Aeroqual Module Technical Performance Guide

aeroqual

Introduction Procedures

This document contains everything needed to evaluate the technical performance of Aeroqual's most popular modules, compatible with a range of air quality monitoring systems.

Each section contains a brief measurement principle, specifications and performance data, field test results including R^2 (where applicable), information on calibration and interferences, and the expected lifetime of module components.

If you would like to know more about any of these modules or anything contained in this document, please reach out to your Aeroqual representative.

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Nitrogen Dioxide (NO_2) Module

Nitrogen Dioxide (NO_2) is one of six criteria air pollutants identified by the United States Environmental Protection Agency (USEPA) and is monitored extensively around the world by regulatory agencies.

NO_2 can be emitted directly from industrial process and combustion. NO_2 can also be formed as a secondary pollutant by reaction of nitric oxide (NO) and ozone (O_3).

NO_2 module measurement principle

The NO_2 module used in Aeroqual's range of fixed monitors uses a cutting-edge automatic baseline correction (ABC) design to measure nitrogen dioxide (NO_2) in ambient air. It combines an advanced electrochemical NO_2 sensor with an integrated O_3 filter and a sample/zero cycling operation to deliver near reference performance in ambient NO_2 monitoring.

The sensor used in the NO_2 module is an electrochemical gas sensor. The sensor generates an electrical current in nA which is proportional to the concentration of gas that comes in to contact with the sensor.

The module uses a patented design that creates two different flow paths, one of which passes through a proprietary scrubber to remove NO_2 and produce a baseline measurement. The module has a controlled flow rate across the sensor. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 60 mL min^{-1}).

The sensor current is measured during both the baseline and sample measurement states and these values are used to calculate the NO_2 concentration using a proprietary algorithm approximately once per minute.

NO_2 module specifications and performance

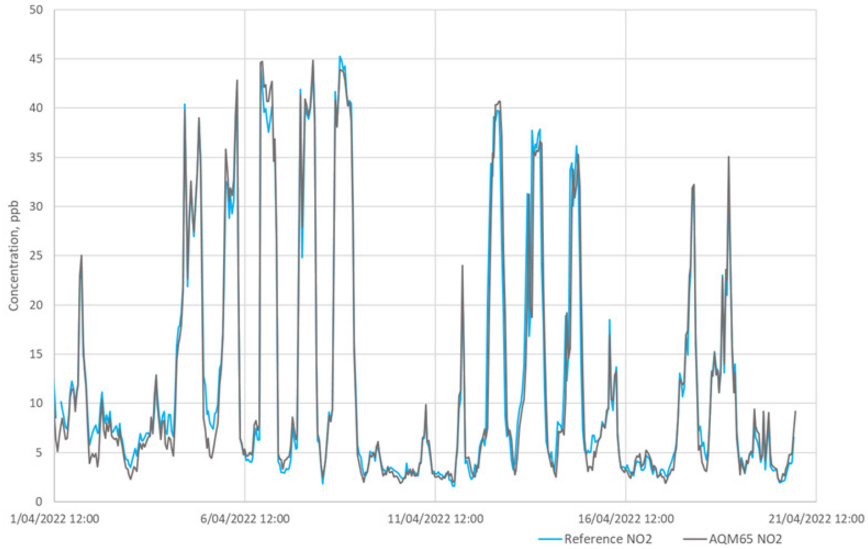
The NO_2 module performance specifications are given in this table.

Range (ppb)	Display Resolution (ppb)	Noise Zero (ppb) Span (% of reading)	Limit of Detection (ppb)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppb) Span (% of FS)
0 - 500	0.1	<1 1%	<1	2% of reading or 2 ppb	1.5%	1 0.2%

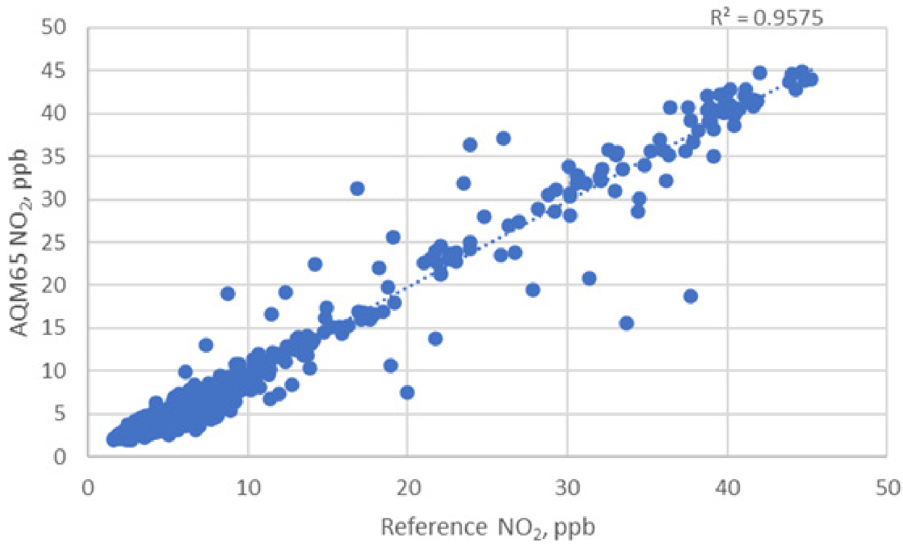
NO_2 Field Test Results

An Aeroqual AQM65 containing an NO_2 module was co-located in April 2022 at an air quality regulatory station in Riverside, Southern California and its data compared with the reference data downloaded from the USEPA AirNow website. The NO_2 module produced an R^2 of 0.96 and a mean absolute error (MAE) of 1.3 ppb. The low MAE value is indicative that the module has low zero and span drift.

Time series plot



Scatter plot of data with linear regression and coefficient of determination (R^2)



The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 100 ppb, was calculated as 5.8%. Note that an expanded relative uncertainty of less than 15% is required for an NO_2 monitor to be considered regulatory grade (Directive 2008/50/EC). The NO_2 module meets this requirement.

1 Directive 2008/50/EC downloaded 10/02/2023 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0050&from=en

Expanded relative uncertainty calculated for the Aeroqual NO_2 module based on the “Guide to the Demonstration of Equivalence” method and spreadsheet.

Uncertainty of calibration	0.98	ppb
Uncertainty of calibration (forced)	0.67	ppb
Random term	2.25	ppb
Additional uncertainty (optional)	0.00	ppb
Bias at LV	1.80	ppb
Combined uncertainty	2.88	ppb
Expanded relative uncertainty	**5.8%**	**pass**
Ref sampler uncertainty	1.00	ppb
Limit value	100	ppb

NO_2 module calibration and traceability

Just like a regulatory NO_2 analyzer based on chemiluminescence, this sensor-based system can be fully field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The NO_2 module factory calibration is achieved using a zero-air source, certified calibration gas standards and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the NO_2 module in the field.

Calibration frequency will be dependent on the user’s data quality objectives and Quality Assurance Project Plan (QAPP), but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

Aeroqual also offers its patented remote calibration procedure, MOMA, for this module, which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Interferences

The Aeroqual NO_2 module is specific towards NO_2 but other gases in the environment may also cause a response from the NO_2 sensor. These do not indicate a fault. These effects are part of the module behaviour and should be considered when examining data.

The NO_2 module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
O_3	0.1	0.001
CO	1.0	-0.005
SO_2	0.1	-0.003
H_2S	0.1	-0.020
Ethylene	0.5	0.005

NO_2 module expected lifetime

The non-catalytic chemical scrubber has an expected life of 2 to 3 years. The internal solenoid has an expected life of 2 to 3 years. The GSE sensor has an expected life of 2 years in climates with moderate humidity. In climates with very high humidity the expected life may be reduced.

Carbon Monoxide (CO) Module

Carbon monoxide (CO) is one of six criteria air pollutants identified by the USEPA and is monitored extensively around the world by regulatory agencies.

Carbon monoxide is a by-product of combustion; it is emitted from industrial processes and from vehicle exhaust.

CO module measurement principle

The sensor used in the CO module is an electrochemical sensor. The sensor generates an electrical current in nA which is proportional to the concentration of gas that comes in to contact with the sensor. The sensor current is converted to a voltage and the voltage is measured and used to calculate the CO concentration using a proprietary algorithm approximately once per minute.

The module has a single flow state across the sensor. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 150 mL min^{-1}).

CO module specifications and performance

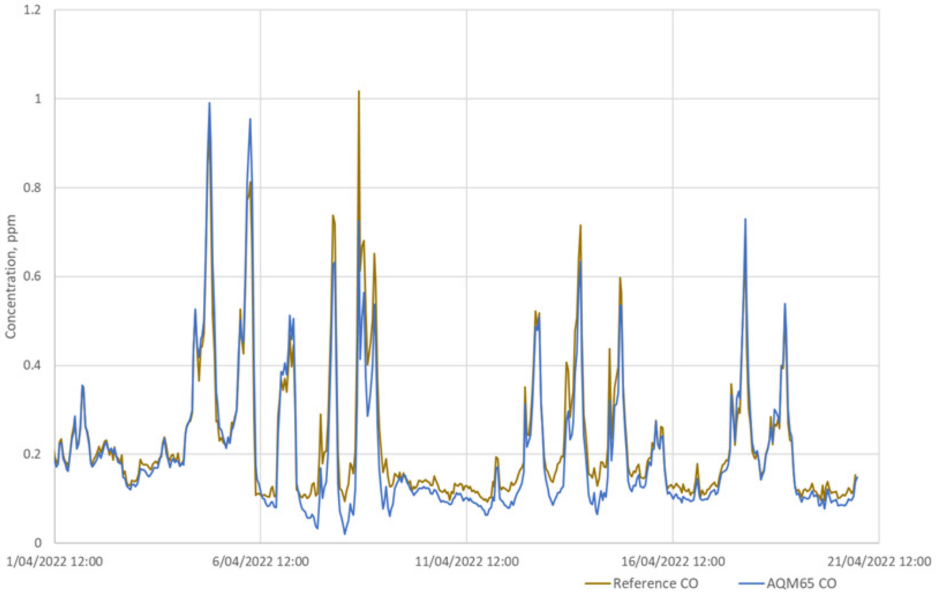
The CO module performance specifications are given in the table below.

Range (ppm)	Display Resolution (ppm)	Noise Zero (ppm) Span (% of reading)	Limit of Detection (ppm)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppm) Span (% of FS)
0 - 25	0.001	0.02 1%	0.04	3% of reading or 0.05 ppm	1%	0.14 2%

CO Field Test Results

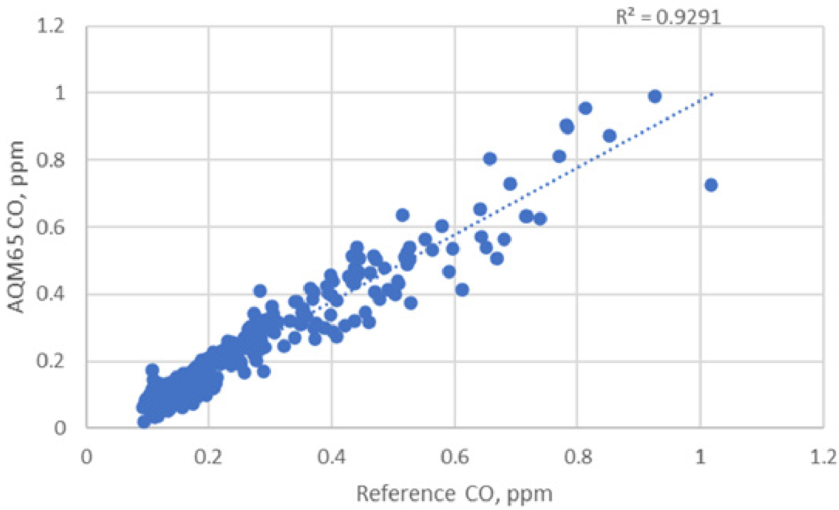
An Aeroqual AQM65 containing a CO module was co-located in April 2022 at an air quality regulatory station in Riverside, Southern California and its data compared with the reference data downloaded from the USEPA AirNow website. The CO module produced a R^2 of 0.93 and a mean absolute error (MAE) of 0.03 ppm. The low MAE value is indicative that the module has low zero and span drift.

Time series plot



Scatter plot of data with linear regression and coefficient of determination (R^2)

The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 9 ppm, was calculated as 7.1%. Note that an expanded relative uncertainty of less than 15% is required for a CO monitor to be considered regulatory grade. The CO module meets this requirement.



Expanded relative uncertainty calculated for the Aeroqual CO module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet.

Uncertainty of calibration	0.11	ppm
Uncertainty of calibration (forced)	0.06	ppm
Random term	0.00	ppm
Additional uncertainty (optional)	0.00	ppm
Bias at LV	0.32	ppm
Combined uncertainty	0.32	ppm
Expanded relative uncertainty	**7.1%**	**pass**
Ref sampler uncertainty	0.05	ppm
Limit value	9	ppm

CO module calibration and traceability

Just like a regulatory CO analyzer using NDIR gas filter correlation, the CO module can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The CO module factory calibration is achieved using a zero-air source, certified calibration gas standards and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the CO module in the field.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

Aeroqual also offers its patented remote calibration procedure MOMA for this module which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Interferences

The Aeroqual CO module is specific towards CO but other gases in the environment may also cause a response from the CO sensor. These do not indicate a fault. These effects are part of the module behaviour and should be considered when examining data.

The CO module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
O_3	0.1	No response
NO_2	0.1	No response
SO_2	0.1	No response
H_2S	0.1	No response
Ethylene	0.5	<0.1

CO module expected lifetime

The GSE sensor has an expected life of 2 years in climates with moderate humidity. In climates with very high humidity the expected life may be reduced.

Ozone (O_3) Module

Ozone (O_3) is one of six criteria air pollutants identified by the USEPA and is monitored extensively around the world by regulatory agencies.

O_3 is formed naturally in the stratosphere by the reaction of oxygen (O_2) and UV light. O_3 in the stratosphere absorbs harmful deep UV light and protects the biosphere on the ground.

O_3 can also be formed at ground level by a complex reaction between UV light, NOx, and volatile organic compounds (VOCs), which come from anthropogenic sources such as vehicles and industrial emissions. O_3 at ground level is harmful to vegetation and humans which is why it is monitored.

O_3 module measurement principle

The sensor used in the O_3 module is a Gas Sensitive Semiconductor (GSS) sensor manufactured by Aeroqual. The sensing material is an n-type semiconductor whose resistance increases when exposed to oxidizing gases such as O_3. Selectivity towards O_3 is achieved by careful control of the sensor material and operating temperature.

The module uses a patented design that creates two different flow states across the sensor: a zero-flow state and a measurement state. The sensor resistance is measured during both the zero and measurement states, and these values are used to calculate the O_3 concentration using a proprietary algorithm approximately once per minute. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 130 mL min^{-1}).

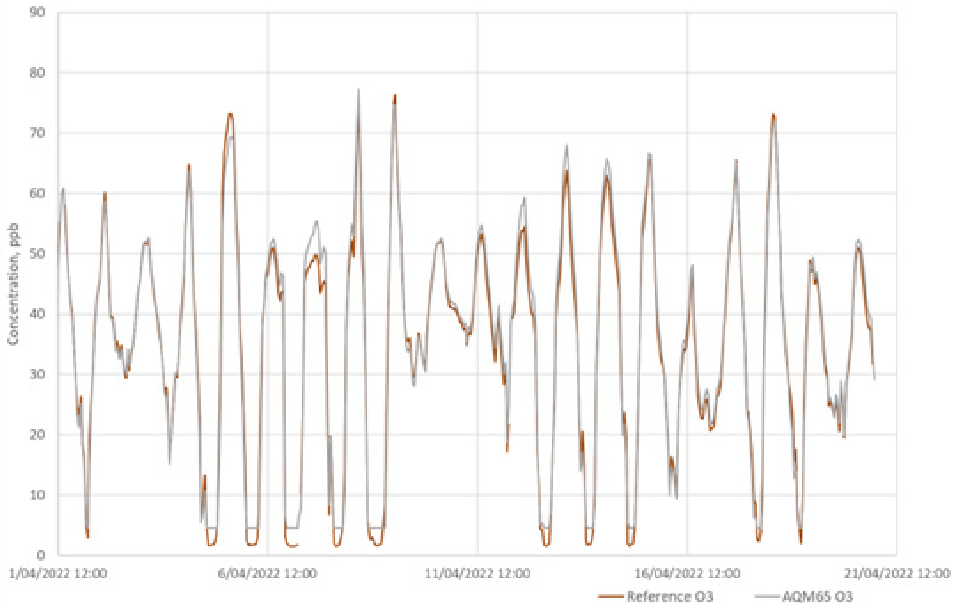
O_3 module specifications and performance

The O_3 module performance specifications are given in the table below.

Range (ppb)	Display Resolution (ppb)	Noise Zero (ppb) Span (% of reading)	Limit of Detection (ppb)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppb) Span (% of FS)
0 - 500	0.1	<1 1%	<1	2% of reading or 2 ppb	1%	1 0.2%

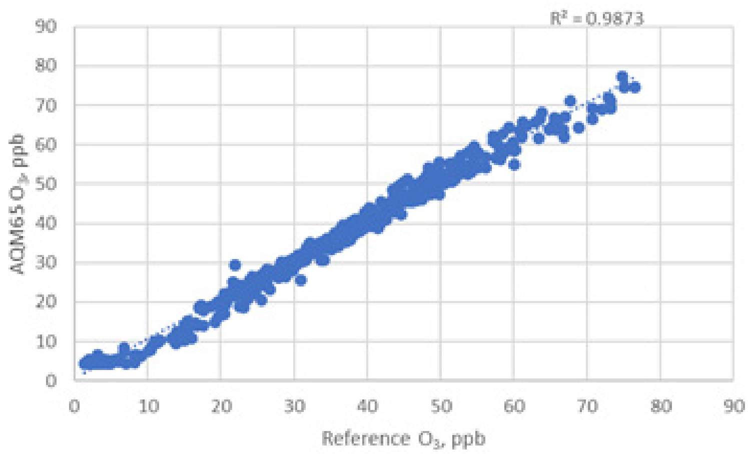
O_3 Field Test Results

An Aeroqual AQM65 containing an O_3 module was co-located in April 2022 at an air quality regulatory station in Riverside, Southern California and its data compared with reference data downloaded from the USEPA AirNow website. The O_3 module produced an R^2 of 0.99 and a mean absolute error (MAE) of 2.1 ppb. The low MAE value is indicative that the module has low zero and span drift.



Scatter plot of data with linear regression and coefficient of determination (R^2)

The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 75 ppb, was calculated as 5.8%. Note that an expanded relative uncertainty of less than 15% is required for an O_3 monitor to be considered regulatory grade. The O_3 module meets this requirement.



Expanded relative uncertainty calculated for the Aeroqual O_3 module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet.

Uncertainty of calibration	0.44	ppb
Uncertainty of calibration (forced)	0.18	ppb
Random term	1.97	ppb
Additional uncertainty (optional)	0.00	ppb
Bias at LV	0.91	ppb
Combined uncertainty	2.17	ppb
Expanded relative uncertainty	**5.8%**	**pass**
Ref sampler uncertainty	0.67	ppb
Limit value	75	ppb

O_3 module calibration and traceability

Just like a regulatory O_3 analyzer using UV absorption, the O_3 module can be field calibrated using standard calibration equipment. This ensures the module calibration is fully traceable to NIST primary standards.

O_3 is not available in a gas cylinder due to its reactivity. The O_3 module span calibration is achieved using a reference grade O_3 source such as the 306 O_3 calibrator from 2B Technologies. The module is zero calibrated using a zero-air source such as the AirCal 1000 or AirCal 8000. The zero calibration step of the O_3 module calibration takes approximately 15 minutes and the span calibration takes between 15 and 30 minutes.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

Aeroqual can also offer its patented remote calibration procedure MOMA for this module which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Interferences

The Aeroqual O_3 module is very specific towards O_3, but other gases in the environment may also cause a response from the O_3 sensor. These do not indicate a fault. These effects are part of the module behaviour and should be considered when examining data.

The O_3 module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
CO	1.0	No response
NO_2	0.1	0.001
SO_2	0.1	No response
H_2S	0.1	-0.02
Ethylene	0.5	-0.005

O_3 module expected lifetime

The module contains a solenoid, which can fail occasionally. The lifetime of the solenoid is typically 2 to 3 years.

The GSS sensor does not contain materials which are consumed during its lifetime and O_3 modules have been observed to provide high quality readings in AQM65s running continuously for up to 4 years in moderately polluted sites with regular instrument servicing. At sites with high pollutant levels and low service levels the lifetime can be reduced to as little as 1 year. Continuous high humidity conditions can also reduce the lifetime.

On average the lifetime of the O_3 module is between 2 and 3 years.

Sulfur Dioxide (SO_2) Module

Sulfur Dioxide (SO_2) is one of six criteria air pollutants identified by the USEPA and is monitored extensively around the world by regulatory agencies.

SO_2 is emitted directly from industrial processes and is also directly emitted by vehicles, especially if fuel quality is poor.

SO_2 module measurement principle

The SO_2 module uses a patented automatic baseline correction (ABC) design to measure SO_2 in ambient air. It combines an advanced electrochemical SO_2 sensor and a sample/zero cycling operation to deliver near reference performance in ambient SO_2 monitoring.

The sensor used in the SO_2 module is an electrochemical gas sensor. The sensor generates an electrical current in nA which is proportional to the concentration of gas which comes in to contact with the sensor.

The module design creates two different flow paths, one of which passes through a proprietary scrubber to remove SO_2 to produce a baseline measurement.

The module has a controlled flow rate. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 60 mL min^{-1}).

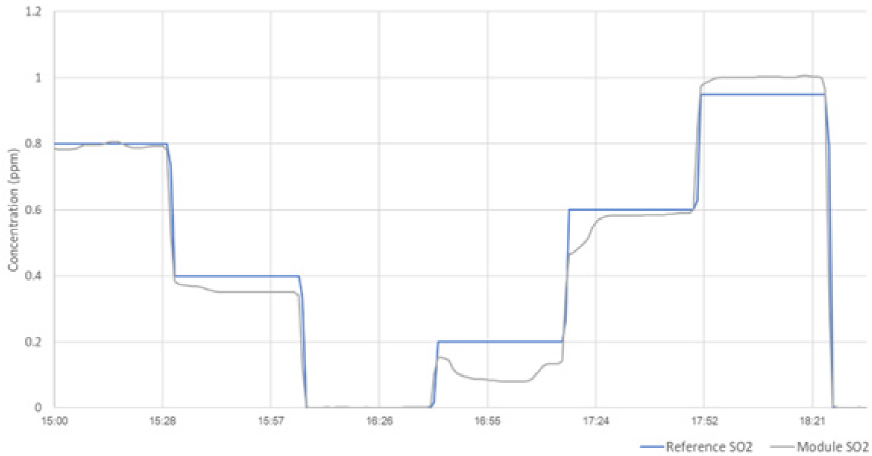
The sensor current is measured during both the baseline and sample measurement states and these values are used to calculate the SO_2 concentration using a proprietary algorithm approximately once per minute.

SO_2 module specifications and performance

The SO_2 module performance specifications are given in the table below.

Range (ppb)	Resolution (ppb)	Noise Zero (ppb) Span (% of reading)	Limit of Detection (ppb)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppb) Span (% of FS)
0-10,000	0.1	1; 0.02%	2	0.14% of reading	0.6%	1; 0.3%

SO_2 module calibration and traceability

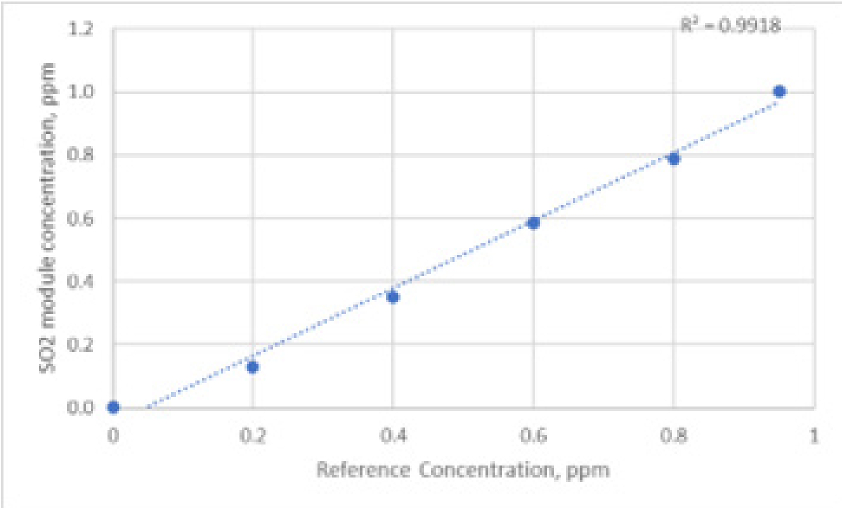


Just like a regulatory SO_2 analyzer using UV fluorescence, the SO_2 module can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The SO_2 module factory calibration is achieved using a zero-air source, certified calibration gas standards and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the SO_2 module in the field.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

To demonstrate performance, a six-point gas test, at known SO_2 concentrations, was carried out using the equipment described above. The module shows good linearly (R^2 = 0.99) over the 0 – 1000 ppb range studied.



Interferences

The Aeroqual SO_2 module is specific towards SO_2 but other gases in the environment may also cause a response from the SO_2 sensor. These do not indicate a fault. These effects are part of the module behaviour and should be considered when examining data.

The SO_2 module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
CO	1.0	0.005
NO_2	0.1	-0.001
O_3	0.1	-0.001
H_2S	0.1	0.02
Ethylene	0.5	No response

SO_2 module expected lifetime

The non-catalytic chemical scrubber has an expected life of 2 to 3 years. The internal solenoid has an expected life of 2 to 3 years. The GSE sensor has an average expected life of 1 to 2 years in climates with moderate humidity and particle loading.

Hydrogen Sulfide (H_2S) Module

Hydrogen sulfide (H_2S) is a strong-smelling compound often associated with industrial processes, such as sewage treatment or waste disposal.

H_2S is not listed among the six criteria health pollutants cited by the US EPA. However, legislation controlling the levels of H_2S in ambient air is defined in most countries and many jurisdictions have ambient exposure standards for H_2S.

H_2S module measurement principle

The H_2S module uses a patented automatic baseline correction (ABC) design to measure H_2S in ambient air. It combines an advanced electrochemical H_2S sensor with a sample/zero cycling operation to deliver near reference performance in ambient H_2S monitoring.

The sensor used in the H_2S module is an electrochemical sensor. The sensor generates an electrical current in nA which is proportional to the concentration of gas which comes in to contact with the sensor.

The module uses two different flow paths, one of which passes through a proprietary scrubber to remove H_2S and produce a baseline measurement. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 60 mL min^{-1}).

The sensor current is measured during both the baseline and sample measurement states and these values are used to calculate the H_2S concentration using a proprietary algorithm approximately once per minute.

H_2S module specifications and performance

The H_2S module performance specifications are given in the table below.

Range (ppb)	Resolution (ppb)	Noise Zero (ppb) Span (% of reading)	Limit of Detection (ppb)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppb) Span (% of FS)
0-5,000	0.1	1; 0.1%	2	1% of reading or 3 ppb	0.5%	<1; <0.5%

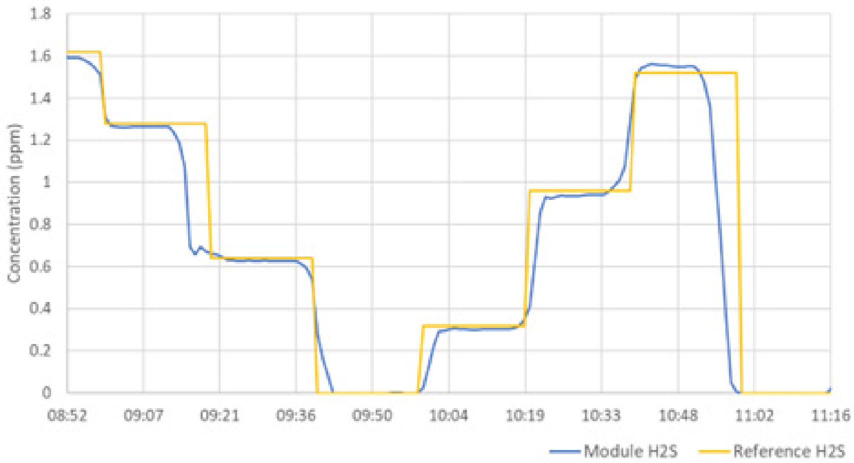
H_2S module calibration and traceability

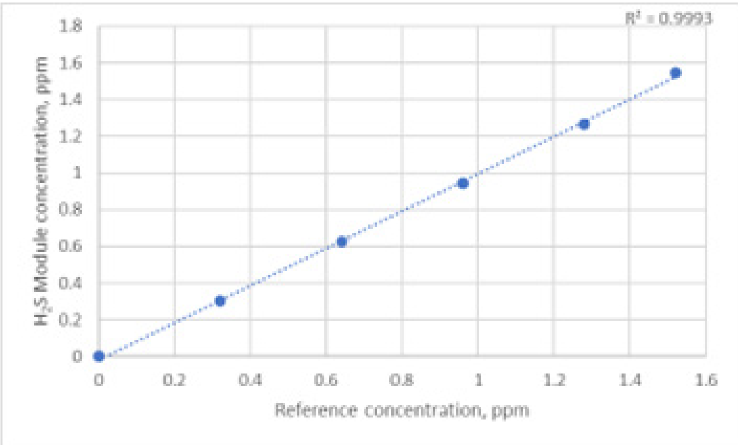
Just like a regulatory H_2S analyzer using UV fluorescence, the H_2S module can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The H_2S module factory calibration is achieved using a zero-air source, certified calibration gas standards and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the H_2S module in the field.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

To demonstrate module performance, a six-point gas test, at known H_2S concentrations, was carried out using the equipment outlined above. The module shows good linearly (R^2 = 0.99) over the 0 – 1600 ppb range studied.





Interferences

The Aeroqual H_2S module is specific towards H_2S but other gases in the environment may also cause a response from the H_2S sensor. These do not indicate a fault. These effects are part of the module behaviour and should be considered when examining data.

The H_2S module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
CO	1.0	0.005
NO_2	0.1	-0.001
O_3	0.1	-0.001
SO_2	0.1	0.010
Ethylene	0.5	0.001

H_2S module expected lifetime

The non-catalytic chemical scrubber has an expected life of 2 to 3 years. The internal solenoid has an expected life of 2 to 3 years. The GSE sensor has an average expected life of 1 to 2 years in climates with moderate humidity and particle loading.

Volatile Organic Compound (VOC) Module

Volatile Organic Compounds (VOCs) is the name given to a group of organic compounds which can exist as a gas in the atmosphere.

VOCs are not listed among the six criteria health pollutants cited by the USEPA. However, the effects of VOC exposure are becoming more understood and demands for ambient VOC monitoring are increasing.

VOC module measurement principle

The sensor used in the VOC module is a photoionization detector (PID) sensor. The sensor generates an electrical current proportional to the concentration of gas that comes in to contact with the sensor. The current generated differs depending on the organic compound, so the PID module is only quantitative towards the compound it is calibrated with; in most applications this is isobutylene.

The VOC module is sensitive to a wide range of VOCs, including benzene and toluene, though not methane, ethane, propane, formaldehyde, or low molecular weight alcohols.

The patented VOC module design cycles between reading the sample air and reading air that has been filtered using a proprietary scrubber. This negates the effect of ambient air humidity changes, known to reduce the performance of a PID-based VOC measurement. The module has a controlled flow rate. The flow rate is determined by a flow control orifice on the exhaust side of the sensor and measured at the inlet to the sensor module (expected to be approximately 60 mL min^{-1}).

The sensor current in converted to a voltage and the voltage is measured and used to calculate the VOC concentration using a proprietary algorithm approximately once per minute.

VOC module specifications and performance

The VOC module performance specifications are given in the table below.

Module	Range	Display Resolution	Noise Zero Span (% of reading)	Limit of Detection	Precision	Linearity (% of FS)	24 hr Drift Zero Span (% of FS)
VOC Low Range	0-500 ppb	0.1 ppb	<1 ppb; 1%	<1 ppb	2% of reading or 1 ppb	1%	1 ppb; 1%
VOC High Range	0-30 ppm	0.01 ppm	<0.1 ppm; 1%	<0.1 ppm	2% of reading or 0.05 ppm	2%	0.1 ppm; 1%

VOC module calibration and traceability

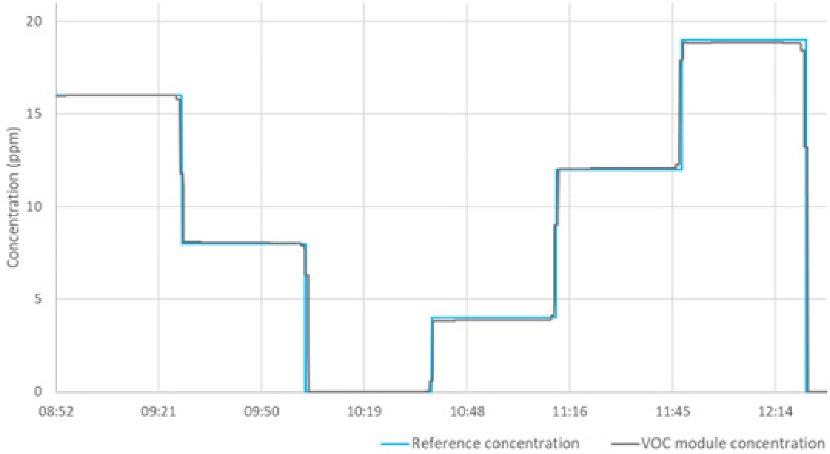
Just like a regulatory VOC analyzer using gas chromatography, the VOC module can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

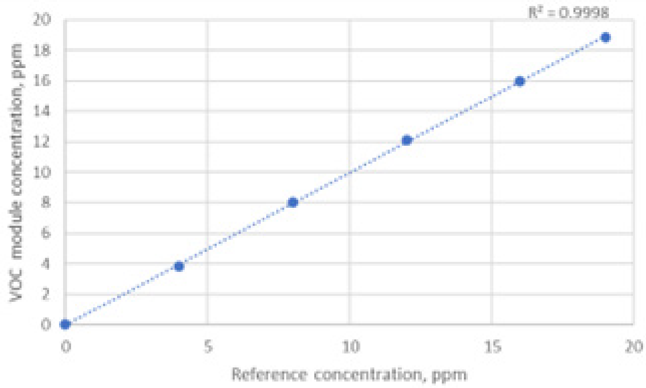
The VOC module factory calibration is achieved using a zero-air source, a certified calibration gas standard and a certified gas dilution calibrator. Isobutylene is the recommended calibration gas to be used for the AQM65 VOC module. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the VOC module in the field.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

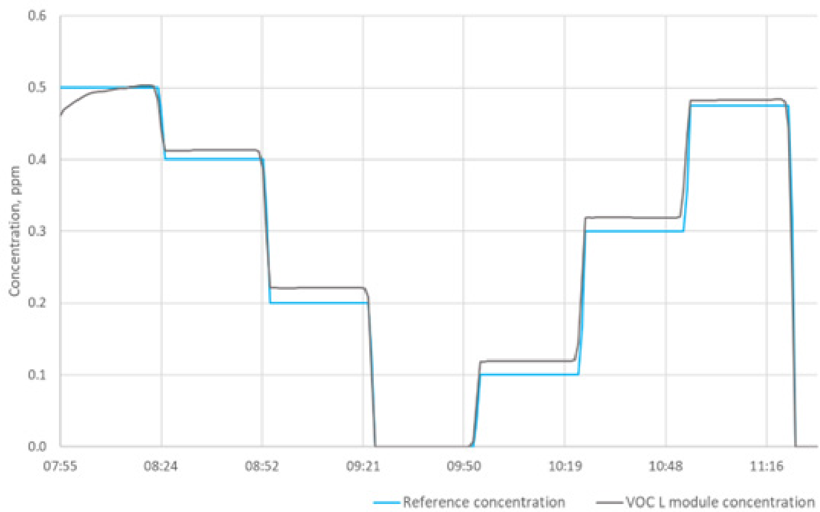
To demonstrate, multi-point gas test at known concentrations was carried out using the equipment described above. The gas test is split into low range and high range. The module shows good linearity ($R^2 = 0.99$) over the entire concentration range studied.

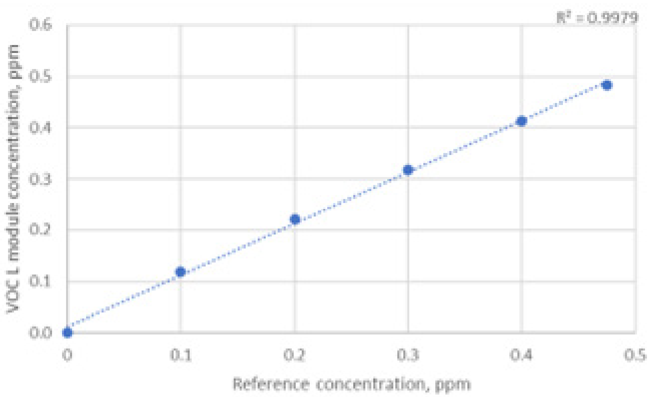
High range: →





Low range: →





Interferences

The VOC module response to other ambient air pollutants is documented in the table below.

Pollutant	Test concentration / ppm	Typical module response / ppm
Isobutylene	1.0	1.0
Benzene	0.1	0.2
CO	1.0	No response
NO_2	0.1	No response
O_3	0.1	No response
SO_2	0.1	No response
Ethylene	0.5	No response
H_2S	0.1	0.025

PID sensors respond to a wide range of VOCs but are calibrated against isobutylene. Response factors for other target gases are used to convert the isobutylene equivalent reading to that of the target gas. PID response factors for a wide range of target gases are well documented and available via Aeroqual.

VOC module expected lifetime

The non-catalytic chemical scrubber has an expected life of 2 to 3 years. The internal solenoid has an expected life of 2 to 3 years. The VOC sensor contains a lamp which has a limited lifetime. The expected lifetime of the lamp is approximately 200 days of continuous operation. The VOC module can be sent back to Aeroqual for a lamp replacement or replaced by a qualified technician using a lamp replacement kit, available for purchase from Aeroqual.

Methane (CH_4) Module

Methane is a potent greenhouse gas that has significant impact on the earth's climate. It is produced by both natural and human activities, including microbial digestion, fossil fuel production, transportation and waste management.

To effectively understand the sources and magnitude of methane emissions and develop strategies to mitigate them, it is crucial to have accurate, real-time, ambient methane measurements.

Methane module measurement principle

The CH_4 module uses a Gas Sensitive Semiconductor (GSS) sensor.

The module contains a proprietary flow design that minimizes baseline drift and the sample air is filtered using a proprietary scrubber to reduce interferences. The sensor output is determined under both baseline and sample conditions, and a proprietary algorithm is used to calculate the methane concentration. The flow rate is controlled by a flow control orifice on the exhaust side of the sensor module (expected to be approximately 60 mL min^{-1}).

Methane module specifications and performance

The Methane module performance specifications are given in the table below.

Module	Range (ppm)	Display Resolution (ppm)	Noise Zero (ppm) Span (% of reading)	Limit of Detection (ppm)	Precision	Linearity (% of FS)	24 hr Drift Zero (ppm) Span (% of FS)
Methane (CH_4)	0-500	0.01	0.02; 0.3%	0.04	0.4% of reading	<1%	0.04; 1%

Note: the methane module requires 4-6 hours to stabilize on start up.

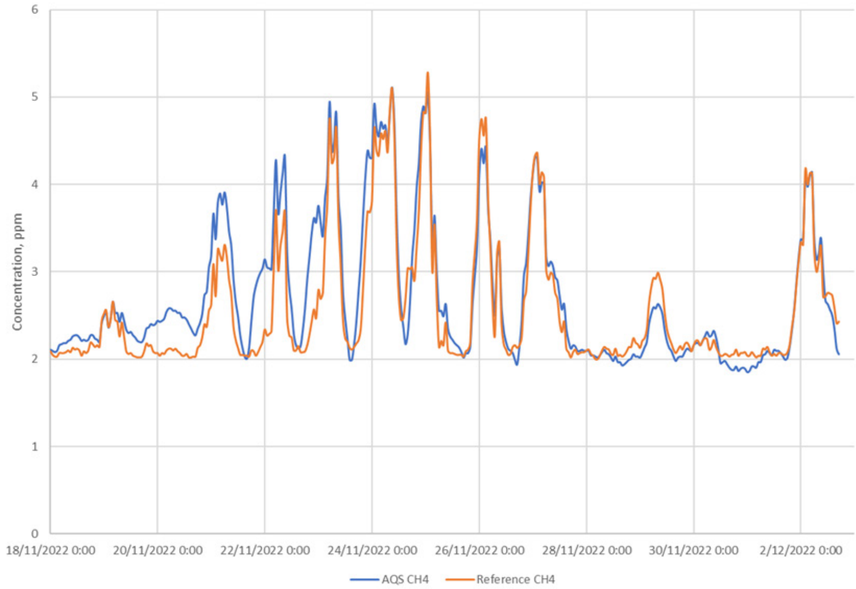
Methane module field test results

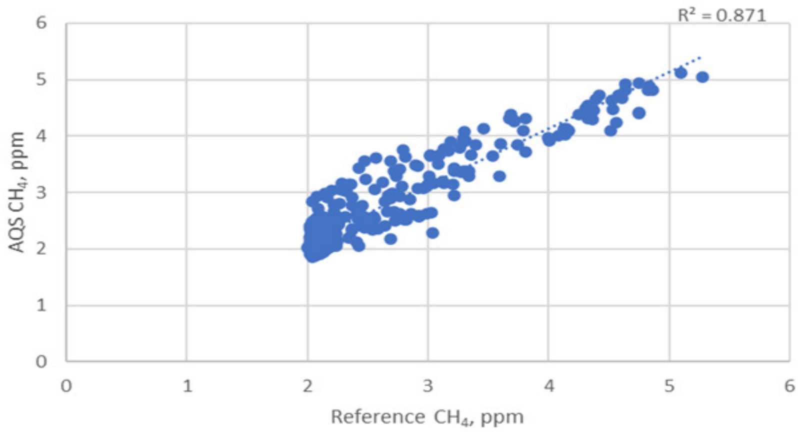
An Aeroqual AQS containing a CH_4 module was co-located in November 2022 with a Picarro methane analyzer. The CH_4 module produced a R^2 of 0.87 and a mean absolute error (MAE) of 0.2ppm. The low MAE value is indicative that the module has low zero and span drift. Performance in an Aeroqual AQM65 would exceed this.

CH_4 module expected lifetime

The chemical scrubber has an expected life of 2 to 3 years. The GSS sensor has an expected life of 2 to 3 years.

Time series plot and scatter plot of data with linear regression and coefficient of determination (R^2)





CH_4 module calibration and traceability

The sensor based CH_4 system can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The CH_4 module factory calibration is achieved using a zero-air source, certified calibration gas standards and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the CH_4 module in the field.

Calibration frequency will be dependent on the user's data quality objectives and Quality Assurance Project Plan (QAPP), but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

Interferences

Pollutant	Test concentration / ppm	Typical module response / ppm
Isobutylene	1.0	No response
H_2S	0.1	No response
CO	1.0	0.05

BTEX Module

The BTEX module is designed to measure ambient benzene, toluene, ethylbenzene, and xylene at levels relevant for human health and ozone precursor studies. The module is ideal for measurement at both fence line and urban sites.

Benzene is found in ambient air because of burning fossil fuels, evaporation at gasoline storage and filling stations, and motor vehicle exhausts. The World Health Organization (WHO) classifies benzene as a group one carcinogen. The EU's outdoor air limit value is 3.5 µg/m^3.

Toluene, ethylbenzene, and xylene are important industrial solvents used in a variety of processes and products. All are ozone precursors.

BTEX module measurement principle

The BTEX module is a carrier gas free miniature gas chromatograph (GC), manufactured by Pollution Analytical Equipment. It uses a MEMS (Micro Electro-Mechanical System) microfluidics design for selective pre-concentration and GC separation. Analyte detection is via a 10.6 eV photoionization detector. Peak quantification is performed automatically using in-built curve fitting algorithms.

The BTEX module measures a sample approximately every 15 minutes. This measurement sequence comprises a 10-minute sample pre-concentration, followed by injection and an approximately 5-minute chromatographic separation. The BTEX inlet samples at approximately 400 mL min^{-1}.

BTEX module specifications and performance

The BTEX module performance specifications are given in the table below.

Module	Range (ppb)	Display Resolution (ppb)	Noise Zero (ppb)	Limit of Detection (ppb)	24 hr Drift
BTEX	0.1-50	0.01	0.05	0.1	<2% FS

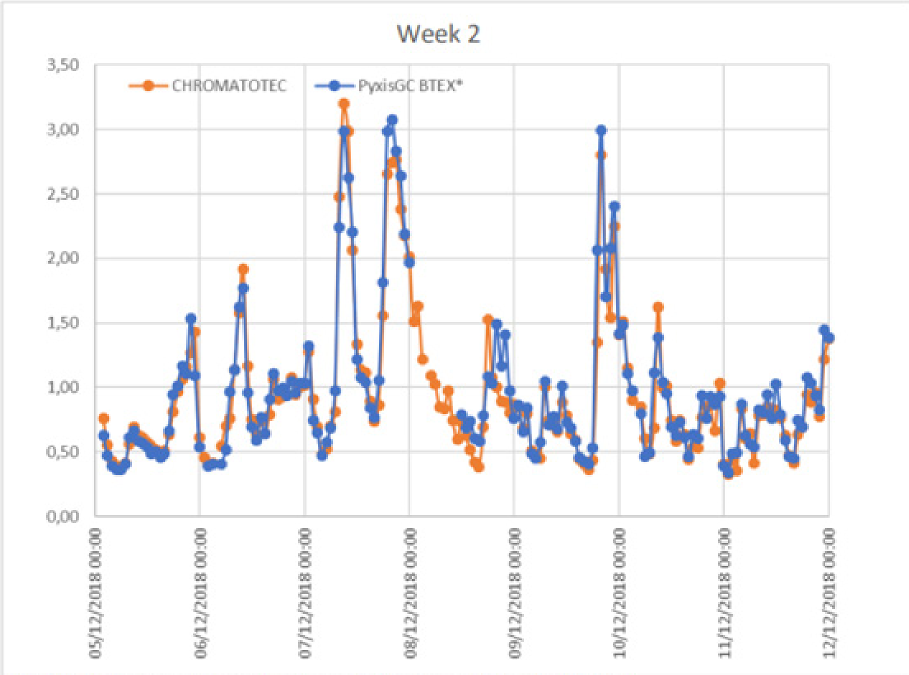
BTEX Field Test Results

The BTEX module was tested by the Puglia Regional Environmental Protection Agency (ARPA) at an air quality station in Taranto, Italy. The module was tested against a Chromatotec GC866 analyzer over a period of 7 weeks, starting December 2018.

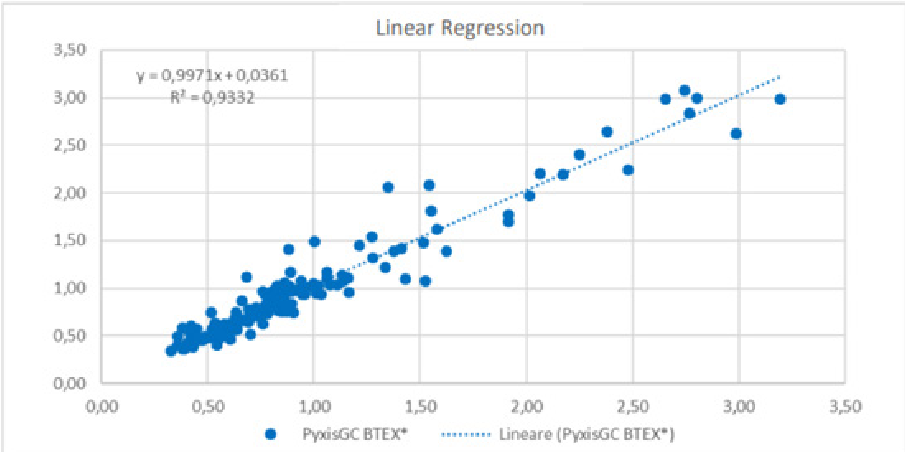
WEEK 2

Time series plot and linear regression of benzene measurements for week 2 of the Pollution co-location study. Results reproduced from Pollution study.

Pollution Analytical Equipment, Technical Report, BTEX ambient air analysis: sources, regulations, technologies for controls. https://pollution.it/app/uploads/sites/2/2021/09/RI-EN0302-0-Technical-Report_PyxisGC-BTEX-and-Arpa-Puglia-1.pdf



Graph 5 - Hourly average Benzene trend (concentrations expressed in ug / m³) Week 2



Graph 6 - Calculation of linear regression between instrumental measurements (Benzene concentrations expressed in ug/m³) Week 2

EQUIVALENCE: 89% ---- R^2: 0.9332

BTEX module calibration and traceability

The BTEX module can be field calibrated using standard calibration equipment and reference gases. This ensures the module calibration is fully traceable to NIST primary standards.

The BTEX module factory calibration is achieved using a zero-air source, a certified calibration gas standard and a certified gas dilution calibrator. The Aeroqual AirCal 1000 or 8000 systems can be used to calibrate the BTEX module in the field.

Calibration frequency will be dependent on the user's data quality objectives and QAPP, but based on the low rate of field drift the recommended calibration frequency is 1-3 months.

BTEX module component life

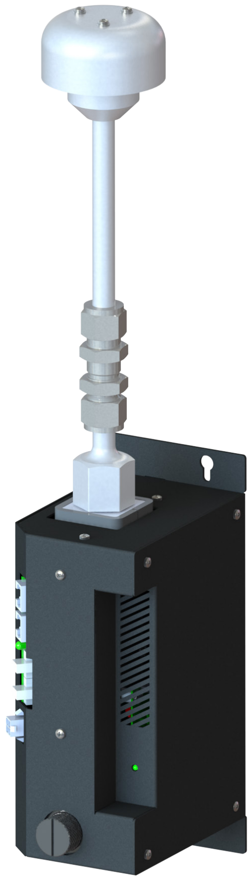
The BTEX module contains several components that need to be maintained for optimum performance.

The carrier gas filter and MEMS pre-concentrator both have an expected life of 1 year of continuous operation. The expected life of the lamp in the PID sensor is approximately 200 days of continuous operation. It can be replaced in the field. The MEMS chromatographic column should be replaced after 2 years of continuous operation. The BTEX module can be returned to Aeroqual for these replacements.

Particulate Matter (PM) Monitoring

Particulate matter (PM) is one of the six criteria air pollutants identified by the USEPA. Two sizes of particulate matter are considered important by the WHO, PM_{10} and $PM_{2.5}$. Both PM_{10} and $PM_{2.5}$ are monitored extensively around the world by regulatory agencies. PM comes from both human and natural sources. Man-made sources include fuel burning, construction, industrial emissions, vehicle exhausts and mechanical crushing of larger particles.
Aeroqual offers two different technologies for monitoring PM: particle counting and nephelometry.

PCX Module



PCX module measurement principle

The PCX PM module comprises an optical particle counter that uses scattered light to size and count particles. The amount of scattered light is converted to a voltage pulse and the amplitude of that voltage pulse is calibrated to a particle diameter. The particles are assigned based on diameter to one of six particle count channels. Using a proprietary algorithm, particle counts for each size fraction are converted into mass measurements, providing continuous and simultaneous measurement of PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP.

The PCX module also includes a controlled heated inlet, and active flow control.

PCX module specifications and performance

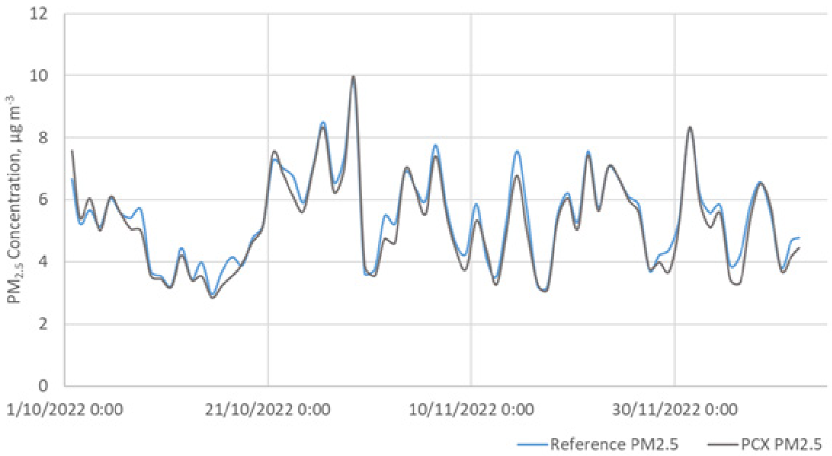
The PCX module performance specifications are given in the table below.

Module	Range (mg m^{-3})	Resolution (µg m^{-3})	Lower Detectable Limit (µg m^{-3})	Precision	Accuracy	Noise Zero (µg m^{-3}) Span (% of reading)	24 hr Drift Zero (µg m^{-3}) Span (% of FS)
PM_1	0-30	0.1	0.1	4.3%	<5%	<0.1 0.8%	-0.2 5.7%
$PM_{2.5}$	0-30	0.1	0.1	3.1%	<5%	<0.1 1.2%	-0.1 3.4%
PM_4	0-30	0.1	0.2	2.8%	<5%	0.1 1.1%	<0.1 5.0%
PM_{10}	0-30	0.1	0.3	2.3%	<5%	0.1 1.2%	0.3 0.7%
TSP	0-30	0.1	0.5	2.7%	<5%	0.2 1.7%	0.6 1.5%

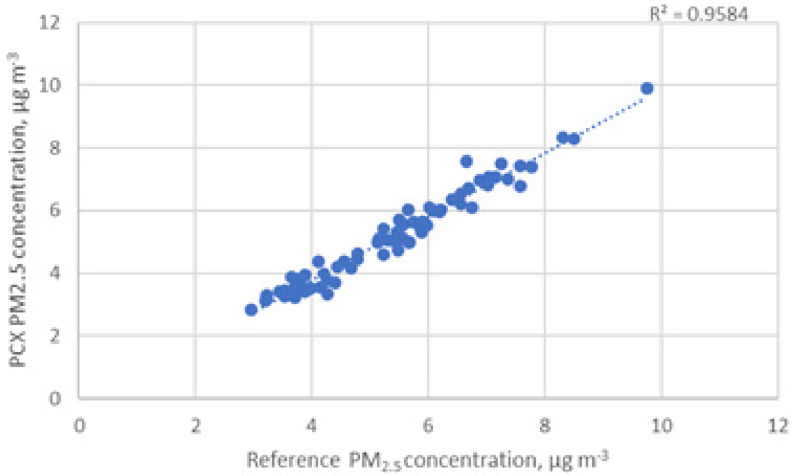
PCX field results

An Aeroqual Dust Sentry containing a PCX was co-located from October until December 2022 at an air quality regulatory station in Auckland, New Zealand, and its data compared with the reference data. The $PM_{2.5}$ data from the PCX module produced an R^2 of 0.96 and a mean absolute error (MAE) of 0.33 µg m^{-3}. The PM_{10} data from the PCX module produced an R^2 of 0.96 and a mean absolute error (MAE) of 0.66 µg m^{-3}.

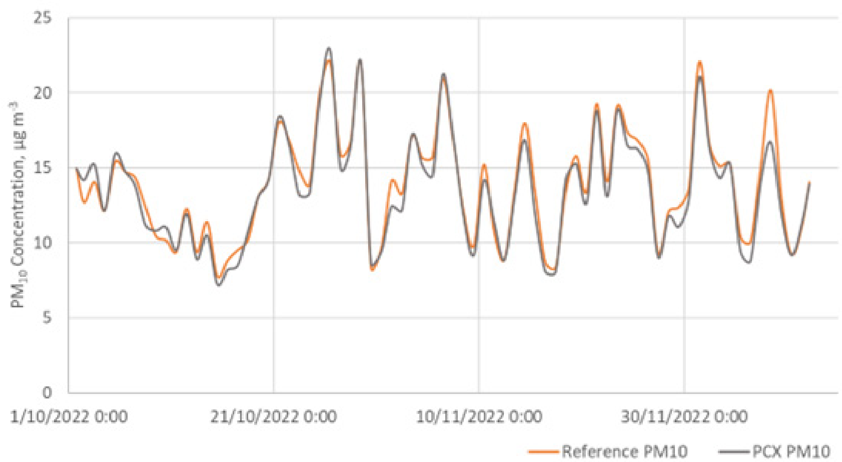
Time series plot – $PM_{2.5}$



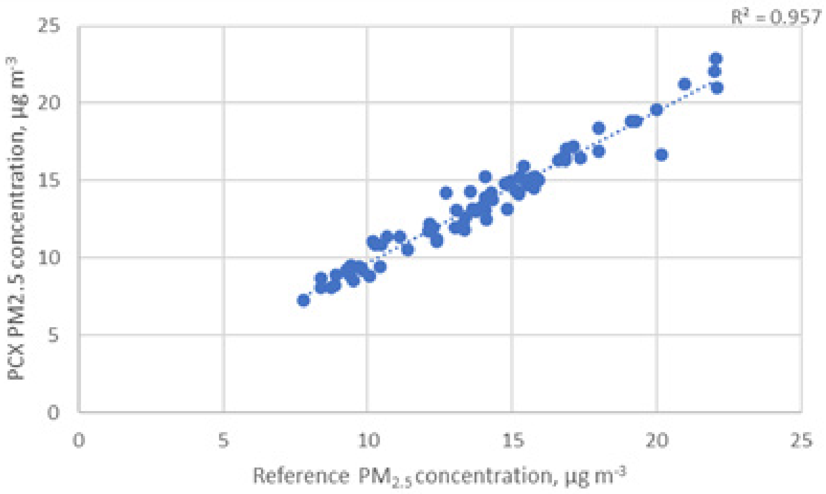
Scatter plot of data with linear regression and coefficient of determination (R^2) for $PM_{2.5}$



Time series plot – PM_{10}



Scatter plot of data with linear regression and coefficient of determination (R^2) for PM_{10}



The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 50 µg m^{-3}, was calculated as 6.2% for $PM_{2.5}$ and 8.6% for PM_{10}. Note that an expanded relative uncertainty of less than 25% is required for a PM monitor to be considered regulatory grade. The PCX module meets this requirement.

Expanded relative uncertainty calculated for the Aeroqual $PM_{2.5}$ PCX module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet.

Calibration	0.816y + 1.777	µg m^{-3}
U(calibration)	1.60	µg m^{-3}
Random term	1.51	µg m^{-3}
Additional uncertainty (optional)	0.00	µg m^{-3}
Bias at LV	-0.34	µg m^{-3}
Combined uncertainty	1.55	µg m^{-3}
Expanded relative uncertainty	6.2%	pass
Ref sampler uncertainty	0.67	µg m^{-3}
Limit value	50	µg m^{-3}

Expanded relative uncertainty calculated for the Aeroqual PM_{10} PCX module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet

Calibration	0.649y + 3.981	µg m^{-3}
U(calibration)	1.99	µg m^{-3}
Random term	2.09	µg m^{-3}
Additional uncertainty (optional)	0.00	µg m^{-3}
Bias at LV	-0.51	µg m^{-3}
Combined uncertainty	2.16	µg m^{-3}
Expanded relative uncertainty	8.6%	pass
Ref sampler uncertainty	0.67	µg m^{-3}
Limit value	50	µg m^{-3}

PCX module calibration and traceability

The PCX module features an automatic internal zero calibration. The module uses an internal zero filter and pump to perform a zero calibration. The zero calibration can be triggered on start-up, placed on a continuous schedule, or manually triggered on the Aeroqual Cloud platform. Correct maintenance ensures the auto zero function operates correctly and prevents negative readings. The automatic zero calibration can be verified in the field by using an external filter placed upon the inlet.

The PCX module can be returned to Aeroqual for factory span calibration. This is recommended every 2 years.

The module can be field calibrated by co-locating it alongside another PM instrument of equal or better performance.

Aeroqual can also offer its patented remote calibration procedure, MOMA, for this module, which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Impact of humidity and water vapor

High humidity can lead to inaccurate measurement from an optical particle sensor if not mitigated. This is because high humidity (including fog) causes aerosol particle growth through adsorption of water vapor, which can lead to erroneously high measurements by the particle sensor. However, the PCX module contains an inlet heater which reduces the sample air humidity and prevents the particle growth. This maintains the accuracy of the PM measurement even when the water content in the air is very high.

PCX module expected lifetime

The PCX module contains two pumps, both expected to last between 18 months and 2 years of continuous operation. The module particle filter needs to be replaced every 6-12 months. The module also contains a laser and a photodetector, requiring factory calibration every 2 years.

Nephelometer Module

PM nephelometer module measurement principle

The PM nephelometer module combines a laser nephelometer with a high-precision sharp cut cyclone to give accurate real-time measurement of ambient particulate matter. By changing the sharp cut cyclone, the particle sensor can be used to measure PM_1, $PM_{2.5}$, PM_{10} or TSP. The sharp cut cyclone physically selects particles of a target size, ensuring precise measurement of only the size fraction of interest.

Following particle size selection, the sample stream is sent to the nephelometer module. A nephelometer is an optical sensor that uses light scattering to measure particle mass. The light source is a visible laser diode and scattered light is measured in the near forward angle using focusing optics and a photo diode.

The nephelometer has an on-board temperature sensor that corrects for thermal drift, a sheath air filter to keep the optics clean, automatic baseline drift correction, and a fiber optic span system to provide a check of the optical components.

PM nephelometer module specification and performance

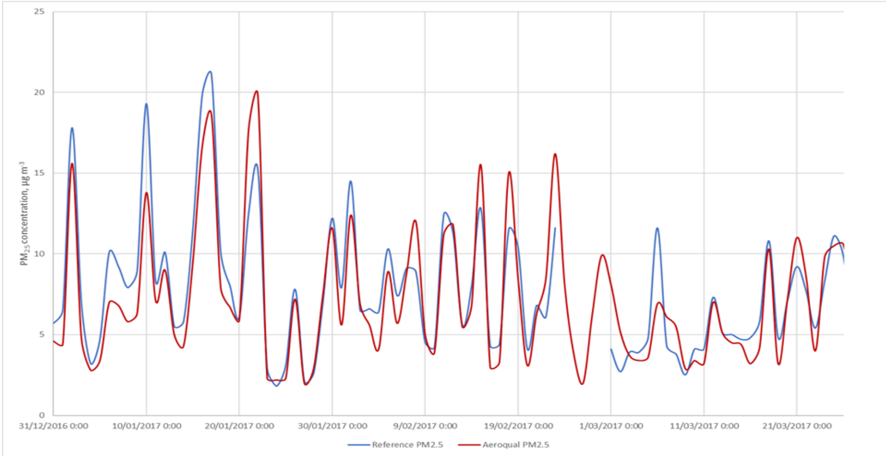
The PM nephelometer module performance specifications are given in the table below.

Sizes	Range (µg m^{-3})	Resolution (µg m^{-3})	Lower Detectable Limit (µg m^{-3})	Accuracy
PM_1, $PM_{2.5}$, PM_{10} OR TSP	0-60,000	0.1	<1	±(2 µg m^{-3} + 5% of reading)

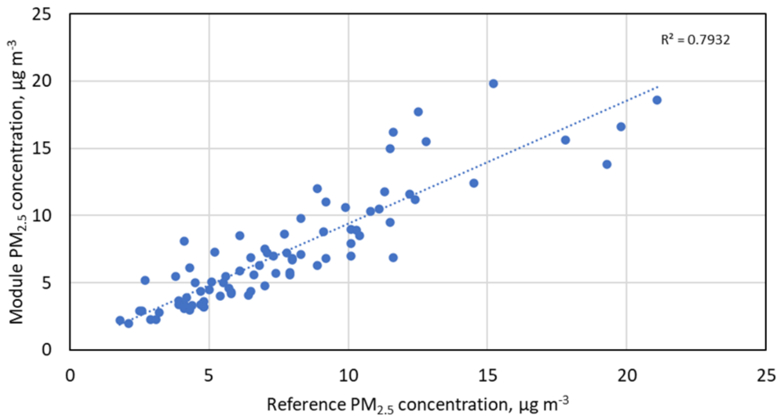
PM nephelometer field test results $PM_{2.5}$

An Aeroqual AQM65 containing an $PM_{2.5}$ nephelometer module was co-located from December 2016 to March 2017 at an air quality regulatory station in Hartford, Connecticut, and its data compared with reference data downloaded from the USEPA AirNow website. The $PM_{2.5}$ nephelometer data produced an R^2 of 0.79 (24-hour average). The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 50 µg m^{-3} was calculated as 12.9%. Note that an expanded relative uncertainty of less than 25% is required for a $PM_{2.5}$ monitor to be considered regulatory grade. The $PM_{2.5}$ module meets this requirement.

Time series plot

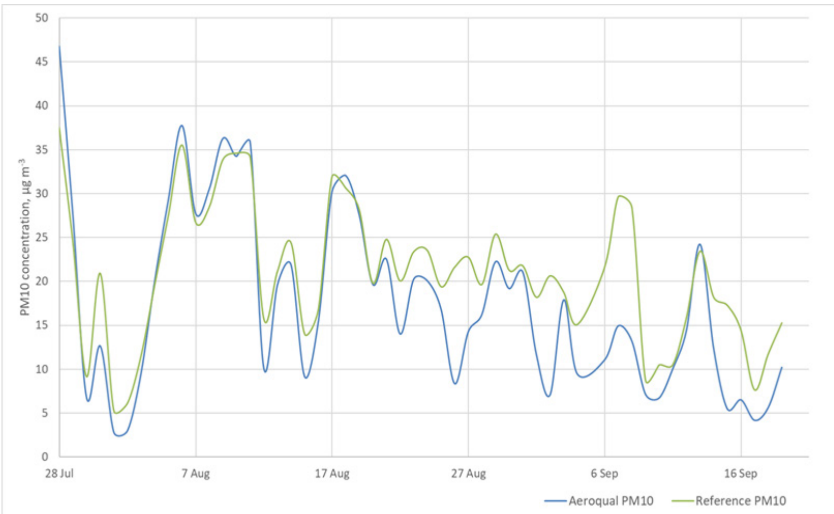


Scatter plot of data with linear regression and coefficient of determination (R^2)



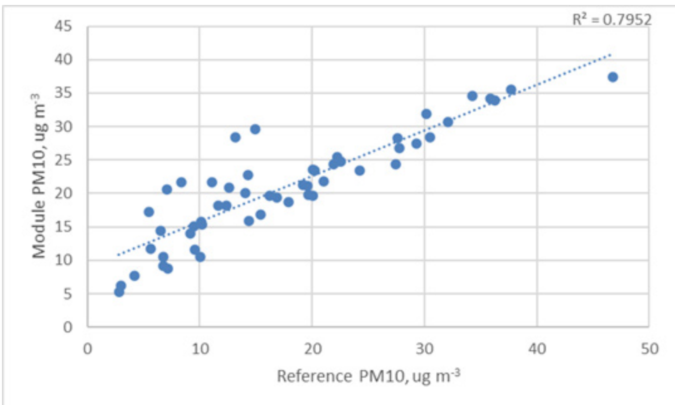
PM_{10}

An Aeroqual Dust Sentry containing an PM_{10} nephelometer module was co-located with two BAM reference instruments from July to September 2012 in Nelson, New Zealand. This co-location study was completed as a requirement for MCERTs certification, which this unit has achieved. The PM_{10} nephelometer data produced an R^2 of 0.79 (24-hour average).



Scatter plot of data with linear regression and coefficient of determination (R^2)

The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 50 µg m^{-3}, was calculated as 15.3%. Note that an expanded relative uncertainty of less than 25% is required for a PM_{10} monitor to be considered regulatory grade. The PM_{10} module meets this requirement.



Expanded relative uncertainty calculated for the Aeroqual PM_{10} nephelometer module based on the “Guide to the Demonstration of Equivalence” method and spreadsheet.

Calibration	0.901y + 5.316	
U(calibration)	2.04	µg m^{-3}
Random term	3.83	µg m^{-3}
Additional uncertainty (optional)	0.00	µg m^{-3}
Bias at LV	-0.23	µg m^{-3}
Combined uncertainty	3.84	µg m^{-3}
Expanded relative uncertainty	**15.3%**	**pass**
Ref sampler uncertainty	0.67	µg m^{-3}
Limit value	50	µg m^{-3}

PM nephelometer module calibration and traceability

The PM nephelometer module features an automatic internal zero calibration. The module uses an internal zero filter and pump to perform zero calibration every 12 hours. Correct maintenance ensures the auto zero function operates correctly and prevents negative readings. The automatic zero calibration can be verified in the field by using an external filter placed upon the inlet.

The nephelometer optical engine can be returned to Aeroqual for factory span calibration, this is recommended every 2 years.

The module can be field calibrated by co-locating it alongside another PM instrument of equal or better performance.

Aeroqual can also offer its remote calibration procedure MOMA for this module which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Impact of humidity and water vapor

High humidity can lead to inaccurate measurement from an optical particle sensor if not mitigated. This is because high humidity (including fog) causes aerosol particle growth through adsorption of water vapor which can lead to erroneously high measurements by the particle sensor. However, the Nephelometer module contains an inlet heater which reduces the sample air humidity and prevents the particle growth. This maintains the accuracy of the PM measurement even when the water content in the air is very high.

PM nephelometer module expected lifetime

The Aeroqual manufactured electronics module responsible for data analysis does not contain any consumable parts and does not contain any components which might wear out or expire and should last between 3 to 5 years.

The Aeroqual manufactured pump module contains two pumps, both expected to last between 18 months and 2 years of continuous operation.

The MetOne manufactured nephelometer module contains filters which are changed as required, usually between 1 and 3 months. The module also contains a laser and photodetector, requiring factory calibration every 2 years.

Particle profiler module

Particle profiler module measurement principle

The particle profiler module comprises an optical particle counter that uses scattered light to size and count particles. The amount of light scattered is converted to a voltage pulse and the amplitude of the pulse is calibrated to particle diameter. The particles are assigned to a particle counts channel based on their particle diameter. Using a proprietary algorithm, particle counts for each channel are converted into mass measurements, providing continuous and simultaneous measurement of PM_1, $PM_{2.5}$, $PM_{10,}$ and TSP.

This mode of measurement is light scattering technology like the nephelometer, but as particle size is determined within the optical module no cyclone is required.

An on-board temperature sensor corrects for thermal drift, and a sheath air filter keeps the optics clean even in harsh environments.

Particle profiler module specification and performance

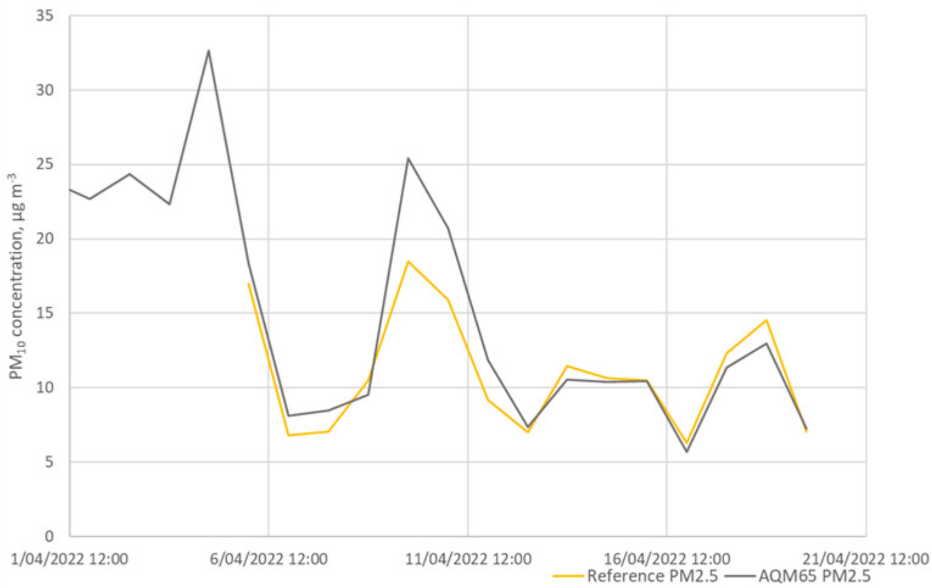
The PM counter module performance specifications are given in the table below.

Sizes	Range (µg m^{-3})	Resolution (µg m^{-3})	Lower Detectable Limit (µg m^{-3})	Accuracy
PM_1	0-200	0.1	<1	±(5 µg m^{-3} + 15% of reading)
$PM_{2.5}$	0-2000			
PM_{10}	0-5000			
TSP	0-5000			

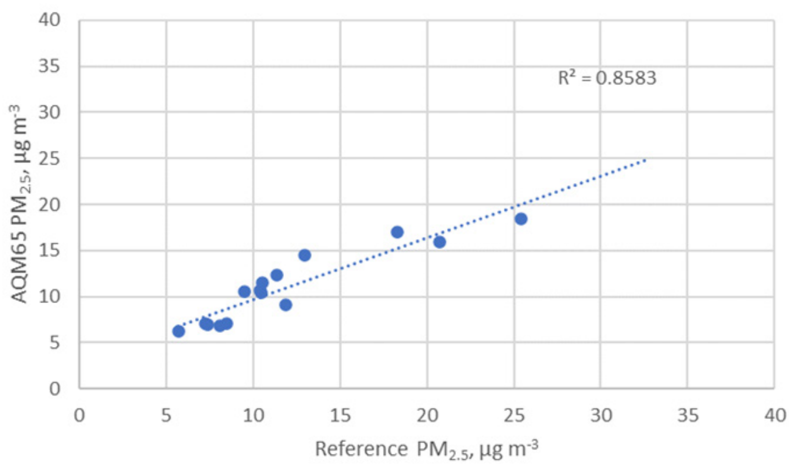
Particle profiler field test results

An Aeroqual AQM65 containing a particle profiler module was co-located in April 2022 at an air quality regulatory station in Riverside, Southern California and its data compared with the reference data downloaded from USEPA Airnow. The $PM_{2.5}$ data from the particle profiler module produced an R^2 of 0.86 and a mean absolute error (MAE) of 2.0 µg m^{-3}. The PM_{10} data from the particle profiler module produced an R^2 of 0.83 and a mean absolute error (MAE) of 4.1 µg m^{-3}.

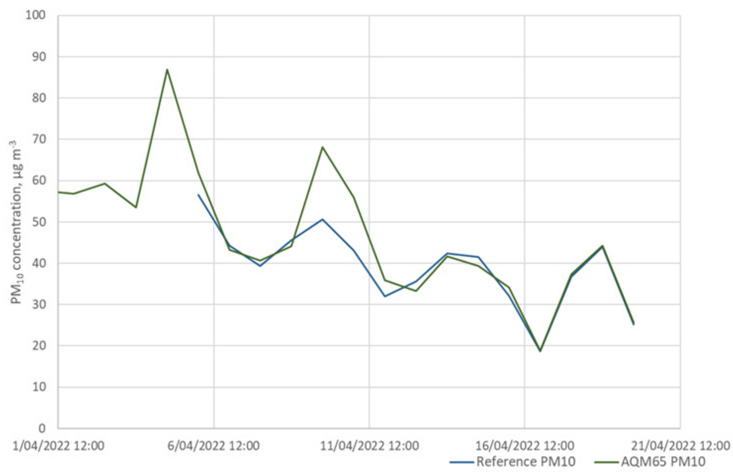
Time series - $PM_{2.5}$



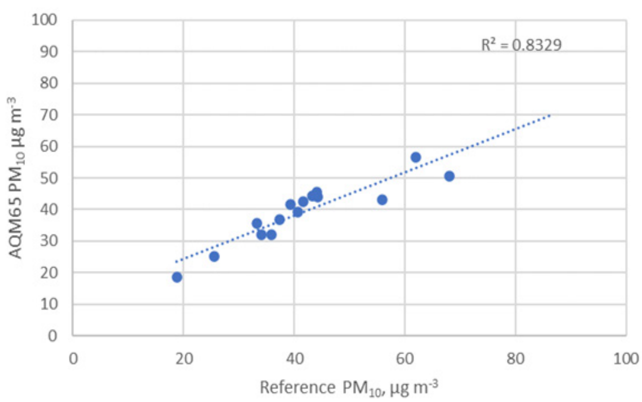
Scatter plot of data with linear regression and coefficient of determination (R^2) – $PM_{2.5}$



Time series - PM_{10}



Scatter plot of data with linear regression and coefficient of determination (R^2) – PM_{10}



The total measurement uncertainty, based on the EU Guide to Demonstration of Equivalence, using an hourly limit value of 50 µg m^{-3}, was calculated as 16.4% for $PM_{2.5}$ and 17.8% for PM_{10}. Note that an expanded relative uncertainty of less than 25% is required for a PM monitor to be considered regulatory grade. The PM particle profiler module meets this requirement.

Expanded relative uncertainty calculated for the Aeroqual $PM_{2.5}$ particle profiler module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet.

Calibration	0.197y -1.371	
U(calibration)	1.23	µg m^{-3}
Random term	3.89	µg m^{-3}
Additional uncertainty (optional)	0.00	µg m^{-3}
Bias at LV	1.27	µg m^{-3}
Combined uncertainty	4.09	µg m^{-3}
Expanded relative uncertainty	16.4%	pass
Ref sampler uncertainty	0.67	µg m^{-3}
Limit value	50	µg m^{-3}

Expanded relative uncertainty calculated for the Aeroqual PM_{10} particle profiler module based on the "Guide to the Demonstration of Equivalence" method and spreadsheet.

Calibration	0.851y + 3.095	
U(calibration)	3.19	µg m^{-3}
Random term	8.77	µg m^{-3}
Additional uncertainty (optional)	0.00	µg m^{-3}
Bias at LV	-1.46	µg m^{-3}
Combined uncertainty	8.89	µg m^{-3}
Expanded relative uncertainty	17.8%	pass
Ref sampler uncertainty	0.67	µg m^{-3}
Limit value	50	µg m^{-3}

Particle profiler module calibration and traceability

It is recommended that the optical particle counter be returned for factory span calibration annually. The particle profiler module can be field calibrated by co-locating the AQM65 or Dust Sentry Pro alongside another PM instrument of equal or better performance.

Aeroqual can also offer its remote calibration procedure MOMA for this module which avoids the need for a site visit while also maintaining traceability to nearby regulatory air monitoring stations. See your Aeroqual representative for more information on this software tool.

Impact of humidity and water vapor

High humidity can lead to inaccurate measurement from an optical particle sensor if not mitigated. This is because high humidity (including fog) causes aerosol particle growth through adsorption of water vapor, which can lead to erroneously high measurements by the particle sensor. However, the particle profiler module contains an inlet heater which reduces the sample air humidity and prevents the particle growth. This maintains the accuracy of the PM measurement even when the water content in the air is very high.

Particle profiler module expected lifetime

The Aeroqual manufactured electronics module responsible for data analysis does not contain any consumable parts and does not contain any components which might wear out or expire and should last between 3 to 5 years.

The Aeroqual manufactured pump module contains one pump, which is expected to last between 18 months and 2 years of continuous operation.

The MetOne manufactured optical particle counter contains a laser and photodetector, requiring factory calibration every 1 years.

Scientific publications featuring Aeroqual modules

1. Crețan Ioana-Alina and Nemeș Nicoleta, Measuring Air Quality in a Construction Site Biotope Using the AQM-65 Analyser, IOP Conf. Ser.: Mater. Sci. Eng., 245, 2017

2. Odu-Onikosi, A.; Herckes, P.; Fraser, M.; Hopke, P.; Ondov, J.; Solomon, P.A.; Popoola, O.; Hidy, G.M. Tropical Air Chemistry in Lagos, Nigeria. Atmosphere 2022, 13, 1059

3. Smit, R.; Kingston, P.; Neale, D.; Brown, M.; Verran, B.; Nolan, T., Monitoring on-road air quality and measuring vehicle emissions with remote sensing in an urban area. Atmospheric Environment 2019, 218, 116978

4. Olszowski, T., Ambient air quality for different weather conditions in two sites of observation. Ecological Chemistry and Engineering. A 2017, 24 (1)

5. Ormanova, G.; Hopke, P. K.; Darvishi, A.; Torkmahalleh, M. A.; Zhakiyev, N.; Shah, D.; Sabanov, S., Particulate Black Carbon Mass Concentrations and the Source Identification in Astana, Kazakhstan. 2023

6. Hernandez, G.; Berry, T.-A.; Wallis, S. L.; Poyner, D. In Temperature and humidity effects on particulate matter concentrations in a sub-tropical climate during winter, Proceedings of the International Conference of the Environment, Chemistry and Biology (ICECB 2017) Queensland, Australia 2017; 20-22

7. Wallis, S. L.; Hernandez, G.; Poyner, D.; Birchmore, R.; Berry, T.-A., Particulate matter in residential buildings in New Zealand: Part I. Variability of particle transport into unoccupied spaces with mechanical ventilation. Atmospheric Environment: X 2019, 2, 100024.

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