WEIGHING GAUGE PERFORMANCE UNDER LABORATORY SIMULATION OF REAL WORLD PRECIPITATION EVENTS

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ABSTRACT

Although weighing gauges (WG) demonstrated better performance than more traditional Tipping Bucket Rain Gauges (TBRG) under previous calibration efforts, under continuous and constant reference flow rates, dynamic effects seem to significantly affect the accuracy of WG measurements under time varying (real world) rainfall conditions. The most relevant issue is due to the response time of the acquisition system and the derived systematic delay of the instrument in assessing the exact weight of the bin containing cumulated precipitation. As expected, when high resolution rain intensity (RI) time series are sought from the instrument, as is the case of many hydrologic and meteo-climatic applications, the WG delay assumes a relevant role. This works demonstrate that even at low resolution in time the WG measurements may prove to be less accurate than those obtained from traditional TBRGs.

A laboratory accuracy assessment of the OTT Pluvio2 rainfall intensity measurements is reported in this work. Tests are carried out by simulating different artificial precipitation events, with non-stationary rainfall intensity, using a highly accurate dynamic rainfall generator. Very high resolution time series measured by drop counters (DC) were aggregated at a one-minute time scale and reproduced in the laboratory to act as the reference events. With the aim of providing a comparative indication of the dynamic behaviour of different instruments, the same simulations were also performed while testing a traditional tipping bucket rain gauge manufactured by MTX (Italy).

The effectiveness of comparing the measured against the reference intensity at a high resolution in time is assured by the sufficiently short time response of the RI generator with respect to the expected weighing gauge behaviour. This work also shows the preliminary development and validation of the rainfall simulator for the laboratory generation of time varying reference intensities.

INTRODUCTION

Weighing gauges (WG) testing under time-varying (unsteady) conditions was performed in the field during the recent World Meteorological Organisation (WMO) Intercomparison in 2007-2009 against a composite field reference obtained from multiple pit gauges where two WG were also part of the field reference itself (see e.g. Lanza and Vuerich, 2009). In that occasion specific tests were also attempted for evaluating the WG dynamic response. The real world data analysis raises the issue of assessing the dynamic behaviour of this type of gauges in case of time-varying rainfall conditions. However, at the time of the Intercomparison the laboratory equipment was not fully suited to perform such kind of tests and various specific issues such as the time response of the laboratory equipment itself were still unsolved.

The dynamic performance of WGs under laboratory simulated time-varying reference rainfall rates is currently under investigation by the WMO/CIMO Lead Centre “Benedetto Castelli” on Precipitation Intensity, established in 2010, and preliminary results are here presented and discussed.

The characteristics and preliminary testing of the equipment used to generate the time-varying reference flow rates in the laboratory are reported in this paper, demonstrating the inherent dynamic behaviour (time constant) of the generator. Eventually, the assessment of the dynamic behaviour of a typical WG was possible over a wide range of dynamic conditions, and the associated measuring errors were determined. One-minute rainfall intensity (RI) measurements are provided from a typical WG with a certain delay caused by the embedded calculation system employed for filtering the load cell signal white noise and handling the sampling limitations of the gauge (which needs to wait a minimum period of time in order to collect a sufficient amount of precipitation).

The results obtained while dynamically testing the OTT Pluvio2 weighing gauge under different event-like conditions are quantified by evaluating the average errors and their deviations under repeated test runs or throughout the event. Eventually, these data are compared with the error figures obtained under the same conditions from a traditional TBRG, manufactured by MTX (Italy).

TEST METHODOLOGY

The installation of a laboratory flow rate generation system suitably endowed with a response time significantly shorter than the typical resolution in time of the instruments under test is required to the aims of the present activity. The system must perform with proper repeatability of the generated flow rates, which constitutes a key-factor to ensure sound dynamic tests when involving unsteady RI conditions. A laboratory test system was therefore designed to involve a fully-controlled automatic flow rate generator of variable rainfall intensities in time based on the cooperative contribution of two high-precision volumetric pumps (see Figure 1). The validation of the water volumes actually generated is obtained by using a precision balance meanwhile the acquisition of the output of any rain gauge under test and of the balance, as well as the automatic control of the pumps, are performed using a PC supported data acquisition system. The two pumps were subject to a series of tests to investigate the trueness (measured by the average relative deviation between the imposed and the generated flow rates) and the repeatability (precision) of the pump in producing the expected flow rates (measured by the standard deviation of relative deviations). A calibration curve was obtained and implemented into the control software to correctly drive the two pumps. Table 1 reports the average percentage relative error and its standard deviation for different values of the generated flow rate, Q_{ref}. Flow rates below 18 ml/min are obtained by using the low-intensities pump while above that figure the second, high-intensity pump was used.

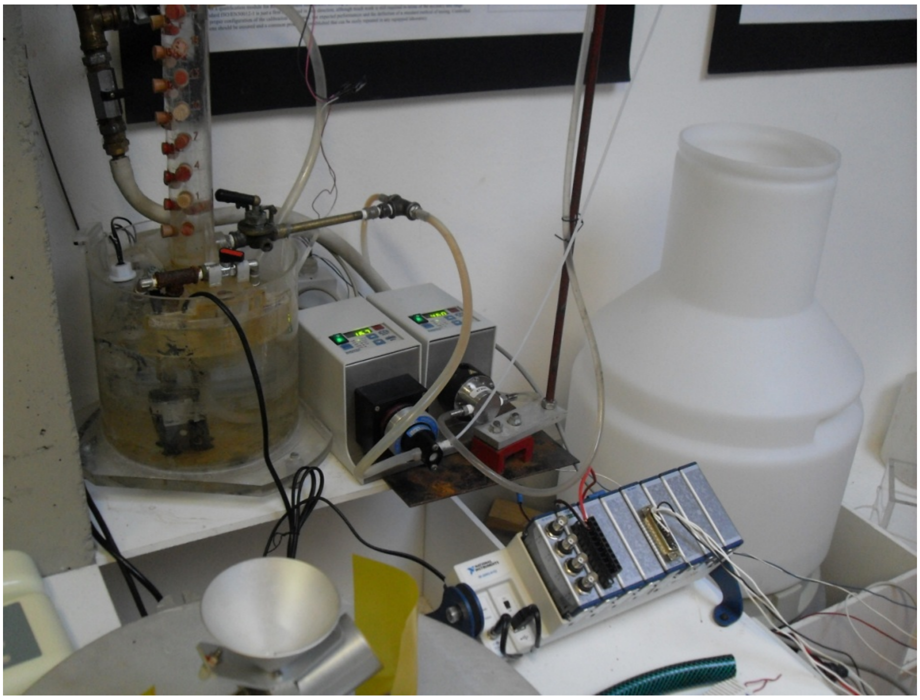

Fig.1: The constant rainfall simulation system and the OTT Pluvio2 weighing gauge

Tab.1: Operative range of the low flowrates Q_{ref} generation system, maximum of the generation residual percentage relative errors e_{res} and of its standard deviation

Q_{ref}	avg(e_{res})	st.dev(e_{res})	Q_{ref}	avg(e_{res})	st.dev(e_{res})
ml/min	*%*	*%*	*ml/min*	*%*	*%*
0.35	0	1.9	25.03	3.7	0.3
0.75	0	0.8	40.28	-0.6	0.7
1.56	0.1	0.2	56.98	-0.3	0.4
3.16	-0.1	0.3	90.35	0.4	0.4
6.38	-0.1	0.1	134.57	0.8	0.2
12.78	-0.3	0.1	178.65	1.1	0.1
18.11	0.4	0.1	241.82	0.2	0

Another important step towards the reliable interpretation of time-varying reference intensity tests is the overall response time of the dynamic flow generation assembly assessment. A video tracking velocimetry technique was employed to detect the water level vertical fluctuations inside a see-through reservoir connected to the pump output, since a high-frequency sampling system is required for a precise description of the pump dynamic behaviour in the time domain. This allows the testing of the activation and deactivation of the pumps transient operation. The maximization of the vertical displacement of the water level despite the range of low flow rates requested from the generator, was obtained by properly designing the shape of the measuring container (Figure 2, left). Moreover, the testing water was darkened using an alimentary additive with the aim of enhancing the contrast in automatic photometric evaluations so that the instantaneous free-surface displacement velocity calculated by a specifically designed image tracking software was used as an indicator of the pumping assembly rapidity in executing commands (responsiveness).

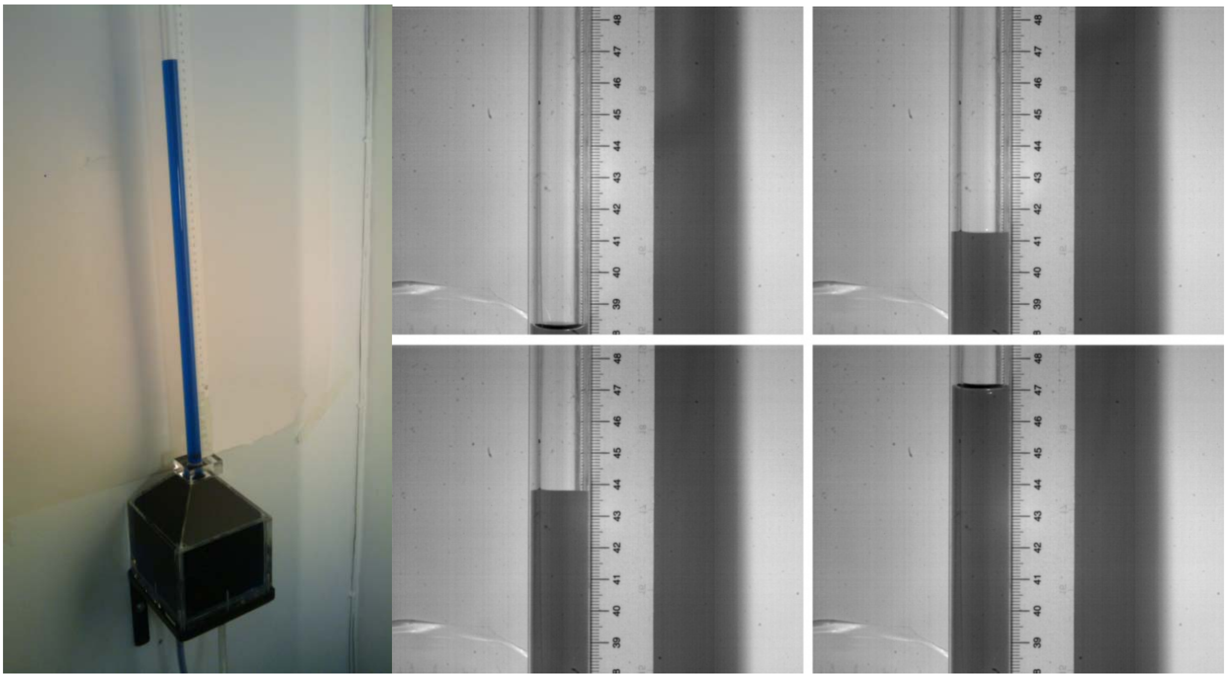

Fig.2: The test column used to evaluate the response time of the generator by means of a video tracking velocimetry technique and a few sample frames used to assess the response time of the pumping system.

The normalized instantaneous water velocity and a moving average over a 0.2 seconds time-window are plotted in the time domain (as sampled in Fig. 3) following the generation of a given single step flow rate value including the start and stop operations. The dynamic performance of the flow rate generator is here synthesized by its time constant τ, defined as the time interval requested by a normalised first order linear dynamical system (with null dead time) to reach a value of 1-1/e, which equals about 63.2% of the step input signal. After performing different repetitions of this test with varying the value of the single-step imposed flow rate, non-constant τ values were obtained always lower than 200 msec, providing a volumetric error on the discharged water always acceptable, the minimum time resolution of the step-varying simulated RI being equal to 10 sec in the present study.

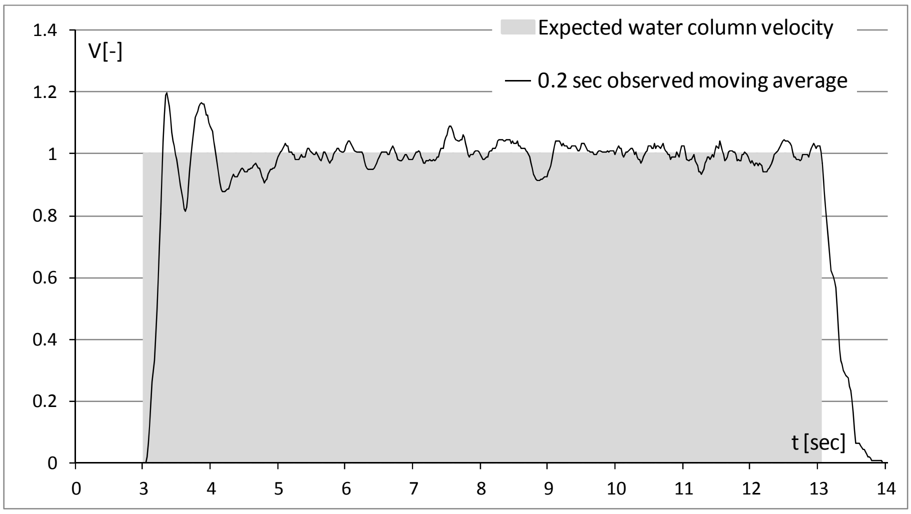

Fig.3: Normalized time-averaged free water surface displacement velocity evaluated by using the tracking velocimetry technique.

The tests performed are focused on the simulation of a selection of real world precipitation events as recorded by an Ogawa drop counter rain gauge (DC) at the Honk Kong International Airport provided with an high sensitivity (equal to 0.005 mm) and a 10 seconds time resolution, allowing the exhaustive reproduction of the real precipitation phenomena time variability (see Colli et al., 2012). The weighing gauge under test is the OTT Pluvio2 (Germany) because of its recent employment on the ongoing WMO Solid Precipitation Intercomparison Experiment (SPICE) as a candidate infield reference instrument, meanwhile the calibrated MTX (Italy) tipping bucket time was selected as a more traditional sensor for a comparative results analysis. A times of tip type correction was applied to the TBR original measurements as illustrated in a preceding work by the LC (Colli et al., 2012a). The selected events duration, cumulated rainfall and maximum RI recorded by the DC are summarized on Table 2.

Tab.2: Selected precipitation events measured by the HKIA drop counter, their duration *d*, total rainfall depth *h* and maximum rainfall intensity RI_{max} .

date	**n. event**	**d**	**h**	**RI_{max}**
	-	*min*	*mm*	*mm/h*
14-15 September 2009	1	222	42.6	64.6
15 September 2009	2	81	18.7	94.3
7 February 2010	3	204	48.5	65.7
7 May 2010	4	202	35.6	173.6
7 May 2010	5	161	33.2	70.8
19 May 2010	6	237	51.4	86.4
26 June 2010	7	369	64	106.1
28 June 2010	8	94	25.4	114.5
17 July 2010	9	207	81.5	170.3
28 July 2010	10	96	7.7	41.8
3 September 2010	11	239	70	74.4
9 September 2010	12	116	57.9	150.9
10 September 2010	13	125	82.4	124

21 September 2010	14	72	39.2	81

The results will be reported in terms of percentage errors of the rain gauge measurements (Ri_m) with respect to the actual rainfall intensity simulated RI_{ref}, calculated as follow:

$$e = \frac{(RI_m - RI_{ref})}{RI_{ref}} * 100 \tag{1}$$

RESULTS AND DISCUSSION

The test results are reported here by considering only the measurements referring to time intervals of effective rain ($Ri_{ref} \neq 0$). The one-minute resolution percentage average relative error avg(*e)* of the WG and TBR measurements and its standard deviation are reported in Table 3 for the full dataset and after excluding cases when RI_m equals zero.

Tab.3: WG and TBR one-minute measurement average error *avg(e)* and its standard deviation *dev.st(e)* for the laboratory simulation when considering the whole dataset (left) and after selecting the events with $RI_m \neq 0$.

	All $RI_{ref} \neq 0$ minutes			Only $RI_{ref} \neq 0$ and $RI_m \neq 0$ minutes			
	N.minutes	**avg(e)**	**dev.st.(e)**	**N. Ri_m= 0**	**N.minutes**	**avg(e)**	**dev.st.(e)**
	-	%	%		-	%	%
WG	2041	-36.3	49.0	1300	741	0.0	11.7
TBR	2041	-9.0	108.2	1550	491	20.8	109.2

If all the minutes of actual rain simulation are considered the test provides a large sample of rain gauges observations suitable to perform statistical considerations, however the large amount of minutes where the two instruments do not detect the generated low intensity precipitation (responsible of *e* values equal to -100%) deviates the results toward a general underestimation of the *avg(e)*. In that case the WG demonstrates a worst behaviour in terms of *avg(e)*, which is equal to -36.3 %, with respect to the TBR affected by an *avg(e)* = -9.0 %. Moreover, the WG sensor lost 741 data out of the 2041 actually generated raining minutes while the TBR only missed 508 minutes. Considering only the observations characterized by $RI_{ref} \neq 0$ and $RI_m \neq 0$ (right hand of Table 3), the behaviour of the WG is shown to be not affected by average errors and the standard deviation is reduced to 11.7% denoting a higher repeatability than the TBR (*dev.st(e)*= 109.2%).

The distribution of the errors at various RI_{ref} classes of the selected measurements (only the $RI_{ref} \neq 0$ and $RI_m \neq 0$ observations are considered) obtained considering the RI_m at one-minute resolution, is represented in Figure 4 in the form of a box plot.

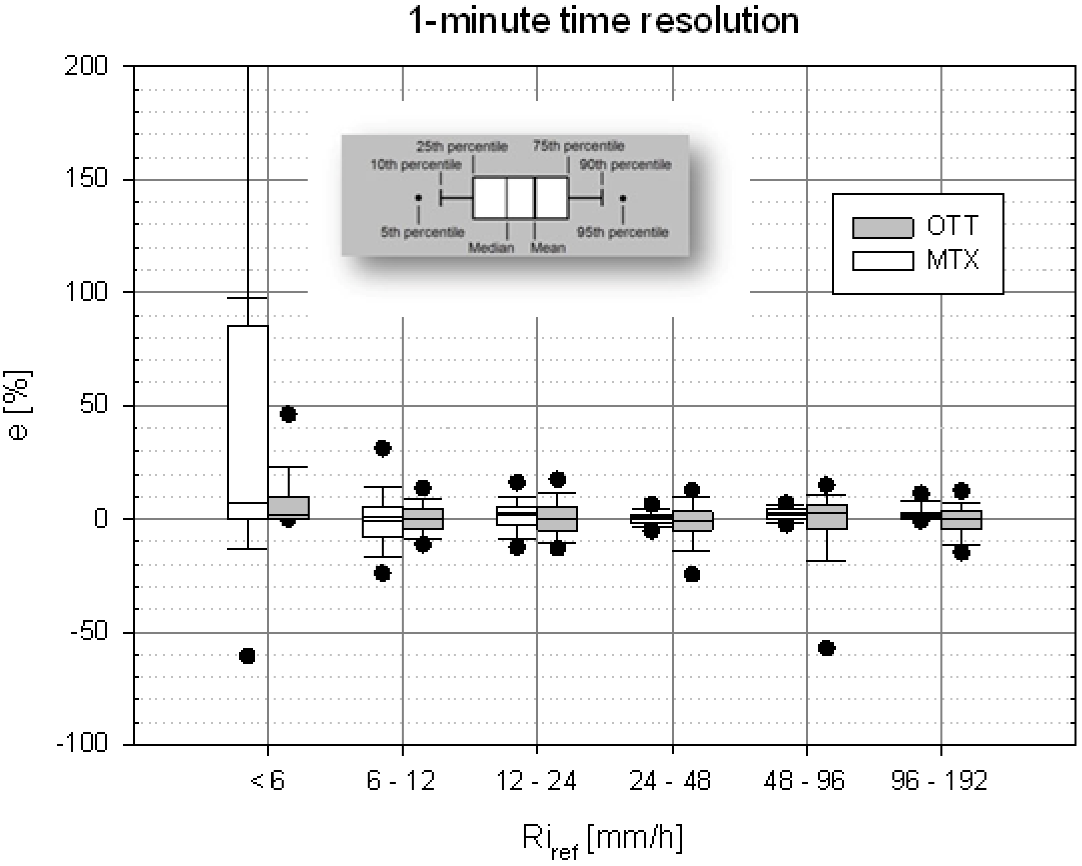

Fig.4: Non parametric distribution of the relative percentage error *e* of the OTT WG and MTX TBR measurements at one-minute time resolution (only $RI_{ref} \neq 0$ and $RI_m \neq 0$ values are considered).

Figure 4 shows the relevance of the <6 mm/h RI_{ref} class in the relative errors evaluation of the TBR, with a spread distribution of *e* values in the 0÷100% interval caused by the rough sampling characteristic of such instrument. Although at low RI_{ref} classes the WG performs better repeatability than the TBR, such behaviour tends to reverse starting at $RI_{ref} \cong 24$ mm/h, and above that value a traditional tipping bucket type instrument features better performance than a weighing sensor with no correction for the dynamic behaviour. This is caused indeed by the dynamic response of the WG, which affect the measurement at high RI_{ref} classes especially due to the strong RI time variability between adjacent minutes when severe RIs occur (Colli et al., 2012b).

Further considerations about the TBR and WG performance under time-varying RI_{ref} tests can be provided by aggregating the RI measurements at different time resolution (Table 4).

Tab.4: Number of WG and TBR measurements available, number of rainy time intervals missed by the instruments (Ri_m=0), measurements averaged errors *avg(e)* and their standard deviation *dev.st(e)* for the DC events simulation performed in laboratory

	WG			TBR		
	N.meas.	**avg(e)**	**dev.st.(e)**	**N.meas.**	**avg(e)**	**dev.st.(e)**
	-	%	%	-	%	%
1 min	1300	0.0	11.7	1550	20.8	109.2
2 min	685	-14.6	23.5	806	6.5	64.0
5 min	308	-20.9	22.7	370	4.5	39.3
10 min	174	-26.4	23.6	197	-6.1	28.6
15 min	117	-26.2	22.4	131	-8.8	18.5
30 min	61	-26.4	20.1	68	-10.8	10.8

The results quoted in Table 4 report about a considerable loss of accuracy and repeatability by decreasing the RI_m resolution from 1 minute to 30 minutes for the tested WG. The WG shows an ever stronger underestimation of the *avg(e*), which reaches a value equal to -26.4% (and a *dev.st(e)*=20.1%) at the 30 min measurements resolution. On the other hand, even if the TBR average error tends towards underestimation as well when increasing the time interval, its repeatability is demonstrated to noticeably benefit from a coarse resolution, moving from a *dev.st(e)*=109.2% (observed for a one-minute resolution) to a value equal to 10.8% (30 min time resolution). The importance of such evaluations takes form when considering the fact that real-world RI measurements operated by weighing type gauges are usually analyzed by considering rough resolutions and disregarding the inaccuracy involved in the matter.

CONCLUSIONS

Following up the validation of a new laboratory rainfall simulator endowed with the necessary response time and accuracy in generating expected values of non steady flows above the catching type rain gauges orifice, the simulation of a ten-seconds resolution real world selection of rainfall events provided important indications about the WG dynamic behaviour and the influence of the output resolution in time on the measurement accuracy.

It has been found that a large amount of minutes characterized by low values of the generated RI are not detected when polling the WG and TBR at the one-minute time resolution, leading to a strong rainfall underestimation. The analysis was hence carried out on a restricted dataset (only

$RI_m \neq 0$ mm/h values were considered) showing favourable results performed by the weighing type

rain gauge, if compared to what can be retrieved using a tipping bucket gauge, in terms of average error and measurements repeatability. The lack of accuracy of the TBR is observed for very light precipitation, particularly in the range of $RI_{ref} < 6$ mm/h where such instrument suffers from the well known sampling limitations, This notwithstanding the improvements obtained by employing a suitable correction algorithm.

Another aim of the present activity was the testing of different RI outputs when varying the time resolution. A consistent WG underestimation of the real precipitation amounts was observed and a large scatter of the relative errors when the measurement time resolution is decreased. The common circumstance of recording precipitation at low resolution in time is here verified to be less disadvantageous when tipping bucket rain gauges are employed.

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