12. In-situ Precipitation Measurements

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This chapter describes the measuring principles and technological solutions available for in-situ measurements of liquid (rain) and solid (snow) atmospheric precipitation. They can be classified into catching and non-catching precipitation gauges. Instruments belonging to the first family are generally based on gravity-related measuring principles (weighing, tipping buckets, floating devices), while the second group includes instruments based on optical, acoustic, and microwave principles (e.g., disdrometers). All instruments are subject to both systematic (often unknown) biases and measurement uncertainties, depending on the design, the measuring principle, the algorithms used for data interpretation and correction, etc. Moreover, environmental factors affect the measurement accuracy as well, depending on the atmospheric conditions at the collector, the siting characteristics, etc. Typical environmental factors include the gradients of atmospheric temperature, wind speed, and solar radiation and may result in a significant underestimation of accumulated precipitation. The present chapter addresses the achievable accuracy of instruments for in-situ measurement of liquid and solid precipitation, based on both the outcomes of the recent WMO intercomparison initiatives and the accurate laboratoy and field tests presently ongoing within the activities of the WMO/CIMO Lead Centre on Precipitation Intensity (Italy).

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According to the *Guide to Instruments and Methods of Observation* [12.1] published by the World Meteorological Organization (WMO), precipitation is defined as

> the liquid or solid products of the condensation of water vapour falling from clouds. The total amount of precipitation which reaches the ground in a stated period is expressed in terms of the vertical depth of water (or water equivalent in the case of solid forms) to which it would cover a horizontal projection of the Earth's surface.

Precipitation intensity is defined as

> the amount of precipitation collected per unit time interval.

Atmospheric precipitation is commonly experienced in our everyday lives and activities, in both business and leisure time, and its impact is manifest in major socioeconomic sectors including transportation, agriculture, safety, tourism, and recreation.

The extraordinary role of atmospheric precipitation in human society (and natural ecosystems as well) justifies the need to obtain accurate quantitative measurements of the amount of water reaching the ground surface and the duration and intensity of precipitation events.

12.1 Measurement Principles and Parameters

Precipitation varies considerably in both space and time. It is erratic and intermittent in nature, and is composed of a large number of hydrometeors, each of them with its own size, shape, density, and fall velocity in reaching the ground, according to specific frequency distributions. Due to the complex processes of nucleation, accretion, melting, and interactions between the hydrometeors (see e.g., [12.2]), the resulting characteristics of precipitation depend on the generating weather phenomenon and climate at any specific location (temperature, humidity, etc.). In addition, the fall trajectories of single particles are affected by local conditions at a site, including wind and shading by obstacles, and by the aerodynamic behavior of the outer body of the measurement instrument itself.

12.1.1 Measurement Principles

Precipitation is among the most challenging environmental measurements, and accurate measurement of the amount of water that would ultimately land on a well-defined portion of the ground surface in undisturbed conditions is a difficult task. This is the aim of the so-called in-situ measurements at the ground, with the instrument located precisely where the information is sought, at a single location immersed in the precipitation process.

Precipitation measured at a single location is representative of a limited area in space,

> the size of which is a function of the length of the accumulation period, the physiographic homogeneity of the region, local topography and the precipitation-producing process [12.1].

Weather radar and, more recently, satellites are used to define and quantify the spatial distribution of precipitation from a remote sensing perspective, with the sensor generally located far from the precipitation process. The information is inferred from the observed modifications of other physical quantities due to the interference with the precipitation process (e.g., active/passive microwave, infrared temperature).

In-situ precipitation gauges, however, provide the only direct measurement of precipitation at the ground and are usually referred to as the *ground truth*. Remote sensing techniques for extensive observations (essentially weather radar, aircraft, and satellite-borne radiometers) still require the use of in-situ measurements for calibration and validation purposes. Following [12.3],

> measurements at the ground have been proved indispensable, despite advances in several areas of remotely sensing of precipitation. Ground truth seems to be inseparable from any study on precipitation. A better understanding of the behavior of precipitation on the ground with direct measurements can lead to more effective estimations by using other methodologies.

12.1.2 Measured Parameters

The parameters measured by precipitation instruments range quite widely: basic instruments simply inform the status of the rain in that moment, i.e., whether it rains or not, while others detect the particle size distribution of hydrometeors. Traditionally, however, the equivalent volume of water received by a collector through

Table 12.1 Measured parameters of precipitation sensors

Parameter	Description	Unit	Symbol
Rain depth	The total volume of liquid precipitation deposited in a given time interval per unit area of the horizontal projection of the ground surface	mm	*RA*
Snow depth	The liquid water equivalent of the total volume of solid precipitation deposited in a given time interval per unit area of the horizontal projection of the ground surface	mm	*SA*
Rainfall intensity	The rain depth per unit time interval	$mm\,h^{-1}$	*RI*
Snowfall intensity	The snow depth per unit time interval	$mm\,h^{-1}$	*SI*
Particle size	The characteristic dimension (usually the diameter assuming spherical shape) of hydrometeors	mm	D
Number of particles	Number of hydrometeors per class of particle size	–	$N(D)$
Particle fall velocity	Velocity of hydrometeors at the ground surface	$mm\,s^{-1}$	v

Table 12.2 Other relevant parameters for precipitation measurements

Parameter	Description	Unit	Symbol
Temperature	Ambient temperature	°C	T
Wind velocity	Average wind velocity at the sensor's height	$mm\,s^{-1}$	U_w
Wind direction	Prevailing wind direction expressed in degrees clockwise from due north	°	U_d

an orifice of known surface area in a given period is assumed as the reference variable, namely the precipitation depth. The measurement unit of precipitation amount is therefore linear depth, usually expressed in millimeters, obtained as the ratio of the precipitated cumulative water volume over the surface area of the collector.

Under the restrictive hypothesis that precipitation is constant over the accumulation period, a derived variable—the precipitation rate or intensity—can be easily calculated. Using short time intervals ensures that the estimated intensity is close to the real flow of water ultimately reaching the ground. The measurement unit of precipitation intensity is linear depth per unit time, usually expressed in millimeters per hour.

This approximate measure of the precipitation rate has long been accepted as sufficiently accurate to meet the requirements of both scientific and technical applications. Reasons for this are on the one hand that most traditional applications in hydrology operate at the basin scale, thus dealing with aggregated rainfall over large space and timescales, while on the other hand the available technology of measurement instruments—especially in terms of data storage and transmission capabilities—was lower than today.

Although quantitative data regarding the amount (depth) of liquid and solid precipitation are the basis for many practices, the intensity of precipitation has become a variable of almost equal significance. Rainfall and snowfall intensity data are extremely relevant in the case of severe weather. For example, it is clear that events with extremely high precipitation rates affect all types of transportation; they may also destroy crops and vegetation. Precipitation intensity has now been introduced by WMO as a measured parameter, in line with the present recommendations on weather reporting (Table 12.1).

In addition, most automatic precipitation gauges provide the amount of precipitation at a relatively short time resolution, usually less than 1 min. Users of precipitation measurements typically require information on accumulated rainfall/snowfall for longer time intervals, for example, the hourly, daily, monthly, and even annual total rain depth. Modern non-catching instruments include optical and acoustic principles to derive information including drop size distribution (DSD), fall velocity of single drops, crystal types (Table 12.1) and other relevant parameters (Table 12.2).

12.1.3 Requirements

Research and technological development in the field of precipitation measurements obviously proceed at a different pace, so that the instruments commonly deployed on the territory do not have the same level of accuracy of research-devoted instruments installed at a few experimental sites. Even the research instruments in some cases are used under the blind assumption of a high level of accuracy (because of the physical principle used to measure rainfall), but often no evidence is made available to support this assumption. This is the case, for example, with various types of disdrometers, as it was recently shown that their calibration is still a problem [12.4].

Requirements from the many users of precipitation data are becoming tighter and tighter, and sound research and applications in the geosciences require enhanced quality in precipitation measurement. The interpretation of rainfall patterns, speculation about the nature of the rain field, scaling versus nonscaling issues, rainfall event modeling and forecasting efforts, everyday engineering applications, etc., are all based on the analysis of precipitation data that are measured at very fine resolution. Therefore, the relevance of precipitation intensity measurements has increased dramatically, and very high values are increasingly recorded, due to the shortening of the reference period. High accuracy is also sought in the upper range of precipitation intensity.

The timescales required for calculation of precipitation intensity at the ground are already much shorter than in traditional applications. The design and management of urban drainage systems, flash flood forecasting and mitigation, transport safety measures, and in general most of the applications where precipitation data are sought in real time, call for enhanced resolution of such information in time (and space), even down to the scale of 1 min in many cases.

The thirteenth session of the WMO Commission for Instruments and Methods of Observation (CIMO-XIII, 2002), as a result of an Expert Meeting held in Bratislava, Slovakia in 2001, noted that significant efforts were necessary to obtain the required information about uncertainties in precipitation intensity measurement. For liquid precipitation, CIMO-XIII adopted the measurement range and related uncertainties recommended by the expert team, published in the *WMO Guide to Instruments and Methods of Observation* (WMO-No. 8) [12.1] and reported in Table 12.4.

Instruments based on modern technology are increasingly deployed as part of or simply to replace traditional monitoring networks, especially in developed countries, where the high cost of such instruments can more easily be borne. However, little information is available to the user on biases and uncertainties associated with such instruments, and corrections are very seldom applied. Therefore, the quality of the new data sets is not necessarily higher (and is sometime even lower) than what is obtained from traditional networks, while additional inhomogeneities of the time series are added to the picture, with serious consequences, for example, in climate-related studies.

12.1.4 Siting Considerations

Precipitation measurements aim to obtain a sample that is representative of the true amount of water falling over the area that the measurement is intended to represent [12.1]. The quality of the measurement is very sensitive to the exposure of the instrument to the surrounding environment. Appropriate siting is therefore crucial in obtaining accurate precipitation measurements.

The WMO Guide no. 8 [12.1] specifies that

> the best sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or where other objects act as an effective windbreak for winds from all directions.

However, the presence of obstacles and other instruments close to the precipitation gauge should be avoided. The [12.1] imposes certain distances for any obstacle, and defines siting classes depending on the slope of the surrounding area and the type and height of obstacles.

12.2 History

In human history, abundant atmospheric precipitation often had a positive acceptation, while the lack of it was sometimes viewed as a visitation from god and a punishment for human sins. The need for the occurrence and recurrence of precipitation is historically evidenced by the presence of dedicated gods in most ancient religions (Chac—Mayan god of rain, Ishkur—god of rain and storm in the Mesopotamian mythology, Baal—god of storm in the Phoenician mythology, Seth—the *Lord of storm* for Egyptians, and many others). As a first reward in response to good conduct by the acolytes, the Torah promises rainfall, "something that is a natural prerequisite for all specific material blessings" (Akeidat Yitzchak 70:1). However, the Book of Amos (4:6–8) reports: "I also withheld rain from you when the harvest was still three months away (...), yet you have not returned to me". Still today, many religions convene the acolytes to pray for the occurrence of rainfall in periods of intense drought. An exceptional amount of precipitation is equally negative, since it generates floods and inundations, with associated damage and victims, being nowadays among the most common natural disasters on planet Earth.

12.2.1 History of Precipitation Measurements

The early need for measuring atmospheric precipitation in precise quantitative terms in human history seems to be of religious, agricultural, or even taxation-related origins.

Ancient religious texts dated about 400 BCE are often cited in literature as the oldest written documentation of the practice of measuring precipitation in

Palestine [12.2, 5, 6]. The rainfall amount was used to define droughts and the limits of the fast period, thus the question:

> How much rain must fall to constitute the first rainfall? 'Enough to fill a utensil three handbreadths in height', the words of R. Meir. I. R. Judah says, 'The first is to be a handbreadth [of rain], the second, two handbreadths, and the final one, three handbreadths'
> (Jerusalem Talmud, Ta'anit 1, 3).

The utensil mentioned in the text was assumed to be an initial version of a rain gauge, and an estimate of the yearly precipitation in Palestine (divided into three rain periods) was derived from the use of the *handbreadth* (the width of a hand used as an indication of length) by *Julius von Hann* (1839–1921) [12.7]. From the same measurement unit, even the size of the rain gauge was estimated. However, a second version of the same religious text contends:

> How long should it continue to rain to warrant the community breaking their fast? [Until the rain has penetrated] as far as the knee of the plough enters the soil; this is the opinion of *R. Meir*. The Sages, however, say: in the case of arid soil one handbreadth, in the case of moderately soft soil two handbreadths, and in the case of cultivated soil three handbreadths.
> (Babylonian Talmud, Ta'anit 25b).

This second version, as indicated by *Jehuda Feliks* [12.8] and reported by [12.9], makes it clear that the quantity used to define the limits of the fast period was actually a qualitative measurement of water content in the soil (or infiltration) rather than the rainfall amount, and linked to the penetration of a plough (the actual utensil) into the soil. Therefore, no mention of rainfall measurements is actually contained in such religious texts, although it is clear that the occurrence and amount of rainfall has ruled religious practices since very old times.

An ancient Indian treatise on statecraft, economic policy, and military strategy, called Arthashastra and written in Sanskrit, contains clear reference to rainfall measurements in the past [12.10]. Possibly the work of several authors over centuries, its authorship is often attributed to Kautilya, a scholar at Takshashila, the teacher and guardian of Emperor Chandragupta Maurya. Composed, expanded, and redacted between the second century BCE and third century CE, the Arthashastra was influential until the twelfth century, when it disappeared. Shamasastry rediscovered the text in 1905 and published it in 1909; the first English translation was published in 1915.

In Book II–The Duties of Government Superintendents, Chapter V–The Duties of the Chamberlain, the Arthashastra instructs:

> In (front of) the store-house a bowl with its mouth as wide as an *aratni* (the distance from the elbow to the tip of the hand) shall be set up as rain gauge (*varshamána*).

Again, in Chapter XXIV–The Superintendent of Agriculture, it is said that:

> the quantity of rain that falls in the country of Jángala is 16 dronas [1 drona = 13.2×10^{-3} m^3 of water]; half as much more in moist countries. (...) When one-third of the requisite quantity of rain falls both during the commencement and closing months of the rainy season and two-thirds in the middle, then the rainfall is (considered) very even.

The chapter concludes by indicating the intended use of such measurements, stating:

> according as the rainfall is more or less, the superintendent shall sow the seeds which require either more or less water.

In China, the earliest documented memory of rainfall measurement seems to appear in an ancient treatise entitled *Shushu jiuzhang* (1247), or *Mathematical Writings in Nine Sections*, by *Qin Jiushao* (1202–1261), a Chinese mathematician who first developed a method for solving simultaneous linear congruences. The book is divided into nine *categories*, each containing nine problems related to calendrical computations, meteorology, surveying of fields, surveying of remote objects, taxation, fortification works, construction works, military affairs, and commercial affairs [12.11]. The treatise contains a problem on the shape of rain gauges, discussing the determination of the rain falling on a given area of ground from the depth of rainwater collected in vessels of conical or barrel shape [12.12]. It seems that at that time there was one in each provincial and district capital. The same book shows that snow gauges were also in use. These were large cages made of bamboo, and the author gives sample problems concerning them.

In Korea, the first documented rain gauge measuring rainfall by collecting rainwater in a barrel dates back to 1441 (23rd year of King Sejong's reign). However, the only specimen surviving until today was made in 1837 (third year of King Heonjong's reign) in the form of a barrel-shaped rain gauge, 31.5 cm high and having a diameter of 15.3 cm (Treasure 561° of the National Treasures of South Korea, designated within the heritage preservation system of the country). A ruler was used to measure the rainwater depth collected in the barrel. The rain gauge has an associated square stone stand, added when it was on display at the National Gongju Museum. The Korean Meteorological Administration and the National Palace Museum of Korea have also preserved some further rain gauge pedestals made of stone or marble, but the associated rain gauges did not survive.

Father *Benedetto Castelli*, born in Brescia (Italy) in 1578, was an Italian mathematician who entered the Benedictine Order in 1595. He is recognized as the inventor of the rain gauge in 1639 because he was the first to measure rainfall associated with a given interval of time, and therefore the first to measure rainfall intensity (or the average rainfall intensity) at a given site. He designed the first rainfall intensity gauge at the S. Peter Monastery in Perugia (Italy) in order to study the relationship between the observed precipitation and the stages of the Trasimeno Lake in central Italy, following a drought period affecting agriculture in the region.

In a letter to *Galileo Galilei* (1564–1642) in 1639, he writes:

> Given a bucket made of glass, with a cylindrical shape one palm high and half a palm wide, after pouring some water in order to cover the bottom of the bucket, I noted accurately the level of water and left it exposed to the rainfall for a period of one hour.

Assuming that the depth of water would have been the same in any similar nearby bucket (and therefore over the lake area), and noting that for a rainfall duration of 8 h at a similar rate the total water would have been eight times the measured one, Castelli managed to predict the water level rise in the Trasimeno Lake.

This is actually the first documented use of the concept of rainfall intensity as measured by a rain gauge, although the simple bucket used is a storage instrument in modern terminology (Sect. 12.3). For this reason, the first WMO/CIMO Lead Centre on Precipitation Intensity established in Italy in 2010 (www.precipitation-intensity.it, Accessed 05 July 2021) is now dedicated to the memory of, and named after, Benedetto Castelli and his historical work on precipitation measurements. Based on refinements of the instrument used by Castelli in the first half of the 17th century in Italy, both *Giovanni Poleni* (1683—1761) in Padova and *Paride M. Salvago* in Genova started regular observations of precipitation, and analogously in many other countries (e.g., B. Franklin since 1725).

According to *Asit K. Biswas* [12.13], *Sir Christopher Wren* (1632–1723), one-time president of the Royal Society, conceived the earliest English rain gauge in 1662. Unlike the previous instruments, which were all of the nonrecording type, the inventor developed an automatic tipping-bucket rain gauge, which was realized later in 1679. The author notes that reference to the Wren tipping-bucket rain gauge can be seen in the review of the book *De l'origine des Fontaines* by *Pierre Perrault* (1611–1680) in the *Philosophical Transactions* for 1675. The review states that:

> the like to which (estimation of the quantity of rain) hath been attempted here, and proposed to the R. Society, some years since, by Sir. Christopher Wren, who by the contrivance of a rain-bucket had taken an account of all the water that fell for a considerable time. By his weather-clock had, among other particulars, not only taken in the measuring of the quantity of rain that falls, but also the time when it falls, and how much at each time.

The invention of the tipping-bucket rain gauge marks the start of modern rainfall intensity measurements, which today are largely obtained using the same measuring principle, although many other instruments based on different principles are also available today, as detailed in Sect. 12.3 below.

12.2.2 Evolution of Acquisition Systems

Similarly to the measuring principles and instrument design, the whole measurement chain has evolved through the years at the pace of technological development. The technological evolution experienced by acquisition systems affects the measurement accuracy and the capability to meet stringent user requirements in terms of resolution, accuracy, sensitivity, etc.

The electronic recording and digital storage of the measured data in the data logger have largely overcome the traditional mechanical transmission of the modifications induced by the accumulated precipitation on the moving parts of the system. Generally, recording was obtained by a moving pen in contact with a paper chart mounted on a rotating cylinder controlled by a clockwise spring mechanism. The resulting charts report the accumulated rainfall, or the number of impulses of the counting mechanism as a function of time, depending on the measuring principle (Sect. 12.3).

The use of electronic circuits allowed the changes induced by precipitation as sensed by the instrument to be transformed into voltage changes and recorded in some digital form. This increased the resolution of the measured data and reduced the uncertainty due to the mechanical recording systems, resulting in a dramatic reduction of the time interval over which changes in the rain signal could be sensed and recorded. The precision of the temporal labeling of each recorded impulse or voltage change also improved.

One of the major implications is the improved capability of measuring precipitation intensity, since the measured precipitation amount is associated with a much shorter interval than was possible in the past. Since many natural and man-made systems respond to the precipitation intensity forcing rather than to the accumulated water depth (e.g., flash floods, urban drainage systems), the improvement is tangible and valuable for modern applications.

In parallel with the evolution of data acquisition systems, the telemetering capabilities have evolved as well in recent times and are still evolving today. Any need to visit remote gauge stations in order to transfer the recorded measurements to the central archiving site has now vanished thanks to the automated transmission of the data via radio, telephone, or satellite links. In rare cases gauge stations are connected by cable and can transfer data directly over the network. Local storage in the data logger is still preserved for redundancy and safety reasons and can be downloaded, for example, during inspection or maintenance visits.

As an immediate advantage of the data transmission capabilities of modern instruments, the flow of data can now be managed automatically at the archiving station, including the application of quality control procedures, preparation of synthetic reports (e.g., daily average, maximum hourly precipitation intensity, daily accumulation), and data processing in general. This enables failures to be detected in the measurement chain, including instrument problems such as clogging or power supply failures, and timely maintenance to be activated as needed.

The major advantage, however, is the fact that data transmission is made practically instantaneous, so that the information about the ongoing precipitation is obtained at a centralized control station within minutes, and the assessment of impending flooding in urban areas, for example, or level rise in channels can be made in real time. This dramatically improves the efficacy of flood warning systems and the operation of water control systems in a variety of applications.

12.2.3 Homogeneity of Historical Precipitation Records

The technological evolution of the precipitation measurement chain also affects the statistical characteristics of historical records, first of all in terms of the homogeneity of recorded time series. Changes in the instrumentation, acquisition systems, data transmission, and post-processing algorithms indeed introduce both abrupt shifts and smoothed trends in the historical records. These changes should be extensively documented and the related information made available as metadata, although often—especially for past years—this is not the case. While the most relevant shifts in the time series can be easily identified using suitable statistical tools, detecting smoothed trends may require a long period of measurements, since they are hidden in the natural variability of the precipitation process.

Introducing modern technology is always beneficial, and monitoring networks are continuously updated with more reliable and accurate gauges. However, in the case of precipitation, caution should be exercised and such developments accompanied by the appropriate procedures to ensure homogeneity, or at least to clearly document them in the metadata. Even the progressive introduction of the practice of instrument calibration to ensure the traceability of precipitation measurements is prone to generating inhomogeneity, since the oldest data most probably derive from poorly calibrated instruments.

Calibration issues are evident, for example, with the most common technology used to measure precipitation intensity around the world, i.e., the tipping-bucket rain gauge. As described in Sect. 12.4, this instrument is affected by intrinsic systematic mechanical biases that can be easily adjusted by means of dynamic calibration. Good knowledge of systematic sampling and mechanical errors is available in the literature, with efficient correction methodologies widely tested and discussed (see e.g., [12.14–19]).

This notwithstanding, the errors associated with the tipping-bucket device are often understated by the user, even by national meteorological services (NMS), and data are seldom corrected to account for such errors, with non-negligible consequences in terms of the quality and reliability of the derived data sets (see e.g., [12.20]). Moreover, the time series recorded at each location would experience an artificial climatic trend toward increasing climatological precipitation if mechanical errors affecting historical data were systematically neglected. Since rain gauge manufacturers are progressively distributing dynamically calibrated instruments and smart interpretation algorithms embedded in the data logger, the risk of introducing artificial trends in rainfall time series is far from just academic.

Finally, the reduction of the time resolution of precipitation intensity measurements increasingly allows higher intensity values to be measured that were also present in the past but had been smoothed by the measurement process itself. This might support the false notion that precipitation intensity is increasing at a given location, when in fact the improved measuring capabilities are simply enabling a better representation of the precipitation process at a finer timescale.

12.2.4 Instrument Testing and Intercomparisons

The history of instrument intercomparisons in the case of precipitation measurements dates back significantly to past centuries, experiments in the field being reported by Stow [12.21] and recently by Goodison [12.22]. This is in line with the well-established awareness of the relevance of intercomparison in atmospheric sciences. Father Francesco Denza, member of the Italian Meteorological Society, stated already in 1872 that:

> ... in order that meteorological studies produce advantages for human beings ... it is not only necessary to have lots of observatories and observations/measurements be done with intelligence and accuracy, but it is moreover requested a meteorological investigation with same methodology and with well compared instruments.

An overview of the list of WMO intercomparisons of precipitation gauges, including the reference standard measurement used and the results obtained, and a a short description of each intercomparison was provided by [12.23]. Early international rain gauge intercomparison efforts were focused on accumulated amounts of precipitation, low-intensity events (including solid precipitation), and sometimes only on qualitative rainfall intensity (*RI*) information (light, moderate, and heavy). The *International Comparison of National Precipitation Gauges with a Reference Pit Gauge* [12.24] and the *WMO Solid Precipitation Measurement Intercomparison* [12.22] were conducted comparing only the accumulated amounts of precipitation. Precipitation intensity was first investigated in the *WMO Intercomparison of Present Weather Sensors/Systems* [12.25], but this intercomparison did not focus in particular on quantitative values, and precipitation intensity was reported as a qualitative parameter (light, moderate, heavy).

The latest international intercomparison efforts were designed to assess and compare quantification and catching errors for both catching and non-catching types of rainfall intensity gauges, with an emphasis on high rainfall intensity.

Following the recommendations of the WMO/CIMO Expert Meeting on Rainfall Intensity held in Bratislava, Slovakia, in 2001, the WMO first organized a laboratory intercomparison, followed by a field intercomparison. Only catching-type instruments were considered for the laboratory intercomparisons, while both catching and non-catching types were included in the field intercomparison.

In September 2004, The WMO Laboratory Intercomparison of Rainfall Intensity (*RI*) Gauges was launched simultaneously in the laboratories of the Royal Netherlands Meteorological Institute, Météo-France, and the Department of Environmental Engineering (University of Genova, Italy). As recommended by the thirteenth session of the Commission for Instruments and Methods of Observation (CIMO-XIII), Bratislava, Slovakia, 23.09.–03.10.2002, a standardized procedure for generating consistent and laboratory-reproducible flow rates for use as the laboratory reference rainfall intensity was developed for calibration of catching-type gauges. All participating instruments, manufactured in various countries, were catching-type gauges, and a pair of instruments was available for each type. The main objective of the intercomparison was to test the performance of different types of precipitation gauges based on different measuring principles under documented conditions. Results can be found in the final report [12.26].

To ensure the continuity of the performance assessment, a Field intercomparison (2007/2009) was organized, where the instruments already tested in the laboratory were given priority. The results reported an estimation of the overall operational accuracy to be expected in the measurement of *RI* in the field and can be found in the final report of the intercomparison [12.4] and in various published papers [12.27–30].

The WMO/CIMO agreed in 2010 to organize an intercomparison for assessing the impact of automation on the measurement of snowfall, snow depth, and solid precipitation in cold climates, dubbed the WMO Solid Precipitation Intercomparison Experiment (WMO–SPICE). The SPICE objectives focus on the use of automatic instruments for measuring and reporting:

- Precipitation amount, over various time periods (minute, hour, day, season), as a function of the precipitation phase, with a focus on solid precipitation
- Snow on the ground (snow depth); as snow depth measurements are closely tied to snowfall measurements, the intercomparison planned to investigate the linkages between them.

SPICE provides guidance on the use of modern automated systems for measuring solid precipitation amount and snow depth, and recommends appropriate automated field reference system(s) for the unattended measurement of solid precipitation in cold climates. Recommendations are presented for adjustments to account for the undercatch of solid precipitation due to gauge exposure as a function of variables available for an operational site such as wind, temperature, and precipitation type. Additionally, the sources and magnitudes of errors due to instrument characteristics, field exposure, shielding, environmental conditions, and data processing methods are investigated. The final report of SPICE was published by WMO in December 2018 [12.31].

12.3 Theory

Precipitation is measured using various methods, and the theory behind precipitation measurements encompasses basic mechanical, electromechanical, optical, and acoustic principles.

12.3.1 Measurement Principles and Accuracy

Many types of instruments and measurement techniques are in operational use. Because of the extended experience, most of these techniques are well described and understood, but new instruments are appearing and still need deeper testing and investigation [12.26]. Recommendations on standardization of equipment and exposure are well documented [12.1], while procedures for instrument calibration have been proposed in the literature. The basic classification of precipitation gauges is between catching and non-catching instruments. In the first case, precipitation is collected into a container for a given period before water is conveyed to the sensor and measured. They may or may not include a funnel to convey the collected precipitation toward a nozzle for dispensing water to the sensor unit. In non-catching instruments, the precipitation flux is *sensed* when crossing or impacting on a given section, or volume, of the atmosphere in the vicinity of the ground surface. Instruments of the first family are generally based on gravity-related measuring principles (weighing, tipping, floating devices), while the second group includes optical, acoustic, and microwave principles.

All instruments are subject to both systematic (bias) and random measurement errors (Sect. 12.6), depending on the construction of the device, the measuring principle, the algorithms used for data interpretation and correction, etc. The errors themselves can be classified into catching- and counting-type errors.

The errors due to the weather conditions at the collector and those related to wetting, splashing, and evaporation processes are referred to as catching errors. They all indicate the ability of the instrument to collect the total amount of water falling over the projection of the collector's area at ground level. Non-catching instruments (which are based upon a contactless measurement) have no collector and may also show *catching* errors, which in this case implies that the instrument is not able to let the full amount of precipitated water pass through the area or volume where the measurement is taken.

Counting errors are related to the ability of the instrument to correctly quantify the amount of water that is collected or detected by the instrument. They can be experienced in both catching and non-catching types of instruments, although in the latter case, the assessment of such errors is very difficult and hard to be performed in controlled laboratory conditions. These errors may originate from the very different aspects of the sensing phase, since the available instruments differ, for example, in the measuring principle applied, construction details, or operational solutions.

The impact of such errors on the overall accuracy of precipitation measurements at a site also varies in relation to the type of precipitation (solid, liquid, or mixed) and the range of precipitation intensity. The counting inaccuracies generally have a much stronger impact on the measurement of liquid precipitation, with sampling errors generally affecting low rates and mechanical or dynamic errors mainly affecting higher rain rates. The catching capabilities of the gauge assembly are a major issue in the case of solid precipitation measurements or whenever the rate of liquid precipitation is very low [12.32].

The impact of inaccurate measurements on the results of scientific investigation in precipitation-related fields is not yet fully clear nor quantified [12.33]. With the exception of a few dedicated papers (e.g., [12.20, 34–36]), or papers dealing with the analysis of measurement errors themselves [12.14–17, 37], the issue of how deeply the accuracy of the data sources actually affects the obtained results is rarely addressed. The scarce attention paid to the quality of data often gives rise to serious doubts about the significance of the experimental results made available in the literature. Obviously the effects will not be dramatic in all cases, since the error propagation could be negligible as well, depending on the application.

Nonetheless, scientific soundness requires that all possible uncertainties be properly taken into account, and it is therefore clear that the quality of basic data sources—such as precipitation measurements—should not be an exception. In addition, certified accuracy is needed for meteo-hydrological networks operating within the framework of a quality assurance system.

12.3.2 Volumetric Methods

Precipitation accumulates on the surface of the ground whenever it is not allowed to infiltrate (impervious surfaces) or run away along the terrain slope because of gravity forces (flat or concave surfaces). Accumulation enables the preservation of the water in natural or man-made reservoirs in order to exploit it for various purposes. One such purpose is precipitation measurement, and volumetric methods simply detect how much water is cumulatively collected within a given period in a small reservoir of known geometry.

Water Level

Measurements based on the water level employ a calibrated container, usually a cylinder, used to collect precipitation. The level reached by the water surface is periodically measured to obtain the volume of water accumulated in a given period, based on the known cross section area of the container. Since the method is quite trivial, the earliest measurements of precipitation (Sect. 12.2.1) were based on a direct reading of the water level accumulated in a container.

The measurement can be performed by an operator reading the level directly on a graduated cylinder or by pouring the water collected by the gauge into a reference container of known volume. Usually measurements are performed once or twice a day, then the container is emptied. Depending on the length of time between measurements and the environmental conditions (temperature, humidity), evaporation from the container can significantly affect the measurement accuracy.

An improvement of this method employs a float inside the container to measure the water level and record the data on a strip chart. In automatic precipitation gauges, the measurement of the water level collected in the container is performed by automatic sensors based on conductivity, acoustic distance, or hydrostatic pressure measurements.

Tilting Siphon

A tilting siphon is a particular method that differs from the more traditional water level measurements by employing the automatic emptying principle.

The tilting siphon mechanism consists of a bucket that collects the precipitation and a float connected to a pen that records the signal on graph paper attached to a drum. The float rises with the water level in the container and its movement is recorded by the pen. When the water reaches the top, the bucket tips over one side, and the siphon comes into operation and releases the water outward. The natural siphon recorder consists of two coaxial tubes; when the water reaches the top of the outer tube, the siphon mechanism is activated. The siphoning stops abruptly once the air reaches the top of the tube.

12.3.3 Gravimetric Methods

Gravimetric methods use the action of gravity on the collected water to detect the precipitation amount or intensity. The weight of a given water volume is exploited either directly, by measuring the induced deformation or vibration of sensitive elements, or indirectly by activating the movement of mechanical parts, releasing droplets, etc.

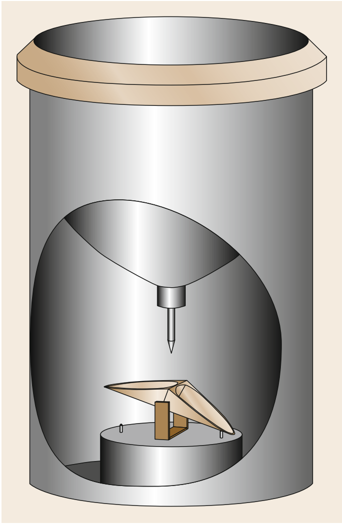

Fig. 12.1 Scheme of the tipping-bucket measuring principle

Tipping bucket

The mechanical principle of tipping-bucket gauges (TBG) was the first used to measure precipitation intensity. It consists of a tilting balance holding a bucket divided into two compartments having the same volume (Fig. 12.1). The compartments are balanced on a horizontal axis in unstable equilibrium, and two stop screws allow the initiation of the movement to be adjusted, i.e., setting the volume of water required to trigger the rotation, and avoid complete tilting on one side. The water mass content of the bucket is constant (M (g)). Therefore, by assuming the density of water $\rho = 1\,\mathrm{g\,cm^{-3}}$, the corresponding volume (V (cm^3)) is derived, and consequently the corresponding accumulation height (h (cm), usually expressed in mm) is retrieved after dividing by the surface area of the collector (S (cm^2)).

When precipitation occurs, the gauge conveys the water to the twin compartments placed under the funnel through a nozzle. The balance starts moving when one compartment reaches the critical volume. During the rotation the first compartment moves to the emptying position and the second compartment moves below the water flux. The bucket takes a small but finite amount of time to tip, and during the first half of its motion, additional rain may enter the compartment that already contains the calculated amount of rainfall; therefore, this water is lost and not measured (Sect. 12.6.1). The water losses during the tipping movement result into a systematic mechanical error inducing an underestimation bias that increases with the rainfall intensity. This must be corrected by means of suitable calibration procedures (Sect. 12.6.1).

The rotation of the bucket is used to trigger a reed relay (a pen writing on a rotating chart in ancient versions) and to produce an electrical impulse per each tip as the signal output, which is then recorded by a data logger or an analogue-to-digital converter. This mechanism provides a continuous measurement process without the need of manual interaction. Given the nominal bucket volume, the total volume is calculated from the number of tips in a chosen time interval (1 min is recommended). However, the rainfall intensity is best calculated from the information about inter-tip times, obtained by recording the time stamp of each tip.

Weighing

Precipitation is collected in a bucket and the weight of the container, together with the collected water, is recorded by means of a spring mechanism or using a system of balance weights (Fig. 12.2). The weighing of the container allows the volume of water present in the gauge collector to be measured, and the precipitation rate can be calculated as the difference between the amount of water from two consecutive measurements over a given time interval.

Generally, these gauges do not use any mechanical moving part in the weighing mechanism, and only elastic deformation occurs. The weighing mechanism depends on the sensor employed in the instrument to obtain the water weight of the bucket and usually uses a balance, a load cell, or vibrating wire load sensors.

Recently, fiber Bragg grating (FBG) technology has been developed to measure the rainfall water weight. The FBG has been employed to measure the deformation of a cantilever beam induced by a collecting tilting bucket [12.38] or applied on a rubber thin film with a defined cross section area [12.39]. In the latter case, the rain weight loads the rubber film and causes the deformation of the fiber, changing the grating wavelength.

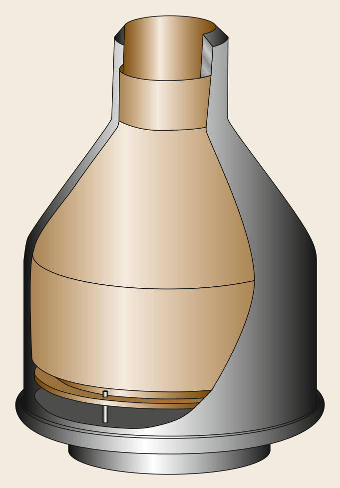

Fig. 12.2 Scheme of the weighing measuring principle

Drop Counting

In the drop-counting catching-type gauge, the precipitation collected by the funnel is conveyed to a calibrated thin nozzle, which starts dispensing droplets with a known volume. A suitable sensor, usually optical, detects the transit of each falling droplet as dispensed by the nozzle and counts the total number of droplets falling within a specific interval.

The size of each droplet depends mainly on the dimensions and characteristics of the dispensing nozzle, but also on the precipitation rate, which affects the frequency of droplets released and the drop formation and detachment process.

The volume of the droplets dispensed by the nozzle requires calibration. By measuring the dropping frequency, and possibly adjusting for the droplet volume changes with frequency, the precipitation depth (or intensity) is obtained.

12.3.4 Optical Methods

Instruments that use optical methods to measure precipitation are typically called disdrometers, and their technology is based mainly on infrared or laser sensors (Fig. 12.3). These methods are able to sense the precipitation particles falling through a measuring area, detect the type of precipitation (rain, snow, hail), measure the number, transit time, and dimensions, and provide the precipitation rate or amount by integrating over the to-

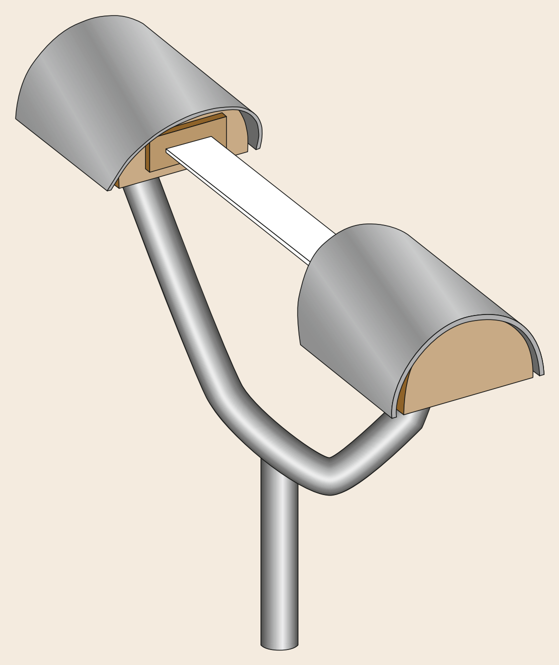

Fig. 12.3 Scheme of the optical measuring principle

tal number of particles in a given time window. The type and size of particles are usually obtained by measuring their fall velocity and assuming a fixed relationship between the fall velocity, size, and density.

Infrared Methods

The infrared gauges measure precipitation by detecting the irregularities in the infrared light beam of the sensor. These irregularities, known as scintillations, are induced by the precipitating particles falling within the infrared sampling volume; by measuring scintillation intensity, the sensors provide precipitation information.

Laser Methods

Optical disdrometers based on laser technology are composed of one or two thin laser light sheets to detect particles crossing the beam. Each particle falling within the laser beam occludes part of the transmitted laser light and decreases the light intensity in proportion to the particle diameter.

12.3.5 Other Methods

Impact Methods

These methods exploit the kinetic energy of the falling droplets impacting on the exposed surface of the instrument. A plastic or metal membrane is used at the measurement surface to sense the impact of single precipitation particles. In some systems, the mechanical movement of the membrane is transduced into an electrical signal by an attached moving coil system. In other solutions, the amplitude and the frequency spectrum of vibrations generated by precipitation particles hitting the membrane are detected and analyzed to determine the number and size of the particles, and therefore the precipitation amount (or intensity), over a given time window.

Thermodynamic Methods

These methods employ the thermodynamic effect of the latent heat of water to obtain the measurement of both solid and liquid precipitation intensity.

The concept involves monitoring of the electrical power needed to maintain the sensor's temperature constant and high enough to melt and evaporate the snow or rain. The power provided to the sensor depends on the amount of water on the collector, while it is affected by ambient temperature, wind, and humidity conditions. Two sensor surfaces are used, one designated to collect the particles and facing upward, and one serving as the reference, facing downward to avoid collecting any precipitation. The two sensors are influenced by the same temperature, wind, and ambient humidity conditions, but only the upper one is exposed to precipitation. The difference in the power supplied to the twin sensors is attributed to the latent heat absorbed by precipitation, and is employed to determine the precipitation rate.

Microwave Methods

The microwave disdrometers use small radars to acquire the spectrum of the signal backscattered by falling particles. The intensity of the backscattered signal is related to the number of particles, and using a Doppler shift, the fall velocity of particles can be obtained.

Fourier processing of the signal is typically executed by a processor that calculates average spectrum, retrieves drop size distribution from this spectrum, and finally calculates the accumulated precipitation over a given time resolution.

12.4 Devices and Systems

The various measuring principles are exploited by different types of instruments, each of them characterized by specific measurement biases and uncertainties.

12.4.1 Catching-Type Gauges

Catching-type instruments are the traditional and by far the most common type of instrument employed worldwide for the measurement of atmospheric precipitation. They are subject to catching errors, since their capability to collect the amount of precipitation that would reach the equivalent surface area at the ground in the absence of the instrument is seldom guaranteed, and their collection efficiency may be low in the presence of wind. They are also subject to counting errors depending on the measuring principle adopted.

Storage Gauges

The storage gauge consists of a container with a known geometry, and the measuring principle is based on the water level. The most common gauges have a cylindrical shape, but different shapes, especially with reduced section area at the bottom, are used to enhance the measurement of light precipitation events (e.g., see Fig. 12.4).

The gauges are made of metal, glass, or plastic. To permit the reading of the water level by the operator, a transparent gauge is preferable; otherwise a transparent window of glass is provided in many metal buckets. Graduation marks are drawn on the container to allow the reading of the water level.

Since these gauges are able to measure the volume of water inside the collector, they are not suitable in the

Fig. 12.4 Plastic storage gauges developed for agricultural purposes (WMO-METAGRI project; photo © Mattia Stagnaro)

Fig. 12.5 Tipping-bucket gauge (photo © Emanuele Vuerich)

case of solid precipitation. Although deicing liquid may be employed to melt snow precipitation, these instruments are not recommended for use in cold regions.

If the measurement is performed by an operator, the reading of the water level is taken once or twice a day. When automation is employed by introducing different methods to measure the water level inside the gauge, the time resolution increases and can reach the 1 min recording time interval recommended by WMO. The measurements taken by this type of rain gauge are affected by evaporation losses, especially in the case of low recording time resolution.

One particular type of capacitive rain gauge measures the water collected by storing it in a deep cylinder that contains two electrodes acting as the plates of a capacitor, the water between the plates performing the role of dielectric. By including the capacitor in a tuned circuit, the water depth can be measured. It must be emptied periodically.

Tipping-Bucket Gauges

Tipping-bucket rain gauges (TBRs) are widely employed in national meteorological services worldwide to measure rain and snow depth and the associated precipitation intensity. The reasons for extensive use of this type of instrument include their relative ease of maintenance and limited production costs.

The instrument uses a metallic or plastic twin bucket balance to measure the incoming water. It is equipped with a funnel that collects and conveys the water through a nozzle in an alternating manner into the two compartments of the tipping bucket. The gauge typically has a cylindrical shape (Fig. 12.5), although aerodynamic shapes were recently developed to reduce the impact of wind on the collection efficiency of the gauge (Sects. 12.6.1 and 12.6.3). The tipping of the bucket moves a magnet that triggers a reed relay contact and is recorded by a data logger.

Although there is no standard for the construction of precipitation gauges, recommendations from the WMO and the many years of experience with tipping-bucket instruments have led to typical solutions (now widely accepted), especially for the size of the collector area and the volume of the bucket compartments. Actually, these two construction characteristics are related to each other through the instrument sensitivity, which is generally required to be between 0.1 and 0.5 mm, with 0.2 mm being the most common. The collector area is usually between 200 and 1000 cm^2. For a tipping-bucket instrument with a 400 cm^2 collector and sensitivity of 0.2 mm, the bucket size would be 8 cm^3.

The shape of the bucket and the collector vary with the manufacturer but the bucket size is quite standardized. It is indeed a sort of compromise between a very small size to limit sampling error during low-intensity precipitation, and a large size to better handle high-intensity events.

The main advantage of tipping-bucket gauges is the automatic emptying principle: when the bucket tips, the water is released outside the instrument body through dedicated apertures. However, the presence of moving parts in the sensor requires periodic maintenance of the instrument (Sect. 12.8).

Weighing Gauges

A weighing gauge (WG) consists of a bucket, usually made of metal or plastic, used to collect and measure liquid and solid precipitation by means of a weighing principle. This type of gauge is widely used to measure solid precipitation because it does not require the snow

Fig. 12.6 Weighing gauge (photo © Emanuele Vuerich)

to be melted before taking the measurement. In the absence of an automatic emptying system, the dimensions of the container are usually larger than for other instruments, and this leads to the common *chimney* shape, with a larger section area at the bottom (Fig. 12.6). The capacity of the bucket can vary with the manufacturer and ranges from 250 to 1500 mm. Low-capacity models should be avoided in areas where large accumulation may occur over a short period of time. The addition of oil or other evaporation suppressants inside the container allows a film to be formed over the water surface to minimize evaporation losses (Sect. 12.6.1).

The large capacity of the bucket has the objective of minimizing the emptying operation, which is manually performed in many cases. Some instruments use an automatic emptying principle based on a siphon. A small automatically emptying weighing gauge has recently been developed, consisting of a balance that measures the weight of the water collected in alternating fashion in the two compartments of a tipping bucket (conveyed through a funnel and a nozzle). When the bucket tips, the water is released outward, and the empty compartment is then placed under the nozzle to be filled and weighed. This automatic emptying principle leads to a reduction in the size of the instrument and ensures that the amount of weighted water is small and constant, therefore increasing the resolution of the gauge. However, these emptying principles result in underestimating precipitation during the emptying process, which can be long when using the siphon or short but frequent in the tilting-bucket gauges. Moreover, the presence of moving parts, typical of tipping-bucket rain gauges, requires additional maintenance operation. Note that the sensitivity of the weighing system can be very high (e.g., 0.01 mm), although the actual gauge sensitivity is generally lower due to the need to eliminate noise from the high-resolution raw signal. The resolution of the transducer affects the noise filtering efficiency, resulting in lower sensitivity that in many cases is comparable to that of tipping-bucket gauges.

Drop Counter

The catching-type drop-counting gauge consists of a funnel that collects the precipitation and conveys water toward a calibrated nozzle, which starts dispensing droplets within an internal chamber before releasing them outside the instrument. An optical sensor is located below the nozzle and detects each falling drop. The rainfall intensity can be calculated from the drop releasing frequency by assuming a constant volume for the calibrated droplets. A recent study [12.40] using dynamic calibration tests (Sect. 12.6.2) revealed that the volume of the released droplets varies with the drop frequency. Traditional calibration of this instrument, assuming a constant volume of the droplets as declared by the manufacturer, is not compliant with WMO requirements. Instead, by using the dynamic calibration curve to adjust the drop size according to the detected frequency, the performance can be improved to meet the WMO recommendations.

The resolution of drop-counting gauges depends on the size of the droplets generated by the nozzle, in the order of 0.005 mm of precipitation, and is suitable for the measurement of light precipitation rates. Indeed, an operational limit of this type of instrument is given by the rainfall intensity at which the water flux from the nozzle starts to be continuous or irregular. The measured frequency then abruptly decreases, and very high inaccuracies result. A stand-alone installation is therefore discouraged, and a colocated rain gauge is required to avoid significant underestimation of severe rainfall intensity.

12.4.2 Non-Catching-Type Gauges

These instruments differ from traditional ones in that the precipitation flux is not collected in any container, but just *sensed* when crossing or impacting a given section, or volume, of the atmosphere in the vicinity of the ground surface. Non-catching instruments are drawing increasing interest from national weather services (NWS) due to the lower maintenance required and unattended operation. They have a number of advantages over the more common catching-type gauges, including the possibility to provide information beyond precipitation intensity alone (e.g., drop size distribution, visibility, etc.), and are especially suitable for automatic weather stations. Having neither a funnel nor a collector, their calibration and uncertainty evaluation are more difficult than for catching-type gauges, since direct comparison with an equivalent reference flow rate is not possible.

Optical Disdrometers

Optical disdrometers consist of a laser or infrared emitter, a receiver, and a digital signal processing unit (Fig. 12.7). The distance between the emitter and the receiver is usually of the order of some tens of centimeters, and the measuring beam is a few centimeters wide. This sensor measures the diameter and velocity of hydrometeors and, from these measurements, identifies the type of precipitation and calculates rainfall rate and amount, reflectivity, visibility, and drop size distribution. The diameter of the particles typically ranges between 0.2 and 8 mm and allows the volume of each droplet to be derived. Consequently, the rainfall intensity can be directly calculated by integrating over the number of particles detected in a given time period, usually ranging from 15 s to 1 min. Depending on the diameter and fall velocity, measurements are grouped into different precipitation classes.

When hydrometeors cross the sensing volume of the disdrometer, the measuring beam is partially obscured. The shadow on the receiver leads to a decrease in the voltage generated by the receiver's photodiode. The digital signal processing unit monitors the photodiode voltage and calculates the diameter of the drop from the minimum observed voltage during the passage of the drop. The velocity is calculated from the duration of the voltage reduction by dividing the sum of the diameter and beam breadth by the drop residence time.

The *RI* resolution is typically between 0.001 and 0.005 $\mathrm{mm\,h^{-1}}$, so it is possible to measure even very light rain (drizzle events). The maximum detectable precipitation rate varies with the instrument, and ranges from 200 to more than 1000 $\mathrm{mm\,h^{-1}}$.

The collision of droplets is a possible error source; in that case, droplets are detected as a single *macro-drop*, leading to a systematic overestimation of the water volume. In order to reduce this error, a statistical correction is applied. Measurement errors can also occur when droplets cross the rim of the light sheet; in this case, the droplets are interpreted as smaller particles than they are in reality, causing an underestimation of the volume.

Impact Disdrometers

Impact disdrometers can be divided into two categories: acoustic disdrometers and displacement disdrometers.

Acoustic disdrometers record an electrical signal using a piezoelectric sensor whenever a drop falls on a diaphragm. Based on the relationship between kinetic energy and drop size, this electrical signal is converted into kinetic energy via the measured acoustic energy. The accuracy of drop size estimation is limited due to differences in the acoustic response from the various parts of the diaphragm. The instrument is also limited with regard to measuring small drops, because

Fig. 12.7 Optical non-catching-type gauge (photo © Emanuele Vuerich)

the diaphragm is not sensitive enough and because of the splashing. In addition, higher intensities are hardly measured due to the background noise, which reduces the measurement accuracy.

Displacement disdrometers translate via magnetic induction the energy generated by drops falling on the top surface and estimate the sizes of rain drops by analyzing the associated electrical pulses. The instrument consists of a surface exposed to precipitation and connected to a magnet that, after displacement induced by the raindrop impact, slides within a coil, activating magnetic induction.

Both acoustic and displacement disdrometers are designed to measure liquid precipitation, since the energy of the droplets is directly proportional to the mass and density of the water droplets. Snowflakes and hailstones, on the other hand, have a completely different impact on the sensors, and lead to underestimation or overestimation of the precipitation measurements. A proper calibration of impact disdrometers was recently proposed with the aim of adapting this type of instrument for measuring hail precipitation events [12.41].

Thermodynamic Sensor

The thermodynamic sensor is a new type of instrument recently developed to measure light or solid precipitation [12.42]. The system consists of two identical heated aluminum plates, one facing upward to collect the precipitation, and the other facing downward to serve as a reference. The lower plate is insulated from

Fig. 12.8 Microwave precipitation gauge (photo © Emanuele Vuerich)

the top plate and serves as a reference because it is only affected by wind and ambient temperature and not by precipitation. The two plates are heated to nearly identical constant temperatures (above 75 °C), hot enough to melt large snowflakes in a few seconds. The plates are maintained at a constant temperature during wind and precipitation conditions by either increasing or decreasing the supplied power. During precipitation, the top plate cools because of the melting and evaporation of the hydrometeors, and the difference between the power required to heat the top plate and the bottom one is proportional to the precipitation rate. The two plates are usually located at a height of 2 m above the ground. The diameter of the plate is large enough to permit collection of falling rain or snow particles and small enough that power demand during heavy precipitation events and high wind speed is not too high.

To convert the power difference to a liquid-equivalent rate, a theoretical conversion factor is calculated, assuming that 100% of the heat of vaporization/sublimation from the precipitation is transferred to the instrument. The conversion factor is based on the area of the plate, the heat capacity of water, the density of water, and the latent heat of sublimation and evaporation. The shape of the instrument body is designed in order to minimize the wind-induced undercatch [12.42], which is however quite low, and was quantified in a recent study [12.43]. This instrument provides precip-

Table 12.3 Advantages and disadvantages of the different methods

Device	Advantages	Disadvantages
Storage gauge (manual)	No power supply, no moving parts, low cost, and easy operation	Not suitable for solid precipitation, reading of the water level only once or twice a day, evaporation losses, operator-related reading uncertainty, limited capacity (requires manual emptying)
Water level gauge	Wide range of intensity, high temporal resolution	Not suitable for solid precipitation, lower sensitivity, limited capacity (requires manual or automatic emptying)
Weighing gauge	No funnel required, no mechanical moving parts. Liquid and solid precipitation. Wide range of intensity, high temporal resolution. High accuracy after dynamic calibration	Influence of dynamic response. Manual emptying: large size, the shape enhances the wind effect on the collection. Periodic emptying maintenance. Automatic emptying: no measure while emptying
Tipping-bucket gauge	High accuracy after dynamic calibration, high temporal resolution. Low cost and simple mechanics. Long-term experience available. No emptying required, small size	Upper intensity limits depending on sensitivity, sampling errors. Heating required to measure solid precipitation. Maintenance of mechanical parts and to prevent clogging
Drop counter	High sensitivity, high accuracy after calibration for low precipitation intensity	Upper intensity limits, not suitable for stand-alone installation. Requires maintenance to prevent clogging
Optical disdrometer	Derives precipitation intensity from particle diameter and velocity measurements and provides additional information such as visibility and particle size distribution (PSD)	High cost. Error due to drop collisions and when particles cross the rim of the light sheet. No standardized calibration available
Impact disdrometer	Small size, low cleaning maintenance	Influence of the drop impact position on the surface. Noise for high precipitation intensity. Not suitable for small drops, snowflakes, and hailstone measurements. No standardized calibration available
Thermodynamic sensor	Small size, suitable only for low precipitation intensity	Additional power consumption. No standardized calibration available
Microwave sensor	Low cleaning maintenance. Provides additional information on columnar profile of vapor content, non-raining cloud liquid water, and temperature	High cost, additional power consumption. No standardized calibration available

itation measurements every minute and can accurately measure rainfall rates up to 35 mm h^{-1}.

Microwave Sensor

Since the 1960s, microwave-based technologies have been developed and improved in both the communication and meteorological fields. Ground-based microwave radiometry (Fig. 12.8) has its traditional applications in meteorology in the estimation of columnar profiles of vapor content, non-raining cloud liquid water, and temperature [12.44].

Precipitation measurements employing microwave sensors have appeared in recent decades, and are based on the signal power reduction through the atmosphere during a precipitation event.

The attenuation and scattering of the sensor emissions are related to the precipitation rate, but also depend on the physics of the precipitation particles, such as the liquid or solid phase and the different particle sizes, but the frequency of the emitting signal also has a fundamental role [12.44, 45]. Radar disdrometers have *RI* resolution up to 0.1 mm h^{-1}.

12.4.3 Comparison of the Methods

Automatic stations have replaced manual measurements in many developed countries, while manual methods remain common practice in less developed regions of the world. Storage gauges are indeed the most widely used instrument for rain depth measurements, while tipping-bucket gauges are the most common for rainfall intensity measurements. The low cost, easy operation and maintenance, and the many years of experience available with tipping-bucket instruments are the main reasons for their large-scale exploitation. Weighing gauges are mainly used in regions where solid precipitation is expected, but their cost is higher and maintenance is not easy, although the absence of mechanical moving parts is an advantage. Non-catching-type gauges are the new frontier of precipitation measurements and, notwithstanding their high cost, are particularly well suited for automated weather stations, and provide additional valuable parameters such as particle size distribution, precipitation type, and visibility (Table 12.3).

12.5 Specifications

Following the outcomes of the *WMO Field Intercomparison of Rainfall Intensity Gauges* [12.4, 27] and the decisions of the WMO CIMO (Annex I and II of the CIMO XV Session Report, Helsinki, Finland, 02.–08.09.2010), the CEN (Comité Européen de Normalisation) Technical Report no. 16469 [12.46] recommended the specifications presented below. Terminology and related concepts are also consistent with WMO [12.1], *ISO Guide to the Expression of Uncertainty in Measurement* [12.47] and the *International Vocabulary of Metrology* [12.48].

Specifications for precipitation measurement instruments depend on the intended use of the derived information (Sect. 12.8); therefore, recommendations are reported here with reference to the highest level of performance and do not necessarily apply to all applications. Network managers aiming at a broad spectrum of users may need to conform to such specifications in order to meet the requirements of the most demanding application. Those managing a single station (or a small network) for a specific use may reduce the required performance to fit their need.

12.5.1 Specifications for Catching-Type Gauges

Catching-type gauges should follow the recommendations detailed in the WMO Guide no. 8 [12.1].

The minimum list of technical parameters provided below should be included in the user manual of each instrument, and sufficient advice on the choice of output values should be provided to the user to meet different applications:

- Measurement range
- Delay time
- Linearity
- Instrumental measurement uncertainty, for the whole measurement range
- Resolution
- Step response time
- Threshold
- Time constant for those instruments classified as first-order response instruments
- Internal calculation cycles (if any) and data reporting interval.

Further recommendations apply to specific instrument technologies. Tipping-bucket rain gauges should be corrected to compensate for the inherent underestimation and the sampling error at high and low precipitation rates, respectively. Software correction algorithms using the time stamp of each tip and applying dynamic calibration curves provide the best results [12.19]. The internal clock (or the clock of the data logger) must be checked and possibly adjusted automatically on a daily basis, at least to the nearest tenth of a second.

For weighing gauges, in the case of precipitation intensity measurements, the time constant should be less than 1 min. Therefore, any filtering algorithm used to reduce the noise in processing the data produced by the weighing device should not increase the response time of the instrument. It is important that the information provided about precipitation intensity and total accumulation be consistent (accumulated precipitation is obtained by integrating precipitation intensity over time), and both values reported separately.

In any case, information about the achievable measurement accuracy must be provided in the technical documentation. For operational rainfall intensity measurements, the achievable accuracy is indicated by WMO [12.1] in the following terms:

- Under laboratory, constant flow conditions: 5% above 2 mm h^{-1} and 2% above 10 mm h^{-1}
- In field conditions: 5 mm h^{-1} up to 100 mm h^{-1} and 5% above 100 mm h^{-1}.

A calibration certificate from an independent third party (possibly a certified or WMO-recognized laboratory) should be included with each individual instrument. The certificate must include a description of the calibration procedure and results to check compliance with the relevant recommendations, and should document the traceability of the reference used, the environmental conditions (such as temperature, humidity, etc.), and the time frame used for averaging the precipitation signal.

In order to reduce the wind-induced undercatch of precipitation particles, the aerodynamic shape of the gauge should minimize the deformation of the wind field above the gauge orifice, as suggested by WMO [12.1] and supported by [12.49] using numerical simulation. The use of windscreens is advisable, especially for solid precipitation, but the positive effect of the shield should be documented by means of wind tunnel measurements or computational fluid dynamics simulations. Correction of the wind-induced undercatch can be applied according to the precipitation intensity, wind speed, and environmental temperature, as suggested by [12.50] and [12.51], but the raw data should be preserved as well.

Precipitation intensity at 1 min should be measured and used for further analysis only if all 1 min data are transmitted and used (1 min intensity should not be used in a temporal sampling scheme, i.e., one synoptic measurement every hour or 3 h, as a single 1 min value is not representative of a longer period of time).

12.5.2 Specifications for Non-Catching-Type Gauges

At the time of writing, no specification for non-catching-type gauges has been provided by WMO. However, the following additional specifications are recommended. The minimum list of technical parameters provided below should be included in the user manual of each instrument, and sufficient advice on the choice of output values should be provided to the user to meet different applications:

- List of the measured quantities, (precipitation particle diameter, terminal velocity, precipitation intensity, etc.)
- Measurement range of each measured quantity
- Delay time of each measured quantity
- Linearity of each measured quantity
- Instrumental measurement uncertainty, for the whole measurement range
- Resolution of each measured quantity
- Step response time of each measured quantity
- Threshold of each measured quantity
- Time constant for those instruments classified as first-order response instruments
- Internal calculation cycles (if any) and data reporting interval of each measured quantity.

Precipitation intensity should be expressed in the usual measurement units (mm h^{-1}), and any classification by intensity intervals should not replace the numerical value. The measurements of the precipitation particle diameter, counting, terminal velocity, precipitation intensity, and the total accumulation should be consistent, and reported separately.

12.6 Quality Control, Uncertainty, and Calibration

The increased need for traceability and comparability of precipitation measurements collected from various sites and monitoring networks worldwide demands greater attention to their overall quality and accuracy. Quality control is the ultimate tool to prevent the propagation of errors and to ensure the traceability of precipitation measurements to international standards, so that precipitation data from different sources can be soundly compared and used in a variety of applications.

12.6.1 Precipitation Measurement Biases and Uncertainties

Both instrumental and environmental factors may cause biases and uncertainties in precipitation measurements (e.g., the systematic mechanical bias of TBRs, the dynamic response of WGs, the wind-induced undercatch). Calibration and correction may overcome instrumental and environmental measurement biases, but they themselves are subject to uncertainties.

Further sources of uncertainty arise from the field operation of precipitation measurement instruments and can hardly be quantified unless undertaking suitable instrument intercomparison campaigns. In order to support network managers in evaluating the quality of their installations in the field, the Siting Classification for Surface Observing Stations on Land was developed as a common ISO/WMO standard. It was published as ISO standard 19289:2015 (EN) [12.52], and by WMO in the *Guide to Instruments and Methods of Observation* [12.1] (Volume I, Chapter 1, Annex 1.D). The siting classification allows the user to assess how well the siting of an instrument meets the siting recommendations provided in the Guide.

Instrumental Biases

Instrumental biases affect all types of precipitation gauges, with different characteristics depending on the specific measurement principle adopted.

Tipping-bucket gauges are known to suffer from systematic mechanical biases; they underestimate rainfall, especially at high precipitation intensities, because of the amount of water that is lost during the tipping movement of the bucket. Although this can be remedied by dynamic calibration (performed over the full operational range of precipitation intensity values as described below), usual operational practice in hydrometeorological services and instrument manufacturing companies relies on single-point calibration (obtained at a single reference intensity as described below). This derives from the assumption that dynamic calibration has little influence on the total recorded precipitation amount, although it is essential to reflect the actual pattern of precipitation intensity over time. The related biases, known as systematic mechanical errors, result in an overestimation at lower intensities (depending on the single-point calibration operated) and underestimation at the higher precipitation intensities. To ensure that this bias is independent of the rainfall intensity, some tipping-bucket gauges are equipped with a siphon able to deliver water to the bucket at a constant rate during tilting. This would imply that the bucket is always operated at the same flow rate but with different frequencies depending on the rainfall intensity. In this case, single-point calibration is sufficient to limit the bias.

Tipping-bucket gauges are also subject to the unbalancing of the buckets that can be corrected by reproducing a constant flow rate for a sufficient duration in laboratory conditions and by recording the time between consecutive tips (inter-tip time). If the inter-tip time is not regular, the two buckets are not balanced, and the volume collected in the two buckets is not the same. By acting on the stop screws, the bucket position is adjusted until accurate balancing is obtained.

Finally, tipping-bucket gauges are affected by sampling errors due to the discrete nature of the measurement principle. The hypothesis at the basis of the measurement principle is that precipitation is constant between consecutive tips. Sampling errors strongly influence the assessment of light precipitation events, which commonly results in recording many isolated tips, resulting in substantial overestimation of the precipitation rate at the corresponding time step and underestimation in the contiguous steps. The presence of a certain amount of water previously stored in the bucket before the start of a new event and the amount that remains inside the bucket at the end of the event may affect the measurement of the precipitation rate.

A fundamental characteristic of weighing gauges when measuring precipitation intensity is the response time, which leads to measurement errors (systematic delay due to the filtering algorithm adopted to reduce the signal noise). The response time is of the order of 6 s to a few minutes depending on the gauge design and model. The actual sensitivity of weighing gauges can be very different from gauge to gauge and depends on the transducer resolution.

Catching-type drop-counting gauges are subject to biases due to the changing size of drops generated by the nozzle with precipitation intensity, while the counting system assumes a fixed volume of the droplet. The volume actually varies in a nonlinear fashion with precipitation intensity, and a corresponding bias arises in measurements that may reach 10–20% depending on the instrument design [12.40].

Catching-type rain gauges are affected by so-called catching errors related to wetting and splashing. The associated losses are about 2–10% and 1–2%, respectively, as reported by [12.32]. Wetting losses depend on the geometry and material of the gauge collector and container, the amount and type of precipitation, and the number of events during the time needed to dry the container. For solid precipitation, the loss is smaller than for liquid precipitation, because the collector is usually wetted only once during snowmelt.

The WMO Guide no. 8 [12.1] recommends that the collector be designed to prevent precipitation from splashing in and out. This can be achieved if the vertical wall is sufficiently deep and the slope of the funnel is sufficiently steep (at least 45%).

Environmental Factors

Catching errors also include the effects of evaporation and wind on precipitation measurements.

The first measurements of evaporation losses started in the nineteenth century, as reported by [12.32]. They were based on the difference between the amounts of precipitation simultaneously measured in two storage gauges: one observed daily and the other observed monthly. The annual accumulation was corrected using the difference between the two measures, but the wetting losses from daily emptying of the container were also included; therefore, the method could not be used to single out the evaporation losses. Also, differences in readings from a pit gauge (with the orifice located at the level of the surrounding ground) and an elevated gauge occur due to differences in the temperature of the collected water, and thus the pit gauge is not a good reference for estimating evaporation losses.

Since the end of the nineteenth century, the method employed to assess evaporation losses has involved measuring the evaporation rate of simulated precipitation during precipitation-free periods. As an alternative, comparing the total accumulation from a storage gauge with the time integral of precipitation intensity measurements from a weighing gauge provides a good estimate of the evaporation losses. Weighing gauges may provide measurements of evaporation as negative precipitation values should the weight of the water collected in the container decrease.

Evaporation losses are season-dependent and usually quite low, especially for rain intensity measurements: according to the WMO Guide no. 8 [12.1], they may account for less than 5% of the total precipitation amount. The [12.1] also suggests that, in storage and weighing gauges, errors associated with evaporation are minimized by using an oil surface layer in the container.

Wind is the main environmental factor affecting precipitation measurements. The effects of the immediate surroundings of the measurement site on the wind field can give rise to local variations in precipitation. To reduce the effect of wind on the measured precipitation, the choice of the measurement site, including the location of precipitation gauges within the area of interest, is important. The WMO Guide no. 8 [12.1] reports that objects should not be closer to the gauge than a distance of twice their height above the gauge orifice, and sites on a slope or the roof of a building should be avoided. In general, the best sites are in clearings among trees or where other objects act as an effective windbreak for winds from all directions. The effects of the wind, and of the site on the wind, can be reduced by using a pit gauge for liquid precipitation, or by making the airflow horizontal above the gauge orifice using homogeneous dense vegetation kept at the same level of the gauge orifice or appropriate fence structures, or by using windscreens around the gauge.

Furthermore, the wind effect on precipitation measurements is due to the interaction between the gauge body and the airflow. Indeed, the airflow surrounding any precipitation gauge is deformed by the presence of the gauge body, resulting in the acceleration of wind above the orifice of the instrument, which deflects the hydrometeors away from the collector, usually resulting in precipitation undercatch. The main factors of influence are the gauge shape, the wind speed, and the type of precipitation. The resulting measurement error is considered the most significant cause of environmental or *catching* bias, and quantification of this error is essential to obtaining accurate measurements. For rainfall and snowfall, the losses relative to the total amount are about 2–10% and 10–50%, respectively [12.32]. At high wind speed (8–10 $\mathrm{m\,s^{-1}}$), collection losses of up to 40% and 80% have been reported by [12.53] and [12.51] for liquid and solid precipitation, respectively.

12.6.2 Laboratory Tests and Field Experiments

Counting errors are related to the ability of the instrument to correctly quantify the amount of water that is collected or detected by the instrument. They can be experienced both in catching and non-catching types of instruments, although in the latter case the assessment of such errors is very difficult, and is hard to perform in controlled laboratory conditions. Laboratory calibration is needed to obtain high-quality measurements and may provide a classification of catching-type measurement instruments based on their laboratory performance.

The laboratory calibration is performed under constant equivalent rainfall intensity, obtained by means of steady water flow generation (e.g., using volumetric pumps or gravimetric methods).

The operational status of precipitation gauges can be verified in the field by means of portable calibration devices in order to detect malfunctions, output anomalies, and calibration drifts. Field calibration tests are based on the same principles as laboratory calibration, using the generation of a few constant equivalent precipitation rates within the range of operational use of the instrument.

Catching errors are detectable in the field by comparison with a reference gauge, and intercomparison campaigns lead to their quantification.

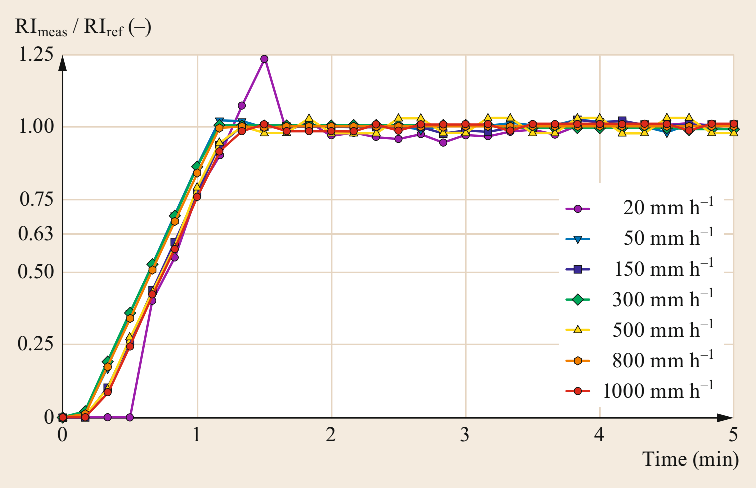

Fig. 12.9 The response time of a weighing gauge: 63.2% of the reference equivalent intensity is measured in less than 1 min

Calibration of Catching-Type Gauges

The CEN/TR 16469:2013 *Hydrometry–Measurement of the Rainfall Intensity (Liquid Precipitation): Requirements, Calibration Methods and Field Measurements* [12.46] reports the procedure for performing the calibration of catching-type gauges as follows. The calibration is performed in a certified laboratory, and a constant water flow, equivalent to a reference precipitation intensity, is conveyed to the funnel of the instrument. The constant flow regime is obtained from a suitable hydraulic device for different precipitation intensity values (dynamic calibration) within the range of operational use declared by the instrument's manufacturer. The flow is measured by weighing the water over a given period after passing through the rain gauge. The output of the instrument under test is recorded when a pulse occurs at regular intervals. The two measurements are compared in order to assess the difference between the actual flow of water conveyed through the instrument and the precipitation intensity measured by the instrument itself. The relative percentage error can be expressed as follows

$$e_{\text{rel}}[\%] = \frac{I_\text{m} - I_\text{r}}{I_\text{r}} \times 100\,, \tag{12.1}$$

where

I_m is the measured liquid precipitation intensity,
I_r is the reference equivalent precipitation intensity.

In the case of weighing gauges, the performance is also based on the step response, expressed in terms of the time constant, i.e., the amount of time that is required by the instrument to measure 63.2% of the reference intensity value (assuming a first-order type of response). Figure 12.9 shows the response time of a weighing gauge for different equivalent precipitation intensity values.

The calibration procedures described above are in agreement with Annex 1 of the report of the fifteenth WMO/CIMO session, where a standardized procedure for laboratory calibration of catching-type gauges is recommended. The result is a calibration certificate presenting the results of the calibration including corrections as required. The Italian standard [12.54] describes the same calibration procedure and, in addition, classifies precipitation gauges into three classes of performance, as follows, according to the calibration results:

- Class A: the maximum deviations are less than or equal to ±3% against the reference precipitation intensity at the temporal resolution of 1 min. Weighing rain gauges shall also have a step response time within the same time interval.
- Class B: the maximum deviations are less than or equal to ±5% against the reference precipitation intensity at the temporal resolution of 1 min. Weighing rain gauges shall also have a step response time within the same time interval.
- Class C: the maximum deviations are less than or equal to ±10% against the reference precipitation intensity at the temporal resolution of 1 min. This also applies to weighing rain gauges where the step response time is less than or equal to 1 min. Where the weighing rain gauge step response is greater than 1 min, the maximum deviations shall be within ±5%.

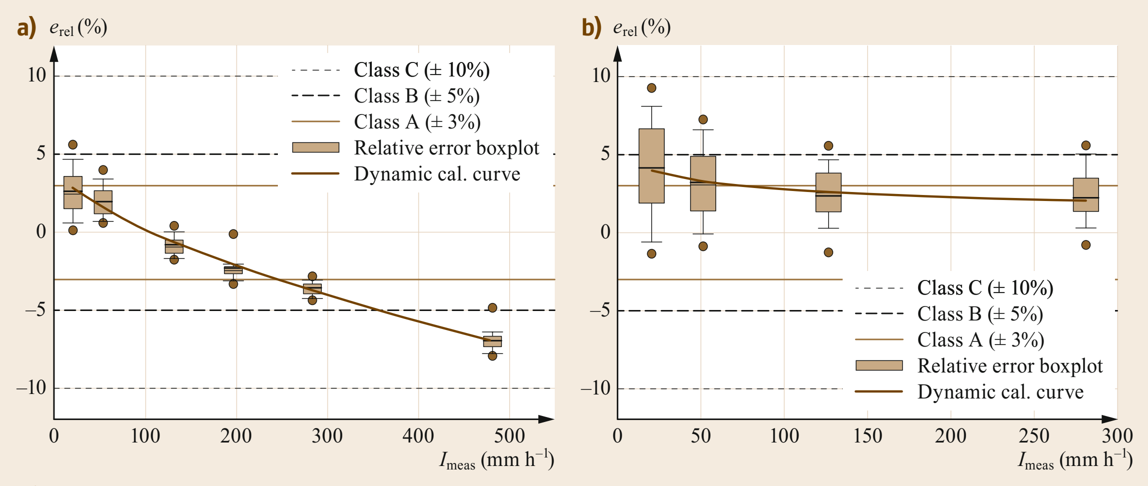

Fig. 12.10a,b Relative percentage errors at various equivalent reference intensities and correction curves for a tipping-bucket gauge **(a)** and a weighing gauge **(b)**

If the precipitation gauge tested has a maximum deviation greater than ±10% in measuring the reference precipitation intensity at the temporal resolution of 1 min, it cannot be classified according to this standard.

The same instrument can be assigned to different classes of performance over different measuring ranges.

The calibration certificate must contain the average value and the 10° and 90° percentiles of the percentage relative error distribution e_{rel} (%), for each value of the tested reference precipitation. This is presented in the form of a table. The dynamic calibration curve, obtained by fitting to the relative errors of tested precipitation intensities, must be reported in the certificate to enable correction of the readings. Figure 12.10 shows the performance of a tipping-bucket and a weighing gauge in terms of relative errors e_{rel} (%).

The standard also requires consistency of information. Any inconsistency between the precipitation intensity output at 1 min resolution and other quantities provided by the instrument (e.g., the precipitation amount) must be declared.

Although less efficient, hydro-meteorological services and instrument manufacturers often rely on the single-point calibration. In this case, only one reference precipitation intensity is checked, and the associated adjustment is applied mechanically by operating on the stop screws, so that the error becomes zero at that particular intensity. For any other precipitation intensity, some underestimation or overestimation persists. This is equivalent to assuming a conventional measure for the amount of water associated with each tipping of the bucket, which is different from the actual bucket size.

Calibration of Non-Catching-Type Gauges

No relevant international standard yet exists to define rigorous methods and procedures for calibration of non-catching-type gauges and for the evaluation of the associated uncertainty. As there is no funnel/container to collect precipitation, the calibration and uncertainty evaluation is more difficult than in the catching-type gauges, and the use of an equivalent reference flow rate is not possible. Instead, the actual characteristics of precipitation must be reproduced, including the drop size distribution, drop frequency, and fall velocities.

Laboratory and field tests were used by [12.55] to evaluate the measurement capabilities of an optical disdrometer. In the laboratory tests, high-precision spherical lenses made of silica and sapphire, with known refraction indices, were generated with diameters of 0.5, 1, 3, and 5 mm. These tests provided information on the maximum percentage errors in the diameter measurements. Free-falling water drops of different sizes were also generated using needles connected to a tank maintained at a constant water head. These were collected in a graduated cylinder, and the total volume of the collected water was compared with the cumulative volume of the drops measured by the instrument.

Other authors (e.g., [12.56]) reported that the calibration of optical disdrometers is essentially based on spheres with known diameter falling through the measuring area. A similar principle, based on the fall of small spheres on the sensor membrane, is used to calibrate impact disdrometers.

12.6.3 Correction Methods

Systematic instrumental and environmental biases must be corrected either in real time or in post-processing using calibration curves and suitable algorithms able to maximize the efficiency of the correction. Two examples are reported in detail in this section regarding the correction of systematic mechanical errors of tipping-bucket rain gauges and the wind-induced undercatch.

Correction of Systematic Mechanical Errors

Systematic mechanical biases are corrected using a suitable calibration curve obtained from dynamic calibration tests, as the best-fit regression function. Figure 12.11 shows the performance of the same tipping-bucket and weighing gauges of Fig. 12.10 after correction is applied, thus reporting the residual errors e_{res} (%).

Dedicated post-processing algorithms must be employed to achieve sufficient accuracy and to minimize the impact of sampling errors and the discrete nature of the measurement. Various algorithms have been proposed to this end, as are discussed in the literature [12.19, 57, 58]. However, the operational practice of most users, including national weather services, still relies on the trivial counting of the number of tips occurring in the desired period. The number of tips counted in each 1 min interval (the WMO-recommended time resolution for rain intensity measurements) multiplied by the nominal volume of the bucket provides the 1 min precipitation intensity record.

This method (as already observed by [12.57]) results in a general underestimation of precipitation intensity figures and a high level of uncertainty, due to the random nature of the number of tips per minute within any real-world, highly variable event. Moreover, the correction of systematic mechanical biases is not optimized with this method, since it would be applied to the averaged values only, and most tipping-bucket gauges show a nonlinear correction curve after laboratory calibration [12.29].

A better method employs the inter-tip time algorithm (see, e.g., [12.19, 57]), which is based on the assumption that the nominal volume of each bucket is equally distributed over the inter-tip period. The calculation of precipitation intensity for each minute accounts for the portion of the inter-tip period actually falling into that minute. In this way, the calibration is also the most effective, since the correction applied to the volume of the bucket at the variable inter-tip scale is precisely the one corresponding to the measured precipitation intensity.

The performance of different post-processing algorithms employed in the calculation of rainfall intensity from tipping-bucket gauges is compared and discussed by [12.59] using data recorded at a field test site. Two tipping-bucket gauges using different mechanical designs were compared with a catching-type drop-counting gauge used as the working reference due to its high resolution in both time and volume for the investigated rainfall intensities. The comparison highlights the benefits of employing smart algorithms in post-processing of the raw data and their ability to improve the accuracy of precipitation intensity measurements.

In particular, the results allow comparing the performance of the inter-tip time algorithm with the more

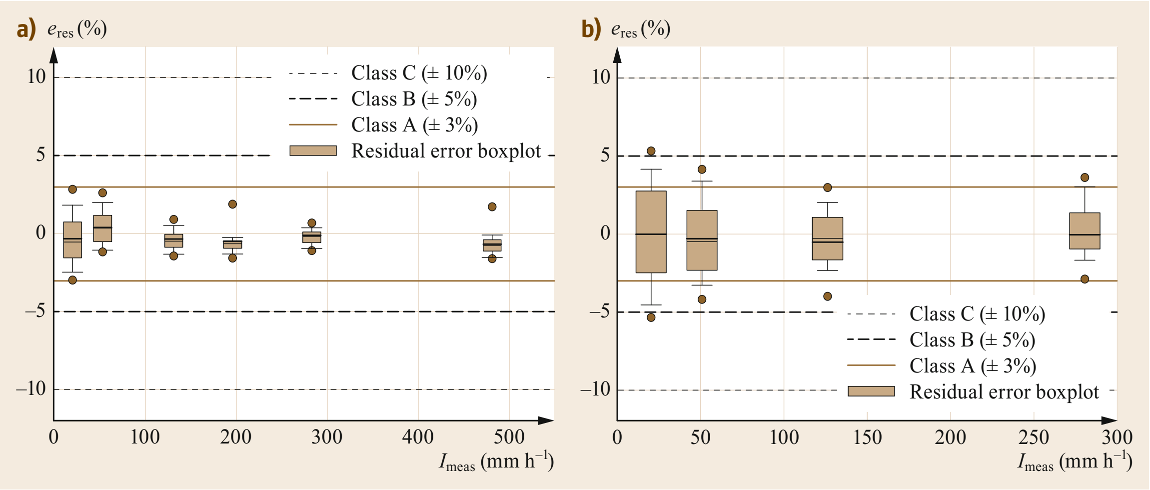

Fig. 12.11a,b Residual errors for a corrected tipping-bucket gauge **(a)** and a weighing gauge **(b)**. After the correction, the TBR (tipping-bucket rain gauge) falls in Class A, while the WG is in Class B for *RI* less than 50 mm h^{-1} and in Class A for *RI* higher than 130 mm h^{-1}

Fig. 12.12a,b The realization of the reference rain gauge pit at Vigna di Valle, Italy (2007) (WMO field intercomparison of rainfall intensity gauges, 2009; photo © Emanuele Vuerich) **(a)** and a DFIR equipped with a Geonor T-200B weighing gauge located at the experimental site in Marshall (Colorado) **(b)** (after [12.62] © American Meteorological Society. Used with permission)

common tip-counting method. The main benefit of adopting the inter-tip time method to calculate rainfall intensity resides in a better representation of the inner variability of rainfall events. The measured rainfall intensity series shows an improved correlation coefficient and a lower root-mean-square error (RMSE) with respect to the reference, closely approaching the performance of an ideal gauge, which is not affected by mechanical biases.

Correction of the Wind-Induced Undercatch

The wind-induced undercatch can be approached by using correction curves obtained as a function of wind speed, gauge geometry, type of precipitation (rain or snow), precipitation intensity, and particle size distribution. Correction curves can be derived using data from experimental sites equipped with different precipitation gauges in operational conditions and a reference one. The WMO recommends as a reference for liquid precipitation a gauge placed in a pit (Fig. 12.12a) with the gauge orifice at ground level, sufficiently distant from the nearest edge of the pit to avoid in-splashing. A strong plastic or metal anti-splash grid with a central opening for the gauge should span the pit. Because of the absence of wind-induced error (see e.g., [12.60]), they generally show more precipitation than any elevated gauge. The reference installation for solid precipitation (Fig. 12.12b) is known as the double fence intercomparison reference (DFIR). It has octagonal vertical double fences surrounding a storage or automatic gauge, which itself has a particular form of wind-deflecting shield known as the single Alter shield. Note that this field reference gauge is itself not free from measurement biases, and its construction could be improved [12.61].

At an experimental site in Haukeliseter (Norway), two Geonor T-200B gauges, one unshielded and one equipped with a single Alter shield, were installed together with the DFIR. Temperature measurements and anemometers at a height of 10 m and at the gauge collector height were also available.

Figure 12.13 shows the catch ratio between the single Alter-shielded gauge and the reference obtained at that site for different temperature classes. For temperatures above 2 °C, where the precipitation is mainly

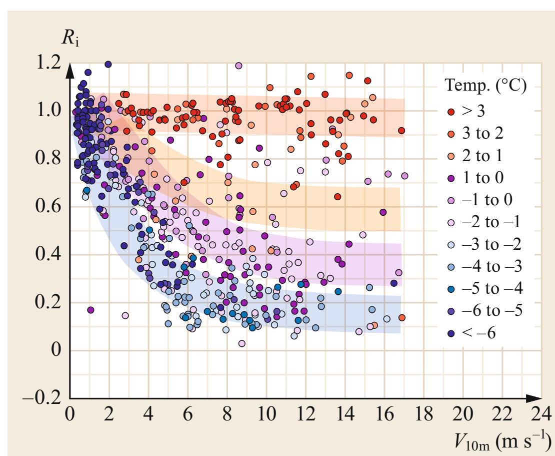

Fig. 12.13 Catch ratio of the Geonor gauge equipped with a single Alter shield when compared with the DFIR for different wind speeds (10 m height), classified according to the air temperature (after [12.63])

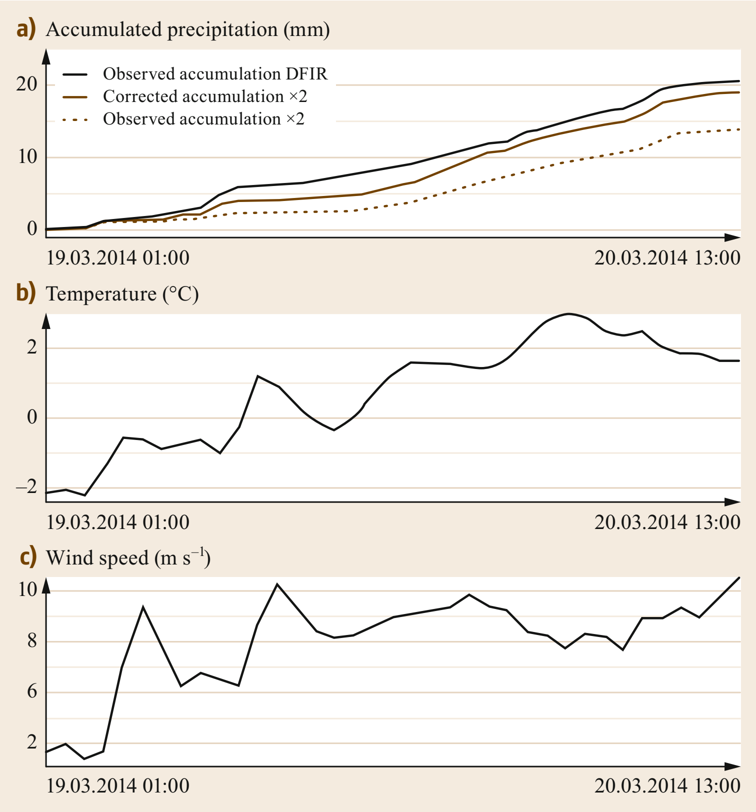

Fig. 12.14 **(a)** Observed and adjusted accumulation from one precipitation event compared with the accumulation observed by the DFIR. Temperature and wind speed during the event are shown in **(b)** and **(c)**, respectively

falling as rain, the catch ratio is less influenced by the wind. For temperatures below $-2\,^{\circ}$C, the precipitation is falling mainly as snow, and the catch ratio has a characteristic rapidly decreasing pattern with wind speed. For temperatures between -2 and $2\,^{\circ}$C, where rain, snow, and mixed precipitation occur, increased scatter appears, depending on the precipitation type. The four temperature classes highlighted as color bands in the figure suggest a continuous change from higher to lower temperature consistent with a gradual change in the distribution of liquid and solid precipitation particles during a mixed-phase event. Based on a three-year data set from the Haukeliseter test site that contains a number of concurrent observations of the catch ratio (R_i), the following correction curve was formulated [12.63]

$$R_i = \left[1-\tau_1-(\tau_2-\tau_1)\frac{\mathrm{e}^{\left(\frac{T_i-T_\tau}{s_\tau}\right)}}{1+\exp\left(\frac{T_i-T_\tau}{s_\tau}\right)}\right]\mathrm{e}^{-\left(\frac{V_i}{\theta}\right)^{\beta}} + \tau_1+(\tau_2-\tau_1)\frac{\mathrm{e}^{\left(\frac{T_i-T_\tau}{s_\tau}\right)}}{1-\mathrm{e}^{\left(\frac{T_i-T_\tau}{s_\tau}\right)}} + \sigma\,(T_i)\,\epsilon_i\,, \quad (12.2)$$

where β and θ are two fitting parameters, T_τ is the threshold temperature and defines the transition between the two limits above, while s_τ indicates the fuzziness between rain and snow, and $\sigma\,(T_i)$ is a parameter governing the variance in the measurement error.

The equation was derived from the assumption that the catch ratio is a function of wind speed (V) and air temperature (T) in the form

$$R = f(V,T) = [1-\tau(T)]\,\mathrm{e}^{-\left[\frac{V}{\theta(T)}\right]^{\beta(T)}} + \tau(T)\,. \quad (12.3)$$

The parameter $\tau(T)$ goes from one limit, dry snow, to another, mixed precipitation, when the temperature increases/decreases. A sigmoid function fits experimental data reasonably well, yielding the parametric function as follows

$$\tau(T) = \tau_1 + (\tau_2-\tau_1)\frac{\mathrm{e}^{\frac{(T-T_\tau)}{s_\tau}}}{1+\mathrm{e}^{\frac{(T-T_\tau)}{s_\tau}}}\,. \quad (12.4)$$

An application of the correction curve is shown in Fig. 12.14. Some difference between the adjusted accumulation (brown line) and the reference one (black line) remains, which is probably ascribable to the actual (unknown) particle size distribution.

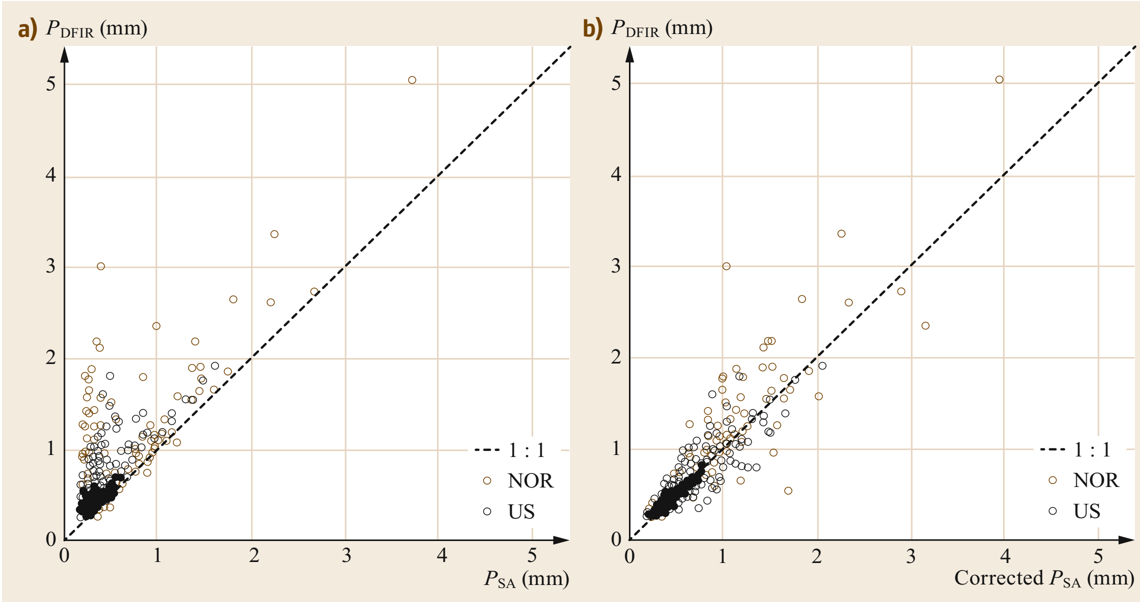

Fig. 12.15a,b Uncorrected **(a)** and corrected precipitation **(b)** from a Geonor T-200B weighing gauge equipped with a single Alter shield (P_{SA}) versus the DFIR (P_{DFIR}) for snow events (after [12.64] © J. Kochendorfer et al.)

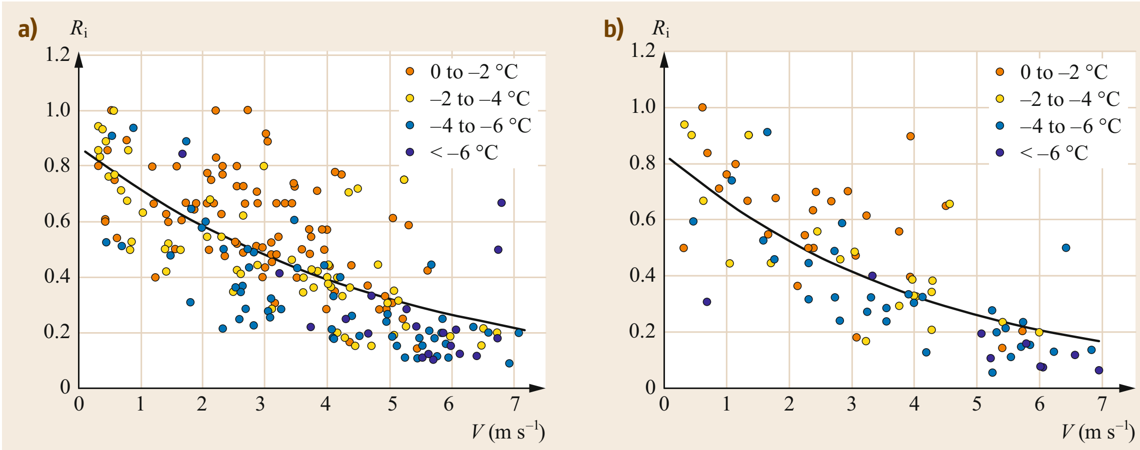

Fig. 12.16a,b The relationship between the catch ratio R_i (TBR/double fence automatic reference) and wind speed V for accumulation periods of **(a)** 1 h and **(b)** 3 h. The mean temperature during each accumulation period is color-coded (after [12.66] © S. Buisán et al.)

Data from the 2010 winter in the two experimental sites of Marshall (USA) and Haukeliseter (Norway) were analyzed by [12.64]. The authors proposed a correction function with exponential shape

$$R = e^{-a(U)\left(1-\left[\tan^{-1}(b(T_{air}))+c\right]\right)}\,, \qquad (12.5)$$

where the experimental parameters a, b, and c vary with the height of the anemometer and the type of instrument (unshielded, single Alter-shielded, etc.).

The effect of the correction is shown in Fig. 12.15, where the uncorrected and corrected precipitation is compared with the DFIR measurements in Fig. 12.15a and Fig. 12.15b, respectively. After the correction, a significant scatter of the residuals persists, which is probably due to the effect of noise, the spatial variability in precipitation, and the spatial variability in crystal type that are not fully taken into account in this study. With the aim of deriving correction curves that could be extended to other sites, data from eight experimen-

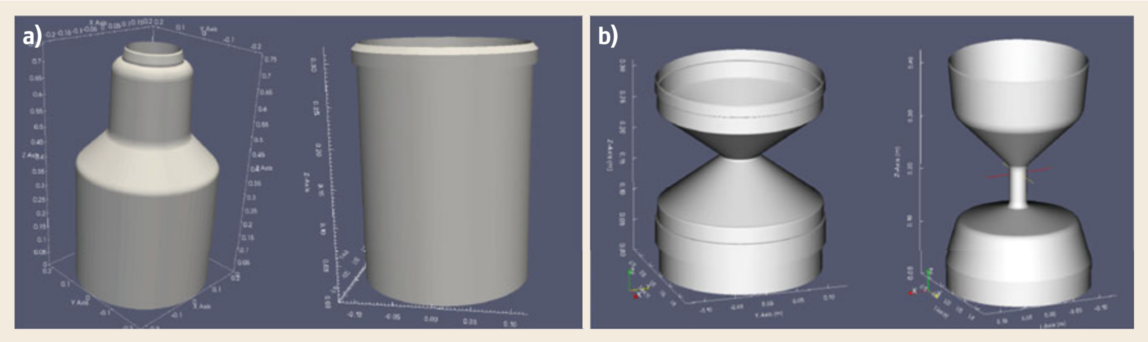

Fig. 12.17a,b 3-D models of the OTT Pluvio2VR weighing gauge and the Casella tipping-bucket rain gauge **(a)** and models of the EML ARG100VR and the EML SBS500VR tipping-bucket rain gauges **(b)**. The orifice diameters are 160, 228, 254 and 254 mm; their heights are 757, 320 310 and 425 mm. The models are not to scale (after [12.49] with permission from John Wiley and Sons, © American Geophysical Union)

tal sites were analyzed by [12.65]. The study provided the parameters of (12.5) for single Alter-shielded and unshielded chimney-shaped weighing gauges, by separating mixed and solid precipitation, and for wind speed measured at 10 m or at the collector height.

The data set obtained by [12.66] at the Formigal (Spain) experimental site was divided into two samples, and the correction curves derived for TBR rain gauges at 1 and 3 h accumulation scales are shown in Fig. 12.16. For 1 h accumulation, the authors propose (12.6), where a contribution of the melting of snow during the previous hour of accumulation is also included.

$$\begin{aligned}\text{TrueAcc}\,(1\,\text{h}) = {} & \frac{\text{Acc}}{\text{CR}} - 0.095\,\frac{\text{Acc}}{\text{CR}} \\ & + 0.095\,\text{Acc}(\text{prev h})\,,\end{aligned} \tag{12.6}$$

where the catch ratio CR is a function of wind speed and air temperature.

The wind-induced undercatch of precipitation gauges is also addressed in the literature by means of numerical simulations to calculate the flow velocity and turbulence around the gauge collector and the consequences of the aerodynamic disturbance on the hydrometeor trajectories.

This is obtained by performing finite-volume computational fluid dynamics (CFD) simulations based on the solution of Reynolds-averaged Navier–Stokes (RANS) equations or large-eddy simulations (LES) to obtain the airflow patterns close to the gauge collector (e.g., by [12.67, 68]). The computation of the particle trajectories is conducted with a Lagrangian method assuming no influence of particle motion on the airflow [12.69].

CFD simulations based on the RANS model allow for an Eulerian description of the air velocity components over the three-dimensional spatial domain in time-averaged terms. The LES simulations allow the time-dependent airflow patterns to be described down to the computational mesh dimension that represents the detached scale.

Particle trajectories are simulated by solving the equation of motion that depends on the relative velocity between air and particles ($v_p - v_a$), the drag coefficient (C_d), and the gravitational contribution, as follows

$$\begin{aligned}V_p \rho_p \boldsymbol{a}_p = {} & -C_d \boldsymbol{A}_p \rho_a 0.5 \left(\boldsymbol{v}_p - \boldsymbol{v}_a\right) \left|\boldsymbol{v}_p - \boldsymbol{v}_a\right| \\ & + V_p \left(\rho_p - \rho_a\right) \boldsymbol{g}\,,\end{aligned} \tag{12.7}$$

where $\boldsymbol{a}_p$ is the particle acceleration vector, $\boldsymbol{v}_p$ is the particle velocity vector, ρ_a is the air density, and ρ_p is the particle density.

The physical shape of a gauge has a significant impact on the aerodynamic effect and on the collection efficiency. It has been shown that appropriate *aerodynamic* shapes are able to reduce the deformation of the airflow [12.49]. The authors employed computational fluid dynamics simulations to evaluate the time-averaged airflow realized around *aerodynamic* rain gauge shapes (Fig. 12.17b) when impacted by wind. The results are shown in terms of comparison with the aerodynamic response of two *conventional* rain gauge shapes (chimney and cylindrical shapes, Fig. 12.17a).

Figure 12.18 shows the nondimensional magnitude of velocity (normalized with the undisturbed wind speed) on a stream-wise vertical plane for gauges of different shapes. The white band displayed for all gauges represents the shear layer; the wind speed here equals the undisturbed wind velocity. This layer separates the strong airflow regime above the collector (red shaded colors) from the recirculating airflow zone inside the gauge (blue shaded colors). In the case of aerodynamic

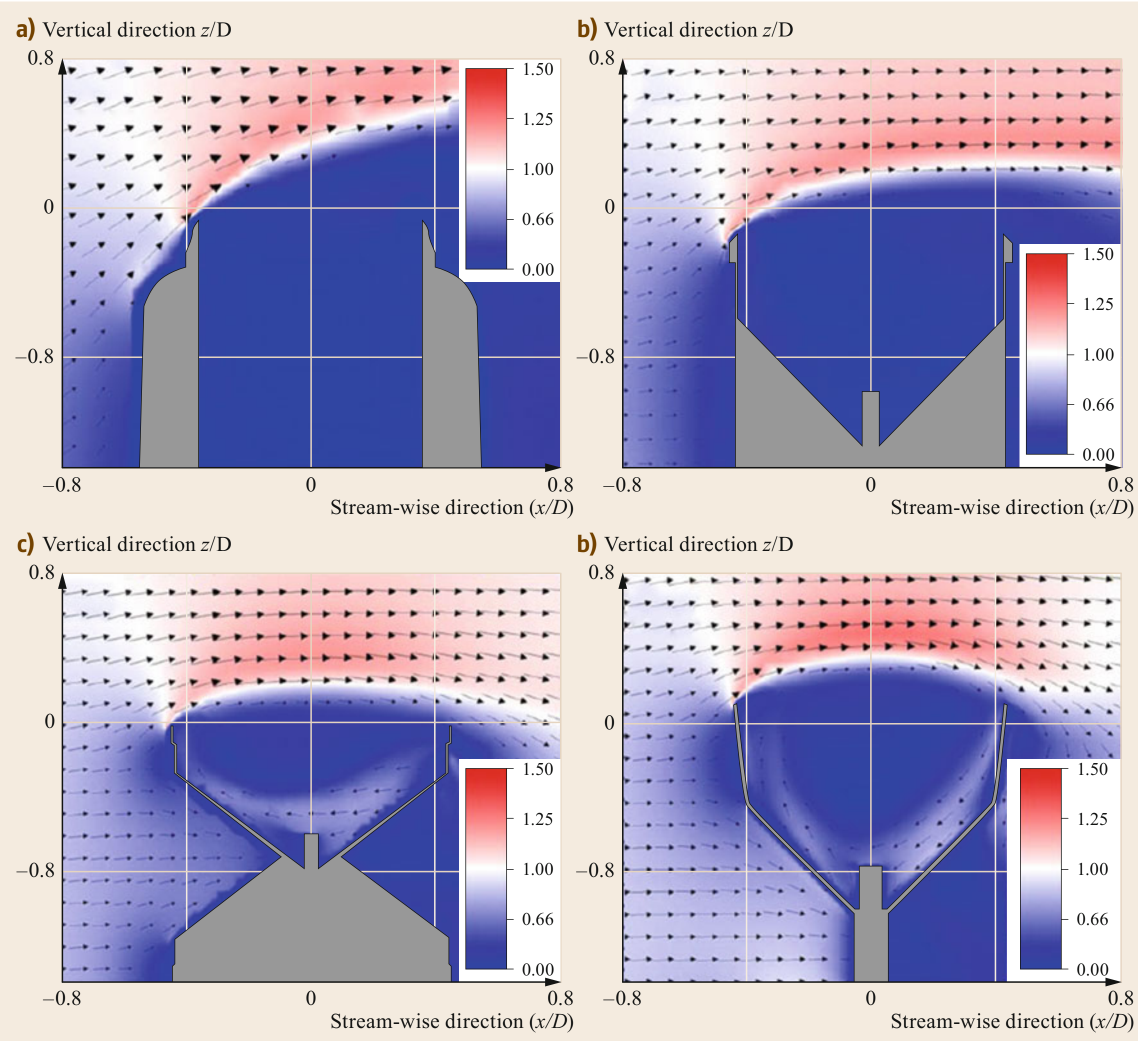

Fig. 12.18a–d Color plots of the vertical stream-wise section of the airflow nondimensional magnitude of velocity for the **(a)** OTT Pluvio2, **(b)** Casella, **(c)** EML ARG100, and **(d)** EML SBS500 gauges. The velocity fields were computed by executing RANS k-ω simulations with a horizontal wind speed U_w equal to $2\,m\,s^{-1}$. The arrows represent the time-averaged magnitude and direction of the airflow (after [12.49] with permission from John Wiley and Sons, © American Geophysical Union)

rain gauges (Fig. 12.18), the shear layer spans all over the orifice and touches the downwind edge of the collector.

The Lagrangian model of hydrometeor trajectories was improved by dynamically updating the drag coefficient estimation along each trajectory according to the computed particle Reynolds number [12.51, 70]. Figure 12.19 presents a comparison of the simulated collection efficiency for an unshielded (Fig. 12.19a) and a shielded (Fig. 12.19b) gauge for three different particle size distributions of solid precipitation based on field observations.

The impact of wind on the accuracy of non-catching-type gauges is still poorly understood and depends on the specific geometry of the gauge. While for catching-type gauges, three main geometry classes can be easily identified (cylindrical, *chimney*, and *champagne glass* shape), non-catching-type gauges show a broader variety of design and geometric solutions. Most important, they generally lack the axial-symmetric features of catching-type gauges, therefore introducing a new dependence of their measurement accuracy on the wind direction, in addition to wind velocity. Detailed studies are needed to quantify

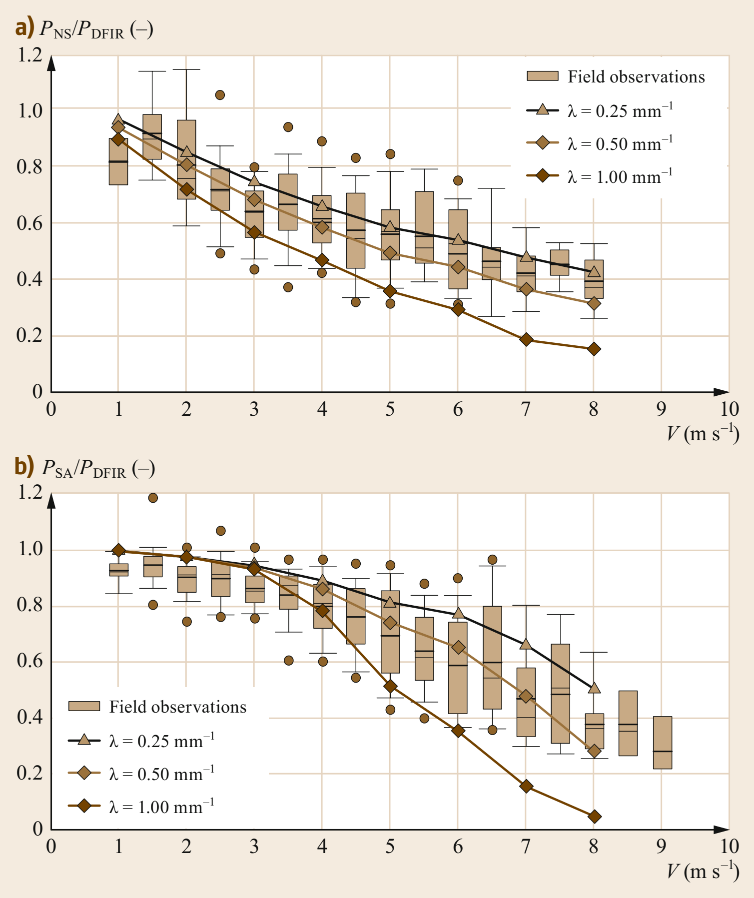

Fig. 12.19a,b Collection efficiency versus horizontal wind speed V ($\mathrm{m\,s^{-1}}$) for an **(a)** unshielded and **(b)** single Alter-shielded Geonor T-200B gauge computed using a dynamically updated C_d (after [12.51]). Three different particle size distributions for snow are simulated according to the slope parameter λ ($\mathrm{mm^{-1}}$) of the assumed inverse exponential distribution. Experimental data from the Marshall field site are shown in the boxplots (after [12.71] © American Meteorological Society. Used with permission)

such errors and to derive a possible correction curve to account for the aerodynamic performance of the gauge.

12.6.4 Measurement Uncertainty

The measurement result MR can be described as the sum of the raw measurement M, the correction of systematic errors C, and the uncertainty contribution $\pm U$

$$MR = M + C \pm U\,. \tag{12.8}$$

The measurement uncertainty, which produces the dispersion around the mean value of rainfall intensity measurements (see boxplot in Figs. 12.10 and 12.11), must be estimated. The uncertainty is due to random factors; some sources of uncertainty are observed in the field (wind, evaporation, splashing, etc.), while others may occur during the laboratory calibration [12.72, 73].

The uncertainty of experimental measurements can be synthetically described by (12.9), where the total uncertainty U_T is equal to the sum of field uncertainty U_F, specification uncertainty U_M provided by manufacturer, and laboratory uncertainty U_L

$$U_T = U_F + U_M + U_L\,. \tag{12.9}$$

The field uncertainties are estimated to be about −1% for evaporation, +0.5% for adherence, −0.5% for the inclination of the sensor, +1% for splashing, and from −5% to +80% for wind and 0.5% for other sources [12.74]. For U_M, some contributions must be taken into account at the time of calibration, such as drift and nonlinearity. The U_L component varies according to the calibration system. For liquid precipitation, the measuring ranges and the associated uncertinties are reported in Table 12.4, as published in [12.1].

The calibration methods can be classified as input (volumetric) or output (gravimetric) methods. The input method consists in using a calibrated device to drain water into the rain gauge (RG), thus simulating rain with a known amount of water and then verifying the amount of rain measured by the rain gauge under test. The device can be a measuring cylinder, a peristaltic pump, dispensers with interchangeable orifice, etc. The output method consists in using a calibrated weighing to determine the volume of precipitated water after it

Table 12.4 Typical characteristics of precipitation measurements according to WMO Guide no. 8, Volume 1, Chapter 1, Annex 1.A [12.1]

Variable	Range	Required measurement uncertainty	Achievable measurement uncertainty
Rainfall depth (*RA*)	0–500 mm	0.1 mm for $RA \leq 5$ mm 2% for $RA > 5$ mm	The larger of 5% or 0.1 mm
Snow depth (*SA*)	0–25 m	1 cm for $SA \leq 20$ cm 5% for $SA > 20$ cm	1 cm
Precipitation intensity (RI/SI)	0.02–2000 mm h^{-1}	n/a for 0.02–0.2 mm h^{-1} (trace) 0.1 mm h^{-1} for 0.2–2 mm h^{-1} 5% for > 2 mm h^{-1}	In laboratory: 5% above 2 mm h^{-1} 2% above 10 mm h^{-1} In field: 5 mm h^{-1} 5% above 100 mm h^{-1}

Note: EN 17277:2019 [12.75] recently published by CEN defines three classes of catching-type instruments based on their measurement uncertainty: ±3%, ±5%, and ±10%.

drains off the rain gauge; the control device is a precision balance.

The uncertainty sources during the calibration can be summarized as follows:

- Repeatability of measurements of air temperature, air relative humidity, atmospheric pressure, and water temperature
- Calibration certificate of thermometer (for air and water), hygrometer, barometer
- Repeatability of measurements of calibrated caliper, resolution of caliper, intra-laboratory measurement with caliper
- Repeatability of measurements of calibrated weighing, calibration certificate of weighing, specification of weighing, calibration certification of standard weight
- Only for input method: repeatability of measurements of calibrated graduated cylinder, resolution of measures of calibrated cylinder, calibration certificate of graduated cylinder, error of parallax and/or meniscus reading using measuring cylinder, specification of measuring cylinder.

The rainfall intensity is obtained indirectly using a rain gauge and a data acquisition system or a data logger to record the times when pulses occur. During a laboratory calibration, the data logger must be calibrated in time and frequency in the pulse channel used for acquisition of the signal from the instrument under calibration, because physical and electrical factors can influence the stability and accuracy of the data logger. The largest contribution to the uncertainty budget may be due to the internal clock of the data logger. Another source of uncertainty for tipping-bucket rain gauges is the repeatability of the time interval between tips (balancing of the buckets).

12.6.5 Specific Quality Control Methods

Quality control (QC) of data is a fundamental component of the measurement chain, used to verify the reliability of data obtained by the user and to prevent the propagation of errors. General guidelines are described in the WMO Guide no. 8 [12.1]. These procedures can be applied in both real time and non-real time for data quality assurance. QC consists of all processes that are used to generate confidence and ensure that the data produced will have the required quality. They also include the examination of data at stations and data centers to verify that the data are consistent with the goals of a quality management system, and to detect errors so that the data can be flagged as unreliable, corrected, or—in the case of gross errors—deleted.

The formal procedures for quality management and quality assurance prescribed by the International Organization for Standardization (ISO) are appropriate for meteorological data. The ISO 9000 [12.76] standard was developed to assist organizations in implementing and operating quality management systems, and describes the fundamentals of quality management systems and gives definitions of the related terms. The ISO 9001 [12.77] standard specifies the requirements for a quality management system that can be certified. The ISO 9004 [12.78] standard gives guidelines for continuous improvement of the quality management system. The ISO 19011 [12.79] standard provides guidance on auditing the quality management system.

In the case of precipitation measurements, suspicious data (doubtful, missing, value beyond the expected limits, etc.) are flagged with a specific number to identify the type of problem and are never deleted.

Typical test criteria for precipitation measurements are summarized in Table 12.5. An example of a suitable

Table 12.5 Typical test criteria for precipitation measurements

Method	Error	Reason
All instruments	Missing data. Value exceeding admissible range	Instrument malfunctioning, power outage, or data transmission error (see instrument diagnostic information)
Tipping-bucket gauges	Low constant value for long periods No value during liquid precipitation No value during solid precipitation	Water storage in the funnel Clogging of the nozzle Snow capping, ice formation (heating failure if present)
Weighing gauges	Spurious values in no-precipitation periods No value during solid precipitation	Vibrations (wind) or temperature induced algorithm error Snow capping, ice formation (heating failure if present)
Non-catching-type gauges	Anomalous number of occurrences in the no-precipitation particles class	Dirt accumulation on the optics (e.g., spider webs, dust). Beam obstruction

quality control procedure for 1 min precipitation data may include the following control actions:

- Number of samples and missing data: for the same sensors the data logging system acquires the raw data on a timescale of less than 1 min. If the number of samples collected in 1 min is less than the expected minimum for each instrument that minute is tagged and the flag is coded.
- Native errors and doubtful/erroneous data: 1 min data can be identified as doubtful or erroneous according to the corresponding diagnostic parameter reported in technical manuals.
- Plausible value check and doubtful/erroneous data: the operational range is declared by the manufacturer; if is not declared or is declared unlimited the 1 min data is assumed plausible if less than the WMO upper limit ($2000\,\mathrm{mm\,h^{-1}}$). A different and bespoke upper limit, related to the local climate conditions, can be assumed. Therefore, if the *RI* value on 1 min exceeds the upper limit it is flagged as doubtful. If the 1 min *RI* value is negative it is flagged as erroneous.
- Data collected during the maintenance actions are flagged to exclude them from data analysis.

Ancillary data can also be controlled by means of a QC procedure. The QC takes into account the working limits of ancillary sensors and the plausible values related to climatic conditions. The maximum and minimum limits for air temperature, relative humidity, atmospheric pressure, wind direction, wind speed, wind gust, and global solar radiation are fixed. Also, the maximum and minimum variability of data in 1 min is checked.

12.6.6 Intercomparison Results

The main objective of the WMO Laboratory Intercomparison of Rainfall Intensity Gauges was to test the performance of catching-type rainfall intensity gauges of different measuring principles under documented conditions. The involved rain gauges were divided into three groups and were tested in three different laboratories (the Royal Netherlands Meteorological Institute, Netherlands; Météo France, France; University of Genova, Italy) during a period of about 3 months, and the instruments were then rotated from one laboratory to another. Seven fixed reference intensities were tested (2, 20, 50, 90, 130, 170, $200\,\mathrm{mm\,h^{-1}}$), and if the maximum declared intensity was larger than $300\,\mathrm{mm\,h^{-1}}$, further reference intensities were tested between 300 and $500\,\mathrm{mm\,h^{-1}}$.

The manufacturers of the majority of the tipping-bucket rain gauges did not apply any correction based on dynamic calibration. For some instruments, a single-point calibration was applied at a single rain intensity around $30{-}50\,\mathrm{mm\,h^{-1}}$. On a smaller group of instruments, a correction based on dynamic calibration was applied. Results were presented in the form of two graphs, which report the relative percentage error and the response curve.

Figure 12.20a shows the overall response curves for the uncorrected tipping-bucket gauges, derived by averaging the measured data obtained at all three laboratories for the two identical instruments when applicable. Each curve is therefore representative of the observed behavior of one particular instrument. The deviation from the reference value increases with the equivalent reference rainfall intensity. As for corrected instruments, the correction proposed by the manufacturer and implemented in the data logger was able to reduce the errors in most cases to fall within the limits $\pm 5\%$ defined by WMO for the required uncertainty of rainfall intensity measurements. The performance of instruments after correction is shown in Fig. 12.20b.

For weighing gauges, the bias in terms of relative errors is less than uncorrected tipping-bucket rain gauges over the entire range of intensities. Nevertheless, for this type of instrument, the delay in detecting the variation in the rainfall intensity is sometimes relevant. An assessment of the step response was therefore per-

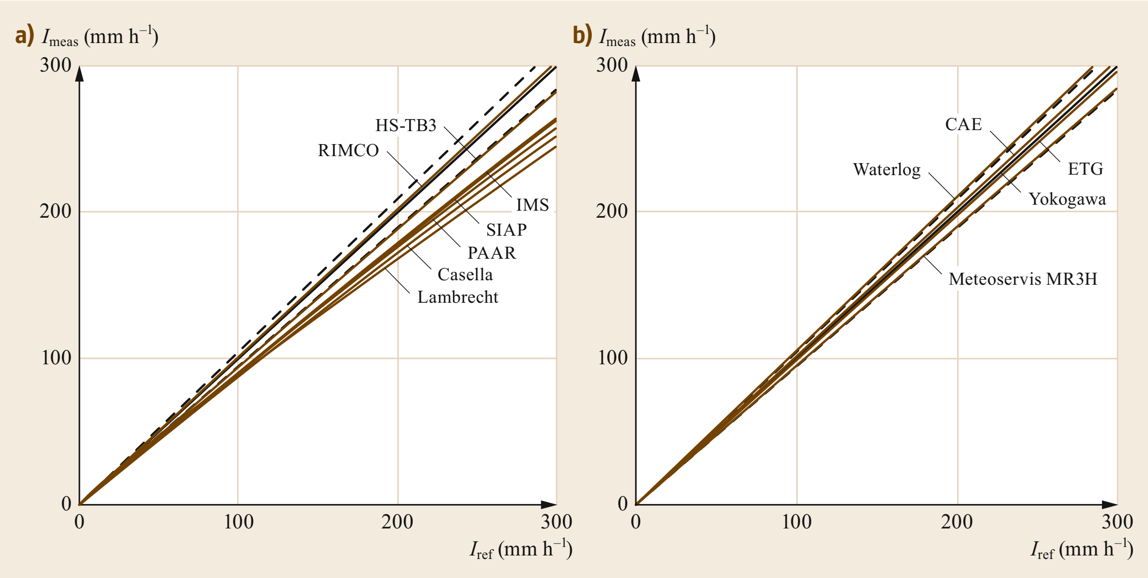

Fig. 12.20a,b Ensemble of response curves for the uncorrected TBRG **(a)** and those applying some correction for systematic mechanical errors **(b)**. *Dashed lines* indicate ±5% (after [12.4])

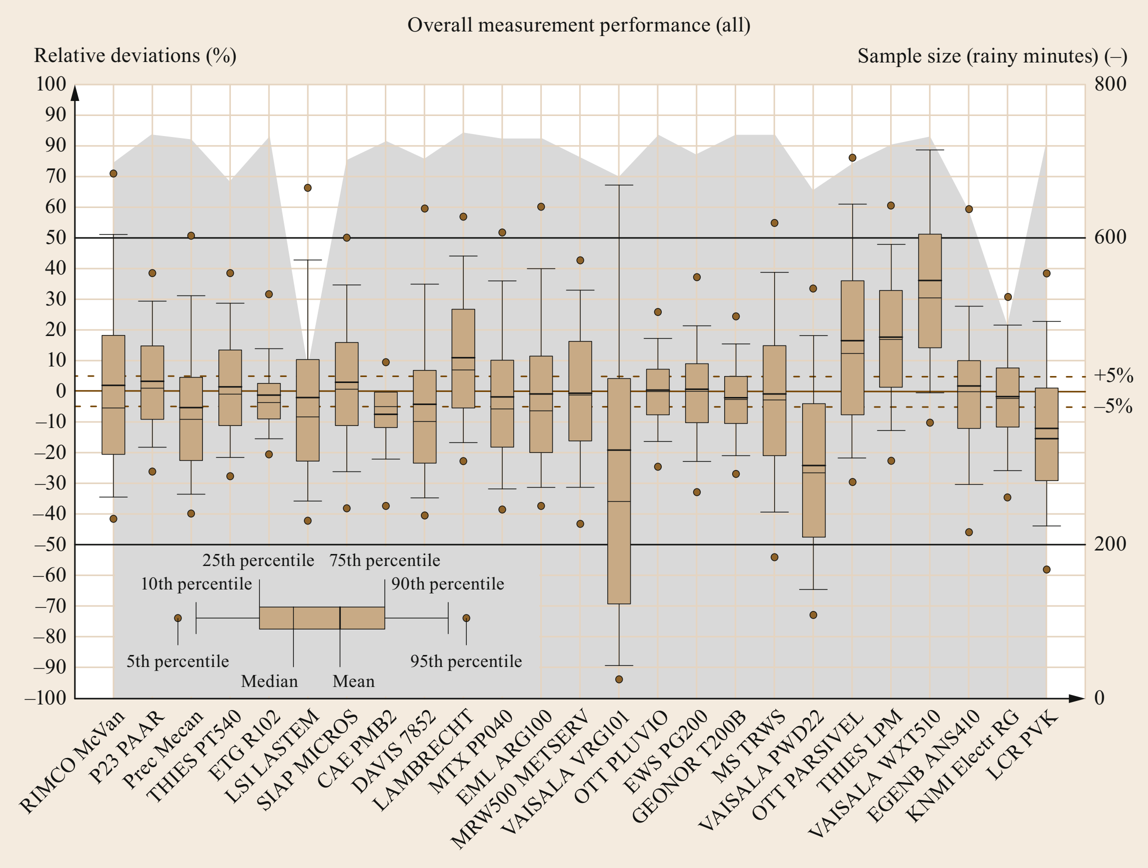

Fig. 12.21 Nonparametric distribution of relative deviations from the reference for all instruments involved, with sample size (number of rainy minutes) indicated in *gray background* (after [12.28] with permission from Elsevier)

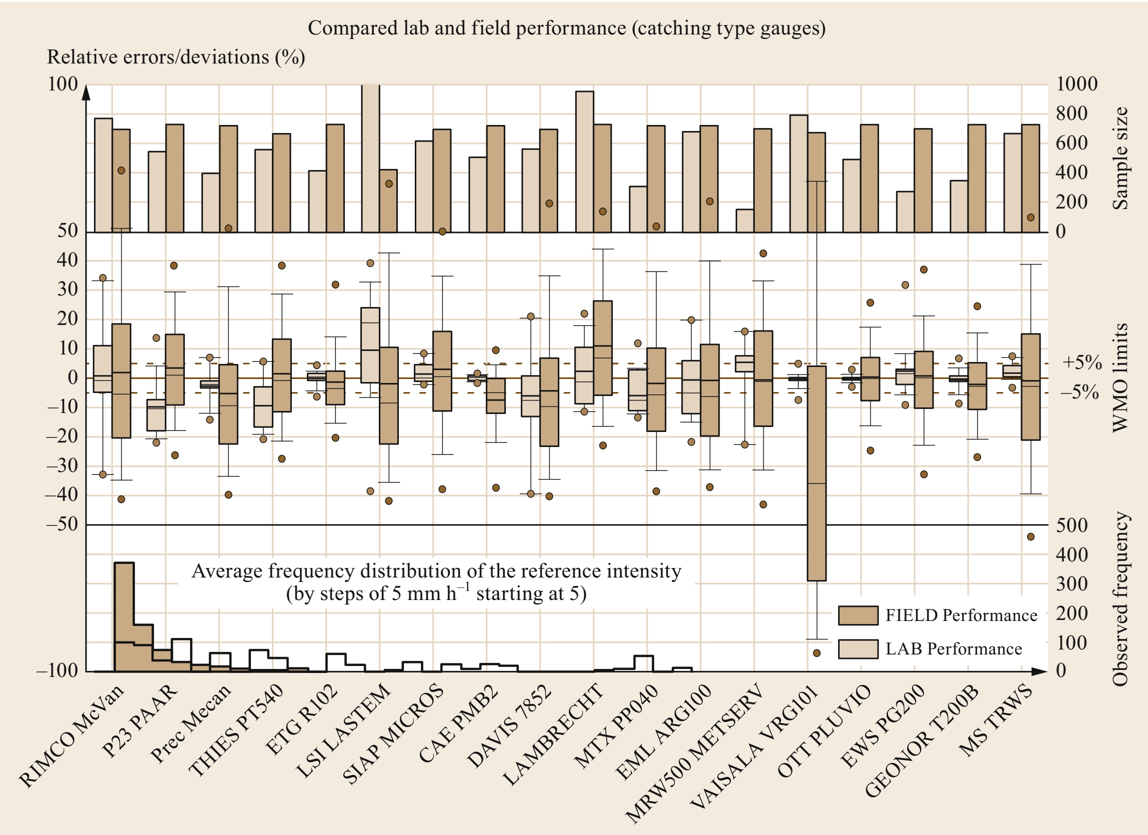

Fig. 12.22 Comparison between relative deviations in the field (*dark brown boxplot*) and laboratory test results (*light brown boxplot*) for catching-type gauges. The sample size and the observed frequency distribution are shown at the *top* and *bottom* of the graph, respectively

formed by switching the flow rate from 0 to 200 mm h^{-1} and then back to zero, with the duration of the input flow being determined based on the time needed for stabilization.

The WMO Field Intercomparison of Rainfall Intensity Gauges was carried out in Vigna di Valle, Italy from October 2007 to April 2009. The main objective was to compare the performance of in-situ rainfall intensity instruments of different measuring principles under high rainfall intensity. This experiment enabled the influence of the operational conditions on precipitation measurements to be assessed (e.g., wind effect on precipitation collection, variability of rainfall intensity). Preliminary laboratory tests were carried out on the catching-type rain gauges involved in the field experiment.

Both catching and non-catching types of gauges were involved in the field test, and ancillary instruments were installed (anemometers, wetness sensor, temperature and relative humidity probes, atmospheric pressure sensor, global irradiance pyranometer). Based on the results of the WMO Laboratory Intercomparison, only some corrected TBRs and WGs with short step response and low residual errors were used as working reference instruments.

The results are summarized in Figs. 12.21 and 12.22. In the first graph, the performance of all instruments (catching and non-catching) are reported in terms of relative deviations, with the associated sample size (number of 1 min rain data). The results show that all catching-type gauges have similar performance in terms of both biases and dispersion (with some outstanding cases), while the non-catching types of gauges have much larger biases and dispersion against the reference. Figure 12.22 shows a comparison between the laboratory and field performance for catching-type rain gauges only. The relative deviations in the field are larger than in laboratory tests, where in some cases the instruments comply with the WMO recommendations of ±5%.

12.7 Maintenance

Although maintenance procedures may be rather expensive and time-consuming, high-quality measurements can hardly be performed in the absence of periodic maintenance and verification of the possible degrading of the instrument performance over time. This is especially true in harsh environments and for instruments employing moving mechanical parts or small orifices that are prone to clogging, such as many catching-type gauges.

12.7.1 Periodic Checks and Maintenance Procedures

The operational status of precipitation gauges in the field is periodically checked in order to detect any malfunction, drift, blockage, etc. Suitable maintenance procedures are adopted to keep the instrument clean and ready to detect and report as soon as precipitation occurs. The frequency of periodic checks and the most suitable maintenance operations depend on the technology and the physical principle exploited to perform the measurement (Table 12.6). Maintenance practices are recommended by WMO [12.1] for the most widely used types of gauges and are reported below. Additional or extraordinary maintenance could be required in the case of different technologies or in locations where the characteristics of the surrounding environment may accelerate ageing or blockage (presence of dust, foliage, ice, etc.).

For any gauge, maintenance and periodic checks should be performed in the absence of precipitation and high wind gusts, and by annotating the period when maintenance is performed and indicating it with a suitable code in the record. For catching-type gauges, checking the conditions of the funnel is a typical maintenance operation and consists of two parts:

- *Clogging*
  The maintenance procedure consists in a preliminary visual inspection of the state of the funnel. In case of obstacles, or leaves or sediment accretion along the funnel walls, the operator should remove the funnel from the gauge and manually clean the walls. In order to verify the conditions of the narrow funnel outlet, the operator could perform one of the following operations. The first is a visual inspection of the funnel outlet, and it may be not possible if the manufacturer applies filters or a sophisticated design of the funnel outlet. The second is pouring a limited amount of water into the funnel and verifying that the water flows through the funnel outlet without accumulating inside the funnel. In any case, the operator should be equipped with a proper pipe cleaner or small brushes in order to clean the narrower parts of the funnel without deformation of the surfaces.
- *Leveling*
  The leveling of the funnel orifice should be verified with the help of an electronic or spirit level. If the status is unsatisfactory, the operator can adjust the mounting screws to restore the leveling. Particular attention should be paid to the stability of the supporting pole that must remain in a perfectly steady position; otherwise the operator should plan the execution of a new installation of the supporting pole.

For storage gauges,

the outer container of the gauge and the graduated cylinder should be kept clean, both inside and outside, by using a long-handled brush, soapy water, and a clean water rinse. Worn, damaged, or broken parts should be replaced, as required. The vegetation around the gauge should be kept trimmed to 5 cm (where applicable). The exposure should be checked and recorded. The operation and maintenance of storage gauges in remote areas poses several problems, such as the capping of the gauge by snow or difficulty in locating the gauge for recording the measurement, which require specific monitoring. Particular attention should be paid to assessing the quality of data from such gauges [12.1].

Table 12.6 Maintenance of precipitation instruments

Maximum interval	Water level	Tipping bucket, weighing, and drop counter	Optical	Thermo	Microwave
6 months	Check for clogging and leveling		Sensor cleaning and check of leveling		Check of leveling
1 year	Check of the graduated scale	Field verification of the dynamic calibration curve	No standard calibration procedure available		
3 years	Volumetric calibration	Dynamic calibration in the laboratory	No standard calibration procedure available		
After every extreme/high-precipitation event—check of the instrument status					

For weighing gauges, the WMO suggests that routine maintenance be conducted every three to four months, depending on precipitation conditions at the site:

> Both the exterior and interior of the gauge should be inspected for loose or broken parts and to ensure that the gauge is level. Any manual readout should be checked against the removable data record to ensure consistency before removing and annotating the record. The bucket or catchment container should be emptied, inspected, cleaned if required, and recharged with oil for rainfall-only operation or with antifreeze and oil if solid precipitation is expected. The recording device should be set to zero in order to make maximum use of the gauge range. Both the digital memory and power supply should be checked and replaced, if required. Timing intervals and dates of record must be checked [12.1].

Weighing gauges with no automatic emptying devices require regular maintenance in order to maintain the level of the water accumulated in the container below the total capacity. For this reason, the operator must continuously monitor the water level in the gauge and be prepared for a timely intervention according to the magnitude of the precipitation.

Typical checks and maintenance procedures should cover the following aspects:

- Antifreeze solution: every time the operator discharges the container, a minimal amount of liquid must be preserved in a solution of water and antifreeze agent (usually a propylene glycol mixture with alcohol in the quantity specified by the manufacturer) to permit the operation of the gauge when the environmental temperature decreases to −40 °C.
- Anti-evaporation agent: every time the operator discharges the container, a given quantity of oil must be added to the solution of water and antifreeze agent (in the quantity specified by the manufacturer). The role of the oil is to reduce the evaporation of volatile antifreeze solutions and precipitation and to reduce splashing, while allowing solid precipitation to penetrate the anti-evaporation film.
- Snow capping and bridging: when long periods of low environmental temperature and solid precipitation occur, the gauges should be monitored regularly in order to detect possible snow accumulation on the gauge orifice rim. Modern gauges are equipped with heating systems to reduce snow capping, but the low electrical power of such devices does not ensure efficient snow melting in the case of very low temperature. The operator should monitor the power consumption of the heating system (in cases where the information is provided by the data logger) or perform technical inspections to remove any snow/ice residual on the gauge orifice rim.

For tipping-bucket gauges, routine maintenance should include:

> cleaning the accumulated dirt and debris from funnel and buckets, as well as ensuring that the gauge is level. It is highly recommended that the tipping mechanism be replaced with a newly calibrated unit on an annual basis. Timing intervals and dates of records must be checked [12.1].

The annual replacement of the mechanism may not be necessary, and is subject to careful checking and/or field verification as detailed below.

The checking of mechanical elements is aimed at verifying the absence of debris inside the buckets and ensuring that the small counting balance rotates without abnormal friction. If the first check fails, the operator should clean the buckets with a small brush. This operation must be performed with great care for the delicate mechanical elements, since the balancing of the bucket could be easily compromised. In the case of abnormal friction during the rotation of the buckets, the operator should return the gauge to the laboratory for an in-depth cleaning of the mechanical components and follow the manufacturer-prescribed procedures if provided, or just replace the bucket assembly. While the verification of the counting performance of the mechanical sensor is not part of the routine maintenance operations, it is good practice to perform a complete field verification after performing any manual intervention on the tipping-bucket balance system.

The characteristics of non-catching-type gauges may differ significantly according to the measuring principle and the design adopted by the manufacturer. It is difficult to provide general maintenance procedures for such gauges; however, many non-catching types of gauges adopt optical elements such as lenses, mirrors, or light/radiation beam orifices that are often subject to occlusion caused by the presence of dirt/dust. The operator should perform periodic checks at intervals depending on the sensor characteristics (usually specified by the manufacturer). In the case of occlusion, the debris must be carefully removed using soft brushes, or the specific products occasionally provided by the manufacturer, in order to prevent damage to the lenses or optical elements of the sensor.

12.7.2 Field Calibration/Verification

For catching-type gauges, the WMO [12.1] suggests that:

> a proper field calibration, and field calibration check or field inspection should also be conducted on a regular basis as part of the routine maintenance and check, taking into account site and operational constraints.

For catching-type gauges, a recommended procedure using a portable device to generate reference flow rates is given by WMO [12.1].

The main purpose of the field verification is to detect calibration drifts during operational use, as described by [12.46]. This calibration also provides valuable insights into data analysis and interpretation. The field calibration should be performed using a portable field calibration system (Annex B of [12.46]) based on the same principle as the laboratory calibration, using the generation of constant equivalent rainfall rates within the range of operational use (steady water flow). From the operational viewpoint, the portable field calibrator should permit rapid tests and should not contain any sophisticated components, in order to provide a cost-effective solution. The repeatability of the field calibrator (and its accuracy) should be assessed in a laboratory before operational use and its (expanded) uncertainty determined.

During the WMO Field Intercomparison of Rainfall Intensity Gauges, a dedicated portable calibrator was designed and used for calibration and verification. Its performance and results are described in the final report [12.4].

The field calibrator designed at the University of Genova is a modified Mariotte bottle composed of a cylindrical water container of suitable capacity (about 2 L), a combination of air intakes and output nozzles for generating different rainfall intensities, and an electronic system to detect the emptying time. A suitable combination of air intakes and nozzles can be selected based on the gauge collector size and the reference intensity chosen for the calibration. By opening the top tap and bottom nozzle, a constant flow is conveyed to the funnel of the gauge, and the reference intensity is determined according to the emptying time and the conversion table (volume–time–intensity). Air intakes provide the pressure compensation, thus maintaining a constant push. The field verification should be performed in operational conditions, in the absence of precipitation or fog and at low wind speed.

12.7.3 Metrological Confirmation

Metrological confirmation is defined as a set of operations required to ensure that measuring equipment conforms to the requirements for its intended use, according to [12.80]. Once the instruments are calibrated and their accuracy certified by an independent third party so that measurements are traceable to the international standards, it is the duty of the station manager to periodically check that the instruments still preserve their original characteristics. This is the role of field inspection, i.e., the practice of testing the performance of an instrument in the field and sending it back to the laboratory for recalibration if needed. Indeed, the instrument performance is subject to deterioration over time due to aging, operating conditions, the surrounding environment, and other random or unexpected events.

For example, in the case of catching-type gauges, a typical procedure would involve periodically checking the performance of the instrument using a suitable field calibrator. The results of the field test are then compared with the expected performance of the gauge, such as from the calibration certificate, and deviations from the expected behavior are calculated. If deviations remain within a satisfactory margin (say $\pm 1\%$), the instrument is still suitable to operate. When deviations are larger, the instrument is either replaced with a new one or sent back to the laboratory for recalibration. The period between two successive field inspections can be set to an initial value (e.g., 1 or 3 years) and then expanded or reduced depending on the results of the first test (if the instrument performance is close to the original behavior, the next inspection can be delayed, and vice versa).

12.8 Application

The use of liquid and solid precipitation measurements covers such a broad spectrum of applications that compiling any detailed list would inevitably fail to be comprehensive. Most of these are based on the observation and investigation of typically measured characteristics of precipitation such as the rainfall amount, intensity, and duration, in addition to the frequency of intense rainfall events [12.73]. The most common ones include precipitation climatology studies, statistics of extreme events for engineering design, meteo-hydrological warnings and flood protection, optimization of irrigation for agriculture, water resources management and potable water supply, pollution control, among others.

Since liquid and solid precipitation are the forcing input of the land phase of the hydrological cycle, the knowledge of precipitation, its variability, and the observed patterns of precipitation events in both space and time are of paramount importance for most hydrological studies. The consequences of such studies for the engineering practice are exploited in everyday technical operations for the design, management, and maintenance of any man-made structure that interacts with water in the natural landscape. The *design rainfall* is indeed a common variable used in civil engineering for the realization of urban drainage networks, bridges, levees, erosion control structures, and many other civil works. The design rainfall is obtained from the statistical analysis of long time series of rainfall observations and describes the amount of rain that is expected with a given probability of occurrence at a given location and over a predefined time window.

Measurements of precipitation intensity, and especially long records of measurements extending into the past, are of foremost importance in the management of flood hazard, since the return period of extreme events is derived from the statistical analysis of such time series. Analogously, in water resources management, precipitation measurements are essential for evaluating the availability and variability of freshwater resources (springs, aquifers, etc.) and the management of reservoirs. In addition, precipitation is one of the most important sources of renewable energy, as it releases large amounts of water over high-elevation landscape, providing the potential energy exploited by hydropower plants to obtain sustainable energy.

Agriculture is a major user of precipitation measurements, given the need for adjusting the amount of water provided to crops in order to optimize the growth rate and maximize harvests, especially in regions characterized by a scarcity of precipitation. In addition, the protection of crops from hail and other intense precipitation events requires the availability of direct in-situ observations.

Climatological studies should be based on reliable and accurate data sets of precipitation measurements in order to estimate possible long-term trends and cyclical patterns. The correct measurement of precipitation and other meteorological and hydrological variables, as well as the correct interpretation of historical data, will be of foremost importance in the future for the prediction of changes in weather patterns affecting the earth's climate.

In light of the large demand for precipitation measurements, national or regional agencies in most countries are in charge of deploying, maintaining, and managing precipitation monitoring networks in order to supply the measured data to various types of users. Each application, however, has its own specific requirements in terms of both the measured quantities and the sensitivity, resolution, and accuracy of the measurement instruments.

For example, real-time control of urban drainage networks may require precipitation intensity measurements at a fine temporal resolution (1 min) and with high accuracy, while irrigation control for agricultural purposes may require measurements of the precipitation depth at the daily or weekly scale, with lower accuracy. Measurements used to calibrate precipitation estimates provided by remote sensing tools (e.g., radar or satellite-borne sensors) may require highly accurate knowledge of the particle size distribution and type of hydrometeors at the timescale of minutes. For some users, the accuracy of precipitation measurements is not as crucial as timeliness, and thus amateur networks of low-cost/low-accuracy instruments are successful in that they provide real-time access (within minutes) to the measured data over the Internet.

This broad range of requirements is precisely the reason why the national and international standards on the accuracy of rainfall intensity gauges aim at defining the required performance of measurement instruments according to a small number of classes. Each instrument is assigned to a class based on specified and certified performance, so that the user may decide which class of instruments is required for the application in hand. Once the instrument's class is declared by the station manager, with the associated third-party certification, assessing the suitability of measurements thereof for a specific application would be straightforward.

Although a single station or a small network can be easily developed as a fit-for-purpose technical solution, and instruments thus selected according to the most suitable technology and specifications, measurements from national meteorological networks are made available to the general user with little awareness of the intended use. Adhering to a fit-for-purpose philosophy is therefore very difficult in the case of large networks, which are rather multipurpose services. There is a danger that national agencies may interpret their mission as that of fitting a single purpose (e.g., civil protection), or may try to meet the requirements of one category of users alone (especially if this is the least demanding one). Instead, given the complex nature of the targeted phenomena, for precipitation monitoring networks to provide optimal service they should ideally meet the most demanding requirements of fine temporal resolution and high accuracy, allowing users to possibly degrade the information to the scale they actually need for each application.

12.9 Future Developments

The results of the recent WMO intercomparison initiatives and the ongoing accurate lab/field tests within the activities of the WMO/CIMO Lead Centre B. Castelli on Precipitation Intensity, Italy [12.81], enable the following considerations to be highlighted on the achievable accuracy of currently available instruments for in-situ precipitation measurements.

For liquid precipitation, conventional tipping-bucket rain gauges have the potential to achieve reasonable to high accuracy over the medium to upper range of rainfall intensities. In order to achieve such a high level of accuracy, suitable dynamic calibration is required, and appropriate software corrections for both sampling and mechanical errors must necessarily be applied. Note that the common statistics derived from precipitation intensity records are particularly affected if corrections are not applied (see, e.g., [12.20]). In addition, the catching performance of the gauge is affected by the interaction of the gauge body with the wind, and correction or the use of instruments with an aerodynamic shape are recommended.

Weighing-type gauges are the second most widely employed class of instruments currently in operation for precipitation measurements. Advantages include the absence of mechanical parts, better conveying performance because of the absence of the funnel, and suitability for solid precipitation measurements (snow). However, test results indicate that the influence of the dynamic response (time constant) of the measuring system on the accuracy of time-varying precipitation intensities (including the smoothing algorithm used to deal with the noise) is significant for this kind of instrument and must be taken into account accordingly. Otherwise, the overall accuracy of the weighing gauge can be even lower than that of traditional tipping-bucket rain gauges [12.82]. Again, the statistics on precipitation extremes are particularly sensitive to the associated errors [12.30].

For solid precipitation measurements, the catching performance of the gauge is the key issue, and environmental error sources (especially wind) are the most influential factors. The shape of the gauge body is critical in determining its aerodynamic response when impacted by the wind, and correction curves (either empirically or numerically derived) must be applied to account for the associated undercatch. The use of windscreens or the practice of burying the instruments with the orifice at the level of the surrounding ground may attenuate this effect.

Non-catching-type instruments are the emerging class of in-situ precipitation gauges. For these instruments, rigorous testing is more complicated, since rain droplets, crystals, and snowflakes of various size and density should be produced—instead of an equivalent water flow—to provide the reference precipitation. Even the calibration of such instruments is still a problem [12.83], and based on the results of the recent WMO intercomparison of rainfall intensity gauges in the field, caution should be exercised in using the information obtained from non-catching instruments in any real-world application, and even in assessing the results of scientific investigations based on such measurements [12.4].

However, the development of highly accurate non-catching gauges for both liquid and solid precipitation is an increasingly relevant and pressing requirement in the atmospheric and hydrological sciences and their applications. Indeed, national meteorological services and other organizations in charge of the management of monitoring networks over large regions generally prefer such kinds of instruments. This is because of their potential for reducing maintenance costs (by eliminating any moving part or containers to be periodically emptied), the high temporal resolution, and their suitability for use as part of a fully automated monitoring network. Drawbacks can be easily identified in the higher complexity of the exploited technology, such that the user's ability to correctly maintain and calibrate the instrument may be limited.

Whatever the instrumentation employed, the actual requirements for precipitation monitoring networks are primarily their accuracy and reliability. Therefore, the measuring principle alone is insufficient in discriminating between the various types of gauges. Rather, the performance of each instrument over the measuring range of interest for the application in hand should be the focal point, based on well-documented procedures for the assessment and certification of such performance in fully controlled conditions, as well as on the traceability of the measurement to the international standards of mass and time.

This philosophy was the basis for the development of the WMO recommendations on the accuracy of rainfall intensity measurements [12.1], which indicate a range of $\pm 5\%$ as the maximum admissible error (in the laboratory) for *RI* measurements at the time resolution of 1 min. Based on such indications, national standards on the accuracy of precipitation measurements are appearing (e.g., [12.54, 84, 85]), and the standardization process within CEN and ISO has already begun.

12.10 Further Reading

Further information on precipitation measurements can be found in the following publications:

- WMO: Guide to Instruments and Methods of Observation, WMO-No. 8, Volume I - Measurement of Meteorological Variables. (World Meteorological Organization, Geneva, 2018)
- CEN: Hydrometry—Measurement requirements and classification of rainfall intensity measuring instruments, EN 17277:2019
- L. Lanza, C. Leroy, M. Alexandropoulos, L. Stagi, W. Wauben: Laboratory Intercomparison of Rainfall Intensity Gauges, World Meteorological Organisation Instruments and Observing Methods (Rep. No. 84, WMO/TD No. 1304) (2006)
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