WMO LABORATORY INTERCOMPARISON OF RAINFALL INTENSITY GAUGES

De Bilt (The Netherlands)
Genoa (Italy)
Trappes (France)
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L. Lanza (Italy)

M. Leroy (France)
C. Alexandropoulos (France)
L. Stagi (Italy)
W. Wauben (The Netherlands)

Final Report

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EXECUTIVE SUMMARY

The present document is the Final Report of the WMO Laboratory Intercomparison of Rainfall Intensity (RI) Gauges that was launched, simultaneously, in September 2004, in the laboratories of the Royal Netherlands Meteorological Institute (The Netherlands), Météo-France (France) and the Department of Environmental Engineering of University of Genoa (Italy) in collaboration with the Italian Meteorological Service.

No intercomparisons of instruments for the measurement of RI had been organized so far. Following the recommendations of the Expert Meeting on Rainfall Intensity Measurements, Bratislava, Slovakia, April 2001, it was proposed, as the first and necessary step, to organize an intercomparison of RI instruments in the laboratory conditions. Some laboratory tests of rain gauges were done and reported in the literature, however no intercomparison of RI instruments, in one or several laboratories, had been conducted.

The main objective of the Intercomparison was to test the performance of catchment type rainfall intensity gauges of different measuring principles under documented conditions. Other objectives were to define a standardized procedure for laboratory calibration of catchment type rain gauges, and to provide information relevant to improving the homogeneity of rainfall time series with special consideration given to high rainfall intensities. Finally, a comment on the need to proceed with a field intercomparison of catchment type of RI gauges was required as well as to identify and recommend the most suitable method and equipment for reference purposes within the field intercomparison of catching and non-catching types of gauges.

The CIMO Project Team consisted of the Chair of the Expert Team (ET) and the International Organizing Committee (IOC) on Surface-Based Instrument Intercomparisons, the Project Leader and three Site Managers, coordinated the work of the laboratories involved in the intercomparison. The 19 pairs of participating instruments from 18 manufacturers were divided into three groups, with each group being tested for a period of about three to six months in each of the laboratories, in order to obtain a high degree of confidence in the results. The first phase of tests had successfully concluded by 15 February, the second by 15 May 2005 and the third by September 2005. All the cost related to laboratory intercomparisons was born by the laboratories and the manufacturers involved.

The majority of the participating instruments were tipping-bucket gauges, which are the most widely used in operational networks. Second group of instruments were weighing gauges; the third group consisted of two participating instruments only using a non-common measuring principle, namely, a water level based on conductivity measure.

A general methodology was adopted for the tests, based on the generation of a constant water flow from a suitable hydraulic device within the range of operational use declared by the instrument's manufacturer. The water was conveyed to the funnel of the instrument under test in order to simulate constant rainwater intensity. The flow was measured by weighing the water over a given period of time. The relative difference between the measured and generated rainfall intensity was assumed as the relative error of the instrument for the given reference flow rate. In addition to measurements based on constant flow rates, the step response of each instrument was checked based on the suitable devices developed by each laboratory.

Each laboratory developed its own testing device, with some differences in the principle and technology used to generate a constant water flow, as well as in the way the water is weighed in the device. These provided a basis for the development of a standardized procedure for generating consistent and repeatable precipitation flow rates for possible adoption as a laboratory standard for calibration of catchment type RI gauges.

The results of the Intercomparison showed that the tipping-bucket rain gauges that were equipped with proper correction software provided good quality rainfall intensity measurements. The gauges where no correction was applied had larger errors. In some cases problems of water storage in the funnel occurred that could limit the usable range for rain intensity measurement.

The uncertainty of the rainfall intensity is generally less for weighing gauges than for the tipping-bucket rain gauges under constant flow rate condition, provided the instrument is properly stabilized. The measurement of rainfall intensity is affected by the response time of the acquisition system. Significant delays were observed in “sensing” time variation of the RI by weighing gauges. The delay is the result of the internal software which is intended to filter the noise. Only one instrument had a delay that met the WMO 1-minute rainfall intensity requirement.

The two gauges using a conductivity measurement for determining water level showed good performances in terms of uncertainty under controlled laboratory conditions. Siphoning problems for one gauge limits its ability to measure a wide range of rainfall intensity. For the other one, a limitation is related to the emptying mechanism, in which case 2-minute delay was observed. These gauges are potentially sensitive to the water conductivity, with no demonstrated problems during the laboratory tests.

The laboratory tests were performed under controlled conditions and constant flow rates (rainfall intensities) so as to determine the intrinsic counting errors. It must be considered that RI is highly variable in time, thus catching errors may have a strong influence on the overall uncertainty of the measurement. The need to combine the assessment of both counting and catching errors for the instrument analyzed in the laboratory is paramount. Provided the instrument is properly installed in the field, according to the WMO specifications, the question to be answered is what kind of instrument (measuring principle, manufacturer, model) is the most suited to the specific requirements of the user. This question cannot be answered based on the laboratory Intercomparison alone, although the results obtained can provide preliminary information to manufacturers and the first-step selection criterion for the user.

Therefore, it is necessary to proceed with the quality assessment procedure initiated in the laboratory by organizing a follow-up Intercomparison in the field where the instruments tested in the laboratory should have a priority. This would allow continuity in the performance assessment procedure and result in the estimation of the overall operational error to be expected in the measurement of RI in the field. Also other instruments would be included in the field intercomparison, even if not tested in the laboratory phase, with a priority given to the non-catching type of instruments.

For the Field Intercomparison a working reference rain gauge(s) should be inserted in a pit according to the EN-13798 standard Reference Raingauge Pit, adopted by ISO, in order to minimize the effect of weather related errors on the measured rainfall intensities. According to the results of the laboratory intercomparison, it is recommended to select the best performing dynamically corrected tipping bucket rain gauge(s) and the weighing gauge(s) showing the shortest step response and the lowest uncertainty as reference gauges. The combined analysis of the reference gauges allows the best possible estimation of the rainfall intensity in the field, given their demonstrated performance in the laboratory. The use of one reference instrument alone is not recommended.

Finally, the improvement of the uncertainty of RI gauges introduces the risk of affecting the homogeneity of rainfall time series. The improvement of the measurement of RI may produce a discontinuity of the historical rainfall intensities records, which could influence especially the studies of extreme events. The bias introduced by non-corrected records propagates through any rainfall-runoff model down to the statistics of flow rates in water courses, with non negligible effects on the study of floods and flash floods. An example of the correction of the historical rainfall series was demonstrated using the result of the laboratory intercomparison.

PART I

RAINFALL INTENSITY MEASUREMENT INSTRUMENTS AND UNCERTAINTY

1. Rainfall Intensity (RI)

For a considerable long time, series of rainfall amounts are recorded worldwide. Such amounts, expressed in mm or $kg \cdot m^{-2}$ and collected during a day or an hour are not only useful for general meteorological and climatological practices, but are of special interest for hydrology and agricultural meteorology.

Trends in precipitation events, water balance calculations, estimation of potential run off and river flow forecasts have a long history for which the measurement of precipitation is an essential requirement. For this purpose, many types of instruments and measurement techniques are developed and in operational use. Because of the extended experience, most of these techniques are well described and understood. Recommendations on standardization[1] of equipment and exposure, calibration and correction of data are well documented.

Although data of quantitative amounts 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 cases of severe weather. It is clear that events with extremely high precipitation intensities affect all types of transportation; it may also destroy crops and vegetation by its violence. Moreover, constructions may collapse, wetting can damage property and under-estimation of run-off systems and local canals can have unexpected and considerable consequences. Therefore, *precipitation intensity* is introduced as a numerical quantity, in line with the recommendation on reporting present weather. Until now, precipitation intensity is generally reported in qualitative and subjective terms like ‘light’, ‘moderate’ or ‘heavy’ as part of present weather data. With the introduction of the BUFR code however, precipitation intensity is reported as a quantitative value.

1.1 Definition

Precipitation intensity is defined by WMO[2] as the amount of precipitation, collected per unit time interval. According to this definition, precipitation intensity data can be derived by the measurement of precipitation amount using an ordinary precipitation gauge. In that sense, precipitation intensity is a secondary parameter, derived from the primary parameter precipitation amount. However, precipitation intensity can also be measured directly. For instance, using a gauge and measuring the flow of the captured water, or the increase of collected water as a function of time. A number of measurement techniques for the determination of the amount of precipitation are based on these direct intensity measurements by integrating the measured intensity over a certain time interval. Typical examples are optical and electromagnetic sensing rain gauges. In fact, all remote sensing techniques measure intensity as primary variable. As a consequence of automation, conventional (manual) rain gauges are being replaced by automatic recording gauges, which may measure intensity as primary quantity. It is important to evaluate these automatic gauges for measuring precipitation intensity.

Because of these developments, CIMO-XII has underlined the need for standardization of precipitation intensity measurements. For this purpose, an Expert Meeting on Rainfall Intensity Measurements was organized[3] (April 2001, Bratislava, Slovakia). This meeting formulated “present and future requirements for rainfall intensity measurements” because no such requirement and related guidance were available. These recommendations on measuring range and uncertainty requirements were approved by CIMO-XIII[4] for publication in the WMO Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8). The expert meeting, held in Bratislava,

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[1] See WMO-No. 8 and WMO-No. 168. Based on these Guides CEN approved the European Standard EN 13798 by specifying a *Reference Raingauge Pit*, which is adopted by ISO as ISO Standard.
[2] See WMO-No. 182, P1430
[3] See Final Report on WMO’s website.
[4] See Final Report CIMO-XIII (WMO-No. 947), Annex 1.

recommended that the unit to report precipitation intensity should be "$mm \cdot h^{-1}$". Although it reflects an instantaneous situation, confusion may arise if the quantity is regarded as the total amount of rain, which has fallen during an hour. Therefore it was proposed to indicate time resolution when reporting precipitation intensity. For this practice a minimum time resolution of one minute is adopted which is the same for many other variables. To stay in line with SI, $mm \cdot h^{-1}$ should be used instead of $mm \cdot min^{-1}$. Instead of the quantity volume, the quantity mass (per unit of area) can be used as well, where $1\ mm \cdot h^{-1} = 1\ kg \cdot m^{-2} \cdot h^{-1}$.

1.2 Measurement range and related uncertainties

CIMO-XIII adopted for precipitation intensity the measuring range and related uncertainties as recommended by the expert team and published in the WMO Guide to Instruments and Methods of Observation (WMO-No. 8, 7th edition):

Full range:	0.02 to 2000 $mm \cdot h^{-1}$
0.02 to 0.2 $mm \cdot h^{-1}$	reported as "trace" (or "rain detected")
Output averaging time:	1 minute
Required measurement uncertainty:	
0.2 to 2 $mm \cdot h^{-1}$:	0.1 $mm \cdot h^{-1}$
2 to 2000 $mm \cdot h^{-1}$:	5 %

1.3 Frequency and spacing of observations

Generally, the frequency and spacing of observations should be adjusted to the physical scales of the meteorological phenomena to be described. The WMO Guide to Instruments and Methods of Observation (WMO-No. 8, 7th edition) describes those scales. Although the necessary scaling in space and time depends on the application or service, it is clear that precipitation phenomena in many cases are typical "small scale" events (see WMO-No. 488, Fig. II.1), *i.e.* horizontal and timescales of meteorological phenomena down to a couple of kilometers and couple of minutes. This Guide states that for precipitation a spatial separation of about 10 km may be required (*e.g.* for very-short-period forecasting, climatology and hydrological forecasting). In general, precipitation intensity measurements in conjunction with remote sensing measurements will provide small-scale forecasts and services most effectively. In line with these statements, a time resolution of one minute is recommended, to be provided within 10 minutes intervals. Such intervals are in line with the current trends in reporting synoptic observations within national networks.

1.4 Services using precipitation intensity

Information on precipitation is widely used in all disciplines of meteorology and climatology. Not only in relation to precipitation reaching the earth's surface, but also as a present weather phenomenon. Typically, precipitation intensity is of interest for:

- <u>Synoptic meteorology</u>, in particular
  - o <u>Road meteorology</u>
  - o <u>Urban meteorology</u>

It is evident that high precipitation intensities (liquid and solid) affect transportation and commerce. Buildings can be damaged; roads and other infrastructure can be blocked in case of insufficient drainage and run-off. Timely short-term-forecasts may reduce the risk. Also, reliable records of intensity measurements can help to improve the design of run-off systems.

- <u>Climatology</u>

It is stated that due to the ongoing global warming, local showers with extreme high precipitation intensities are expected more frequently. For the assessment of these events appropriate measurement techniques should be established.

- Hydrology

The measure of infiltration of rainwater in the ground depends on the rainfall intensity. It is relevant to measure these intensities for appropriate design and modeling of run-off systems. Timely forecasts and warnings can reduce risks.

- Agricultural meteorology

Crops and vegetation are sensitive to precipitation intensity and serious damage can occur in case of extreme events. Such events may also cause soil erosion. Protection efforts and further studies on the impact of such events can result in a reduction of such damage.

2. Rainfall Intensity (RI) Gauges

All types of rain gauges can be divided into catching and non-catching instruments. Gauges of the first group collect precipitation through an orifice of well-defined size and measure its water-equivalent volume or mass that has been accumulated in a certain amount of time. At present catching rain gauges are widely used in operational networks to measure rainfall intensities and amounts.

Instruments of the second group are commonly used as disdrometers for the detection of droplet size distributions. Rainfall intensity or amount can be calculated by mathematical integration over all particles passing a cross section in a certain time interval.

As a point of concern it has to be stated that at present there is no primary or generally agreed reference standard for the calibration of any type of rain gauge. Nevertheless many calibration practices have been developed, especially for catching rain gauges.

2.1 Catching rain gauges

Catching rain gauges can be characterized as follows:

- They can be calibrated in the laboratory;
- They are able to measure RI within sampling time intervals ranging from a few seconds to several minutes;
- They have finite resolution ranging from 0.001 mm to 1 mm;
- They have reasonably good reproducibility and long-term stability;
- They are widely used in operational practice and cost effective;
- They are prone to wind-induced catching losses (depending on appropriate wind shielding);
- They are prone to wetting and evaporation losses, especially in low RI;

Regular maintenance, annual calibration and servicing, is recommended to obtain high quality measurements.

2.1.1 Tipping bucket rain gauges

A tipping bucket rain gauge uses a tipping balance with two buckets as the measuring element. The balance tips whenever a fixed mass of water (e.g. corresponding to 0.2 mm of rain) has been filled into one of the buckets. A tip of the balance removes the filled bucket from the filling nozzle and it is emptied while the second, empty bucket is moved underneath the filling nozzle. Each tip produces an electrical impulse as signal output and is recorded by the data acquisition system. This mechanism provides a continuous measurement without manual interaction.

Rainfall intensity can be calculated at best over the period of time between 2 tips. In other words, for low intensities the temporal resolution depends on the size of the bucket and the RI. A tip resolution equivalent to 0.2 mm leads to a RI resolution of 12 $mm \cdot h^{-1}$over a period of 1 minute.

Tipping bucket gauges generally suffer from systematic non-linear and significant measuring errors, strongly dependent on rainfall rate. Especially with higher intensities these errors can amount to 20% for some types of tipping bucket gauges.

2.1.2 Tipping-bucket rain gauges with software correction

To overcome the underestimation of RI, a suitable rainfall intensity dependent correction has to be applied, e.g. in the data acquisition system. Some tipping bucket gauges apply this correction in real time operation. The measurement errors related to the rainfall intensity (and total amount) can be reduced to ≤ 2%, in laboratory conditions.

2.1.3 Tipping-bucket rain gauges with mechanical correction

Some tipping bucket gauges use a mechanism to prevent the loss of water during the tip of the balance.

2.1.4 Level measurement rain gauge

Water is collected in a tube of specified diameter. By measuring the water level in the tube the volume of collected water is determined. The level measurement can be done by a conductivity measurement, an acoustic distance measurement or by a floater. The water level can thus be measured with any desired temporal resolution. The measurement resolution is typically between 0.01 mm and 0.1 mm leading to a RI resolution between 0.6 mm·h^{-1} and 6 mm·h^{-1}.

At a maximum level, the tube can be siphoned providing an almost continuous measurement without manual intervention. Due to the siphoning process the measurement can be interrupted for about 1 minute.

2.1.5 Weighing rain gauge

In all weighing rain gauges, precipitation is collected and instantaneously weighed. In contrast to other measurement principles mentioned above, weighing rain gauges do not use any moving mechanical parts in the weighing mechanism, only elastic deformation occurs. Therefore, mechanical degradation and consequently the need for maintenance is significantly reduced. The weighing is accomplished by various methods, e.g. by using a pressure sensor, a frequency measurement of a string suspension, or an electronic precision balance. All weighing gauges can have temperature dependencies in the weighing mechanism and/or element. Noise in the weight measurement due to the water input has to be filtered out appropriately. Another characteristic of a weighing rain gauge is the time delay in the RI output of the measurement that can be of the order of 1 to 10 minutes.

Weighing gauges usually have a one-minute data output cycle while the internal sampling rate can be in the order of some Hz. Therefore, precipitation amount is available each minute and RI over a one minute period can be easily calculated from the differences of two successive measurements. The resolution of rain amount ranges typically between 0.01 and 0.1 mm, leading to a RI resolution between 0.6 to 6 mm·h^{-1}.

2.1.6 Weighing rain gauge with funnel

Instruments that use a pressure sensor need to collect the rainfall water by a funnel in order to fill it into a thin sampling cylinder of known diameter with the pressure sensor mounted at the bottom. Knowing the base area of the cylinder, the force of the water column (weight) can be determined.

These gauges are sometimes equipped with an automatic emptying mechanism.

2.1.7 Weighing rain gauge without funnel

Some weighing rain gauges collect precipitation directly in a bucket without using a funnel. The total weight of the sampling bucket and its content is determined by an electronic weighing mechanism using a tensiometer as the measuring element.

The absence of a funnel reduces the wetting losses significantly and minimizes the delay of the residual water being measured later. It provides the opportunity to directly measure the mass of solid precipitation which otherwise has to melt first. Problems related to contamination are mitigated. Because of the open bucket design the decrease of mass due to evaporation has to be taken into account.

By principle all weighing gauges without funnel are often affected by:

- Dynamic pressure fluctuations generated by wind over the orifice of the rain gauge;
- Noise in the weight measurement due to the direct impact of precipitation particles.

Signal processing software has to be added to filter out the variations related to these effects. This may introduce a delay in the output.

The maximum capacity of the bucket ranges between 100 mm to about 1000 mm. Some of these instruments have no siphoning mechanism; in all other cases the siphoning process takes about 2 minutes during which the instrument cannot measure ongoing precipitation.

2.1.8 Drop counters

These instruments use a thin nozzle to produce single uniform droplets corresponding to a fixed volume of water. Each droplet is detected by an optical system giving a single pulse output that is counted. The measurement resolution can be < 0.001 mm with an upper limit of the RI range of about 50 $mm \cdot h^{-1}$. The single droplet resolution of approx. 10 mm^3 results in a high temporal resolution.

Higher RI (within the allowed measurement range) can be measured instantaneously and directly by a frequency measurement of the output pulses.

Because of the thin nozzle for the droplet formation, field operation needs great attention and service. Therefore, these systems are mainly used for research purposes.

2.2 Non-catching precipitation sensors

The primary use of non-catching precipitation sensors is mainly for present weather observations including rainfall intensity measurements.

Compared to the procedure used for catching rain gauges, the calibration of this sensor type is difficult. The lack of established laboratory test procedures led to the decision to exclude non-catching sensors from the WMO Laboratory Intercomparison of RI Gauges. Therefore, little knowledge is available on attainable measurement uncertainty of these devices.

2.2.1 Impact disdrometers

For this type of sensors a membrane of plastic or metal is used as 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. Other systems detect the amplitude and analyze the frequency spectrum generated by precipitation particles hitting the membrane to determine the number and the size of the drops. Integration of these parameters leads to RI over a selected period of time.

As a drawback, these disdrometers are not capable to measure smallest droplets of diameters less than 0.3 mm. Moreover, snowflakes of low mass density may not be detected. Software filtering techniques have to be used to reduce environmental acoustic noise.

In the past, sensors of this group were expensive and not suitable for the use in a large network. Recently more cost effective sensors have become available.

2.2.2 Optical disdrometers

Optical disdrometers use one or two thin laser light sheets to detect particles crossing it. Each particle within the beam blocks the transmitted light intensity to a certain amount proportional to its diameter. The measurement range for particle diameters is typically 0.2 mm to > 8 mm. RI can be directly calculated by integration of the number of the detected particles and their size over a time period ranging from 15 seconds to one minute. The RI resolution is typically 0.01 $mm \cdot h^{-1}$.

One possible error source arises from coincident drops, which are detected as one “big” drop. This leads to a systematic overestimation of the determined water volume for which a statistical correction has to be applied. The upper limit of the measurement range is also restricted by this effect to typically 250 $mm \cdot h^{-1}$. Another error source is due to droplets hitting the rim of the light sheet that are interpreted as too small particles.

Besides the pure disdrometer functionality, these instruments are able to measure the falling speed of each individual drop, which results in a matrix of falling speed versus particle diameter. By cluster analysis of this matrix, the type of precipitation can be assigned which is used for Present Weather functionality.

As mentioned above, a laboratory calibration is at least very difficult and agreed methods have to be established. In particular, there is no well-defined rainfall simulator accepted as a standard. The long-term stability of these instruments has to be demonstrated but is expected to be in the range of years.

2.2.3 Some other principles for precipitation measurements

Some optical sensors use the scattering by particles passing through a given volume to determine precipitation intensity and sometimes the type of precipitation.

Small X-band radars can be used to determine the spectrum of the signal backscattered by falling particles. The spectrum is related to the Doppler shift associated to the falling speed of these particles. The intensity of the backscattered signal is related to the number of particles and/or their water content. Calibration is generally difficult and cannot be carried out in the laboratory.

3 Uncertainty Sources and Measurement Errors

The correct measurement of liquid precipitation (rain) 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 whole climate of the Earth. In this respect, rain gauges provide the only direct measurements of rainfall intensity at the ground and are usually referred to as the “ground truth” in rainfall monitoring. Newly developed techniques for extensive rainfall observations based on remote sensing (essentially weather radar, airborne radiometers and satellites) provide a space-time description of rainfall fields, but still require the use of rainfall measurements from rain gauges for calibration and validation purposes. Improvement of the reliability of Rain Intensity measurements as obtained by traditional Tipping-Bucket Rain Gauges (TBRG) and other types of gauges (optical, weighing, floating/siphoning, etc.) is therefore required for use in climatological and hydrological studies and operationally, e.g. in flood frequency analysis for engineering design. Standardization of high quality rainfall measurements is also required to provide a basis for the exchange and evaluation of rainfall data sets among different countries, especially in case of transboundary problems such as severe weather/flood forecasting, river management, and water quality control.

The measurement of rainfall intensity is subject to a number of uncertainties and instrumental errors. The WMO Laboratory Intercomparison focused on the inherent mechanical and/or electronic errors and uncertainties of rainfall intensity gauges. The traditional assessment of errors in precipitation gauges refers to the so-called weather related errors. It is well recognized that the measurement of liquid precipitation at the ground is affected by different sources of both systematic and random errors, mainly due to wind, wetting and evaporation induced losses (e.g. Sevruk, 1982) which make the measurement of light to moderate rainfall scarcely reliable in the absence of an accurate calibration. Wind induced errors still have an influence on rainfall intensities of the order of 20-50 mm·h^{-1} with an incidence around 5% observed in a few intercomparison stations in central Europe (Sevruk and Hamon, 1984, pp. 86). Solid precipitation measurements (snow) are even more difficult as snow is more sensitive than rain to weather related errors. Sampling errors due to the discrete nature of the rain measurement are also recognized to be dependent on the bucket size and sampling interval, though not on rain intensity, and can be analytically evaluated.

In precipitation measurements, systematic errors are commonly accounted for by means of correction models that can be generally expressed in the form:

$$P_c = k[P_g + \sum_i \Delta P_{gi}] \ ,$$

where P_c is the corrected figure, P_g is the gauge measured precipitation, $\Sigma_i \ \Delta P_{gi}$ is the sum of correction terms for various error sources, and k is the wind deformation coefficient. The detailed model, originally proposed by Sevruk (1982), was later modified by Legates and Willmott (1990) to account for both liquid and solid precipitation and can be written as:

$$P_c = k_r(P_{gr} + \Delta P_{wr} + \Delta P_{er} + \Delta P_{mr}) + k_s(P_{gs} + \Delta P_{ws} + \Delta P_{es} + \Delta P_{ms}) \ ,$$

where ΔP_w, ΔP_e and ΔP_m are the correction terms for wetting, evaporation and mechanical errors respectively, while subscripts *r* and *s* refer to liquid (rain) and solid (snow) precipitation.

The errors due to the weather conditions at the collector, as well as those related to wetting, splashing and evaporation processes, are referred to as catching errors. They indicate the ability of the instrument to collect the exact amount of water that applies from the definition of precipitation at the ground, i.e. the total water falling over the projection of the collector's area over the ground. Non-catching instruments may also show "catching" errors although they do not have any collector for rain water and the water is simply observed while falling through the sensing volume of the instrument.

Counting errors are on the other hand related to the ability of the instrument to "sense" correctly the amount of water that is collected by the instrument. They can be experienced both in catching and non-catching type of instruments, although in the latter case the assessment of such errors is very difficult, and is hard to be performed in laboratory conditions. Therefore, this Laboratory Intercomparison concentrated on the counting errors of the catching type of instruments. Obviously, these errors may derive from very different aspects of the sensing phase since the instruments may differ in the measuring principle applied, construction details, operational solutions, etc.

When dealing with rainfall intensity measurements, the most common type of rain gauge at the global scale exploits the tipping-bucket principle. Due to its wide use in operational networks, some details are provided here about the most relevant counting errors involved. It is known that the tipping-bucket rain gauge underestimate rainfall, especially at high intensities, because of the rainwater amount that is lost during the tipping movement of the bucket (see e.g. Becchi, 1970; Calder and Kidd, 1978; Marsalek, 1981; Niemczynowicz, 1986). Although this inherent shortcoming can be easily remedied by dynamic calibration, usual operational practice in hydro-meteorological services and instrument manufacturing companies rely on single-point calibration, based on the assumption that dynamic calibration has little influence on the total recorded rainfall depth (Fankhauser, 1998). The related biases are known as systematic mechanical errors and result in the overestimation of rainfall at lower intensities and underestimation at the higher rain intensities. The systematic underestimation of intense rainfall can be quantified on average as 10-15 % at rain intensities higher than 200 mm·h^{-1}. Note that such intense rainfall intensities can be commonly observed at very fine resolution in time even during precipitation events totalizing low to intermediate intensities at the event scale. In case of intense events, the extreme components of the intensity spectrum contribute significantly to the event, leading to higher average errors on the rain totals.

In the last 20 years, the traditional measurement of precipitation at the ground has experienced increased technological developments, mainly oriented to better networking and telemetering performance. One most important feature that has been continuously updated is the resolution of the measurement in time, which is now in the order of one minute or less. Since the interest of meteorologists seldom requires such enhanced resolution, a total accumulated value is usually provided over a period of 10 to 60 minutes. The measurement sampling depends however on the rain intensity and is controlled by the inherent mechanics of the rain gauge. Enhanced resolution in time involves increasing the absolute value of the average rain rate that is recorded at the smallest time steps during a given event. In other words, the probability of measuring any high intensity rainfall rate increases when the reference time interval is being reduced. Note that rainfall intensity is an indirect measure obtained from the accumulated volume (depth) of water over a given interval in time by assuming a constant flow rate over the sampling interval.

The relevant effect of this bias, which is shown to increase with rain intensity, is more evident on the derived rainfall statistics than it is with respect to the underestimation of rain totals (La Barbera *et al.*, 1998; Molini *et al.*, 2005). Assessment of the return period of rainfall extremes, both at a single site and in the framework of regionalization studies, is indeed significantly affected by systematic mechanical errors if associated underestimation is not taken into account.

Water losses that are observed during the tipping movement of the bucket can be explained as follows. Considering the tipping movement as starting at that instant in time when the bucket is completely filled in with its nominal volume of water. Initiation of the movement of the two paired compartments is subject to inertial forces and completion of the bucket tipping around its rotation axis requires a certain amount of time. During such a time window, the incoming rain intensity continues to supply water through the funnel. The amount of water received by the rotating bucket during half of its tipping movement is lost in the measurement process.

The relevance of such losses, affecting each single tipping of the bucket, increases with rainfall intensity and is a function of the total time ΔT for the bucket to complete its rotation. According to Marsalek (1981), the relationship between the measured (I_m) and actual (I_r) intensities as a function of ΔT is given by:

$$I_m / I_r = h_n /(h_n + I_r \cdot \Delta T)$$

where h_n is the nominal rainfall depth increment per one tip. Note that $I_m / I_r = 1$ only in the case of $\Delta T = 0$ and that ΔT is a function of rainfall intensity. The relationship presented by Marsalek (1981, Fig. 4) between ΔT and I_r shows significant durations of the bucket movement ranging between 0.3 and 0.6 s for the instruments analyzed. However, the uncertainty involved in the measurement of the time of tipping - due to the very slow initiation of the bucket rotation - makes the comparison of experimental and theoretical calibration curves hardly appreciable. Sophisticated measurement of ΔT allows better success in comparing the experimental calibration curve with its theoretical expression. However, direct estimation of the calibration curve is far more reliable than its theoretical derivation as it does not involve sophisticated measurements of very short intervals in time as a function of varying rain rates. A simple hydraulic apparatus can be used to this aim, which allows high precision measurements and reliable dynamic calibration of TBRG. The objective is to provide the gauge with a constant flow rate at a number of calibration points in the (I_r, I_m) space. This is achieved by connecting a constant water level tank with the gauge by interposition of a nozzle with specified diameter. By modifying the water head over the orifice and the nozzle diameter, constant flows can be generated at various flow rates as desired (see Lombardo and Stagi, 1997; Humphrey *et al.*, 1997; Lanza and Stagi, 2002). It can be also achieved by using a peristaltic pump, which allows a constant flow and can be set to different flow rates.

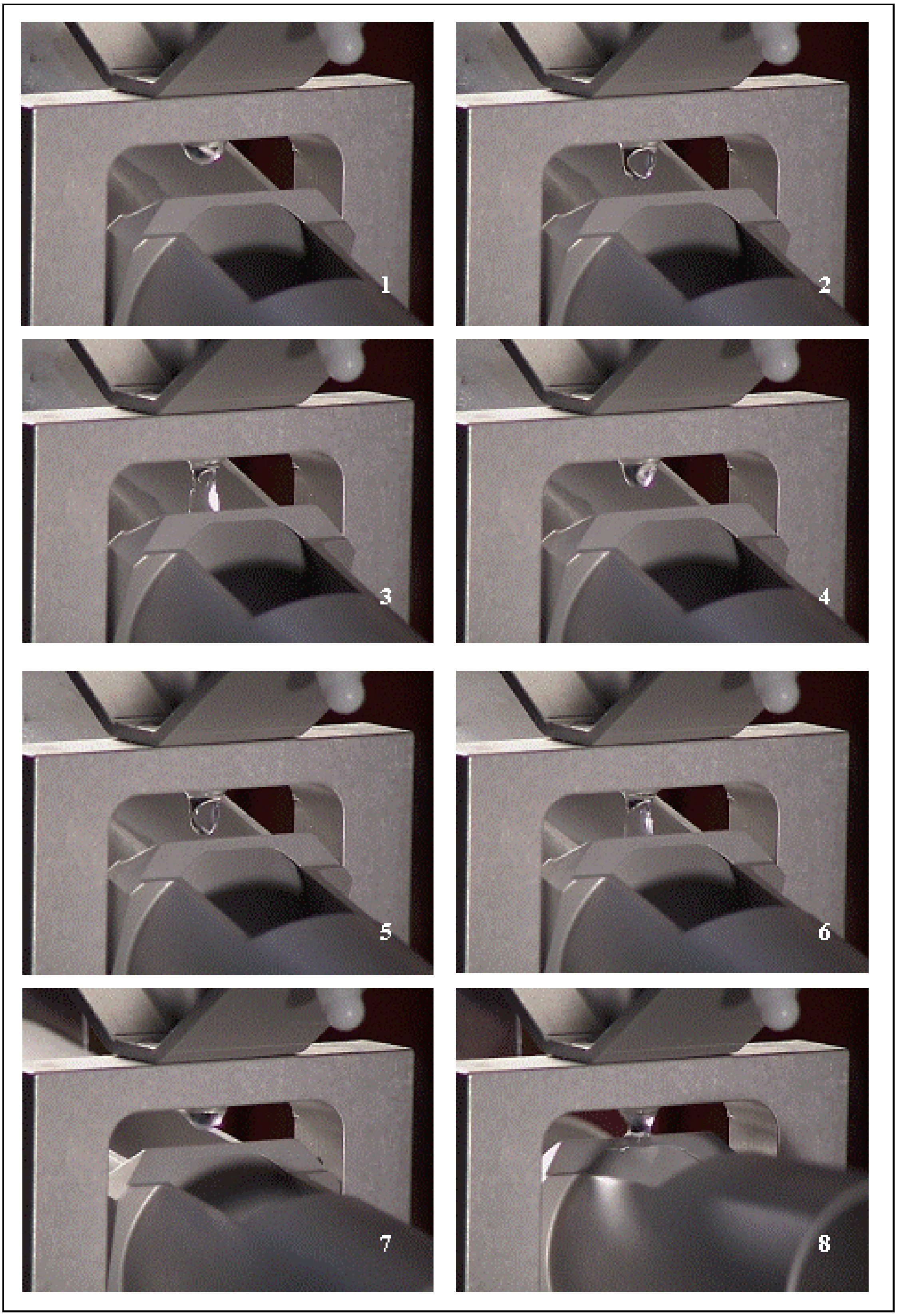

Figure 1: The inherent systematic mechanical error of tipping-bucket rain gauges, visualized in a video sequence from the initiation of the tipping movement of the bucket (top left picture 1) to the instant when water starts filling the second bucket (bottom right picture 8) at a low intensity flow. The duration of the sequence from picture 1 to picture 8 is half a tip and the water (drops) flowing during that period falls into the left bucket, which is already filled in with its nominal volume. This amount of water is lost in the measuring process.

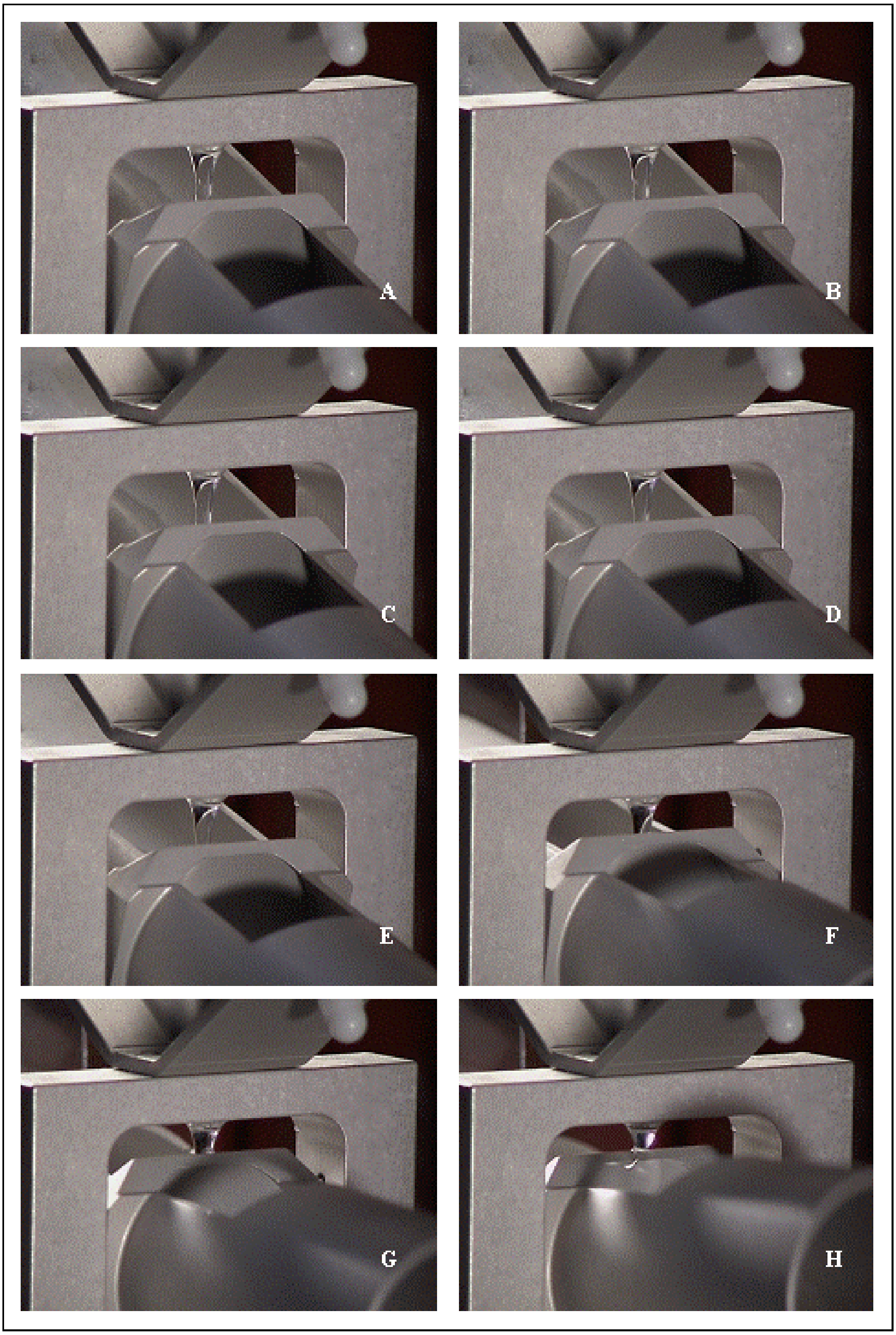

Figure 2: The inherent systematic mechanical error of tipping-bucket rain gauges, visualized in a video sequence from the initiation of the tipping movement of the bucket (top left picture) to the instant when water starts filling the second bucket (bottom right picture) at a medium intensity flow. The duration of the sequence from picture 1 to picture 8 is half a tip and the water flowing during that period falls into the left bucket, which is already filled in with its nominal volume. This amount of water is lost in the measuring process.

4. Previous related intercomparisons

Previous international intercomparisons of rain gauges were conducted comparing the accumulated amounts of precipitation:

- International Comparison of National Precipitation Gauges with a Reference Pit Gauge, (Sevruk *et al.*, 1984).
- WMO Solid Precipitation Measurement Intercomparison, (Goodison *et al.*, 1998).

The WMO intercomparison during which precipitation intensity was investigated for the first time, was on the assessment of present weather systems (PWS):

- WMO Intercomparison of Present Weather Sensors/Systems (Leroy *et al.*, 1998).

However, because of requirements on present weather observations, RI is usually reported by PWS as a qualitative parameter (light, moderate, heavy). Therefore, the intercomparison did not focus in particular on quantitative values of RI.

No intercomparisons of instruments for the measurement of RI were organized. Following the recommendations of the Expert Meeting on Rainfall Intensity Measurements, Bratislava, Slovakia, April 2001, it was considered as the first and necessary step to organize an intercomparison of such instruments in the laboratory.

Some laboratory tests of rain gauges were done and reported in the literature (Muller *et al*., 1983). However no intercomparison of a large number of instruments, in one or several laboratories, has yet been conducted.

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PART II

LABORATORY INTERCOMPARISON RESULTS AND CONCLUSIONS

1. Rationale

The WMO Laboratory Intercomparison of Rainfall Intensity (RI) Gauges was launched, simultaneously, in September 2004, in the laboratories of the Royal Netherlands Meteorological Institute, Météo-France and the Department of Environmental Engineering (University of Genoa). The 19 pairs of participating instruments from 18 manufacturers were divided into three groups, with each group being tested for a period of about three to six months in each of the laboratories, in order to obtain a high degree of confidence in the results. The first phase of tests had successfully concluded by 15 February, the second by 15 May 2005 and the third by September 2005. All the cost related to laboratory intercomparisons was born by the laboratories and the manufacturers involved. The CIMO Project Team, consisted of ET/IOC Chair, the Project Leader and Site Managers coordinated the work of laboratories related to the intercomparison.

The following paragraphs provide insight into the planning and decision making process of the intercomparison.

1.1 Background

The thirteenth session of the Commission for Instruments and Methods of Observation (CIMO-XIII), Bratislava, Slovakia, 23 September - 3 October 2002, noted with appreciation the results of the Expert Meeting on Rainfall Intensity Measurements, Bratislava, Slovakia, April 2001, which formulated “present and future requirements for rainfall intensity (RI) measurements” because no such requirements and related guidance were available. In that regard, the Commission recommended that:

(a) A standardized procedure for generating consistent and laboratory-reproducible flow rates designated for use as the laboratory standard for rainfall intensity calibration of catchment type gauges be developed. That should include calibration equipment and its proper configuration, and the expected performance as well as standard method(s) of testing, taking into account the variability of conditions including intermittence of the test facilities;

(b) Appropriate correction procedures and instrument specific factors for the application on long-term data series to maintain temporal homogeneity be developed with a special consideration to extreme values.

The Commission, recognizing the needs for further instrument comparisons and evaluation tests, agreed on the programme of WMO intercomparisons including the WMO Rainfall Intensity Intercomparison.

1.2 Expert Team and International Organizing Committee on Surface-Based Instrument Intercomparisons

Based on the mandate given by CIMO-XIII to its President and the Management Group (CIMO-MG), the membership of the Expert Team on Surface-Based Instrument Intercomparisons and Calibration Methods (ET) was determined at the first session of the CIMO-MG, Los Angeles, USA, 13-15 February 2003.

Further, according to the Procedures for WMO Global and Regional Intercomparisons of Instruments, *Guide to Meteorological Instruments and Methods of Observation, Part III, Chapter 5, Annex 5.A and 5.B*, Dr. R.P. Canterford, the Acting President of CIMO, established, in September 2003, an International Organizing Committee for Surface-Based Instrument Intercomparisons (IOC).

At the first session of the Joint ET and IOC (ET/IOC-1), Trappes, France, 24-28 November 2003, both operational and organizational aspect for the WMO Laboratory and Field Intercomparisons of Rainfall Intensity Gauges were discussed.

The ET/IOC-1 agreed on the main objectives, possible places, dates and duration of the WMO Laboratory and Field RI intercomparisons. Also operational aspects were discussed in details, namely conditions for participation, type of instruments, intercomparison rules, responsibility of host(s) and participants, data acquisition, processing analysis methodology and publication results. See CIMO/IMOP website for details: http://www.wmo.int/web/www/IMOP/reports.html

1.3 Laboratory vs. Field Intercomparison

The CIMO-XIII noted that, as a result of an Expert Meeting held in Bratislava, Slovakia, in 2001, significant efforts had been made to initiate an International Rainfall Intensity Measurement Intercomparison. It was agreed that, as the first step in obtaining the required information, intercomparison of suitable types of rain gauges should be carried out in at least two independent recognized laboratories, with the aim of determining performance characteristics and, depending on the results, to consider both organizing a field test and the development of a secondary standard suitable for field tests. Depending on those results, field tests under the required climatological conditions might be undertaken.

While laboratory tests were performed under the controlled environment, the field intercomparisons should be preferably conducted in an area where there is a high probability of high intensity rainfall events.

Only in situ catchment types of instruments were considered for the laboratory intercomparisons, while both the catchment and non-catchment types would be allowed to participate in the field intercomparison.

The ET/IOC-1 requested the WMO Secretariat to initiate actions to start the WMO Laboratory intercomparisons of RI Gauges in September 2004. The field intercomparison should preferably start as soon as the laboratory intercomparisons are concluded.

1.4 Selection of Laboratories, Instruments and Management Team

Based on the proposals from Members, the ET/IOC-1 suggested that Laboratory Intercomparisons of RI gauges should be held in recognized laboratories of the Royal Netherlands Meteorological Institute (KNMI), De Bilt, the Netherlands, Météo France, Trappes, France and University of Genova, Genova, Italy (in collaboration with the NMS of Italy). An overview of the laboratories is given in Annex I.

ET/IOC-1 decided that only catchment type of instruments that were currently being used in national networks or were being considered for use in national networks and were capable of measuring rainfall intensity of at least 200 $mm \cdot h^{-1}$ at a time resolution of 1 minute would be accepted for participation.

The ET/IOC-1 agreed on the procedures for selection of the participating instruments. It defined two questionnaires (Annex II and III), the first one aimed at receiving proposals on potential participants from WMO Members and the second one seeking more detailed information on selecting instruments.

The ET/IOC-1 also agreed on the Management Team for the WMO Laboratory Intercomparison of RI Gauges, comprising:

- Mr Michel Leroy, the ET/IOC chairman;
- Professor Luca Lanza, the Project Leader;
- Mr Luigi Stagi, Site Manager, University of Genova, Italy;
- Mr Christophe Alexandropoulos, Site Manager, Météo France, France;
- Mr Alexander Mazee, Site Manager, KNMI, Netherlands, who retired in 2005 and was replaced by Mr Wiel Wauben.

Nineteen (19) instruments, out of twenty-eight (28), were selected for the WMO Laboratory Intercomparison of RI Gauges in a way to represent individual model types and regions according to the Procedures for Intercomparisons agreed by the ET/IOC-1. Based on the mandate, the ET/IOC chairman approved the list of the selected instruments. (See Part II, Section 13, Participating Instruments).

1.5 Objectives of the Laboratory Intercomparison

The main objective of the WMO Laboratory Intercomparison of RI Gauges was to test the performance of catchment type rainfall intensity gauges of different measuring principles under documented conditions.

ET/IOC-1 agreed on further objectives as follows:

(a) To define a standardized procedure for laboratory calibration of catchment type rain gauges, including uncertainty of laboratory testing devices within the range from 2 to 2000 $mm \cdot h^{-1}$.

(b) To evaluate the performance of the instruments under test.

(c) To comment on the need to proceed with a field intercomparison of catchment type of rainfall intensity gauges.

(d) To identify and recommend the most suitable method and equipment for reference purposes within the field intercomparison of catching and non-catching types of gauges.

(e) To provide information on different measurement systems relevant to improving the homogeneity of rainfall time series with special consideration given to high rainfall intensities.

(f) To make available the executive summary of the intercomparison within three months after the end of the testing period and to publish the Final Report of the intercomparison within the WMO IOM Report Series within 9 months after the testing is finished;

(g) To draft recommendations for consideration by CIMO-XIV.

2. Applied Methods

2.1 Methodology

A general methodology (see Fig. 1) was adopted based on the generation of a constant water flow from a suitable hydraulic device within the range of operational use declared by the instrument's manufacturer. The water is conveyed to the funnel of the instrument under test in order to simulate constant rainwater intensity. The flow is measured by weighing the water over a given period of time. The output of the instrument under test is measured at regular periods of time or when a pulse occurs. The two measurements are compared in order to assess the difference between the actual flow of water conveyed through the instrument and the "rain intensity" measured by the instrument itself. The relative difference between each measured and actual "rain intensity" figure is assumed as the relative error of the instrument for the given reference flow rate.

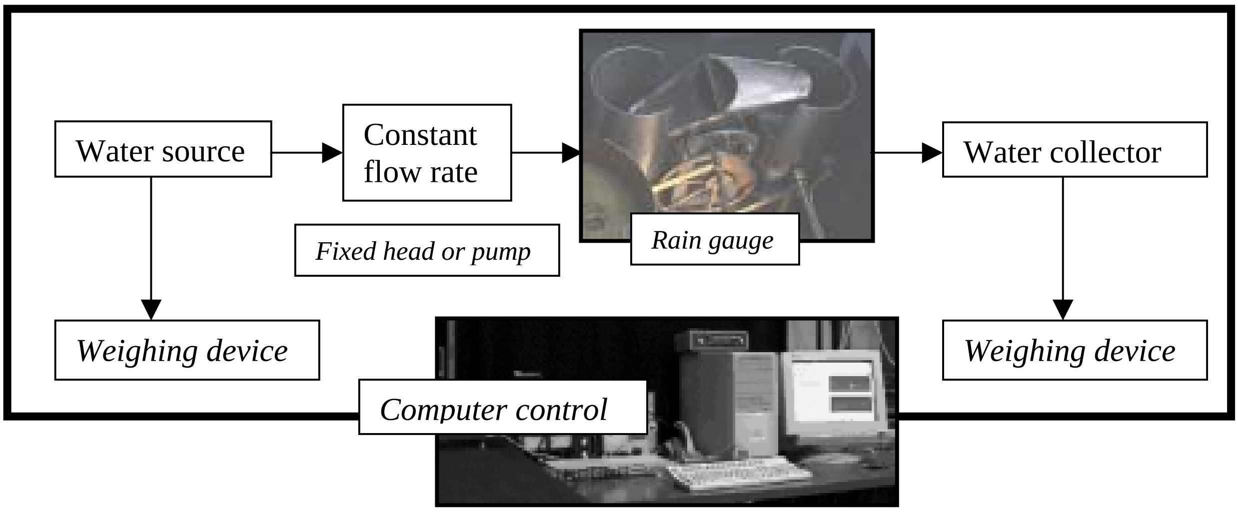


Figure 1: General methodology of the laboratory intercomparison.

2.2 Data Protocol

It was decided at the initial joint ET/IOC-1 to establish common procedures for data analysis and processing, as well as for the presentation of results and the sharing of the information among the laboratories involved.

2.3 Number of intercomparison tests and duration

The instruments were tested in each laboratory during a period of about 3 months and then the instruments were rotated from one laboratory to another, for a new period of 3 months and so forth until all instruments were tested in all laboratories.

For each of the instruments involved in the intercomparison, each laboratory performed five tests. The number of tests performed for each of the instruments, their description and duration (in terms of time units and/or number of tips, etc.) were noted and reported.

2.4 Environmental conditions during intercomparison

For each test the following parameters were noted and recorded:

- Date and hour (start/end);
- Air temperature [°C];
- Water temperature [°C];
- Atmospheric pressure [hPa];
- Ambient relative humidity [%];
- any special condition that may be relevant for the single test.

2.5 Intercomparison procedures

2.5.1 All gauges

The duration of the test and the mass measurement were controlling factors for determining the uncertainty of the test. Therefore, mass and duration used for each test were chosen so that the uncertainty of the reference intensity was less than 1% (see Annexes IV, V, VI), taking also into account the resolution of the instrument. These masses and durations were noted and reported, together with the number of tips involved in each test.

Each test was performed at least at seven reference flow rates. However, since the higher rainfall intensities are of utmost importance for the intercomparison, the whole range of operation declared by the manufacturer was also investigated. In particular:

- Seven reference intensities were fixed at 2, 20, 50, 90, 130, 170, 200 $mm \cdot h^{-1}$;
- If the maximum declared intensity was less or equal to 500 $mm \cdot h^{-1}$, further reference intensities were determined at 300 and 500 $mm \cdot h^{-1}$.
- Otherwise, three further reference intensities were determined within the remaining range of operation of the instruments by dividing it logarithmically from 200 $mm \cdot h^{-1}$ up to the maximum declared intensity.

Since some of the instruments could show serious problems at the higher intensities (or due to any specific reason) the Site Managers had the possibility to increase the number of testing points at their own judgment.

In case water storage should occur for an intensity below the maximum declared intensity, the intensity at which water storage begins was reported and intensities above this limit were not been taken into account.

The reference intensities were obtained within the following limits:

- 1.5 – 4 $mm \cdot h^{-1}$ at 2 $mm \cdot h^{-1}$
- 15 – 25 $mm \cdot h^{-1}$ at 20 $mm \cdot h^{-1}$,

and within a limit of ± 10 % at higher intensities.

2.5.2 Weighing gauges

In addition to measurements based on constant flow rates, the step response of each instrument was checked based on the devices developed by each laboratory.

The step response of the weighing gauges were measured by switching between two different constant flows, namely from 0 $mm \cdot h^{-1}$ to 200 $mm \cdot h^{-1}$ and back to 0 $mm \cdot h^{-1}$. The constant flow was applied until the output signal of the weighing rain gauge was stabilized. The sampling rate was at least one per minute or higher for those instruments that allowed it.

Precautions were taken to minimize the effects of vibrations.

2.5.3 Level measurement gauges

In addition to measurements based on constant flow rates, the step response of each instrument was tested based on the devices developed by each laboratory.

Attention was paid to assess the effects of water conductivity and the siphoning process in cases of large rainfall intensities.

2.6 Further remarks

For each relocation of the instruments from one laboratory to another, the delivering laboratory provided a summary of problems encountered with the instruments transported to the next laboratory, including information on how they were solved. This enabled a better sharing of the knowledge.

3. The testing devices

Each laboratory developed its own testing device, with some differences in the principle and technology used to generate a constant water flow, as well as in the way the water is weighed in the device. These provided a basis for the development of a standardized procedure for generating consistent and repeatable precipitation flow rates for possible adoption as a laboratory standard for calibration of catchment type rainfall intensity gauges.

Below is a description of the testing devices used in the laboratories.

3.1 The Laboratory of Météo-France, Trappes (France)

The Météo-France laboratory uses a bench (see Figure 2) composed of an electronic balance and a peristaltic pump, both connected to a standard PC with dedicated software. A water container is weighed. Water is injected through a tube into the buckets by a peristaltic pump. This pump is also controlled by the PC, both for its flow rate, start and stop. This bench allows the generation of intensity from 3 $mm \cdot h^{-1}$ up to 2000 $mm \cdot h^{-1}$ intensity range.

The range may be adjusted by the selection of different tubes. The tip detector (such as a contact closure) for tipping buckets is connected to a junction signal of a RS232 line of the PC. The measure of mass for weighing gauges or the conductivity converted in rain accumulation for other rain gauges are available also on a serial line. The dedicated software controls the pump, sets a given intensity, counts a selected number of tips (or records mass or conductivity) and gets the mass variation of the water container. It outputs the rain gauge measured precipitation quantity, compared to the decrease in mass on the balance, and calculates the difference expressed in percentage. The uncertainty associated with the calibration bench is about 1%. It depends on the duration of the test and the amount of water used.

A succession of tests at various intensities can be programmed, leading to an automatic establishment of an intensity error curve.

Figure 2: The calibration bench at the Météo France laboratory in Trappes.

3.2 The Laboratory of the University of Genoa (DIAM), Genoa (Italy)

The University of Genoa, the Department of Environmental Engineering (laboratory DIAM) uses an automatic device that was designed to satisfy the requirements of the Intercomparison and is illustrated in Figure 3. The device, named “Qualification Module for RI Measurement Instruments” (QM-RIM), is based on the principle of generating controlled water flows at a constant rate from the bottom orifice of a container where the water levels is varied using a cylindrical bellow. The water level and the orifice diameter are controlled by software in order to generate the desired flow rate. This is compared with the measure that is obtained by the RI measurement instrument under consideration so that dynamic calibration is possible over the full range of rain rates usually addressed by operational rain gauges.

The QM-RIM calibration procedure is based on the capability of the system to produce a constant water flow. This flow is provided to the RI gauge under test and the duration and the total weight of water that flows through the instrument are automatically recorded by the acquisition system. The weight measurement is determined using a precision balance shown in Figure 3. During the test the ensemble precision balance/weighing tank is protected by a plastic structure which also supports the RI gauges under calibration.

Figure 3: Present configuration of the QM-RIM with (right) and without (left) a RI gauge under test. The inner rectangle also shows a close view of the precision balance, while on the right hand side the plastic support for gauges can be seen.

The total water weight and the duration of the test determine the value of the generated rainfall intensity (reference intensity Ir). Accordingly, the efficiency of the QM-RIM in calibrating RI measurement instruments strictly depends on its capabilities in generating different constant flow rates. A constant flow rate is a basic requirement for an accurate estimation of the reference intensity Ir. The flow rate Q is simply provided by the classic equation:

$$Q = \xi \cdot \Omega \sqrt{2gH} \quad ,$$

where *g* is gravitation constant and ξ is a suitable coefficient.

Based on such equation and assuming ξ as constant, different steady flow rates can be generated by simply varying the water head *H* and the section area of the orifice Ω.

In the QM-RIM the water head *H* is varied using a cylindrical bellows (see Figure 4). The expansion of the bellows is controlled by a motor with encoder while the water flow is maintained by a submerged pump. The diameter of the bottom orifice is otherwise regulated by a set of three electro valves equipped with different nozzles (see Figure 4). The water level and the orifice diameter are software controlled in order to generate the desired flow rates.

Moreover, since only variations of the water head *H* can produce variations of Q, the system has been developed to rapidly compensate *ΔH* by means of an overflow control mechanism. The spilling mechanism at the top of the bellows allows compensation of both the possible decrease and increase of the water level. This particular feature of the QM-RIM is particularly relevant when the uncertainty for the constant flow generation apparatus is calculated.

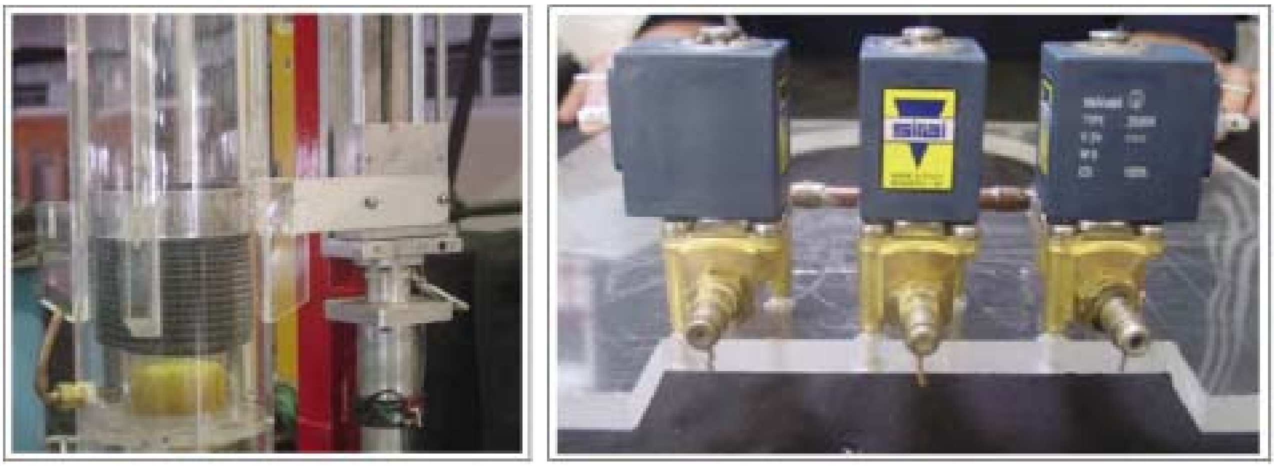


Figure 4: Close view of the cylindrical bellows which allows varying the water level in order to produce different water heads. The top of the bellows is connected to a motor with encoder controlled software. On the right hand side there are three electrovalves that allow to combine different nozzles diameters in order to produce a wide range of water flow rates.

3.3 The Laboratory of the Royal Netherlands Meteorological Institute (KNMI), De Bilt (The Netherlands)

The test setup at KNMI consisted of two electronic scales and 2 peristaltic pumps connected to a PC. The pumps are used to generate a constant flow of water that is pumped from a reservoir into the instrument under test. The reservoir is located on a scale so that the reference intensity can be determined from the decrease of the weight of the reservoir over time. One pump is used for the low intensities whereas the other is used for the moderate and high intensities. Tuning the speed of the pump and the diameter of the tubes control the flow rate. Of the 2 scales generally only one is used for test practices since water is only pumped from one reservoir. The second reservoir/scale is used to determine the rate of evaporation. However, at high intensities both reservoirs/scales are used in order to be able to generate a constant flow during the required period. The PC is not only used to collect the measured weights of the reservoirs and to control the pumps (setting of their speed, start and stop), but also to acquire the readings of the instrument under test. Instruments having a serial output are directly connected to the PC whereas the other instruments are connected to a data-acquisition and interface unit that is connected to the PC. Instruments with an analog signal like a voltage, current or a pulse output are connected to the corresponding input of the data-acquisition unit, but the signal of a raw reed contact first goes through a so-called monostep in order to convert it to a well behaved pulse.

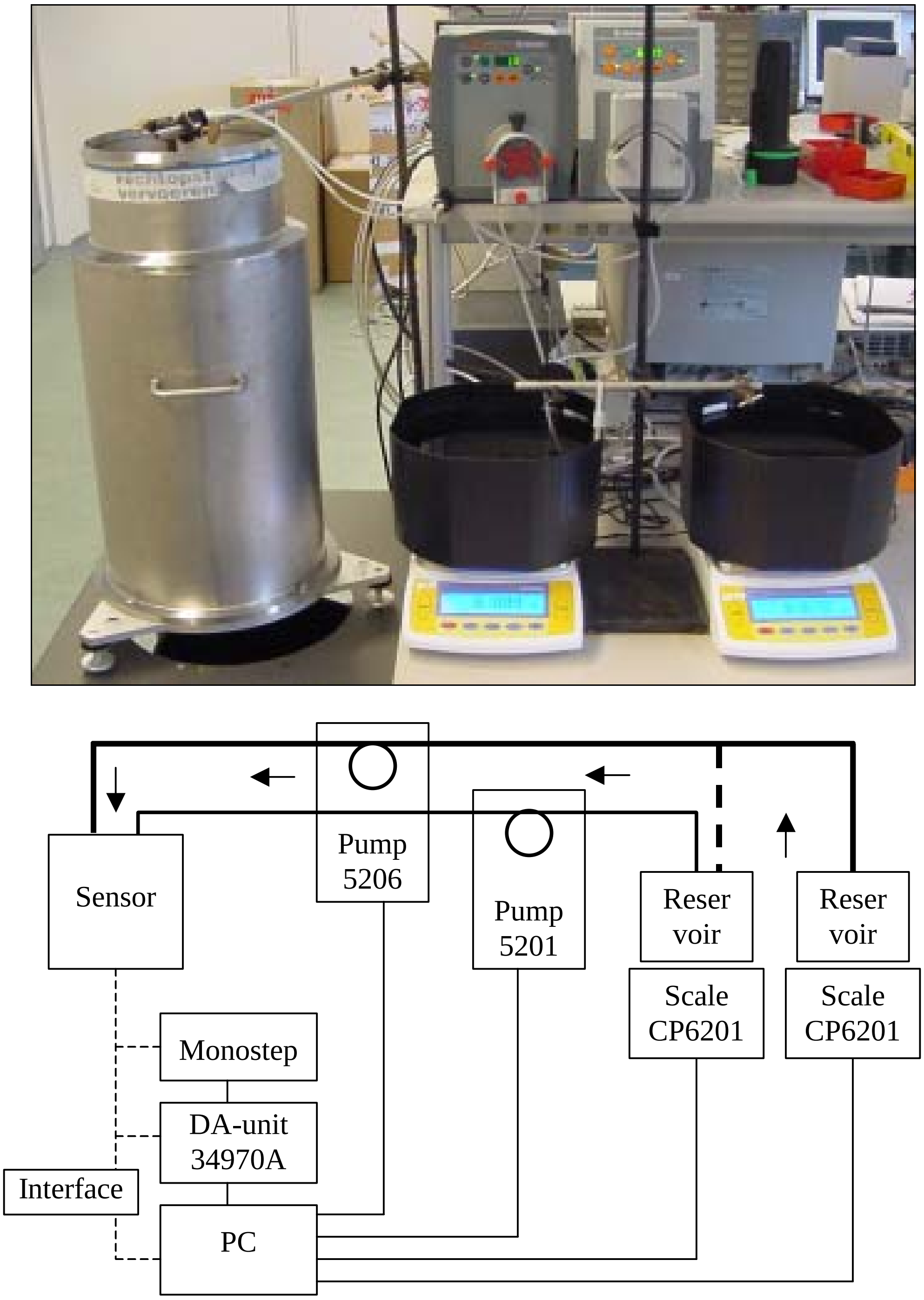


Figure 5: Sketch of the KNMI calibration setup used for the WMO laboratory intercomparison of rainfall intensity gauges and a photograph of the setup with the KNMI precipitation gauge.

The software application on the acquisition PC controls the tests. At start-up the application initializes the connections and requests the serial number of the rain gauge and the environmental parameters. Next, the application goes through a cycle of measurements as specified in a control file. Each line specifies the pump, tube, flow rate and duration of each test for a specific intensity. The application automatically performs the individual intensity tests, i.e. one intensity after another. If desired a flow rate of 0 can be used to introduce a waiting period during which no precipitation is given to the instrument. The application waits for an acknowledgement of the operator when the tube changes, because after a change manual activation of the pump must be carried out in order to fill the tube. Such stops can also be used to refill the reservoir. Once a new intensity level has been set the application restarts the pump with the desired flow rate and after a short delay performs a measurement of the scales and instrument or data acquisition unit every 5 seconds. The scales, data acquisition unit and instruments are generally polled, but some sensors cannot be polled but give a data telegram automatically. In that case the application checks regularly for the receipt of a new data telegram and at the 5-second interval the last received telegram is stored. During the test of the first batch of instruments at KNMI, a sampling rate of 10 seconds was used, but for better sampling an interval of 5 seconds was chosen afterwards. When the intensity test has been completed for a specified duration, the pump is stopped by the PC application. This TestPoint application reads the next line of the control file and starts either the next intensity run or, in case of end-of-file, asks the user for the environmental parameters and stops the test.

The environmental parameters, the parameters for each intensity run and the 5-seond readings of the scales and instrument are stored in a file during the test. The raw data from of the instrument is generally stored. Analysis of the results is performed off-line in predefined standard Excel spreadsheets as agreed within the ET/IOC-1.

4. Uncertainty of reference intensity

Accurate metrological validation is a crucial issue in testing the performance of any calibration apparatus. Reliability of calibration is in fact strictly connected with the capability in controlling and managing inherent calibration uncertainties. In this section the explanation is provided on the metrological validation of the devices for generation of constant flow rates developed at the Laboratories involved in the Intercomparison. The objective of such activity is the assessment of the uncertainty of the reference flow rate used to investigate the performance of the various rain gauges. The effectiveness of laboratory calibration is based on the inherent uncertainties of the calibration apparatus that, as stated above, must assure a relative uncertainty better than 1%.

The automatic devices were designed for the calibration of rain intensity measurement instruments by means of a simple reproducible laboratory procedure and are able to provide calibration curves for different types of rain gauges. All the proposed standard procedures refer to the typologies of systematic and random errors as defined in the ISO Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, Switzerland, 1993).

The uncertainty of the result of a measurement generally consists of several components which may be grouped in two categories according to the method used to estimate their numerical values of:

- Those which are evaluated by statistical methods,
- Those which are evaluated by other means.

Metrological analysis is performed in terms of “a priori” uncertainty estimation and the proposed procedure only refers to the Type B class of uncertainties.

Moreover, in the metrological validation the “maximum error principle” is here adopted. The interest is not put on a precise estimation of the uncertainty of the system but on the assessment of the maximum uncertainty, which can be attributed to the calibration procedure.

Type B evaluation of the standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include:

- Previous measurement data,
- Experience with, or general knowledge of, the behavior and property of materials/instruments,
- Manufacturer’s specifications,
- Data provided on calibration and other reports, and
- Uncertainties assigned to reference data taken from handbooks.

The error assessment procedure and the uncertainty budget performed on the calibration apparatus at the three laboratories are presented in Annex IV, V and VI.

5. Description of the database

All data collected by the WMO Project Team during the intercomparison were entered into a comparison database. Validation of the data was made according to the quality control procedure outlined below. After validation no changes were allowed in the comparison database.

The database containing the results of the intercomparison is publicly available and is structured in such a way to allow easy access to the information about instruments characteristics and numerical results of all tests described in section 2 above.

The database is composed of a series of spreadsheets files, one for each of the instruments involved in the intercomparison, containing the tests performed in all three laboratories. Each file also includes the graphs described in section 4-9 below and used for the presentation of the results.

The data contained depends on the type of measuring principle employed. Indeed, in case of tipping-bucket rain gauges the database contains the results of the five tests undertaken for each reference intensity, as well as the calculation of the relative errors and the average assumed as the final error figure. In the case of weighing gauges the database also contains the step response tests undertaken to obtain a measure of the delay in sensing the rainfall signal.

All environmental data recorded during each test were also reported in the database.

6. Quality control

A procedure for quality control was set up prior to the intercomparison. The first meeting of the ET/IOC-1, Trappes, 2003, agreed on the suitable ancillary tests and documentation on environmental information.

Each laboratory recorded raw data and ancillary information in its own database, according to the procedure adopted. Periodic meetings of the laboratories were been held at the end of every stage of the intercomparison (Genoa, Italy, 17 January 2005; Bucharest, Romania, 5 May 2005, De Bilt; The Netherlands, 13 September 2005), when the instruments were moved from one laboratory to the other.

At each meeting, an accurate verification and revision of the procedures were adopted, the tests performed, and the preliminary results obtained were discussed by the Site Managers, the Project Leader and the ET chair. In particular, error figures much larger or much lower than expected were discussed, as well as the reason for the observed differences in the results obtained on the same instrument by the different laboratories.

The collection and collation of raw data from all tests performed during the intercomparison was accomplished after the last meeting in De Bilt, and all data were organized into the database. During this phase all three laboratories had the opportunity to check out their own results as included in the database and to compare them once again with those from other laboratories. Errors and/or inconsistencies were corrected and a commonly agreed database was produced.

A verification of the final results was undertaken by the ET/IOC-2 during the meeting in Geneva on 5-9 December 2005, where the final version of the database and Final Report were agreed on.

7. Data policy

The following is the guidance principles for data policy of the intercomparison:

- The WMO has the copyright on the comparison database.
- After the Intercomparison, every participant could get a copy of the comparison database, containing any further raw data obtained during the tests, related to its own instruments.
- The complete comparison database is kept by WMO Secretariat, the ET/IOC chair, the Project Leader and Site Managers. WMO may, if requested by the IOC, export whole or part of the comparison database on to the CIMO/IMOP website. In particular, the data sheets

prepared for each of the instrument involved can be published on the Web site as soon as the Final Report is published.

- The WMO authorizes the Project Leader, with the agreement of the ET/IOC chair, to publish full results of the intercomparison on behalf of the IOC.
- The comparison database may be provided to other parties for the purpose of scientific studies on the subject. This requires an approval of the ET/IOC chair, and is possible only after the full results of the intercomparison have been published.
- For the publication and for the third parties, the participants are only allowed to use their own data. In doing so, they will avoid qualitative assessment of their instruments in comparison with other participating instruments.

8. Participating Instruments

Due to limited resources, the number of participating instruments was initially limited to a maximum of twelve pairs of gauges. However, given the higher demand and based on the proposal of the Project Leader, the ET/IOC-1 selected nineteen instruments, based on the following criteria:

a) Instruments are to be selected in a way to cover a variety of measurement techniques;

b) Preference should be given to new promising measuring techniques;

c) Preference should be given to instruments that are widely in use in Member countries.

The list of selected instruments is in Table 1.

Therefore, three laboratories involved in the WMO Laboratory Intercomparison of RI Gauges tested the performance of 19 rain gauges, with usually 2 instruments of the same type. All instruments were tested in each laboratory.

MANUFACTURER (PROPOSED BY)	MODEL TYPE	PRINCIPLE	Number of instruments
MC VAN Instruments (Australia)	RIMCO 7499	Tipping Bucket	2
Hydrological Services (Australia/HMEI)	TB-3	Tipping Bucket	2
PAAR (Austria)	AP23	Tipping Bucket	1
AXYS Environmental Systems (Canada)	ALLUVION 100	Water Level	2
METEOSERVIS (Czech Republic)	MR3H	Tipping Bucket	2
METEOSERVIS (Czech Republic)	MRW500	Weighing	2
VAISALA (Finland)	VRG101	Weighing	2
SEROSI (France)	SEROSI	Water Level	2
Germany, OTT HYDROMETRY	Pluvio	Weighing	2
India Meteorological Dept. (India)	TBRG	Tipping Bucket	2
CAE (Italy)	PMB2	Tipping Bucket	2
ETG (Italy)	R102	Tipping Bucket	2
SIAP (Italy)	UM7525	Tipping Bucket	2
YOKOGAWA DENSHI KIKI (HMEI)	WMB01	Tipping Bucket	2
GEONOR (Norway/HMEI)	T-200B	Weighing	2
MPS SYSTEM (Slovakia)	TRWS	Weighing	2
LAMBRECHT (Switzerland)	1518 H3	Tipping Bucket	2
CASELLA (United Kingdom/HMEI)	100000E	Tipping Bucket	2
WATERLOG (USA/HMEI)	H340 – SDI	Tipping Bucket	1

Table 1: The participating instruments, listed by country and measuring principle.

8.1 Description of the instruments

The majority (12) of the participating instruments were tipping-bucket gauges which are the most widely used in operational networks.

Another group of instruments are weighing gauges, represented by five models.

Two participating instruments measure water level by conductivity.

A short description of the rain intensity gauges submitted for testing is provided in the following sections for each of the measuring principles involved. References to any special solution adopted by the various manufacturers in order to improve the performance of their instrument were included. The main technical specifications and features are reported in the forms included in the Data Sheets.

8.2 Tipping-Bucket Rain Gauges

Twelve (12) tipping-bucket rain gauges participated in the intercomparison:

1. Five (5) apply some post-processing correction to account for systematic mechanical errors;
2. Three (3) includes mechanical solutions to reduce the occurrence of systematic mechanical errors;
3. Four (4) do not take systematic mechanical errors into account.

The various gauges mainly differ from each other in the construction of the buckets and the tipping mechanism. Resolution is the volume of water required to initiate the tipping movement of the bucket and ranges from the equivalent of 0.1 to 1 mm for the instruments tested, with the distribution indicated in Figure 6.

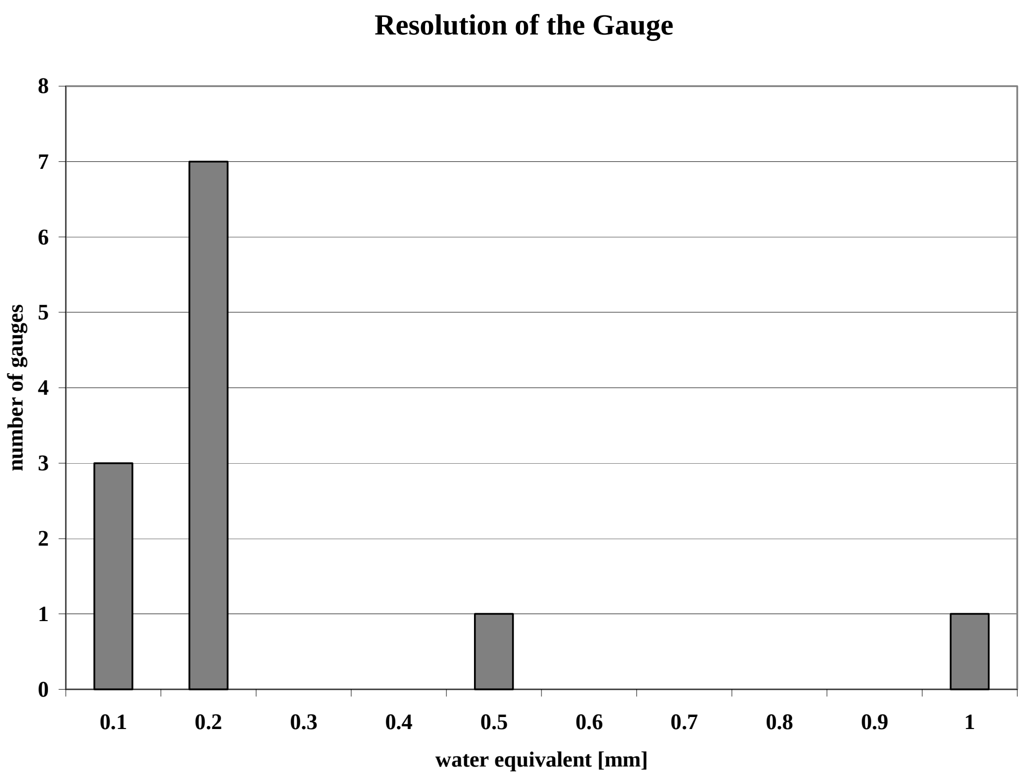


Figure 6: Distribution of tipping bucket rain gauge resolution

The distribution of different collecting areas for tipping bucket gauges is shown in Figure 7.

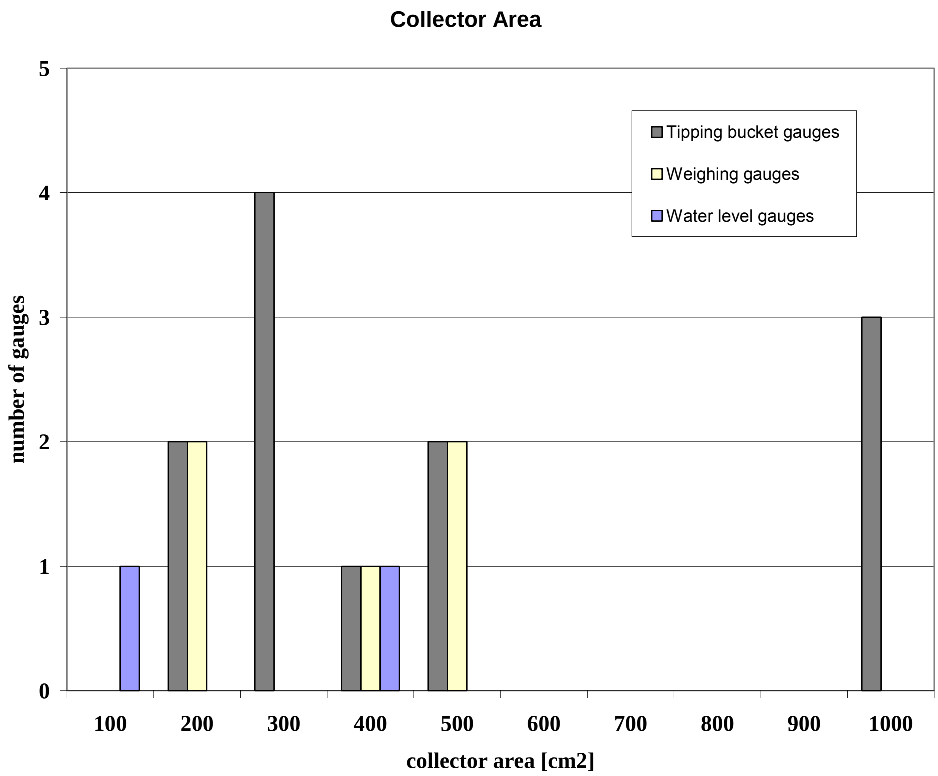


Figure 7: Distribution of the collector area for all the involved rain gauges

Internal corrections used to account for systematic mechanical errors by the instrument itself are done in two ways: (1) mathematical equation to adjust the measured value, and (2) additional artificial tip added whenever there is a total error equivalent to the resolution of a bucket.

8.3 Weighing Gauges

For all gauges in this group, the measurement of rainfall intensity is based on the capability of the instrument to continuously weigh the water collection tank. The increase in weight is interpreted as a growing volume with time, and the rainfall intensity is therefore derived over a given sampling interval. Water losses, e.g. due to evaporation, are taken into account.

Calibration or adjustment of the gauge is usually performed by inserting predetermined weights inside the tank, which are interpreted as a total rainfall accumulation. In addition, some weighing gauges use internal software to minimize noise which may introduce a delay of the response to an increase of the mass.

8.4 Water Level Gauges

Two (2) further instruments use the principle of water level measurements based on conductivity. Once the water reaches a given threshold level in the tank, this is automatically emptied in a very short period so as not to loose continuity in the recording of the current rain intensity. A siphoning mechanism is used to this aim.

8.5 Resolution

All catching types of instruments have a finite resolution which is expressed in mm. The resolution of RI ($mm{\cdot}h^{-1}$) is equal to the resolution of the instrument multiplied by 60. For example, if the instrument resolution is 0.1 mm the resolution of RI is 6 $mm{\cdot}h^{-1}$ for a one minute interval.

9. Results

9.1 Presentation of the results

The results are presented in the form of two graphs, which are derived as follows:

1) First graph:

- The error is evaluated for each reference flow rate as:

$$e = \frac{I_m - I_r}{I_r} \cdot 100 \ \% ,$$

where I_m is the intensity measured by the instrument and I_r the actual reference intensity provided to the instrument;

- Five tests were performed for each set of reference intensities, so that five error figures are associated with each instrument;

  The average error and the average values of I_r and I_m are obtained by discarding the minimum and the maximum value of *e* obtained for each reference flow rate, then evaluating the arithmetic mean of the three remaining errors and reference intensity values.

  On the same graph, the average error curve obtained at each of the three laboratories is plotted.

- For each reference intensity of each laboratory, an error bar encompassing all the five error values used to obtain the average figures is reported.

2) Second graph:

- For each laboratory, I_r versus I_m is plotted, with linear scales for X and Y axis;
- I_m and I_r are average values, calculated as indicated above;
- All data are fitted with a power law trend line:

$$I_m = a \cdot I_r^b ,$$

where a, b are constants.

The errors derived for each of the instruments in the intercomparison are discussed here, along with the related calibration curves. Data from these curves are showed in Annex VII and discussed below in this section.

9.2 Data correction algorithms

The rain gauges were analyzed considering the actual uncertainty in the measurement and calibration of the instrument. No corrections were applied to the data so as not to influence the performance of the gauges.

9.3 Tipping-Bucket Rain Gauges

The results obtained for the tipping-bucket rain gauges cannot be considered as a comparable set for all twelve instruments. Large differences in the uncertainty of the measurement are encountered depending on whether the instrument correction procedure is internally applied based on the dynamic calibration. Residual errors after using the correction can be ten times smaller than the original figures, at least at the highest rain intensities.

The gauges were classified into two groups based on applying the dynamic calibration. Results are for instruments with and without corrections are discussed separately.

9.3.1 Tipping bucket gauges without corrections

The majority of the tipping-bucket rain gauges analyzed (seven out of twelve) do not apply any correction based on dynamic calibration. Single point calibration is applied in some cases at a single rain intensity around 30-50 mmh^{-1}. This is used to obtain a relative error very close to zero at a given rainfall intensity that is of practical interest for operational purposes. Outside of this range the errors are not generally within the limits of ± 5 % defined by WMO for the required uncertainty of rainfall intensity measurements.

The most relevant characteristic of this group of instruments is the large errors associated with the highest rain rates (rising up to 15-20 % at intensities of around 300 mm·h^{-1}). The relative error increases with rainfall intensity and is well fitted by a second order polynomial.

In Figure 8 the overall response curves are presented for all instruments with no correction applied and derived by averaging the measured data obtained at all three laboratories for the two identical instruments when applicable. Each curve is therefore representative for the observed behavior of one particular instrument. Clearly, significant deviations from the reference value can be expected at high intensities for most of these instruments.

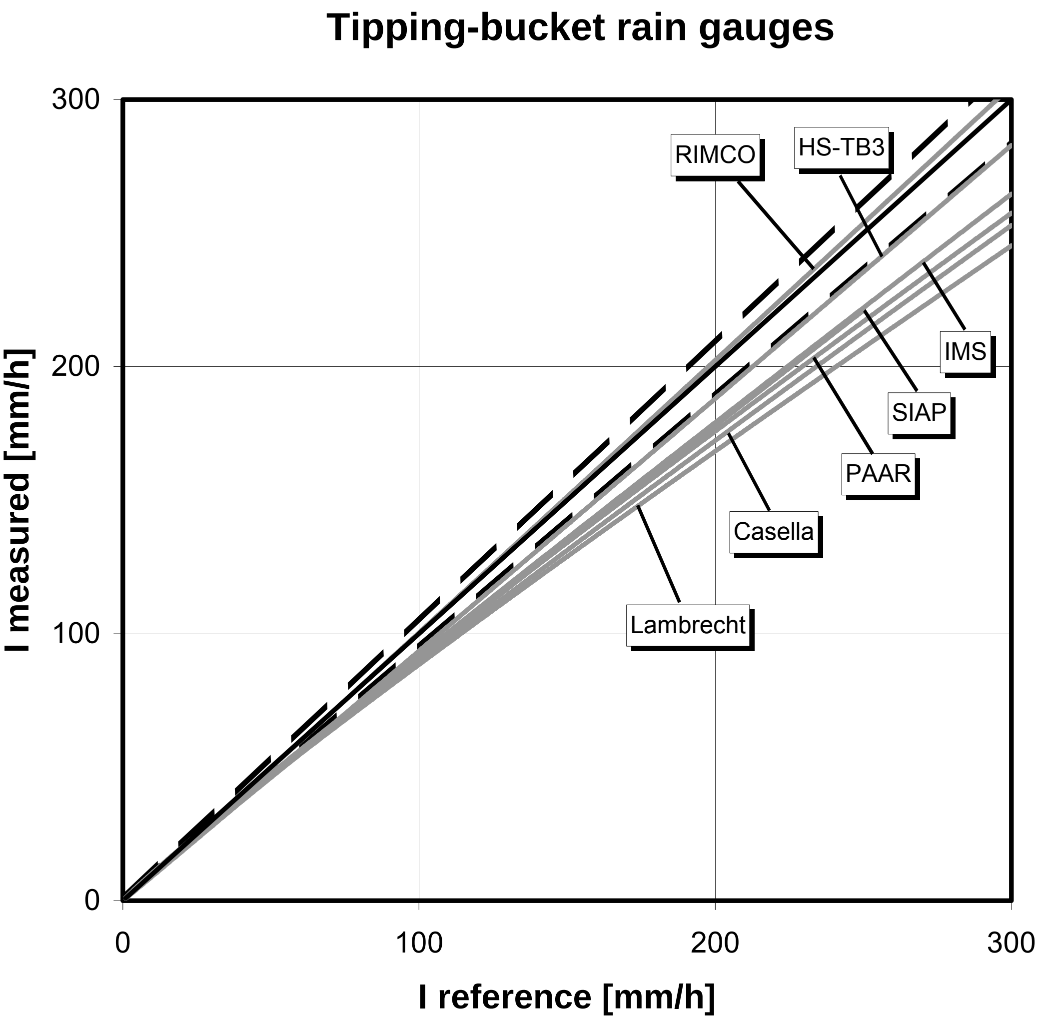


Figure 8: Ensemble of response curves for the non-corrected TBRG (dashed lines indicate ±5%).

It should be noted that some of the rain gauges analyzed can apply corrections via a post-processing software that was not submitted to the Intercomparison, or just provide a correction curve in the form of a graph or table, its application being left to the user.

9.3.2 Tipping bucket gauges with corrections

The second group of tipping-bucket rain gauges contains those instruments (five out of twelve) that apply some correction, which tends to reduce the relative error over the whole range of measurement of the instrument.

These instruments have lower relative errors but a larger variability in the resulting error curve, which depends on the type of correction applied and its effectiveness in improving the rain measurement performance. The correction proposed by the manufacturer and implemented was able to reduce the errors in most cases so as to fall within the limits ± 5% defined by WMO for the required uncertainty of rainfall intensity measurements.

In Figure 9 the overall calibration curves are presented for all instruments with dynamic calibration applied, each of them being derived by averaging the experimental data obtained at all three laboratories. Each curve is therefore representative of the expected behavior of one particular instrument.

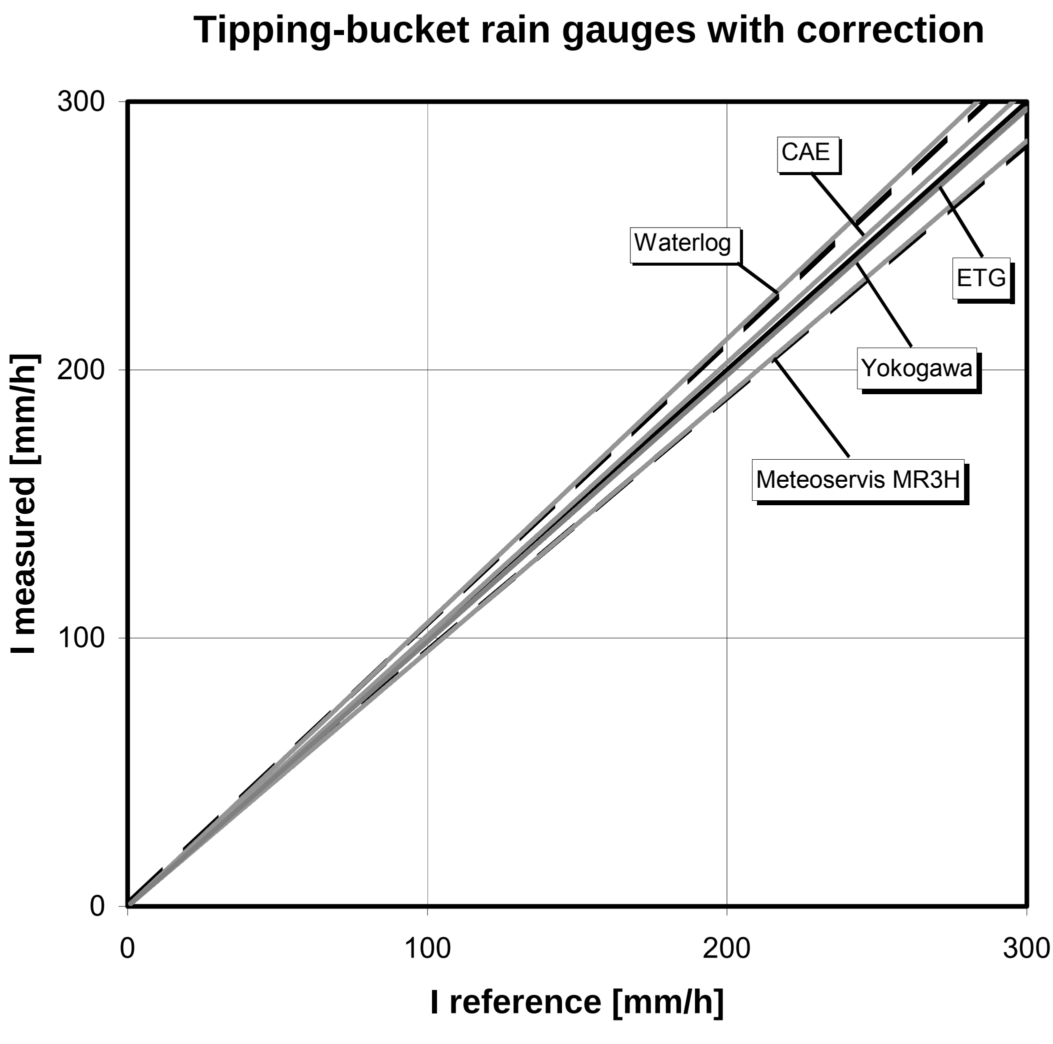


Figure 9a: Ensemble of calibration curves for corrected TBRG (dashed lines indicate ±5%) over the range of reference rainfall intensities from 0 to 300 mm·h^{-1}.

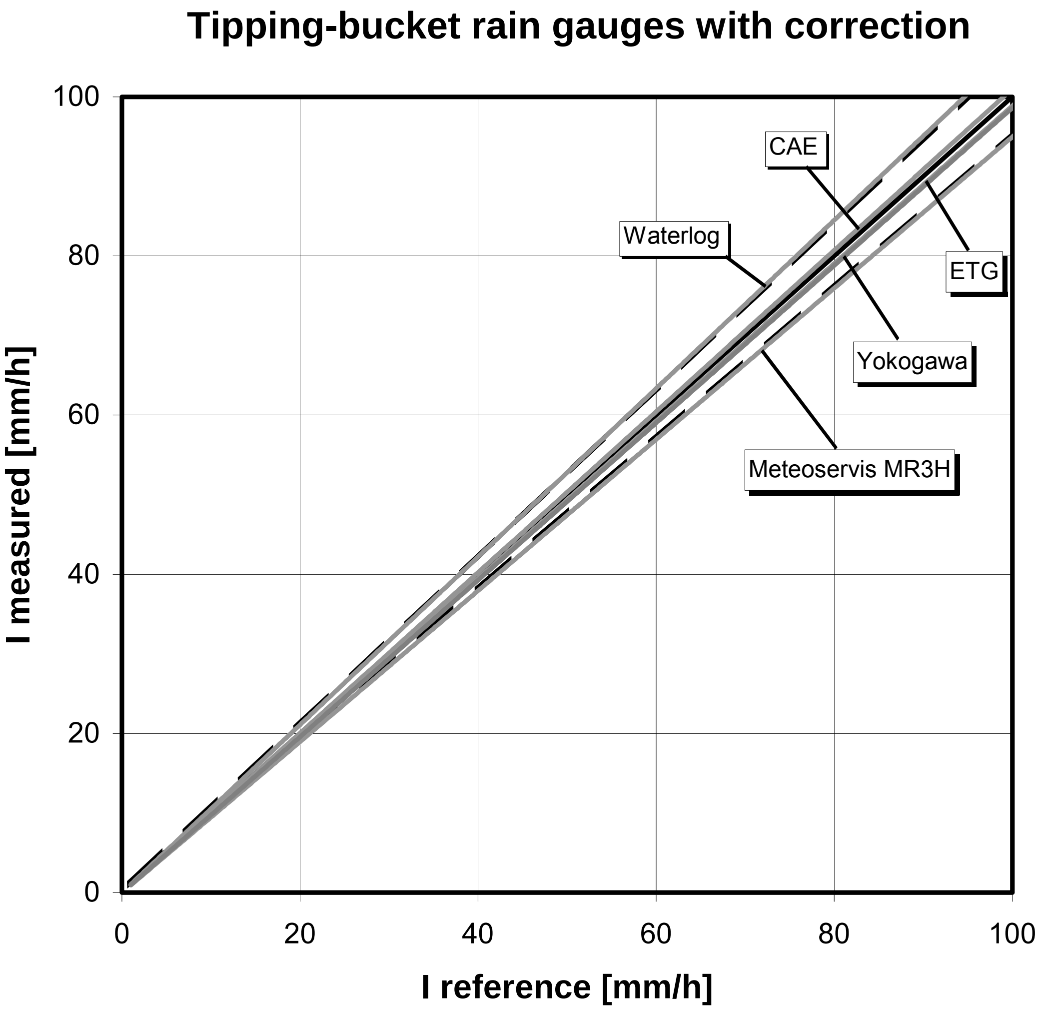


Figure 9b: Ensemble of calibration curves for corrected TBRG (dashed lines indicate ±5%) over the range of reference rainfall intensities from 0 to 100 mm·h^{-1}.

By inspection of the various curves, it is evident that the errors are generally smaller with respect to the non-corrected gauges; it can be said that the ETG and CAE gauges (Italy) are the most accurate for the measurement of rainfall intensity since providing the less relevant errors over the respective actual range of intensities.

In some cases it was possible to compare the corrected and non-corrected data provided by the rain gauge, since both were produced as output by the instrument. This is the case e.g. for the CAE PMB2. The performance of both corrected and non-corrected measurements are reported in Figure 10, as obtained from the tests performed at the DIAM laboratory.

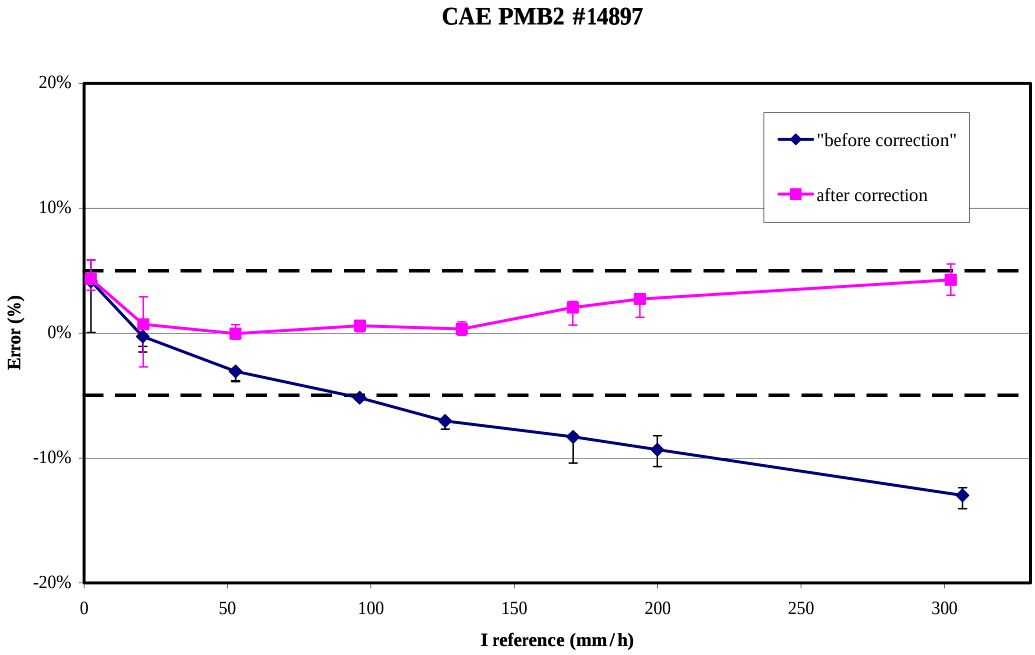


Figure 10: Sample comparison between the original and corrected curve for the CAE instrument.

In both the corrected and non-corrected groups of rainfall intensity gauges, storage was observed within some instrument. Storage heavily affects the rain intensity measurement since, as soon as water starts accumulating in the funnel, it generates the flow of a "false" rainfall intensity towards the buckets that depends on the water head established over the orifice rather than on the real rain intensity. Due to this fundamental drawback the initiation of storage determines the inability of the instrument to measure the rain intensity.

The actual range of measurement of a given instrument was therefore determined within the intercomparison by assuming the reference intensity where storage occurred as the upper limit of the measuring range. Storage was observed in four out of the twelve instruments analyzed.

9.4 Weighing Gauges

All of the weighing gauges analyzed can be grouped together and their performance discussed with reference to common parameters. It was decided by the ET/IOC that also the step response of the gauge should be evaluated.

In general, the uncertainty of this type of gauge in terms of relative errors is less than uncorrected tipping-bucket rain gauges over the entire range of intensities (see below Figures 17a and b).

The assessment of the step response of the weighing gauges illustrates some of the drawbacks that can affect their suitability for rainfall intensity measurement. Tests were performed in order to investigate the step response behavior of the weighing gauges submitted to the intercomparison. The reference intensity provided to the gauge was a constant flow rate, obtained by switching from 0 to 200 mm·h $^{-1}$ and then back to zero flow, with the duration of the input flow being decided based on the time needed for stabilization. The constant flow had therefore been applied until the output signal of the weighing rain gauge was stabilized.

The results of these further tests are presented below for the weighing gauges analyzed. The single tests are reproduced in the forms reported in the Data Sheets. There was a definite time delay with respect to the sudden variation in intensity (the step response). This delay varies between 0.33 and 9 minutes, being around 3-4 minutes for the majority of the instruments, as depicted in Figure 11.

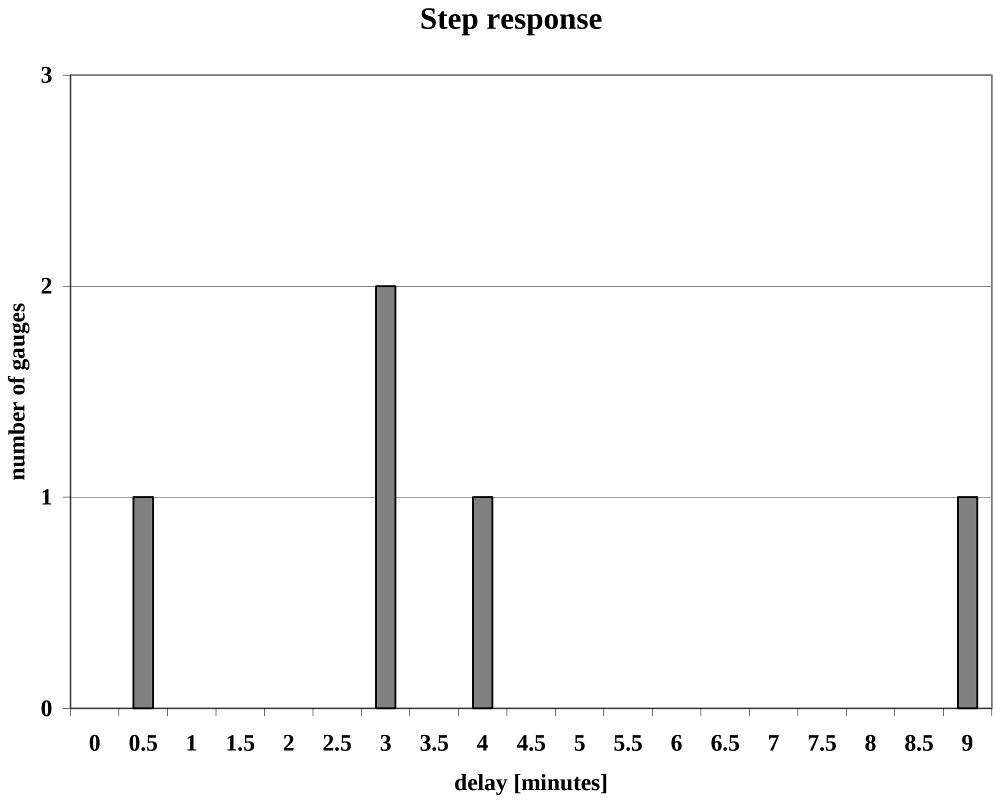


Figure 11: Distribution of the step response for the weighing gauges analyzed.

It is evident that only in one case (0.33 minutes) the delay can be considered as acceptable for the measurement of rainfall intensity with a resolution of one minute. The best performing gauge of the weighing type in this respect is therefore the Meteoservis MRW500 (Czech Republic). The step response for the best performing weighing gauge is reported in Figure 12.

CIMO-XIII approved an output averaging time of 60 seconds for the determination of RI (see Part I, par. 1.2). This implies that RI, reported by an ideal RI-gauge capturing a step-function alike RI, should be as indicated in Fig. 12 (dotted line). As a consequence, only those instruments with a sufficient low response time (like the gauge shown in the figure) comply with this requirement.

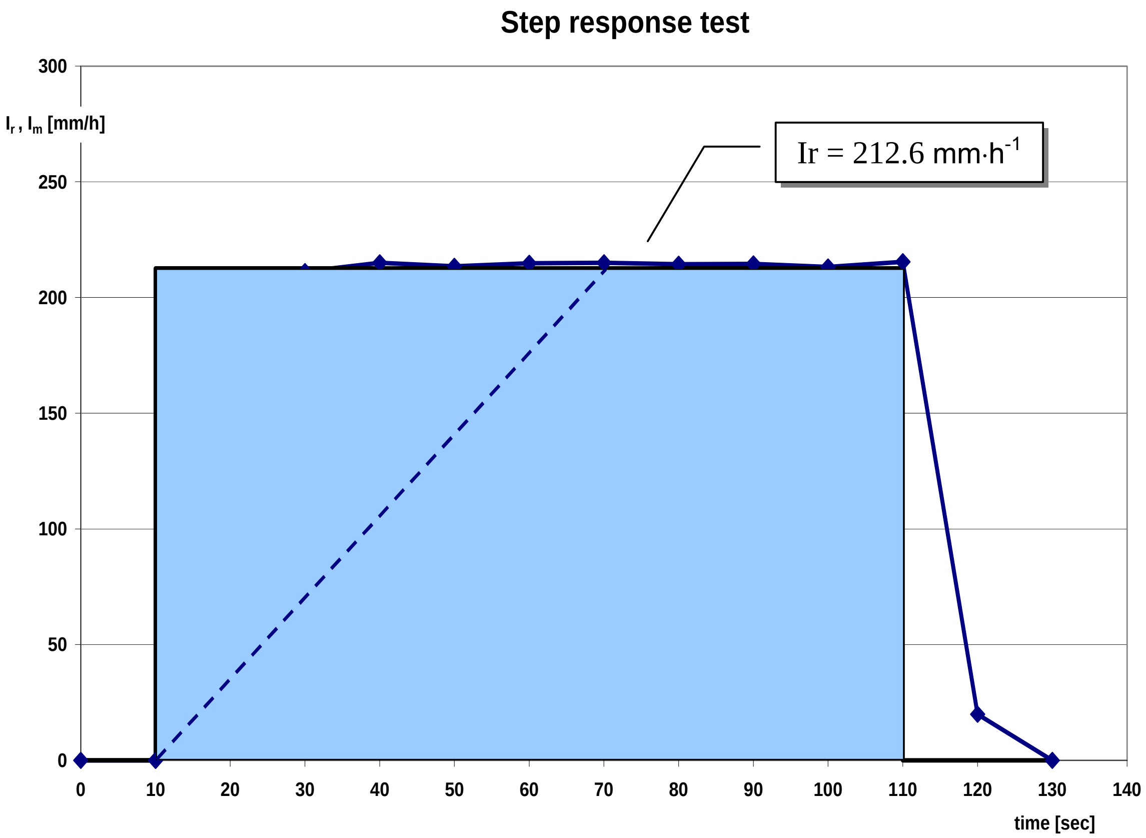


Figure 12: Step response for the Meteoservis MRW500 weighing gauge, showing a delay in sensing the rain rate signal of about 20 seconds. The dotted line shows the response curve to be reported by an ideal RI-gauge, based on the defined averaging interval of 60 s.

The response tests were performed by sudden application of a constant flow obtained at the reference intensity, and then waiting until the instrument is stabilized. The errors reported in the calibration curves are therefore related to such an “ideal” rainfall event with constant intensity and practically infinite duration in time.

Following the significant delay observed for some of the instruments under test, it was decided to perform additional tests on the weighing gauge showing the longest delay, i.e. the OTT Pluvio, so as to infer the impact of such behavior on real rain intensity measurements.

To this aim, a theoretical event was generated by rapidly switching over different reference rainfall intensities, and by observing the related errors in the measurement. In Figure 13, results are reported of the test where the reference rainfall varied from 0 to 12.3 and then 186.6 mm·h^{-1} for a duration of five minutes each, and then back to 12.3 mm·h^{-1} for other five minutes and finally to 0. This simulates the variation in time of the rainfall intensity during a real event, although in the real world the variability of rain rates is higher and occurs over finer scales in time.

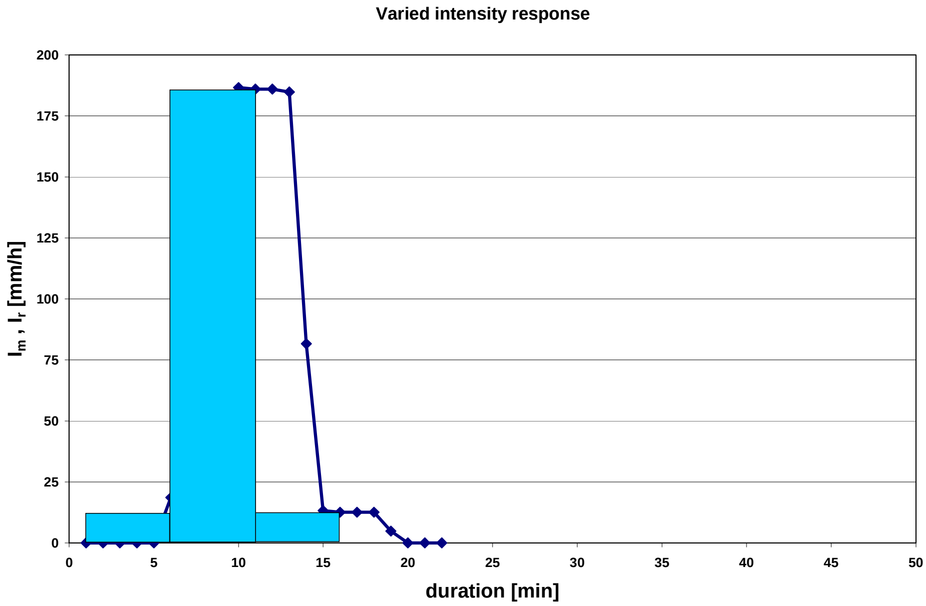


Figure 13: Simulation of a rain event and the response of the instrument.

It is evident from Figure 13 that there is a time delay in the ability of the instrument to correctly sense rainfall intensity, however the total rainfall accumulation may be quite accurate few minutes after the end of the precipitation event. The second event was generated by varying the reference rainfall from 0 to 12.3 and then 186.6 mm·h^{-1} for a duration of 15 minutes each, and then back to 12.3 mm·h^{-1} for other 15 minutes and finally to 0. The results are reported in Figure 14.

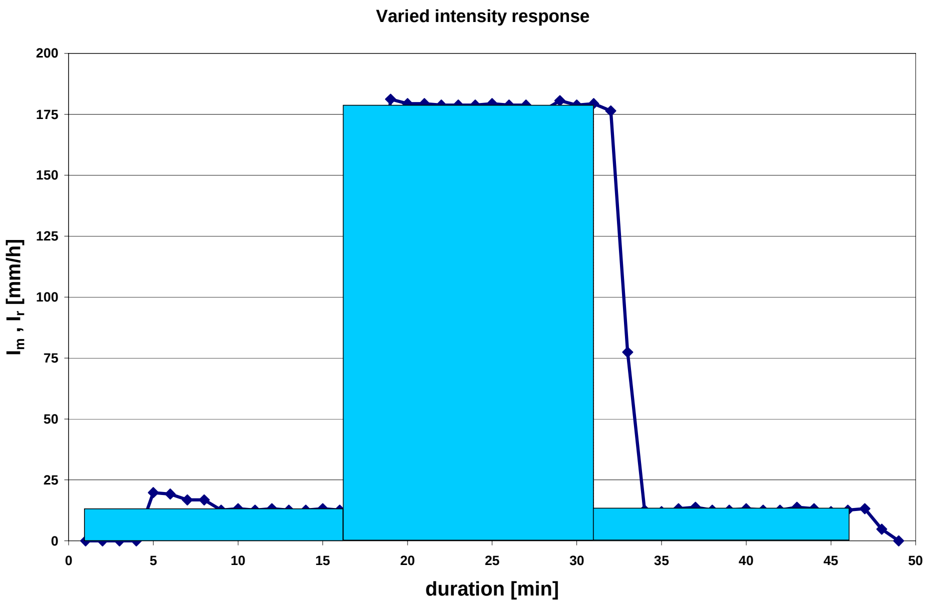


Figure 14: Simulation of the second rain event with representation obtained by the measurement instrument.

It is well known that the real rain events behave differently, and that rainfall intensity is a highly variable signal in time, with fluctuations at even smaller scales than one minute. This was taken into account by assuming a common minimum-averaging interval of one minute for all instruments involved in the intercomparison.

Figure 15 shows the response of OTT Pluvio rain gauge to a pulse with increasing duration, from 1 to 10 minutes. No time was allowed for the stabilization of the output intensity measured by the instrument.

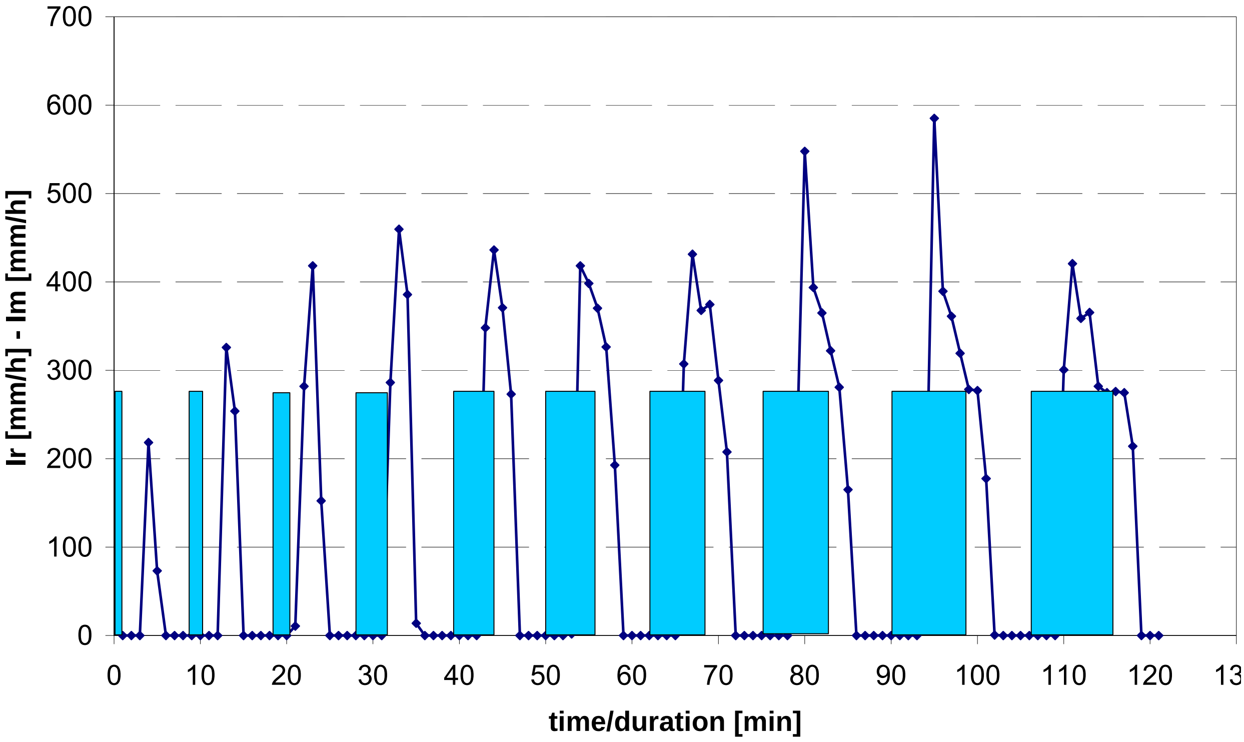


Figure 15: Step response for the OTT Pluvio weighing rain gauge, at varying pulse duration but the same reference intensity. The data points indicate the rain intensity values reported by the instrument with a resolution of one minute.

It is evident from Figure 15 that the response function of the instrument varies with duration of the test pulse. Large errors are evident at the reference resolution of one minute and decrease with the increasing duration of the constant pulse.

This delay in response is relevant when accurate measurements of rainfall intensity are required. This must be taken into account when comparing the graphs in the Data Sheet (and later in this section in Figure 17). The step response delay parameters play the most important role in assessing the performance of the instrument and even its overall suitability for rainfall intensity measurements.

Finally, in Figure 16, the error estimated as the relative difference between the reference and measured rainfall intensity averaged over the period of the rainfall event is plotted as a function of the duration of the rainfall event, again for the OTT Pluvio gauge, and compared to the error obtained by averaging over a sufficient period of time.

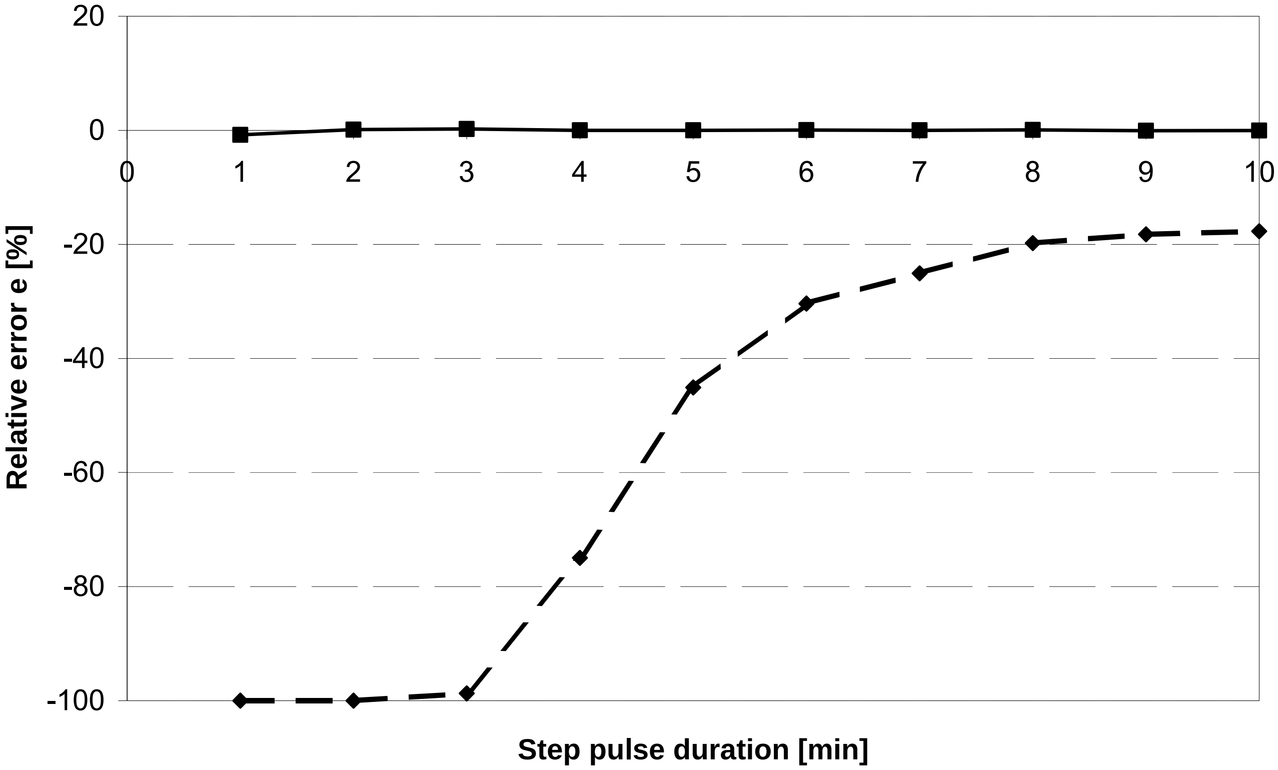


Figure 16: Relative errors (diamonds and dashed line) as a function of the time interval that is used as the averaging period for calculation of the intensity (under constant flow rate). The dots (and solid line) indicate the relative errors obtained after waiting a sufficient period of time after the end of the rain pulse.

9.5 Water Level Gauges

Two other instruments are based on the measurement of water level, by using the conductivity of water to detect the level with several stacked detectors. The two instruments analyzed showed different performances, mainly related to the efficiency of water siphoning or draining.

One instrument sometimes presented a continuous activation of the siphon.

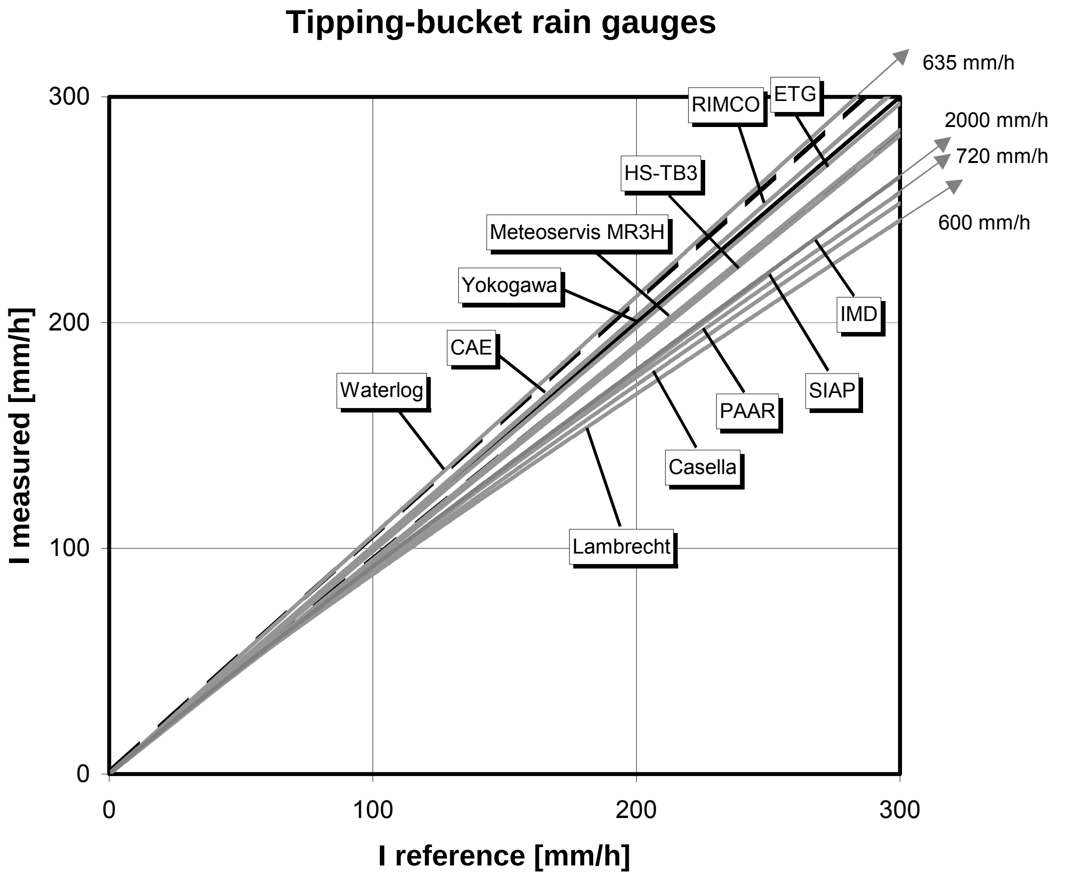
One model gave results within the +/- 5% WMO limits.

These instruments are potentially sensitive to the water conductivity, if it falls outside the stated limits.

It is advisable that both of them are included in the foreseen follow-on intercomparison in the field for additional investigations involving real rain-water and operational environmental conditions.

9.6 Overall comparison of gauges

The below figures show comparisons between all the gauges used in the intercomparison.



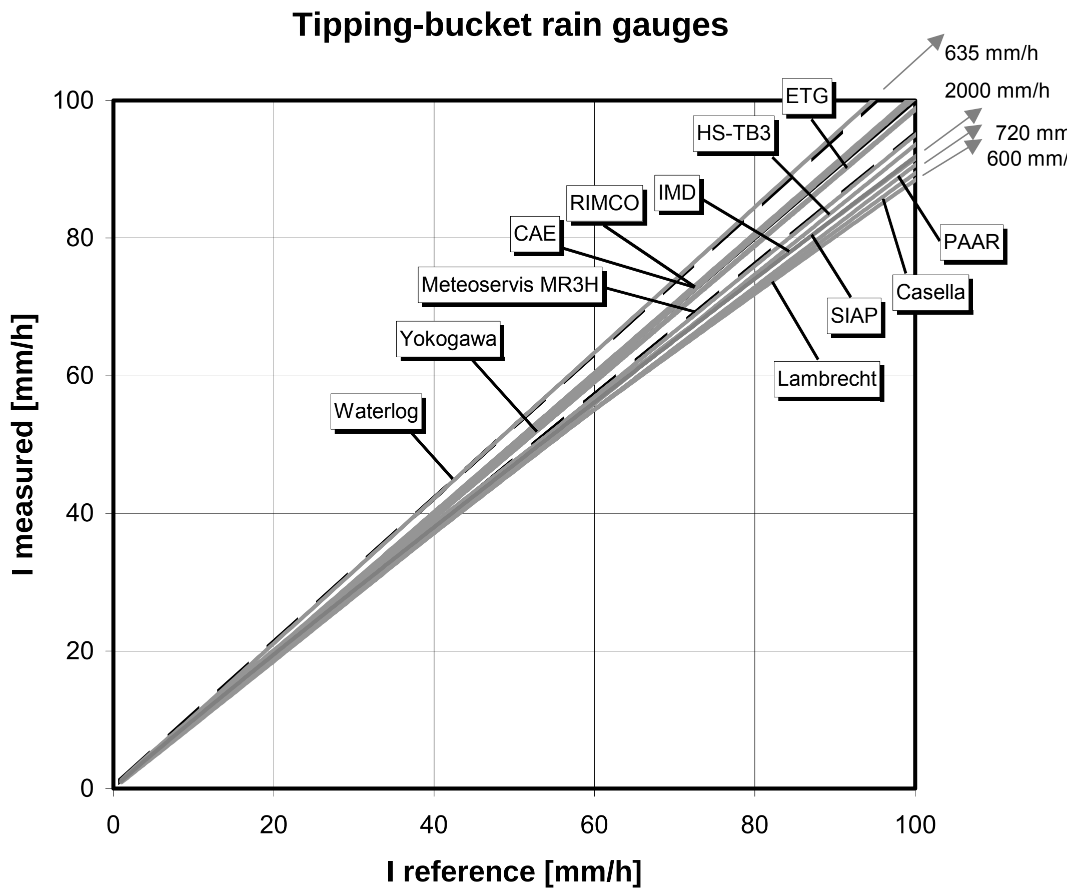
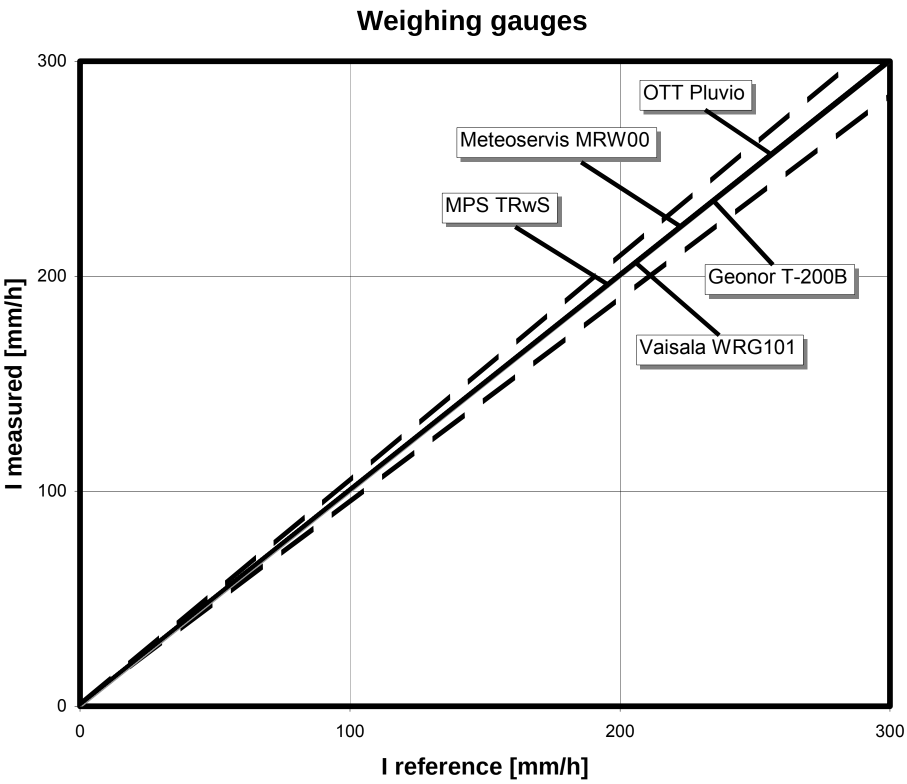


Figure 17a: Overall comparison of all tipping-bucket rain gauges analysed over different ranges.



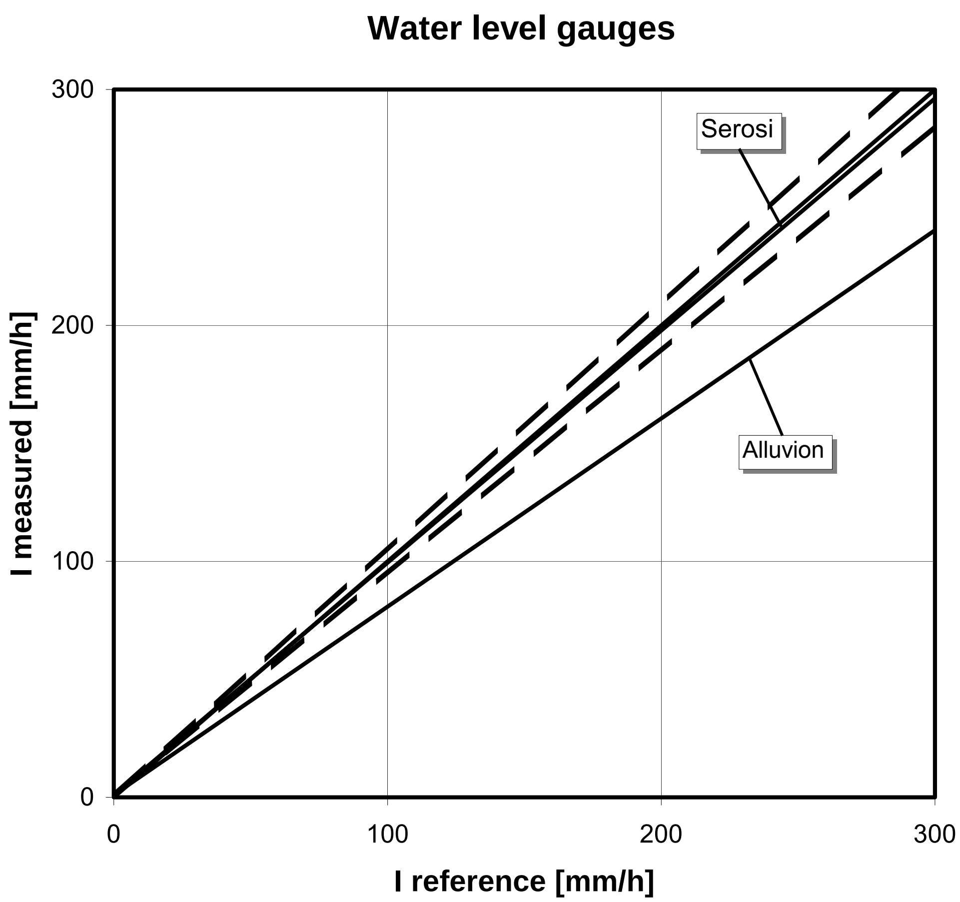


Figure 17b, c: Overall comparison of all weighing and water level gauges over different ranges.

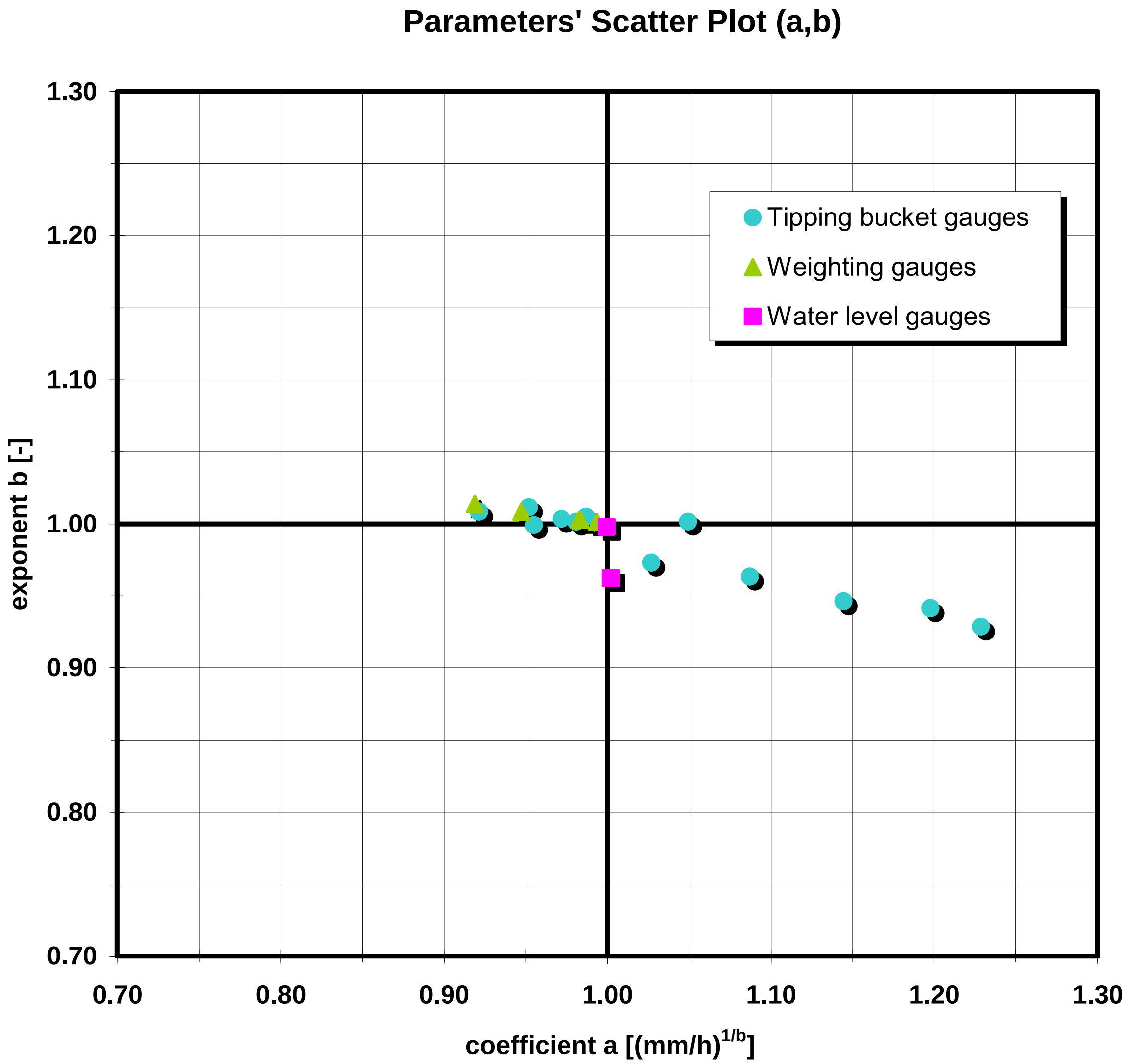


Figure 18: Scatter plot of the parameters' values for the power law calibration curve of all the instruments analyzed. The perfect rain intensity gauge is associated with the pair (a, b) = (1, 1).

In order to compare at once the performances of the various rainfall intensity gauges submitted to the Intercomparison, the average relative error over the range of measurement of the instrument was calculated.

This can be defined as the relative difference between the total area A_m subtended by the power law fitting of the calibration curve in the graphs reported above and the reference total area A_r subtended by the bisector of the same graphs, which represent the expected behavior or the "perfect" instrument. The average error e_{avg} is therefore defined as:

$$e_{avg} = \frac{(A_m - A_r)}{A_r}$$

The first value is calculated by integrating the power law calibration curve within the limits from 0 to 300 mm·h^{-1}, while the second is simply given by 0.5·I^2_{max}, having in this case I_{max} = 300 mm·h^{-1}. An example is provided in Figure 19.

The complement to one of the above ratio is reported in Figure 20 for all gauges investigated.

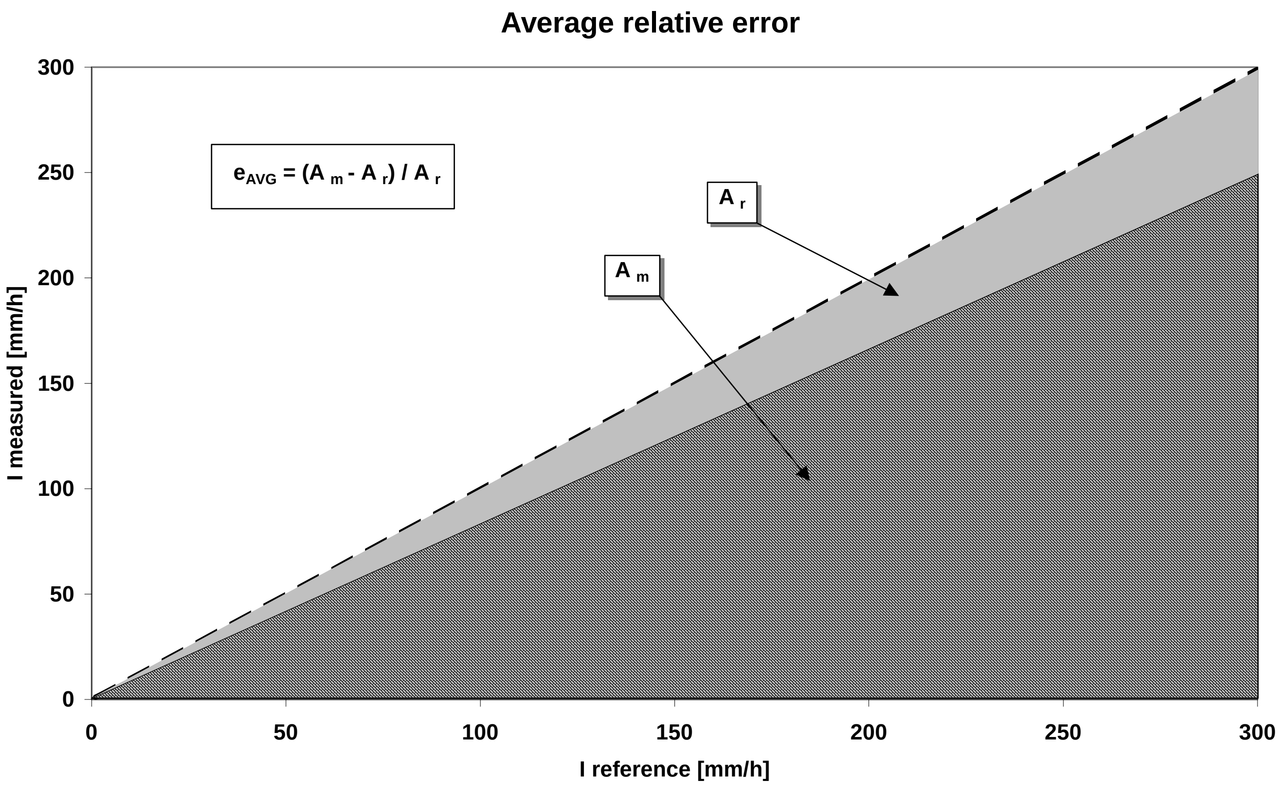


Figure 19: Definition of the average relative error for a sample calibration curve.

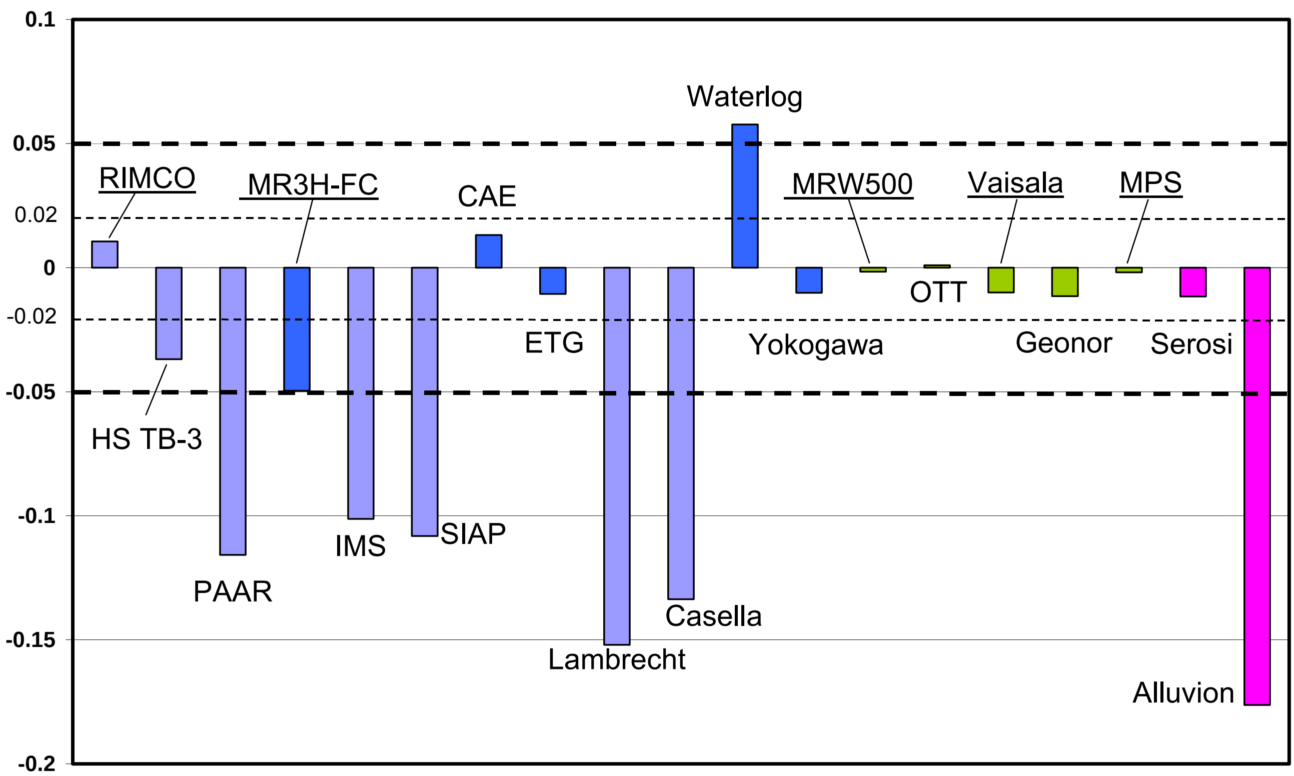


Figure 20: Average relative error over the whole range of measurement of all instruments analyzed.

10. Conclusions

This Laboratory Intercomparison of RI Gauges is the very first attempt at understanding of their performance, thus providing quantitative information regarding various errors associated with this measurement. This report certainly constitutes a basic step for the planning of the WMO Field Intercomparison of RI gauges.

1. All instruments analyzed are subject to errors and uncertainties in the measurement of rainfall intensity, and the selection of the best suited rain gauge must be performed according to its intended use and operational conditions;
2. The tipping-bucket rain gauges that were equipped with proper correction software provided good quality rainfall intensity measurements. The gauges where no correction was applied had larger errors. In some cases problems of water storage in the funnel occurred that could limit the usable range for rain intensity measurement;
3. The uncertainty of the rainfall intensity is generally less for weighing gauges than for the tipping-bucket rain gauges under constant flow rate condition, provided there is a sufficient time to stabilize the instrument. The measurement of rainfall intensity is affected by the response time of the acquisition system. Significant delays were observed in "sensing" the variation in time of the rain intensity. The delay is the result of the internal software which is intended to filter the noise. Only one instrument had a delay that met the WMO 1-minute rainfall intensity requirement.
4. The two gauges using a conductivity measurement for determining water level showed good performances in terms of uncertainty under these controlled laboratory conditions. Siphoning problems for one gauge limits its ability to measure a wide range of rainfall intensity. For the other one, a limitation is related to the emptying mechanism, in which case 2-minute delay was observed. These gauges are potentially sensitive to the water conductivity, but with no demonstrated problems during the laboratories' tests.
5. In many cases significant differences were recorded between two identical instruments. Tests on a large number of gauges, say at least 30, would provide a better assessment of the uncertainty;
6. The laboratory tests were performed under controlled conditions and constant flow rates (rain intensities) so as to determine the intrinsic counting errors. It must be considered that rainfall intensity is highly variable in time. Furthermore, catching errors may have a strong influence on the overall uncertainty of the measurement;

11. Recommendations

11.1 Standardized procedure for laboratory calibration of catchment type rainfall intensity gauges

1) Principles

It is recommended that a laboratory will use a calibration system, based on the following principles:

- Capability of generating a constant flow from 0.2 $mm \cdot h^{-1}$ up to 2000 $mm \cdot h^{-1}$.
- Measurement of the flow by weighing the amount of water over a given period of time.
- Measurement of the output of the tested instrument at regular periods of time or when a pulse occurs (typical for the majority of tipping-bucket rain gauges).

2) Requirements

The calibration system should be designed to obtain uncertainties below 1% for the generated RI. The calculation of the flow rate is based on the measurements of mass and time. The measurement of mass is made with at least one order of magnitude better than 1%. The duration of the test should be long enough to guarantee an uncertainty lower than 1%. The maximum time resolution should be a Δt = 1 min.

In considering possible error sources related to laboratory calibrations, the following issues should be considered for any related laboratory activity:

- The quality (purity) of the water used for calibration should be well determined / defined;
- The reproducibility of the calibration conditions should be a high priority;
- Suitable control and registry equipment should be applied (such as PC-controlled);
- All acquisition systems must comply with electromagnetic compatibility (to avoid parasite pulses, for example).

It was noticed that the quantity for which measurements of precipitation is reported, is a height expressed in millimeters although the weighing gauges measure mass. Since the density of rain depends on ambient temperature (and therefore the relation between mass and the equivalent height of rainfall), inaccuracy is introduced and is taken into account during calibration.

The environmental conditions during each calibration shall be noted and recorded:

- date and hour (start/end);
- air temperature [°C];
- water temperature [°C];
- atmospheric pressure [hPa];
- ambient relative humidity [%];
- any special condition that may be relevant for the calibration (e.g. vibrations);
- evaporation losses must be estimated.

The laboratory will perform suitable calibration tests according to the different apparatus used. The number of tests performed for each instrument, their descriptions (in terms of time units and/or number of tips, etc.) shall be noted and reported.

3) Uncertainty calculation

All parameters that can influence measurement of the bench calibration will be taken in account:

- Pressure difference inside water content and for distribution pipes;
- Error sources weighing mass;
- Time measurement errors.

11.2 The need to proceed with a field intercomparison of RI gauges

Following the last item of the above general conclusions, it must be considered that the laboratory tests were performed under controlled conditions and constant flow rates (rain intensities). However, for atmospheric conditions, rainfall intensity is a highly variable parameter over very small time and space scales. The catching errors in the atmosphere are dependent on the wind field and during any field comparison tests the spatial variability of the precipitation must be considered in the interpretation of the results.

The weather related conditions (wind, wetting, evaporation, etc.) that may produce significant catching errors could hardly be reproduced in the laboratory, unless very large economical and human resources are involved. The same is true for calibration of non-catching types of gauges that were excluded for this reason from the Laboratory Intercomparison, although of great interest to the meteorological community.

The need to combine the assessment of both counting and catching errors for the instrument analyzed in the laboratory is paramount. Provided the instrument is properly installed in the field, according to the WMO specifications, the question to be answered is what kind of instrument (measuring principle, manufacturer, model) is the most suited to the specific requirements of the user. This question cannot be answered based on the Laboratory Intercomparison alone, although the results obtained can provide preliminary information to manufacturers and the first-step selection criterion for the user.

It is therefore necessary to proceed with the quality assessment procedure initiated in the laboratory by organizing a follow-up intercomparison in the field where the instruments tested in the laboratory should have priority. This would allow continuity in the performance assessment procedure and result in the estimation of the overall operational error to be expected in the measurement of rainfall intensity in the field. Other instruments could be included in the field intercomparison, even if not tested in the previous laboratory phase, with priority given in this case to the non-catching type of instruments.

11.3 Methods and equipment for reference purposes within the field intercomparison

It is clear that no sensor meets all criteria as recommended by WMO. The combined analysis of the reference gauges allows the best possible estimation of the rainfall intensity in the field, given their demonstrated performance in the laboratory. The use of one reference instrument alone is not recommended. Instead, a set of gauges acting as a working reference is recommended.

The working reference rain gauge(s) should be inserted in a pit according to the EN-13798 Reference Raingauge Pit, adopted by ISO, in order to minimize the effect of weather related errors on the measured rain intensities.

According to the results of the laboratory intercomparison, it is recommended to select the best performing dynamically corrected TBRG and the weighing gauge showing the shortest step response and the lowest uncertainty as reference gauges. The TBRGs that meets this requirement are ETG R102 (Italy) and CAE PMB2 (Italy), even if their resolution is 0.2 mm. The weighing gauges that meet this requirement are Meteoservis MRW500 (Czech Republic) and WG Geonor T200B (Norway), with the shortest response delay.

11.4 Improving the homogeneity of rainfall time series with special consideration given to high rainfall intensities

The improvement of the uncertainty of rainfall intensity gauges brings the risk of affecting the homogeneity of rainfall time series. The improvement of the measurement of rainfall intensity may produce a discontinuity of the historical rain intensities records.

The above considerations especially apply to the handling of high rainfall intensities, as is the case for the study of extreme events. The bias introduced by non-corrected records propagates through any rainfall-runoff model down to the statistics of flow rates in water courses, with non negligible effects on the prediction and mitigation of floods and flash floods.

The correction of historical rain records is not trivial due to the time resolution of the recorded rain intensity values, which may prevent the application of simple correction procedure. In order to better explain the concepts above, an example is reported in Annex VIII with reference to the performance of tipping-bucket rain gauges (the most commonly used for rainfall intensity) and to the derivation of the so-called Depth-Duration-Frequency (DDF) curves, which is a common statistical tool used to infer the probability of intense rainfall events (Molini *et al.*, 2005a,b).

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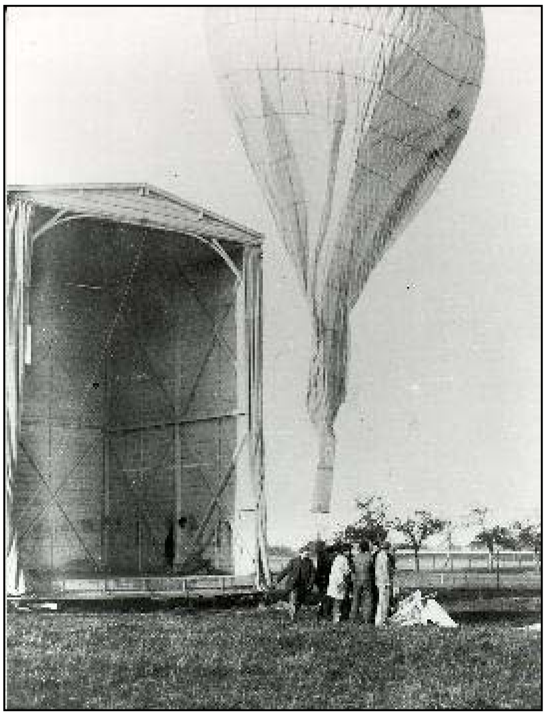
APPENDIX - Data Sheets

Data sheets reporting synthetic data from the tests performed per each instrument – see separate files.

ANNEX I

OVERVIEW OF THE LABORATORIES

The Laboratory of Météo France, Trappes (France)



The Trappes observatory has been established in 1896 by Leon Teisserenc de Bort, a French scientist, who discovered the stratosphere in 1902. After his death in 1913, the family gave the observatory to the French state, to continue the atmospheric researches.

In January 1929, the first radio-sounding in the world is launched from the observatory, by MM Bureau and Idrac.

Radiosondes are still launched twice a day from Trappes.

On site are the headquarters of the Direction of Observing System (DSO), a central direction of Météo-France, in charge of the definition, setting up and maintenance of the observing systems (upper air, weather radar and surface measurements). Formely called SETIM (For Service of Instrumental Techniques and Equipements for Meteorology), this service has a long background in calibration, tests of instruments and intercomparisons. The DSO is a Regional Instrument Center for RA VI. It organized a WMO international intercomparison of wind sensors at Mont Aigoual (1992-93) and PREWIC, the WMO Present Weather Sensors/Systems Intercomparison (1993-95).

It participated also to the EUMETNET program, SWS (Severe Weather Sensors), by testing instruments in harsh icing conditions at Mont Aigoual, during winter 2001-2002.

A national intercomparison of thermometer screens has been conducted in 1996-1998.

Considering rain gauges, a large pit gauge is used. Field tests and laboratory tests have been conducted for Météo-France needs. Therefore a laboratory is equipped with two calibration benches, regularly used for various evaluation and routine control of rain gauges, mainly after procurement.


Google

Laboratory of University of Genoa (DIAM), Genoa (Italy)

DIAM Laboratory

Department of Environmental Engineering

University of Genoa

Viale Cambiaso 6 -16145 Genova - Italy

tel. +39 010 3532493

fax +39 010 3532481

www.diam.unige.it

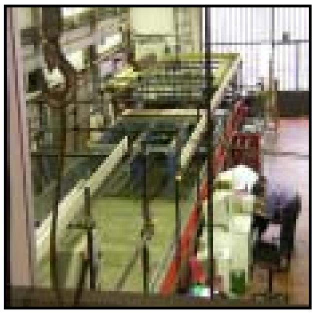
luigi@diam.unige.it

Overview of the DIAM Laboratory

The laboratory is the centre for the experimental activity of the Department of Environmental Engineering of the University of Genoa. Such activity is concerned with theoretical research, analysis and development of technical solutions for businesses. To the traditional proficiency of the institute of hydraulic and to its scientific reputation new skills have been added, which have contributed to widen the interest for the innovative aspects of environmental issues of engineering concern. The laboratory equipments and facilities allow research and experimental activity both basic and applied to the different fields of hydraulic (fluid mechanics, fluvial and maritime engineering, hydrology and environmental monitoring) as well as the characterization and qualification of instruments and processes relevant for environmental protection.

The Laboratory is classified as highly qualified according to D.L. 297/99.

Activities



Tests on physical and numerical models of hydraulic, fluvial and maritime works, hydrological processes and instruments for environmental monitoring. Scientific and technical consulting, regarding fluid-structure interaction. Hydraulic and hydrological studies with reference to water resource management, hydraulic infrastructures and technology of soil defence from hydro meteorological hazard. Calibrations and certification of rain gauges, both in laboratory and on field, valves, filters, ultrasound area velocity meters and hydraulic devices in general. Characterizations of pollutants present in first rain waters and washing of waterproof surfaces. Tests on physical and validation mathematical models of transformation processes: electrochemical processes of energy generation and of sewage treatment, water and soil treatment processes.

Certifications

The Laboratory currently makes calibrations and hydraulic instruments according to the European EN ISO 10012:2004 with reference to:

Area-Velocity flow meters.

The determination of the calibration curve and the following certification are made with measurements in a rectangular channel with a variable slope and known flows. A data acquisition system allows to computerize the certification process.

Tipping bucket rain gauges

A qualification module of rain instruments is used, which has been created by the laboratory staff for the generation of constant flows and the determination of the dynamic calibration curve of the instrument for different rain fall intensities. The process is completely handled via computer and managed by a LabView software.

Head losses on hydraulic devices. The Laboratory is equipped with a hydraulic system for flow measurements and the assessment of local head losses caused by devices (valves, filters, etc.) conveniently supervised.

Instruments

- Basins with wave generators
- Channels with and without sediment transport
- Channels with variable slopes
- Basins with tide generator
- Two-component laser velocimetry
- PIV - Particle Image Velocimetry
- Capacitive profile indicator
- Laser profile indicator
- Ultrasound level measurement
- Pressure transducers
- “in situ” velocity and flow measurement
- Electronic precision weighing
- Basic chemical laboratory

The Laboratory of the Royal Netherlands Meteorological Institute (KNMI), De Bilt (The Netherlands)

The Royal Netherlands Meteorological Institute (KNMI) is the national meteorological institute for the Netherlands. KNMI is part of the Ministry for Transport and Water Management. KNMI provides meteorological information for safety, economy and environmental purposes to the public domain, governmental organizations and to the aeronautical and maritime sectors. For the long term, KNMI performs research in the field of climate change. KNMI employs a staff of about 450 people - which are mainly working at the main premises in De Bilt.

Figure 1: Photograph of the main location of KNMI at De Bilt showing satellite reception dishes on top of the building and the precipitation radar.

The instrumental department of KNMI is responsible for the development and maintenance of the national meteorological measurement network. The meteorological network is used for synoptic, climatological, aeronautical and hydrological purposes and is run by the instrumental department in cooperation with other departments within KNMI as well as with the Royal Netherlands Air Force, the Royal Netherlands Navy and sister organizations for inland waters, the coastal regions and the North Sea within the ministry of Transport and Water Management. The meteorological network consists of meteorological sensors, sensor interfaces, automatic weather stations, airports, airbases and production platforms in the North Sea. Sensor data is acquired and processed real-time for aeronautical purposes, but for all sites the sensor information is acquired centrally, processed and made available from a central database every 10 minutes. Furthermore 2 precipitation radars, a lightning detection network and satellite reception systems are part of the responsibility of the instrumental department. The measurement network is in a large extent automated and all components of the measurement network have a high availability. The instrumental department is ISO 9001-2000 certified.

Figure 2: A picture of the operational precipitation gauge setup used by KNMI.

The instrumental department has a staff of 28 people that are distributed over: (i) a production and maintenance section that monitors the status of the network and takes care of corrective and preventive maintenance; (ii) a calibration laboratory that calibrates all meteorological sensors prior to operational use in the field and checks each sensor after operational use; (iii) a instrument research & development group that tests and introduces new sensors and systems to the network. The KNMI contribution to the WMO Laboratory Intercomparison of Rainfall Intensity Gauges has been provided by all three sections of the instrumental department. The calibration laboratory provided support using their experience regarding the setup and calibration of precipitation gauges. The production and maintenance section provided the staff to perform the calibrations. The instrument research group developed the software and performed the data analysis as well as the overall coordination of the KNMI contribution to the laboratory test.

Figure 3: The calibration setup for the KNMI precipitation gauge at the laboratory of KNMI.

ANNEX II

WORLD METEOROLOGICAL ORGANIZATION

QUESTIONNAIRE I

on potential participants

of the WMO Laboratory Intercomparison of Rainfall Intensity (RI) Gauges

France/Italy/Netherlands 2004-2005

1. Member Country:

2. Expert (point-of-contact) for the intercomparison:
   Name, First Name: ……………………………………………………………………
   Address: ………………………………………………………………………………
   Tel./Fax: ……………………………………………………………………………..
   E-mail: ……………………………………………………………………………..

3. Basic information on sensor/systems foreseen in the intercomparison:
   …………………………………………………………………………………………………
   …………………………………………………………………………………………………
   …………………………………………………………………………………………………
   …………………………………………………………………………………………………

3.1 **Model/Type I** (1) (highest priority for participation):

a) Model/Type: ……………………………………………………………………
b) Manufacturer: …………………… Country: …………………………………
c) Number of sites where the instrument is in operational use or intended to be in your country: ……………………………………………………………
d) Will you submit **one [ ]** or **two [ ]** identical instruments (2), (8)
e) Principle of operation (2)(3)
   TB [ ] WG [ ] DC [ ] OT [ ] (4)
f) What kind of parameter does the sensor/system report (2), (5)
   RI [ ] RA [ ] TT [ ] (4)
g) What kind of output does the sensor/system provide
   DG [ ] PS [ ] OT [ ] (4)

3.2 **Model/Type II** (1)(7) (lower priority for participation):

a) Model/Type: ……………………………………………………………………
b) Manufacturer: …………………………Country: ………………………………

c) Number of sites where the instrument is in operational use or intended to be in your country: …………………………………………………………………

d) Will you submit **one [ ]** or **two [ ]** identical instruments (2), (8)

e) Principle of operation (2)(3)

TB [ ] WG [ ] DC [ ] OT [ ] (4)

f) What kind of parameter does the sensor/system report (2)(5)

RI [ ] RA [ ] TT [ ]

g) What kind of output does the sensor/system provide (6)

DG [ ] PS [ ] OT [ ] (4)

____________________ __________________________________

Date | Signature of the Permanent Representative

NOTES:

Further information on organizational and technical issue for the preparation of the intercomparison will be distributed in due course to the experts designated by you, as appropriate.

(1) It is necessary to prioritize the submission on participation because of limited testing facilities.

(2) Please tick the appropriate box.

(3) Principle of operation

TB = Tipping Bucket WG = Weighing Gauge DC = Drop counter OT = Other

(4) If “Other”, please attach a brief description of the applied principle/sensor output.

(5) Parameters reported

RI = Rainfall Intensity RA = Rainfall Accumulation TT = Time of Tipping

(6) Sensor/System Output

DG = Digital Output PS = Pulse Signal OT = Other

(7) In case it is intended to submit more than two types of rainfall intensity gauges, attach another completed copy of this questionnaire.

(8) To achieve more confidence in the results, preferences will be given to testing of two identical instruments, however this is not a condition for participation.

Please return the completed questionnaire, as soon as possible, but not later than March 30, 2004 to the following address:

Secretary-General
World Meteorological Organization
P.O. Box 2300
1211 Geneva 2
Switzerland
Telefax: +41 32 7342326

ANNEX III

WORLD METEOROLOGICAL ORGANIZATION

QUESTIONNAIRE II

Addressed to Selected Participants of the

WMO laboratory intercomparison of Rainfall Intensity (RI) gauges

France/Italy/Netherlands 2004-2005

Note: please complete a separate questionnaire for each type of Sensor /System. If necessary, attach additional pages.

1.	Member country	
2.	Name of participating institution/company	
	Address	
3.	Person responsible for the intercomparison	
	Surname	First name
	Tel.:	Fax:
	E-mail:	Other:
4.	Alternative contact person	
	Surname	First name
	Tel.:	Fax:
	E-mail:	Other:
5.	Name of manufacturer *(if different from no.2 above)* same ☐ different ☐	
	Address	

6.	**Shipment of participating instruments**
	Approx. commercial value Euro / Total weight of consignment kg
	Number of boxes / Overall volume of boxes cm^3
	Overall dimension, in cm (i.e. for storage purposes) Length **x** Width **x** Height cm
	Other information concerning shipping
7.	**Instrument specifications** *Please enclose a diagram showing, preferably, the different elements (photos are welcomed).*
	Instrument name / Model/Type
	Principle of operation
	Rain Intensity (RI) range *(for a sensor measuring rain accumulation (RA), it should be possible to calculate RI over a period of one minute. RI range must be stated in such conditions).* RI from mm/h to mm/h
	Rain accumulation limit *(if the sensor has an accumulation limit (i.e. weighing sensor), please indicate it and the related limitation for RI range.* Accumulation limit mm, and corresponding RI range from mm/h to mm/h over a period of minutes.
8.	**Information for laboratory installation**
	Notes on the power supply: Sensors should be able to operate on 220V AC, 50 Hz or unregulated 12V DC (if power supply is necessary); *For other voltages, converters must be provided.*
	Overall dimensions of the instrument, in cm Length **x** Width **x** Height cm / Total weight kg
	Dimensions: Length **x** Width **x** Height (in cm); and Weight (in kg) of main elements
	Part id L **x** W **x** H kg
	Part id L **x** W **x** H kg
	Part id L **x** W **x** H kg
	Part id L **x** W **x** H kg
	Part id L **x** W **x** H kg
	Part id L **x** W **x** H kg
	Power supply/Voltage required / Maximum total power consumption (watts)

9.	**Sensor/System siting requirements**
	Installation alignment required Yes ☐ No ☐
	Maximum distance to the data logger cm
	Will an expert from the Member country assist with the installation of the Sensor/System Yes ☐ No ☐
	Will an installation tools kit accompany the shipment? Yes ☐ No ☐
	Any special tools required for the installation? Yes ☐ No ☐ Please describe
	Special fixtures required for the installation? Yes ☐ No ☐ Please describe
	Any other special requirements? Yes ☐ No ☐ Please specify
11.	**Calibration**
	Calibration reference
	Calibration intervals
	Procedure

12.	**Sensor/System Output**		
	Pulse	Duration	Voltage
	Reed Relay Yes ☐ No ☐		
	Digital	RS232 Yes ☐ No ☐	
		Other Yes ☐ No ☐	please specify
	Or propose and clearly describe an interface for data acquisition		
13.	**Any other relevant information.** For example, if internal processing software introduces smoothing over a period of time longer than 1 minute, this should be carefully documented.		

Date	Name of person who completed this form

Please send an electronic copy of the completed form as an E-mail Attachment to Dr Ondras:

Dr Miroslav Ondras
Senior Scientific Officer
WMO/OMM
World Weather Watch
P.O. Box 2300
Geneva, Switzerland

E-mail address: Mondras@wmo.int

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ANNEX IV

UNCERTAINTY ASSESSMENT FOR THE QM-RIM DEVELOPED AT THE DIAM LABORATORY, ITALY

From a metrological point of view, the QM-RIM apparatus can be divided in two basic modules:

- the synthetic rainfall intensity generation module;
- the actual rainfall intensity Measurement module.

Sources of uncertainty within the QM-RIM architecture can be in fact of two main types:

- Uncertainty on the flow steadiness deriving from possible variations in water head *H*;
- Uncertainties due to the weighing apparatus, to delays in acquisition and to the variation of experimental conditions such us Temperature and Relative Humidity .

Moreover, these two sources of uncertainty are independent from each other and therefore a separate analysis for the two modules has been performed, later combining the results into a unique uncertainty budget.

Uncertainty budget for the RI Generation Module

The uncertainty associated with the RI generation module essentially depends on the uncertainty on the water head *H*. Indeed we observed in Section 2 that the law controlling the generation of synthetic flow rates in the QM-RIM is:

$$Q = \Omega \cdot \xi \sqrt{2gH}$$

Since Ω and ξ can be assumed as constant for a given configuration of the QM-RIM in standard conditions of maintenance, the evaluation of standard uncertainty on the RI Generation Module only depends on the value of *H*.

On the other hand, the maximum observed variation of *H* in RI generation module can be acceptably considered as:

$$\Delta H \leq 0.1\ mm$$

and so we obtain, assuming the variation of the water head *H* as uniformly distributed, the expression for the uncertainty on *H*, as:

$$u_H = \frac{\Delta H}{\sqrt{3}} \approx 0.06\,mm$$

The uncertainty on the synthetic flow rate Q due to the maximum observed variation of *H, ΔH*, is therefore given by:

$$u_Q^{(H)} = \sqrt{\left(\frac{\partial Q}{\partial H}\right)^2 \cdot u_H^2} = \frac{1}{2} \cdot \frac{u_H}{H} \cdot Q$$

In Figure 5 the relative uncertainty on *Q* due to the water head variation *ΔH* is represented as a function of *H* and obviously, since $u_Q(H)$ is given as a maximum uncertainty, the relative $u_Q(H)/Q$ is maximum for the lowest water head (about 0.1%).

Uncertainty Budget of the Actual RI Measurement Module

The evaluation of the standard uncertainty on the Actual RI Measurement Module depends on the value of u_W (uncertainty on weight measurement) and u_t (uncertainty on the time interval measurement).

The value of u_W is a function of the temperature variation (ΔT) during the experiment and of the linearity, resolution and repeatability characteristics of the precision balance.

Therefore, assuming the distribution of the weight (W) variations due to linearity, resolution and environmental temperature as uniform and since the repeatability is just given for the QM-RIM precision balance in terms of uncertainty, we obtain:

$$\Delta W_{LIN} = 0.02\,g \quad \Rightarrow \quad u_W^{(LIN)} = \frac{\Delta W_{LIN}}{\sqrt{3}} = 0.012\,g \tag{1}$$

$$\Delta W_{RIS} = 0.01\,g \quad \Rightarrow \quad u_W^{(RIS)} = \frac{\Delta W_{RIS}}{2\sqrt{3}} = 0.003\,g \tag{2}$$

$$u_W^{(REP)} = 0.01\,g \tag{3}$$

$$u_W^{(T)} = \alpha_T \frac{\Delta T}{\sqrt{3}} \cdot W \approx 0.014\,g \tag{4}$$

with $\alpha_T = 6 \cdot 10^{-6}$ °C^{-1} the thermal sensitivity coefficient, $\Delta T \approx 2$ °C the Maximum ΔT estimation during the experiment and $W = 2000\,g$ the standard water amount provided to the RI gauge during a single test.

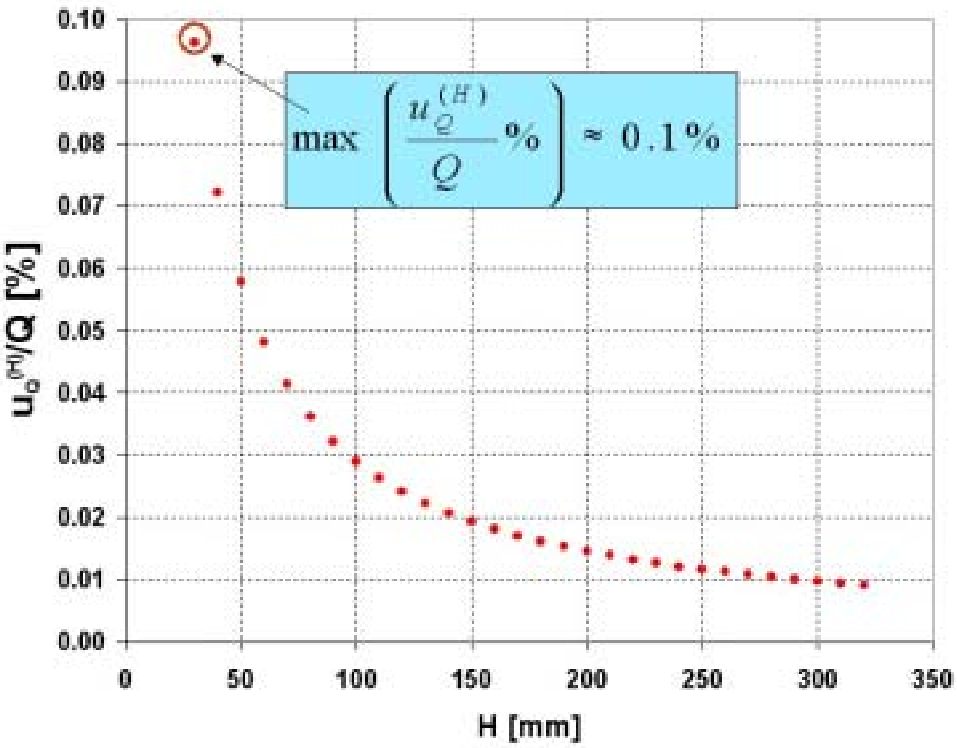

Figure 5: The relative uncertainty on Q (flow rate) due to *H* (water head) as a function of *H.*

Equations 1-4 respectively represent the uncertainties on weight measurement (*W*) due to the linearity, resolution and repeatability characteristics of the precision balance and uncertainty on *W* deriving from environmental temperature variations.

Then, we can obtain an overall expression for u_W, in the form:

$$u_W = \sqrt{\left(u_W^{(T)}\right)^2 + \left(u_W^{(LIN)}\right)^2 + \left(u_W^{(REP)}\right)^2 + \left(u_W^{(RES)}\right)^2} = 0.021g$$

At the same time, assuming *Δt = 10-1 s* (maximum deviation in the measurement of the time *t*), the uncertainty on the time interval estimation is:

$$u_t = \frac{\Delta t}{\sqrt{3}} \cdot \sqrt{2} \approx 0.08\,s$$

and we finally obtain that the standard uncertainty on the Actual RI Measurement Module is given by:

$$u_Q^{(W,t)} = \sqrt{\left(\frac{\partial Q}{\partial W}\right)^2 \cdot u_W^2 + \left(\frac{\partial Q}{\partial t}\right)^2 \cdot u_t^2} = \sqrt{t^{-2} \cdot u_W^2 + \left(\frac{W}{t^2}\right)^2 \cdot u_t^2}$$

Combined Standard Uncertainty and Expanded Uncertainty

The next step in the metrological validation of the QM-RIM consists in combining the uncertainties on the RI generation module and the actual RI measurement module in order to obtain the total uncertainty u_Q on the synthetic flow rate Q, in the form:

$$u_Q = \sqrt{\left(u_Q^{(W,t)}\right)^2 + \left(u_Q^{(H)}\right)^2}$$

From the above equation the total uncertainty on the synthetic rainfall intensity uRI can be easily extracted as:

$$u_{RI} = k \cdot \sqrt{\left(u_Q^{(W,t)}\right)^2 + \left(u_Q^{(H)}\right)^2}$$

with $k = \rho^{-1} S^{-1} = 0.01\,mm\,g^{-1}$

where ρ is water density and *S* the RI gauge collector area. By calculating u_{RI} *(W,t)* as a function of *t* we obtain, for the relative uncertainty on RI due to the uncertainty on weight and time measurements:

$$\frac{u_{RI}^{(W,t)}}{RI} = 2 \times 10^{-2} \div 0.15\%$$

while:

$$\frac{u_{RI}^{(H)}}{RI} = 0.1 \div 0.01\%$$

Since we have, for the maximum relative uncertainty on rainfall intensity: $\frac{u_{RI}^{\max}}{RI} \approx 0.2\%$

And assuming 2.576 as the coverage factor (corresponding to a confidence level of 99%) we obtain the expanded relative uncertainty for the actual rainfall intensity:

$$\frac{U_{RI}^{\max}}{RI}\% = 0.46\%$$

The QM-RIM is an experimental apparatus able to generate constant flow rates and measures the response of RI gauges under test to synthetic rain rates. The objective of the above procedure is the metrological validation of the QM-RIM based on the “a priori” evaluation of total uncertainty associated with the considered calibration device.

Using the Type B uncertainty evaluation, it was possible to assign a maximum expanded relative uncertainty to the QM-RIM measurements of rainfall intensity, representing a protective estimation of the uncertainty on the actual rainfall intensity I.

Such uncertainty, calculated from overestimated values of *H*, *W*, *t* and *T*, is about 0.46% and is then coherent with the Laboratory Intercomparison threshold of 1% imposed for calibration devices included in the RI gauges intercomparison program of WMO.

ANNEX V

UNCERTAINTY ASSESSMENT FOR THE BENCH CALIBRATION AT THE TRAPPES LABORATORY, FRANCE

The principle of this bench is to control the mass over a given period of time, assuming that the decrease of mass of the recipient containing the water represents the quantity of water going into the rain gauge under test. This assumption has been verified by using a balance in place of the rain gauge, thus measuring the water coming in a recipient weighted by this balance and comparing the result with the decrease of mass measured by the first reference balance. Disequilibrium between the input and output of water would indicate some variable storage of water in the tubes carrying the water. Some air bubbles may exist in the tubes after a long period without use, but these bubbles are eliminated very quickly when the system is running, and the assumption of the equality between the water out (the recipient on the balance) and the water in is very well verified. The remaining uncertainty is included in the uncertainty used for the mass measurement.
The uncertainty calculation of intensity is mainly dependent on the duration of the test and on total mass of water used.

1) Duration of test
   The electronic weighing machine outputs a message each 0.17s: we get a new mass each 0.17s. To get a maximal error on mass lower than 0.1% due to this time factor, a duration of test of at least 170 s is chosen. An uncertainty $\mathbf{U_1}$ about this error is calculated (0.17/t, t being the duration of the test).

2) Total mass of water to use
Errors of calibration with reference weights, linearity, repeatability, drift dependence on temperature and resolution according to specifications of the balance manufacturer, allows to calculate an uncertainty on mass U_2. U_2 is equal to 0.12 g for bench A and to 0.36 g for bench B. For low intensity values, a limiting factor is time (we want to avoid a too long test). Therefore, the mass M is chosen so that $U_2/M < x$ %, x being to define so that (a) be verified.
For high intensity values, the mass M is quickly much higher than U_2 so the constraint becomes the duration of test chosen to be higher than 170 s (cf§1). The total uncertainty U is a square-law addition of U_1 and U_2 and we applied a enlargement factor **c** =2 :

$$\mathbf{U} = \mathbf{c}\sqrt{\mathbf{U}_1^2 + \mathbf{U}_2^2}$$

Finally, the mass of water **M** is chosen to define relative uncertainty U/M for one intensity so that :

$$\mathbf{U/M \leq 1\%.} \quad \mathbf{(a)}$$

For common tipping bucket rain gauges, the tips detections are used to start and stop the measurement of mass. If some storage (due to the conception of the rain gauge) occurs between the output of the tube carrying the water from the bench and the bucket itself, this storage introduce an additional uncertainty which may be large. Some designs have a storage of water which may vary from 0 to several grams (8 for one of the sensor). In such conditions, the uncertainty U on M is several grams. If the uncertainty U on M is 4 g, the total mass M used must be more than 400g, to get an uncertainty below 1% . At a low intensity of 2 $mm \cdot h^{-1}$, with a rain gauge with a 314 cm^2 collector, the quantity of water is about 63 g in one hour. Therefore, the test must last at least 6,4 hours to get an uncertainty U/M lower than 1%. So the test is quite long. For usual tipping bucket rain gauges with no intermediary storage , the uncertainty on U is equal to 0.25 g for bench A and 0.8 g for bench B . Therefore, the total mass M only needs to be higher than 25 g for bench A and the test may stay short in time. A minimum number of tips between 4 and 10 has been usually used, which give a duration of test less than 1.5 hour. For some sensors with internal water storage, due to practical reasons, the test at low intensities has been too short and an uncertainty below 1% was not respected. This may explain some variations between successive tests for some sensors.

For weighing and conductivity principle rain gauges, the rain gauge measurement mass uncertainty (provided by the manufacturer) induces an uncertainty on the calculation of the error. The relative error is defined as:

$$e = \frac{I_m - I_r}{I_r}$$

Given **m’** the mass measured by the rain gauge, **Δm’** as the rain gauge measurement mass uncertainty and **m** the water mass used for the test, the measured intensity is then:

$$\frac{I_m}{Ir} = \frac{m'}{m} \pm \frac{\Delta m'}{m}$$

As the ratio **Δm’/ m** is larger at low intensities than at high intensities, the uncertainty on Im is larger for low intensities than for high ones.
That explains why there is more scattering visible on the graphs for low intensities tested on devices than for high intensities .

UNCERTAINTY ASSESSMENT FOR THE BENCH CALIBRATION AT THE KNMI LABORATORY, THE NETHERLANDS

The reference intensity is defined in relation to the decrease in mass (∆mass) of the water in the scale(s) over a time interval (∆time) according to:

Intensity (mm·h^{-1}) = 36000 × ∆mass (g) / ρ (g/cm^3) / area (cm^2) /∆time (sec)

The absolute measurement uncertainty of the scales used in test is 0.2 g. Note that for mass the uncertainty of the measurement of the total mass is not of importance, but only the change in mass over a certain time period, hence an uncertainty for ∆mass of dm = 0.14 g is adopted (uncertainty is expressed by the symbol 'd'). The density of water is defined as ρ =1 cm^3/g and varies slightly with temperature, pressure, and composition. The density of pure water is 0.999 g/ml at 15.6°C, 0.998 g/ml at 21°C, 0.997 g/ml at 25.2°C and 0.996 g/ml at 28.8°C. The density of tap water is only slightly higher than for pure water, but seawater is about 2.5 % heavier than pure water. In this report a density of tap water 1 g/ml is adopted with a relative uncertainty of $d\rho/\rho$= 0.5 %. The area of the orifice of the sensor is specified by manufacturer and adopted without modification. Note that environmental impacts like wind usually affect the measurement in the field. Estimated corrections are sometimes incorporated in the value of the orifice area by defining an "effective orifice area", provided by the manufacturer. For this laboratory intercomparison only the real orifice area is used. The uncertainty of the time interval as measured by the acquisition PC is better than 1 s over the time intervals in question. Some sensors update at a regular time interval and some sensors report the increment of a precipitation level directly. The data-acquisition PC reads and stores the sensor and scales every 5 s. Note that for the first batch of gauges calibrated at KNMI a sample interval of 10 s was used. Hence an uncertainty of the absolute time stamps t of dt=7 s (14 s for first batch) is used in case the sensor reports a measurement asynchronously. The time uncertainty for tipping bucket sensors is furthermore scaled with the number of tips per sample interval according to dt = 7 s/#tip where the number of tips is 1 or higher. An uncertainty of dt = 1.4 s is adopted in case the sensor can be polled and replies with an instantaneous value. The measurement of mass m is in addition affected by evaporation E. The second identical scale is used to measure the intensity of evaporation, I_E, and the reference intensity I_r is corrected for evaporation. At high intensities, when both scales are used to provide the larger amounts of water, or during the first batch when the second scale was sometimes not used to determine the evaporation, an estimated value of the evaporation is used (see Table 1). The uncertainty of the evaporation correction is assumed to be given by dI_E = 0.02 mm·h^{-1}. The overall uncertainty is determined by the errors caused by evaporation, the uncertainty in the density of tap water and in the measurement of mass and time. The contribution of each of these error sources is assumed to be independent. From the relation

$$I_r - I_E = \Delta m/\Delta t \times 1/\rho$$

and assuming that $I_E \ll \Delta m/\Delta t \times 1/\rho < I_r$ it can be shown that the relative uncertainty of the calibration setup is given by:

$$dI_r/I_r = \sqrt{[\,(dm/\Delta m)^2 + (dt/\Delta t)^2 + (d\rho/\rho))^2 + (dI_E/I_r)^2\,]}.$$

The uncertainty depends on the duration and the total amount of mass used for the calibration, which vary. The amount of water used in the calibration setup generally increases with precipitation intensity and hence the uncertainty of the results increases for higher intensities. Furthermore gauges with a larger surface area require, for a given intensity, more water than sensors with a smaller surface area resulting in a higher uncertainty for sensors with a larger surface area. In order to compensate for these effects the calibration runs at low intensities and for sensors with a smaller surface area have a longer duration. The duration of the runs was determined such that for a tipping bucket gauge at least 10 tips occur with a minimum of 16 minutes, and for the other sensors such that at least 10 ml = 10 g is pumped into the sensor with a minimum of 5 minutes.

When applicable the delay of the sensor was taken into account. The relation between the time interval between 2 tips of a tipping bucket sensor and the intensity is given by:

Δtip (sec) = tipping bucket content (ml) / flow rate (ml/min) × 60,

and since tipping bucket content (ml) = tipping bucket resolution (mm) × collector area (cm^2) / 10 this leads to:

Δtip (sec) = tipping bucket resolution (mm) / intensity ($mm{\cdot}h^{-1}$) × 3600.

Note that the above expression also determines the minimum time interval that is required in order to be able to calculate the precipitation intensity for a tipping bucket gauge since the occurrence of at least 2 tips is required for that purpose. The uncertainties obtained with the above expression are given in Table 1. For that purpose the decrease in mass and the time interval between the start and end of each intensity run are considered. For tipping bucket sensors the interval is restricted to the interval between the first and last tip reported in an intensity run.

Gauge	Orifice area (cm^2)	Max. intensity ($mm{\cdot}h^{-1}$)	Resolution tipping bucket (ml / mm)	Relative uncertainty of I_r (%)					I_E ($mm{\cdot}h^{-1}$)
				2 $mm{\cdot}h^{-1}$	**20** $mm{\cdot}h^{-1}$	**50** $mm{\cdot}h^{-1}$	**200** $mm{\cdot}h^{-1}$	**max**	
Rimco 7499	323.7	500	6.47 /	1.2	1.5	1.3	0.7	0.6	0.07
TB-3	314.2	700	6.28 /	1.2	1.5	1.3	0.7	0.5	0.06
AP23	500.0	720	5.00 /	1.2	0.9	0.9	0.6	0.5	0.07
Alluvion 100	98.5	300	1.97 /	1.3	1.7	1.5	0.9	0.7	0.07*
MRW500	500.0	400		1.1	0.6	0.8	0.8	0.8	0.09
MR3H-FC	500.0	500	5.00 /	1.4	1.6	1.2	0.6	0.5	0.05
VRG101	400.0	2000		3.4	3.0	3.0	3.0	3.0	0.05
Nilometre	400.0	200		1.4	1.4	1.4	1.4	1.4	0.07
Pluvio 250	200.0	1200		1.6	1.8	1.7	1.7	3.0	0.25
TBRG	324.3	2000	16.21 /	1.0	1.0	0.9	0.9	0.6	0.09
UM7525	1000.0	300	20.00 /	1.2	0.9	0.9	0.8	0.6	0.03
PMB2	1000.0	300	20.00 /	1.2	0.9	0.9	0.8	0.6	0.03
R102	1000.0	300	20.00 /	1.2	1.0	0.9	0.9	0.9	0.02
WMB01	314.2	200	31.42 /	1.2	1.1	1.9	1.6	1.6	0.10*
T-200B	200.0	600		1.7	1.0	0.9	0.8	0.8	0.08*
TRwS	500.0	600		1.2	0.8	0.8	0.8	0.8	0.11
1518 H3	200.0	600	2.00 /	1.3	0.9	0.9	0.6	0.5	0.16
100000E	400.0	500	8.00 /	1.1	0.9	0.9	0.8	0.6	0.08
H-340-SDI	324.3	635	8.24 /	1.1	0.9	0.9	0.8	0.6	0.10

Table 1: Overview of the uncertainties for the calibration runs with the different precipitation gauges and intensity levels. The last column reports the typical evaporation that was measured during the calibration runs ('*' indicates an estimated evaporation value).

All rain intensity gauges analyzed – synthesis of the results

Manufacturer	Model	Measuring principle	Correction applied	Actual range of measurement (mm·h^{-1})	Max error range (%)	WMO compliant range (+/- 5%)	Resolution (mm)	Notes
CAE (Italy)	PMB2	TBRG	YES	2 – 300	-5 , +5	2 – 300	0.2	
CASELLA (UK)	100000E	TBRG	NO	2 – 400*	-20 , 0	2 – 100	0.2	1
ETG (Italy)	R102	TBRG	YES	2 – 300	-5 , +5	2 – 300	0.2	
IMD (India)	MKII	TBRG	NO	2 – 2000	-20, 0	2 – 100	0.5	
LAMBRECHT (Switzerland)	1518H3	TBRG	NO	2 – 600	-30 , +10	2 – 70	0.1	2
METEOSERVIS (Czech Rep)	MR3H	TBRG	YES	2 – 300*	-10 , 0	2 – 200	0.1	1
PAAR (Austria)	AP23	TBRG	NO	2 – 720	-25 , +10	2 – 100	0.1	
SIAP (Italy)	UM7525	TBRG	NO	2 – 250	-20 , 0	2 – 20	0.2	
WATERLOG (USA)	H340 SDI	TBRG	YES	2 – 635	0 , +10	2 – 150	0.2	
YOKOGAWA (Japan)	WMB01	TBRG	YES	2 – 2000	-5 , +5	2 – 2000	1.0	1, 3
RIMCO (Australia)	7499	TBRG	NO	2 – 400*	-5 , +5	20 – 400	0.2	1
H.S. PTY LTD (Australia)	TB3	TBRG	NO	2 – 700*	-5 , +5	2 – 700	0.2	1
GEONOR (Norway)	T200B	WG	-	2 – 2000	-5 , +5	20 – 2000	0.1	
METEOSERVIS (Czech Rep)	MRW500	WG	-	2 – 400	-5 , +5	2 – 200	0.1	
MPS SYSTEM (Slovakia)	TRWS	WG	-	2 – 600	-5 , +5	2 – 600	0.001	
OTT (Germany)	PLUVIO	WG	-	2 – 1200	-2 , +2	2 – 1200	0.01	
VAISALA (Finland)	VRG1	WG	-	2 – 2000	-10 , +10	2 – 1500	0.1	
SEROSI (France)	Nilometre	WLG	-	2 – 200*	-5 , +5	2 – 200	0.1	4
ALLUVION (Canada)	100	WLG	-	2 – 300	-40 , +10	none	0.2	5

* The actual range is different from the one declared by the manufacturer.
1 Storage occurs in the funnel.
2 A correction curve is recommended and was provided in a table form by the manufacturer, its application is up to the user. Based on such table the error is within about the –5 , +5 % range.
3 Problems in recording the rain signal were encountered at very low intensities probably due to the use of a rain detector.
4 The measure is highly dependent on water conductivity and the device works in the range (0 – 200 μS/cm)
5 The siphon is activated continuously in time under some circumstances

PARAMETERS OF THE CORRECTION CURVE

TIPPING BUCKET GAUGES Manufacturer	Model	Correction applied	Instrument 1			Instrument 2		
			a	b	R^2	a	b	R^2
CAE (Italy)	PMB2	YES	0.9772	1.0056	0.9999	0.9969	1.0044	0.9999
CASELLA (UK)	100000E	NO	1.1497	0.9448	0.9971	1.1394	0.9481	0.9978
ETG (Italy)	R102	YES	0.9757	1.0035	0.9997	0.9873	0.9997	0.9999
IMD (India)	MKII	NO	1.0938	0.9638	0.9996	1.0804	0.9631	0.9995
LAMBRECHT (Switzerland)	1518H3	NO	1.2218	0.9310	0.9986	1.2358	0.9262	0.9981
METEOSERVIS (Czech Rep)	MR3H	YES	0.9739	0.9956	0.9998	0.9407	1.0017	0.9997
PAAR (Austria)	AP23	NO	1.1978	0.9416	0.9991	-	-	-
SIAP (Italy)	UM7525	NO	1.0273	0.9769	0.9995	1.0280	0.9679	0.9994
WATERLOG (USA)	H340 SDI	YES	1.0494	1.0015	0.9997	-	-	-
YOKOGAWA (Japan)	WMB01	YES	0.9810	1.0029	0.9999	0.9901	0.9992	0.9999
RIMCO (Australia)	7499	NO	0.9446	1.0135	0.9995	0.9463	1.0129	0.9987
H.S. PTY LTD (Australia)	TB3	NO	0.9095	1.0108	0.9977	0.9326	1.0064	0.9994

WEIGHING GAUGES Manufacturer	Model	Delay (min)	Instrument 1			Instrument 2		
			a	b	R^2	a	b	R^2
GEONOR (Norway)	T200B	3	0.9013	1.0153	0.9995	0.9363	1.0129	0.9995
METEOSERVIS (Czech Rep)	MRW500	0.33	0.9703	1.0057	1.0000	0.9971	1.0001	0.9999
MPS SYSTEM (Slovakia)	TRWS	3	0.9905	1.0013	1.0000	0.9766	1.0043	0.9999
OTT (Germany)	PLUVIO	9	0.9792	1.0036	1.0000	0.9972	1.0014	0.9999
VAISALA (Finland)	VRG1	4	0.9920	0.9993	0.9991	0.8969	1.0196	0.9998

WATER LEVEL GAUGES Manufacturer	Model	Principle	Instrument 1			Instrument 2		
			a	b	R^2	a	b	R^2
SEROSI (France)	Nilometre	Conduct.	0.9988	0.9987	0.9999	1.0010	0.9968	0.9995
ALLUVION (Canada)	100	Conduct.	0.8622	0.9842	0.9981	1.1341	0.9436	0.9887

Notes: TBRG: Tipping Bucket Rain Gauge, WG: Weighing Gauge, WLG: Water Level Gauges

CORRECTION OF HISTORICAL RAIN SERIES: A SAMPLE EXERCISE

Since mechanical errors of the tipping-bucket rain gauges affect the higher rain rates that are usually recorded at very short intervals in time (even within events totalizing low to average rain volumes), recovering of rain records by means of suitable correction is only possible at very fine resolution in time. Unfortunately, most of the historical information is stored in the form of accumulated rainfall values over intervals of 30 to 60 minutes at best and the details of the rain process at finer time scales are irremediably lost. In those cases correction can be performed based on suitable downscaling of the recorded figures at least down to resolution in the order of five minutes, where the rain rate is higher and significant biases arise. Obviously correction would result in a statistical sense, and no deterministic assessment can be performed of the actual impact of the error on design values.

In case the rain series is available at fine resolution in time (e.g. in the order of 1 to 10 minutes) direct correction is possible by simply modifying recorded values at each single time step. Correction is obtained by using the calibration curve, with the actual intensity now being the unknown variable. The specific correction parameters must be preliminarily available for the instrument in hand, as derived from suitable dynamic calibration of the gauge. The calibration exercise should be periodically repeated since the performances of the instrument changes with time and wear, so that at least yearly checking would be desirable.

At coarser resolution scales, since the rainfall intensity decreases with increasing aggregation of the rain depth increments in time, the correction would be applied on artificially lower rain rate figures that do not correspond to the original rain rates actually recorded by the instrument. On the contrary the error affects the originally recorded rain rates, thus higher values than those resulting from aggregation at the hourly scale, and direct correction of such information would inevitably result in large underestimation of the biases involved.

Reconstruction of the original variability at sub-hourly scales is therefore required, at least down to a resolution in the order of one to five minutes, since at lower scales sampling errors may become also relevant. Appropriate downscaling methodologies allow performing this exercise in a statistical sense, i.e. by generating a set of possible scenarios of the inner rainfall structure that are compatible with the recorded pattern at the coarser (hourly) scale. Once small scale data are available for each of the generated scenarios, direct correction is possible and data are re-aggregated at the original resolution in order to allow comparison with the original data set. Ensemble statistics for the whole set of corrected time series may finally provide the required parameters and their dispersion characteristics.

In case of direct correction performed over high resolution data sets, the procedure is therefore deterministic and the statistics derived from original and corrected rain records can be easily compared. In Figure 1, the DDF curves for a sample station are reported, with return periods from 2 to 50 years. Higher return periods are not shown because of the limitation deriving from the short time period of the available observations (about 10 years). In each graph the curves based on the original and corrected data are reported so as to facilitate comparison between design rainfall estimates in the two cases. Obviously, results can be read from different viewpoints and other representations are used in Molini *et al.* (2005) to allow an easy assessment of the ratio between original and corrected design rainfall for any duration of the rain event and for a given choice of the associated return period. The same information is synthesized in Figure 2, where the actual “gain” obtained after direct correction is applied is expressed as a function of duration for all the return periods analyzed.

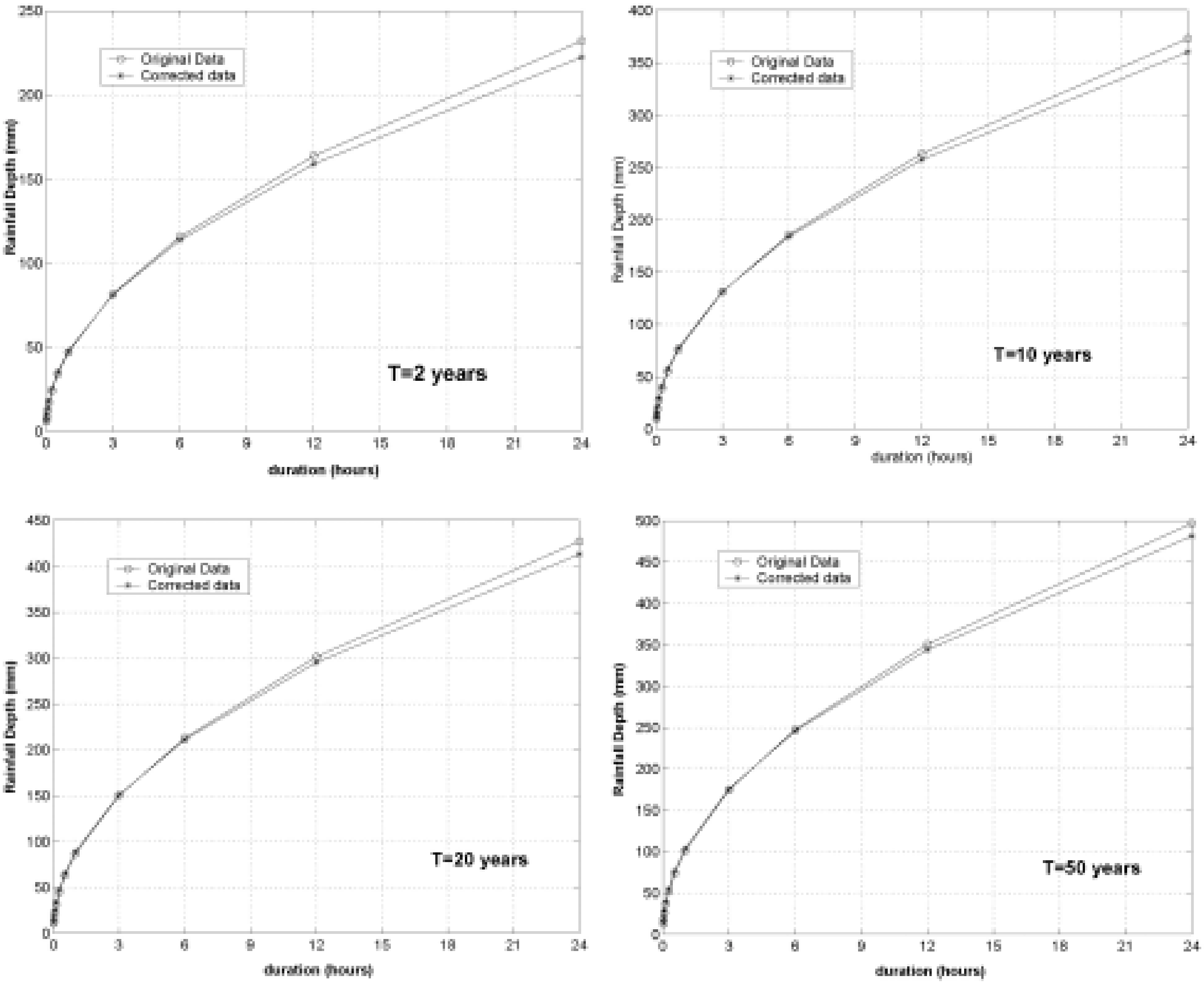

Figure 1: Original and corrected DDF curves for a sample station at various return periods.

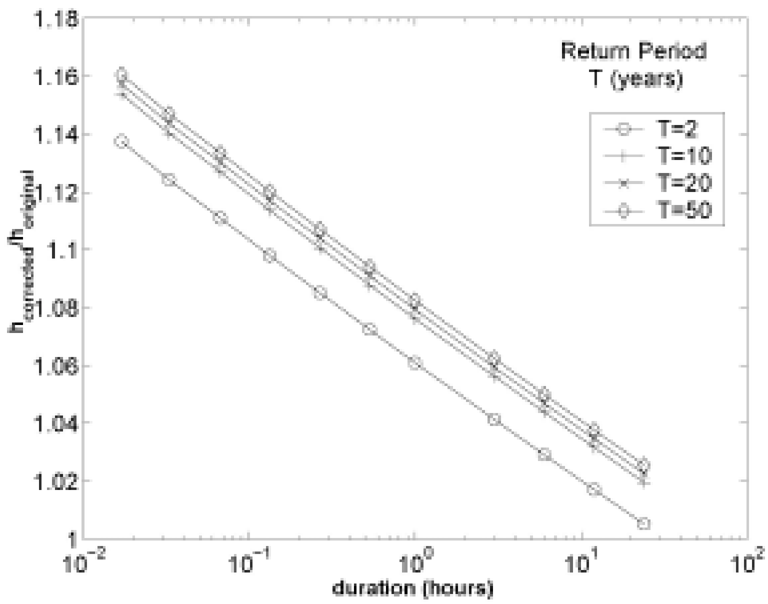

Figure 2: Synthetic representation of the "gain" obtained after direct correction on the high resolution data set from the sample station.

Note that the gain decreases with increasing duration, since the relative weight of low intensity components of the rain event (where correction is not significant) increases. On the contrary, the gain obviously increases for any fixed duration with increasing return periods, since the error increasingly affects the higher intensities. Negative gains may appear towards longer durations and for short return periods, due to the fact that correction inversely affects the rain intensity figures when these are lower than the single point calibration value usually provided by rain gauge manufacturer on all instruments (these are calibrated at a rain rate around 30-50 $mm \cdot h^{-1}$).

A second high resolution time series is obtained as an ensemble of possible realizations, and the parameters of the DDF curves are evaluated per each single realization, therefore allowing interpretation only in statistical terms. Downscaling is performed by means of a multiplicative random cascade. An average curve and a measure of dispersion can be easily provided to describe the results. In Figure 3, the original DDF curve and the ensemble of the corrected curves derived from 1000 realizations of the possible rain intensity pattern at sub-hourly scale are represented on the same graph, together with the average corrected curve. The information is now provided for return periods from 2 to 200 years, since the original hourly records cover in this case a longer period of time.

Also in this case results can be read from different viewpoints and another representation is used in Figure 4, where the actual "gain" obtained after statistical correction is applied is expressed as a function of duration for all the return periods analyzed. The figures reported in this graph refers to the average corrected curve.

The above figures are estimated both by direct correction of the available high resolution rain records and after suitable downscaling of a coarser data set. In the first case correction is deterministic and does not require any sophisticated algorithm. Therefore, when original records with a resolution of at least five minutes are available the use of non corrected data seems not be justified in any even practical application. Dynamic calibration is indeed easily attainable and rain gauge manufacturers are progressively producing self-calibrating instruments, which overcome the problem and provide more accurate rain intensity measurements.

In the more common case where the original data set is available at coarser resolution scales, typically in the order of one hour in most meteorological stations, correction of systematic mechanical errors involves the implementation of some suitable downscaling algorithm in order to apply direct correction on rain data described at proper resolution in time. Whatever the algorithm selected to this aim, correction is applied in this case on a set of possible scenarios of the unknown small scale pattern of rain intensity over time. The results are therefore available only in the form of statistical estimates and a suitable measure of dispersion must be provided in order to better qualify such information. The structure of the downscaling model may actually influence the results obtained in terms of statistics of the corrected data. For the methodology and use of different algorithms see e.g. Molini et al. (2005a,b).

One last comment about the homogeneity of temporal rainfall series relates to climate change. Indeed, any typical monitoring network that is continuously updated with more reliable gauges would experience an artificial climatic trend towards increasing climatological precipitation in case mechanical errors affecting historical records are systematically neglected. Since rain gauge manufacturer companies are progressively distributing dynamically calibrated instruments, the risk of introducing artificial trends in rainfall series is far from being just academic.

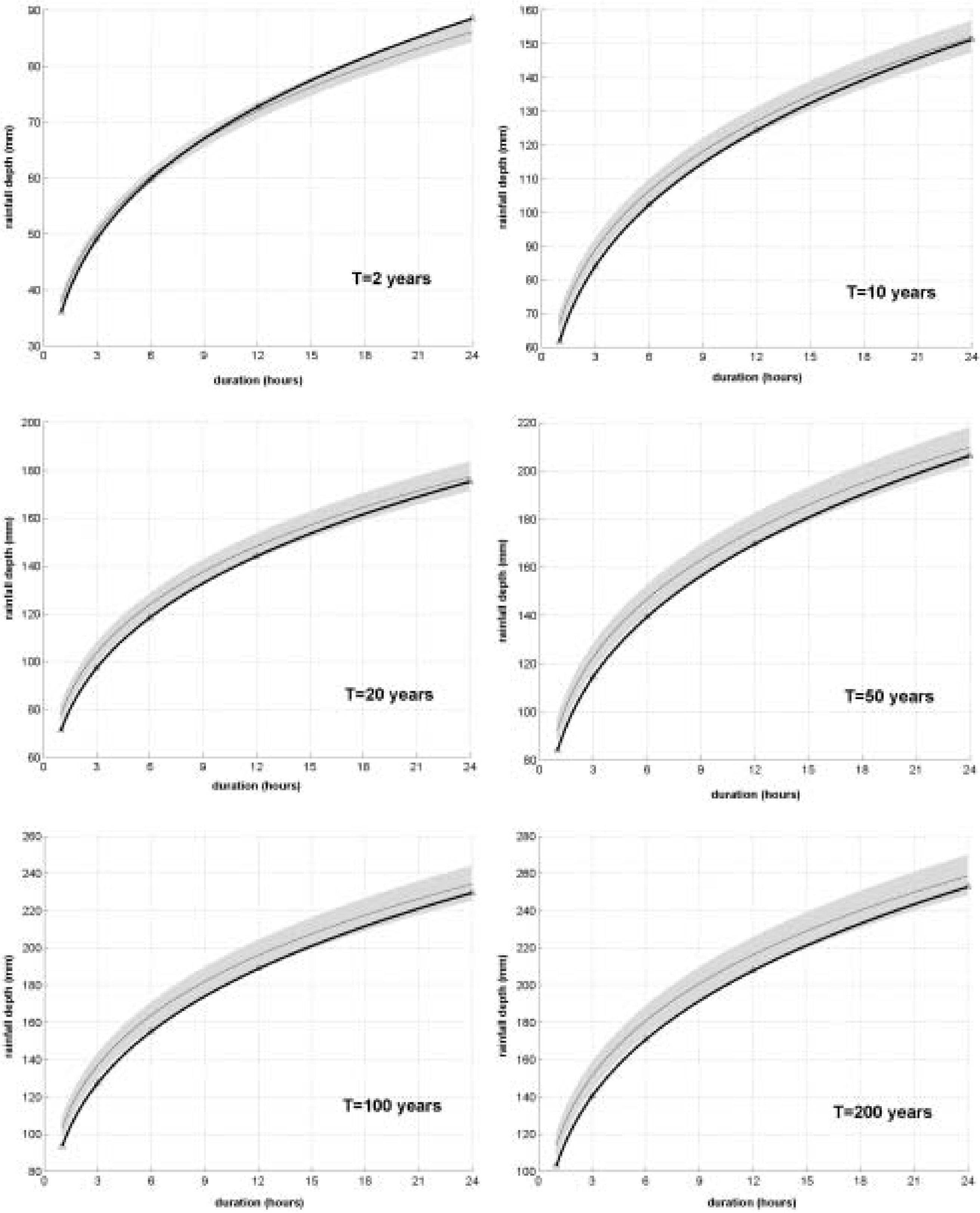

Figure 3: Original and ensemble of corrected DDF curves for the second station at various return periods.

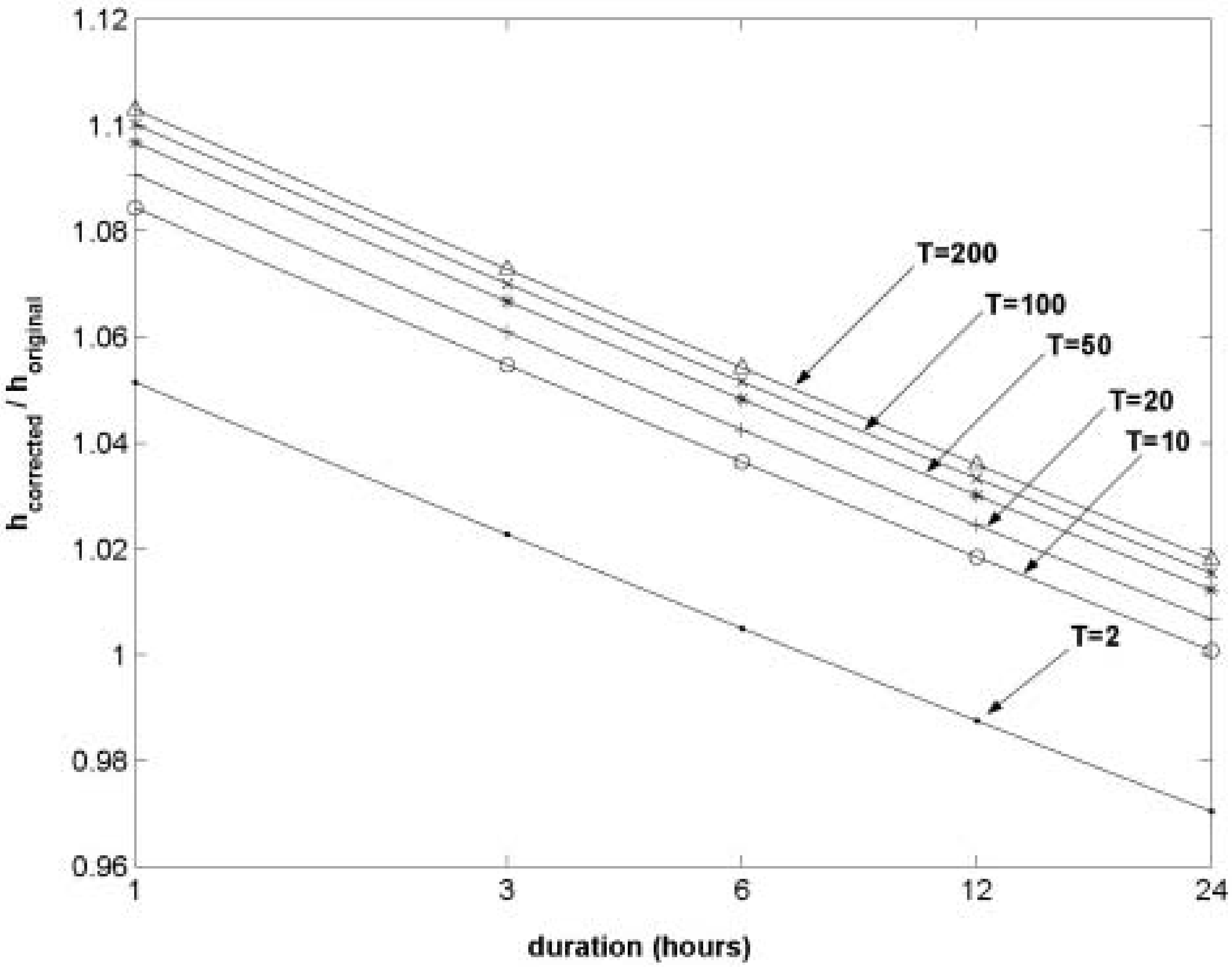

Figure 4: Synthetic representation of the "gain" obtained after correction of the high resolution realizations obtained from the downscaling of hourly records.