GUIDE

Gravimetric Methods in Air Quality Control

MEASUREMENT PRINCIPLES / APPLICATIONS / INSTRUMENT DESIGN / OPERATING CONDITIONS

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1. Introduction

Ambient air quality has always been an important indicator of environmental conditions; however, in the past, its assessment was considerably underestimated due to the lack of appropriate measurement methods and instrumentation. Recent advances in gravimetric weighing technology, particularly improvements in metrological performance, now enable mass measurements to be carried out with a level of precision that meets the requirements of modern environmental monitoring. It is well established that ambient air quality is assessed by determining the mass concentration of particulate matter using the gravimetric differential weighing method. In this approach, the mass of a clean sampling filter is first determined prior to exposure, after which the same filter is weighed again following sample collection. The difference between the two measurements corresponds to the mass of particulate matter deposited on the filter. Each weighing result is inherently affected by random measurement error, and the lower this variability, the higher the quality of the measurement. Such variability may originate from the metrological performance of the balance, instability of environmental conditions during weighing, or the influence of unbalanced electrostatic charges accumulated on the filter surface. To minimise the effect of these factors, the filter mass is typically determined as the arithmetic mean of at least two measurements whose difference does not exceed 40 µg or 60 µg, depending on the applicable measurement procedure. This constitutes one of the fundamental requirements specified in EN 12341:2024, the reference standard for determining the mass concentration of PM2.5 and PM10 in ambient air.

A slightly different approach is specified in EN 13284, Stationary Source Emissions – Determination of Low Range Mass Concentration of Dust – Part 1: Manual Gravimetric Method. Under this standard, filter conditioning periods are considerably shorter, and the filter mass is determined as the arithmetic mean of three measurements recorded at one-minute intervals during the continuous weighing of the same filter.

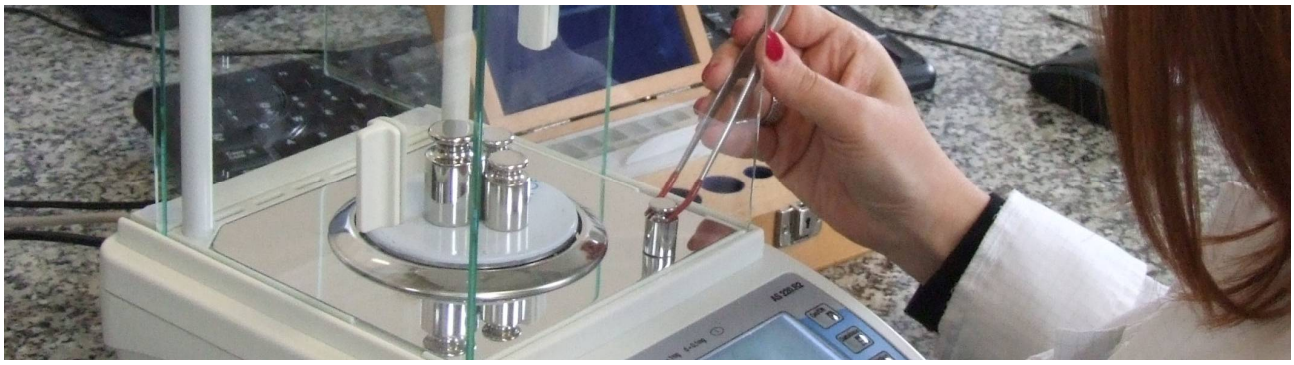


Figure 1. Verification of the Balance's Metrological Performance – **RADWAG Quality Control Department**

Experimental observations and studies of the measurement performance of operator-operated balances clearly indicate that, given the current state of technology, there are inherent limits to measurement accuracy that cannot be exceeded. Although substantial financial investment could potentially extend these limits, such an approach would not be economically justified.

The underlying causes of these limitations may be attributed to several factors. Some arise from the fundamental principles of gravimetric mass measurement, which is based on determining the gravitational force acting on the filter being weighed. Others are associated with physical phenomena accompanying the weighing process, such as air movement within and around the balance. Another significant factor is the instability of the filter mass itself, particularly in the case of PTFE filters or filters coated with PTFE. Scientific studies have also demonstrated that variations in filter mass may result from fluctuations in the environmental conditions under which the filters are conditioned.

It should be noted that, according to EN 12341:2024 and EN 13284, the permissible variation in conditioning conditions is 2°C for temperature and 5% for relative humidity. These conditioning limits result from the fact that the standards are intended to be practical documents; therefore, the required filter conditioning conditions should be achievable using conventional methods and equipment. On the other hand, the uncertainty associated with the determination of particulate matter mass concentration is of considerable importance, requiring an assessment of the contribution of all components included in the uncertainty budget. From a broader perspective, this is not a straightforward issue, particularly since, in addition to measurement accuracy, the ergonomics and economic aspects of the weighing process are also important. This has encouraged laboratories and R&D departments to seek improved solutions supported by digital technologies, providing higher throughput while maintaining acceptable metrological limits. Automation and robotic systems for mass measurement are already available; however, they are still far from inexpensive, as they invariably require optimisation in terms of mechanical design, software, and measurement methodology.

Figure 2. Automation of Mass Measurement – **RB 2.5Y Robotic Weighing System**

Legend: 1 – mass standard, 2 – filter, 3 – reference filter magazine, 4 – QR code reader, 5 – sample filter magazine, 6 – robotic arm, 7 – microbalance, d=0.001mg.

The aim of this publication is to present the measurement capabilities of the principal systems used for filter mass determination, including both manual systems and those equipped with automation solutions of varying levels of complexity. The characteristics of the individual systems focus primarily on their functional features rather than their marketing aspects, thereby enabling an objective assessment of their suitability for industrial applications and research and development (R&D) activities.

2. Suspended Particulate Matter

The term particulate matter (PM) is used to describe the dispersed phase of solid or liquid particles suspended in air. It is the terminology adopted by international organisations responsible for assessing air pollution and its impact on human health and ecosystems, including the United States Environmental Protection Agency (US EPA), the European Environment Agency (EEA), and the World Health Organization (WHO). Particulate matter may be defined as the solid phase of a two-phase solid–gas or gas–solid system, in which the degree of fragmentation of the solid material is sufficiently high that, in still air at a pressure of 760mmHg, a temperature of 20°C, and a relative humidity below 50%, particles acted upon solely by gravitational force, after a very short acceleration period caused by aerodynamic drag, either settle at a constant velocity of less than 500 cm/s or undergo Brownian motion.

Figure 3. Primary Particulate Matter Emissions from Industrial Sources – View of PM Particles

Source: https://www.flickr.com/photos/cambridgeuniversity-engineering/5862356585

Simon Payne - Scanning electron micrograph of diesel engine particulate matter captured in the pore of a ceramic wall-flow filter

The term aerosol is also used in the assessment of ambient air quality to describe suspensions of solid and liquid particles dispersed in a dispersing medium, i.e. air. The terms particulate matter and aerosol are closely related and are sometimes used interchangeably. However, by convention, the term particulate matter refers to the dispersed solid phase of a two-phase solid–gas system, whereas aerosol refers to a multiphase system comprising all fine solid and liquid particles suspended in air.

Particulate matter should be regarded as a heterogeneous atmospheric pollutant originating from numerous natural processes, such as wildfires, volcanic eruptions, and rock weathering, as well as anthropogenic activities, including industrial processes, fossil fuel combustion, and road transport. These fine particles, present predominantly in the solid or liquid phase and suspended in the atmosphere, form atmospheric aerosol. Its properties, and consequently its impact on human health, depend on particle morphology, size fraction, and chemical composition. The chemical composition of particulate matter is highly variable and may therefore provide valuable information on emission sources. Total Suspended Particulates (TSP) are defined as all particles with an aerodynamic diameter ranging from a few nanometres to approximately 100 µm.

The assessment of ambient air quality should also take into account that atmospheric particulate matter may be of both primary and secondary origin. Primary particulate matter is emitted directly from natural and anthropogenic sources, whereas secondary particulate matter is formed through the transformation of gaseous precursors, including sulphur dioxide, nitrogen oxides, ammonia, hydrocarbons, and existing airborne particles, as a result of chemical and physical processes. This leads to the formation of secondary particulate matter composed of fine solid and liquid particles, commonly observed in large urban agglomerations in the form of smog.

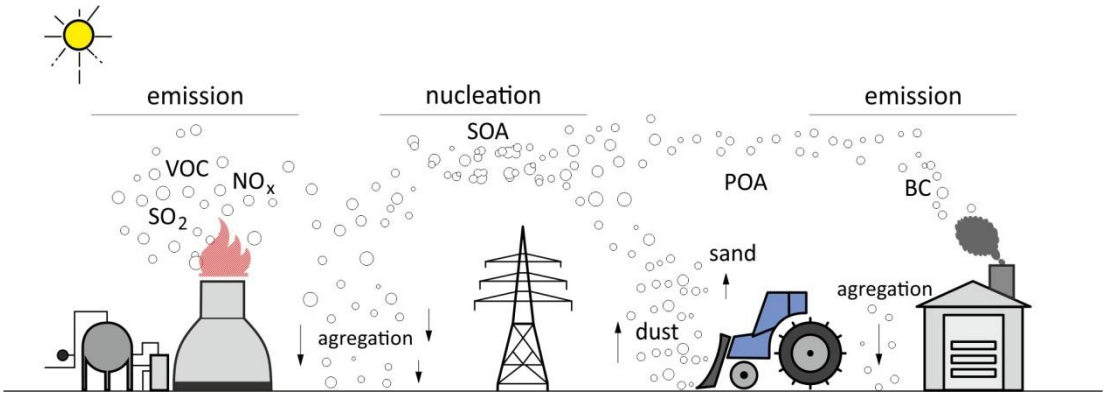


Figure 4. Schematic Representation of the Formation and Transformation of Particulate Matter in the Atmosphere.
Legend: SO_2 – sulphur dioxide, NO_x – nitrogen oxides, VOC – volatile organic compounds, SOA – secondary organic aerosol, POA – primary organic aerosol, BC – black carbon (soot).

The heterogeneous nature of particulate matter means that the same $PM_{2.5}$ mass concentration measured at two different locations may have different effects on human health. It is the composition of particulate matter, rather than its mass concentration alone, that determines its adverse effects, although the duration of exposure may also be a significant factor. The principal constituents of particulate matter include organic and inorganic carbonaceous material, elemental carbon (black carbon), mineral matter, including trace elements, secondary inorganic aerosols (primarily sulphates, nitrates, and ammonium compounds), and water.

From a practical perspective, ambient air quality assessment involves determining the concentrations of undesirable constituents in particulate matter and comparing the measured values with the applicable limit values. It should be noted that particulate matter components such as benzo(a)pyrene, arsenic, lead, cadmium, and nickel have been shown to exert adverse effects on human health as well as on terrestrial and aquatic ecosystems. Consequently, the analytical method should take these constituents into account and enable their determination. Although the adverse effects of particulate matter are most often discussed in relation to human health, its impact on ecosystems through the deposition of pollutants onto soils and vegetation, as well as its detrimental effects on physical infrastructure, including buildings, monuments, and engineering structures, should not be overlooked.

Particle size is one of the most important parameters used to describe the properties of particulate matter, including its adverse effects on the human body. In this context, particulate matter is classified into size fractions, with each fraction defined by its maximum aerodynamic particle diameter. The general classification distinguishes fine particles with an aerodynamic diameter of d < 2.5µm from coarse particles with an aerodynamic diameter of d > 2.5µm. A more detailed classification based on particle size is presented below.

- PM10 – particles with an aerodynamic diameter of d ≤ 10µm,
- PM2.5÷10 (PM_{coarse}) – coarse particles with an aerodynamic diameter of d = 2.5–10µm,
- PM2.5 – fine particles with an aerodynamic diameter of d ≤ 2.5µm,
- PM1 – submicron particles with an aerodynamic diameter of d ≤ 1.0µm,
- PM0.1 – ultrafine particles with an aerodynamic diameter of d ≤ 0.1µm.

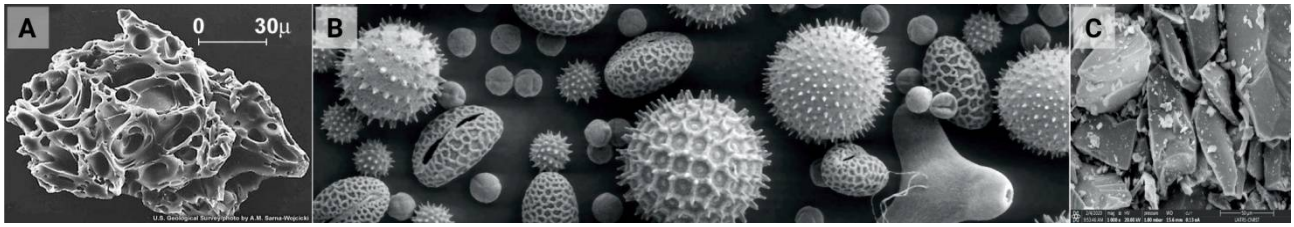


Figure 5. Different Types of Solid Particles

A – Glass shard of volcanic ash, approximately 0.1 mm in length, originating from the 1980 eruption of Mount St. Helens. B – Pollen grains from different plant species, ×500 magnification. C – Ground glass from glass bottles, Source: https://www.usgs.gov/media/images/ash-particle-1980-mount-st-helens-eruption-magnified-200-times source: https://commons.wikimedia.org/wiki/File:Misc_pollen.jpg, https://www.mdpi.com/2073-4352/11/5/488

The chemical composition of particulate matter is largely determined by geographical location, defined not only by urban and industrial infrastructure but also by the natural movement of atmospheric air masses. Meteorological conditions at the sampling site and the season of the year are also of considerable importance, particularly in highly urbanised areas. Regardless of these factors, particulate matter may contain the following constituents:

- crustal material,
- sea salt,
- primary biogenic aerosol particles (PBAP),
- elemental carbon (EC),
- organic carbon (OC),
- secondary organic aerosols,
- secondary inorganic aerosols (SIA): sulphate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) ions,
- trace elements.

The assessment of particle size is of particular importance in the context of particle transport and deposition within the human respiratory tract. Depending on their aerodynamic diameter, particles may be deposited in three principal regions[1] of the respiratory system:

- the extrathoracic airways – including the oral cavity, nasal cavity, pharynx, and larynx,
- the tracheobronchial region – comprising the trachea, bronchi, bronchioles, and terminal bronchioles,
- the gas-exchange region – consisting of the respiratory bronchioles, alveolar ducts, and alveoli.

Accordingly, particulate matter is classified into the following size fractions: the inhalable fraction, which enters the nose and mouth during breathing; the thoracic fraction, which penetrates beyond the larynx; and the respirable fraction, which reaches the lower region of the respiratory tract.

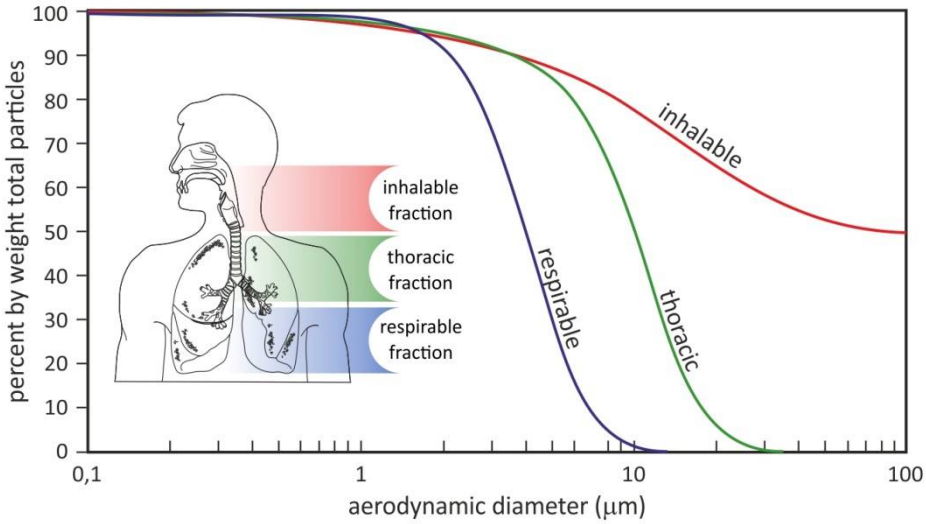


Figure 6. Percentage Distribution of the Inhalable, Thoracic, and Respirable Fractions in Total Airborne Particles According to EN 481.

Source: Sampling and determining aerosols and their chemical components

The gravimetric assessment of workplace air quality is based on determining the change in filter mass before and after exposure. Consequently, this is a well-established method in which, apart from the accuracy of mass measurement, other factors may also be of considerable importance, such as the presence of unbalanced electrostatic charges and the sorption of moisture by particulate matter collected on the filter. Particulate matter sampling in the workplace is carried out using personal samplers attached to the worker's clothing. A sampling pump draws a specified volume of air, typically 1.9–2.0L/min, through the sampler, where solid particles are collected on the surface of the filter.

Air monitoring should be representative of the exposure periods experienced by workers. Longer sampling times allow greater quantities of particulate matter to be collected, thereby reducing the potential uncertainty associated with gravimetric weighing. For this reason, the sampling period should be as long as practicable and should preferably cover the entire work shift. The minimum sampling duration should be at least 25% of the work shift, although a sampling time of not less than four hours is recommended.

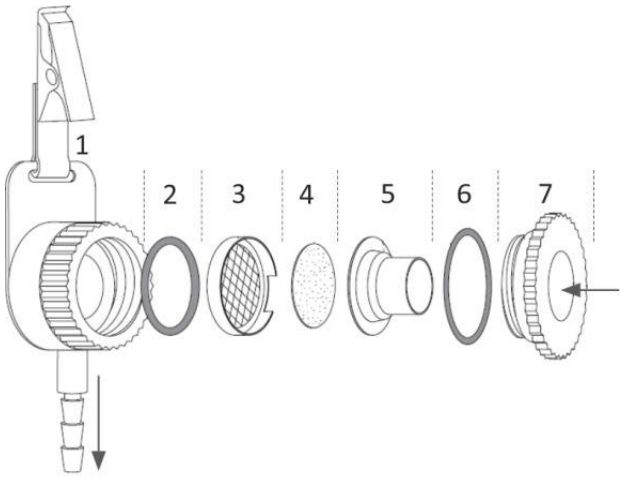


Figure 7. Example of a Personal Sampler.

Source: Health and Safety Laboratory ,,MDHS 14/3 General methods for sampling and gravimetric analysis of respirable and inhalable dust"

Legend: 1 – sampler body, 2 – retaining ring, 3 – lower filter holder, 4 – filter, 5 – upper filter holder, 6 – sealing ring, 7 – outer sampler cover.

The mass of particulate matter is determined from the difference in filter mass before and after sampling, the volume of air drawn through the filter during sampling, and the influence of environmental conditions on the measurement result.

$$C = \frac{M_2 - M_1 - B}{V_s} \quad (1)$$

Legend

C particulate matter concentration (mg/m³)

M_1 mass of the filter (including the cassette, if used) before sampling (mg)

M_2 mass of the filter (including the cassette, if used) after sampling (mg)

B average mass change of the blank samples (mg)

V_S volume of air sampled (m³)

The analysis of particulate matter concentrations in the workplace should take into account both the limit of detection (LOD) and the limit of quantification (LOQ). Both parameters depend on the volume of air sampled, the sensitivity of the balance, and the stability of the weighing process. Detailed information on the determination of LOD and LOQ for the gravimetric analysis of airborne particulate matter samples can be found in ISO 15767:2009, Workplace atmospheres — Controlling and characterizing uncertainty in weighing collected aerosols. In practice, it is convenient to define the LOD of the gravimetric analysis as three times the standard deviation of the mass changes observed for blank samples.

3. Sources of Primary Particulate Matter Emissions

Dust should be considered a pollutant that can originate from both natural phenomena and human activity. Direct emissions into the atmosphere include primary dust, which can be supplemented by secondary dust as a result of chemical reactions and transformations of its precursors, i.e., sulfur and nitrogen compounds and volatile organic compounds. It is no secret that fine dust can be transported over considerable distances, which can increase the concentration of suspended dust in areas where industrial activity is not particularly active. The main sources of primary dust emissions are the combustion of solid fuels in the industrial sector, such as the energy sector, manufacturing technology, and so-called stationary sources. These include local boiler rooms, individual home heating systems, craft workshops, agriculture, and others.

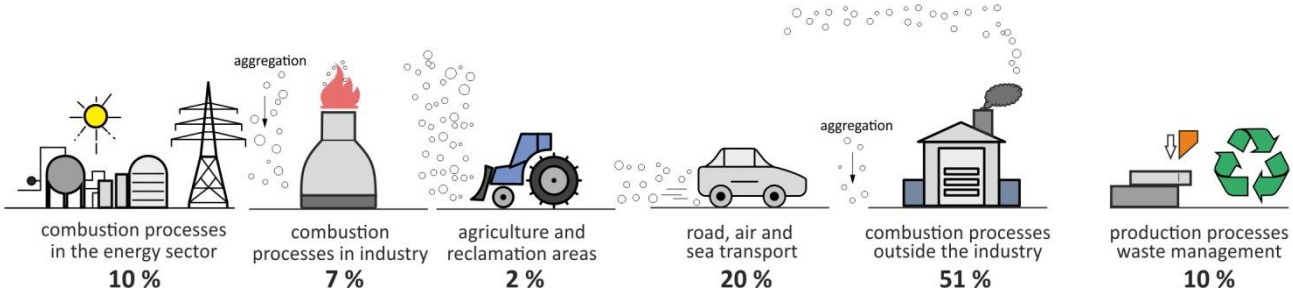


Figure 8. Anthropogenic Sources of Particulate Matter Emissions

Solid fuels used in combustion processes generally consist of carbon, hydrogen, sulphur, and non-combustible mineral constituents. During combustion, these constituents give rise to coarse particulate matter, which, following mechanical fragmentation, forms dispersion particles. Combustion is accompanied by high temperatures at which some mineral constituents evaporate and sublimate, and the products of these transformations are carried away with the hot flue gases. As the temperature decreases, condensation occurs, leading to the formation of colloidal particles. Particles containing elemental carbon are produced as a result of the incomplete combustion of fossil fuels and biomass. In industrial applications, this process is closely monitored because both combustion efficiency and process economics are of considerable importance.

The situation is somewhat different in the case of individual heating sources, where there is often insufficient knowledge and, in many cases, inadequate financial resources to improve the efficiency of these heating systems. The quantity and characteristics of particulate matter generated during fuel combustion depend on the type of fuel used, its degree of fragmentation, the content of non-combustible constituents, mineralogical composition, moisture content, volatile matter content, and other fuel properties, as well as on the combustion conditions, including the type of furnace, grate design, combustion temperature, excess air ratio, fuel feeding method, and other operating parameters. It should also be noted that road transport constitutes a significant source of particulate matter emissions. This sector should be considered not only in terms of emissions resulting from fuel combustion, but also with regard to particulate matter generated by tyre wear, brake pad wear, and other abrasion processes.

During the type approval of motor vehicles, Commission Regulation (EU) 2017/1151 on the type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles is applied. One of the requirements of this regulation is the determination of particulate emissions from internal combustion engines. Such testing may be carried out under laboratory conditions in accordance with the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) or under real driving conditions using the Real Driving Emissions (RDE) test.

Figure 9. Determination of Particulate Matter Emissions Using the WLTP and RDE Test Procedures

Source: Automotive Research and Development Institute – BOSMAL, https://www.automobil-produktion.de/management/verbrauch-bei-neupkw-rund-42-prozent-hoeher-als-angegeben/1029378

The development of the automotive industry is moving towards so-called zero-emission mobility, a concept that is most commonly associated with electric vehicles. In this case, however, attention should primarily be paid to particulate emissions generated by brake systems and tyre wear, particularly in view of the significantly higher curb weight of vehicles equipped with electric powertrains. Nevertheless, electric vehicles are expected to remain a minority of the global vehicle fleet for many years to come. Consequently, research aimed at reducing harmful emissions from conventional internal combustion engines should continue. The phenomena occurring within an internal combustion engine during fuel combustion are illustrated in Figure 10.

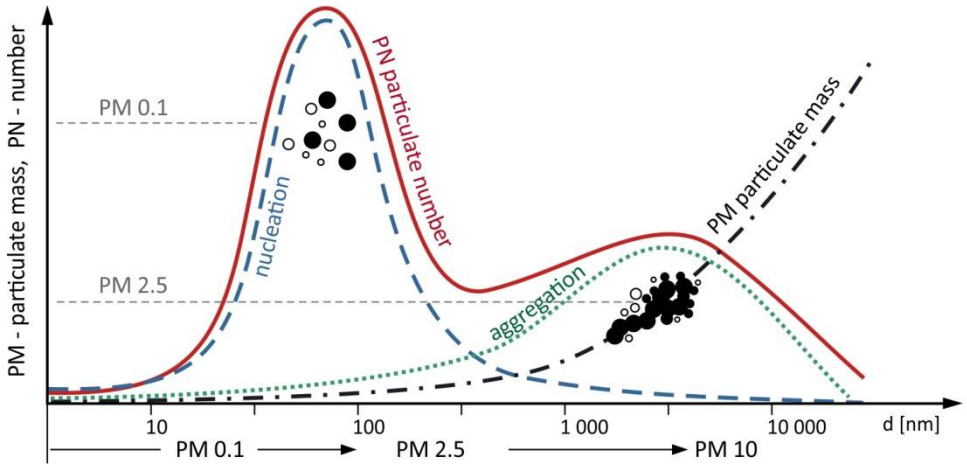


Figure 10. Schematic Representation of Particulate Matter Formation in Internal Combustion Engines.

Source: J. Merkisz, J. Pielecha, Particulate Matter Emissions from Road Transport, PP 2014.

The PM10 and PM2.5 emission levels recorded in Poland in 2023 are presented in Table 1. The largest share of emissions, approximately 77% for PM10 and 93% for $PM_2$2.5, originated from fuel combustion, clearly indicating the sector in which significant improvements are required. Within this sector, the dominant contribution is associated with the combustion of hard coal and biomass in residential households. Agriculture also accounts for a significant proportion of total emissions (approximately 12%), while industrial processes contribute approximately 9%.

Table 1. Main Sources of PM2.5 and PM10 Emissions in Poland – 2023
Source: Assessment of Air Pollution at Regional Background Monitoring Stations in Poland in 2024: Composition of PM_{10} and $PM_{2.5}$ Particulate Matter and Deposition of Heavy Metals and PAHs. GIOŚ, 2025.

	PM10 (Gg)	PM 2,5(Gg)
1. Energy	**248,08**	**217,26**
A. Fuel Combustion	239,89	215,91
Power Industry	4,11	2,09
Manufacturing Industry and Construction	6,16	5,81
Transport	14,49	9,54
Other Sectors	215,14	198,47
B. Fugitive Emissions from Fuels	8,19	1,35
Fugitive Emissions from Solid Fuels	8,07	1,30
Fugitive Emissions from Natural Gas and Oil Systems	0,12	0,05
2. Industrial Processes	**30,03**	**7,76**
Mineral Products	19,41	2,90
Chemical Industry	2,31	1,72
Metal Production	1,55	0,88
Solvent and Other Product Use	4,00	0,54
Other	2,75	1,72
3. Agriculture	**38,57**	**3,97**
Manure Management	11,11	2,37
Agricultural Soils	27,40	1,55
Agricultural Residue Burning	0,05	0,05
5. Waste	**4,58**	**4,45**
A. Solid Waste Disposal	0,00	0,00
Waste Incineration and Open Burning	1,72	1,60
Wastewater Management	0,00	0,00
Other	2,85	2,85
Total	321,26	233,44

The economic structure of individual countries varies considerably, with certain sectors playing a dominant role, such as green energy and renewable energy sources. Consequently, particulate matter emission levels may also differ significantly between countries. Within the European Union, legislation governing emissions is based on the implementation of the Industrial Emissions Directive (IED) and the National Emission Reduction Commitments Directive (NEC), which establishes national emission reduction obligations.

4. Filters Used in Ambient Air Quality Assessment

Table 2 presents the principal types of filters used in ambient air quality studies. The selection of a particular filter material depends on the analyses to be performed, especially chemical analyses. Filters are available in a wide range of thicknesses, basis weights, thermal resistance ratings, and dimensions. This extensive range of products makes it possible to select the solution best suited to the requirements of a given analytical method. Although mass measurement may appear to be the least problematic aspect of the procedure, this is not always the case, particularly when the weighing process is affected by air movement, thermal instability, or electrostatic charges.

Table 2. Types of Filters Used in Ambient Air Quality Studies

Name	Specification	Application
Glass Fibre Filters	Used for general gravimetric air sampling and analysis. They are suitable where no analyses other than gravimetric weighing are required. They are free from binders and additives. They are not susceptible to electrostatic charging but react with acidic compounds, particularly SO_3. Maximum operating temperature: 200°C.	Gravimetric analysis, isocyanates, ethylene glycol, ambient air particulate matter fractions.
MCE	Manufactured from a blend of cellulose acetate and cellulose nitrate, these filters are suitable for air monitoring applications requiring analyses beyond gravimetric determination. They dissolve completely and readily become transparent, making them suitable for fibre counting. They are not affected by moisture. Maximum operating temperature: 125°C.	Metallic particulate matter analysis; asbestos and man-made fibre analysis; ambient air quality monitoring.
PVC	High-quality filters designed for the determination of particulate matter, crystalline silica, and chromium. They are characterised by low tare weight, making them suitable for samples with low particulate loading while providing excellent gravimetric stability. Their low ash content prevents interference during the determination of crystalline silica.	Gravimetric analysis; hexavalent chromium determination; crystalline silica analysis.
PTFE	Chemically resistant and hydrophobic filters suitable for use in aggressive environments. They are appropriate for high-sensitivity analyses with minimal analytical interference. Their low tare weight provides excellent gravimetric stability, making them suitable for samples with low particulate loading. Maximum operating temperature: 230°C. Poor mechanical strength and susceptibility to electrostatic charging may affect weighing results.	Alkaline particulate matter analysis; polycyclic aromatic hydrocarbons (PAHs); pesticide analysis; isocyanate determinat.; ambient air quality monitoring.
Polycarbonate	These filters have a smooth, glass-like surface with a precisely controlled pore size and pore size distribution, providing highly efficient filtration and particle separation for microscopic analysis. They are transparent and non-staining, making them ideal for sample observation. They are chemically and biologically inert and offer good mechanical strength.	Asbestos fibre analysis; scanning electron microscopy (SEM).
Quartz	Heat- and acid-resistant filters suitable for stack emission sampling and diesel engine exhaust applications. They provide high flow rates and are free from binders and additives. Maximum operating temperature: 700°C. They offer a high filtration rate but have relatively poor mechanical strength. They are resistant to chemical attack by flue gas constituents, including HF, HCl, SO_2, SO_3, H_2SO_4, and NO_2.	High-temperature applications; stack gas sampling; particulate matter in flue gases; acidic gases.
Silver	Manufactured from high-purity silver (99.97%), these filters offer excellent resistance to high temperatures and chemical attack. They feature uniform pore size and thickness, can be cleaned and reused, and have a smooth surface that is well suited for particle observation.	Bromine analysis; asbestos analysis by transmission electron microscopy (TEM); crystalline silica analysis by X-ray diffraction XRD

4.1. Standard Requirements for Filters and Weighing Systems

Table 3. Requirements for Gravimetric Weighing Systems

Title of the Standard / Legal Act	Filter size	Readability	St. Dev.
Directive 2005/55/EC on the approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive-ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles.	47mm 70/90/110	d ≤ 1µg d ≤ 10µg	≤ 2µg ≤ 20µg
Commission Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information.	47mm	d ≤ 1µg	2µg
EPA 40 CFR Part 1065 – Engine-Testing Procedures.	47mm	d = 0,1µg	0,5µg
China V/VI – Emission standards for heavy-duty vehicles with a gross vehicle mass exceeding 3,500 kg, equipped with compression-ignition engines or spark-ignition engines fuelled by natural gas (NG) or liquefied petroleum gas (LPG).	47mm	d ≤ 1µg	2µg
PN-EN 12341:2024 – Ambient Air — Standard Gravimetric Measurement Method for the Determination of the PM10 or PM2.5 Mass Concentration of Suspended Particulate Matter.	47mm	d ≤ 10µg	U ≤ 25µg
PN-EN 13284-1 – Stationary Source Emissions — Determination of Low Range Mass Concentration of Dust — Part 1: Manual Gravimetric Method.	47 ÷ 150mm	d ≤ 0,01mg	x
ISO/AWI 7708 – Workplace Air — Size Fraction Definitions for Measurement of Airborne Particles *(in progress).*	25 ÷ 37mm	d ≤ 0,01mg	x
EPA 40 CFR Part 50 – National Primary and Secondary Ambient Air Quality Standards. Quality Assurance Guidance, Document 2.12: Monitoring PM2.5 in Ambient Air Using Designated Reference or Class I Equivalent Methods.	47mm	d ≤ 1µg	1µg
China VI / GB 18352.6-2016 – Limits and Measurement Methods for Emissions from Light-Duty Vehicles.	47mm	d ≤ 1µg	1µg

4.2. Filter Conditioning and Weighing Methods

The assessment of changes in filter mass for ambient or indoor air quality monitoring may appear to be relatively straightforward, as it is based simply on the difference between the filter mass before and after exposure. However, it should be remembered that every analytical method consists of a number of stages at which significant errors may be introduced. A typical measurement procedure used for filter mass determination is illustrated in figure 11. Regardless of the complexity of the measurement system, every balance whether operated manually or automatically—will determine the filter mass. The key question, however, is whether the result will be sufficiently accurate.

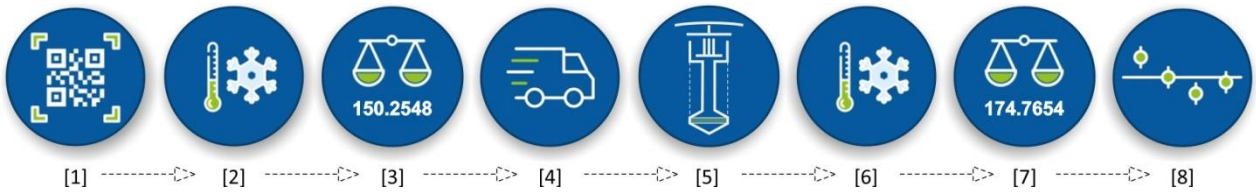


Figure 11. Filter Mass Measurement Procedure

Legend: 1 – filter identification, 2 – conditioning, 3 – first mass measurement, 4 – transport, 5 – exposure, 6 – conditioning, 7 – second mass measurement, 8 – data analysis.

It may be assumed that weighing results will always be accurate provided that the measurement conditions remain stable. This is, however, a considerable simplification, since from a metrological point of view, measurement accuracy is determined by the combined effect of random and systematic errors associated with mass measurement. In this case, only the random error, i.e. the repeatability of the balance readings, is of practical importance. Repeatability depends on:

- measurement conditions, including the stability of temperature and relative humidity,
- the properties of the object being weighed, such as its surface area and electrostatic charge,
- the operator's weighing technique (good handling practice),
- laboratory disturbances, including air movement, floor vibrations, and other environmental factors.

The influence of these factors on measurement accuracy is indisputable and has therefore been taken into account in the relevant standards. For this reason, according to EN 12341:2024, the filter mass before and after exposure is determined as the average of two or three weighings, provided that:

- the difference between successive weighings of a clean filter does not exceed 0.040 mg,
- the difference between successive weighings of an exposed filter does not exceed 0.060 mg.

A different approach to the assessment of measurement accuracy and the estimation of the mass of test filters is presented in the Health and Safety Laboratory (HSL, UK) guidance document Methods for the Determination of Hazardous Substances: General Methods for Sampling and Gravimetric Analysis of Respirable and Inhalable Dust. Under stable weighing conditions, the random error of the weighing process may be estimated as three times the repeatability (standard deviation) obtained from repeated weighings of blank filters. A similar requirement is specified in Commission Regulation (EU) 2017/1151. In this case, the filter mass is considered stable when the variation in the mass of reference (blank) filters does not exceed 0.005 mg, provided that the following weighing room conditions are maintained:

- temperature: 22°C ± 2°C,
- relative humidity: 45% ± 8%

These provisions clearly indicate that the seemingly simple determination of filter mass is not a straightforward measurement. Consequently, specified tolerances for the environmental conditions during filter conditioning are required. These requirements are presented in Table 4.

Table 4. Filter Conditioning Conditions for Different Application Areas

Title of the Standard / Legal Act	Humidity	Temperature
Commission Regulation (EU) 2017/1151 on the type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6).	45% ± 8%	22°C ± 2°C
EPA 40 CFR Part 1065 – Engine-Testing Procedures. **Limitation:** Variations in relative humidity shall not significantly affect the mass of the collected particulate matter; verification by the laboratory is required.	45%	22°C ± 2°C
PN-EN 12341:2024 – Ambient Air — Standard Gravimetric Measurement Method for the Determination of the PM10 or $PM_2$2.5 Mass Concentration of Suspended Particulate Matter.	45% ± 5%	20°C ± 2°C
PN-EN 13284-1 – Stationary Source Emissions — Determination of Low Range Mass Concentration of Dust — Part 1: Manual Gravimetric Method	40% ÷ 50%	20°C ÷ 30°C
ISO/AWI 7708 – Workplace Air — Size Fraction Definitions for Measurement of Airborne Particles *(in progress).*	50% ± 5%	20°C ± 2°C
EPA 40 CFR part 50 National Primary and Secondary Ambient Air Quality Standards / Quality Assurance Guidance. Document 2.12. Monitoring PM2.5 in Ambient Air Using Designated Reference or Class I Equivalent Methods	30% ÷ 40% ± 5%	20°C ÷ 23 ± 2°C

In many cases, particularly for manual weighing methods, the conditioning conditions are determined by the capabilities of the laboratory, including the installation, integration, and control of external equipment. This is the simplest and most cost-effective approach to achieving compliance with the applicable standard and, consequently, to minimising potential errors arising from variations in temperature and relative humidity.

The main limitation of such systems is the lack of temperature uniformity within the weighing room when a conventional office air-conditioning system is used. In addition, excessively low relative humidity may be expected during the winter season, when supplementary heating systems are operating to maintain the required room temperature.

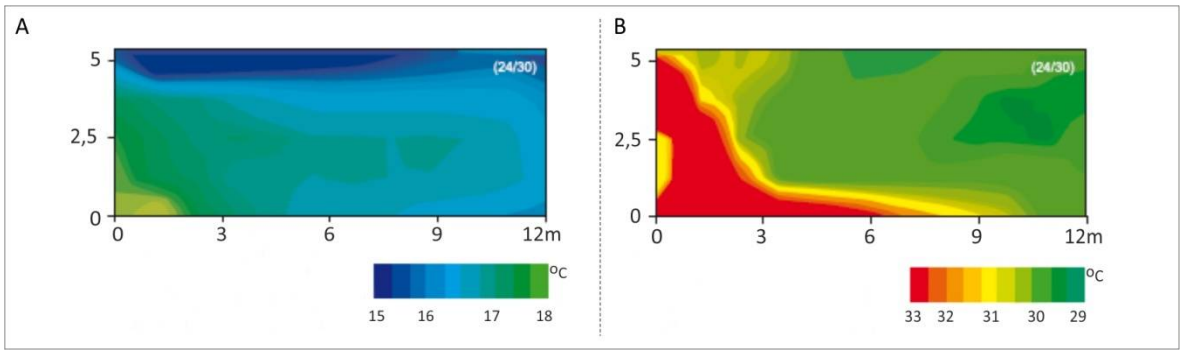


Figure 12. Temperature Distribution in a Weighing Room Equipped with a Conventional Office Air-Conditioning System. Source: Fuji Electric Inverter RSG18LF, A – vertical airflow, T_{Max} 18°C, B – horizontal airflow, T_{Max} 30°C, airflow directed downward and forward

With regard to filter conditioning, a considerably better solution is one in which stable temperature and relative humidity conditions are maintained within the enclosure housing the weighing station. Such a solution is provided by the RB 2.5Y.F robotic weighing system, which operates in accordance with the requirements of EN 12341:2024. The influence of filter conditioning conditions on filter mass variability is defined in EN 12341:2024 (Clause 9, Performance Characteristics of the Method Concept). It appears that relative humidity has the greater influence, primarily due to the surface adsorption of moisture by the filter. However, this issue should always be considered in relation to the specific filter material and the particulate matter collected on it. Any unintended deviations in measurement results caused by environmental conditions should be detected by monitoring changes in the mass of blank filters.

The influence of conditioning conditions on filter mass variability has also been investigated in scientific studies, providing a more detailed understanding of this phenomenon. Filter mass stability was evaluated under conditions of constant temperature with varying relative humidity, as well as constant relative humidity with varying temperature. The experiments were carried out at the Institute of Environmental Engineering of the Polish Academy of Sciences in Zabrze using the UMA 2.5Y.FC automated weighing system.

The results showed that clean glass fibre, quartz fibre, and PTFE filter media exhibit a stable structure and are less sensitive to environmental changes than the same filters after particulate matter collection. Fine particulate fractions, such as PM1 and PM2.5, are more sensitive to variations in temperature and relative humidity. Hygroscopic PM constituents, including nitrates, sulphates, and sea salt, may absorb moisture at elevated relative humidity, thereby increasing filter mass, whereas temperature fluctuations may cause particle expansion or contraction.

For filters equipped with PTFE sealing rings, irregular fluctuations in mass readings were observed as a result of electrostatic charge accumulation. Prior to mass measurement, the filter surface must therefore be deionised. The problem of electrostatic charge is explicitly addressed in virtually every relevant standard, as it is one of the principal factors affecting mass measurements when PTFE filters are used. The results obtained demonstrate the stability of blank filters under varying environmental conditions. Any minor variations observed for loaded filters are most likely attributable to the physical or chemical behaviour of the collected particulate matter rather than to any significant effect of changing environmental conditions on the filter media themselves. Appropriate weighing technique and the quality of the filters used are also important factors.

In a separate study, project C2-001/2020/NP-I, the RB 2.4Y.F robotic weighing system was used. The objective of the study was to demonstrate the equivalence of the automated method to the manual method specified in EN 12341:2024 and to evaluate the influence of changes in relative humidity and temperature on filter mass variability.

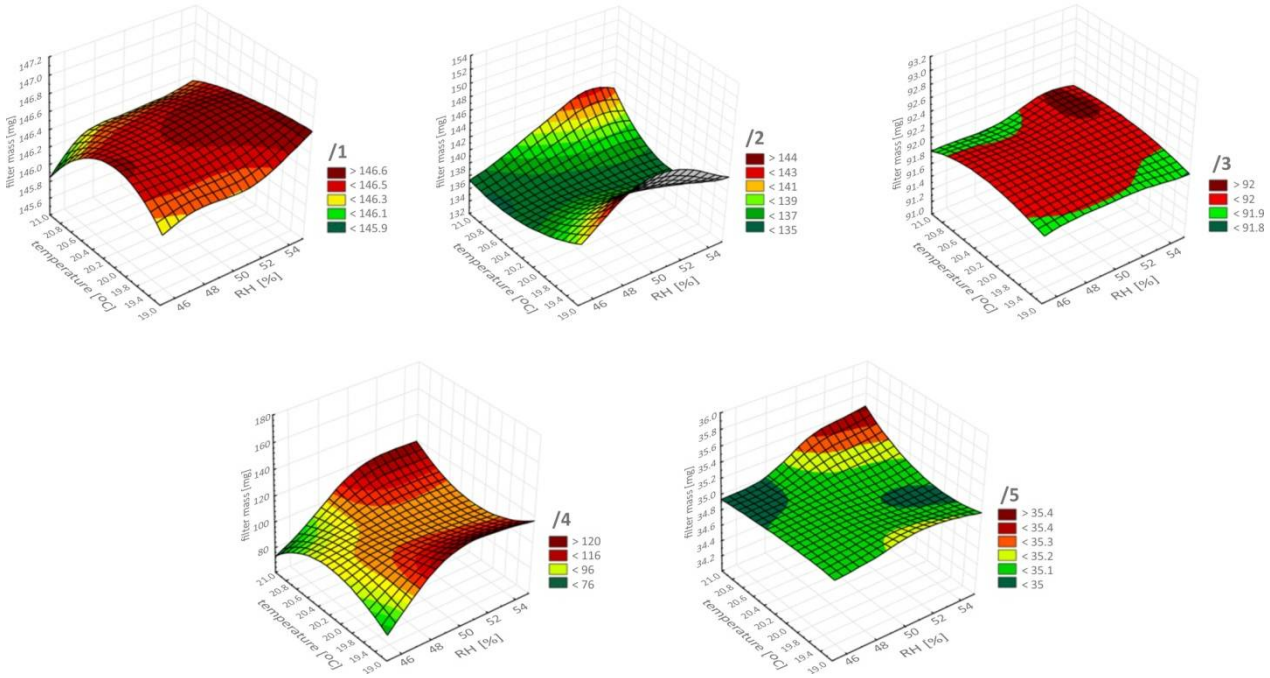


Figure 13. Variation in Filter Mass During Conditioning

Source: Widziewicz-Rzońca K, Janas S, Błaszczak B, et al. Advancing the understanding of PM filter mass stability: unveiling the influence of humidity and temperature. Scientific Reports of Fire University. (2023);1(88):7-26. https://doi.org/10.5604/01.3001.0053.9741

The variability of filter mass under conditioning conditions of 50±5% relative humidity and 20 ± 1°C is presented below.

- /1 Quartz Filters m = 146.01 + 0.003RH + 0.015T
- /2 PFTE m = 157.28 + 0.186RH – 1.473T
- /3 Glass Fibre Filters m = 90.038 + 0.018RH + 0.055T
- /4 Nylon Filters m = 51.799 + 2.242RH – 2.907T
- /5 Polycarbonate Filters m = 35.76 + 0.004RH – 0.046T

5. Concept of Mass Measurement

Mass measurement is based on determining the force with which the object being weighed is attracted by the Earth and expressing this value in units of mass, such as grams, milligrams, or other units obtained through the application of appropriate conversion factors. Displaying the weighing result in units of mass is possible because every balance is factory calibrated (adjusted) using certified mass standards. During this process, the buoyancy force is not taken into account, and adjustment is performed using steel mass standards with a density of approximately 8 g/cm³. In reality, the density of the objects being weighed may differ considerably from that of the calibration standards. For this reason, the reported value is referred to as the conventional mass of the object.

Figure 14. Factory Adjustment Using Certified Mass Standards

In many weighing methods, the effect of buoyancy on the measurement result is negligible. An exception is the study of particulate emissions from internal combustion engines, where the filter mass measurement result must be corrected for the effect of air buoyancy. The general functional diagram of the scale is shown in figure 15.

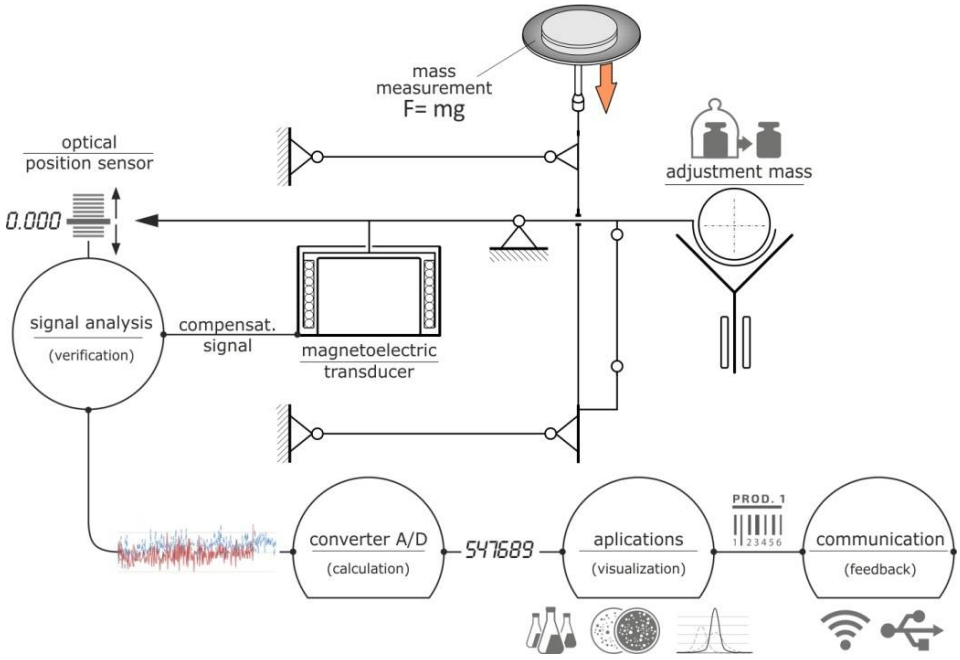


Figure 15. Functional diagram of a scale with an electromagnetic transducer

Resolution ~ 60 mln. division, St. dev. ~ 0,5x10^{-6}, application UYA, MYA, XA balances

A typical mass measurement consists of a single determination of the mass of the object being weighed. However, a closer examination of the weighing process reveals that information is required about the state of the balance both when it is unloaded and when the sample is placed on the weighing pan. From a metrological point of view, these are in fact two separate measurements. The unloaded balance does not necessarily indicate a perfect zero, and even the "empty" weighing pan is effectively weighed, although the result is conventionally displayed as 0.0 g.

These considerations are particularly important in gravimetric methods in which the mass of an object is determined as the difference between two measurement states. This applies to the evaluation of various thermal processes, such as heating, ageing, and ashing, as well as to filtration and absorption processes. In such cases, the procedure may be referred to as differential weighing. In some applications, the time interval between successive weighings may extend over several hours, introducing additional disturbances due to changes in environmental conditions. This is particularly relevant in the determination of particulate matter emissions from stationary sources, the measurement of ambient particulate matter mass concentrations, and the assessment of particulate emissions from internal combustion engines.

Figure 16. Manual Filter Mass Measurement Using the MYA 5.5Y Microbalance
Max 5g, Readability d=1µg, Precision St.dev.=0.05 µg, Automatic Internal Adjustment, OIML Certified

When the mass change resulting from these processes is substantial (m > 50% of the balance capacity), the accuracy of the analysis is determined by changes in balance sensitivity and the magnitude of the random error. In contrast, for objects with very low masses, such as filters or filter papers, whose masses are typically in the milligram range, measurement accuracy depends almost exclusively on the magnitude of the random error.

Figure 17. Factors Affecting Random Error in Mass Measurement

5.1. Adjustment

Mass measurement in industry must be both rapid and reliable, particularly when the measurement result is used as an important quality parameter or as part of a production control system. Consequently, weighing systems are expected to operate accurately under all conditions, regardless of variations in the external environment. This assumption is generally valid for balances with relatively large readabilities (d ≥ 1 g). Such instruments are typically used for technical weighing applications and are generally based on strain-gauge load cells. More accurate mass measurements in industrial and laboratory applications require considerably more sophisticated weighing systems employing electromagnetic force compensation (EMFC) technology. Their measurement accuracy is maintained through periodic balance adjustment.

The purpose of balance adjustment is to correct the balance indication by comparing the weighing result obtained for the internal adjustment weight with its assigned reference value. This procedure may be performed automatically, for example in response to changes in temperature or after a specified time interval, or semi-automatically before measurements are started, following operator intervention. The internal adjustment weight does not have its own calibration certificate. However, since calibration is performed for the balance as a complete measuring instrument to verify its measurement performance, it also confirms the assigned value of the internal adjustment weight. The principle of balance adjustment is illustrated in figure 18.

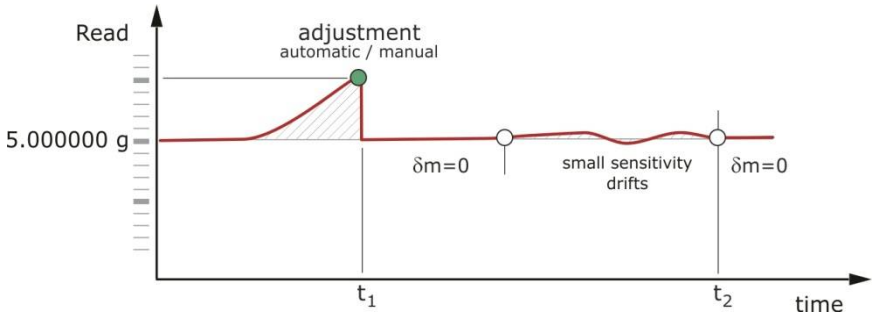


Figure 18. General Principle of Electronic Balance Adjustment

In general, balance adjustment is essentially a standard weighing operation. From a metrological point of view, the quality of this process may therefore be characterised by its measurement precision. As is well known, the precision of any measurement depends strongly on the conditions under which it is performed and on the operator's skills. It should be noted that automation of the adjustment procedure and the integration of the internal adjustment weight within the balance significantly improve measurement precision compared with manual adjustment. This is particularly important because the result of weighing the internal adjustment weight is used to correct the sensitivity of the balance. There is no universal technical solution for balance adjustment, as it is always an integral part of the balance and may differ in terms of design, location, dimensions, and operating principle. Examples of adjustment mechanisms used in laboratory balances are shown in figure 19.

The value of the internal adjustment weight is typically between 70% and 90% of the maximum balance capacity. Consequently, correcting changes in balance sensitivity by means of the adjustment procedure is most effective when weighing relatively heavy objects.

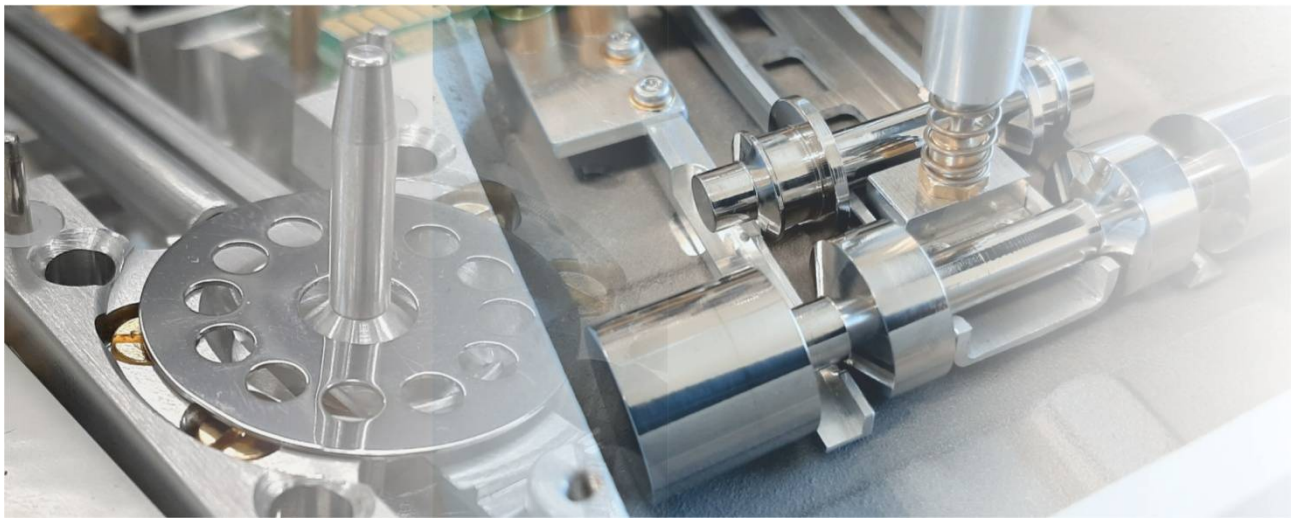


Figure 19. Internal Adjustment Weights of the **MYA** Series Microbalance and the **XA** Analytical Balance

It should be noted that the assessment of measurement accuracy requires the evaluation of both systematic and random errors. As discussed previously, the systematic error, i.e. changes in balance sensitivity, is significantly reduced by the balance adjustment procedure, whereas the random error remains essentially constant, provided that the measurement conditions are stable. This is, however, a simplification, since in practice the magnitude of the random error is also influenced by the operator's weighing technique and the stability of the objects being weighed. A practical conclusion regarding the role of internal balance adjustment may therefore be stated as follows: the accuracy of mass measurements for filters and other low-mass objects depends almost exclusively on the magnitude of the balance's random error. This relationship is illustrated graphically in figure 20.

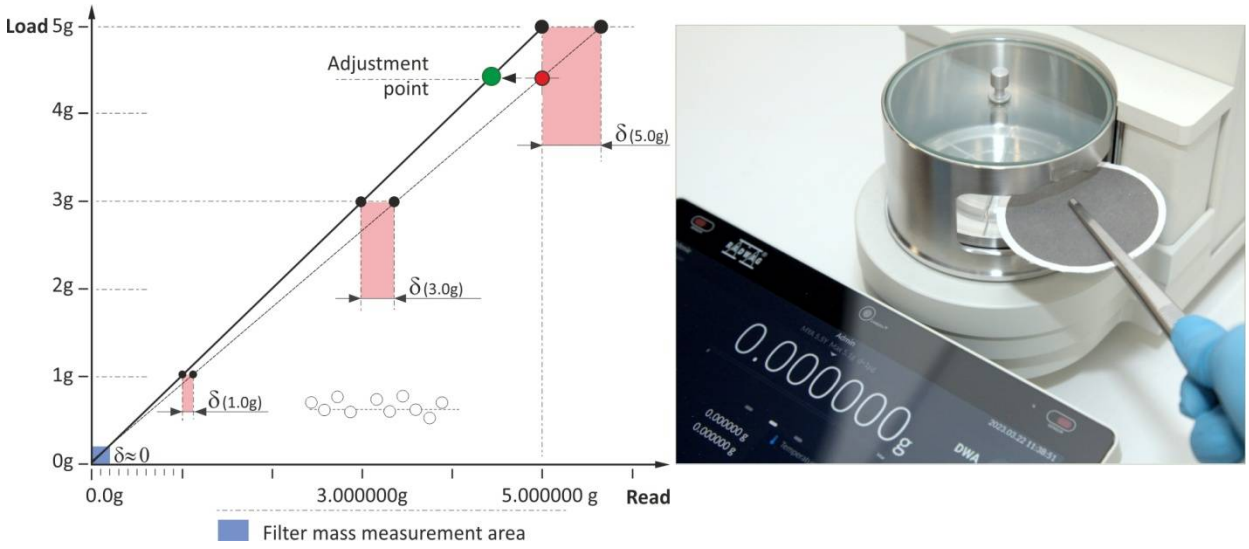


Figure 20. Balance Sensitivity Correction Using the **MYA 5.5Y.FA** Microbalance

Max 5g, Readability d=1µg, Precision St.dev.=0.5µg, automatic internal adjustment, OIML certified

5.2. Legal Verification of Weighing Systems – Facts and Myths

Legal verification is the means by which the State exercises regulatory control over important aspects of public life. In trade, it protects customers against potential fraud, while in business-to-business (B2B) transactions it provides confidence in both the quality and the quantity of the products supplied. In both cases, legal verification operates primarily at the macro level and is governed by OIML recommendations implemented through national legislation. Environmental protection, and particularly the measurements performed in this field, is directly related to the protection of human health. Consequently, such measurements must be subject to monitoring and supervision within the framework of legal metrology. In principle, this requirement is beyond dispute. It should be emphasized that the foundation of metrology is measurement traceability, which is based on an unbroken chain of calibrations linking measurement results to recognized measurement standards. The smallest conventional mass standard has a nominal value of 1 mg (10^{-3} g), which significantly limits the ability of legal metrology authorities to verify the performance of balances with extremely high resolution. It is also important to note that legal metrology classifies balances according to the value of the verification scale interval (e), thereby defining their accuracy class and the corresponding maximum permissible errors (MPEs). Today, mass measurements can be performed with a readability of 10^{-6} g, which requires a fundamentally different approach to the evaluation of weighing instrument performance.

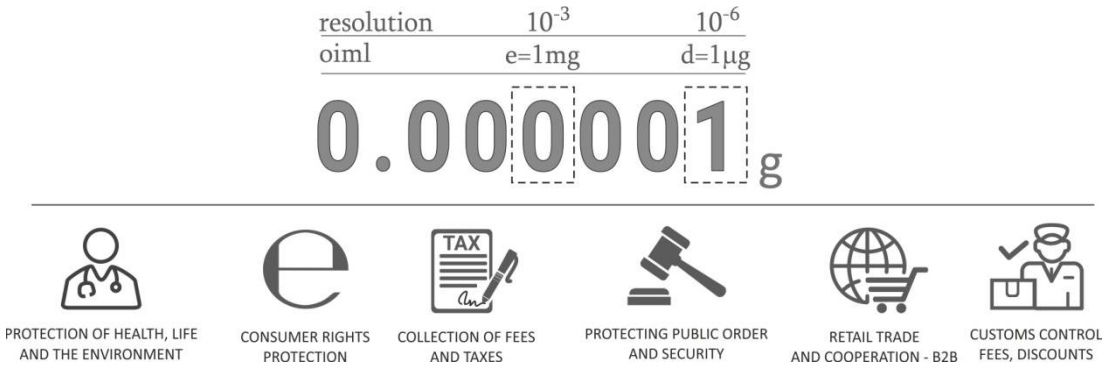


Figure 21. Weighing Instrument Categories and Readability in Legal Metrology

Does this mean that legal metrology is outdated and no longer useful? Certainly not. On the contrary, it provides standardized and internationally recognized procedures for evaluating the performance of weighing instruments. As a result, the same weighing system can be assessed objectively and repeatedly, regardless of its installation site. Although the maximum permissible errors specified in legal metrology are considerably larger than those achieved by modern electronic balances, this merely illustrates the remarkable progress that has been made in mass measurement technology. A good example of this technological development is Radwag Electronic Balances. Balances used for environmental measurements must undergo periodic legal verification whenever this is required by national legislation. At the same time, Quality Management Systems require documented metrological control through routine performance checks and periodic calibration.

This creates a dual system of metrological supervision, which applies not only to electronic balances but also to many other measuring instruments. In practice, however, the most important element is routine day-to-day verification carried out in accordance with the laboratory's Standard Operating Procedures (SOPs), as it provides the most realistic assessment of the current technical condition and measurement performance of the balance. This procedure is not always straightforward, particularly in the case of robotic weighing systems.

The metrological performance of a balance may be evaluated in terms of indication accuracy (systematic error), repeatability (random error), eccentric loading error, and the accuracy of indications when using the tare function, among other characteristics. According to legal metrology requirements, the evaluation includes tests of indication accuracy for increasing and decreasing loads, a repeatability test at one-half of the maximum capacity (½ Max) and at a load close to the maximum capacity (approximately Max), as well as an eccentric loading test. The maximum permissible deviations for these tests are identical to those applied during conformity assessment, namely 0.5e, 1e, and 1.5e.

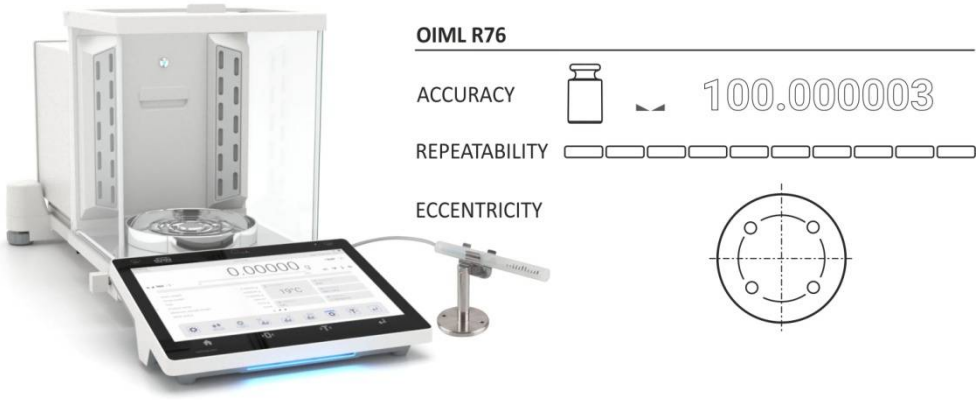


Figure 22. Basic Metrological Tests Performed on the **XA 82/220.5Y.A** Analytical Balance

From both a metrological and an engineering perspective, the repeatability of balance indications, provided that the test conditions are stable, is a constant characteristic of a given mechanical and electronic design. In accordance with GLP/GMP principles, the load should always be placed at the centre of the weighing pan; consequently, the eccentric loading error, although present, is generally negligible. In practice, the only metrological characteristic requiring routine verification is the balance sensitivity error.

This is typically evaluated using certified mass standards at two load levels: a low load (approximately 1–5% of the maximum capacity) and a high load (approximately 50–100% of the maximum capacity). Examples of the metrological requirements applicable to the XA 110.5Y.A analytical balance in accordance with legal metrology are presented in tables 5 and 6.

Table 4. Main Metrological Parameters of the XA 82/220.5Y.A Analytical Balance

Maximum capacity	Minimum capacity	Readability	Verification unit	Number of Verification unit	OIML class
Max 82/220g	Min 1mg	d=0.01/0,1mg	e=1mg	n= 22 000 000	I

Table 5. OIML Requirements for the XA 82/220.5Y.A Analytical Balance

Balance load in verification units	Balance load in grams	MPE in verification units (e)	MPE in balance units (g)	MPE in use	MPE According to Radwag QC
(n)	(g)	Conformity Assessment / Subsequent Verification		(g)	(g)
0e ≤ m ≤ 50 000e 50 000e < m ≤ 200 000e 200 000e < m	0g ≤ m ≤ 50g 50g < m ≤ 200g 200g < m ≤ 220g	± 0,5e ± 1,0e ± 1,5e	± 0,5mg ± 1mg ± 1,5mg	± 1,0mg ± 2,0mg ± 3,0mg	± 0,06mg

Beyond metrology, assessing the quality of a balance can also include the time it takes for the weighing result to be ready for reading. There's a lot of ambiguity here, as "weighing time" isn't a standardized concept. The weighing process consists of at least several steps, such as sample preparation, placing it on the weighing pan, measuring, and reading. This is especially important when the balance has a weighing chamber with sliding glass panes. It can be stated that the higher the balance's resolution ($10^{-3} \rightarrow 10^{-6}$), the longer the measurement time.

Accurately determining the mass of a sample with a resolution of 0.001 mg takes some time. Marketing is known for conveying the information the customer is looking for, although sometimes it doesn't reflect reality. Therefore, you can find information for balances such as weighing times of 1 second or 1.5 seconds, which doesn't make much sense: measurement accuracy is important; fast doesn't necessarily mean precise. Another approach is to determine the time it takes for the weighing result to fall within the tolerance zone; the weighing result doesn't have to be stable. The challenge here is how to define this tolerance zone, especially on a micro scale. This solution is possible using the bar graph offered by the 5Y series scales. Minimum and maximum values can be defined, and the colour of the load indicator informs the operator of the correct sample weight.

The procedure used to verify the correctness of balance indications through a Standard Operating Procedure (SOP) should be simple, concise, and capable of providing an immediate and objective assessment of balance performance. An example of an SOP verification worksheet is presented in Table 7.

Table 6. Daily Verification of Balance Indications Using an SOP at Two Load Levels

Instruction	**Status**
1. Remove all objects from the weighing pan.	ok.
2. Press the adjustment key and perform the balance adjustment.	ok.
3. Zero the balance indication, if necessary.	ok.
4. Place the first certified mass standard on the weighing pan.	M_{wz} = 0.5000028 g
5. Record the balance indication, **R (g)**.	R = 0.49999
6. Compare the balance indication with the reference value stated in the calibration certificate and determine the deviation, **D (g)**.	$D = M_{wz} - R$ 0.5000028 – 0.49999 D = -0,0000128g
7. Place the second certified mass standard on the weighing pan.	M_{wz} = 50.00006 g
8. Record the balance indication, **R (g)**.	R = 49.99998g
9. Compare the balance indication with the reference value stated in the calibration certificate and determine the deviation, **D (g)**.	$D = M_{wz} - R$ 50.00006 - 49.99998 D = - 0.00008 g
10. Compare the calculated deviations with the limits specified in the Quality Management System.	
11. Example: Acceptance limit for the **0.5 g** mass standard: **±0.00005 g** relative to the reference value. b. Acceptance limit for the **50 g** mass standard: **±0.00010 g** relative to the reference value.	
12. Acceptance limits for the 0.5 g mass standard: a. Upper acceptance limit: HI = 0.5000028 g + 0.00005 g = 0.5000528 g ≈ 0.500053 g**.** b. Lower acceptance limit: LO = 0.5000028 g − 0.00005 g = 0.4999528 g ≈ 0.499953 g**.** c. Verification: 0.499953 g ≤ R = 0.49999 g ≤ 0.500053 g**.**	
13. Acceptance Limits for the 50 g mass standard a**.** Upper acceptance limit: HI = 50.00006g + 0.00010g = 50.00016g b. Lower acceptance limit: LO = 50.00006g – 0.00010g = 49.99996g c. Verification: HI = 50.00016g < R = 49.99998g < LO = 49.99996g	

Legend

M_s – reference value of the mass standard as specified in the calibration certificate. Determine this value by adding or subtracting the certified correction from the nominal mass.
R – balance indication obtained when weighing the mass standard. Record the value only after the balance indication has stabilized.
D – deviation between the balance indication and the reference value of the mass standard, representing the indication error of the balance at the applied load.

6. Manual Measurements

Manual mass determination by placing a load directly on the weighing pan is the simplest and most cost-effective weighing method and is widely used in many laboratories. At the milligram scale (10^{-3} g), it is a reliable technique; however, at the microgram scale (10^{-6} g), certain limitations become apparent. In mass measurement, the most important factor is the size of the object being weighed in relation to the balance resolution[1] (d). Higher balance readability generally requires the use of draft shields, clearly demonstrating that physical phenomena such as air movement have a significant adverse effect on mass determination. These considerations are particularly relevant to methods involving the weighing of filters and filter papers, i.e. objects with low mass but relatively large surface area.

Figure 23. Manual Weighing of a Filter Paper for Suspended Solids Determination in a Wastewater Treatment Plant Using an **XA 82/220.5Y** Analytical Balance

Furthermore, this method usually requires multiple determinations of the filter mass, which may introduce additional errors at different stages of the analytical procedure. From a metrological point of view, the accuracy of the measurement method in this case depends almost exclusively on the magnitude of the random error. Assuming stable measurement conditions, the random error is influenced primarily by the human factor. The ability to perform proper weighing, commonly referred to as good handling, encompasses a range of theoretical knowledge and practical skills, including shock-free placement of the sample, positioning the load at the centre of the weighing pan, monitoring the stability of the balance indication, and following the prescribed weighing procedure.

6.1. Design Features of Manual Weighing Systems

From the user's perspective, most laboratory balances appear to be very similar. Consequently, even relatively small differences in balance design provide little indication of how accurately the mass of a sample can actually be determined. The presence of potential factors that may interfere with the weighing process further complicates this assessment. Most users seek universal weighing systems capable of performing measurements over the entire weighing range, from the minimum load (Min) to the maximum capacity (Max). Although such versatility is economically attractive, it is not necessarily the optimal solution from a metrological point of view, particularly with respect to the accuracy of gravimetric measurements.

[1] [1] OIML International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM), 3rd Edition, 2007

The required balance readability is usually specified in standards or technical guidelines. For example, EN 872, Water Quality, Determination of Suspended Solids, Method by Filtration Through Glass Fibre Filters, specifies "an analytical balance capable of weighing with an accuracy of at least 0.1mg." Similarly, EN 13284-1:2017, Stationary Source Emissions, Determination of Low Range Mass Concentration of Dust, Part 1: Manual Gravimetric Method, requires "a balance with a readability of 0.01 mg to 0.1 mg; the weighing range shall be appropriate for the masses to be determined." A similar requirement is given in EN 12341:2024, Ambient Air, Standard Gravimetric Measurement Method for the Determination of the PM10 or PM2.5 Mass Concentration of Suspended Particulate Matter, which states: "The balance shall be installed and operated in a weighing room, and its readability shall be equal to or better than 0.01mg."

The above requirements reveal a certain degree of ambiguity in the applicable standards, as they refer either to measurement accuracy or to balance readability. In the first case, measurement accuracy should be understood as the combined effect of the balance's random and systematic errors. In the second case, it should be recognised that balance readability is not synonymous with measurement accuracy, particularly when filters are being weighed. What, then, do balances designed for manual weighing actually offer in terms of metrological performance?

The balance readability displayed to the user represents only a small part of the balance's digital signal-processing system. The internal measurement signal processing system operates with a resolution of approximately 40 to 90 million internal divisions. These signals are continuously analysed, digitally filtered, and subsequently converted into the displayed readability used for routine sample weighing. The readabilities of typical balances used in laboratory applications are presented in table 8.

Table 7. Basic Specifications of Laboratory Balances

Model	Maximum capacity	Readability	Number of verification units	Repeatability as St. Dev.
AS 220.X7	220g	0.1mg	2 200 000	0.06 ÷ 0.07mg
AS 520.X7	520g	0.1mg	5 200 000	0.07 ÷ 0.2mg
AS 82/220.X7	82/220g	0.01/0.1mg	22 000 000	0.01 ÷ 0.06mg
XA 210.5Y	210g	0.01mg	21 000 000	0.005 ÷ 0.012mg
MYA 5.5Y	5g	0.001mg	5 000 000	0.0004 ÷ 0.0012mg
UYA 2	2.1g	0.0001mg	21 000 000	0.00015 ÷ 0.00035mg

A better understanding of balance readability and its practical significance can be obtained by comparing it with distance measurement. Measuring a distance of 2,000 m with a readability of 1 mm requires the measurement error to be no greater than approximately 0.5mm. This level of performance is comparable, in terms of relative resolution, to that of a typical analytical balance, such as the AS 220.X7. Mass measurements performed in the pharmaceutical industry are considerably more demanding. To achieve an equivalent level of performance, a distance of 2,000 m would have to be measured with a readability of 0.1mm while maintaining a maximum measurement error of only 0.05÷0.07mm.

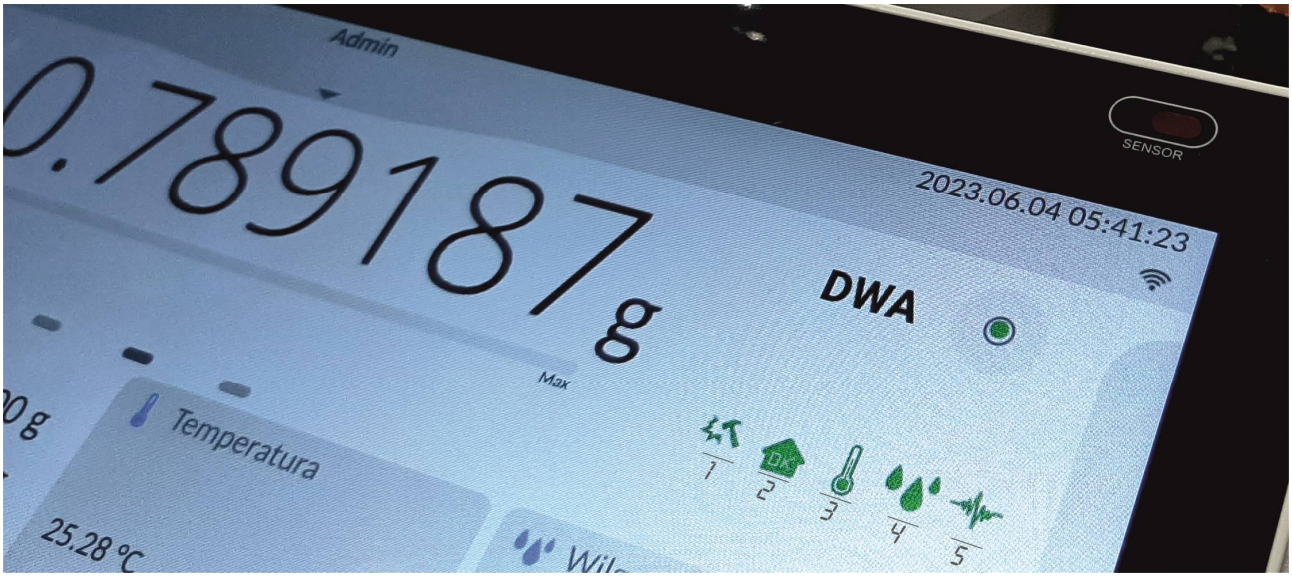


Figure 24. Balance Readability and Applications Supporting the Weighing Process
Legend: 1 – weighing quality monitoring (shock detection), 2 – Digital Weighing Auditor status, 3 – temperature monitoring, 4 – relative humidity monitoring, 5 – vibration detection.

Achieving such a high level of measurement accuracy requires the use of highly sophisticated weighing systems, such as the XA 5Y series balances. As is well known, these instruments combine advanced mechanical and electronic components with sophisticated software algorithms for the analysis and processing of measurement signals.

One of the most important characteristics of any balance is its ability to produce repeatable measurement results. This property is a measure of weighing precision and is commonly expressed in terms of the standard deviation, which indicates the dispersion of repeated measurements of the same quantity and thus reflects the magnitude of the random error.

Unfortunately, one of the major factors contributing to an increase in random error is excessive air movement in the vicinity of the balance. The larger the surface area of the object being weighed, the greater the adverse effect. Consequently, increasing the balance readability from 0.1mg to 0.01mg and further to 0.001mg requires appropriate modifications to both the balance design and the weighing pan. Such design solutions are also standard features of balances manufactured by Radwag.

From an economic perspective, it is not practical to pursue an ideal solution capable of weighing large-area objects with an extremely high readability of 0.0001mg, at least in manual weighing systems. An example of the design optimisation implemented in the AS X7 series balances is presented in figure 25.

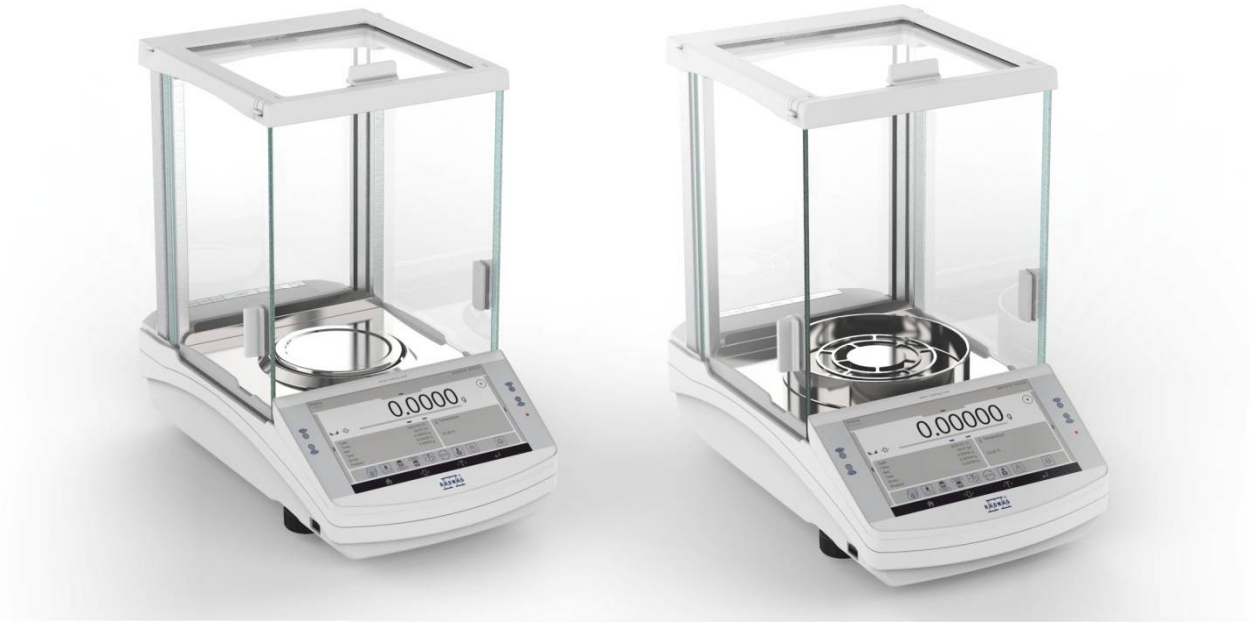


Figure 25. Comparison of Weighing Pan Designs: **AS 220.X7**, readability 0.1 mg and **AS 82/220.X7**, readability: 0.01/0.1 mg

Similar design solutions have been implemented in the MYA 5Y series microbalances, enabling filter mass measurements with a readability of 0.001mg. In the standard configuration, the microbalance is equipped with a 26mm diameter weighing pan, allowing the determination of the mass of filters up to 25mm in diameter. The universal MYA 5.5Y.FA model accommodates filters with diameters of up to 70mm. In this case, the design of the weighing pan is optimized for the specific measurement method.

Figure 26. MYA 5.5Y and **MYA 5.5Y.FA** Microbalances with a readability of 0.001mg

6.2. Accuracy of Manual Weighing Methods

An accurate measurement is one that provides information about the true mass of a sample. However, accuracy is a qualitative concept, it describes a measurement as either accurate or inaccurate and, therefore, cannot be expressed numerically. How, then, should measurement accuracy be evaluated? When discussing measurement accuracy, two fundamental aspects must always be considered: the systematic error, which is associated with trueness (measurement bias), and the random error associated with the measurement process. The systematic error, or measurement bias, is defined as the difference between the measured value and the true (or reference) value. This relationship is established during the manufacturing process by means of certified mass standards. At Radwag, this procedure is performed at multiple stages of production and quality control and constitutes an essential element of ensuring metrological traceability.

Figure 27. Verification of Balance Indication Accuracy Using Certified Mass Standards in the Radwag Quality Control Department and Filter Weighing as a Qualitative Assessment of Balance Performance for Laboratory Applications

The accuracy of the mass standards used to establish the relationship between the balance indication and the units of mass represented by the reference standards is of fundamental importance in this process. Systematic error may be regarded as a constant offset in the balance indication error, which decreases approximately linearly as the applied load decreases. This observation provides valuable practical guidance for laboratories performing measurements of very small masses.

A parameter describing the accuracy of a balance over its entire weighing range is linearity, or more precisely, the linearity error. Good linearity ensures that the change in the balance indication (ΔR) is always proportional to the corresponding change in the applied load (ΔL). In practice, particularly at the microgram level, perfect linearity cannot be achieved. The linearity error therefore includes a component of the systematic error, although its magnitude is generally small, typically not exceeding a few balance divisions.

A fundamental characteristic of every balance is its random error, expressed as the repeatability of indications, which determines measurement precision, provided that the measurement conditions remain stable. In practical terms, repeatability is the ability of a balance to produce the same indication when the same object is weighed repeatedly under repeatability conditions. In legal metrology (OIML), the dispersion of repeated measurement results is expressed as the difference between the maximum (Max) and minimum (Min) indications. In most other metrological applications, measurement precision is quantified by the standard deviation (SD), which is a measure of the dispersion of repeated results. A low standard deviation indicates high measurement precision, meaning that the results are closely grouped and the balance is operating correctly. Examples illustrating measurement precision under different operating conditions are presented in figure 28.

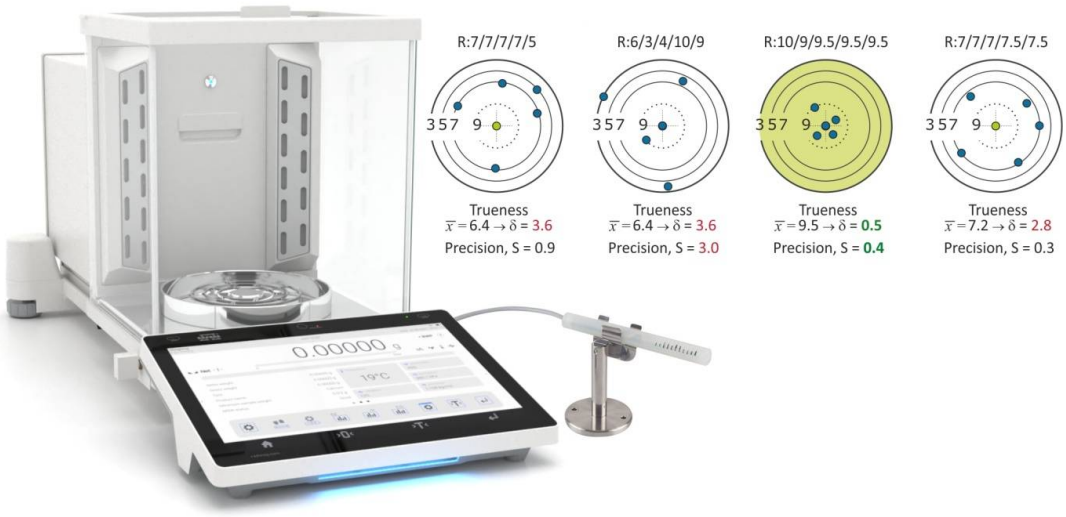


Figure 28. XA 82/220.5Y.A Analytical Balance Equipped with a THB Environmental Sensor

In some applications, the accuracy of mass measurements depends almost exclusively on the magnitude of the balance's random error. Typical examples include dispensing small quantities of pharmaceutical substances, weighing filter papers, and determining the mass difference of filters for the gravimetric determination of PM10 and PM2.5 mass concentrations in ambient air. Unfortunately, measurement precision depends not only on the performance of the balance itself but also on the following factors:

- test conditions – variations in temperature and relative humidity, floor vibrations, and excessive air movement;
- the size and geometry of the object being weighed – a larger surface area, for example a filter of greater diameter, results in increased dispersion of balance indications;
- weighing technique (good handling) – avoiding mechanical shocks and placing the load on the weighing pan without contact with the draft shield or other balance components;
- the thermal stability of the balance – adequate acclimatization time and warm-up time;
- the specific properties of the sample – hygroscopicity and thermal instability.

Considering the influence of these factors, the performance of some balances should be verified at the place of use as part of an operational qualification (OQ). When evaluating the accuracy of a measurement method, it should be recognised that the mean value obtained from a series of measurements is not always an objective indicator of analytical performance, as illustrated in table 9.

Table 8. Arithmetic Mean and Random Error in a Series of Measurements – Weighing of a Micro Flask Using an XA 6.5Y Microbalance

No.	SERIES 1	SERIES 2
1	0,876543	0,876543
2	0,876519	0,876541
3	0,876541	0,876544
4	0,876565	0,876545
5	0,876532	0,876539
6	0,876528	0,876542
7	0,876543	0,876540
8	0,876528	0,876541
9	0,876544	0,876542
10	0,876548	0,876544
$\bar{x}$	0,876539	0,876542
S	0,013 (!)	0,002 :)

The standard deviation, as a measure of the dispersion of measurement results, can be used to estimate the interval within which the mass of the weighed sample is expected to lie with a given probability. This relationship is described by the so-called three-sigma (3σ) rule, which applies to data following a normal (Gaussian) distribution. According to this rule, the mass of the sample falls within the following intervals with the corresponding probabilities:

- 68.27% probability that the sample mass lies within ±1S of the arithmetic mean;
- 95.44% probability that the sample mass lies within ±2S of the arithmetic mean;
- 99.73% probability that the sample mass lies within ±3S of the arithmetic mean.

These statistical principles have been applied in quality control for decades. One of the best-known examples is the Six Sigma methodology, developed at Motorola in the 1980s by Dr. Mikel Harry.

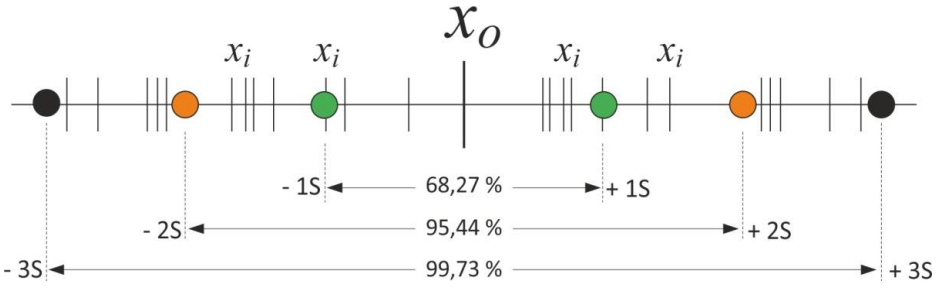


Figure 29. Three-Sigma Rule

Table 9. Repeatability of Indications (mg) for Small Loads as a Function of the Balance Maximum Capacity and Readability

Load	UYA	MYA	XA micro	XA		AS_X7		AS_R	
Max (g)	Readability d (mg)								
	0,0001	0,001		0,01	0,1	0,01	0,1	0,01	0,1
2	0,00015	0,0004	x	x	x	x	x	x	x
5	x	0,0004	x	x	x	x	x	x	x
6	x	0,0004	0,0008	x	x	x	x	x	x
11	x	0,0007	x	x	x	x	x	x	x
21	x	0,0007	0,0009	x	x	x	x	x	x
30	x	0,0009	x	x	x	x	x	x	x
41	x	x	x	0,004	x	x	x	x	x
52	x	x	x	0,005	x	x	x	x	x
53	x	x	0,0007	x	x	x	x	x	x
62	x	x	x	x	x	0,01	x	0,012	x
60/220	x	x	x	x	x	0,01	x	0,012	x
82/220	x	x	x	0,005	x	0,01	x	0,012	x
110	x	x	x	0,005	x	x	x	x	x
120	x	x	x	x	x	0,01	x	0,012	0,06
160	x	x	x	x	x	x	0,06	x	0,07
210	x	x	x	0,005	x	x	x	x	x
220	x	x	x	x	0,05	x	0,07	x	0,07
310	x	x	x	x	0,05	x	0,07	x	0,08
520	x	x	x	x	0,07	x	0,07	x	0,08

Another important aspect of assessing the quality of mass measurements, closely related to the magnitude of the random error, is measurement uncertainty. As is well known, the estimation of Type A uncertainty is based on the standard deviation (S) calculated from a series of repeated measurements. It should also be noted that, as the number of measurements increases, the relative uncertainty decreases owing to the averaging of random errors.

$$\delta x = \frac{\Delta x}{|\bar{x}|} = \frac{\left(\frac{S}{\sqrt{n}}\right)}{|\bar{x}|} \qquad (2)$$

Legend

δx relative uncertainty; Δx absolute uncertainty;

$\bar{x}$ mean of the measurements; S standard deviation

n number of measurements;

Table 10. Relative Uncertainty as a Function of the Number of Measurements in a Measurement Series

Number of measurements	2	3	4	5	6	7	8	9
Relative Uncertainty	43%	38%	34%	31%	28%	25%	22%	7%

6.3. Ergonomics of Manual Weighing

Radwag offers three main series of laboratory balances: R, X7 and 5Y, which differ in their design, appearance, and measurement performance. Based on the type of user interface, these balances can be classified into three categories:

- **Basic** – 5.3” LCD display in R series;
- **Intermediate** – 7” touchscreen in X7 series;
- **Professional** – 10” touchscreen in 5Y series.

All of these balances can be effectively used in various filter-weighing applications, since each of them measures the gravitational force acting on the filter. The principal differences between the balance series lie in their functionality and the way they interact with the user. In the era of personal digital assistants (PDAs), and particularly smartphones, an intuitive and advanced user interface has become an important element of modern laboratory instrumentation.

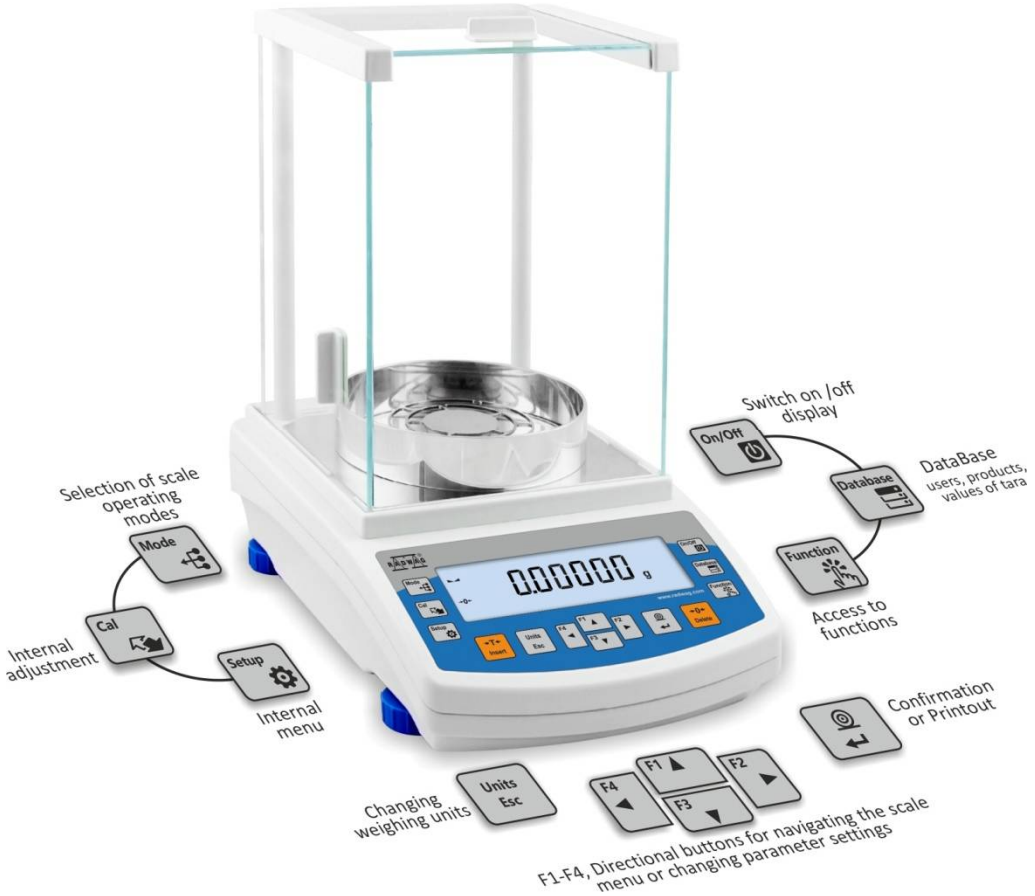


Figure 30. AS 82/220.R2 PLUS Balance – Functional Capabilities

For many prospective users, the key consideration is the "accuracy" of a balance, which is often mistakenly equated with its readability. It should be emphasized that it is not possible to achieve a measurement accuracy equal to the value of the balance readability (d). On the other hand, standards and technical guidelines typically specify only the required balance readability, i.e., the value of the scale interval, without addressing other important metrological characteristics. This creates a degree of ambiguity in the interpretation of the performance requirements.

The information presented in table 10 may assist users in assessing the suitability of a balance for a particular analytical application. It should be noted, however, that laboratory balances are continuously improved as manufacturers develop new design solutions. Consequently, their metrological characteristics and technical specifications may change over time.

Figure 31. Functional Capabilities of the **AS 82/220.X7** Analytical Balance

Legend: 1 – IR sensors, 2 – Pull-out side panel – display layout configuration, 3 – Information panel, 4 – Main balance function keys, 5 – Hot-key buttons, 6 – Widgets, 7 – Weighing result display, 8 – Main balance menu, 9 – Dual Click system – quick removal of the draft shield

In more advanced weighing systems, additional capabilities become increasingly important, including communication with external devices, data acquisition and processing, secure data storage, wireless connectivity, and system integration. For applications involving sensitive data, particular emphasis is placed on data integrity, traceability through an audit trail, and compliance with Quality Management System (QMS) requirements. These capabilities are provided, for example, by the Radwag 5Y series of balances.

Figure 32. MYA 5.5Y Microbalance – Digital Weighing Auditor (DWA) Function Icons

Conventional laboratory balances are generally designed to be as versatile as possible, allowing their use in a wide range of weighing applications. However, a universal design is not always the optimal solution, particularly when weighing objects with a large surface area, such as filters. For balances with a readability of 0.1mg, filter weighing is generally unproblematic. At a readability of 0.001mg, however, the influence of external disturbances becomes much more pronounced, resulting in increased random error, greater indication drift, and longer stabilization times. Practical experience has shown that balances dedicated to such applications should be specifically optimized for filter weighing, taking into account not only their metrological characteristics but also the influence of adverse physical phenomena, particularly electrostatic charges.

Figure 33. **MYA 5.5Y Microbalance**, Max 5g, Readability d=1μg, Precision St. Dev.=0.5μg, Automatic Internal Adjustment, OIML Cert., weighing Chamber optimized for ϕ25 mm filters

The optimization of balance design is always aimed at achieving the best possible metrological performance for a specific weighing application. One of the main challenges is the relatively large surface area of filters, which ranges from approximately 4.9cm^2 to 17.5cm^2 (corresponding to filter diameters of 25mm to 150mm). Another important issue is the influence of electrostatic charges, whose effect on the weighing process should be minimized. However, no universal solution is currently available. An example of such optimization is the MYA 5.5Y.FA microbalance. In this design, the filter is introduced into the weighing chamber through a side opening in a rotating draft shield. This solution minimizes air exchange and air movement within the weighing chamber compared with conventional designs, in which the upper draft shield is opened during filter loading.

Figure 34. MYA 5.5Y.FA Microbalance, Max 5g, Readability 1μg, Precision St. Dev.=0.5μg, Automatic Internal Adjustment, OIML Cert., weighing chamber optimized for ϕ70 mm filters

Dedicated balance designs are also available for specific analytical methods. One example is a balance equipped with a specially designed holder for weighing A4-format filter media. The XA 52.5Y.F balance features an additional internal glass draft shield and a modified weighing pan designed to accommodate the filter material. Although the balance offers a readability of 0.01 mg, it is, in fact, a fully certified laboratory balance equipped with an automatic internal adjustment system. Its practical application is limited only by its maximum capacity of 52 g.

Figure 35. **XA 52.5Y.F**

Max 52g, Readability d=0.01mg, Automatic Internal Adjustment, OIML Cert., weighing filter media up to 297 × 210mm

6.4. Electrostatic Charges on Filters During the Weighing Process

The occurrence of unbalanced electrostatic charges is common when filters are manufactured from polytetrafluoroethylene (PTFE) or coated with this material. Several standards and regulations explicitly require the neutralization of electrostatic charges prior to weighing such filters, including 40 CFR Part 1065 – Engine-Testing Procedures, § 1065.190 PM Stabilization and Weighing Environments for Gravimetric Analysis; Commission Regulation (EU) 2017/1151, Sub-Annex 5, Test Equipment and Calibration, Section 4.2.2.3 Elimination of Electrostatic Effects; and EN 12341:2024, Sections 6.6 Weighing Room Procedures and 9.3.2.9 Effects of Static Electrical Forces During Weighing. The influence of electrostatic charges on weighing performance was investigated at the Centre for Metrology, Research and Certification. The results are presented in Tables 12 and 13, which compare the weighing performance obtained with certified mass standards and with charged filter samples.

Table 11. MYA 2.4Y.F Microbalance – Manually Operated Weighing Chamber

	m=2g	m=10mg	m=5mg	m=1mg	Filter PVC 37mm	Filter PVC 25mm
St. Dev. (mg)	0,0024	0,0007	0,0006	0,0005	0,0041	0,0024

Table 12. UYA 2.5Y.F Ultramicrobalance with an Automatically Operated Weighing Chamber

No.	Filter PVC 25 mm			M1 = 1mg	M2 = 5mg
1	0,0067431	0,0067395	0,0067979	0,0010023	0,0050021
2	0,0067436	0,0067423	0,0067438	0,0010024	0,0050025
3	0,0067558	0,0067436	0,0068067	0,0010029	0,0050032
4	0,0067604	0,0067551	0,0067919	0,0010025	0,0050030
5	0,0067605	0,0067679	0,0067517	0,0010012	0,0050022
6	0,0067606		0,0067508	0,0010024	0,0050028
7	Drift ↑	Drift ↑	0,0067800	0,0010018	0,0050023
8	x	x	0,0067897	0,0010027	0,0050024
9	x	x	0,0069187	0,0010025	0,0050028
10	x	x	0,0068579	0,0010019	0,0050021
			random errors		
St. Dev (mg)	0,008	0,012	0,029	0,0006	0,0005

Regardless of the ultramicrobalance design (4Y or 5Y series), the weighing of certified mass standards consistently produced correct results. This indicates that the excessive measurement errors observed during filter weighing are primarily associated with electrostatic charges present on the filters rather than with the balance itself. To reduce the influence of this phenomenon, the filters were neutralized using a DJ-04 ionizer, and the weighing chamber of the ultramicrobalance was redesigned. Each filter was subjected to a single ionization treatment prior to the measurement series. Both sides of the filter (upper and lower surfaces) were treated. The weighing results obtained after this procedure are presented in table 14.

Table 13. Filter Weighing Results After Electrostatic Charge Neutralization

No.	Filter OH 2262		Filter OH 1187	Filter PVC (225-5-25)
1	0,0074442	x	0,0067402	0,0067029
2	0,0074441	x	0,0067390	0,0067036
3	0,0074429	0,0074429	0,0067388	0,0067031
4	0,0074423	0,0074423	0,0067387	0,0067030
5	0,0074420	0,0074420	0,0067389	0,0067037
6	0,0074419	0,0074419	0,0067390	0,0067030
7	0,0074427	0,0074427	0,0067396	0,0067041
8	0,0074430	0,0074430	0,0067403	0,0067043
9	0,0074424	0,0074424	0,0067394	0,0067038
10	0,0074423	0,0074423	0,0067396	0,0067034
11	0,0074424	0,0074424	0,0067397	0,0067037
St. dev. (mg)	0,00077	0,00037	0,00055	0,00047

The results obtained confirm the effectiveness of the modified weighing procedure. Following electrostatic charge neutralization, the repeatability of filter weighing became comparable to that achieved when weighing certified mass standards (see tables 12 and 13).

7. Automated Measurements

The primary objective of automation is to increase operational efficiency, which in turn contributes to lower operating costs. As a general rule, higher speed is often associated with reduced measurement accuracy. However, this principle does not apply to filter-weighing methods. In practice, automation involves a comprehensive optimization of the weighing system, including its mechanical design, the measurement procedure, and the operating sequence. The result is a potentially unattended system that complies with applicable standards and regulatory requirements. Although the balance continues to perform its fundamental function of measuring mass, its operation is fully synchronized with the automation system, which is typically controlled by dedicated software. Technical solutions developed and validated through R&D activities can be implemented in both simple automated systems, such as the AK-6 5Y.F, and advanced platforms, such as the RMC 2.5Y.F.

7.1. AK-6 5Y.F – Ultramicro-Scale Automation

The detection of small changes in the mass of filters used in both scientific research and commercial applications requires highly sensitive weighing instruments characterized by excellent long-term stability. It should be noted that conventional manual weighing systems, despite careful operation by laboratory personnel, are inherently affected by human error. Practical experience has shown that introducing automation into the weighing process can improve measurement accuracy by a factor of approximately two to three while maintaining the same balance readability. The simplest solution for automated filter weighing is the six-position AK-6 5Y.F system, shown in figure 36.

Figure 36. AK-6 5Y.F Automated Filter Weighing System,
Readability d=0.001mg, Automatic or Semi-Automatic Operation, for Filters with Diameters from ϕ25 ÷ 47mm

From a metrological perspective, measurement accuracy is determined by two key aspects of the weighing process. The first is the accuracy of the balance itself, which can be ensured by adjusting the instrument using a certified external mass standard. In addition, the measurement procedure may include periodic verification of the balance indication using a dedicated reference weight (5) stored in the magazine (2). However, such verification is not mandatory if the objective of the analytical method is solely to determine changes in filter mass. In this case, a reference filter (4), whose mass is verified before each weighing session, may serve as the measurement reference.

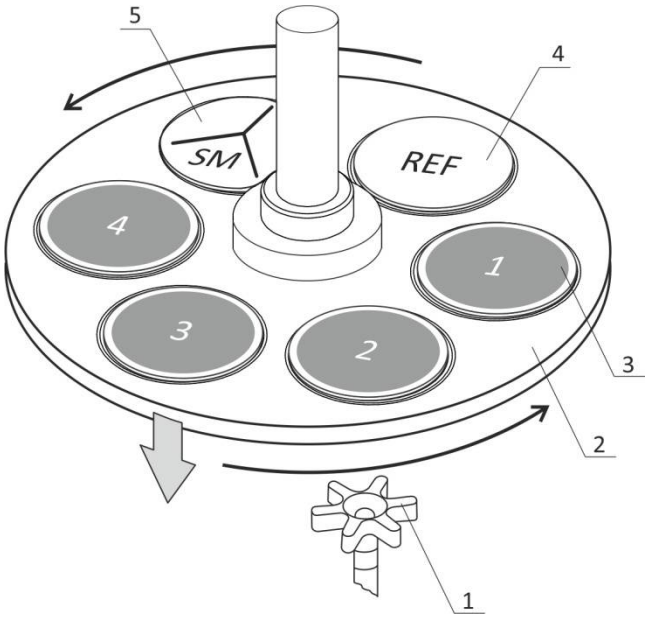


Figure 37. AK-6 5Y.F Filter storage – general view

Legend: 1 – Balance weighing pan, 2 – Magazine for filters and mass standards, 3 – Test filter, 4 – Reference filter, 5 – Certified mass standard

The second key parameter affecting the accuracy of filter weighing is repeatability, defined as the ability of a weighing system to produce consistent results when the same filter is weighed repeatedly under repeatability conditions. As discussed earlier, repeatability depends on several important factors, including:

1. the stability of environmental conditions, particularly temperature and relative humidity;
2. air movement in the vicinity of the weighing station;
3. operator handling, including mechanical shocks caused during the placement and removal of filters;
4. the thermal stability of the filter, including proper conditioning before weighing.

The AK-6 5Y.F system eliminates the adverse effects of factors 2 and 3 on the mass measurement process. It should be noted that maintaining a stable laboratory temperature generally requires the periodic supply of conditioned air with strictly controlled parameters. Unfortunately, this also generates air movement, which disturbs the equilibrium of the weighing system and results in increased scatter of the measurement results.

A substantial reduction in the influence of this factor has been achieved by incorporating a sealed weighing chamber in which each filter is weighed inside a dedicated cassette (Figure 38). During the conditioning stage (A), the filter remains inside the cassette (3), which provides a stable microenvironment. During weighing (B), the filter magazine (5) moves downward, allowing the filter (2) to be gently placed on the weighing pan (4). The cassette housing (3) together with its upper cover (1) minimizes air movement within the weighing chamber, thereby enabling highly precise filter mass measurements.

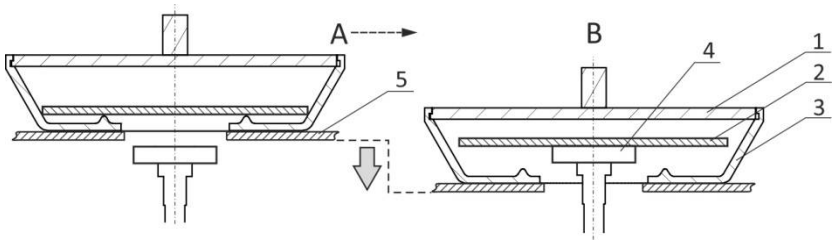


Figure 38. **AK-6 5Y.F**, filter cassette

Legend: 1 – filter cassette cover, 2 – tested filter, 3 – filter cassette housing, 4 – AK-4/6 pan, 5 – filter storage

The random error of the AK-6 5Y.F system was evaluated at the Centre for Metrology, Research and Certification using a balance with a readability of 0.0001mg, as required for particulate matter (PM) measurements in vehicle type-approval emission testing. For 47mm diameter filters, the measurement precision was R = 0.4µg when expressed as the absolute difference between successive measurements, or approximately S = 0.14µg when expressed as the standard deviation (table 15). A slightly better result was obtained for the certified mass standard because of its considerably smaller surface area.

Table 14. Measurement Precision for a Certified Mass Standard and Ø47 mm Filters

Measurement	Mass standard	Filter 1	Filter 2	Filter 3
1	0,1483208	0,1333503	0,1327184	0,1333415
2	0,1483206	0,1333500	0,1327186	0,1333416
3	0,1483207	0,1333500	0,1327184	0,1333414
4	0,1483208	0,1333501	0,1327184	0,1333415
5	0,1483206	0,1333503	0,1327182	0,1333416
6	0,1483206	0,1333502	0,1327183	0,1333417
7	0,1483207	0,1333500	0,1327183	0,1333417
8	0,1483208	0,1333500	0,1327182	0,1333418
9	0,1483208	0,1333501	0,1327183	0,1333417
10	0,1483206	0,1333499	0,1327182	0,1333419
Max-Min	0,2µg	0,4µg	0,4µg	0,5µg
S	0,09µg	0,14µg	0,13µg	0,15µg

7.2. UMA 2.5Y.F – Medium-Scale Automation

The UMA FC automated system is a more advanced platform for monitoring changes in filter mass, offering the additional capability of conditioning filters under controlled temperature and humidity conditions. It is intended for laboratories that do not have dedicated facilities for maintaining stable environmental conditions. As in the AK-6 5Y.F system, both test and reference filters are stored in stainless-steel containers mounted on a rotating magazine. A microbalance with a readability of either 0.001 mg or 0.0001 mg is installed on an anti-vibration concrete support in the lower section of the instrument. A general view of the system is shown in Figure 39.

Figure 39. UMA FC Automated System for Monitoring Filter Mass Changes,
Filter Conditioning with Controlled Temperature and Humidity, Maximum Capacity 2g, Readability d=1μg or 0.1μg, Capacity up to 24 Filters, Compliant with EN 12341:2024

The conditioning process and the periodic weighing of filters are controlled and monitored by dedicated software. The application provides a high degree of flexibility, allowing the measurement procedure to be optimized with respect to conditioning time, acceptable limits for filter mass variation, and the recording of reference filter and certified mass standard measurements. In addition, the software enables the association of each filter identification code with its sampling location and other information relevant to the analytical procedure.

Maintaining stable environmental conditions inside the instrument, typically a temperature of 20±1^{o}C and a relative humidity of 45±5%, requires continuous air circulation. As discussed previously, air movement is one of the principal factors adversely affecting the accuracy and precision of mass measurements . The influence of this factor was minimized by placing the filters inside stainless-steel containers. The smaller the air volume surrounding the filter during weighing, the lower the effect of air movement on the measurement result.

The design of the UMA FC system is shown in Figure 40. Filters enclosed in stainless-steel containers (6a, 6b) are stored in a rotating magazine. The magazine (7) is driven by an automation module (4), which provides both rotational movement and vertical motion when a filter is transferred to the weighing position. The required temperature and relative humidity are maintained within the weighing chamber (8) by an environmental conditioning system operating in a closed-loop configuration with temperature and humidity sensors. The cleanliness of the air inside the weighing chamber is ensured by HEPA filters (5) installed at both the air inlet and the air outlet.

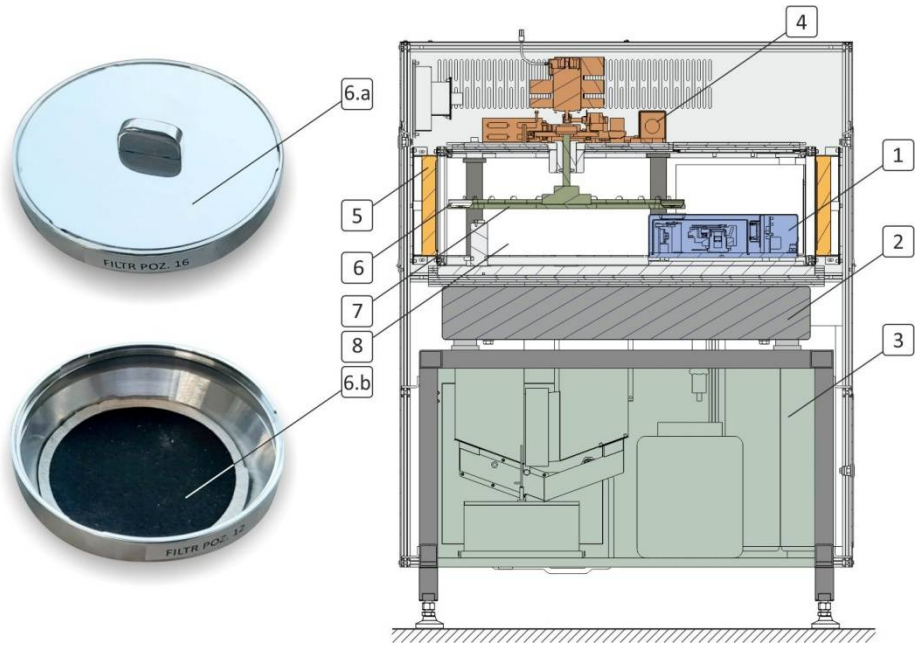


Figure 40. UMA 2.5Y.FC – Schematic of the Measurement System

1 – Weighing module (mass measurement), 2 – Anti-vibration support for the measurement system, 3 – Humidity and temperature control system, 4 – Automation module, 5 – HEPA filter, 6 – Filter container (6a – container; 6b – filter inside the container), 7 – Filter magazine, 8 – Filter conditioning chamber

The weighing module (1), together with the entire system structure, is mounted on an anti-vibration stone base (2). The measurement cycle is fully programmable using dedicated software, in which the user defines the number of measurement cycles and the positions of the filters in the magazine whose masses are to be monitored. The UMA 2.5Y.FC weighing system was used in the research project No. 2021/42/E/ST10/00209 (ID 526286), entitled "Water – A Matter of Great Importance for the Measurement Uncertainty of Aerosol Mass." The objective of the project was to determine the actual influence of permissible variations in conditioning humidity on the mass variability of test filters.

This issue is of particular importance because current scientific research and commercial monitoring are increasingly focused on the determination of the mass concentration of PM1 (submicron) and PM0.1 (ultrafine) particulate matter. The results of this project are published regularly by the Institute of Environmental Engineering of the Polish Academy of Sciences. Tables 16, 17, and 18 present the random error measurements obtained for the UMA 2.5Y.FC system (maximum capacity 2g, readability d = 0.001mg) during the metrological evaluation of the instrument as part of the validation and installation qualification process.

Table 15. UMA 2.5Y.FC – Repeatability of Indications

	Filter Position in the Magazine					
No.	**m_1 (g)**	**m_2 (g)**	**m_3 (g)**	**m_4 (g)**	**m_5 (g)**	**m_6 (g)**
1	0,301529	0,152508	0,151359	0,151084	0,154776	0,151989
2	0,301529	0,152507	0,151359	0,151084	0,154776	0,151989
3	0,301529	0,152509	0,151360	0,151086	0,154775	0,151989
4	0,301528	0,152507	0,151359	0,151086	0,154775	0,151989
5	0,301528	0,152508	0,151359	0,151086	0,154776	0,151989
6	0,301528	0,152507	0,151359	0,151085	0,154776	0,151990
$\bar{x}$ (g)	0,301529	0,152508	0,151359	0,151085	0,154776	0,151989
St. dev. (µg)	0,55	0,82	0,41	0,98	0,52	0,41

Table 16. UMA 2.5Y.FC – Repeatability of Indications

	Filter Position in the Magazine					
No.	**m_7 (g)**	**m_8 (g)**	**m_9 (g)**	**m_{10} (g)**	**m_{11} (g)**	**m_{12} (g)**
1	0,152326	0,152953	0,152579	0,155078	0,684378	0,140174
2	0,152326	0,152955	0,152579	0,155079	0,684378	0,140174
3	0,152326	0,152954	0,152580	0,155078	0,684378	0,140173
4	0,152326	0,152956	0,152580	0,155079	0,684378	0,140173
5	0,152325	0,152954	0,152579	0,155078	0,684378	0,140174
6	0,152326	0,152955	0,152580	0,155079	0,684378	0,140174
$\bar{x}$ (g)	0,152326	0,152955	0,152580	0,155079	0,684378	0,140174
St. dev. (µg)	0,41	1,05	0,55	0,55	0,41	0,52

Table 17. UMA 2.5Y.FC – Repeatability of Indications

	Filter Position in the Magazine					
No.	**m_{13} (g)**	**m_{14} (g)**	**m_{15} (g)**	**m_{16} (g)**	**m_{17} (g)**	**m_{18} (g)**
1	0,147518	0,147748	0,126705	0,148678	0,138993	0,146117
2	0,147517	0,147748	0,126703	0,148676	0,138993	0,146117
3	0,147518	0,147748	0,126704	0,148677	0,138993	0,146117
4	0,147518	0,147748	0,126704	0,148677	0,138991	0,146116
5	0,147518	0,147749	0,126705	0,148677	0,138993	0,146117
6	0,147518	0,147747	0,126706	0,148676	0,138992	0,146117
$\bar{x}$ (g)	0,147518	0,147748	0,126705	0,148677	0,138993	0,146117
St. dev. (µg)	0,41	0,63	1,05	0,75	0,84	0,41

The random error obtained for the individual filter positions ranged from 0.41 to 1.05µg, which is consistent with the performance objectives and satisfies the requirements of EN 12341:2024.

A less advanced solution, intended for laboratories capable of maintaining environmental conditions within the required limits, is the UMA 2.5Y.F system. Its filter-weighing method and measurement capabilities are identical to those of the FC version. However, the weighing module is mounted on an aluminium base, resulting in a significantly smaller and lighter instrument. The UMA 2.5Y.F is a compact system that can be installed at virtually any location within a laboratory, provided that it is placed on a stable bench with minimum dimensions of 1000 × 600mm.

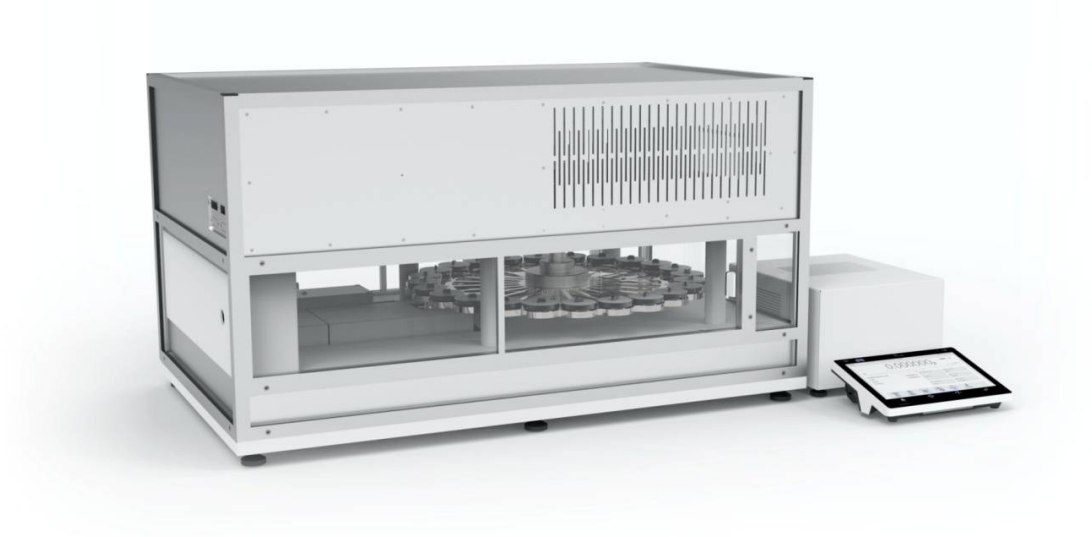


Figure 41. UMA 2.5Y.F - Automated System for Monitoring Filter Mass Changes,
Maximum Capacity 2g, Readability d = 1μg or 0.1μg, Capacity up to 24 Filters, Compliant with EN 12341:2024

The UMA 2.5Y.F weighing system was used in a comparative study of particulate matter emissions from internal combustion engines. The study was carried out at the Automotive Research and Development Institute BOSMAL. Particulate matter mass emissions were determined in accordance with the requirements of Commission Regulation (EU) 2017/1151. Filter samples for gravimetric analysis were collected during chassis dynamometer tests performed under various driving cycles, including the WLTC cycle in accordance with Commission Regulation (EU) 2017/1151, the NEDC cycle in accordance with UN Regulation No. 83, and the RDE, RTS, and TFL cycles, which are non-standardized driving cycles developed by vehicle manufacturers. The particulate matter mass emissions were calculated using Equations (3) or (4).

$$PM = \frac{(V_{mix} + V_{ep}) \times P_e}{V_{ep} \times d} \quad (3)$$

$$PM = \frac{V_{mix} \times P_e}{V_{ep} \times d} \quad (4)$$

Legend

V_{mix}	Volume of diluted exhaust gas under standard conditions
V_{ep}	Volume of diluted exhaust gas passing through the particulate matter sampling filter under standard conditions
P_e	Mass of particulate matter collected on the sampling filter(s), mg
d	Distance travelled over the test cycle, km.

The measurement accuracy of the automated system and the manual balance was evaluated using certified stainless-steel mass standards and borosilicate glass microfiber filters reinforced with a glass fabric and coated with PTFE (Pallflex® Emfab™ TX40HI20WW). The results of this comparison are presented in table 19.

Table 18. Comparison of Mass Measurement Precision for a Certified Mass Standard and a Filter Using a Manual Balance and an Automated System

	MSE 2.7S-000-DF[*)]	**UMA 2.4Y.F**[**)]	**MSE 2.7S-000-DF**[*)]	**UMA 2.4Y.F**[**)]
No.	Mass Standard Indication (mg)		ϕ 47 mm Filter Indication (mg)	
1	150,2548	150,2440	102,1241	102,0771
2	150,2545	150,2429	102,1215	102,0774
3	150,2553	150,2432	102,1232	102,0770
4	150,2553	150,2429	102,1197	102,0772
5	150,2549	150,2430	102,1176	102,0768
6	150,2550	150,2428	102,1156	102,0770
7	150,2550	150,2427	102,1152	102,0772
8	150,2548	150,2428	102,1163	102,0772
9	150,2545	150,2429	102,1151	102,0772
10	150,2545	150,2428	102,1173	102,0774
St. dev. (mg)	0,0003	0,0004	0,0034	0,0002

Legend: *) Manual balance operated by an operator
**) UMA automated system, equipped with a 4Y series weighing terminal

The measurement accuracy obtained for the certified mass standard was virtually identical for both the manual balance and the automated system, as the small surface area of the standard makes it essentially insensitive to disturbances caused by air movement. In contrast, a clear difference was observed for the filter measurements. The measurement precision of the automated system remained stable because the filter was weighed within the confined space of the filter container (figure 38). In the case of the manual balance, greater variability of the measurement results was observed, most likely due to air movement within the weighing chamber and, to some extent, electrostatic effects.

Figure 42. UMA 2.4Y.F Weighing System and Chassis Dynamometer Test Facility

7.3. RB 2.5Y.F – Quantity and Quality in Research

The principal advantages of automation include the repeatability of operations, reduced operator influence on the measurement process, and increased throughput. These advantages, together with several additional features offered by the RB 2.5Y.F robotic system, formed the basis for the development of an efficient air quality monitoring system in Poland and Romania.

Traditionally, air quality monitoring has relied on individual sampling stations and separate weighing facilities. In such a system, measurement data are dispersed and more susceptible to human error. At present, filter mass measurements, performed both before and after exposure, are centralized and carried out at dedicated facilities using the RB 2.5Y.F robotic system, six centres in Poland and ten in Romania.

Figure 43. **Robotic System RB 2.5Y.F**, Maximum Capacity 2g, Readability d=1μg,
Filter Magazine Capacity: 1 050 Filters, Controlled Temperature 20±1 °C, Relative Humidity 45±5%, Compliant with EN 12341:2024

The RB 2.5Y.F robotic system can be used as one of the components of the reference method for the determination of particulate matter mass concentration. This method employs particulate matter samplers, each typically equipped with 14 filter cassettes. The mass of each filter is determined before exposure in accordance with the requirements specified in EN 12341:2024. Each filter is then automatically transferred to a sampling inlet operating at a constant airflow rate for a 24-hour sampling period. During this time, particulate matter (PM) representative of the sampling location and period is collected on the filter. Each filter must remain fully identifiable throughout the process, as after exposure it is reconditioned and weighed again. The particulate matter mass concentration is calculated from the difference between the filter masses before and after exposure, the sampled air volume, and the sampling time, according to Equation (5).

$$c = \frac{m_1 - m_u}{\varphi_a \times t} \tag{5}$$

Legend: c mass concentration of particulate matter (μg/m^3)
m_1 mass of the clean filter before exposure (μg);
m_u mass of the filter after exposure (μg)
φ_a air flow rate during sampling (m^3/ h);
t sampling time (h)

A representative schematic of a sampler used for particulate matter collection is shown in Figure 44.

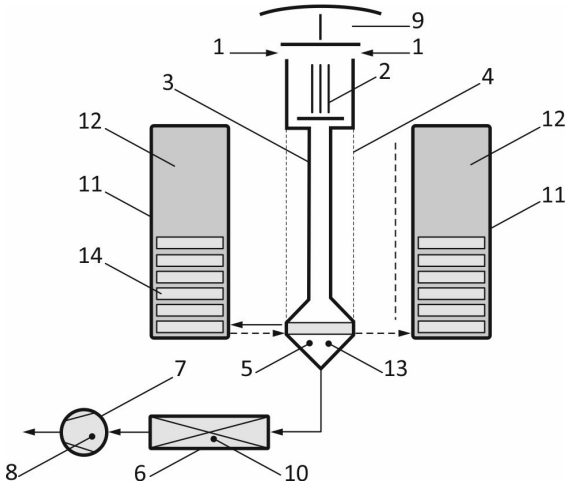


Figure 44. Schematic of a Particulate Matter Sampler

1 – Ambient air sample (T_a, P_a), 2 – Impactor inlet, 3 – Sampler housing, 4 – Air inlet, 5 – Filter holder, 6 – Air flow measurement, 7 – Pump, 8 – Flow control system, 9 – Pressure and temperature measurement, 10 – Pressure and temperature measurement (optional), 11 – Filter magazine, 12 – Filter storage temperature measurement, 13 – Temperature measurement in the vicinity of the filter during sampling, 14 – Filter

The key components of the RB 2.4Y / RB 2.5Y measurement system are shown in figure 45. Periodic monitoring of the masses of the reference filters (1) is used to assess the influence of conditioning conditions on the mass stability of the test filters. This is essential for the accurate determination of particulate matter mass using the differential weighing method.

Figure 45. Structural Components of the **RB 2.5Y.F** Robotic System

1 – Reference filter magazine and microbalance, 2 – Certified mass standard, 3 – Test filter magazine

The certified mass standard (2) is used to verify the accuracy of the balance indications. Monitoring potential drift in the microbalance indication by periodically weighing the mass standard provides an indicator of the long-term stability of the measurement system. The test filter magazine (3) has a maximum capacity of 1 050 filters, which are conditioned both before and after exposure. Filter identification is based on a QR code printed directly on the filter surface; therefore, the filter position within the magazine is not critical. Each filter is weighed before exposure, allowing its measurement results to be linked to its storage position in the magazine. The QR code is printed using metal-free ink, which is essential to avoid interference with subsequent chemical analyses of the particulate matter collected on the filter.

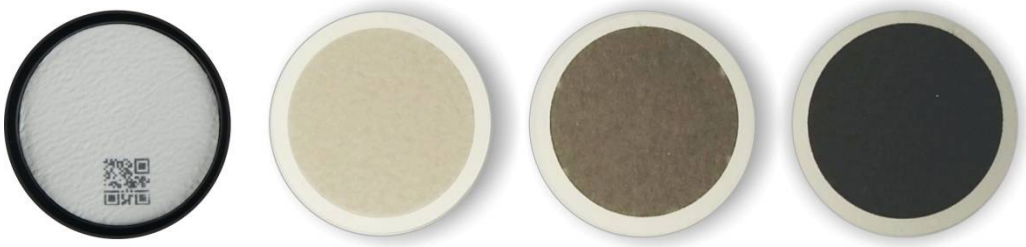


Figure 46. Filter Before Exposure with a QR Code, Filter Placed in an Antistatic Cassette, and Filters After Exposure

The measured filter mass, both before and after exposure, depends on the stability of the environmental conditions. Since perfectly stable conditions are only theoretical, it is essential to demonstrate the magnitude of temperature and humidity fluctuations and their compliance with the requirements of EN 12341:2024. Assuming that the environmental conditions remain sufficiently stable, any differences in repeated measurements of the same filters, weighed using the same method and the same measurement algorithm, can be attributed solely to the random error of the balance. It should also be noted that PTFE filters may accumulate unbalanced electrostatic charges, which should be neutralized prior to weighing.

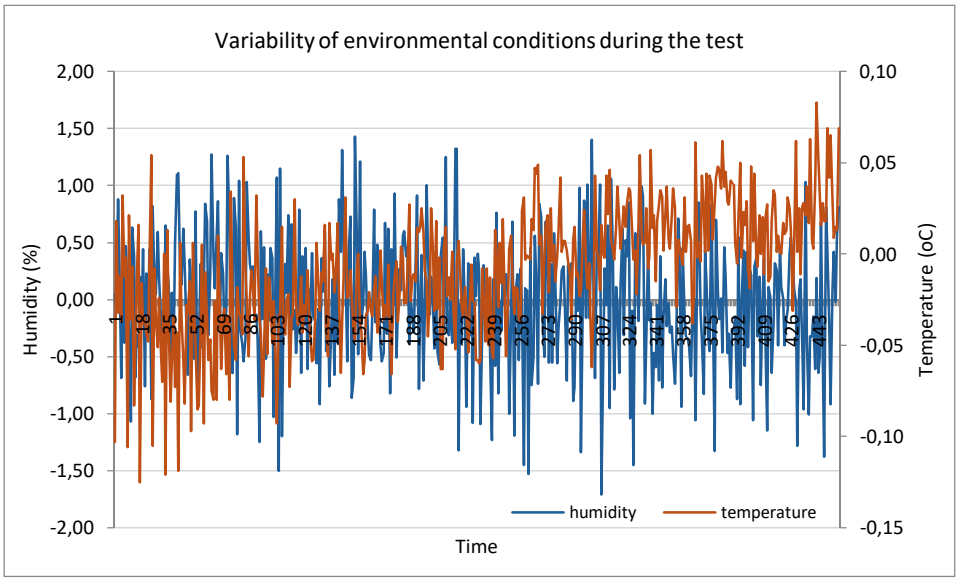


Figure 47. RB 2.5Y.F – variation of conditioning conditions

Temperature ~ 0.2°C, Relative Humidity ~ 1.5%

A comprehensive assessment of the suitability of the RB 2.5Y.F system and its compliance with the requirements of EN 12341:2024 should be performed during Operational Qualification (OQ). The recommended qualification tests are specified in Annexes C and D of the standard. It should be noted that, owing to the relatively large surface area of the filter (approximately 17.34cm^2), the repeatability of filter mass measurements will always be poorer than that obtained for a certified mass standard. This relationship is illustrated in table 20.

Table 19. Random Error of the Balance for a Certified Mass Standard and a Filter

L.p.	Mass standard		QMA 47mm filter	
1.	0,152497	x	0,147926	x
2.	0,152494	0,152494	0,147921	0,147921
3.	0,152493	0,152493	0,147919	0,147919
4.	0,152494	0,152494	0,147918	0,147918
5.	0,152494	0,152494	0,147914	0,147914
6.	0,152495	0,152495	0,147914	0,147914
7.	0,152495	0,152495	0,147913	0,147913
8.	0,152496	0,152496	0,147912	0,147912
9.	0,152496	0,152496	0,147912	0,147912
10.	0,152495	0,152495	0,147912	0,147912
St. dev.	1,20µg	1,06µg	4,75µg	3,46µg

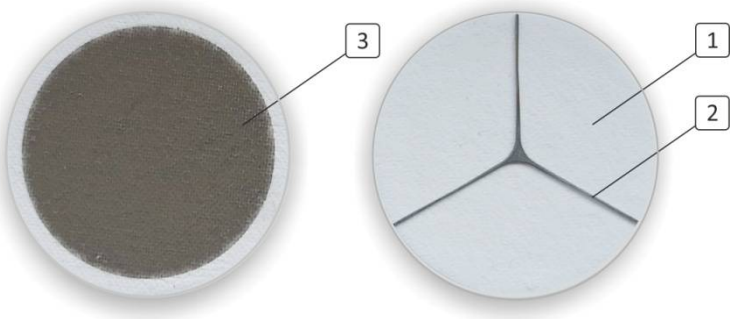


Figure 48. Certified Mass Standard for the **RB 2.5Y.F** Robotic System
1 – 47 mm filter before exposure, 2 – Certified mass standard (approximately 150mg),
3 – 47 mm filter after exposure

The RB 2.5Y robotic system is undoubtedly one of the most advanced solutions currently available for filter mass measurements in terms of both design and operational capabilities. However, the development of such systems is largely driven by market requirements. The ultimate goal appears to be the development of a system capable of accurately weighing filters of different diameters using any of the available weighing methods. Achieving this objective remains a significant challenge for manufacturers from both engineering and metrological perspectives.

7.4. RMC 2.5Y.FC – Throughput and Precision

The RMC robotic system combines the key advantages of the RB and UMA platforms: the high throughput of the RB system and the measurement precision of the UMA system. The RMC 2.5Y.FC is equipped with a multi-level linear magazine accommodating filters with diameters ranging from 25 to 47mm, which are conditioned and weighed inside stainless-steel containers. The automatic container handling mechanism is identical to that used in the RB series. It should be emphasized that the substantial reduction of the air volume surrounding the filter during weighing significantly improves measurement accuracy. A general view of the RMC system is shown in Figure 49.

Figure 49. RMC 2.5Y.F – robotic weighing system

Max 2g, Readability 0.001mg or 0.0001mg, Compliant with EN 12341:2024
Legend: 1 – HEPA filter, 2 – Filter magazine, max 156 filters, 3 – Control system, 4 – Robotic handling system, 5 – Microbalance, 6 – Operator panel

It should be recognized that the quality of any product is the result of a continuous improvement process based on the PDCA cycle. This fundamental principle has enabled the ongoing refinement of the ergonomic features, functional capabilities, and metrological performance of the automated systems manufactured by RADWAG Electronic Balances. The starting point for implementing corrective and improvement actions is the analysis of market demands, customer requirements, in-house research results, and concepts for new product functionalities. This approach also applies to the RMC 2.5Y.FC system, which can be further optimized to meet specific customer requirements and to ensure compatibility with existing information management systems.

7.5. RW 5Y.F 153 – Unlimited Mass Measurements

The RW 5Y.F153 robotic weighing system is a portable workstation designed for filter mass measurements and based on a collaborative robot (cobot). In this system, mass measurements are performed at one or more dedicated weighing stations, which may be equipped with balances of different readabilities, depending on the application requirements. Filters can be stored and conditioned in multiple magazines located within the working envelope of the cobot. As the cobot is designed to operate safely in collaboration with humans, it does not require enclosure within a safety cage. Filter transfer from the storage magazine to the weighing station is performed by a six-axis robotic arm. Each filter is stored in a steel container, but a different application is possible in this regard → mounting a different holder in the cobot arm. A schematic representation of the workstation is shown in figure 50.

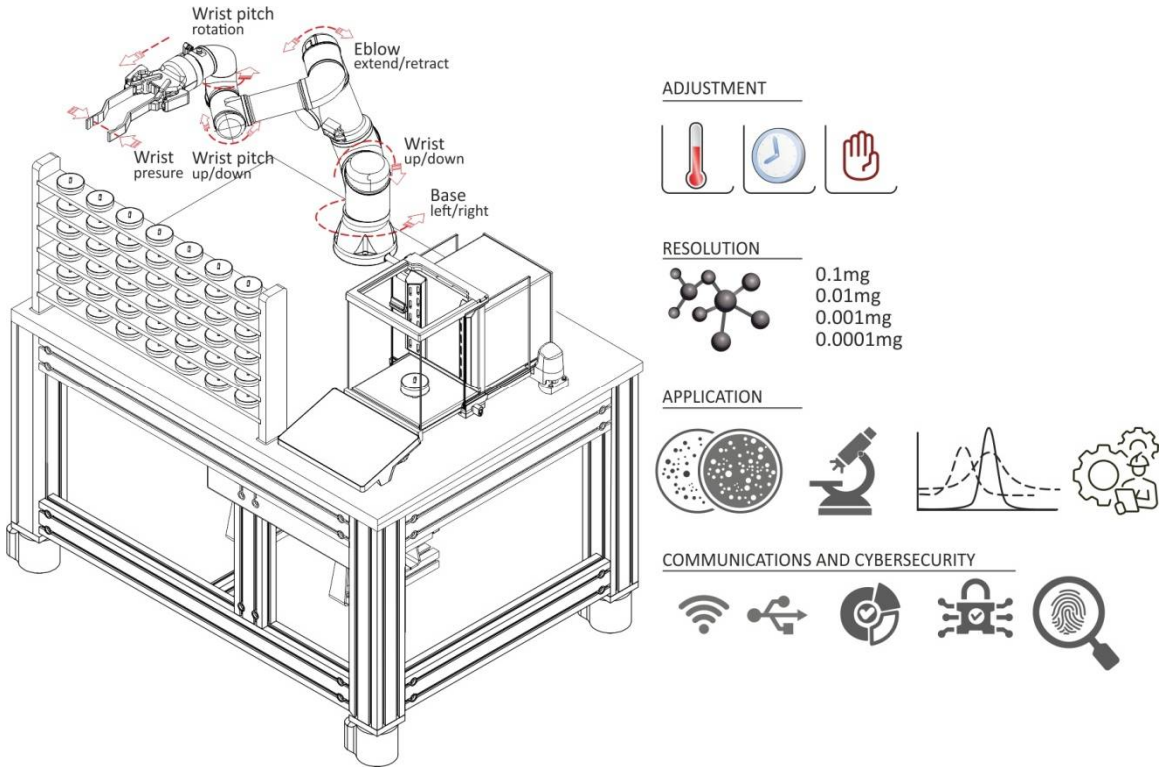


Figure 50. Schematic of a Cobot-Assisted Weighing Workstation

The operating cycle is controlled by the cobot, which performs all operations associated with transferring filters between the storage magazine and the balance. Mass measurement results are stored in the balance's internal database together with the information required for filter identification. The data can also be transferred to external software applications for further processing. Environmental conditions required for filter conditioning, in accordance with applicable standards, must be provided by dedicated laboratory equipment external to the weighing system.

The presented solution is only one of many possibilities enabled by the flexibility of a six-axis cobot. This versatility opens entirely new opportunities for the development of custom automated systems dedicated to mass measurement applications.

Figure 51. Stages of Cobot Operation: Filter Cassette Pickup and Mass Measurement.

Each filter must be stored in a dedicated holder or container. Although this may appear to be a limitation, it also offers a significant advantage, as reducing the air volume surrounding the filter during weighing improves measurement precision. This is particularly important for filters with diameters greater than 47mm, such as the 150mm filters used in high-volume (HV) air samplers. At the same time, cobot-based systems offer the potential to handle filters of different diameters by using multiple storage magazines located within the robot's working envelope. Implementing such flexibility in conventional Cartesian robotic systems is considerably more complex from an engineering standpoint.

8. Electrostatic Charge Imbalance – Deionization

Electrostatic charge imbalance is a common phenomenon, although it is usually only noticed when charge levels become significant. In environmental protection, mass measurements are often performed with a precision of 10^{-5} to 10^{-6}g, making it possible to detect even the smallest external influences. Unfortunately, electrostatic effects are highly undesirable in such applications, as they can introduce significant weighing errors. Eliminating static charge imbalance requires the use of a deionizer, typically a device that alternately generates positive and negative ions. This creates a virtually neutral environment in which electrostatic charges are balanced, ensuring more accurate and reliable weighing results.

Figure 52. Measurement of Electrostatic Charges on a Filter Using an SMC IZD10-510 Meter

Electrostatic charges present on the surfaces of various objects can be measured, as shown in figure 52. It is worth noting that the fundamental relationship governing electrostatic interactions is described by Coulomb's law: "The force of interaction between two point electric charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them."

$$F = k \cdot \frac{q_1 \cdot q_2}{r^2} \tag{6}$$

The situation described above, in which the electric field originates from a point charge, is essentially a theoretical model, as such an idealized charge distribution does not occur in practice. In weighing applications, electrostatic effects arise from the interaction between charges present on the sample being weighed and those on components of the weighing chamber, such as the glass draft shield. In this case, the interaction is better described in terms of the electric field strength between two regions rather than between two point charges. Since these regions may differ significantly in shape and size, the interaction is commonly approximated by that between two parallel plates. The electric field strength is described by equation 7, while the resulting electrostatic force is given by equation 8.

$$E = \frac{U}{d} \tag{7}$$

Legend: U – potential difference between the plates
d – distance between the plates

$$F = \frac{Q^2}{2\varepsilon_0 \varepsilon_r S} \tag{8}$$

Legend: F – electrostatic attractive force (N),
Q – charge accumulated on one plate (C),
S – plate surface area (m²),
ε_0 – vacuum permittivity,(~ 8,85 x 10^{-12} F/m),
ε_r – relative permittivity of the medium between the plates (vacuum: $\varepsilon_r = 1$; air: $\varepsilon_r \approx 1.0006$).

An important aspect of static electricity is the so-called principle of conservation of charge, which states that "in an electrically isolated system, the total charge, the algebraic sum of positive and negative charges, does not change – the charge does not disappear, it can only be displaced." Therefore, there is practically no way to eliminate excess charges except by neutralizing them with a deionizer. The simplest solution is a DJ-04 or DJ-05 deionizer.

Figure 53. **External DJ-05 Deionizer,**

12 VDC power supply, stainless steel ion emitter,
recommended sample-to-deionizer distance during deionization: 5–50 mm.

The deionizer is a versatile device suitable for use in virtually any laboratory, regardless of its specific application. Deionization is performed by slowly moving the charged object over the surface of the ionizer. In the case of a filter, this procedure should be carried out on both sides—the upper and lower surfaces. Once the filter has been deionized, the weighing result should become stable. However, it is important to remember that excessive air movement remains another significant factor that can adversely affect weighing accuracy.

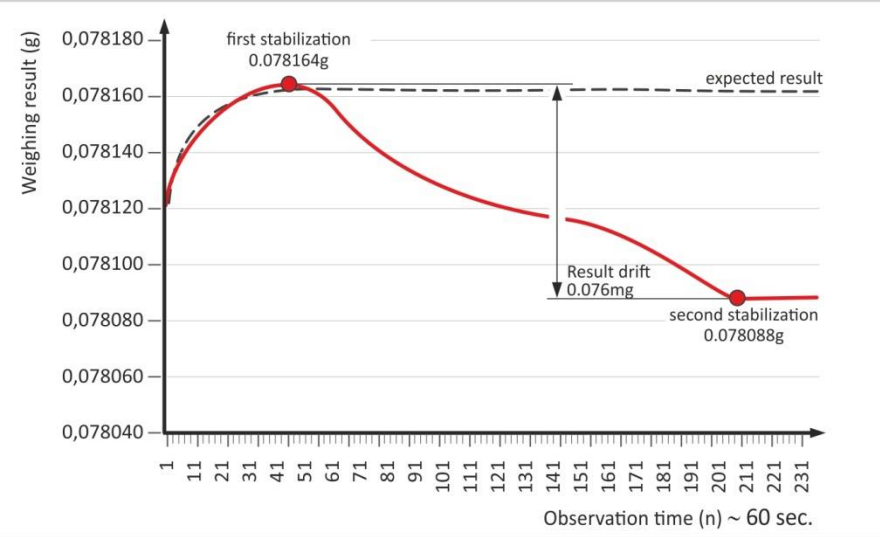


Figure 54. Weight drift of a Pallflex EMFAB TXT H2O-WW, 47mm filter due to unbalanced static charges

Figure 54 illustrates the drift in the weighing result of a filter carrying an imbalance of electrostatic charges on its surface. Although the reading eventually stabilizes and may be interpreted as the correct measurement, the gradual change in the displayed value is a clear indication of electrostatic interference. Under normal conditions, the weighing process should be completed within approximately 5–15 seconds, depending on the balance resolution.

An alternative solution is the ionizer integrated into the weighing chamber of the XA.5Y.A series balances. The ion-generating elements are mounted on both the left and right sides of the weighing chamber. The ionizer can be operated manually via programmable Hot-Key buttons or configured to start automatically whenever the weighing chamber doors are opened. Thanks to its integrated design, electrostatic charge imbalance on the sample is neutralized during the weighing process, improving measurement stability and accuracy.

Figure 55. **XA 210.5Y.A** Analytical Balance with Integrated Ionizer,
Max 210 g, readability d=0,01mg, automatic internal adjustment, OIML certified.
Compliant with EN 12341:2024

Compliance of Ionizers with Applicable Standards

Due to their design, the integrated ionizers used in the XA 5Y series balances should not be regarded as devices intended to neutralize electrostatic fields throughout the workstation. According to ANSI/ESD S20.20 and IEC 61340-5-1, which define the requirements for establishing and maintaining an Electrostatic Discharge (ESD) Control Program to protect ESD-sensitive electronic components, the balance and its integrated ionizer may constitute one element of an overall ESD management system.

The primary purpose of the balance's ionizer is to provide conditions that ensure accurate mass measurements. All items to be weighed particularly those handled in ESD-protected areas should have any accumulated static charges neutralized during the manufacturing or inspection process before weighing takes place.

9. Automatic Measurement of Dust Concentration

Gravimetric methods based on mass measurements are unfortunately relatively time-consuming, especially when all stages of the measurement procedure are taken into account. In the era of digitalization, rapid automatic measurement techniques have become increasingly important, as they provide real-time information on the current state of ambient air quality. A wide range of instruments is currently in use, most of which operate based on one of two measurement principles: the light scattering method or the beta radiation absorption method.

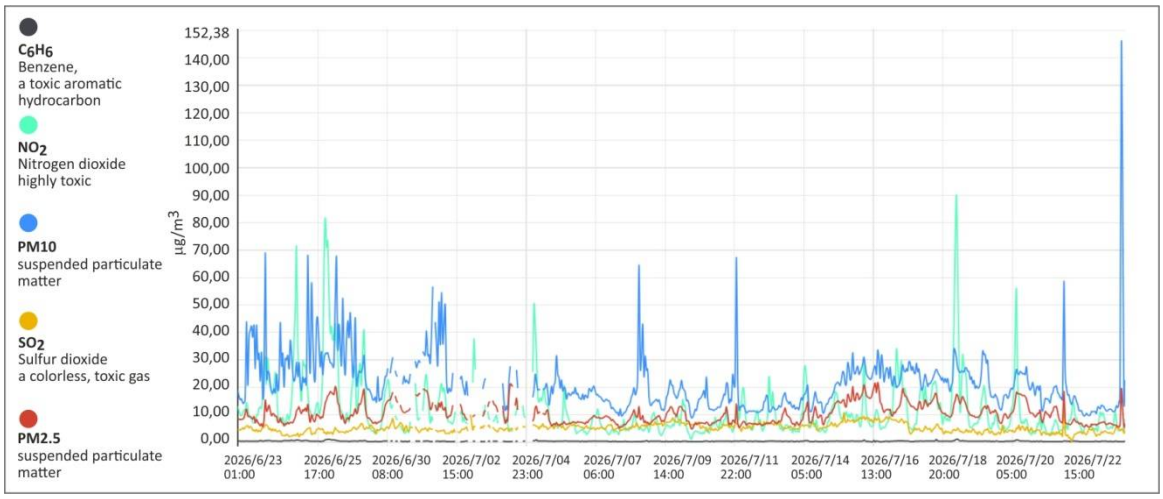


Figure 56. Example of automatic air quality monitoring

Hourly data, Radom, Tochtermana Street, monitoring station location: Latitude (N): 51.399084°, Longtitude (E): 21.147474

The laser light scattering method (OPC) → optical particle counter, is based on measuring the intensity of light reflected and scattered by suspended particulate matter in an air stream. A dust particle moving through the measurement chamber is illuminated by laser light at an angle of 90°. The light scattered by each particle is collected by a mirror and detected by a photodiode. This signal is then transmitted to a multichannel particle size classifier, where a pulse height analyzer classifies each pulse in proportion to the particle size. Each flash of light represents one particle, so counting these pulses is sufficient to determine the particulate matter concentration.

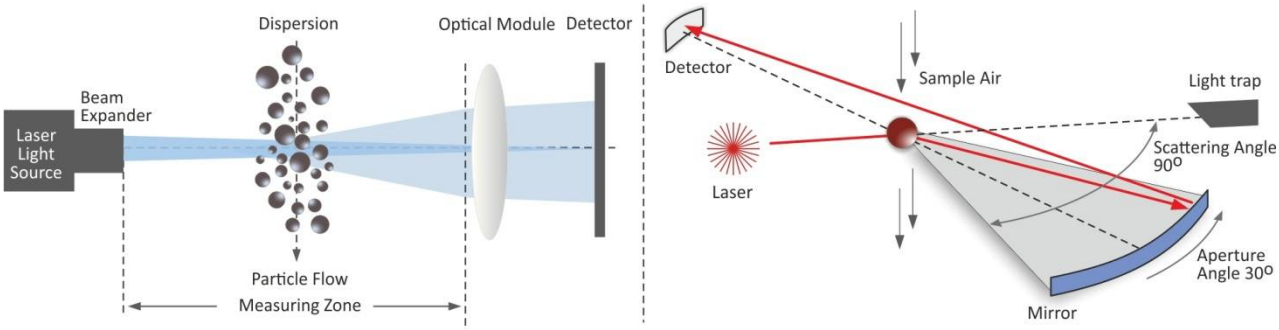


Figure 57. Automatic light scattering method

In automatic optical analyzers, the internal reference source is a built-in optical standard, known as an optical span reference, or a reference filter with a constant, known light scattering or

attenuation coefficient. An internal mechanical shutter directs the laser beam onto a material simulating a constant dust concentration, such as frosted glass or a special scattering element, instead of the measurement chamber containing air. This allows automatic verification of the stability of the emitted laser beam, the cleanliness of the optical lenses, and the sensitivity of the photo-detector.

The beta radiation absorption method (BAM) is based on measuring the extent to which particulate matter collected on a filter attenuates the stream of emitted electrons. Beta rays are high-speed electrons, i.e., charged particles emitted during the radioactive decay of unstable atomic nuclei. As beta rays pass through a substance, ionization and excitation of the atoms in the material collected on the filter tape occur. This results in a reduction in the intensity of the beta radiation, which is proportional to the mass and thickness of the material through which the radiation passes. The more particulate matter is deposited on the filter tape, the less beta radiation reaches the detector. This method is based on Lambert's law, or the Beer Lambert law, which states that the absorption of electrons depends almost exclusively on the mass of the substance, rather than on its chemical composition, colour, or particle shape. A schematic diagram of this method is shown in figure 58.

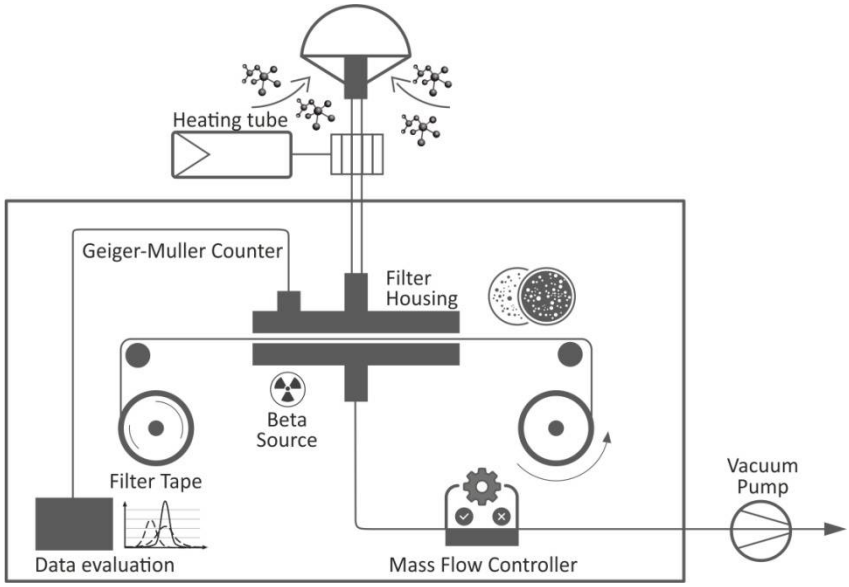


Figure 58. Beta radiation absorption method

In the first stage, the instrument transmits beta radiation through a clean filter tape to the detector in order to determine the baseline signal the reference point. Next, a pump draws air through a size-selective inlet (e.g., PM10 or PM2.5), and particulate matter is deposited on the measured section of the filter tape. After sampling, the tape advances, allowing beta radiation to pass through the section containing the collected sample. Based on the measured attenuation and the attenuation of the clean tape (blank), the mass of the collected particulate matter and its concentration in $\mu g/m^3$ are calculated, provided that the volume of filtered air is known. In this method, the radiation source is a weak radioactive isotope, most commonly carbon ^{14}C or krypton ^{85}Kr.

The internal reference source in this method consists of certified calibration foils, known as span foils or calibration shims, with a precisely known surface density. Recalibration involves performing a periodic test during which the foil is automatically inserted into the measurement gap between the beta radiation source and the detector. The attenuation of the radiation by the reference foil is constant and factory-defined, and the detector verifies whether the measured mass reading agrees with the reference value. This makes it possible to compensate for, among other things, the aging of the radiation source and electronic drift.

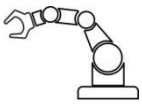
From the perspective of the practical use of automatic methods, quality control procedures such as Quality Assurance Level (QAL) 1–3 and the Annual Surveillance Test (AST) are of key importance. With regard to standardization, the implementation and use of internal reference sources are regulated by EN 14181, Stationary source emissions – Quality assurance of automated measuring systems. The periodic verification of instrument drift using an internal filter or reference foil is an obligation of the operators of these systems. The results should be recorded, for example, using Shewhart control charts, allowing drift in the optical or radiometric system to be detected before a failure occurs.

The importance of this issue is evident; therefore, other standards also apply, such as EN 15267-1 and EN 15267-2. These standards define the general principles for the certification and quality management system assessment of manufacturers of measuring instruments. They require that each internal reference source is produced in a repeatable manner, its parameters should comply with the requirements - measurement traceability.

The legal basis for ambient air quality monitoring remains EN 12341:2024. Current standardization work on automatic monitoring systems aims to ensure that the analyzer's daily self-check using an internal reference source eliminates the need for frequent calibration of automatic particulate monitors with gravimetric filters. It should be noted that these standardization efforts do not focus on the mere existence of an optical reference standard, but rather on the mathematical formulation and formalization of the way in which the instrument interprets the signal from this reference source.

The main quality-related issues associated with automatic methods concern maintaining an identical air sampling rate at the inlet and a constant volume of sampled air. Another problem is excessive humidity, which causes an artificial increase in particle mass. Particles absorb moisture and swell, which is a source of error in the beta radiation method. As is well known, water also binds fine particles into conglomerates, which distort the results obtained by the optical method—PM2.5 particles may be recorded as PM10. In inexpensive optical sensors, microscopic droplets of fog or water vapor are interpreted by the sensor as solid particles; consequently, the AQI during rainfall may be overestimated by several times.

10. Main metrological parameters

Name of the type series	Maximum capacity	Readability	Measurement method	Maximum filter size
UYA*)	2g	0.0001mg		ϕ 25mm
MYA*)	2g ÷ 51g	0.001mg		ϕ 25 ÷ 150mm
XA*)	51g ÷ 210g	0.01mg		ϕ 25 ÷ 90mm 210x297mm
AS*)	62g ÷ 520g	0.1mg ÷ 0.01mg		ϕ 25 ÷ 90mm
AK-6.5Y.F**)	0.5g	0.001mg ÷ 0.0001mg		ϕ 25 ÷ 47mm
UMA 2.5Y.F**)	2g	0.001mg ÷ 0.0001mg		
RB 2.5Y.F**)	2g	0.001mg		
RMC 2.5Y.FC**)	2g	0.001mg ÷ 0.0001mg		
RW 5Y.F153**)	2g ÷ 520g	0.1mg ÷ 0.0001mg		ϕ 25 ÷ 90mm

*) The scale has a software function called differential weighing, which calculates the difference between two sample states. Measurement results are saved in the scale's database and can be sent to any external application. Filters marked with an EAN code can be registered using an external barcode scanner. Filter deionization for UYA, MYA, and AS series scales is performed using an external deionizer. XA series scales can be equipped with an internal deionizer. Scale readings are checked using standard mass standards.

**) The system works with a computer program to generate and collect test results for a series of filters before and after exposure. Filter deionization is performed using external deionizers for the AK-6.5Y.F and UMA.2.5Y.F systems, or internal deionizers for the RB, RMC, and RW systems. The accuracy of readings from automated and robotic systems is verified using certified mass standards stored in the systems' warehouses.

11. Summary

The quality of the environment in which we live has always been a subject of assessment. However, with the availability of highly advanced measurement techniques, we have gained a much better understanding of how harmful and hazardous its components can be. Usually, the health effects are strongly emphasized, which is obvious, but scientific research also indicates the destruction of the inanimate sphere. This includes the corrosion of buildings and bridges, chemical changes in material structures, the influence of microorganisms on aging processes, and many other forms of degradation. Recognizing the importance of this issue, measurement methods should be designed to meet the requirements of economy, ergonomics, and the desired analytical accuracy.

It can be said that the current state of technology and engineering capabilities allows the development of highly sophisticated solutions for mass measurements. The main limitations in this area are project implementation time and economic considerations, particularly manufacturing costs. In many cases, basic manual balances with a resolution of $10^{-5} \div 10^{-6}$g are sufficient; however, there is still considerable potential for optimizing the weighing procedure, especially when filters accumulate electrostatic charges. In such cases, the manufacturer's research provides significant support, often leading to modifications of balance components and the identification of optimal solutions. Such applications are also developed by the Research Laboratory of the Centre for Metrology, Research and Certification at Radwag.

It has long been recognized that time is money, particularly in large-scale production. This principle also applies to air quality monitoring and surveillance systems. Increasing efficiency and minimizing risk an inherent element of every process has required the introduction of automation, including in mass measurement procedures. The nature of the weighing method, which is based on obtaining an average value, requires several mass measurements of the same filter. When hundreds of filters must be analyzed, this becomes difficult to accomplish manually. To address this challenge, Radwag has developed the UMA series of automatic weighing systems and the RB/RMC series of robotic weighing systems. It is worth noting that these instruments are also used in scientific research, where measurement accuracy significantly exceeding the minimum requirements specified in standards is expected. This presents a considerable challenge for the manufacturer in terms of optimizing instrument design, environmental conditions, and measurement signal processing systems.

The continued development of weighing methods available on the market is possible only through the work of manufacturers' research laboratories there is no alternative. Consequently, the search for optimized solutions and instruments for research projects is most successful through close cooperation between users and manufacturers, providing benefits for both parties. Radwag, with its own engineering and software development facilities, is an excellent example of how market needs can be translated into the design and implementation of advanced measuring instruments, including highly sophisticated systems.

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12. Bibliography

1. Fine Particulate Matter in the Atmosphere - A compendium of knowledge on particulate matter air pollution in Poland. Katarzyna Juda-Rezler, Barbara Toczko red. GIOŚ, Warsaw 2016, polish ver.
2. ISO 7708:1995. Air quality. Particle size fraction definitions for health-related sampling
3. Health and Safety Laboratory. General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols. https://www.hsl.gov.uk/
4. EH40/2005 Workplace exposure limits. Reference EH40/2005. ISBN 9780717667031. The Stationery Office, 2020
5. Pollen grains from various plant species, 500x magnification, author: Dartmouth College Electron Microscope Facility, license: Public Domain, source: Wikimedia Commons. Source: https://commons.wikimedia.org/wiki/File:Misc_pollen.jpg
6. Scanning electron micrograph (SEM) of a highly vesicular glass shard of ash measuring just over 0.1 mm long, erupted during the 18 May 1980 eruption of Mount St. Helens. Source: https://www.usgs.gov/media/images/ash-particle-1980-mount-st-helens-eruption-magnified-200-times
7. https://en.wikipedia.org/wiki/Particulate_matter
8. dr hab. Edward Więcek. Health criteria for aerosol sampling in the work environment. Fundamentals and Methods of Work Environment Assessment. 2011, nr 2(68), s. 5–21, polish ver.
9. EN 481:1998 Workplace exposure - Size fraction definitions for measurement of airborne particles
10. Hebisch, Ralph & Fricke, Hajo-Henning & Hahn, Jens-Uwe & Lahaniatis, Majlinda & Maschmeier, Claus-Peter & Mattenklott, Markus. (2005). Sampling and determining aerosols and their chemical components. http://doi.org.10.13140/2.1.4181.9202
11. EN 872, Water quality. Determination of suspended solids. Method by filtration through glass fibre filters
12. EN 12341:2024 ,,Ambient air - standard gravimetric measurement method for the determination of the PM10 or PM2,5 mass concentration of suspended particulate matter”
13. ISO 5725-1:2023, Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definition
14. ISO/IEC Guide 98-3:2008 Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement.
15. EN ISO/IEC 17025:2018-02, General requirements for the competence of testing and calibration laboratories
16. ISO 10012:2026, Quality management — Requirements for measurement management systems
17. PN-EN ISO 9001:2015-10, Systemy zarządzania jakością – Wymagania.
18. Chyzhykov, D., Widziewicz-Rzońca, K., Błaszczak, M., Rogula-Kopiec, P. & Słaby, K. Automatic weighing system vs. manual weighing precision comparison in PM-loaded filter measurements under different humidity conditions. Environ. Monit. Assess. 195 (11). https://doi.org/10.1007/s10661-023-11939-7 (2023).
19. EN 14181:2014. Stationary source emissions - Quality assurance of automated measuring systems.

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