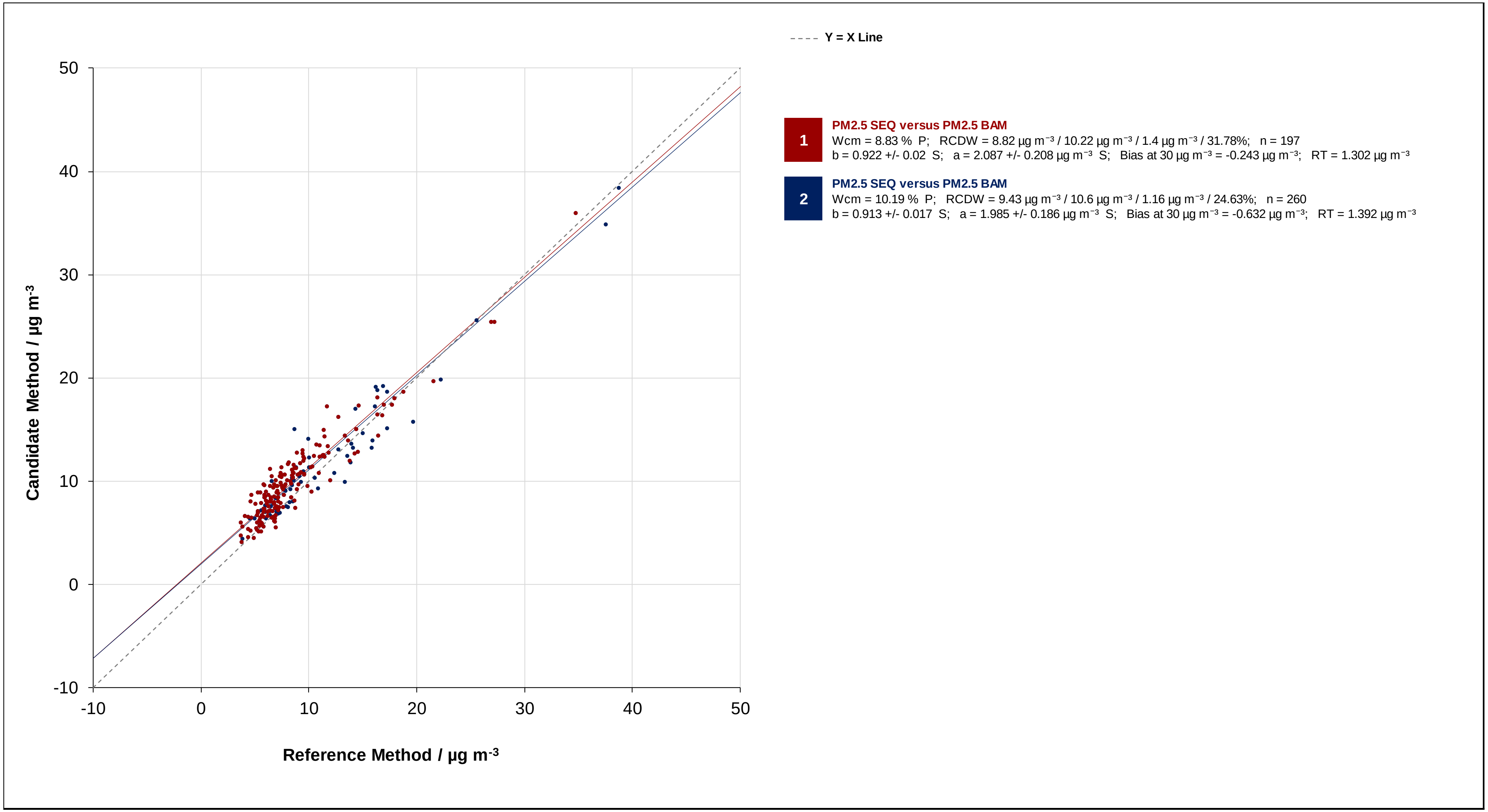
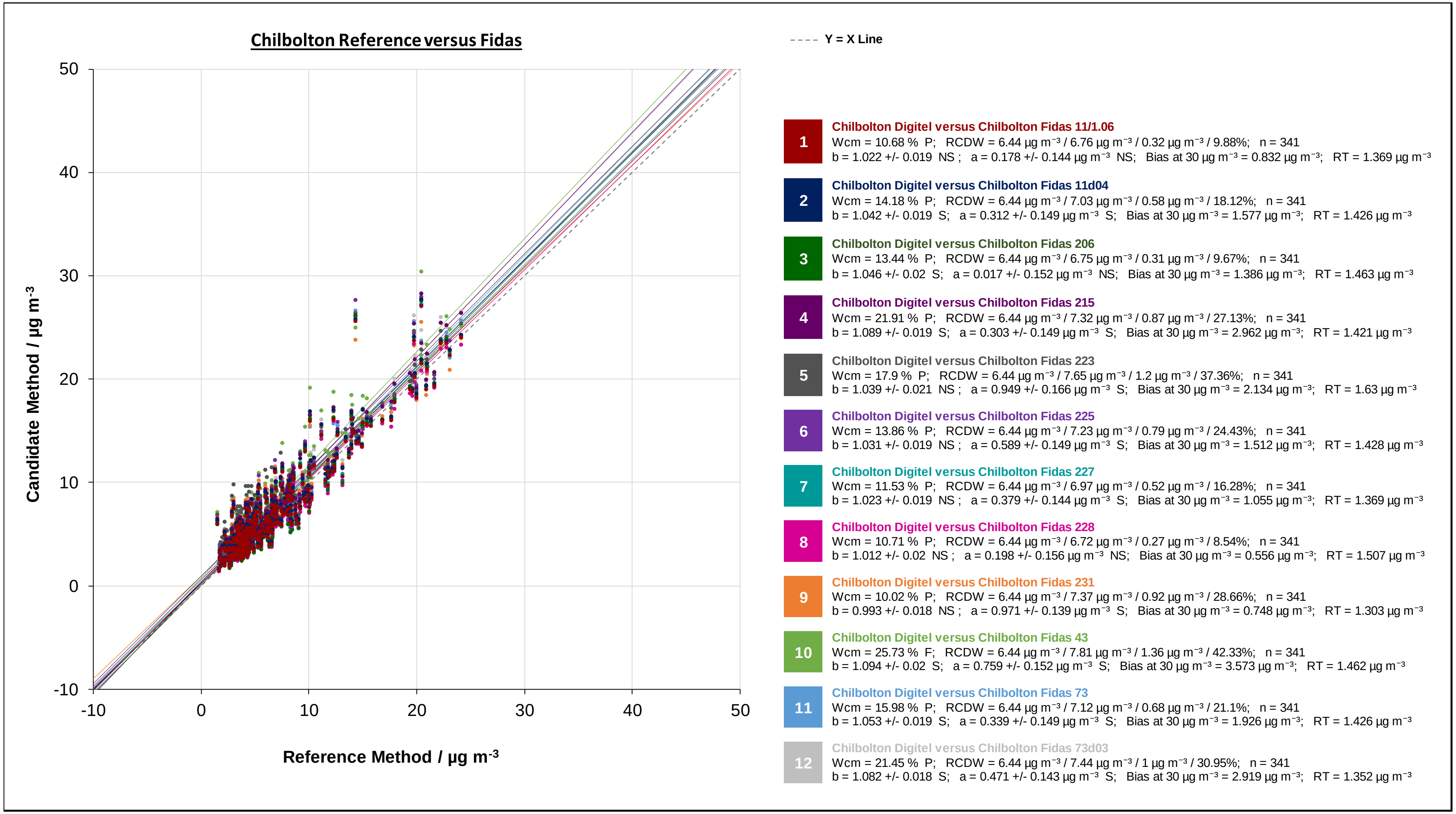


Figure B.16 Equivalence calculations for multiple Fidas algorithms at Chilbolton



1 Chilbolton Digitel versus Chilbolton Fidas 11/1.06
Wcm = 10.68 % P; RCDW = 6.44 µg m^{-3} / 6.76 µg m^{-3} / 0.32 µg m^{-3} / 9.88%; n = 341
b = 1.022 +/- 0.019 NS ; a = 0.178 +/- 0.144 µg m^{-3} NS; Bias at 30 µg m^{-3} = 0.832 µg m^{-3}; RT = 1.369 µg m^{-3}

2 Chilbolton Digitel versus Chilbolton Fidas 11d04
Wcm = 14.18 % P; RCDW = 6.44 µg m^{-3} / 7.03 µg m^{-3} / 0.58 µg m^{-3} / 18.12%; n = 341
b = 1.042 +/- 0.019 S; a = 0.312 +/- 0.149 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.577 µg m^{-3}; RT = 1.426 µg m^{-3}

3 Chilbolton Digitel versus Chilbolton Fidas 206
Wcm = 13.44 % P; RCDW = 6.44 µg m^{-3} / 6.75 µg m^{-3} / 0.31 µg m^{-3} / 9.67%; n = 341
b = 1.046 +/- 0.02 S; a = 0.017 +/- 0.152 µg m^{-3} NS; Bias at 30 µg m^{-3} = 1.386 µg m^{-3}; RT = 1.463 µg m^{-3}

4 Chilbolton Digitel versus Chilbolton Fidas 215
Wcm = 21.91 % P; RCDW = 6.44 µg m^{-3} / 7.32 µg m^{-3} / 0.87 µg m^{-3} / 27.13%; n = 341
b = 1.089 +/- 0.019 S; a = 0.303 +/- 0.149 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.962 µg m^{-3}; RT = 1.421 µg m^{-3}

5 Chilbolton Digitel versus Chilbolton Fidas 223
Wcm = 17.9 % P; RCDW = 6.44 µg m^{-3} / 7.65 µg m^{-3} / 1.2 µg m^{-3} / 37.36%; n = 341
b = 1.039 +/- 0.021 NS ; a = 0.949 +/- 0.166 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.134 µg m^{-3}; RT = 1.63 µg m^{-3}

6 Chilbolton Digitel versus Chilbolton Fidas 225
Wcm = 13.86 % P; RCDW = 6.44 µg m^{-3} / 7.23 µg m^{-3} / 0.79 µg m^{-3} / 24.43%; n = 341
b = 1.031 +/- 0.019 NS ; a = 0.589 +/- 0.149 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.512 µg m^{-3}; RT = 1.428 µg m^{-3}

7 Chilbolton Digitel versus Chilbolton Fidas 227
Wcm = 11.53 % P; RCDW = 6.44 µg m^{-3} / 6.97 µg m^{-3} / 0.52 µg m^{-3} / 16.28%; n = 341
b = 1.023 +/- 0.019 NS ; a = 0.379 +/- 0.144 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.055 µg m^{-3}; RT = 1.369 µg m^{-3}

8 Chilbolton Digitel versus Chilbolton Fidas 228
Wcm = 10.71 % P; RCDW = 6.44 µg m^{-3} / 6.72 µg m^{-3} / 0.27 µg m^{-3} / 8.54%; n = 341
b = 1.012 +/- 0.02 NS ; a = 0.198 +/- 0.156 µg m^{-3} NS; Bias at 30 µg m^{-3} = 0.556 µg m^{-3}; RT = 1.507 µg m^{-3}

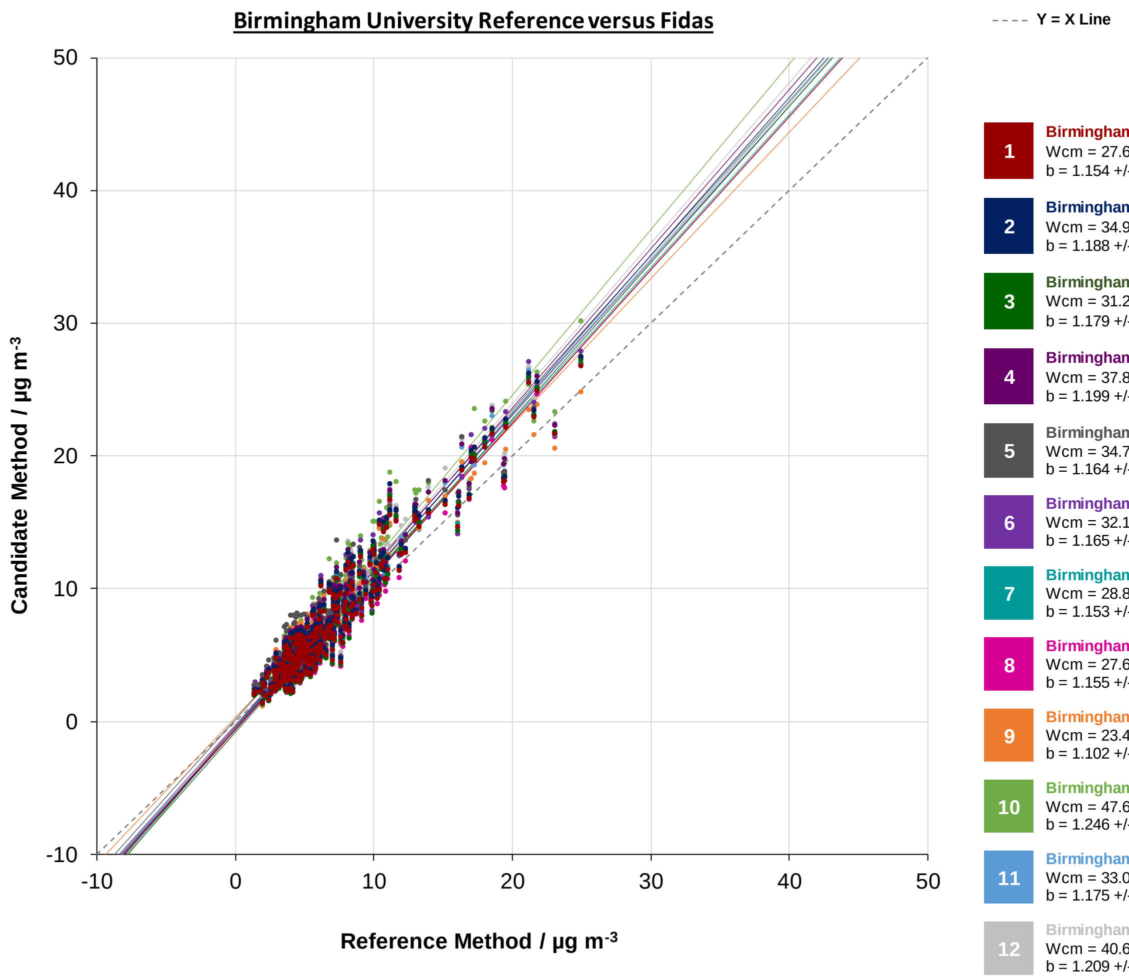
9 Chilbolton Digitel versus Chilbolton Fidas 231
Wcm = 10.02 % P; RCDW = 6.44 µg m^{-3} / 7.37 µg m^{-3} / 0.92 µg m^{-3} / 28.66%; n = 341
b = 0.993 +/- 0.018 NS ; a = 0.971 +/- 0.139 µg m^{-3} S; Bias at 30 µg m^{-3} = 0.748 µg m^{-3}; RT = 1.303 µg m^{-3}

10 Chilbolton Digitel versus Chilbolton Fidas 43
Wcm = 25.73 % F; RCDW = 6.44 µg m^{-3} / 7.81 µg m^{-3} / 1.36 µg m^{-3} / 42.33%; n = 341
b = 1.094 +/- 0.02 S; a = 0.759 +/- 0.152 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.573 µg m^{-3}; RT = 1.462 µg m^{-3}

11 Chilbolton Digitel versus Chilbolton Fidas 73
Wcm = 15.98 % P; RCDW = 6.44 µg m^{-3} / 7.12 µg m^{-3} / 0.68 µg m^{-3} / 21.1%; n = 341
b = 1.053 +/- 0.019 S; a = 0.339 +/- 0.149 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.926 µg m^{-3}; RT = 1.426 µg m^{-3}

12 Chilbolton Digitel versus Chilbolton Fidas 73d03
Wcm = 21.45 % P; RCDW = 6.44 µg m^{-3} / 7.44 µg m^{-3} / 1 µg m^{-3} / 30.95%; n = 341
b = 1.082 +/- 0.018 S; a = 0.471 +/- 0.143 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.919 µg m^{-3}; RT = 1.352 µg m^{-3}

Figure B.17 Equivalence calculations for multiple Fidas algorithms at Birmingham University



1 **Birmingham University Partisol versus Birmingham University Fidas 11/1.06**
Wcm = 27.65 % F; RCDW = 6.54 µg m^{-3} / 6.93 µg m^{-3} / 0.38 µg m^{-3} / 11.76%; n = 326
b = 1.154 +/- 0.018 S; a = -0.623 +/- 0.14 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.996 µg m^{-3}; RT = 1.109 µg m^{-3}

2 **Birmingham University Partisol versus Birmingham University Fidas 11d04**
Wcm = 34.99 % F; RCDW = 6.54 µg m^{-3} / 7.24 µg m^{-3} / 0.7 µg m^{-3} / 21.42%; n = 326
b = 1.188 +/- 0.019 S; a = -0.531 +/- 0.145 µg m^{-3} S; Bias at 30 µg m^{-3} = 5.118 µg m^{-3}; RT = 1.166 µg m^{-3}

3 **Birmingham University Partisol versus Birmingham University Fidas 206**
Wcm = 31.29 % F; RCDW = 6.54 µg m^{-3} / 6.9 µg m^{-3} / 0.35 µg m^{-3} / 10.84%; n = 326
b = 1.179 +/- 0.019 S; a = -0.814 +/- 0.146 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.543 µg m^{-3}; RT = 1.177 µg m^{-3}

4 **Birmingham University Partisol versus Birmingham University Fidas 215**
Wcm = 37.87 % F; RCDW = 6.54 µg m^{-3} / 7.44 µg m^{-3} / 0.89 µg m^{-3} / 27.3%; n = 326
b = 1.199 +/- 0.019 S; a = -0.411 +/- 0.142 µg m^{-3} S; Bias at 30 µg m^{-3} = 5.567 µg m^{-3}; RT = 1.132 µg m^{-3}

5 **Birmingham University Partisol versus Birmingham University Fidas 223**
Wcm = 34.78 % P; RCDW = 6.54 µg m^{-3} / 7.75 µg m^{-3} / 1.21 µg m^{-3} / 36.89%; n = 326
b = 1.164 +/- 0.02 S; a = 0.132 +/- 0.154 µg m^{-3} S; Bias at 30 µg m^{-3} = 5.061 µg m^{-3}; RT = 1.267 µg m^{-3}

6 **Birmingham University Partisol versus Birmingham University Fidas 225**
Wcm = 32.19 % F; RCDW = 6.54 µg m^{-3} / 7.36 µg m^{-3} / 0.82 µg m^{-3} / 25.1%; n = 326
b = 1.165 +/- 0.019 S; a = -0.256 +/- 0.147 µg m^{-3} NS; Bias at 30 µg m^{-3} = 4.681 µg m^{-3}; RT = 1.185 µg m^{-3}

7 **Birmingham University Partisol versus Birmingham University Fidas 227**
Wcm = 28.88 % F; RCDW = 6.54 µg m^{-3} / 7.13 µg m^{-3} / 0.59 µg m^{-3} / 18%; n = 326
b = 1.153 +/- 0.018 S; a = -0.415 +/- 0.14 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.189 µg m^{-3}; RT = 1.108 µg m^{-3}

8 **Birmingham University Partisol versus Birmingham University Fidas 228**
Wcm = 27.67 % F; RCDW = 6.54 µg m^{-3} / 6.87 µg m^{-3} / 0.32 µg m^{-3} / 9.87%; n = 326
b = 1.155 +/- 0.02 S; a = -0.693 +/- 0.151 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.964 µg m^{-3}; RT = 1.234 µg m^{-3}

9 **Birmingham University Partisol versus Birmingham University Fidas 231**
Wcm = 23.43 % P; RCDW = 6.54 µg m^{-3} / 7.48 µg m^{-3} / 0.94 µg m^{-3} / 28.73%; n = 326
b = 1.102 +/- 0.018 S; a = 0.272 +/- 0.14 µg m^{-3} NS; Bias at 30 µg m^{-3} = 3.335 µg m^{-3}; RT = 1.109 µg m^{-3}

10 **Birmingham University Partisol versus Birmingham University Fidas 43**
Wcm = 47.66 % F; RCDW = 6.54 µg m^{-3} / 7.8 µg m^{-3} / 1.26 µg m^{-3} / 38.48%; n = 326
b = 1.246 +/- 0.02 S; a = -0.353 +/- 0.153 µg m^{-3} S; Bias at 30 µg m^{-3} = 7.038 µg m^{-3}; RT = 1.253 µg m^{-3}

11 **Birmingham University Partisol versus Birmingham University Fidas 73**
Wcm = 33.03 % F; RCDW = 6.54 µg m^{-3} / 7.28 µg m^{-3} / 0.74 µg m^{-3} / 22.51%; n = 326
b = 1.175 +/- 0.018 S; a = -0.406 +/- 0.139 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.832 µg m^{-3}; RT = 1.099 µg m^{-3}

12 **Birmingham University Partisol versus Birmingham University Fidas 73d03**
Wcm = 40.67 % F; RCDW = 6.54 µg m^{-3} / 7.65 µg m^{-3} / 1.11 µg m^{-3} / 33.83%; n = 326
b = 1.209 +/- 0.018 S; a = -0.26 +/- 0.136 µg m^{-3} NS; Bias at 30 µg m^{-3} = 6.007 µg m^{-3}; RT = 1.067 µg m^{-3}

Figure B.18 Equivalence calculations for multiple Fidas algorithms at London Honor Oak Park

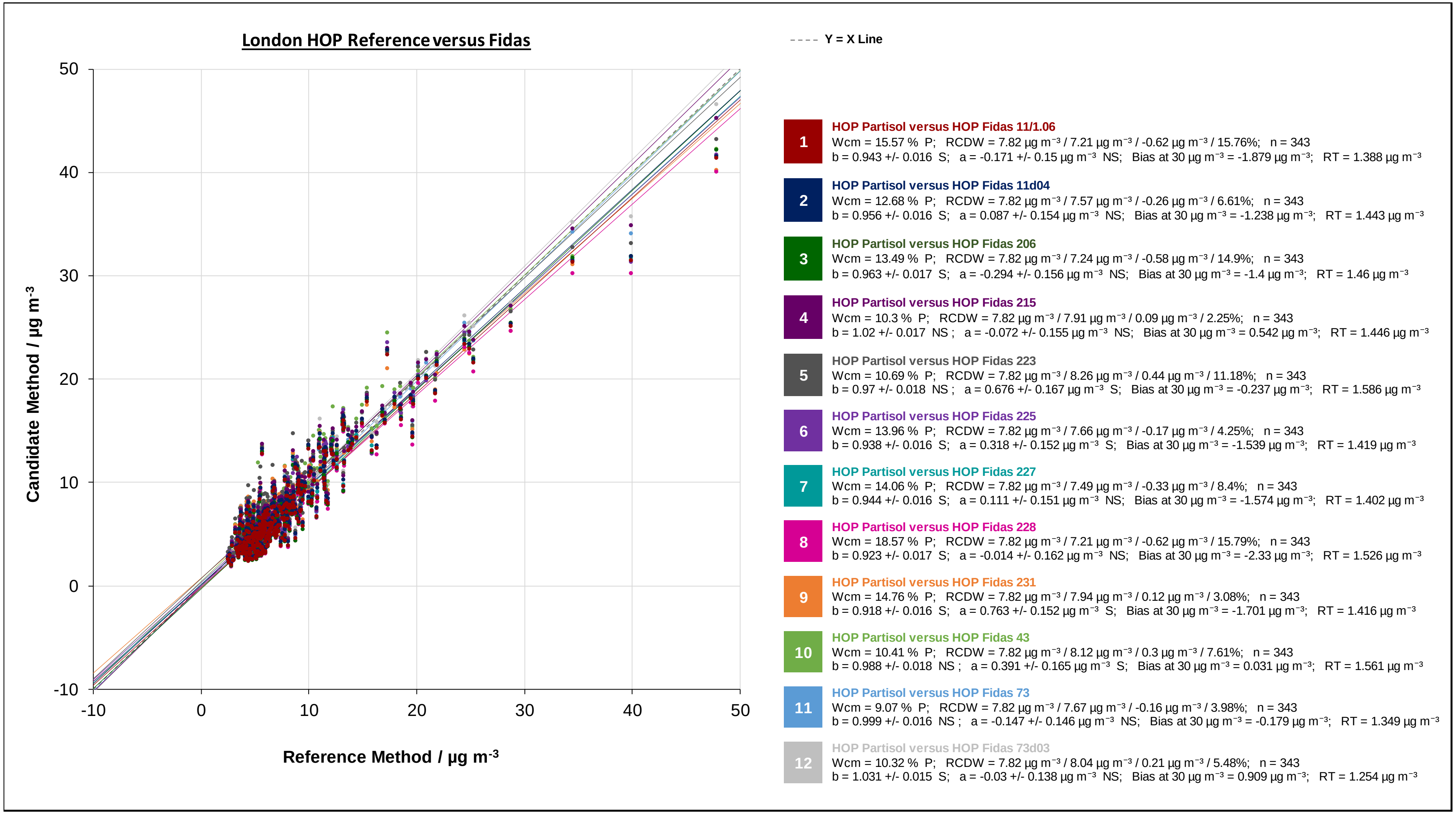
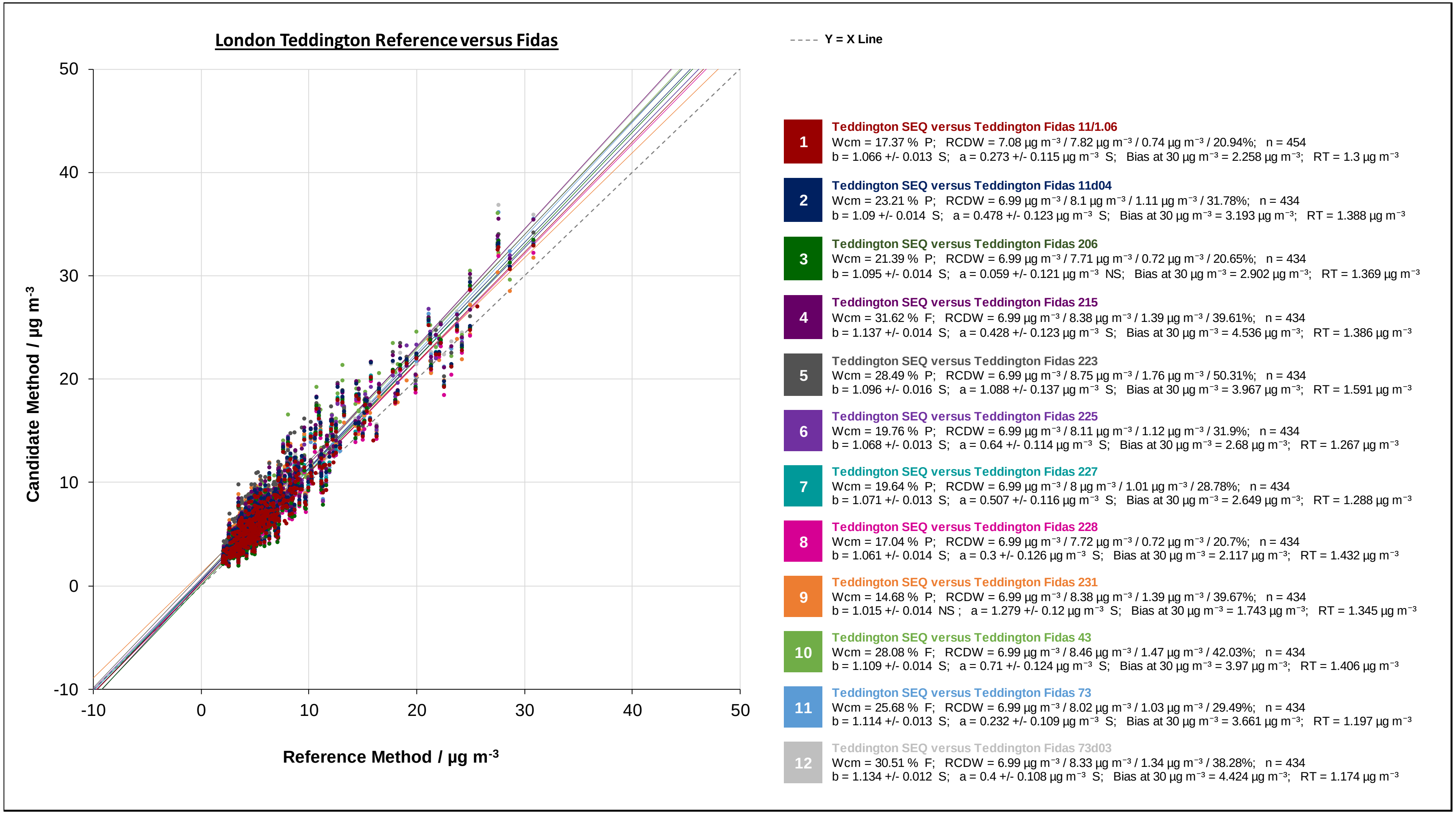


Figure B.19 Equivalence calculations for multiple Fidas algorithms at London Teddington



1
Teddington SEQ versus Teddington Fidas 11/1.06
Wcm = 17.37 % P; RCDW = 7.08 µg m^{-3} / 7.82 µg m^{-3} / 0.74 µg m^{-3} / 20.94%; n = 454
b = 1.066 +/- 0.013 S; a = 0.273 +/- 0.115 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.258 µg m^{-3}; RT = 1.3 µg m^{-3}

2
Teddington SEQ versus Teddington Fidas 11d04
Wcm = 23.21 % P; RCDW = 6.99 µg m^{-3} / 8.1 µg m^{-3} / 1.11 µg m^{-3} / 31.78%; n = 434
b = 1.09 +/- 0.014 S; a = 0.478 +/- 0.123 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.193 µg m^{-3}; RT = 1.388 µg m^{-3}

3
Teddington SEQ versus Teddington Fidas 206
Wcm = 21.39 % P; RCDW = 6.99 µg m^{-3} / 7.71 µg m^{-3} / 0.72 µg m^{-3} / 20.65%; n = 434
b = 1.095 +/- 0.014 S; a = 0.059 +/- 0.121 µg m^{-3} NS; Bias at 30 µg m^{-3} = 2.902 µg m^{-3}; RT = 1.369 µg m^{-3}

4
Teddington SEQ versus Teddington Fidas 215
Wcm = 31.62 % F; RCDW = 6.99 µg m^{-3} / 8.38 µg m^{-3} / 1.39 µg m^{-3} / 39.61%; n = 434
b = 1.137 +/- 0.014 S; a = 0.428 +/- 0.123 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.536 µg m^{-3}; RT = 1.386 µg m^{-3}

5
Teddington SEQ versus Teddington Fidas 223
Wcm = 28.49 % P; RCDW = 6.99 µg m^{-3} / 8.75 µg m^{-3} / 1.76 µg m^{-3} / 50.31%; n = 434
b = 1.096 +/- 0.016 S; a = 1.088 +/- 0.137 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.967 µg m^{-3}; RT = 1.591 µg m^{-3}

6
Teddington SEQ versus Teddington Fidas 225
Wcm = 19.76 % P; RCDW = 6.99 µg m^{-3} / 8.11 µg m^{-3} / 1.12 µg m^{-3} / 31.9%; n = 434
b = 1.068 +/- 0.013 S; a = 0.64 +/- 0.114 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.68 µg m^{-3}; RT = 1.267 µg m^{-3}

7
Teddington SEQ versus Teddington Fidas 227
Wcm = 19.64 % P; RCDW = 6.99 µg m^{-3} / 8 µg m^{-3} / 1.01 µg m^{-3} / 28.78%; n = 434
b = 1.071 +/- 0.013 S; a = 0.507 +/- 0.116 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.649 µg m^{-3}; RT = 1.288 µg m^{-3}

8
Teddington SEQ versus Teddington Fidas 228
Wcm = 17.04 % P; RCDW = 6.99 µg m^{-3} / 7.72 µg m^{-3} / 0.72 µg m^{-3} / 20.7%; n = 434
b = 1.061 +/- 0.014 S; a = 0.3 +/- 0.126 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.117 µg m^{-3}; RT = 1.432 µg m^{-3}

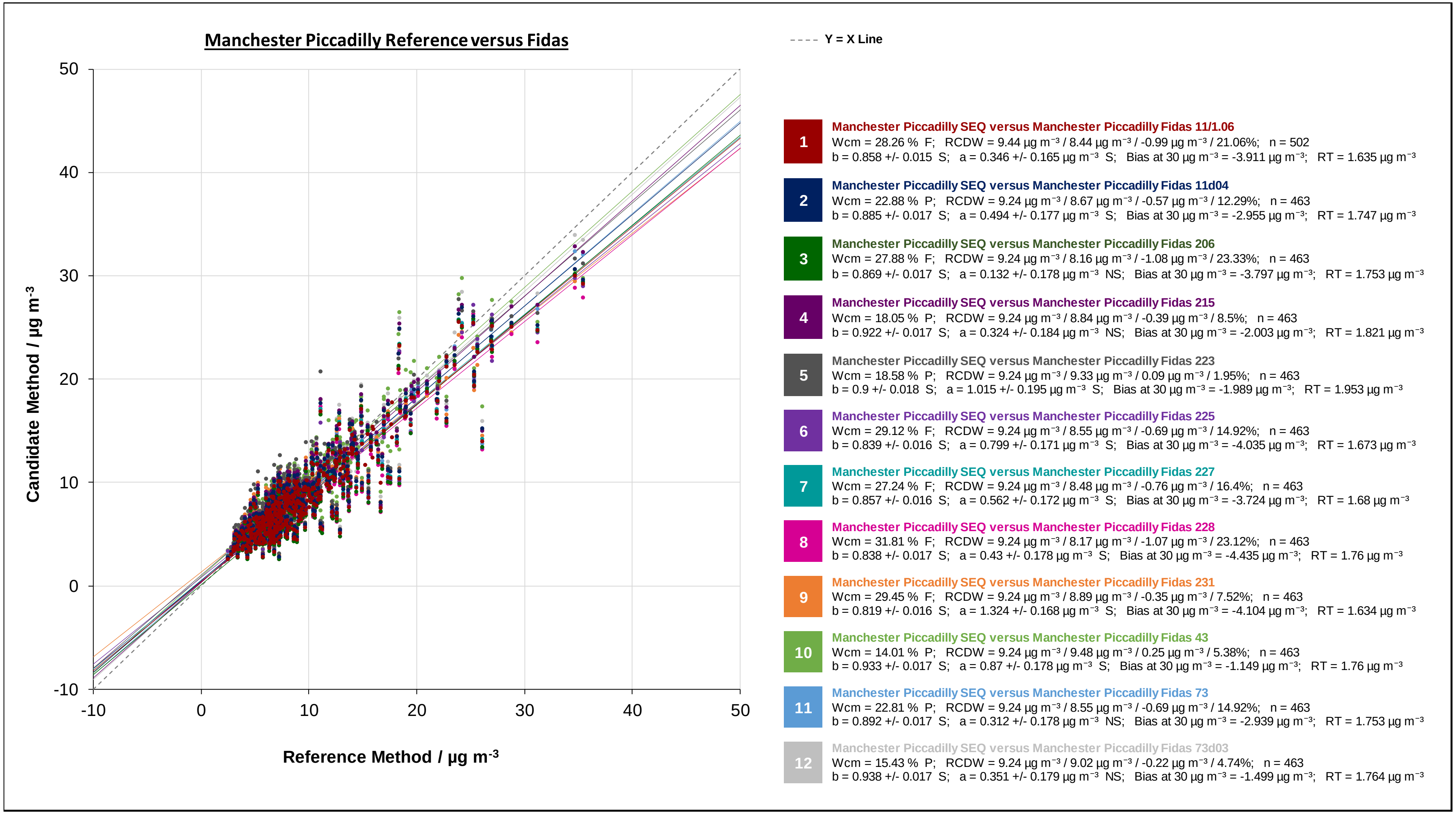
9
Teddington SEQ versus Teddington Fidas 231
Wcm = 14.68 % P; RCDW = 6.99 µg m^{-3} / 8.38 µg m^{-3} / 1.39 µg m^{-3} / 39.67%; n = 434
b = 1.015 +/- 0.014 NS ; a = 1.279 +/- 0.12 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.743 µg m^{-3}; RT = 1.345 µg m^{-3}

10
Teddington SEQ versus Teddington Fidas 43
Wcm = 28.08 % F; RCDW = 6.99 µg m^{-3} / 8.46 µg m^{-3} / 1.47 µg m^{-3} / 42.03%; n = 434
b = 1.109 +/- 0.014 S; a = 0.71 +/- 0.124 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.97 µg m^{-3}; RT = 1.406 µg m^{-3}

11
Teddington SEQ versus Teddington Fidas 73
Wcm = 25.68 % F; RCDW = 6.99 µg m^{-3} / 8.02 µg m^{-3} / 1.03 µg m^{-3} / 29.49%; n = 434
b = 1.114 +/- 0.013 S; a = 0.232 +/- 0.109 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.661 µg m^{-3}; RT = 1.197 µg m^{-3}

12
Teddington SEQ versus Teddington Fidas 73d03
Wcm = 30.51 % F; RCDW = 6.99 µg m^{-3} / 8.33 µg m^{-3} / 1.34 µg m^{-3} / 38.28%; n = 434
b = 1.134 +/- 0.012 S; a = 0.4 +/- 0.108 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.424 µg m^{-3}; RT = 1.174 µg m^{-3}

Figure B.20 Equivalence calculations for multiple Fidas algorithms at Manchester Piccadilly



Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 11/1.06
Wcm = 28.26 % F; RCDW = 9.44 µg m^{-3} / 8.44 µg m^{-3} / -0.99 µg m^{-3} / 21.06%; n = 502
b = 0.858 +/- 0.015 S; a = 0.346 +/- 0.165 µg m^{-3} S; Bias at 30 µg m^{-3} = -3.911 µg m^{-3}; RT = 1.635 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 11d04
Wcm = 22.88 % P; RCDW = 9.24 µg m^{-3} / 8.67 µg m^{-3} / -0.57 µg m^{-3} / 12.29%; n = 463
b = 0.885 +/- 0.017 S; a = 0.494 +/- 0.177 µg m^{-3} S; Bias at 30 µg m^{-3} = -2.955 µg m^{-3}; RT = 1.747 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 206
Wcm = 27.88 % F; RCDW = 9.24 µg m^{-3} / 8.16 µg m^{-3} / -1.08 µg m^{-3} / 23.33%; n = 463
b = 0.869 +/- 0.017 S; a = 0.132 +/- 0.178 µg m^{-3} NS; Bias at 30 µg m^{-3} = -3.797 µg m^{-3}; RT = 1.753 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 215
Wcm = 18.05 % P; RCDW = 9.24 µg m^{-3} / 8.84 µg m^{-3} / -0.39 µg m^{-3} / 8.5%; n = 463
b = 0.922 +/- 0.017 S; a = 0.324 +/- 0.184 µg m^{-3} NS; Bias at 30 µg m^{-3} = -2.003 µg m^{-3}; RT = 1.821 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 223
Wcm = 18.58 % P; RCDW = 9.24 µg m^{-3} / 9.33 µg m^{-3} / 0.09 µg m^{-3} / 1.95%; n = 463
b = 0.9 +/- 0.018 S; a = 1.015 +/- 0.195 µg m^{-3} S; Bias at 30 µg m^{-3} = -1.989 µg m^{-3}; RT = 1.953 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 225
Wcm = 29.12 % F; RCDW = 9.24 µg m^{-3} / 8.55 µg m^{-3} / -0.69 µg m^{-3} / 14.92%; n = 463
b = 0.839 +/- 0.016 S; a = 0.799 +/- 0.171 µg m^{-3} S; Bias at 30 µg m^{-3} = -4.035 µg m^{-3}; RT = 1.673 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 227
Wcm = 27.24 % F; RCDW = 9.24 µg m^{-3} / 8.48 µg m^{-3} / -0.76 µg m^{-3} / 16.4%; n = 463
b = 0.857 +/- 0.016 S; a = 0.562 +/- 0.172 µg m^{-3} S; Bias at 30 µg m^{-3} = -3.724 µg m^{-3}; RT = 1.68 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 228
Wcm = 31.81 % F; RCDW = 9.24 µg m^{-3} / 8.17 µg m^{-3} / -1.07 µg m^{-3} / 23.12%; n = 463
b = 0.838 +/- 0.017 S; a = 0.43 +/- 0.178 µg m^{-3} S; Bias at 30 µg m^{-3} = -4.435 µg m^{-3}; RT = 1.76 µg m^{-3}

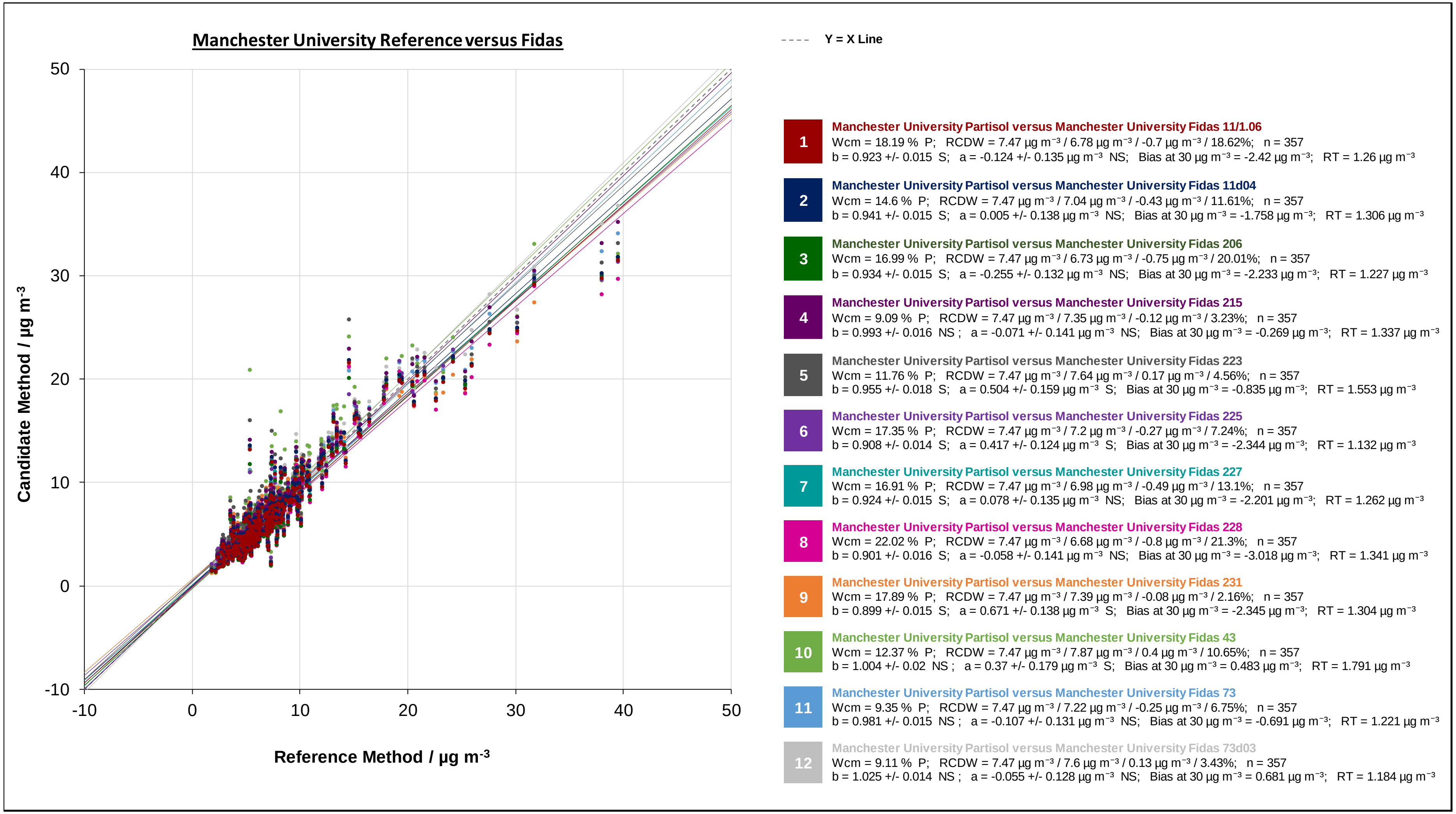
Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 231
Wcm = 29.45 % F; RCDW = 9.24 µg m^{-3} / 8.89 µg m^{-3} / -0.35 µg m^{-3} / 7.52%; n = 463
b = 0.819 +/- 0.016 S; a = 1.324 +/- 0.168 µg m^{-3} S; Bias at 30 µg m^{-3} = -4.104 µg m^{-3}; RT = 1.634 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 43
Wcm = 14.01 % P; RCDW = 9.24 µg m^{-3} / 9.48 µg m^{-3} / 0.25 µg m^{-3} / 5.38%; n = 463
b = 0.933 +/- 0.017 S; a = 0.87 +/- 0.178 µg m^{-3} S; Bias at 30 µg m^{-3} = -1.149 µg m^{-3}; RT = 1.76 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 73
Wcm = 22.81 % P; RCDW = 9.24 µg m^{-3} / 8.55 µg m^{-3} / -0.69 µg m^{-3} / 14.92%; n = 463
b = 0.892 +/- 0.017 S; a = 0.312 +/- 0.178 µg m^{-3} NS; Bias at 30 µg m^{-3} = -2.939 µg m^{-3}; RT = 1.753 µg m^{-3}

Manchester Piccadilly SEQ versus Manchester Piccadilly Fidas 73d03
Wcm = 15.43 % P; RCDW = 9.24 µg m^{-3} / 9.02 µg m^{-3} / -0.22 µg m^{-3} / 4.74%; n = 463
b = 0.938 +/- 0.017 S; a = 0.351 +/- 0.179 µg m^{-3} NS; Bias at 30 µg m^{-3} = -1.499 µg m^{-3}; RT = 1.764 µg m^{-3}

Figure B.21 Equivalence calculations for multiple Fidas algorithms at Manchester University



Manchester University Partisol versus Manchester University Fidas 11/1.06
Wcm = 18.19 % P; RCDW = 7.47 µg m^{-3} / 6.78 µg m^{-3} / -0.7 µg m^{-3} / 18.62%; n = 357
b = 0.923 +/- 0.015 S; a = -0.124 +/- 0.135 µg m^{-3} NS; Bias at 30 µg m^{-3} = -2.42 µg m^{-3}; RT = 1.26 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 11d04
Wcm = 14.6 % P; RCDW = 7.47 µg m^{-3} / 7.04 µg m^{-3} / -0.43 µg m^{-3} / 11.61%; n = 357
b = 0.941 +/- 0.015 S; a = 0.005 +/- 0.138 µg m^{-3} NS; Bias at 30 µg m^{-3} = -1.758 µg m^{-3}; RT = 1.306 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 206
Wcm = 16.99 % P; RCDW = 7.47 µg m^{-3} / 6.73 µg m^{-3} / -0.75 µg m^{-3} / 20.01%; n = 357
b = 0.934 +/- 0.015 S; a = -0.255 +/- 0.132 µg m^{-3} NS; Bias at 30 µg m^{-3} = -2.233 µg m^{-3}; RT = 1.227 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 215
Wcm = 9.09 % P; RCDW = 7.47 µg m^{-3} / 7.35 µg m^{-3} / -0.12 µg m^{-3} / 3.23%; n = 357
b = 0.993 +/- 0.016 NS ; a = -0.071 +/- 0.141 µg m^{-3} NS; Bias at 30 µg m^{-3} = -0.269 µg m^{-3}; RT = 1.337 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 223
Wcm = 11.76 % P; RCDW = 7.47 µg m^{-3} / 7.64 µg m^{-3} / 0.17 µg m^{-3} / 4.56%; n = 357
b = 0.955 +/- 0.018 S; a = 0.504 +/- 0.159 µg m^{-3} S; Bias at 30 µg m^{-3} = -0.835 µg m^{-3}; RT = 1.553 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 225
Wcm = 17.35 % P; RCDW = 7.47 µg m^{-3} / 7.2 µg m^{-3} / -0.27 µg m^{-3} / 7.24%; n = 357
b = 0.908 +/- 0.014 S; a = 0.417 +/- 0.124 µg m^{-3} S; Bias at 30 µg m^{-3} = -2.344 µg m^{-3}; RT = 1.132 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 227
Wcm = 16.91 % P; RCDW = 7.47 µg m^{-3} / 6.98 µg m^{-3} / -0.49 µg m^{-3} / 13.1%; n = 357
b = 0.924 +/- 0.015 S; a = 0.078 +/- 0.135 µg m^{-3} NS; Bias at 30 µg m^{-3} = -2.201 µg m^{-3}; RT = 1.262 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 228
Wcm = 22.02 % P; RCDW = 7.47 µg m^{-3} / 6.68 µg m^{-3} / -0.8 µg m^{-3} / 21.3%; n = 357
b = 0.901 +/- 0.016 S; a = -0.058 +/- 0.141 µg m^{-3} NS; Bias at 30 µg m^{-3} = -3.018 µg m^{-3}; RT = 1.341 µg m^{-3}

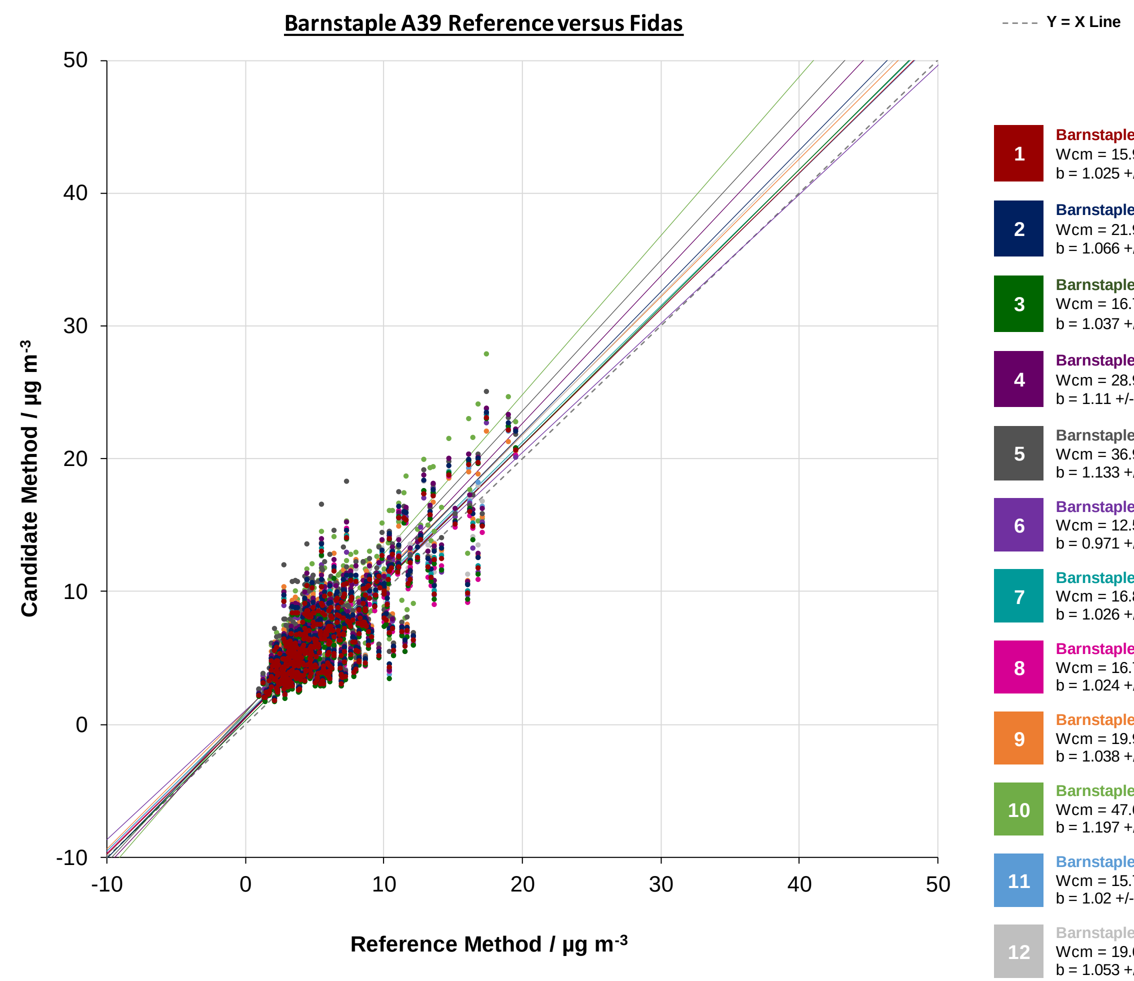
Manchester University Partisol versus Manchester University Fidas 231
Wcm = 17.89 % P; RCDW = 7.47 µg m^{-3} / 7.39 µg m^{-3} / -0.08 µg m^{-3} / 2.16%; n = 357
b = 0.899 +/- 0.015 S; a = 0.671 +/- 0.138 µg m^{-3} S; Bias at 30 µg m^{-3} = -2.345 µg m^{-3}; RT = 1.304 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 43
Wcm = 12.37 % P; RCDW = 7.47 µg m^{-3} / 7.87 µg m^{-3} / 0.4 µg m^{-3} / 10.65%; n = 357
b = 1.004 +/- 0.02 NS ; a = 0.37 +/- 0.179 µg m^{-3} S; Bias at 30 µg m^{-3} = 0.483 µg m^{-3}; RT = 1.791 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 73
Wcm = 9.35 % P; RCDW = 7.47 µg m^{-3} / 7.22 µg m^{-3} / -0.25 µg m^{-3} / 6.75%; n = 357
b = 0.981 +/- 0.015 NS ; a = -0.107 +/- 0.131 µg m^{-3} NS; Bias at 30 µg m^{-3} = -0.691 µg m^{-3}; RT = 1.221 µg m^{-3}

Manchester University Partisol versus Manchester University Fidas 73d03
Wcm = 9.11 % P; RCDW = 7.47 µg m^{-3} / 7.6 µg m^{-3} / 0.13 µg m^{-3} / 3.43%; n = 357
b = 1.025 +/- 0.014 NS ; a = -0.055 +/- 0.128 µg m^{-3} NS; Bias at 30 µg m^{-3} = 0.681 µg m^{-3}; RT = 1.184 µg m^{-3}

Figure B.22 Equivalence calculations for multiple Fidas algorithms at Barnstaple A39



1 **Barnstaple Digitel versus Barnstaple Fidas 11/1.06**
Wcm = 15.96 % P; RCDW = 5.82 µg m^{-3} / 6.47 µg m^{-3} / 0.65 µg m^{-3} / 22.46%; n = 411
b = 1.025 +/- 0.03 NS ; a = 0.506 +/- 0.201 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.265 µg m^{-3}; RT = 2.033 µg m^{-3}

2 **Barnstaple Digitel versus Barnstaple Fidas 11d04**
Wcm = 21.94 % P; RCDW = 5.82 µg m^{-3} / 6.74 µg m^{-3} / 0.93 µg m^{-3} / 31.86%; n = 411
b = 1.066 +/- 0.031 S; a = 0.541 +/- 0.207 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.529 µg m^{-3}; RT = 2.106 µg m^{-3}

3 **Barnstaple Digitel versus Barnstaple Fidas 206**
Wcm = 16.7 % P; RCDW = 5.82 µg m^{-3} / 6.3 µg m^{-3} / 0.49 µg m^{-3} / 16.75%; n = 411
b = 1.037 +/- 0.031 NS ; a = 0.273 +/- 0.206 µg m^{-3} NS; Bias at 30 µg m^{-3} = 1.378 µg m^{-3}; RT = 2.091 µg m^{-3}

4 **Barnstaple Digitel versus Barnstaple Fidas 215**
Wcm = 28.96 % F; RCDW = 5.82 µg m^{-3} / 6.92 µg m^{-3} / 1.1 µg m^{-3} / 37.82%; n = 411
b = 1.11 +/- 0.032 S; a = 0.462 +/- 0.214 µg m^{-3} S; Bias at 30 µg m^{-3} = 3.751 µg m^{-3}; RT = 2.19 µg m^{-3}

5 **Barnstaple Digitel versus Barnstaple Fidas 223**
Wcm = 36.9 % P; RCDW = 5.82 µg m^{-3} / 7.49 µg m^{-3} / 1.67 µg m^{-3} / 57.46%; n = 411
b = 1.133 +/- 0.036 S; a = 0.896 +/- 0.243 µg m^{-3} S; Bias at 30 µg m^{-3} = 4.896 µg m^{-3}; RT = 2.581 µg m^{-3}

6 **Barnstaple Digitel versus Barnstaple Fidas 225**
Wcm = 12.5 % P; RCDW = 5.82 µg m^{-3} / 6.71 µg m^{-3} / 0.89 µg m^{-3} / 30.52%; n = 411
b = 0.971 +/- 0.028 NS ; a = 1.056 +/- 0.188 µg m^{-3} S; Bias at 30 µg m^{-3} = 0.189 µg m^{-3}; RT = 1.865 µg m^{-3}

7 **Barnstaple Digitel versus Barnstaple Fidas 227**
Wcm = 16.81 % P; RCDW = 5.82 µg m^{-3} / 6.68 µg m^{-3} / 0.86 µg m^{-3} / 29.54%; n = 411
b = 1.026 +/- 0.03 NS ; a = 0.708 +/- 0.202 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.489 µg m^{-3}; RT = 2.035 µg m^{-3}

8 **Barnstaple Digitel versus Barnstaple Fidas 228**
Wcm = 16.77 % P; RCDW = 5.82 µg m^{-3} / 6.47 µg m^{-3} / 0.65 µg m^{-3} / 22.46%; n = 411
b = 1.024 +/- 0.032 NS ; a = 0.514 +/- 0.214 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.232 µg m^{-3}; RT = 2.194 µg m^{-3}

9 **Barnstaple Digitel versus Barnstaple Fidas 231**
Wcm = 19.97 % P; RCDW = 5.82 µg m^{-3} / 7.05 µg m^{-3} / 1.23 µg m^{-3} / 42.43%; n = 411
b = 1.038 +/- 0.03 NS ; a = 1.01 +/- 0.204 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.164 µg m^{-3}; RT = 2.072 µg m^{-3}

10 **Barnstaple Digitel versus Barnstaple Fidas 43**
Wcm = 47.66 % F; RCDW = 5.82 µg m^{-3} / 7.82 µg m^{-3} / 2 µg m^{-3} / 68.69%; n = 411
b = 1.197 +/- 0.033 S; a = 0.85 +/- 0.222 µg m^{-3} S; Bias at 30 µg m^{-3} = 6.77 µg m^{-3}; RT = 2.296 µg m^{-3}

11 **Barnstaple Digitel versus Barnstaple Fidas 73**
Wcm = 15.77 % P; RCDW = 5.82 µg m^{-3} / 6.58 µg m^{-3} / 0.77 µg m^{-3} / 26.33%; n = 411
b = 1.02 +/- 0.03 NS ; a = 0.649 +/- 0.199 µg m^{-3} S; Bias at 30 µg m^{-3} = 1.251 µg m^{-3}; RT = 2.007 µg m^{-3}

12 **Barnstaple Digitel versus Barnstaple Fidas 73d03**
Wcm = 19.69 % P; RCDW = 5.82 µg m^{-3} / 6.77 µg m^{-3} / 0.95 µg m^{-3} / 32.69%; n = 411
b = 1.053 +/- 0.029 NS ; a = 0.641 +/- 0.193 µg m^{-3} S; Bias at 30 µg m^{-3} = 2.24 µg m^{-3}; RT = 1.925 µg m^{-3}

Figure B.23 Equivalence calculations for multiple Fidas algorithms at Birmingham A4540

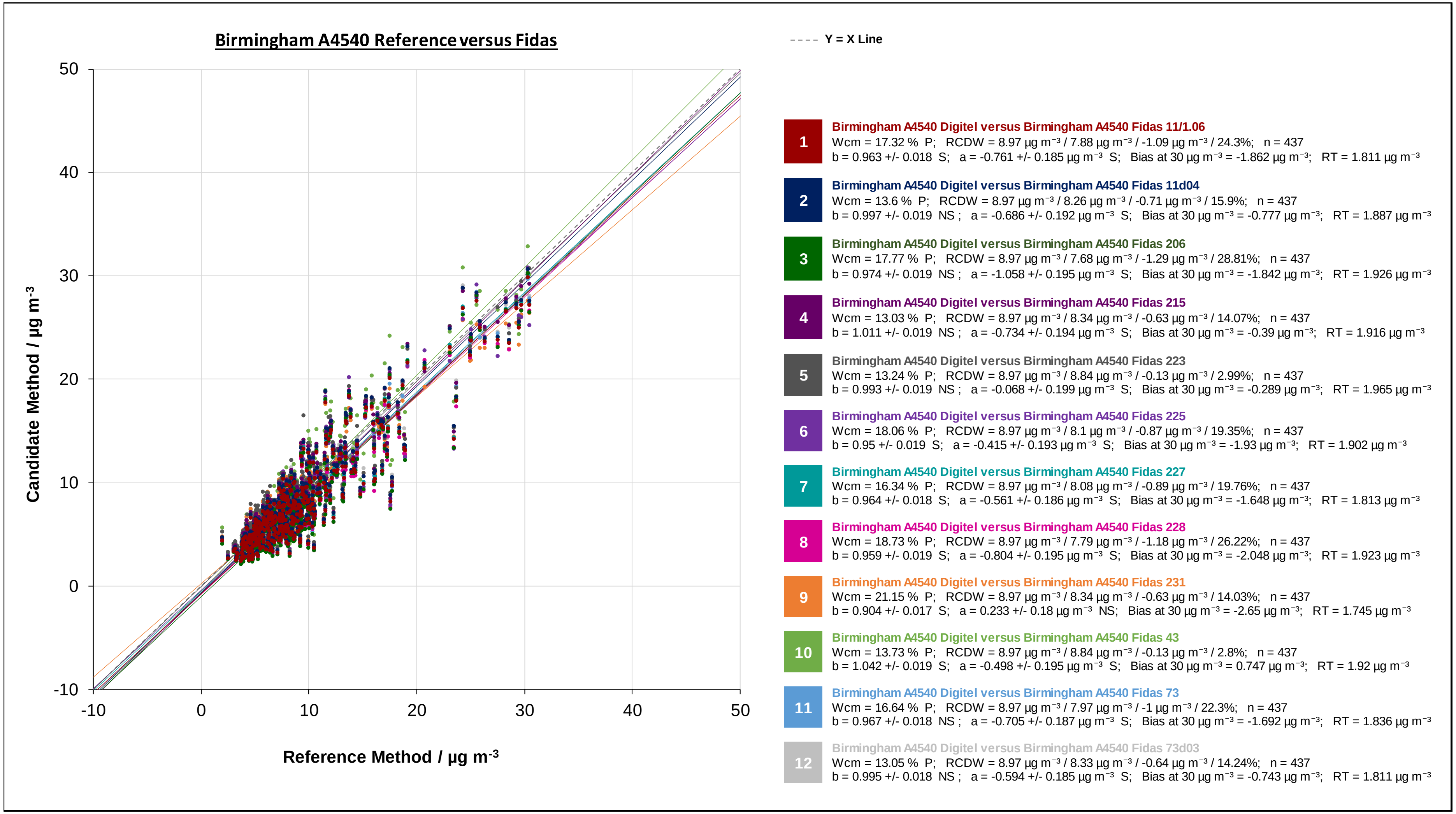
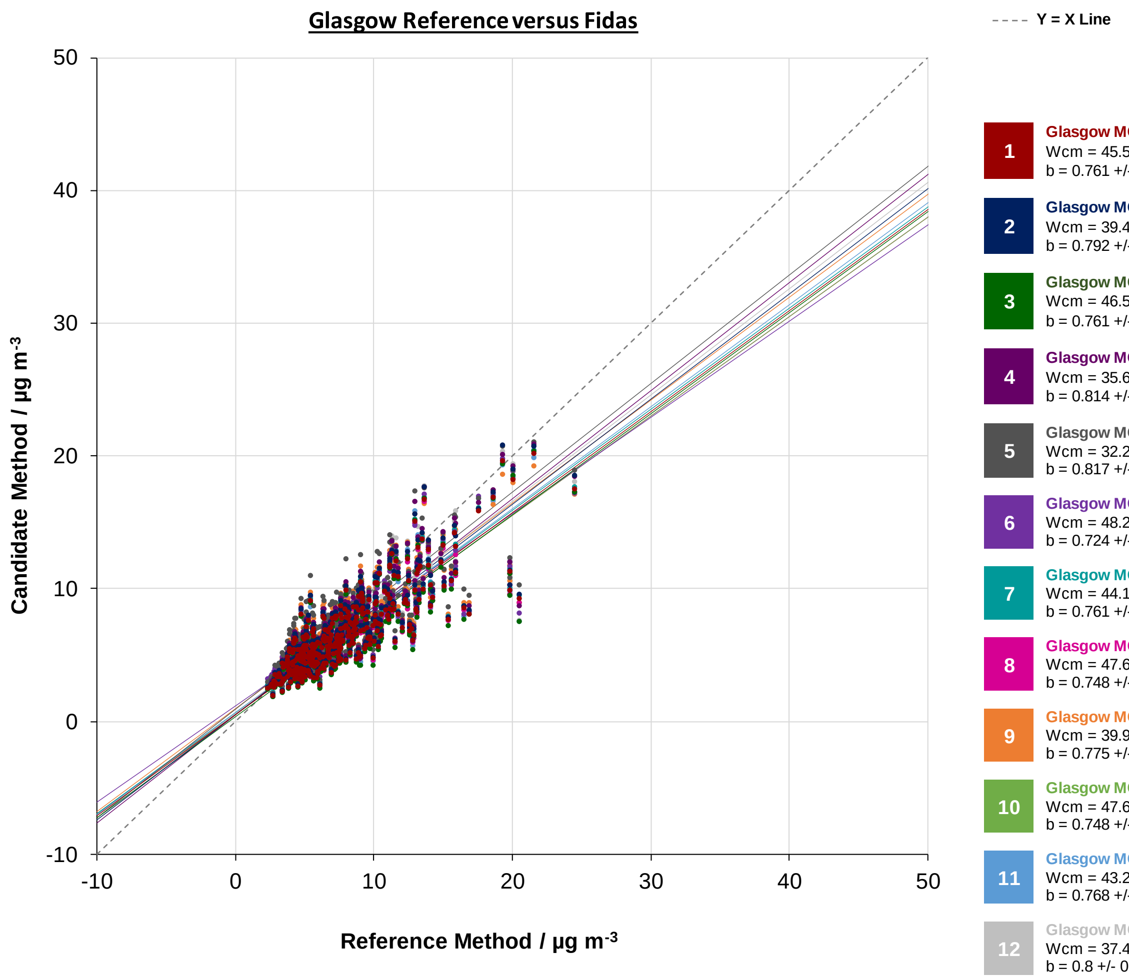


Figure B.24 Equivalence calculations for multiple Fidas algorithms at Glasgow



1 **Glasgow MCZ versus Glasgow Fidas 11/1.06**
Wcm = 45.55 % F; RCDW = 7.71 µg m^{-3} / 6.36 µg m^{-3} / -1.35 µg m^{-3} / 35.08%; n = 382
b = 0.761 +/- 0.022 S; a = 0.492 +/- 0.184 µg m^{-3} S; Bias at 30 µg m^{-3} = -6.686 µg m^{-3}; RT = 1.41 µg m^{-3}

2 **Glasgow MCZ versus Glasgow Fidas 11d04**
Wcm = 39.45 % F; RCDW = 7.71 µg m^{-3} / 6.63 µg m^{-3} / -1.08 µg m^{-3} / 28.14%; n = 382
b = 0.792 +/- 0.023 S; a = 0.52 +/- 0.193 µg m^{-3} S; Bias at 30 µg m^{-3} = -5.725 µg m^{-3}; RT = 1.494 µg m^{-3}

3 **Glasgow MCZ versus Glasgow Fidas 206**
Wcm = 46.54 % F; RCDW = 7.71 µg m^{-3} / 6.23 µg m^{-3} / -1.48 µg m^{-3} / 38.34%; n = 382
b = 0.761 +/- 0.023 S; a = 0.368 +/- 0.194 µg m^{-3} NS; Bias at 30 µg m^{-3} = -6.815 µg m^{-3}; RT = 1.512 µg m^{-3}

4 **Glasgow MCZ versus Glasgow Fidas 215**
Wcm = 35.68 % F; RCDW = 7.71 µg m^{-3} / 6.74 µg m^{-3} / -0.97 µg m^{-3} / 25.08%; n = 382
b = 0.814 +/- 0.024 S; a = 0.468 +/- 0.201 µg m^{-3} S; Bias at 30 µg m^{-3} = -5.116 µg m^{-3}; RT = 1.575 µg m^{-3}

5 **Glasgow MCZ versus Glasgow Fidas 223**
Wcm = 32.22 % P; RCDW = 7.71 µg m^{-3} / 7.25 µg m^{-3} / -0.46 µg m^{-3} / 12%; n = 382
b = 0.817 +/- 0.025 S; a = 0.945 +/- 0.212 µg m^{-3} S; Bias at 30 µg m^{-3} = -4.531 µg m^{-3}; RT = 1.682 µg m^{-3}

6 **Glasgow MCZ versus Glasgow Fidas 225**
Wcm = 48.29 % F; RCDW = 7.71 µg m^{-3} / 6.75 µg m^{-3} / -0.96 µg m^{-3} / 24.93%; n = 382
b = 0.724 +/- 0.021 S; a = 1.166 +/- 0.182 µg m^{-3} S; Bias at 30 µg m^{-3} = -7.109 µg m^{-3}; RT = 1.389 µg m^{-3}

7 **Glasgow MCZ versus Glasgow Fidas 227**
Wcm = 44.14 % F; RCDW = 7.71 µg m^{-3} / 6.56 µg m^{-3} / -1.15 µg m^{-3} / 29.73%; n = 382
b = 0.761 +/- 0.022 S; a = 0.695 +/- 0.184 µg m^{-3} S; Bias at 30 µg m^{-3} = -6.469 µg m^{-3}; RT = 1.41 µg m^{-3}

8 **Glasgow MCZ versus Glasgow Fidas 228**
Wcm = 47.66 % F; RCDW = 7.71 µg m^{-3} / 6.33 µg m^{-3} / -1.38 µg m^{-3} / 35.81%; n = 382
b = 0.748 +/- 0.022 S; a = 0.562 +/- 0.19 µg m^{-3} S; Bias at 30 µg m^{-3} = -6.995 µg m^{-3}; RT = 1.473 µg m^{-3}

9 **Glasgow MCZ versus Glasgow Fidas 231**
Wcm = 39.9 % F; RCDW = 7.71 µg m^{-3} / 6.94 µg m^{-3} / -0.77 µg m^{-3} / 20.09%; n = 382
b = 0.775 +/- 0.023 S; a = 0.963 +/- 0.192 µg m^{-3} S; Bias at 30 µg m^{-3} = -5.797 µg m^{-3}; RT = 1.487 µg m^{-3}

10 **Glasgow MCZ versus Glasgow Fidas 228**
Wcm = 47.66 % F; RCDW = 7.71 µg m^{-3} / 6.33 µg m^{-3} / -1.38 µg m^{-3} / 35.81%; n = 382
b = 0.748 +/- 0.022 S; a = 0.562 +/- 0.19 µg m^{-3} S; Bias at 30 µg m^{-3} = -6.995 µg m^{-3}; RT = 1.473 µg m^{-3}

11 **Glasgow MCZ versus Glasgow Fidas 73**
Wcm = 43.29 % F; RCDW = 7.71 µg m^{-3} / 6.56 µg m^{-3} / -1.15 µg m^{-3} / 29.71%; n = 382
b = 0.768 +/- 0.023 S; a = 0.644 +/- 0.193 µg m^{-3} S; Bias at 30 µg m^{-3} = -6.318 µg m^{-3}; RT = 1.496 µg m^{-3}

12 **Glasgow MCZ versus Glasgow Fidas 73d03**
Wcm = 37.48 % F; RCDW = 7.71 µg m^{-3} / 6.76 µg m^{-3} / -0.95 µg m^{-3} / 24.58%; n = 382
b = 0.8 +/- 0.023 S; a = 0.594 +/- 0.198 µg m^{-3} S; Bias at 30 µg m^{-3} = -5.405 µg m^{-3}; RT = 1.548 µg m^{-3}

Figure B.25 Equivalence calculations for multiple Fidas algorithms at London Marylebone

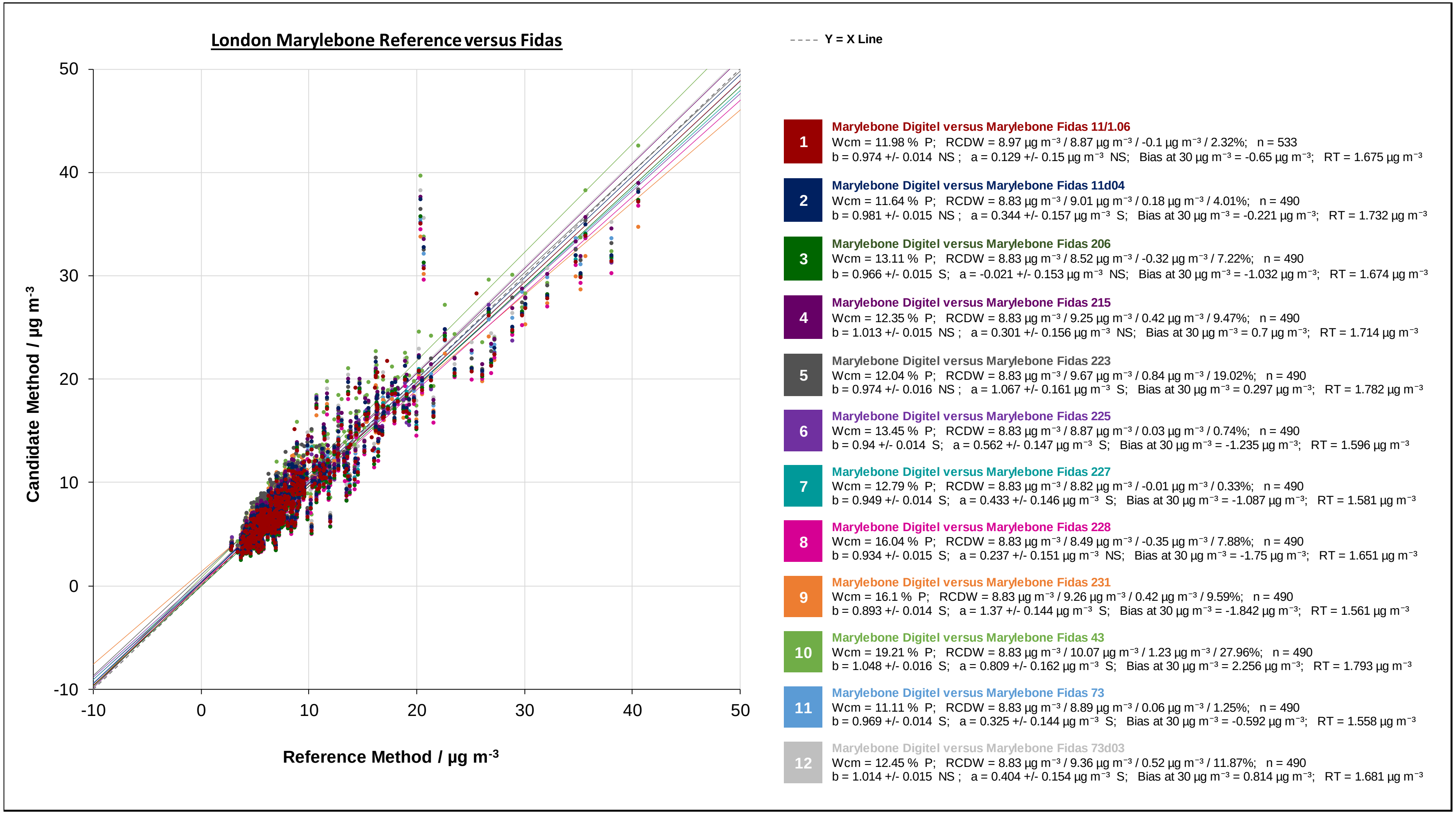
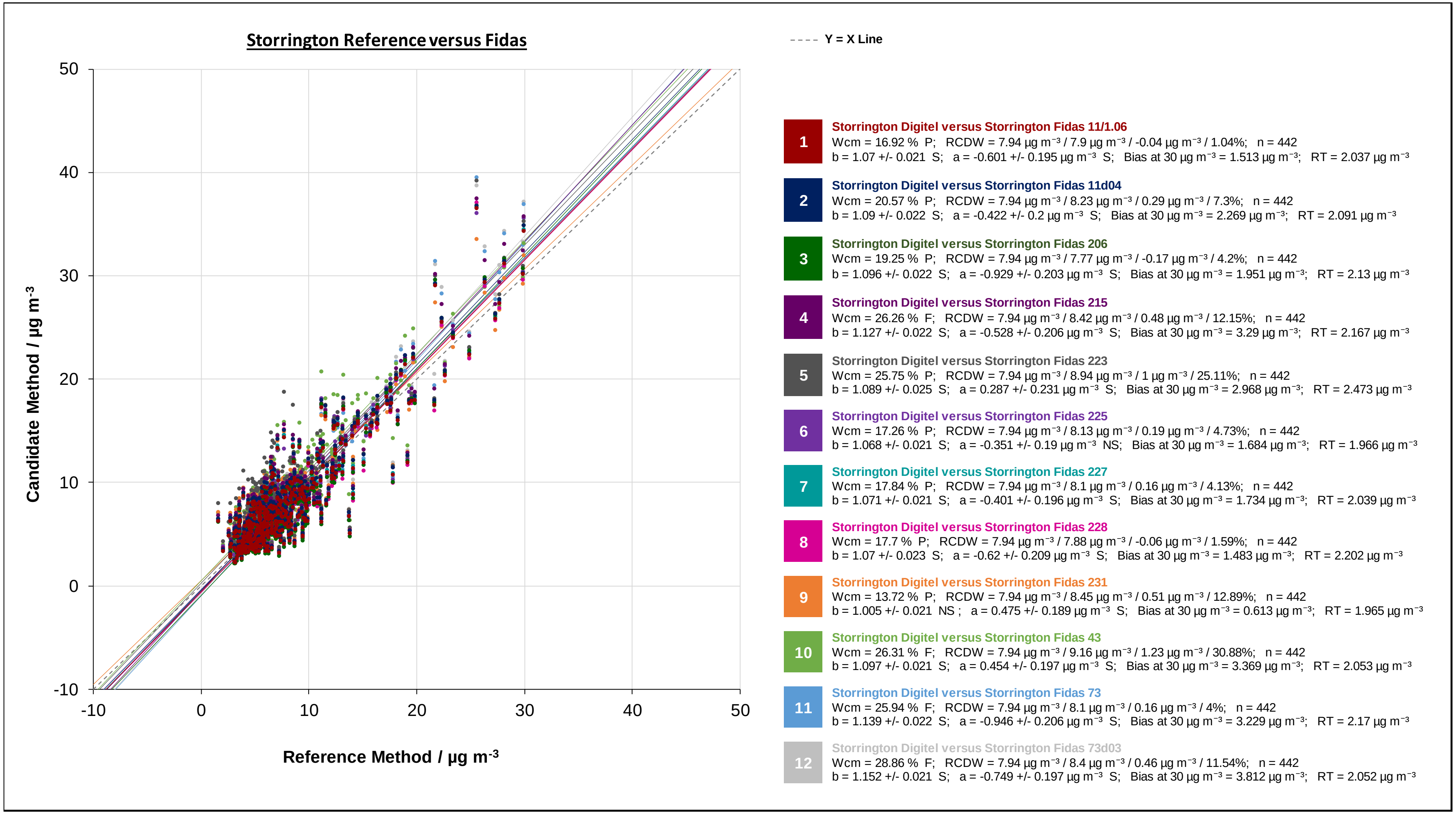


Figure B.26 Equivalence calculations for multiple Fidas algorithms at Storrington



APPENDIX C DELIVERABLE 4

Figure C.1 Time series of hourly HEPA zero data for Teddington (green), and Manchester (red)

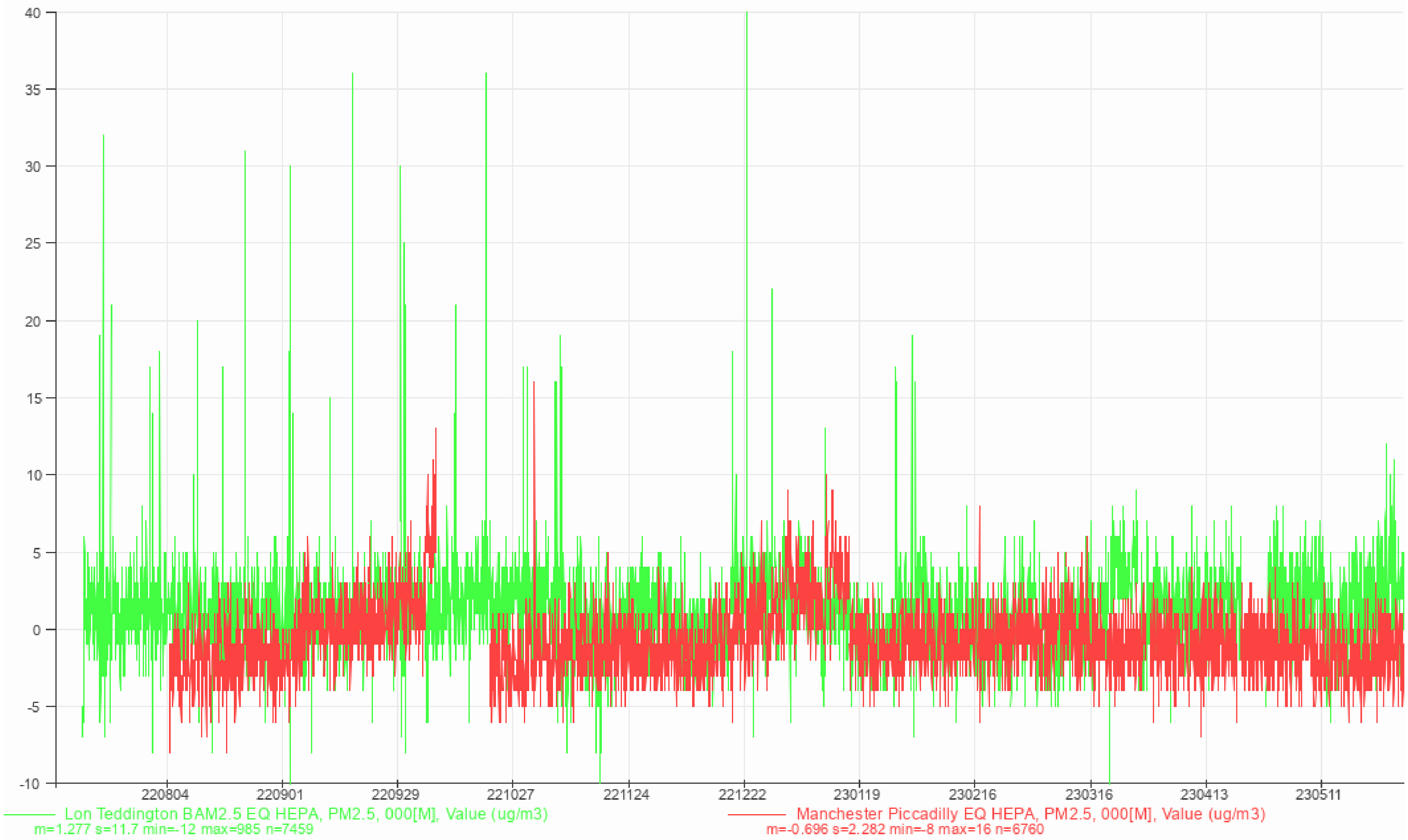


Figure C.2 Time series of 24-hour HEPA zero data for Teddington with Whatman (green), and Manchester with Sibata (red)

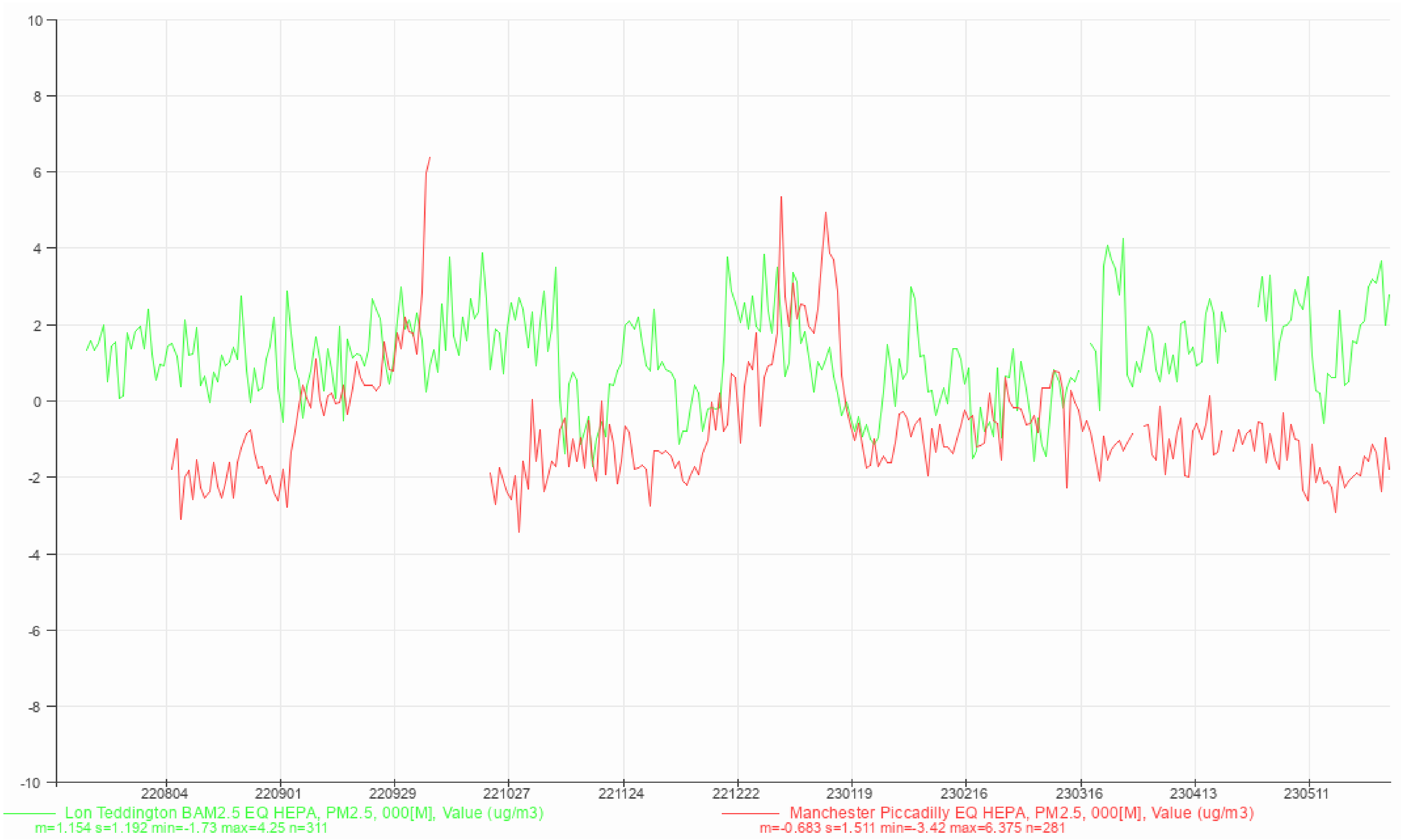


Figure C.3 Average HEPA zero concentration of FDMSs (Blue), BAMs with Sibata Tape (Orange), and BAMs with Whatman Tape (Green)

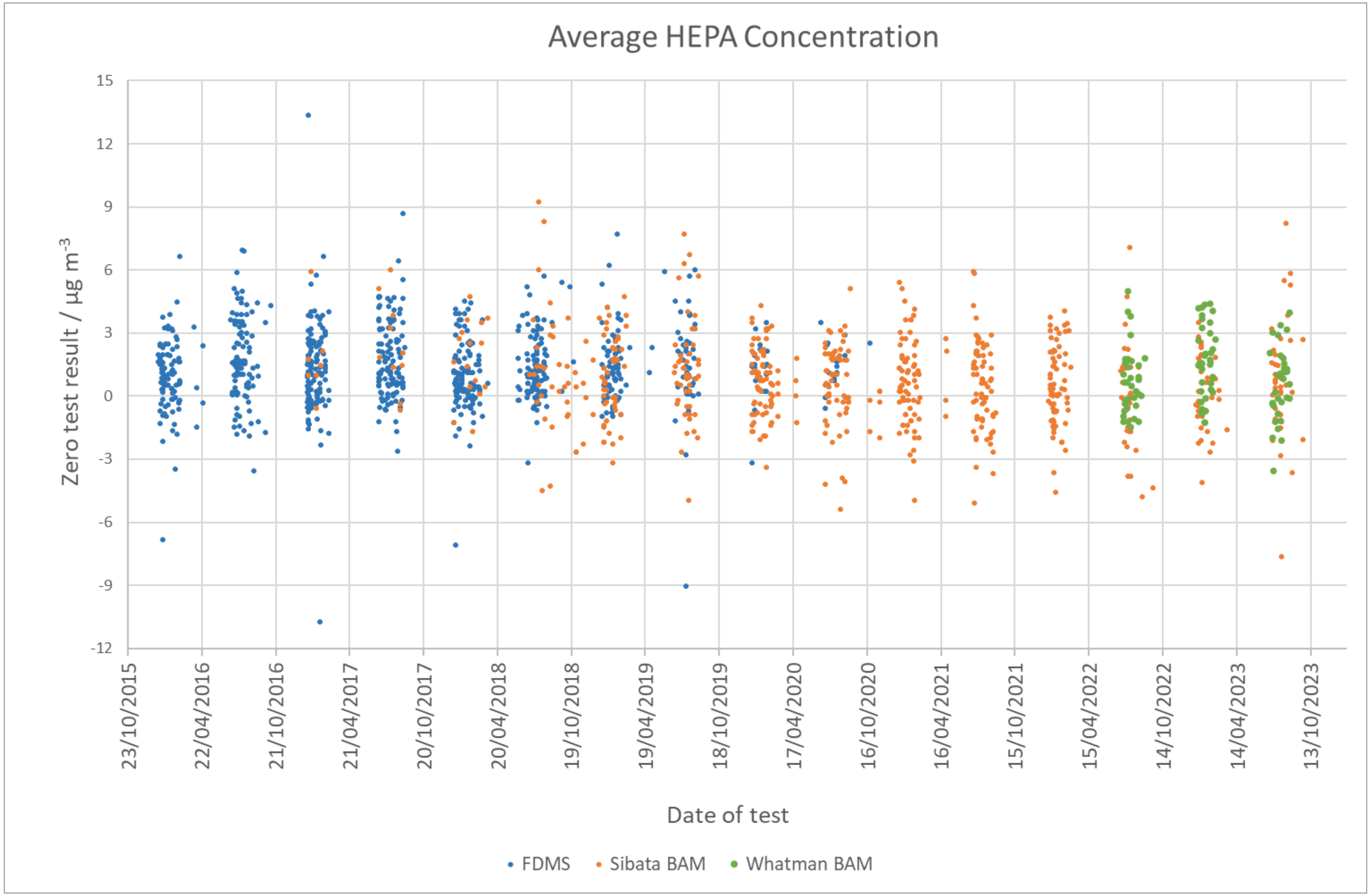


Figure C.4 Time series for those sites retaining Sibata filter tape across the last four audit rounds.

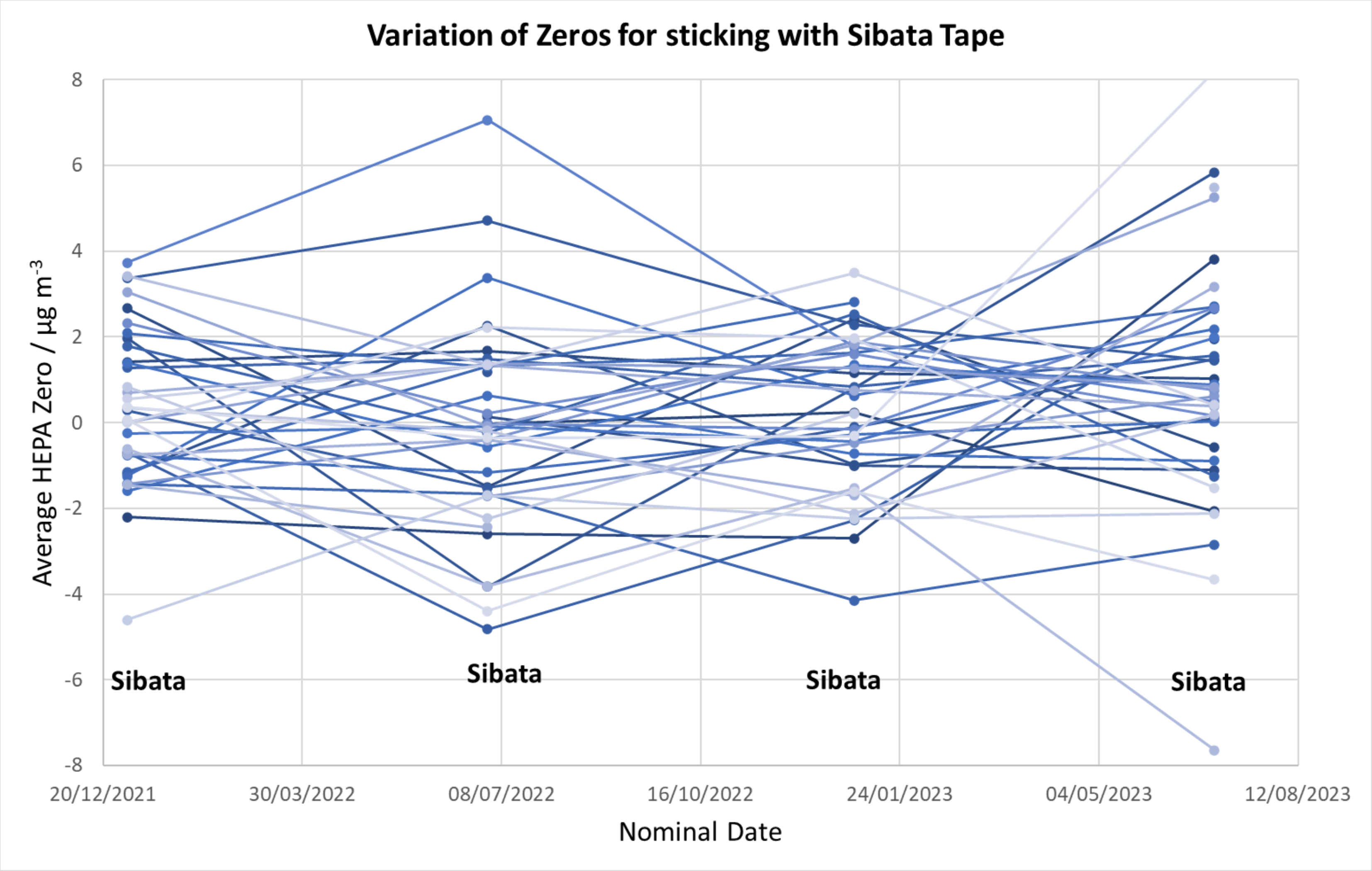


Figure C.5 Time series for those sites switching from Sibata filter tape to Whatman filter tape across the last four audit rounds.

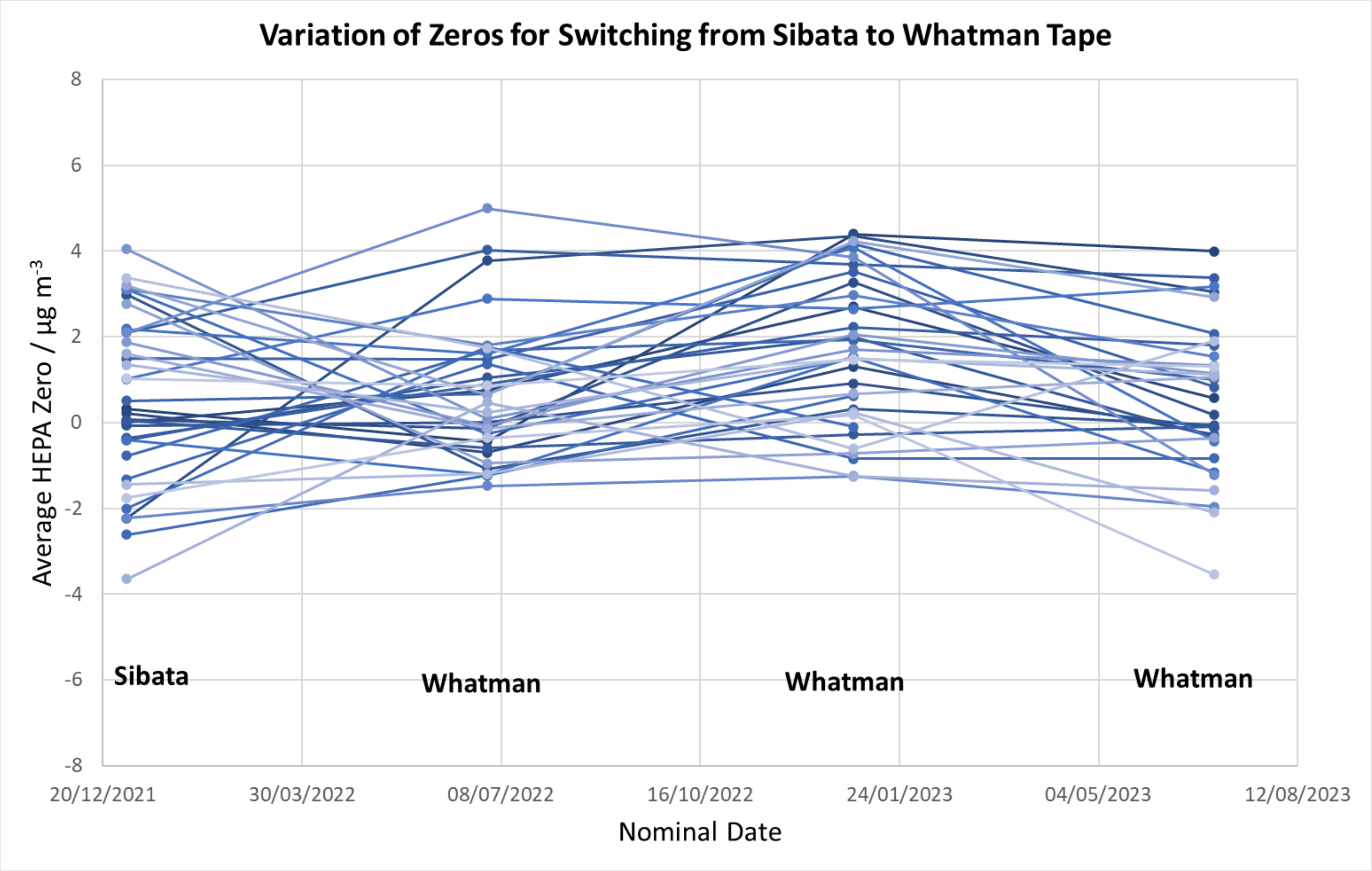
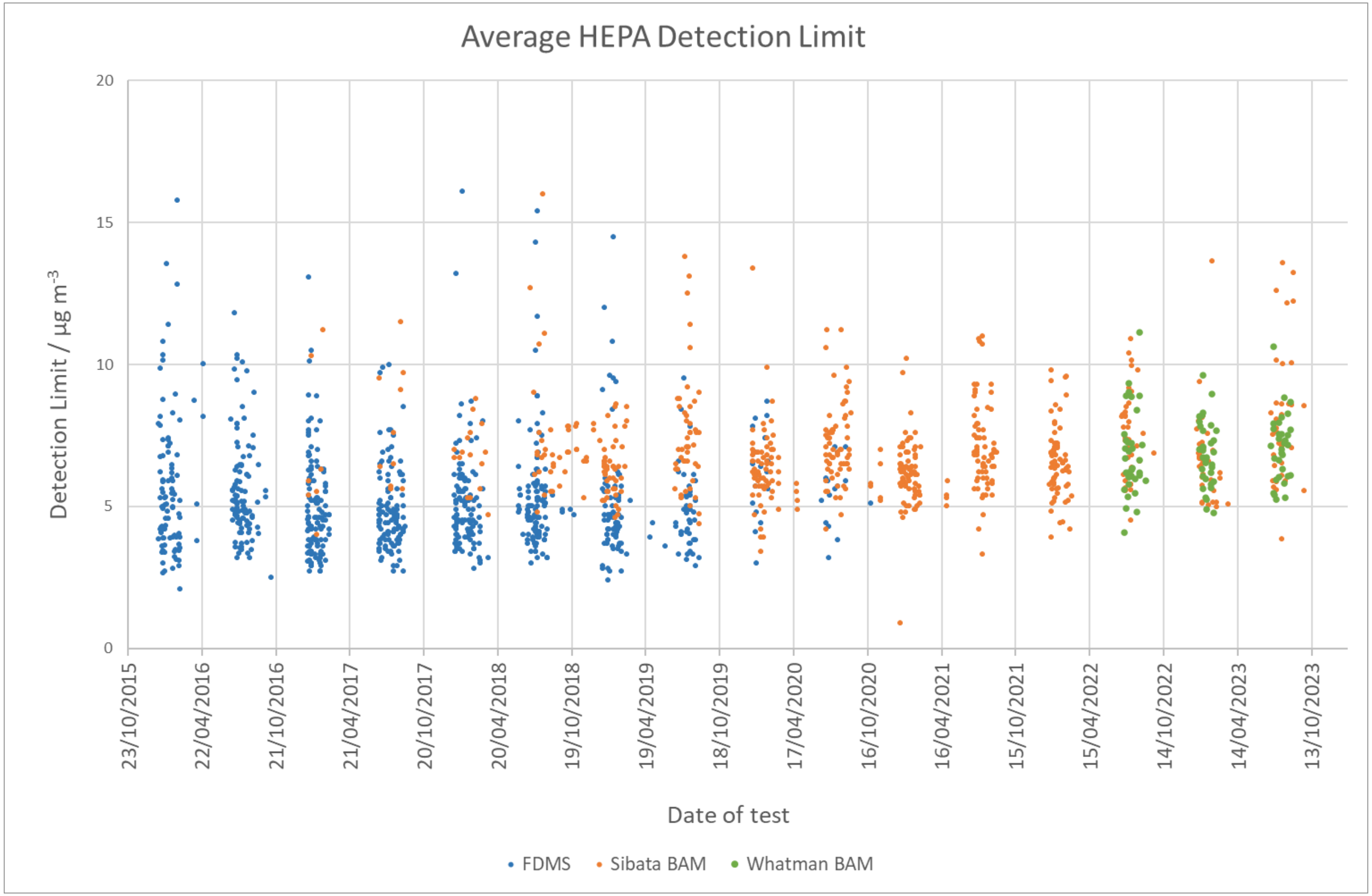


Figure C.6 Average hourly detection limit of FDMSs (Blue), BAMs with Sibata Tape (Orange), and BAMs with Whatman Tape (Green)



APPENDIX D: DELIVERABLE 14

Figure D.1 2021 Modelled layer, Ammonium Nitrate

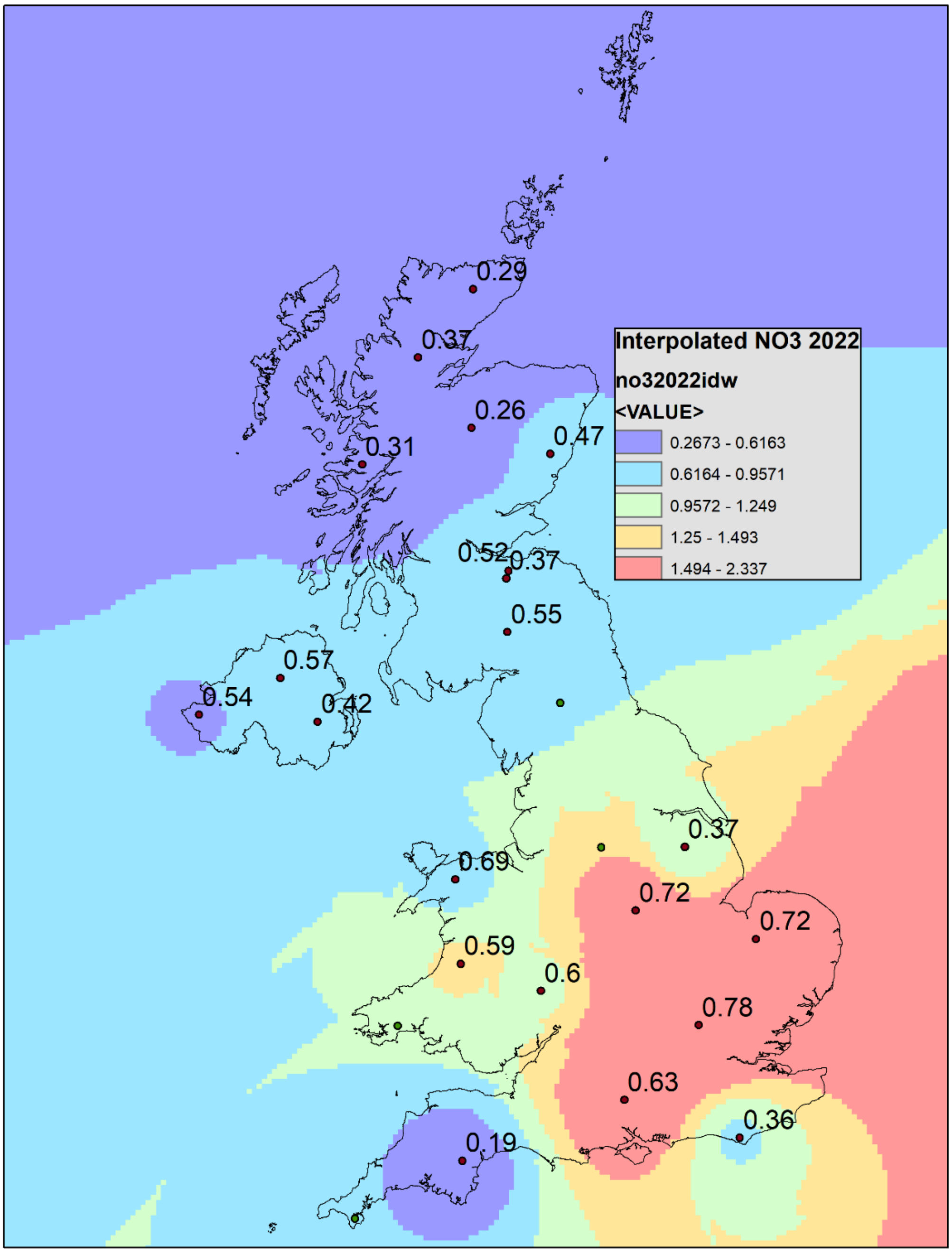
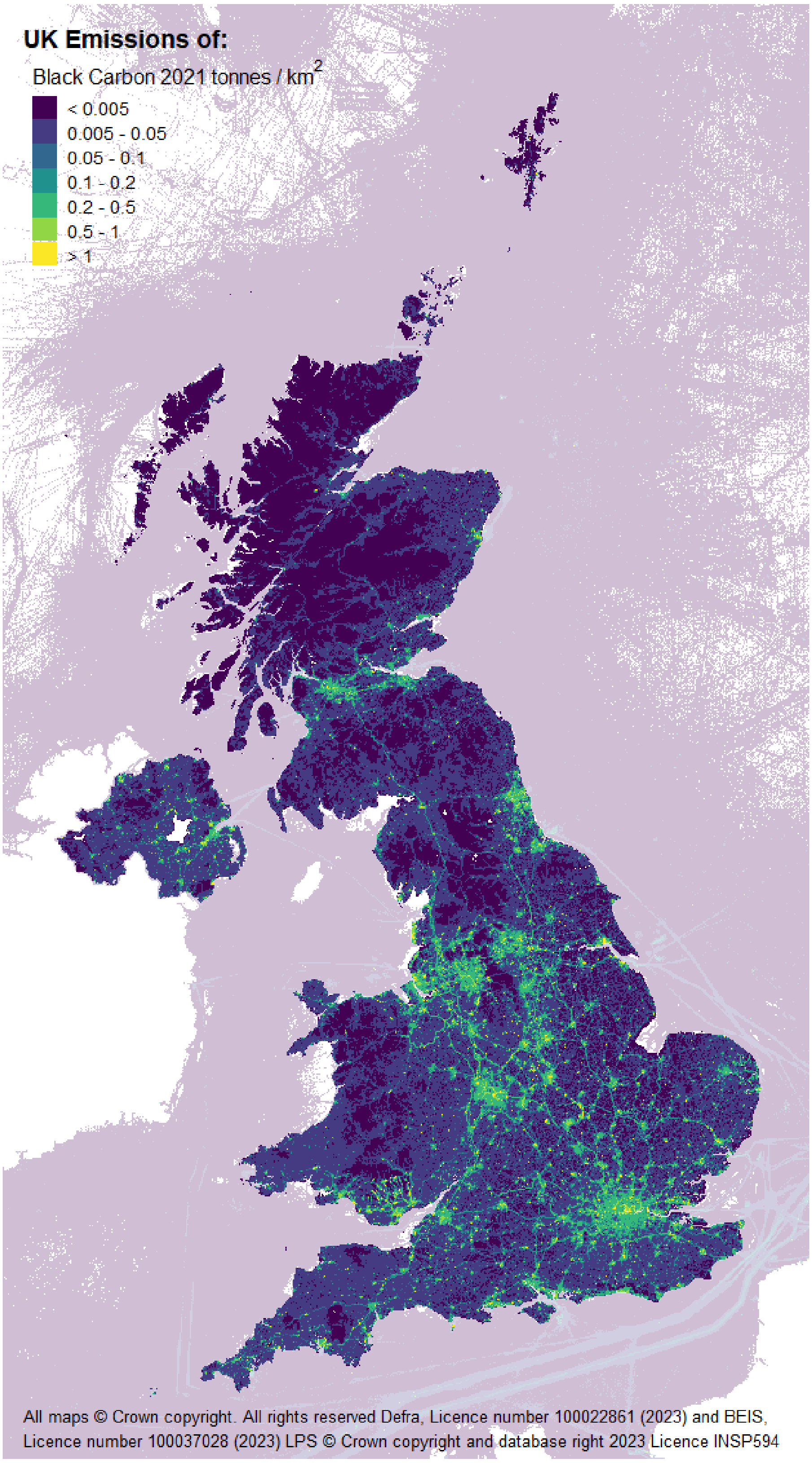


Figure D.2 UK emissions of Black Carbon for 2021[24]



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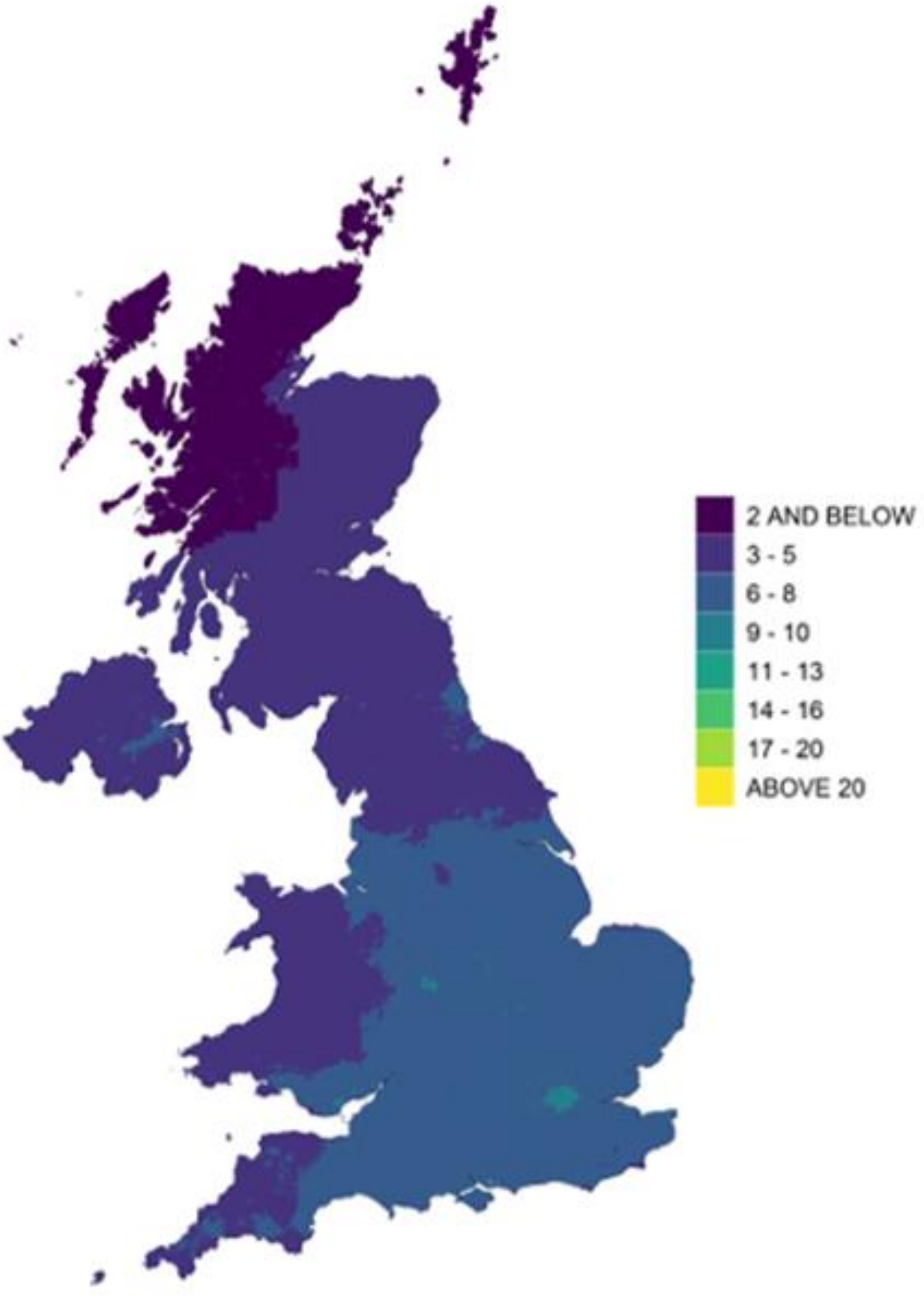
[24] https://naei.beis.gov.uk/data/map-uk-das

Figure D.3 Annual mean background $PM_{2.5}$ concentration, 2021 (µg m^{-3}, gravimetric)[25]



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[25] https://naei.beis.gov.uk/data/map-uk-das?pollutant_id=122&emiss_maps_submit=naei-20240315143851