DEALING WITH UNCERTAINTY IN RAINFALL GAUGES CALIBRATION: THE QM-RIM METROLOGICAL VALIDATION

Molini A., Cassini G., Lanza L.G. and L. Stagi
DIAm - Dept. of Environmental Engineering, University of Genova
Via Montallegro,1 Genova, Italy
Ph.: +39 010 3532485, FAX: +39 010 3532481
E-mail: molini@diam.unige.it

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 paper, we handle the metrological validation of the "Module for Qualification of Rainfall Intensity Measurements" (QM-RIM) developed at the Laboratory of DIAM (Dept. of Environmental Engineering of the University of Genova) and here tested in the period from March 2002 to May 2004. The laboratory is one of the three recognized laboratories involved in the WMO Intercomparison of Rainfall Intensity (RI) Gauges started in September 2004. The QM-RIM is an automatic device designed for the calibration of pluviometric instruments by means of a simply reproducible laboratory procedure and able to provide calibration curves for different types of rain gauges. Metrological analysis is here performed in terms of "a priori" error estimation (Type B errors). All the proposed standard procedures refer to the typologies of systematic and statistical errors as defined in the ISO Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, Switzerland, 1993). We describe the methodology adopted, the main results obtained from the initial testing period, the error assessment procedures, and the uncertainty budget analyses performed on the calibration apparatus.

1. INTRODUCTION

The present paper focuses on the metrological validation of the QM-RIM (Qualification Module for Rainfall Intensity Measurements) developed at the Laboratory of DIAM (Dept. of Environmental Engineering of the University of Genova) in the framework of the WMO Laboratory intercomparison of rainfall intensity (RI) gauges (Lanza et al., 2005).

The QM-RIM (Figure 1a and b) is an automatic device designed for the calibration of RI gauges by means of a simply reproducible laboratory procedure and able to provide adjustment curves for different types of rain gauges. Calibration results are then expressed in terms of the coefficients of the calibration curve, which is usually assumed as a power law in the form:

$$I = \alpha \cdot I_R^{\beta} \tag{1}$$

with I the actual rainfall rate, I_R the rain rate measured by the gauge, and α and β the calibration parameters.

Laboratory calibration aims at the reduction of the systematic uncertainties due to the mechanics/structure/measurement principle of RI gauges, while different components of error (such as the variation of performances on different climatic conditions, the dependence from the installation, the limits of reproducibility of measurements and so on) will be the object of the second phase of the intercomparison to be performed in the field.

For a more complete explanation of issues connected with dynamic calibration and uncertainties in RI gauges measurements see Calder and Kidd (1978), Fankhauser (1997), La Barbera et al. (2002), Lanza and Stagi (2003), Molini et al. (2001), Molini et al. (2004)a and Molini et al. (2004)b.

Moreover, the effectiveness of laboratory calibration bases on the inherent precision of the calibration apparatus that, as stated in the "Quality standards for rain intensity measurements" (Lanza and Stagi, 2002) must assure a relative uncertainty lower than 1% at the very least.

The objective of this paper is to present the development of methodologies adopted in the metrological assessment of the QM-RIM uncertainty budget by means of a simple metrological validation and basing on the "ISO Guide to the Expression of Uncertainty in Measurement" (ISO, 1995).

The validation is performed in terms of "a priori" uncertainty and, in order to assure the consistency of QM-RIM with the proposed calibration standards, the principle of maximum uncertainty was applied.

The paper is essentially divided in two parts: the first dedicated to the architecture of the QM-RIM and the second to the metrological validation of different components of the apparatus.

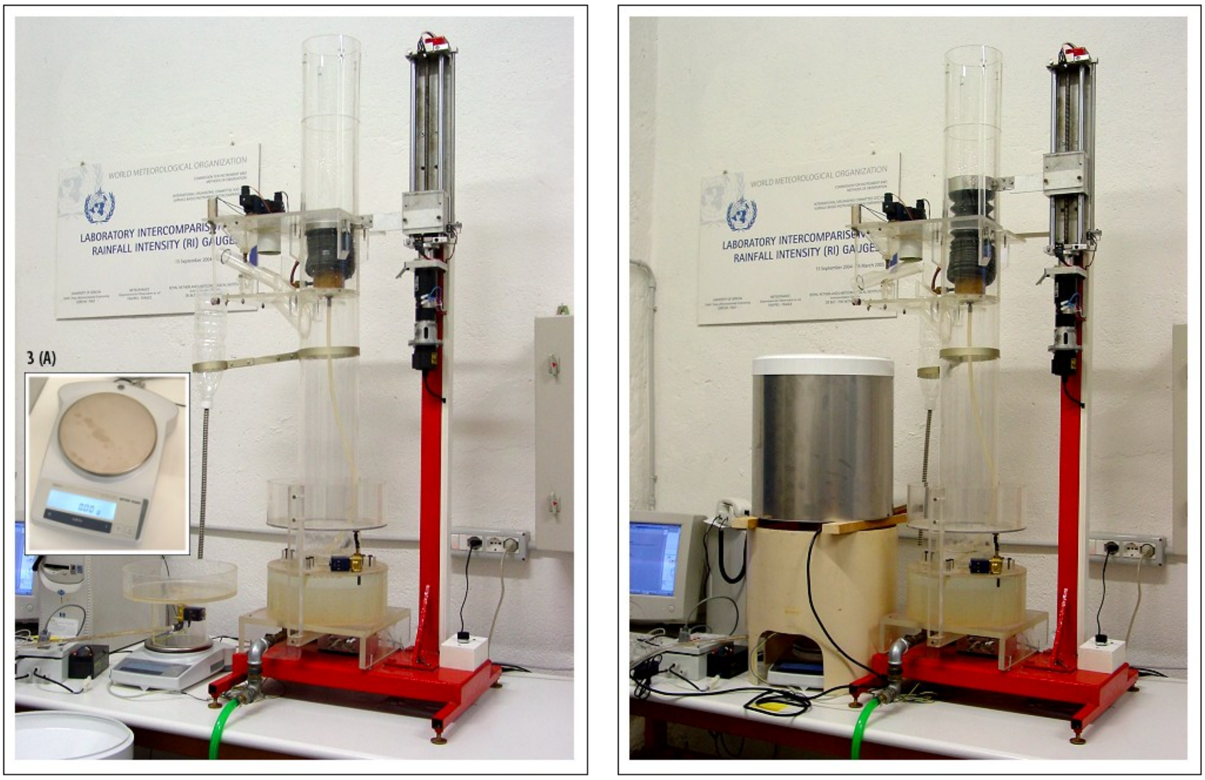

Figure 1: Present configuration of the QM-RIM without (a) and with (b) a RI gauge under test. The inner rectangle also shows a close view of the precision balance, while in figure 1(b) the plastic support for Rainfall Intensity gauges can be observed

In Brief, Section 2 is devoted to the description of the different phases of the QM-RIM assembly. After a concise explanation of the working principle of the module, the whole components of the system are described focusing on their particular functions in the ensemble. Also some photographic documentation is provided in order to facilitate the comprehension of the QM-RIM structure. the module presents in fact a complex structure, which can be basically decomposed in two main components; The constant water head generation component and the weighting system. Both such components are software controlled by a dedicated acquisition system, made up of a pc and an ensemble of acquisition boards. This distinction will be particularly relevant in Sections 3 and 4, where the metrological analysis and uncertainty budget inherent to QM-RIM will be addressed.

Finally, in Section 5 both the total uncertainty budget and the extended uncertainty for the QM-RI module are calculated.

2. THE QUALIFICATION MODULE FOR RAINFALL INTENSITY MEASUREMENTS (QM-RIM)

2.1. Basic Functioning Principle

The QM-RIM’s calibration procedure bases on the capability of the system in producing A constant water flow. This is then provided to the RI gauge under test and both the test duration and the total weight of water flowed through the instrument are automatically recorded by the acquisition system. In particular, the weight measurement is performed by mean of the precision balance shown in Figure 1(a). During the test the ensemble precision balance/weighting tank is protected by a plastic structure (Figure 1(b)) which also supports the RI gauges under calibration.

Knowing the total water weight and the duration of the test assures to obtain, for a given collector, the value of the generated rainfall intensity (actual intensity I).

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 synthetic flow rate is in fact a basic requirement for an accurate estimation of the actual intensity I.

The flow rate Q is simply provided by the classic equation:

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

with ξ a suitable coefficient.

Basing on eq. 2 and assuming ξ as constant, it is possible to generate different steady flow rates by only 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 (reproduced in Figure 2). 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 3). The ensemble pvc bellows – motor with encoder – electro valves is represented in Figure 4. The water level and the orifice diameter are software controlled in order to generate the desired flow rates.

These are compared with the measure that is contemporary obtained by the RI gauge under consideration and dynamic calibration is possible over the full range of rain rates usually addressed by operational rain gauges (see Lanza and Stagi, 2002).

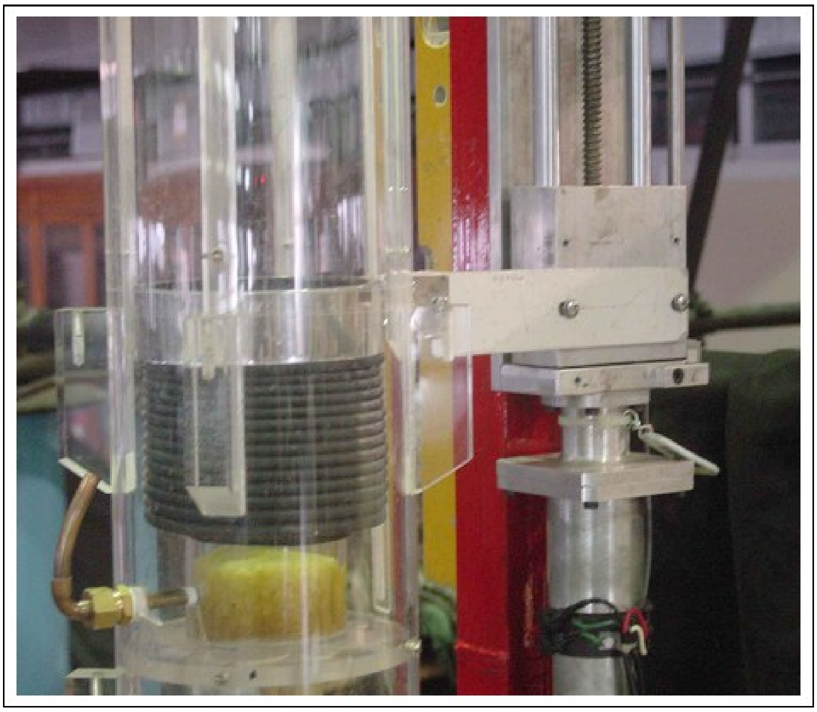

Figure 2: Close view of the cylindrical bellows which allows varying the water in order to produce different water heads. The top of the pvc bellows is connected to a motor with encoder controlled by software.

Moreover, since only variations of the water head *H* can produce variations of *Q*, the system has been developed to rapidly compensate Δ*H* by means of a 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 features of the QM-RIM will turn out particularly relevant in the following, when the uncertainty budget for the constant flow generation apparatus will be calculated.

Figure 3: The three electrovalves that allow to combine different nozzles diameters in order to produce a wide range of water flow rates.

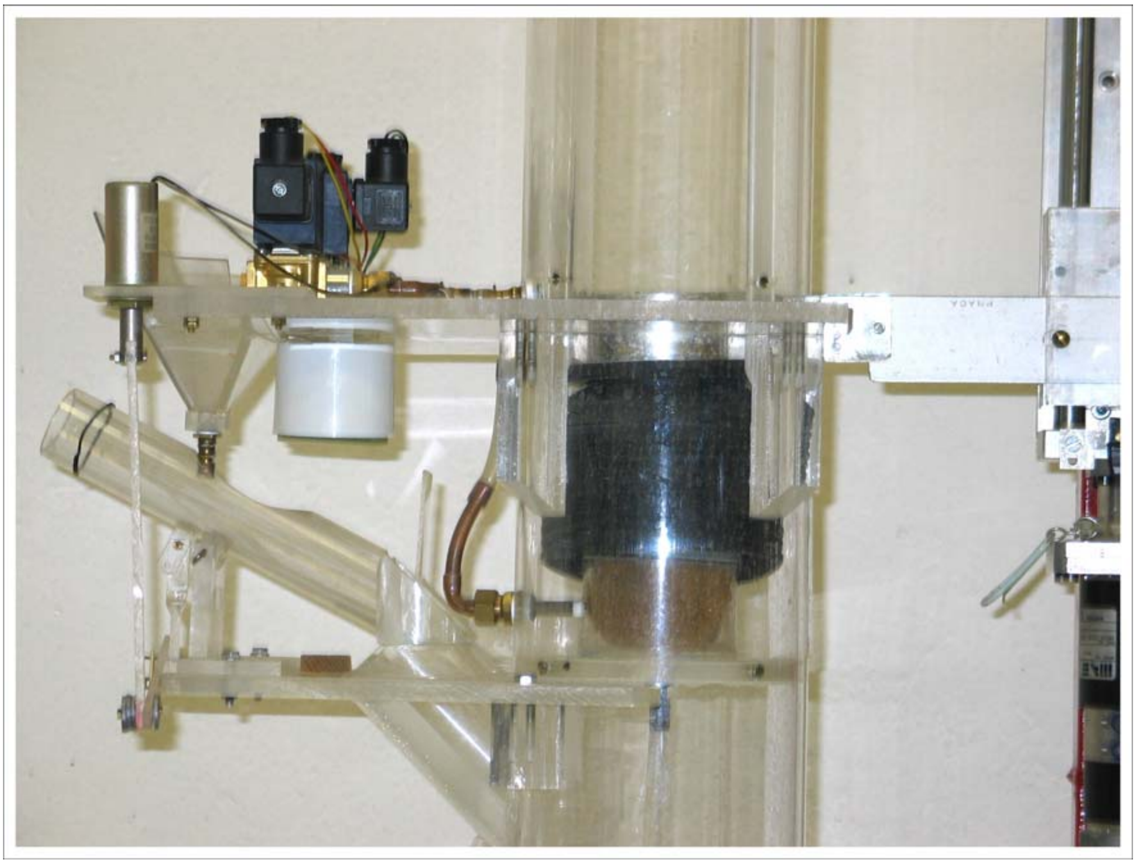

Figure 4: The ensemble electrovalves/pvc bellows/motor of the QM-RIM

3. THE QM-RIM FROM THE METROLOGICAL VALIDATION POINT OF VIEW

In the previous section we analysed the architecture of the QM-RIM and we also pointed out its specific design aimed at producing synthetic rainfall intensities in a robust way.

This section is devoted to a brief overview of basic uncertainty analysis concepts and to the explanation of the procedure adopted for metrological validation of the QM-RIM.

3.1. Uncertainty analysis in brief: type A and B error evaluations

The uncertainty of the result of a measurement generally consists of several components which, based on the ISO *Guide to the Expression of Uncertainty in Measurement* (ISO, 1995), may be grouped in two categories according to the method used to estimate their numerical values:

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

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

Moreover, in the QM-RIM metrological validation we adopted the “maximum error principle”, namely, we are not interested in a precise estimation of the uncertainty of the system but simply to assess the maximum uncertainty which can derive from the calibration procedure.

3.2. Type B evaluation of standard uncertainty

A Type B evaluation of the standard uncertainty (*u*) 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 behaviour and property of relevant materials and instruments,
- manufacturer’s specifications,
- data provided in calibration and other reports, and
- uncertainties assigned to reference data taken from handbooks.

In general, Type B evaluation of standard uncertainty *u* can be a useful tool where, as in QM-RIM case, the objective of the metrological validation is the estimation of a maximum uncertainty and not a precise evaluation of the error.

4. UNCERTAINTY BUDGET OF QM-RIM

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

1. the synthetic rainfall intensity generation module
2. the actual rainfall intensity Measurement module

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

1. Uncertainty on the flow steadiness deriving from possible variations in water head H
2. Uncertainties due to the weighting 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 one from the other and for this reason we will perform in the following a separate analysis for the two modules, later combining the results in a unique uncertainty budget in section 5.

4.1. 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:

$$Q = \Omega \cdot \xi \sqrt{2gH} \tag{3}$$

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:

$$\Delta H \leq 0.1\ mm \tag{4}$$

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

$$u_H = \frac{\Delta H}{\sqrt{3}} \approx 0.06\,mm \tag{5}$$

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

$$u_Q^{(H)} = \sqrt{\left(\frac{\partial Q}{\partial H}\right)^2 \cdot u_H^2} = \frac{1}{2} \cdot \frac{u_H}{H} \cdot Q \tag{6}$$

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%).

4.2. 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:

$$\Delta W_{LIN} = 0.02\,g \quad \Longrightarrow \quad u_W^{(LIN)} = \frac{\Delta W_{LIN}}{\sqrt{3}} = 0.012\,g \tag{7}$$

$$\Delta W_{RIS} = 0.01\,g \quad \Longrightarrow \quad u_W^{(RIS)} = \frac{\Delta W_{RIS}}{2\sqrt{3}} = 0.003\,g \tag{8}$$

$$u_W^{(REP)} = 0.01\,g \tag{9}$$

$$u_W^{(T)} = \alpha_T \frac{\Delta T}{\sqrt{3}} \cdot W \approx 0.014\,g \tag{10}$$

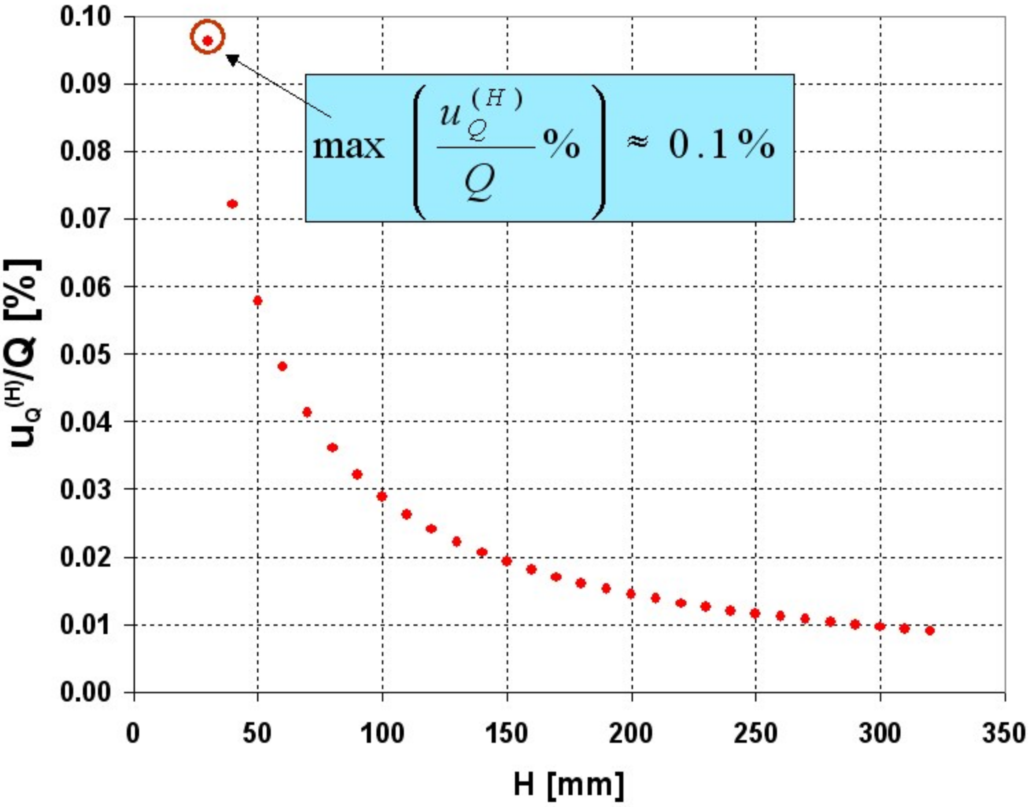

Figure 5: The relative uncertainty on Q (flow rate) due to H (water head) as a function of H

with α_T=6 X 10^{-6} °C-1 the thermal sensitivity coefficient, ΔT ~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.

Equations 7-10 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 T variations.

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

$$u_W = \sqrt{\left(u_W^{(T)}\right)^2 + \left(u_W^{(LIN)}\right)^2 + \left(u_W^{(REP)}\right)^2 + \left(u_W^{(RES)}\right)^2} = 0.021\,g \tag{11}$$

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:

$$u_t = \frac{\Delta t}{\sqrt{3}} \cdot \sqrt{2} \approx 0.08\,s \tag{12}$$

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

$$u_Q^{(W,t)} = \sqrt{\left(\frac{\partial Q}{\partial W}\right)^2 \cdot u_W^2 + \left(\frac{\partial Q}{\partial t}\right)^2 \cdot u_t^2} = \sqrt{t^{-2} \cdot u_W^2 + \left(\frac{W}{t^2}\right)^2 \cdot u_t^2} \tag{13}$$

5. 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:

$$u_Q = \sqrt{\left(u_Q^{(W,t)}\right)^2 + \left(u_Q^{(H)}\right)^2} \tag{14}$$

From the above equation the total uncertainty on the synthetic rainfall intensity u_{RI} can be easily extracted as:

$$u_{RI} = k \cdot \sqrt{\left(u_Q^{(W,t)}\right)^2 + \left(u_Q^{(H)}\right)^2} \tag{15}$$

With:

$$k = \rho^{-1} S^{-1} = 0.01\, mm\ g^{-1} \tag{16}$$

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:

$$\frac{u_{RI}^{(W,t)}}{RI} = 2 \times 10^{-2} \div 0.15\% \tag{17}$$

while:

$$\frac{u_{RI}^{(H)}}{RI} = 0.1 \div 0.01\% \tag{18}$$

Since we have, for the maximum relative uncertainty on rainfall intensity:

$$\frac{u_{RI}^{\max}}{RI} \approx 0.2\% \tag{19}$$

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:

$$\frac{U_{RI}^{\max}}{RI}\% = 0.46\% \tag{20}$$

6. CONCLUSION AND REMARKS

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 main objective of this paper 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.

7. REFERENCES

1. Calder I.R. and Kidd C.H.R. (1978). *A note on the dynamic calibration of tipping-bucket gauges*. J. Hydrology, 39, 383-386.
2. Fankhauser R. (1997). *Measurement properties of tipping bucket rain gauges and their influence on urban runoff simulation*. Wat. Sci. Tech., 36(8-9), 7-12.
3. ISO, (1995) *GUM "Guide to the Expression of Uncertainty in Measurement".*
4. La Barbera, P., Lanza, L.G., Stagi, L., (2002) *Influence of systematic mechanical errors of tipping-bucket rain gauges on the statistics of rainfall extremes*, Water Sci. Techn., 45(2), 1-9.
5. Lanza L.G., Stagi L., (2002) *Quality standards for rain intensity measurements*, WMO Techn. Conf. On Meteorological and Environmental Instruments and Methods of Observation (TECO-2002), Bratislava, Slovakia, 23-25 September 2002. Published on CD-ROM, 4 pp.
6. Lanza L.G., Stagi L., (2003) *Sulla misura dell'intensità di pioggia con pluviometri a vaschette basculanti: errori sistematici e statistiche dei valori estremi Rivista di Meteorologia Aeronautica*, 63(1), 13-21 (IN ITALIAN).
7. Lanza, L.G., Leroy, M., Van Der Menlen, J. And M. Ondras, (2005) *The WMO Laboratory Intercomparison of Rainfall Intensity (RI) Gauges*. TECO 2005 (this volume).
8. Molini, A., La Barbera, P., Lanza, L. G., Stagi, L., (2001) *Rainfall intermittency and the sampling error of tipping-bucket rain gauges*, Phys. Chem. Earth (C), Vol. 26, No. 10-12, pp. 737-742.
9. Molini, P. La Barbera, L.G. Lanza, (2004) *The impact of TBRs measurement errors on design rainfall for urban-scale applications*, Hydrological Processes, in press.
10. Molini, L.G. Lanza, P. La Barbera, (2004) *Improving the accuracy of tipping-bucket rain records using disaggregation techniques*, Atmospheric Research, in press.