ON THE QUALITY OF TIPPING-BUCKET RAIN INTENSITY MEASUREMENTS

Luca G. Lanza and Luigi Stagi

University of Genova, Dept. of Environmental Engineering, 1 Montallegro, 16145 Genova, Italy
Tel. +39-010-3532123, Fax: +39-010-3532481, E-mail: luca@diam.unige.it

Abstract

The WMO Laboratory Intercomparison of Rainfall Intensity (RI) Gauges - described in a companion paper - was the very first attempt at understanding the performances of various types of rainfall intensity gauges in controlled laboratory conditions, and provided quantitative information regarding various errors associated with RI measurements. The conclusions report that all instruments analyzed were subject to errors and uncertainties in the measurement of rainfall intensity. Also, it was established that Tipping-Bucket Rain gauges (TBRs) that were equipped with proper correction software provided good quality rainfall intensity measurements. Where no correction was applied the gauges had larger errors. The uncertainty was generally less for weighing gauges than for the tipping-bucket ones, under constant flow rate conditions, provided there is a sufficient time to stabilize the instrument. The measurement of rainfall intensity is affected in these cases by the response time of the acquisition system: significant delays were observed in "sensing" the variation in time of the rain intensity.

Despite their low installation and maintenance costs, the very simple mechanics, and the long lasting experience available, the asserted lower accuracy of tipping-bucket rain gauges has been considered one of the major drawbacks of this traditional technique for many years, and this lead to the development and spreading of weighing gauges or other types of non-catching sensors.

On the contrary the results obtained in the laboratory show that the errors associated with the measurement of rainfall intensity obtained by tipping-bucket rain gauges can be reduced at less than 1% over a wide range of rain rates, which is not possible with other type of gauges in real world conditions (variable rainfall intensity). All such issues are discussed, together with the most advanced quality procedures required to obtain high precision in the measurement of rainfall intensity with TBRs.

Introduction

This paper investigates the performances of tipping-bucket rain gauges (TBRs) in measuring rainfall intensity, using results from laboratory tests performed under constant flow rate conditions.

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.

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.

On the other hand counting errors are 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. The WMO Laboratory Intercomparison of Rain Intensity Gauges (described in a companion paper) concentrated on the counting errors of the catching type instruments. These errors may derive from the very different aspects of the sensing phase since the instruments may differ in the measuring principle applied, construction details, operational solutions, etc.

Results from the WMO Laboratory Intercomparison report that only those tipping-bucket rain gauges that apply proper correction to account for mechanical errors comply with the WMO specifications on the required accuracy for rainfall intensity measurements. As for the performance of weighing gauges, their accuracy is generally higher than tipping-bucket rain gauges, although many of them are subject to a quite long delay in response, with large errors applying to rainfall intensity measurements, so that the WMO requirements are not met. Other measuring principles were also tested, but the small number of instrument submitted (two) did not allow to obtain any conclusive information.

This paper concentrates on tipping-bucket rain gauges (TBRs) and specifically on the correction procedure that can be applied by software codes operating appropriate post-processing of raw measured data. Although the residual uncertainty of such instruments generally complies with the WMO specifications (± 5%), the errors under constant flow rate conditions are still higher than those associated with other types of gauges. Although under variable (real) rain intensity, TBRs have the potential to perform fairly better than other types of gauges since they have practically no delay in sensing rainfall variations at sufficiently intense rain rates, the objective of the present work is to demonstrate that the residual uncertainty of TBRs can be reduced to less than ± 1% provided that accurate procedures are used for calibration and suitable post-processing software codes are implemented.

Description of the laboratory tests

The development of a laboratory device for qualification and testing of rain intensity measurement instruments and the demonstration of the relevant errors associated with non calibrated gauges have been addressed before and during the WMO Laboratory Intercomparison.

At the laboratory of the Department of Environmental Engineering of the University of Genoa, an automatic device has been designed and a prototype, that is illustrated in Figure 1, has been realised. 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 level 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 contemporary 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 is determined using a precision balance. During the test the ensemble precision balance/weighing tank is protected by a plastic structure which also supports the RI gauges under calibration.

The duration of the tests and the mass measurement are 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%, taking also into account the resolution of the instrument.

Fig 1: The Qualification Module for Rain Intensity Measurement Instruments developed at DIAM.

Each test was performed at least at six reference flow rates. However the whole range of operation declared by the manufacturer was also investigated.

The reference intensities were obtained within the following limits:

- 1.5 – 4 mm·h^{-1} at 2 mm·h^{-1}
- 15 – 25 mm·h^{-1} at 20 mm·h^{-1}

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

Five tests were performed for each set of reference intensities, so that five error figures are associated with each instrument. The average errors are obtained by discarding the minimum and the maximum value obtained for each reference flow rate, then by evaluating the arithmetic mean of the three remaining errors and reference intensity values.

For the second set of gauges three tests were performed at each reference intensity and the average of the three tests was used to derive the error and correction curves.

Test results

The investigated gauges were selected on account of the final results of the recently concluded WMO Laboratory Intercomparison of RI gauges (Lanza, 2006), where the performances of various types of rain gauges from different manufacturers were compared under laboratory conditions. This is consistent with the purpose of this work to concentrate on counting errors.

In particular, the results of the Intercomparison as for tipping-bucket rain gauges were taken into account. By inspection of the various curves presented in the Final Report (Lanza et al., 2005) it is evident that the errors of TBRs with post-processing correction are generally smaller with respect to the non-corrected gauges. The Report concludes 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.

This two Italian models were therefore investigated further in the present work in order to assess their potential performances after suitable calibration in the laboratory is performed and the related correction applied. A single correction curve, suitable for the whole family of gauges belonging to each model is sought as indicative of an average behaviour.

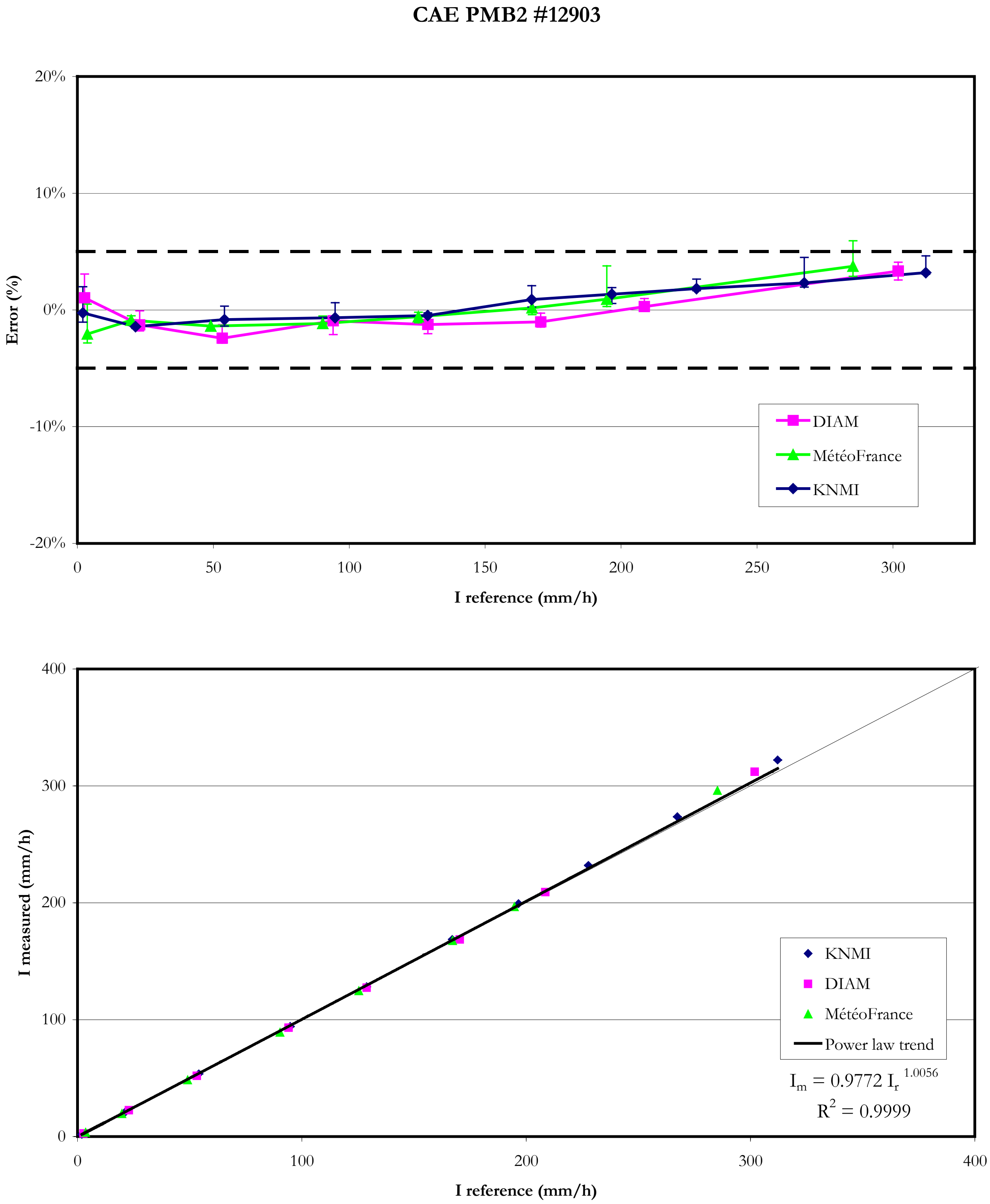

Fig. 2: Relative error and correction curve for the CAE-PMB2 as obtained during the WMO Laboratory Intercomparison of Rainfall Intensity Gauges at the three independent laboratories.

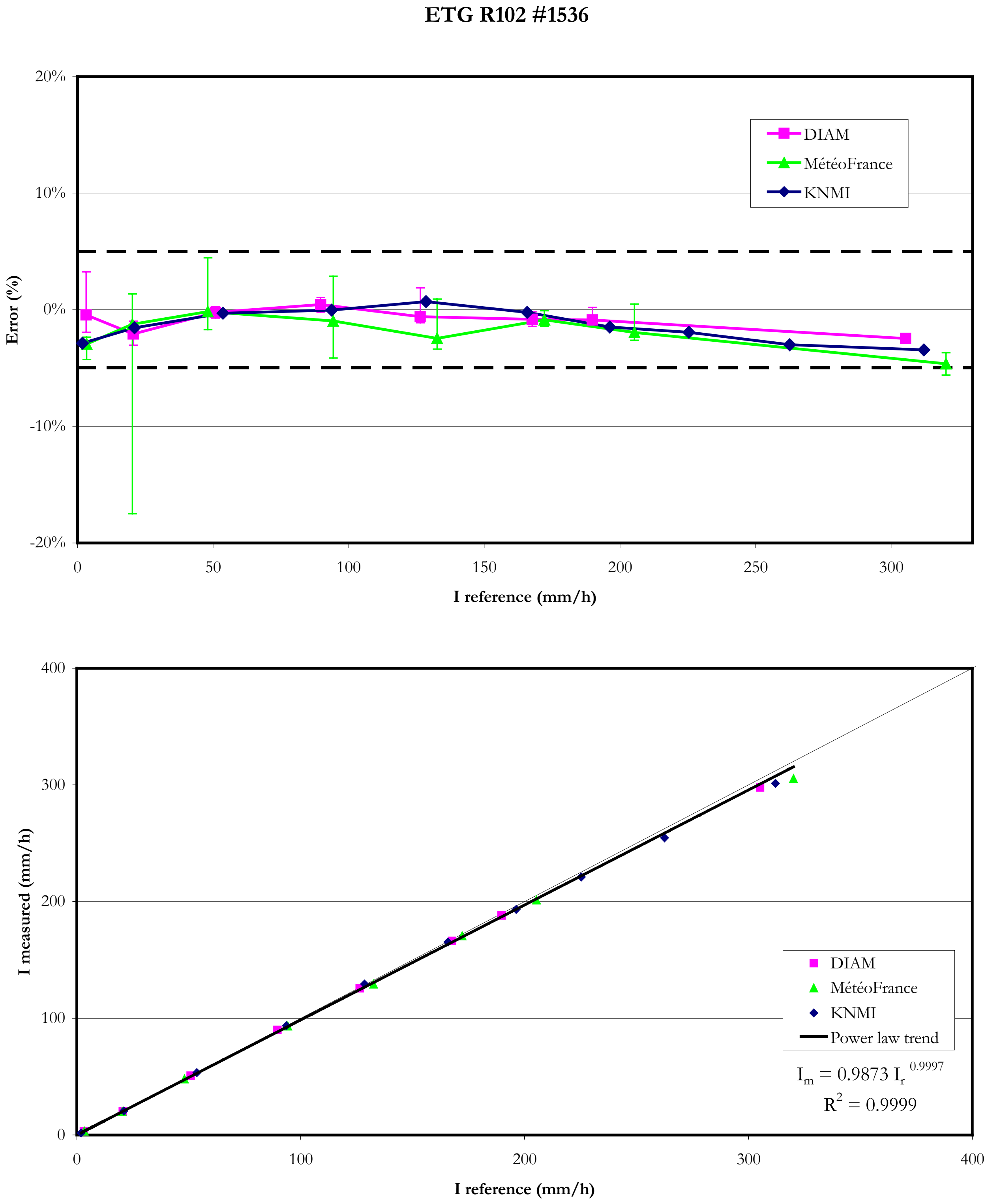

Fig. 3: Relative error and correction curve for the ETG-R102 as obtained during the WMO Laboratory Intercomparison of Rainfall Intensity Gauges at the three independent laboratories.

Rainfall intensity measurement errors that are typical of tipping-bucket rain gauges derive from the combination of different factors, that can be synthesised as follows:

- the uncertainty about the real volume of the bucket when the tipping movement is initiated;
- the possible different behaviour of the two compartments of the bucket;
- the mechanical error due to the water losses during the tipping movement of the bucket.

The first source of error derives from using a nominal volume instead of the actual figure to calculate the rainfall intensity starting from the number of tips in a given time window. This difference in the bucket volumes can be used to compensate mechanical errors in order to force a zero error condition at a given rain intensity (this is usually achieved by manually adjusting the bucket capacity until the desired condition is obtained).

The second source is due to the difference in the actual volume of the two compartments, which may not be the same in case of inappropriate balancing of the tipping device. This error reduces with increasing rain rates and may result in calculating a different intensity depending on the number of tips recorded for each single compartment.

As for the third source of error, it is well-known that the tipping-bucket rain gauge underestimates 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 rainfall rates can be quantified on average as 10-15 % at 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.

For a discussion on the practical consequences of neglecting mechanical errors in rain intensity measurements, see La Barbera et al. (2002).

The above described errors were estimated by performing laboratory tests for the two types of instruments under examination. A larger number of gauges (about 30) larger than those examined/tested in the WMO Intercomparison was investigated here for each single model, so as to derive a common behaviour and to assess the variability of individual gauges with reference to the average behaviour.

Each gauge was tested using the standard calibration procedure established by WMO, and therefore both an error and a correction curve were derived per each gauge. Since the two manufacturers already apply some correction using a post-processing software, both the raw and corrected data were recorded and plotted as a function of rain intensity (see Figures 4 and 5) using the operational procedure employed by the manufacturer.

Note that while CAE employs a single correction curve for all the examined gauges, ETG applies an individual correction curve per each gauge. In order to obtain homogeneous data sets, an average curve was calculated for the ETG model and applied to all gauges, so the variability shown here is not representative of the actual performances of the individual gauges.

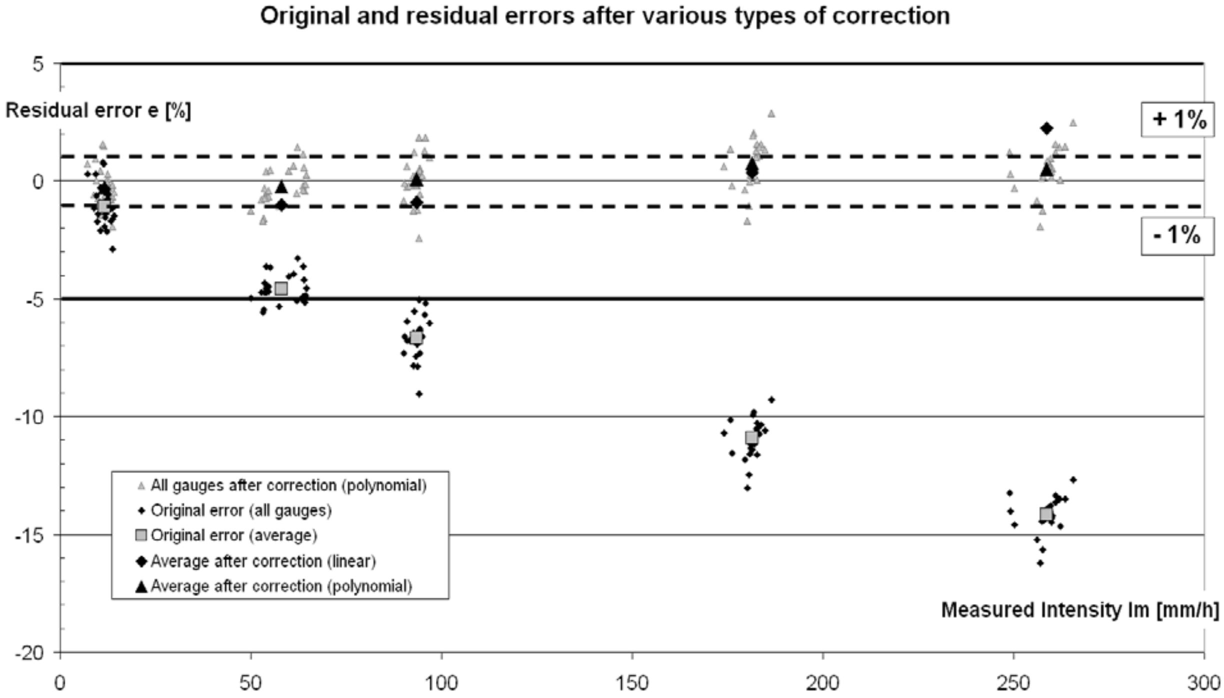

Fig. 4: Variability of individual gauges before and after correction with a linear and polynomial curve for the CAE model.

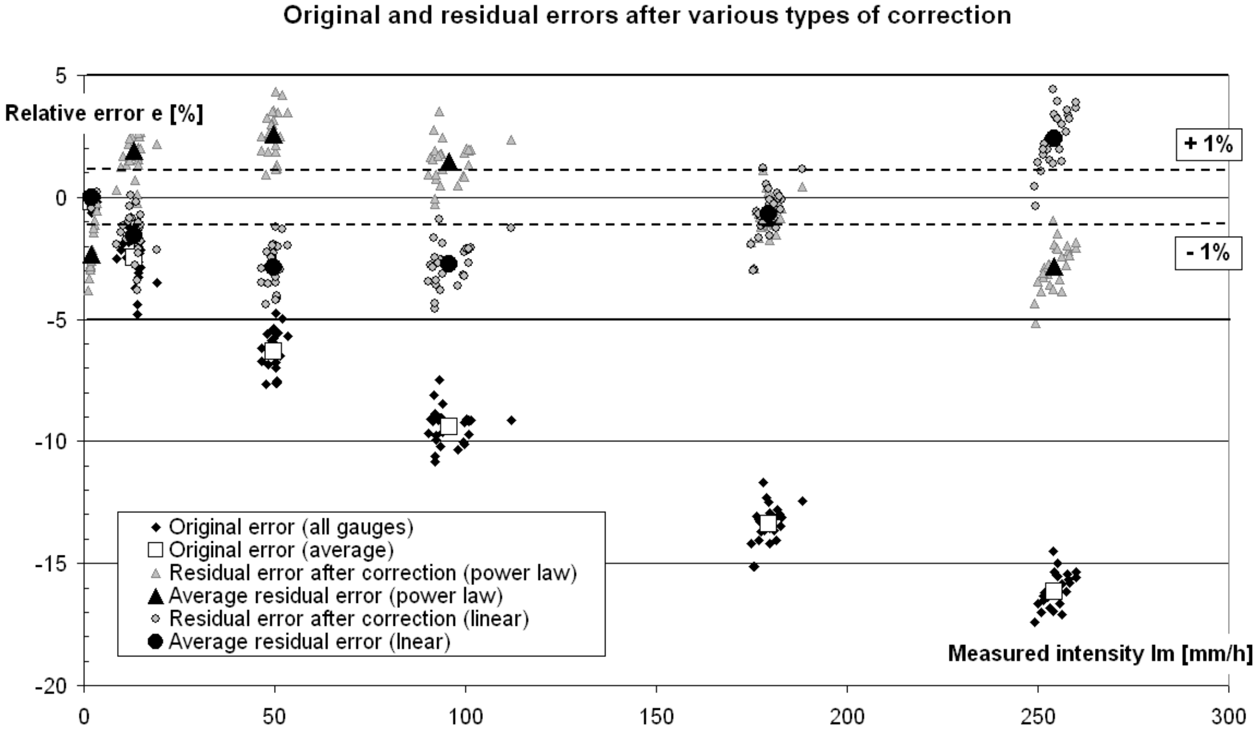

Fig. 5: Variability of individual gauges before and after correction with a linear and polynomial curve for the ETG model

Residual uncertainty of rainfall intensity measurements

In order to improve the correction capabilities of the two instruments, the three sources of error defined in the previous paragraph were separately addressed.

Therefore the actual capacity of the bucket was used in calculating the rain intensity, instead of the nominal volume, so as to later isolate mechanical errors from the uncertainty due to improper counting of the contribution of each tip. The actual capacity was estimated based on the performances observed at intensities where mechanical errors are negligible.

The balancing of the two compartments was carefully performed, although the effect of such calibration is not relevant in this work, since long duration tests are performed and only average results are reported. On the other hand, the unbalanced capacity of the two compartments influences the one-minute rainfall intensity values that are requested in output by the WMO specifications.

Based on the above considerations the contribution due to systematic mechanical errors is then the only component of the relative error obtained as a result of laboratory tests under constant flow rate conditions. Note that relative errors are defined as:

$$e = \frac{I_m - I_r}{I_r} \cdot 100 \ \% \tag{1}$$

where I_m is the intensity measured by the instrument and I_r the actual reference intensity.

An error curve can be fitted to the experimental data in the (e, I_m) space, a second order polynomial being the best suited to represent the behaviour of the gauges over the whole range of operation of the investigated instrument. The error curve is expressed as follows:

$$e(I_m) = a \cdot I_m^2 + b \cdot I_m + c \tag{2}$$

where the coefficients a, b, c are experimentally determined.

Using this curve to derive a proper correction algorithm provides the best results in terms of residual errors, in the form:

$$I_{mc} = \frac{I_m}{e(I_m)/100 + 1} \tag{3}$$

where I_{mc} is the corrected rainfall intensity according to the test results.

The correction algorithm employed by CAE uses a linear expression for $e(I_m)$, while ETG uses a correction curve in the form of a power law in the (I_r, I_m) space.

The residual error is now analogously obtained by comparing the corrected and actual rain rates, using the position:

$$e = \frac{I_{mc} - I_r}{I_r} \cdot 100 \ \% \tag{4}$$

The performances of the instrument after correction can be suitably reported in the two types of graphs used in the WMO Intercomparison, i.e. in the (I_r, I_m) and (e, I_r) space.

In the following diagrams (Figures 6, 7) the results of the tests performed on the investigated instruments are visualised, together with the average residual error obtained after correction using the curves already employed by the two manufacturers (linear and power law) and the one proposed in this work (polynomial). Note that the actual volume of the bucket is here used for calculation of the measured intensity I_m.

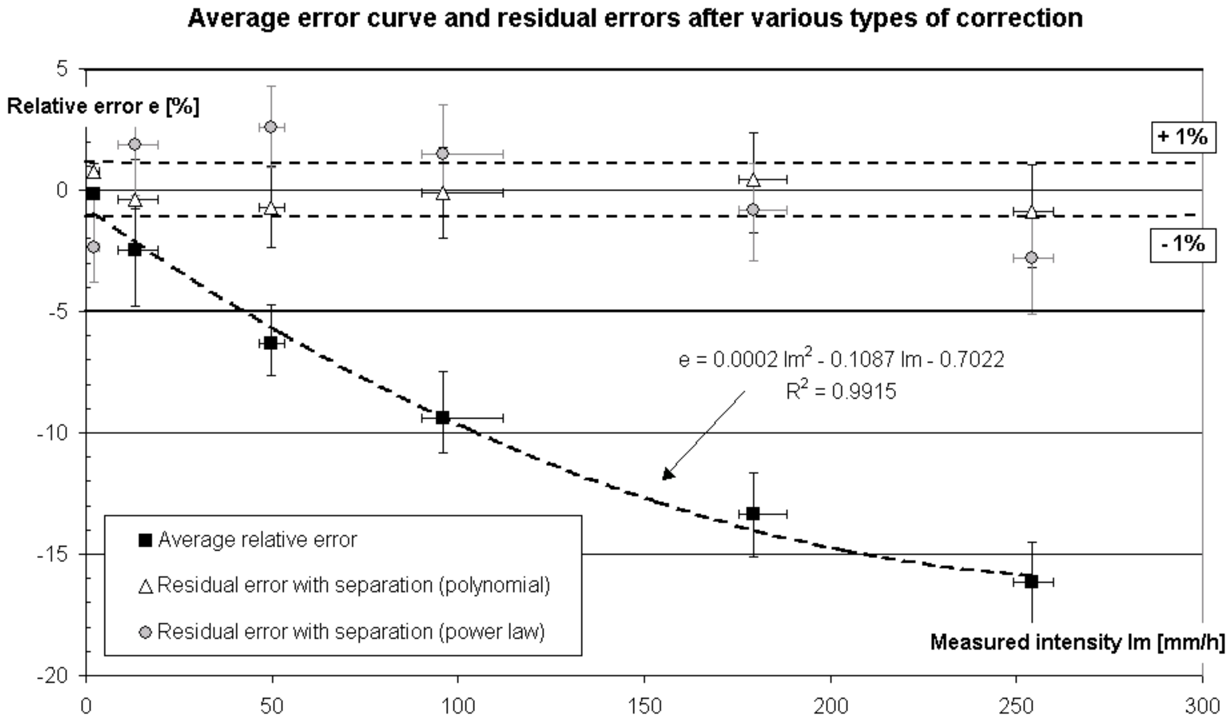

Fig. 6: Average (family) error after separation and correction with a power law and polynomial curve for the ETG model.

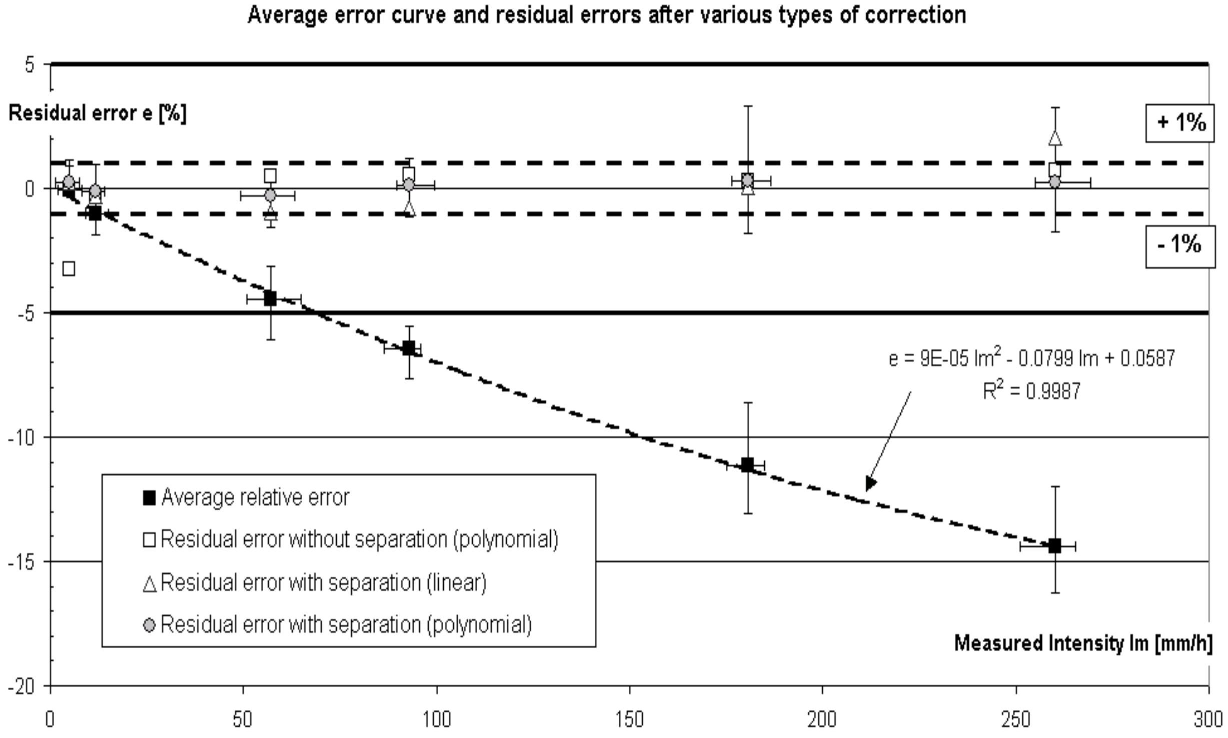

Fig. 6: Average (family) error after separation and correction with a linear and polynomial curve for the CAE model.

Similarly, in Figure 8 and Figure 9 the correction curves providing the best fit of the experimental data are reported for the two types of instruments, and residual errors after correction are shown. Again, the actual volume of the bucket is used for calculation of the measured intensity I_m.

As it is evident from the inspection of the diagrams here presented for both manufacturers, and reported in the Final Report of the WMO Laboratory Intercomparison, the two instruments comply with the WMO requirements for rainfall intensity measurements ($e = \pm 5\%$) already with the correction applied by the manufacturers.

It is also evident that, after separation of the error components and use of the actual capacity of the bucket instead of the nominal one, calibration can be improved and the resulting residual errors can be limited to less than $\pm 1\%$ in case a single curve is used to perform such correction. Correction performed with individual curves further improves this results.

Conclusions

Two sets of rain gauges from two different manufacturers were investigated in this work. Instruments were dynamically calibrated in the laboratory according to the WMO standard procedures recently issued to this aim. A unique calibration curve was determined for the two families of gauges analysed and residual errors after calibration were determined and compared with the WMO requirements and with the performances of other type of gauges.

Results of the tests indicate that:

- correct balancing of the buckets is essential for good instrument performances at one-minute resolution, although the average behaviour is scarcely influenced;
- precise calibration of the bucket capacity is not essential, provided the actual volume is used in calculating the resulting rain intensity instead of the nominal figure;
- the actual volume can be determined based on the performances observed at intensities where mechanical errors are negligible;
- the variability of individual rain gauges with respect to the average correction curve is reduced when the above conditions are met;
- the optimal correction curve can be suitably determined in the laboratory for each model;
- after proper correction the residual error on rain intensity measurements is lower than $\pm 1\%$ for the instruments investigated;
- the errors are comparable to those associated with weighing type of gauges.

Further tests are necessary to investigate the performances of TBRs under variable (real) rain rate conditions. Such tests will be performed during the follow up WMO Field Intercomparison of Rain Intensity Gauges, to be held in 2007-2008 in Vigna di Valle (Rome), Italy.

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