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Development of procedures for calibration of meteorological sensors. Case study: calibration of a tipping-bucket rain gauge and data-logger set

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Abstract. The mechanical assembly of a tipping-bucket rain gauge is often calibrated as a stand-alone instrument. However, the measurement accuracy depends on the associated data-logger as well, especially in case the rainfall intensity is derived from the measurement. This paper reports the calibration of a set comprising the tipping-bucket rain gauge assembly and the associated data-logger. The case study of a specific commercial rain gauge is presented. We conclude that the response time of the data-logger directly affects the measurement of rainfall intensity and that the greatest contribution to the uncertainty budget may arise from the accuracy of the clock of the data-logger.

1. Introduction

Precipitation measurements are very important to the Environmental Sciences. A huge range of applications around the world bases on the observation and investigation of typically measured characteristics of precipitation such as the rainfall amount, intensity and duration, besides the frequency of intense rainfall events [1, 2].

There are instruments that simply inform the status of the rain in that moment, i.e. whether it rains or not, as well as there are those that show the distribution of precipitated drop sizes. The most commonly employed instrument for the measurement of rain amount and intensity is the tipping-bucket rain gauge (TBRG). The TBRG is a device that can send a pulse as an output signal to each nominal amount of rainfall collected in a pivoting two-compartment bucket [3, 4].

Most automatic rain gauges measure a small amount of rainfall over a relatively short time interval, usually less than one minute. Users of rainfall measurements typically require information of accumulated rainfall for longer time intervals, e.g. the hourly, daily, monthly, and even annual total rain depth [4, 5]. Other very important information is the rainfall intensity that is obtained indirectly using a rain gauge and a data acquisition and processing system.

Using a data acquisition system or a data-logger it is possible to record the instant when the various pulses occur, and thus calculate the rainfall intensity (*RI*). Usually, the mechanical device of a tipping-bucket rain gauge is calibrated as a stand-alone instrument. This paper shows the calibration procedure of an instrumentation set comprising a commercial tipping-bucket rain gauge and the associated data-logger, thus making it possible to calculate the uncertainty of the *RI* measurement.

2. Method

Figure 1 shows a classical TBRG. In general, a TBRG opens or closes a contact through a reed-switch sensor, or similar, to each determined volume of precipitated rain, generating a pulse if electrically powered [6]. In order to calculate the accumulated rainfall or rainfall intensity, it is necessary to record the pulses and the instants when they occur in a data acquisition system for suitable processing [7].

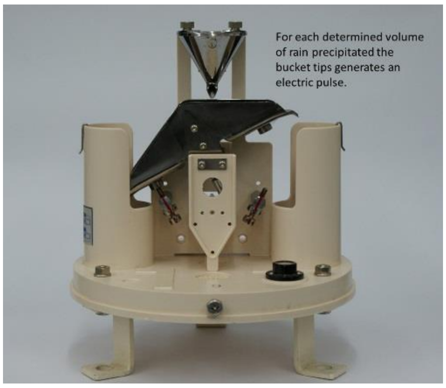

Figure 1. The TBRG and its measuring principle.

Figure 2 shows the set under investigation here, comprising a commercial TBRG, model HD2013, manufactured by Delta Ohm and a commercial data-logger, model CR1000, manufactured by Campbell Scientific as used in a weather station. In the case of TBRGs, at each pulse, the data-logger records the tip and time stamp, i.e. the date and time that pulse occurred. A weather station can also use further sensors to measure other relevant variables. In the case of a rainfall station, the recorded data can be later transmitted using different devices and means of communication. The measured data consist of time stamps of the time of tipping. Depending on the data-logger, it is possible to correct the data and calculate the *RI*, before the transmission.

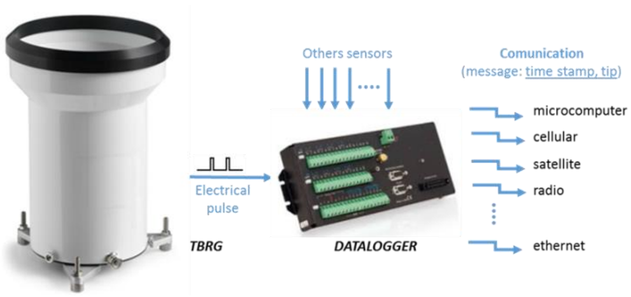

Figure 2. Schematics of a weather station with rainfall record.

The calibration of a TBRG can be performed by the volumetric (input) or gravimetric (output) methods shown in figure 3 [8] and an example of the calibration results is reported in tables 1 and 2. Briefly, the calibration procedure by the input method relies on the indirect comparison to working standards using a peristaltic pump and a data acquisition system, while in the output method the calibration procedure is based on the indirect comparison to the working standards, using a balance and a data acquisition system. A series of fifteen measures are carried out in the verification of the catchment area (here nominally equal to 400 cm^2) and five measurements for each calibration point, and the mean values are reported. The expanded uncertainty of measurement (calibration uncertainty) reported equals the combined standard uncertainty multiplied by the coverage factor "k" for a confidence level of 95.45 %, and was determined according to EURAMET cg-19 - Guidelines on the determination of uncertainty in gravimetric volume calibration [9] and EA-4/02 [10] and ISO / GUM - Guide to the Expression of Uncertainty in Measurement [11].

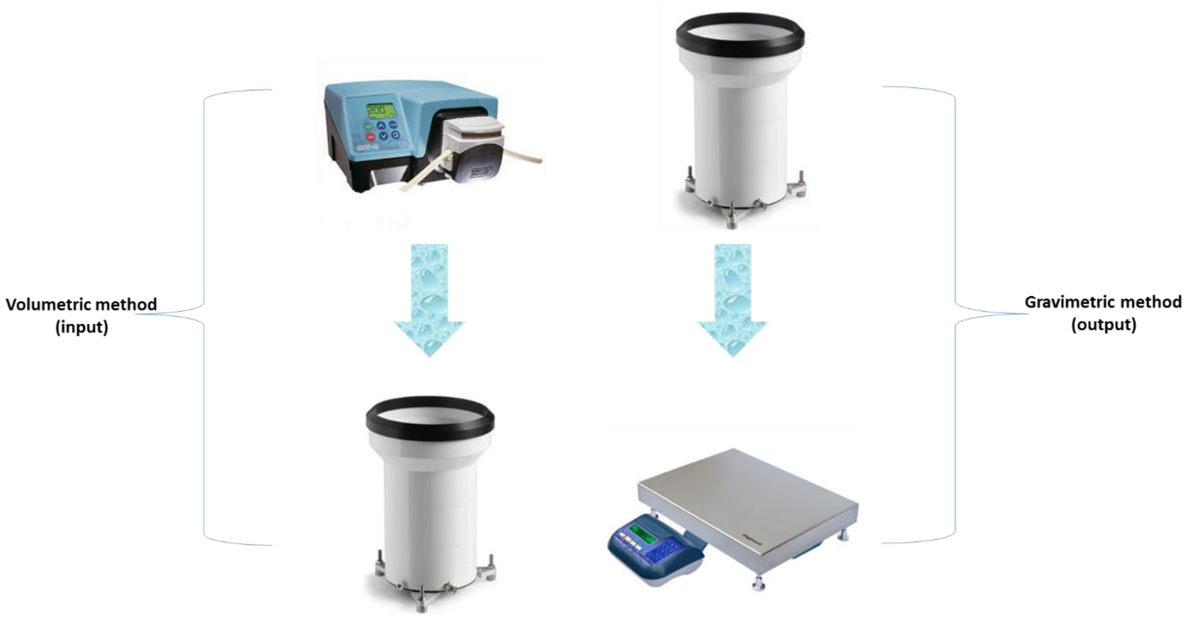

Figure 3. Calibration methods for a TBRG.

Table 1 shows the results of the calibration for a given *RI* using 100 tips (for *RI* around 15 mm/h) and table 2 shows the *RI* for a given number of tips, for example 50 tips. The calibration certificate also reported the environmental conditions (air temperature, t_{air}, water temperature, t_{water}, air relative humidity, H_R and atmospheric pressure, P), the diameter d of area of the collector and the measured mean resolution. The measured quantity Q_M is expressed by equation (1), where W_M is the measured mass of water, δ_{water} is the density of water and δ_{air} is the density of air.

$$QM = \frac{W_M \cdot [\delta_{water}(t_{water}) - \delta_{air}(t_{air}, P, H_R)]^{-1}}{\pi\left(\frac{d}{2}\right)^2} \quad (1)$$

Table 1. Calibration of quantity for *RI* = 12.6 to 13.6 mm/h (example).

Number of tips	Nominal quantity Q_N [mm]	Measured quantity Q_M [mm]	Correction C [%]	Expanded uncertainty U [%]	Coverage factor k
1	0.20	0.19	5.3	± 4.0	2.00
2	0.40	0.39	2.6	± 2.2	2.03
5	1.00	0.99	1.0	± 1.5	2.23
10	2.00	2.00	0.00	± 0.41	2.02
20	4.00	4.00	0.00	± 1.0	2.52
50	10.00	9.96	0.40	± 0.85	2.65
100	20.00	20.01	-0.01	± 0.21	2.52

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Table 2. Calibration of *RI* versus 50 tips (example).

Calculated *RI* [mm/h]	Nominal quantity Q_N [mm]	Measured quantity Q_M [mm]	Correction *C* [%]	Expanded uncertainty *U* [%]	Coverage factor *k*
26		9.94	0.6	± 1.1	2.65
52		10.05	-0.50	± 0.72	2.65
72	10.00	9.97	0.30	± 0.60	2.52
90		10.04	-0.40	± 0.11	2.13
120		10.04	-0.40	± 0.35	2.52

Resolution (average) = 0.20 mm.

The correction *C* is given by (2), where Q_N is the nominal quantity.

$$C = \frac{[Q_N - Q_M].100}{Q_M}\,[\%] \tag{2}$$

In this paper, the calibration of the TBRG in conjunction with the data-logger (figure 4B) was performed based on the calibration of the TBRG itself (figure 4(a)). Figure 4(b) shows the RG calibration system obtaining the output signal of TBRG (pulse) and data from the data-logger (tip and timestamp). The RG calibration system consists of a rain simulator, a device for measuring the volume of simulated rainfall and a data acquisition system (data-logger) as well as meters for air temperature, water temperature, air relative humidity, atmospheric pressure and the diameter of the collector. The calibration certificate of the set TBRG/data-logger must also present the results and uncertainties for the rainfall intensity *RI*, including the corrections to be applied, in compliance with the recommendations of the World Meteorological Organization (WMO) [12].

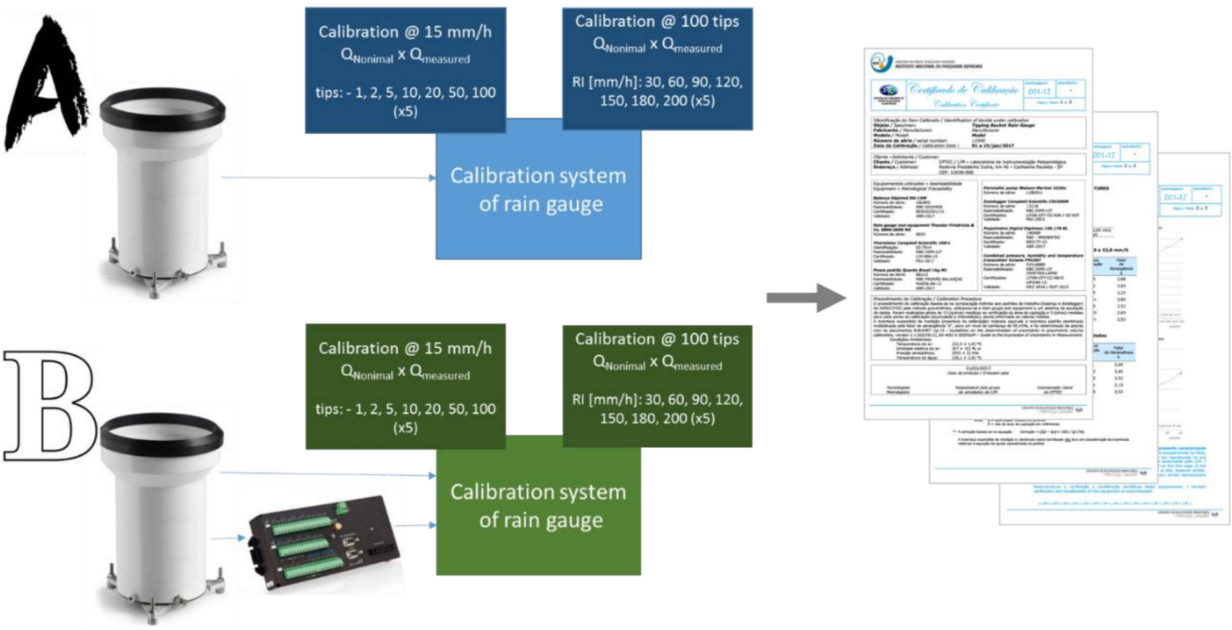

Figure 4. Setups of calibration: (a) TBRG; (b) TBRG + Data-logger.

3. Results

For the calibration of the set comprising the TBRG and the data-logger, the Q_M and *RI* are estimated with their respective uncertainties. The average *RI* in mm/h is expressed by (3), where *Q* is the quantity measured in millimeters and *t* is the time interval, in seconds.

$$\mathrm{RI} = \mathrm{Q.t}^{-1}.3600 \quad (3)$$

In equation (4), n is the number of tips and t_n is the time interval between tips.

$$t = \sum t_n \, .n^{-1} \quad (4)$$

For the measured quantity Q used in equation (5), the uncertainty contributions depend on the method used (volumetric or gravimetric) [8].

$$\mathrm{RI} = \frac{\mathrm{Q}}{\mathrm{t}} + \delta_{\mathrm{RI_{REP}}} \quad (5)$$

For the estimation of the measurement uncertainty of *RI*, the data-logger used as a standard in the calibration system of the rain gauge must have been calibrated in time and frequency in the pulse channel used for the TBRG signal input under calibration. Indeed, physical and electrical factors affecting the crystal oscillator frequency may influence the stability and accuracy of the data-logger [13].

The measurement uncertainty of *RI* is obtained through equation (6), where u_{x1} is the uncertainty of Q, u_{x2} is relative to the calibration certificate of frequency of the data-logger, u_{x3} is due to the specifications of the clock accuracy of the data-logger and u_{x4} is due to the repeatability of the t_n measurements. Equation (7) expresses the relative uncertainty of *RI*.

$$\mathrm{u(RI)} = \left[\sum_{\mathrm{i=1}}^{4} \left(\frac{\partial \mathrm{RI}}{\partial \mathrm{x_i}}\right)^2 \mathrm{u}^2(\mathrm{x_i})\right]^{1/2} \quad (6)$$

$$\mathrm{u(RI)(\%)} = \sqrt{\sum_{\mathrm{i=1}}^{\mathrm{j}} \mathrm{u_R(x_i)}^2} \quad (7)$$

Tables 3 and 4 show the results of calibration (example) where Q_N is the nominal quantity of rain, RI_N is the nominal rain intensity, Q_M is the measured quantity of rainfall, RI_M is the measured rain intensity, C_{QM} and C_{RI} are the corrections, U_{QM} and U_{RI} are the expanded uncertainties and k is the coverage fator for a probability of coverage of approximately 95.45 %.

Table 3. Calibration of quantity for $RI_N \approx$ 13.00 mm/h (example).

		TBRG				TBRG with data-logger			
RI_N [mm/h]	Q_N [mm]	Q_M [mm]	C_{QM} [%]	U_{QM} [%]	k	RI_M [mm/h]	C_{RI} [%]	U_{RI} [%]	k
	0.20	0.19	5.3	± 4.0	2.00			± 4.7	2.00
	0.40	0.39	2.6	± 2.2	2.03			± 3.3	2.00
	1.00	0.99	1.0	± 1.5	2.23			± 2.8	2.00
13.00	2.00	2.00	0.00	± 0.41	2.02	12.99	0.1	± 2.5	2.00
	4.00	4.00	0.00	± 1.0	2.52			± 2.6	2.00
	10.00	9.96	0.40	± 0.85	2.65			± 2.5	2.00
	20.00	20.01	-0.01	± 0.21	2.52			± 2.5	2.00

Table 4. Calibration of *RI* versus 50 tips (example).

		TBRG				TBRG with data-logger			
Q_N [mm]	RI_N [mm/h]	Q_M [mm]	C_{QM} [%]	U_{QM} [%]	k	RI_M [mm/h]	C_{RI} [%]	U_{RI} [%]	k
10.00	25.90	9.94	0.60	± 1.1	2.65	25.75	0.58	± 3.6	2.00
	51.43	10.05	-0.50	± 0.72	2.65	51.67	-0.46	± 0.79	2.00
	72.00	9.97	0.30	± 0.60	2.52	71.81	0.26	± 0.66	2.00
	90.00	10.04	-0.40	± 0.11	2.13	90.34	-0.38	± 0.59	2.00
	120.00	10.04	-0.40	± 0.35	2.52	120.49	-0.41	± 0.82	2.00

Resolution (average) = 0.20 mm.

4. Conclusion

The TBRG and data-logger can be calibrated together or separately. When calibration is separately performed, the TBRG should be calibrated in a pluviometry laboratory and the data-logger in a laboratory in the quantity called time and frequency. In the case of set calibration, the calibration must be performed in a pluviometry laboratory, where the rainfall measurand must be simulated and the results for the rainwater amount and the interval of time between tips are indirectly compared to the working standards with metrological traceability evidenced to the SI.

Based on the presented case study, we conclude that the response time of the data-logger directly affects the measurement of rainfall intensity and the greatest contribution of uncertainty may be due to the accuracy of the internal clock of the data-logger. The results showed that the expanded uncertainties for the rainfall intensity *RI* are increased from 0.06 to 2.5 % on the expanded uncertainties of amount of rain *Q*.

This work is the basis for the development of calibration procedures for TBRG and data-logger sets to obtain the amount of rainfall, the calculation of the rainfall intensity and the estimation of its uncertainties and to comply with WMO recommendations.

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