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1 Overview

Climate studies and everyday hydrological, meteorological, and agricultural applications rely on instruments which measure liquid/solid atmospheric precipitation. However, meaningful comparison and interpretation of data is only possible when a common ground for evaluating the measurement uncertainty is provided. This project developed traceable calibration methods for non-catching precipitation gauges that are implemented in a form that can be incorporated into CEN/ISO standards. The results of this project offer end users with methods for standardized and traceable calibration of non-catching rain gauges, as well as with a metrologically rigorous way of evaluating and drafting an uncertainty budget for measurements comparison across different stations, climates, locations and at different times.

2 Need

Atmospheric precipitation affects our everyday life and impacts on natural ecosystems, transportation, agriculture, safety, tourism, recreation, etc. The characteristics of the precipitation depend on the weather phenomenon and climate at any specific location (temperature, humidity, etc.) together with the fall trajectories of individual particles which are affected by the local conditions at a site.

Non-catching precipitation gauges, which “sense” rather than “catch” the precipitation, have several advantages, including the possibility to provide information in addition to precipitation. However, having no funnel (for tipping bucket gauges) or bucket (weighing gauges) to collect the rainwater, non-catching precipitation gauges cannot be calibrated using a reference flow rate. Instead, the actual characteristics of the rain event have to be reproduced, including the drop size distribution, drop frequency and fall velocities. In order to support their wider use, standardised procedures for the laboratory calibration of non-catching type gauges including the use of laboratory rainfall generators are needed, together with an assessment of the associated calibration uncertainty and repeatability. To estimate the uncertainty of a calibration performed for an instrument based on a specific physical principle it is necessary to model the measurement process i.e. to determine the ‘model function’, including identifying important influence factors which might differ from one technique to another. Comparison of calibration methods between different laboratories is a typical procedure adopted by WMO, the Chief Stakeholder of the project. However, a recent WMO field intercomparison of rainfall intensity gauges indicated unresolved issues with the use of non-catching precipitation gauges in real world applications and challenges in assessing the results of scientific investigations based on such measurements. No standard procedure for non-catching type instruments was available, hence there was a need to compare and evaluate calibration methods and their associated uncertainties for such sensors in different laboratories.

Under the agreement between STAIR and CEN, specific testing and measurement needs for non-catching instruments to measure liquid/solid atmospheric precipitation were submitted by CEN/TC 318 “Hydrometry” in October 2017. The need for standardisation in environmental measurements has also been expressed by WMO Commission for Instruments and Methods of Observation (WMO/CIMO) in documents such as the CIMO Guide nº 8, and the report of the meeting of the CIMO MG 2014.

3 Objectives

The project had two overarching aims, namely (i) to develop calibration methods for non-catching instruments measuring liquid atmospheric precipitation and (ii) to understand and evaluate the uncertainty components and influence parameters for non-catching precipitation gauges.

The specific objectives of the project were:

1. To develop traceable methods and dedicated facilities for the calibration of non-catching precipitation instruments that are used for liquid atmospheric precipitation measurements, including defining the optimal traceability chain, the development and characterisation of at least two different raindrop generators, based on different working principles, and additional tests to detect the possible influence parameters that could affect the measurement results and contribute to the determination of the uncertainty budget.
2. To assess the model functions of the non-catching precipitation gauges, including all relevant input and influence parameters. The calibration uncertainty should be derived from this model function together with a probability distribution associated to each of the input parameters.

3. To validate the calibration methods and uncertainty budgets developed via an appropriate laboratory comparison involving the test calibration of different non-catching precipitation gauges.
4. To provide a substantial metrological contribution to CEN/TC 318 (Hydrometry) /WG12 (Rainfall Intensity) and the ISO/TC 113 (Hydrometry) committees on the development of a technical specification or standard on precipitation measurement using non-catching type instruments, following the identified research needs submitted by CEN/TC 318 under the STAIR-EMPIR agreement. This would include the provision of a technical report with guidelines on recommended traceable calibration methods to measure atmospheric liquid precipitation using non-catching instruments and recommendations for incorporation of this information into future standards or technical specifications at the earliest opportunity.
5. To collaborate with CEN/TC 318 and ISO/TC 113, and the relevant WMO-CIMO* (World Meteorological Organisation-Commission for instruments and Methods of Observation) Expert Teams and end users of the standards (e.g., national meteorological services, manufacturers of environmental measurement instruments) to ensure that the outputs of the project are aligned with their needs and in a form that can be incorporated into standards at the earliest opportunity.

* The Commissions for Basic Systems, for Instruments and Methods of Observations and the Global Climate Observing System transitioned into the new Commission for Observation, Infrastructures and Information Systems (Infrastructure Commission) following adoption of the WMO Governance Reform package by the Eighteenth Meteorological Congress in June 2019[1]."

4 Results

***Objective 1**: "To develop traceable methods and dedicated facilities for the calibration of non-catching precipitation instruments that are used for liquid atmospheric precipitation measurements, including defining the optimal traceability chain, the development and characterisation of at least two different raindrop generators, based on different working principles, and additional tests to detect the possible influence parameters that could affect the measurement results and contribute to the determination of the uncertainty budget."*

To substantiate the work, an initial investigation was performed to review the state-of-the-art of the various non-catching precipitation measuring instruments manufactured by the industry of hydrometeorological sensors, including their working principles, technical characteristics, and calibration practices. This review was not yet available in the literature and was essential as the starting point of this project objective and constitutes an original result of the project. Indeed, a scientific paper was published in an international peer-reviewed journal containing a synthesis of the results.
The work allowed to identify the main working principles used, and to categorize them into optical, acoustic, and radar -based sensors. The most used instruments employ contactless sensors, based on optical principles, including infrared laser beam occlusion and light scatter as induced by the falling hydrometeors moving through the field-of-view of the instrument. Sensors for detecting the impact of hydrometeors on a solid surface are also used, although interacting with the measurand in this case, while radar-based instruments are less common.
The review revealed that calibration is generally performed by the instrument manufacturer, occasionally from researchers in dedicated studies, but a commonly agreed procedure is still lacking, and traceability seldom addressed. The currently adopted calibration techniques were reviewed and criticized in the report in view of the development of a new, fully traceable calibration procedure. Suitable concepts and components were identified, together with the missing or inconsistent aspects that were included into the project focus points.

To enable testing of non-catching instruments to measure liquid atmospheric precipitation, a system that can mimic real precipitation is required. The reason is that such instruments measure the total precipitation in the form of the sum of the individual drops, in contrast to the case for more traditional instrument types (e.g., tipping bucket or gravimetric), which are focussed on the total amount of precipitation. Thus motivated, two different drop generators for calibration purposes (DG1 and DG2) were developed during the project as well as a third generator (DG3) for testing purposes.

[1] https://public.wmo.int/en/our-mandate/how-we-do-it/technical-commissions/commission-instruments-and-methods-of-observation-cimo

The first raindrop generator (DG1, Figure 1) was developed by DTI. The main components of DG1 are 1) a nozzle/needle, 2) a volumetric pump and 3) a piezo-electric membrane (a “buzzer”). In nature, raindrops exist in many different sizes, and therefore this raindrop generator was designed for drop diameters ranging from 0.2 mm to about 7 mm. The corresponding volume range covers more than four orders of magnitude (since $V = \pi\frac{4}{3}r^3$), and hence several different physical principles for drop formation are required to cover this range. The largest drops (> 4 mm) are produces as free-falling drops using a special nozzle. Drops in the diameter range of 1 – 4 mm are produced from flat-tipped needles. These drops are not free falling, and instead the release of the drops is initiated by a pulse from the piezo-electric membrane. Drops with a diameter smaller than 1 mm are ejected from within the inside of a small nozzle. In the latter case, the piezo-electric membrane (the “buzzer”) makes a pulse, causing a small amount of water to be ejected rapidly.

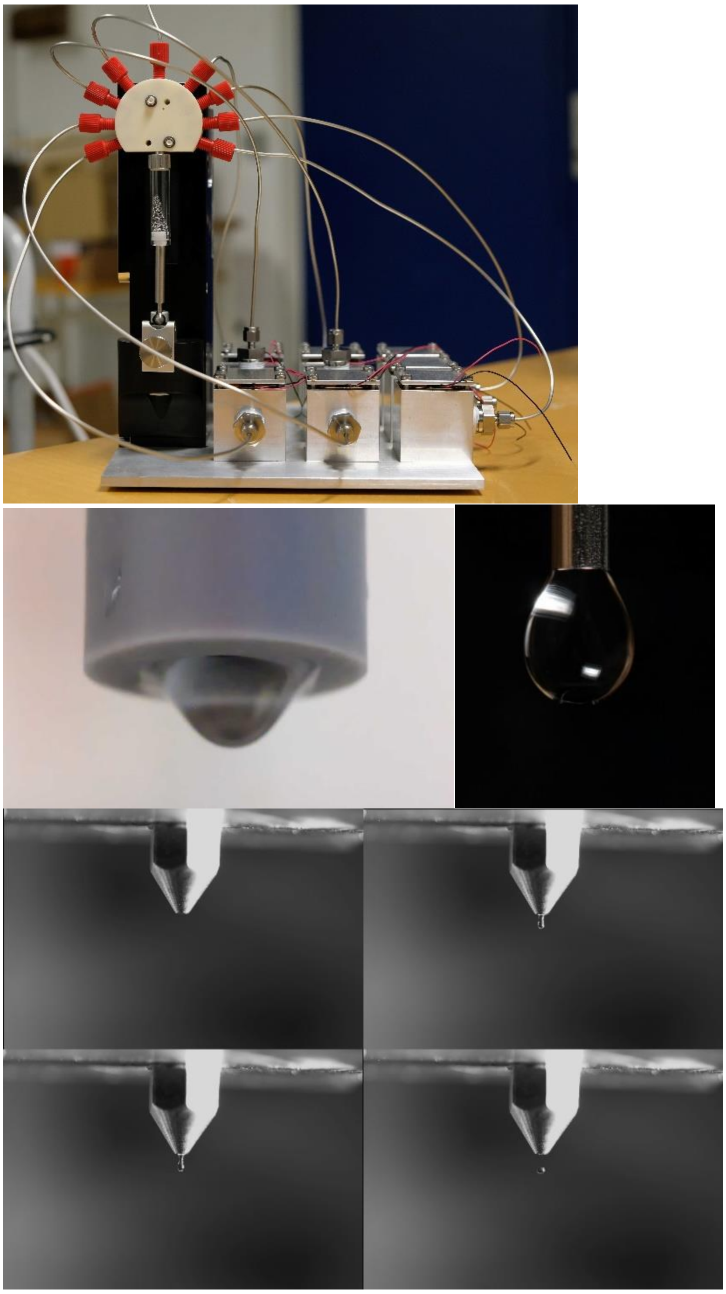


*Figure 1. **Top**: The raindrop generator DG1 with the pump to the left and the buzzers and nozzles to the right; nine different nozzles are employed for different drop sizes. **Below**: Generation of a large drop (centre, left), a medium-sized drop (centre, right) and a small drop (**bottom**), respectively. In the case of the small drop, four steps in the formation process are illustrated.*

A second raindrop generator (DG2) to calibrate non-catching precipitation measuring instruments was developed by UNIGE.
Two high-precision syringe pumps, with a capacity of 20 and 1 ml (and piston diameters of 20 and 4.5 mm, respectively), are used to produce water drops of the required volume (see Figure 2). An electric field, generated by a high voltage trigger, allows releasing each single drop on demand. Each drop is generated at the tip of a suitable nozzle by dispensing the necessary volume to achieve the desired drop size and then detached by exploiting a 5 kV potential difference, where the water is negatively charged and attracted by a metal ring (positively charged), positioned just below the tip of the nozzle. By using different nozzles/needles and the proper syringe pump, drops of various size are produced.

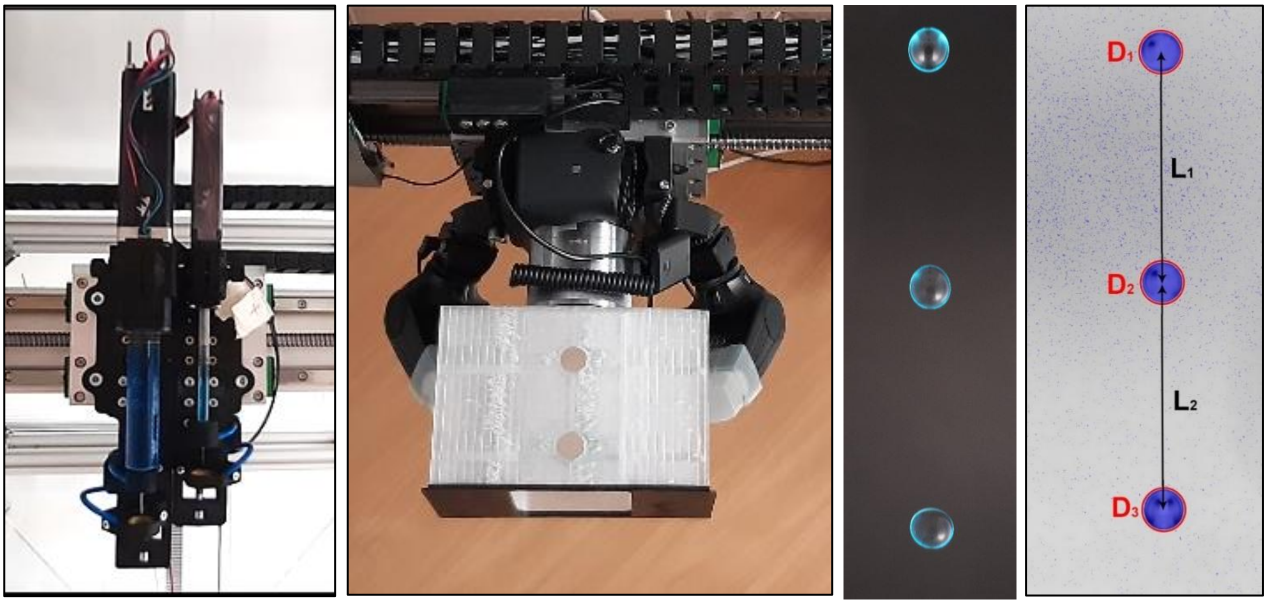


Figure 2: From left to right: DG2 – double-syringe pump for drop formation and detachment, photogrammetric device for the verification of the generated drop size and velocity, and sample image of a single water drop in flight as captured three times in the same picture by the photogrammetric device with the same image reported, after software processing elaboration, to show the detected equivolumetric circular shape of the drop (D1 to D3, in red) and travelled distances (L1 and L2).

To verify the size and fall velocity of the generated drops just above the sensing area of the instrument under test, a photogrammetric device is included in the drop generator assembly (see Figure 2). The system uses a high-resolution camera (Sony a6100) equipped with two flashes, which are triggered three times in a very short sequence (at 4.2 ms intervals) to capture three images of each drop in flight within a single picture (see Figure 2,third image). The timing for the activation of the speedlights and the opening of the camera shutter are defined based on a numerical model of the drop vertical acceleration in still air.

Each image is processed by a dedicated software to derive the drop size (equivolumetric diameter) and fall velocity. An example of the processed images is reported in the right-hand side of Figure 2, where a single drop in three different positions is shown with the automatically detected drop circular contour (in red).
The photogrammetric method is traceable to the international standards of length and time. The time interval is obtained as a differential measure using the internal clock of the acquisition system that monitors the output of a photodiode. As for length measurements, three parameters are necessary: the pixel physical size (pixel pitch, P_p), the lens focal length (Fl) and the shooting distance (S_d). The sensor pixel pitch is provided by the manufacturer with high accuracy. The lens focal length can be measured and certified in optical laboratories. The shooting distance is directly measured on the device once assembled. The equivalent length of one pixel in the captured image (l_p) is obtained as:

$$l_p = (S_d - Fl)/Fl \cdot P_p$$

The uncertainty associated with the definition of Fl and P_p is assumed negligible compared to the uncertainty of S_d and the latter is mainly determined by the drop releasing mechanism. It was calculated from the observed drop positions in multipole images, assuming that the uncertainty of the drop position is isotropic. The resulting standard deviation for the shooting distance S_d ranges between 1.87 and 0.67 mm when the drop size is between 1.5 and 5 mm, respectively. These values lead to an uncertainty between ± 2.4·10-3 mm and ± 8.7·10-3 mm for I_p, depending on the drop size. The uncertainty on the photogrammetric determination of the drop size has a resulting maximum value equal to 0.016 mm when the drop size is equal to 1.5 mm.

The third drop generator (DG3) was designed by SMD with the specific purpose to be used in lab to investigate the errors of different types of non-catching rain gauges (disdrometers) due to multiple simultaneous drops being detected as a single large drop or drops falling at the edge of the detection area and the influence of environmental conditions (temperature, humidity) on instrument responses. DG3 fulfilled the following specific requirements: controlled drops of uniform sizes, possibility to control drop fall position inside the measurement area, possibility to change the falling frequency and the possibility to test for 2 or 3 drops falling in the measurement volume in different positions. The treatment of information in non-catching instruments assumes that only one drop is present in the measurement volume. To test the instrument response when this is not the case the drop generator must be able to release simultaneously 2 drops that will cross at the same time the measurement area.

The DG3 uses pumping (3 peristaltic pumps) and different nozzles geometries to generate drops. The nozzle is mounted on a moving metallic structure in order to allow easy change of the droplet position inside the measurement area. The displacement of the nozzle is controlled by two motors (stepper motor and servo motor). Both nozzle displacement and pumps parameters are controlled through a computer interface.

The system is mounted on a metallic structure of 45 cm on 22.5 cm. Top and lateral photographs showing the constructive elements of the DG3 are shown in Figure 3 and Figure 4.

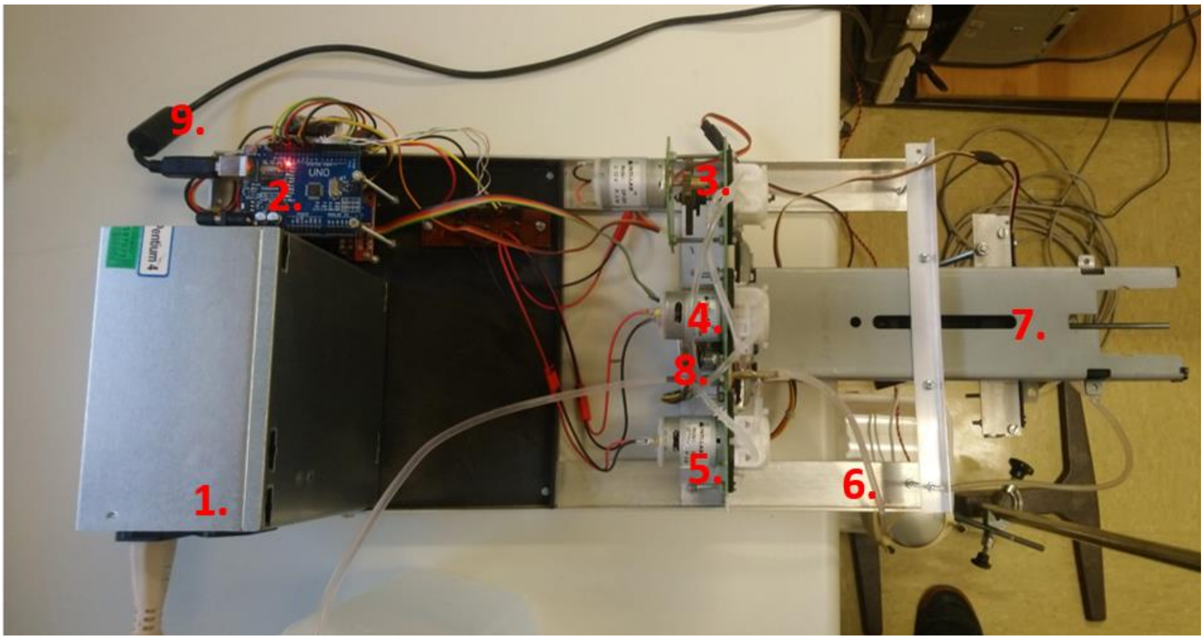


Figure 3: Top view of the DG3. The different components are 1- power supply; 2 - Arduino control board; 3,4 and 5 - the 3 peristaltic pumps; 6 - output tube of the pump going to the nozzle; 7 - rails for the movable part; 8 (under the pump 4) - stepper motor; 9 - USB connection to the computer.

One of the pumps (#3 on Figure 3) was decoupled to obtain slower speed and the 3 pumps are connected to the same tube, itself connected directly to the nozzle. This nozzle is attached to a servo motor (#11 on Figure 4) and the servo motor itself is fixed on a moving part, linked to the stepper motor by a linear screw, allowing a slide movement along the screw.

At the side of the nozzle, a long screw allows to suspend a photodetector (#12 on Figure 4). This is the sensor of a commercial system, StopShot), that can fire 3 different triggers at different temporal intervals after a detection by the photodetector. One of the trigger outputs is redirected to a counter, allowing to keep track of the count of drops that passed through the photodetector.

The drop generator designed and constructed at SMD generates spherical unperturbed drops at a frequency between 2 and 17 drops/s. The 5 nozzles already available and characterized generate drops with sizes ranging from 2.2 to 4.9 mm. Other sizes may be generated with different nozzles, but small drops might be difficult to produce. One of the nozzles releases 2 identical drops simultaneously. The moveable frame allows to change the position of the droplet falling inside the measurement volume in order to test possible detection errors related to the position.

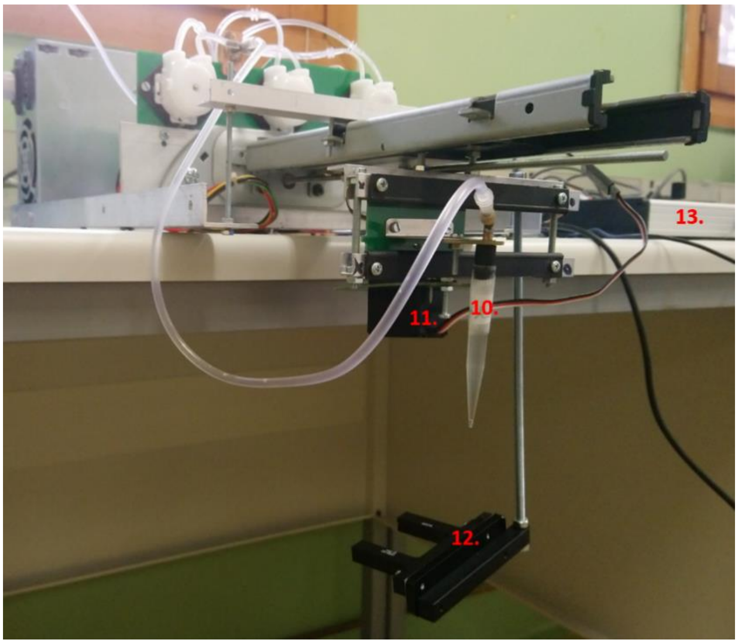


Figure 4: Front view of the DG3. The different parts are 10 - nozzle (can be changed); 11 - servo motor for lateral movement; 12- photodiode detector linked to 13 - StopShot trigger system.

Results are summarised in a scientific paper accepted for publication in the peer-reviewed journal "Sensors" as Baire et al. (2022), "Calibration uncertainty of non-catching precipitation gauges" (Sensors 2022, 22, 6413. https://doi.org/10.3390/s22176413).

The activities of RMG1 can be linked to this objective. The main achievements of the RMG1 are summed up in a scientific report on numerical simulation of free-falling water droplets using COMSOL Multiphysics. First the researcher reviewed the literature on natural rain drops and determined the main expected characteristics such as size, shape and velocity. Then, based on fluid mechanics principles RMG1 described the forces acting on a free-falling drop and the factors that affect its shape during fall. This theoretical study was the basis of the development of a numerical model implemented in COMSOL Multiphysics. After optimization, the numerical model was used to run simulations of drop shape changes during free fall for different drop sizes (ranging from 0.5 to 5.8 mm). In addition, RMG1 calculated, using different available experimental models, the minimal fall distance needed before reaching final velocity. This information was used in INCIPIT project during the experimental in lab campaign to set-up the height of the rain generator with respect to the measuring instrument.

Key Outputs and Conclusions:

A report on the overview of existing models and working principles of non-catching precipitation gauges together with test/calibration schemes for different types of non-catching precipitation gauges, was completed. It contains a complete list of all typologies of commercially available non catching precipitation instruments, with full description of all working principles, measurement 'processes and calibration possibilities. There was nothing similar, at the time of publication, in literature. The report also contains a wide bibliography on the topic, never collected before in other articles or documents. Due to its wide and complete technical content and bibliography, the report has been adjusted in the form of a review paper, published in the international open access peer reviewed journal "Meteorological Applications". The report was transmitted to CEN TC318 as a contribution to the proposal of a new work item for a Technical Report entitled "Calibration and accuracy on non-catching precipitation measurement instruments". The proposal was approved by CEN in February 2022.

Three prototypes of raindrop generator were designed, developed, built, and characterized. Raindrop Generator 1 has been employed successfully for test calibration measurements in the laboratory and in the field tests. Raindrop Generator 2 used a different working principle, and hosted the validation apparatus based on photogrammetry techniques, holding a high-resolution camera and two synchronised flashes to capture drops in flight in three positions, so that the size and fall velocity of each single drop can be accurately detected. Last, raindrop Generator 3 was designed for in-lab tests.

Objective #1, which encompasses the previous two sub-headings, was successfully achieved. As the approval by CEN proves, the report shows methods and technologies currently used by non-catching rain gauges and explores the calibration and accuracy issues of these instruments. Three different raindrop generators were developed, built, and characterized in order to perform experiments and validations for the calibration of the rain gauges.

Objective 2: "*To assess the model functions of the non-catching precipitation gauges, including all relevant input and influence parameters. The calibration uncertainty should be derived from this model function together with a probability distribution associated to each of the input parameters".*

A model for the calibration uncertainty of non-catching precipitation gauges was proposed and detailed. The approach is based on separating uncertainty components into blocks. This gives a flexibility on designing a calibration procedure by combining different blocks (i.e., changing the drop generator or the type of instrument).
The first block element for this model is grouping the sources of uncertainties related to the reference droplet diameter. The second block is related to the disdrometer itself and in particular to the physical principles of operation. Impact, radar or optical disdrometers will show specific uncertainties that can be further explored starting from the specific model equations. One common component is related to the discretization, this latter being not only principle dependent but also manufacturer dependent. The block related to instruments will also include the influence of environmental parameters. The third block in the model groups the effects related to the signal treatment. The information on filtering and calculation algorithms is not publicly available but we observed significant differences in rain intensity values indicated by the instrument and those computed using raw data when available. The main filtering component is related to final velocity of the falling drops, and this might be a major concern when developing an easy to implement calibration procedure. The drop generator needs to either eject drops with an initial velocity or be placed at a height that will ensure reaching the final velocity by free fall, this latter option being not easily obtained in normal laboratory buildings.

The modelling approach proposed in this work depicts the cause-and-effect relationships of the measurements to be analysed and modelled as a block diagram. The block diagram uses three types of standard blocks:

- Parameter sources (SRC): providing measurable quantity.
- Transmission units (TRANS): any kind of signal processing and influencing.
- Indicating units (IND): indicate input quantities.

The two-staged model proposed for the calibration uncertainty of non-catching precipitation gauges is presented in Figure 5. The instruments studied here use drops as measurable quantities, transformed into either Particle Size Distribution (PSD) or Particle Velocity and Size Distribution (PVSD)—depending on the working principle of the instrument. Some instruments provide values for those distributions, others do not. Either way, values of sizes (and velocities) are then used by the instrument to compute the Rainfall Intensity. Therefore, the first IND block, IND1 in Figure 5, is also a parameter source for the indication of rain intensity given by the instrument.

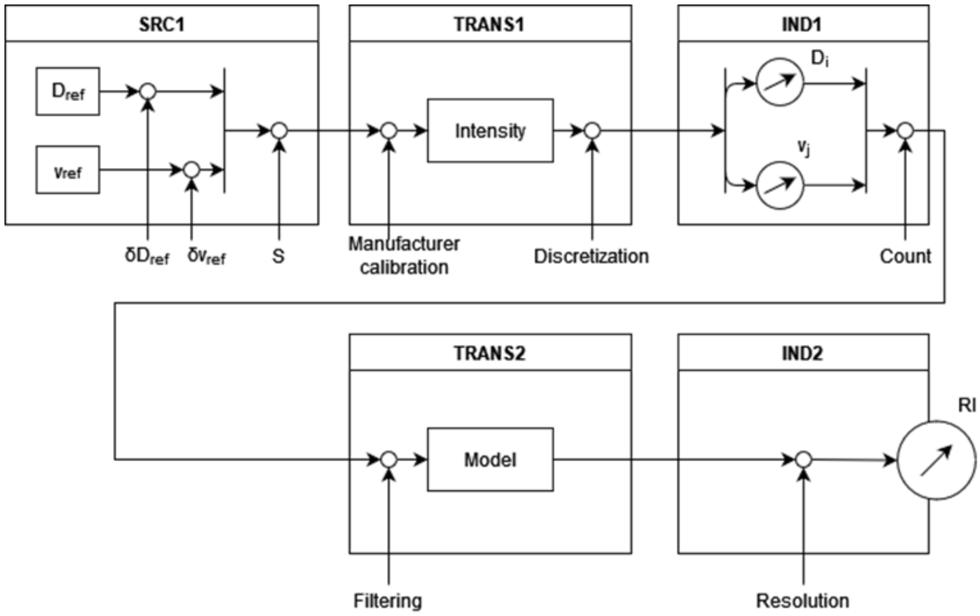


Figure 5: Uncertainty model for non-catching precipitation gauges.

Furthermore, the study of the impact of wind as a major environmental influencing factor on the sensor area for a sample non catching gauge (NCG) was performed by UNIGE. Indeed, according to the measuring principle exploited, NCGs have complex, often non-axisymmetric outer designs because of the geometric constraints imposed by the sensor used. Also, the absence of a collector implies that the measuring volume is not always physically delimited, like for example in radar or optical scatter sensors. An important limitation is that NCGs, regardless of their measuring principle, generally assume that hydrometeors fall vertically at their terminal velocity for the purpose of signal pre-processing. This hypothesis is accurate in controlled conditions or in the absence of wind although, in general, is not verified.
Among the environmental sources of bias, wind is the most relevant one, causing the so-called exposure effect. The gauge body, immersed in a wind field, behaves like a bluff-body obstacle to the undisturbed airflow, producing strong velocity gradients, vertical components, and the development of turbulence close to the gauge surface. The hydrometeors trajectories are diverted by the velocity field around the instrument [6] depending on their diameter, the gauge shape, wind speed and direction. The induced change in the number of hydrometeors that cross the sensing volume/collecting area of the gauge can lead, in windy conditions, to an over or under estimation of the precipitation amount and intensity. The exposure effect therefore introduces a measurement bias, common to all precipitation gauges, simply because of the presence of the instrument itself (invasive measurement). This effect is amplified in the case of NCGs due to their complex shape and measurement principle. The non-axisymmetric shape of the gauge implies a dependency of the aerodynamic effect on the wind direction.
The work demonstrated that such components are significant in the case of the Thies LPM precipitation gauge and quantified their magnitude using CFD simulation, suitably validated against dedicated WT flow velocity measurements. The wind direction is found to be the most relevant influencing factor in deter-mining the magnitude of the airflow perturbation, due to the non-axisymmetric geometry of the gauge. This must be considered when interpreting measurements obtained in windy conditions, since the positioning of the instrument in the field is constrained by the sensor specifications and cannot be aligned with the predominant wind at the installation site to minimize this effect. The observed aerodynamic behaviour of the gauge is indeed expected to induce not negligible bias in operational measurements, especially in strong wind conditions and light precipitation. The proposed airflow numerical simulation framework provides a basis to develop correction curves for the wind-induced bias of NCGs, de-pending not only on the undisturbed wind speed and precipitation intensity, but also on the wind direction.

Results are summarised in a scientific paper published in the peer-reviewed journal “Sensors” as Chinchella et al. (2021), “Investigation of the wind-induced aerodynamic behaviour of the Thies LPM precipitation gauge”, 21, 4880. https://doi.org/10.3390/s21144880.

In addition to this, the evaluation of the influence of air temperature and humidity on different models of non-catching precipitation instruments were performed at CEM. This study was performed under controlled environmental conditions in a 2-m-high climate chamber. The drop generator, designed and manufactured by SMD and previously characterized in terms of its sensitivity to air temperature and humidity variations was used as stable standard. The previous characterization of the drop generator demonstrates that its sensitivity to air temperature variations is low enough to be used for the characterization of the non-catching rain instruments. In addition to the drop generator, the following instrumentation was involved: Calibrated thermometers (Pt-100), an anemometer, hygrometer and a calibrated scale (U(k = 2) =0.10 mg).
A special configuration of the position of the drop generator and the instrument under study was defined in order to minimize the measurements dependence with the air currents, generated inside the climate chamber with the purpose of reaching isothermal conditions inside it. Despite this fact, special attention was paid to fit each generated drop into the sensing area of the rain instrument in each measurement.
Figure 6 shows the variation of one impact disdrometer readings under different air temperature and humidity conditions and for different stable reference rain intensities. The vertical bars are the standard deviation of all measurements taken during a specific time interval (10 min) and this time interval was the same for all the environmental conditions points. Figure 6 suggests that the dependence of impact disdrometers with air temperature and humidity is stronger for high rain intensities and at low temperature.

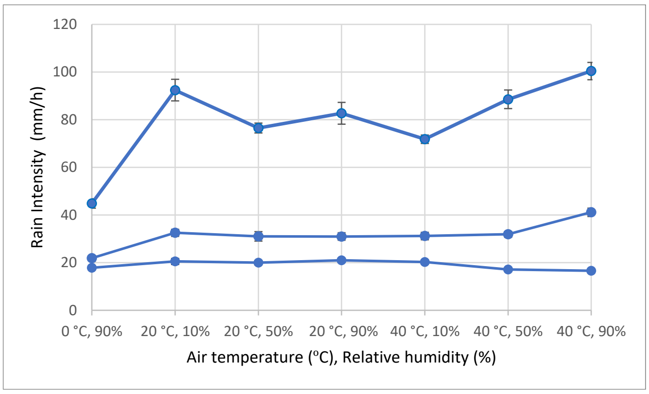


Figure 6: Dependence of one impact disdrometer with the air temperature and humidity conditions and for different stable reference rain intensities.

In addition, three different models of Optical disdrometers were also studied and the results are summarized in Figure 7, where the vertical bars are the standard deviation of the measurements performed at each environmental condition. As in the case of impact disdrometer, 10 minutes was defined as the measurements' interval in all cases.

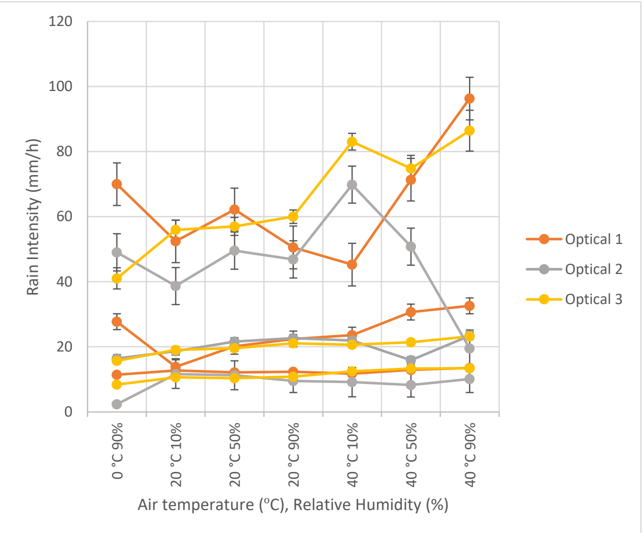


Figure 7: Dependence of three different models of Optical disdrometers with air temperature and humidity conditions and for different stable reference rain intensities.

As in the case of impact disdrometers, the influence of air temperature and humidity is more evident for high intensity rates and for extreme conditions of air temperature and humidity.

Key Outputs and Conclusions:

A report on the model functions has been produced. In this report, the modelling approach for the uncertainty evaluation for non-catching type precipitation instruments are discussed. The measurand was defined as the rainfall rates and a generic formulation for the determination of this measurand was pursued. For each type of instrument, the size of hydrometeors and their distribution is linked to the physical measurement process. For all types of gauges, a first evaluation of the main sources of uncertainties for each quantity was listed. These quantities are the input quantities for the determination of the rainfall rates.

Three rain generators, allowing the production of control rain drops with known characteristics, have been developed. These controlled raindrops allowed to assess quantitatively the influence parameters and estimate their contribution to the measurement uncertainty budget.

Numerical simulation and wind tunnel experiments were performed to assess the impact of wind on the measurement of an optical gauge, the Thies LPM. Initial results revealed the strong influence of the wind speed and direction on the airflow deformation near the instrument sensing area. This was expected to impact on the detection of the hydrometeors size and fall velocity, and therefore on the measurement of the precipitation intensity. To quantify this effect, based on the obtained results, particle tracking simulations were performed. Results have been presented in a paper published on the journal "Sensors". In addition to this, the influence of air temperature on 3 different types of non-catching precipitation gauges was analysed by measurements performed in a climatic chamber, and the conclusions are included in the report "*Calibration and accuracy of non-catching instruments to measure liquid/solid atmospheric precipitation*".

Objective #2 was successfully achieved. For the first time an uncertainty budget for a quantity measured by a non-catching rain gauge was evaluated with metrological rigour. The already mentioned report lists different model functions for different rain gauges technologies, which makes it possible to evaluate uncertainty budget for a wide variety of non-catching gauge models.

Objective 3: *"To validate the calibration methods and uncertainty budgets developed via an appropriate laboratory comparison involving the test calibration of different non-catching precipitation gauges".*

In the case of DG1 developed by DTI, the metrological traceability of the volume of the generated drops was achieved through time (i.e., drop frequency), density, and flow. The total uncertainty on the drop size was 0.5 % ($k = 2$). The dominating contribution to the uncertainty of the drop volume originated mainly from the flowrate calibration of the pump. This calibration was performed in the DTI microflow laboratory: The reference flowrate measurement was based on the gravimetric technique using a calibrated precision scale with 0.000001 g resolution placed on a granite table in a temperature-stabilized environment, and the flowrate determination included relevant corrections such as the effects of displacement, buoyancy, and evaporation. Evaporative loses during the fall of the drops have been estimated by model calculations and measurements; the results by the two methods exhibit good agreement and shows that such loses are about 0.03 % and thus negligible.
The acceleration of the drops is due to the gravity only. As consequence the drop velocity can be adjusted by change their fall height. The resulting drop velocity can be estimated based on calculations assuming spherical geometry of the drops. Furthermore, to measure the drop velocity photographic technique is employed.

For the DG2 developed at UNIGE, validation of drop size measurements was obtained by weighing the total volume of samples of about 20 to 45 drops with a precision balance with having a resolution of 0.001 g. Drops were released at 1.20 m above the centre of the measurement plane of the camera. Results are summarized in Table 1 in terms of the average drop diameter obtained from the software and the balance, and their relative percentage error difference (assuming the balance as the reference). This percentage error difference increases with the drop size, since the photogrammetric detection overestimates the drop diameter when drops present an oblate section due to significant oscillations in their shape. This is due to those drops failing to approach the aerodynamic equilibrium during the flight i.e., their terminal fall velocity (see Table 1).

Table 1: Validation of the photogrammetric device

Test n.	Number of drops	Avg D [mm] from the camera	Avg D [mm] from the balance	Difference [mm]	Fraction of the terminal velocity [%]
1	21	1.538±0.058	1.551±0.344	-0,013	72
2	43	3.072±0.086	3.026±0.090	0,046	54
3	50	5.129±0.276	4.978±0.111	0.152	44

A second set of tests was conducted using the photogrammetric system alone, without weighing the overall water volume. Statistics of the detected drop diameter and fall velocity are listed in Table 2 and Table 3 together with the number of released drops during each test.

Table 2: Characterization of the DG2 in terms of the drop diameter.

Test n.	Number of drops	Avg D [mm]	Std dev D [mm]	Max D [mm]	Min D [mm]	Fall velocity average drop [m/s]	Fraction of the terminal velocity [%]
1	50	3.42	0.15	3.77	3.08	4.47	50.8
2	50	1.77	0.05	1.98	1.70	4.06	68.4
3	50	1.12	0.04	1.25	1.06	3.50	81.4
4	50	0.85	0.01	0.89	0.83	3.02	91.0

Table 3: Characterization of the DG2 in terms of the drop fall velocity.

Test n.	Number of drops	Avg V [m/s]	Std dev V [m/s]	Max V [m/s]	Min V [m/s]	Theoretical fall velocity average drop [m/s]	Fraction of the terminal velocity [%]
1	50	4.36	0.12	4.56	3.98	4.47	50.8
2	50	3.79	0.10	4.08	3.65	4.06	68.4
3	50	3.29	0.05	3.19	4.54	3.50	81.4
4	50	2.72	0.04	2.81	2.65	3.02	91.0

The repeatability of the drop size is quite good, and the deviations of the maxi-mum and minimum generated drop size from the average diameter are about equal to 110 % and 90 %, respectively. Also good is the consistency of the measured fall velocities and their repeatability. It is evident that the fraction of the terminal velocity that can be achieved with the fall height adopted in the tests (1.20 m) is about 90 % for the smallest drops (D = 0.85 mm), while it only reaches about 50 % for the largest drops (D = 3.42 mm).
Note that – although the good repeatability is a positive feature of the developed drop generator – using an embedded photogrammetric device to measure the actual size and velocity of each single drop as released by the system makes the strict repeatability of the drop characteristics a much less relevant issue. The measured diameter rather than the nominal one is indeed used for comparison with the diameter reported by the instrument under test. Analogously, the measurement of the fall velocity of each released drop avoids resorting to theoretical formulations and the need to adopt very tall supporting structures to achieve the terminal velocity of the largest drops.

DG3 rain generator uses different nozzle geometries to generate drops of different sizes. The nozzle is mounted on a moving metallic structure in order to allow easy change of the drop position inside the measurement area. Each nozzle was tested using a precise weighing instrument in order to have information on the drop sizes. Assuming all drops are equal, by weighting 100 drops 10 times for each nozzle, we estimated the uncertainty on the drop weight, see Table 4. This is propagated to the drop size by taking also into account the uncertainty contribution to the density of water at the room temperature.

Table 4: Characterization of the different nozzles available for the DG3. The drop frequency was measured, and the drop weight is the mean weight of at least three different measurements. Drop size is calculated from drop weight assuming spherical shape.

Nozzle	Drop Frequency (drops/s)	Drop Weight (mg)	Drop Size (mm)
A	3.4	9.5 ± 0.09	2.6 ± 0.02
B	2.1	23.5 ± 0.21	3.6 ± 0.02
D	2.8	44.5 ± 0.13	4.4 ± 0.01
E	2.4	61.7 ± 1.56	4.9 ± 0.08
F	5.0	8.1 ± 0.08	2.5 ± 0.02

The repeatability of the measurement is quite good but tends to be better for the smaller sizes. The characterization of the different nozzles shows that the probability density function (pdf) used here must be a normal distribution since the effects not modelled coming from the nozzle shape will affect the repeatability of the measurement. Since this drop generator was built for test purposes, there were no velocity measurements or control. It can thus be used only with estimation for drop velocity through calculation or be used at heights where the drop terminal velocity can be reached.
In addition, during RMG1 performed at SMD, a numerical model for free-falling water droplets was developed using COMSOL Multiphysics software. The simulation of drops fall allowed to estimate the velocity at a given distance from the nozzle but also the drop shape in order to investigate the non-sphericity that can be an uncertainty source for non-catching instruments. Figure 7 shows the shape evolutions for several drop diameters.

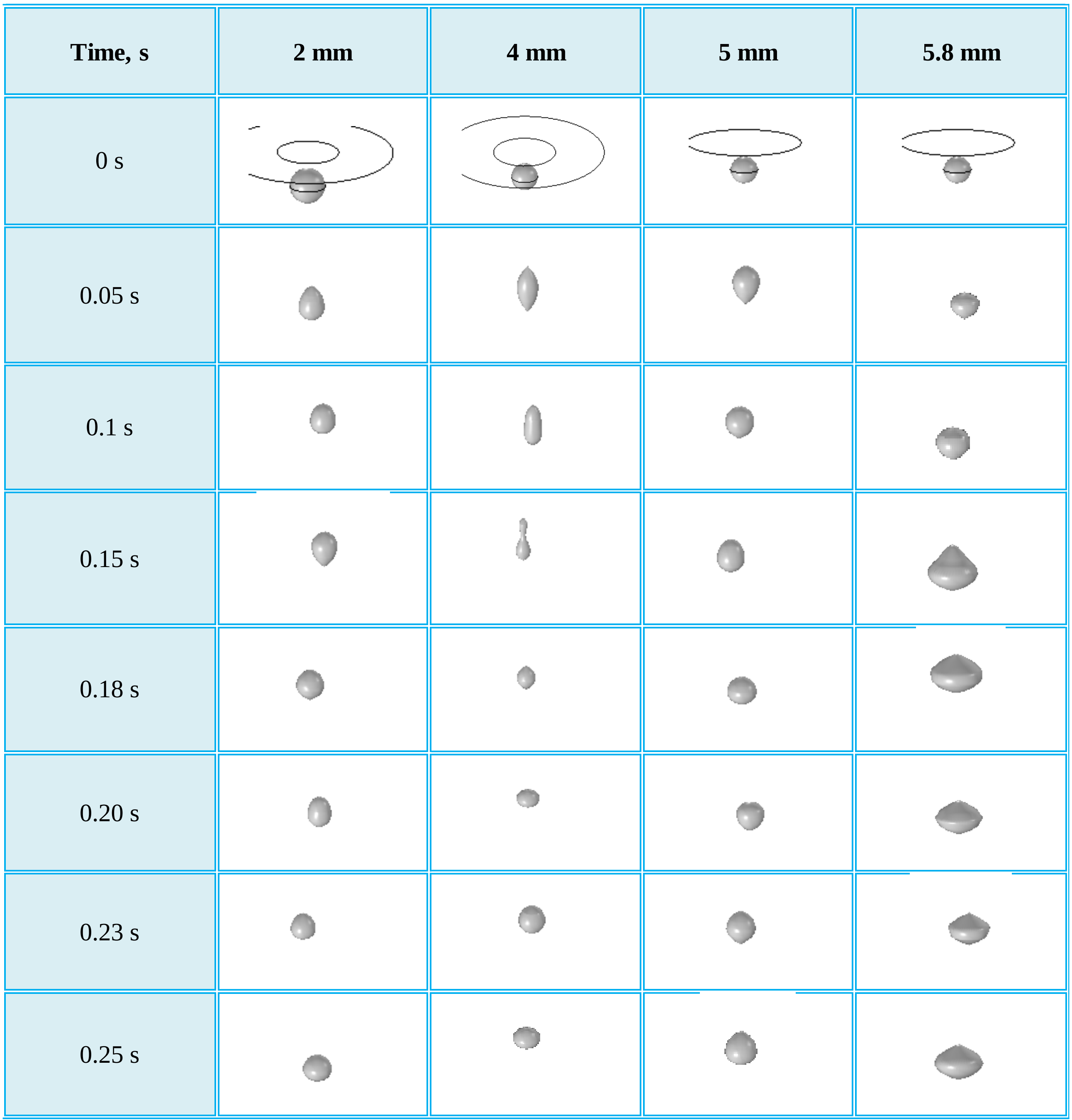


Figure 8: Evolution of a free-falling drop shape in air: numerical simulation.

Results are summarised in a scientific paper accepted for publication in the peer-reviewed journal “Sensors” as Baire et al. (2022), “Calibration uncertainty of non-catching precipitation gauges” (Sensors 2022, 22, 6413. https://doi.org/10.3390/s22176413).).

Further to the laboratory validation, field testing of some available NCGs was performed at the experimental field test sites of Payerne – Switzerland, and Vigna di Valle – Italy, thanks to the availability and support of Météo Swisse and the Italian Meteorological Service, respectively. In Payerne, at the end of March 2022, two rain generators (DG1 and DG2) were mounted used for the verification of the installed Thies laser disdrometer, while in Vigna di Valle, in June 2022, only the DG2 was used for the verification of the Biral light scatter disdrometer.

The metal supporting structure and the photogrammetric verification device for the DG2 was mounted around and above of the Thies LPM instrument in the field. The structure was completed with protecting plastic panels for shielding the generator and the drop vertical trajectories against the wind. Field operations are shown in Figure 9a, where the instrument under test is clearly visible inside of the shielding and supporting structure. Once the mounting and alignment was completed, a first set of drops was generated with a nominal expected diameter of 3.5 mm. The drops were generated on demand, first individually and then in sequences at various frequencies. Sequences of 1, 5 and 10 drops per minute were generated.
The meteorological conditions during the test were those of a sunny but windy morning, and the measured data of interest were obtained from the official meteorological station in Payerne (as shown in Figure 9b). The box-and-whiskers plot reported in Figure 9c indicates that the precision of the generated drop diameter is higher for individual drops than for series of 5 and 10 drops. This confirms that the drop generator is performing better for the release of single drops on demand.
A graphical representation of sample test results as obtained in the field is also proposed in Figure 9d,e. The black bar indicates the released drop characteristics, white diamonds indicate the number and characteristics of the detected drops, red crosses indicate detected drops with inconsistent drop size/fall velocity characteristics. The grey background bars are the multiple drop size/fall velocity classes provided as the possible output of the instrument under test.

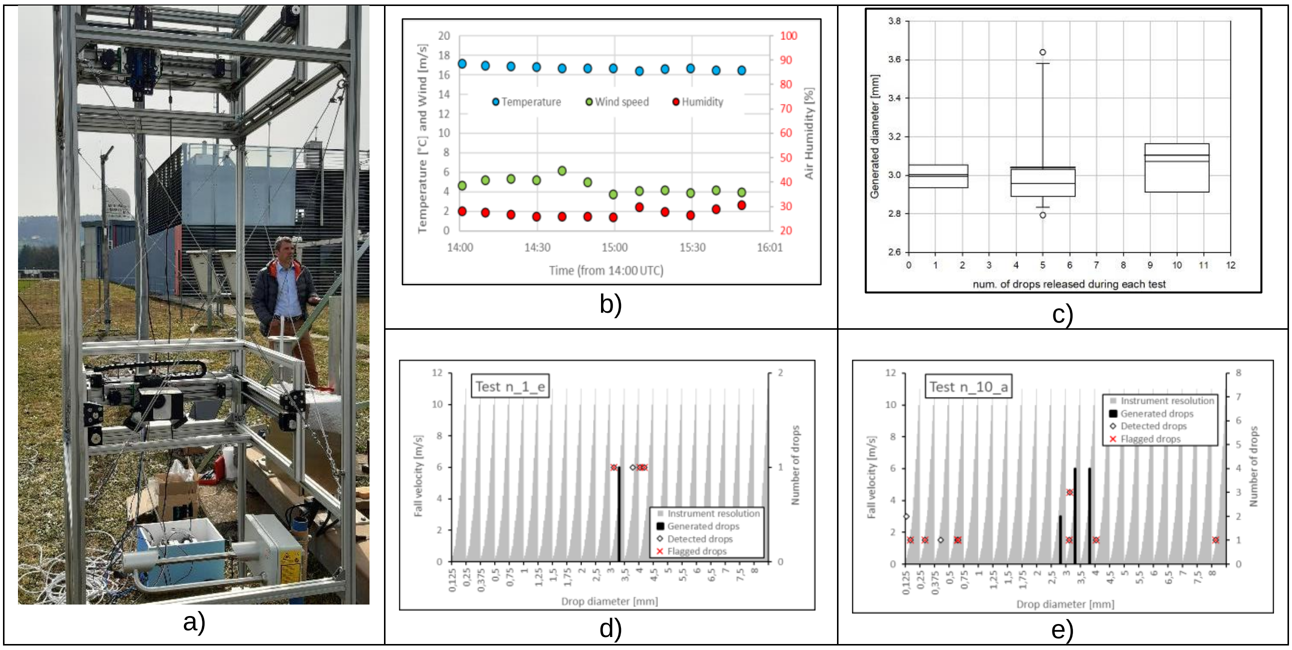


Figure 9: Field operations in Payerne and results.

The response of the Thies LPM in individual drop tests tended, in general, to overestimate the drop number by a factor of three, with the detection of some very large drops (≥ 8 mm) in most cases. However, part of these drops was discarded by the acquisition software since the relationship between the drop size and velocity was not in the acceptable range.

The DG2 was also installed in the field in Vigna di Valle (Rome, Italy) thanks to the hospitality provided by the Italian Meteorological Service, in June 2022. A picture of the installed device is reported in Figure 10a (where the Biral instrument under test is visible inside the raindrop generator assembly), together with sample results of the detected drop sizes (Figure 10b-e). Tests were performed with individual drops having a nominal diameter of 1, 3, 4.5 and 5 mm (with free fall velocity after 1.55 m of 3.82, 6.43, 6.98 and 7.09 m/s, respectively).
The response of the Biral disdrometer tended, in general, to overestimate the drop number and to largely underestimate the drop size. Contrary, the detected fall velocity was largely underestimated, even when associated with detected drops that are larger than the generated ones.

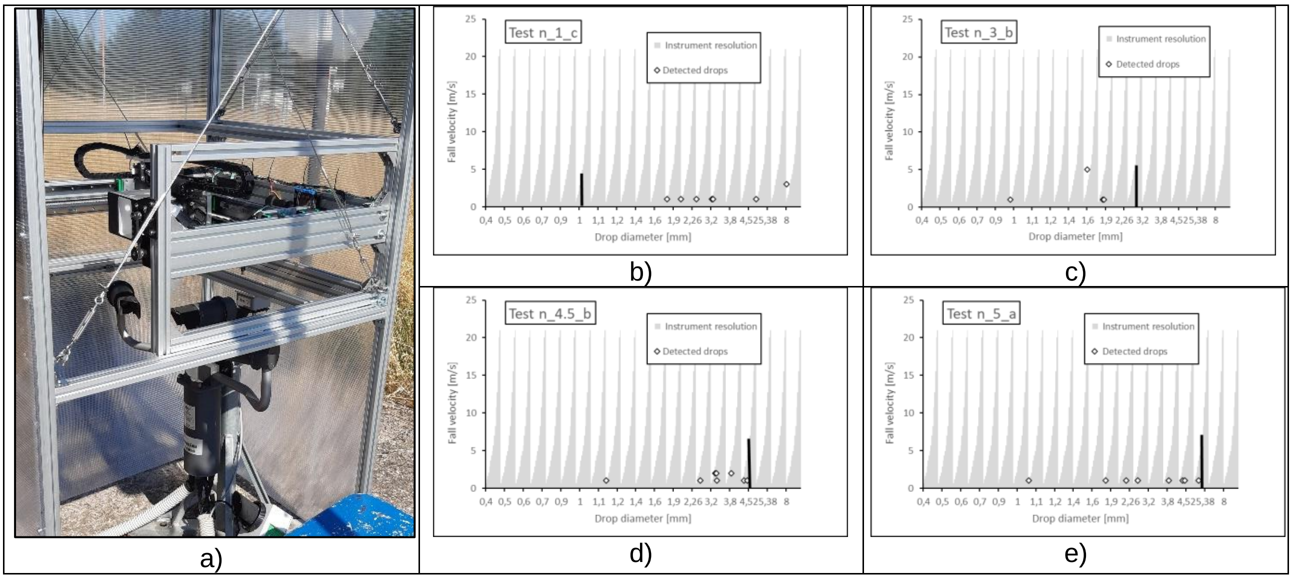


Figure 10: Field operations in Vigna di Valle and results.

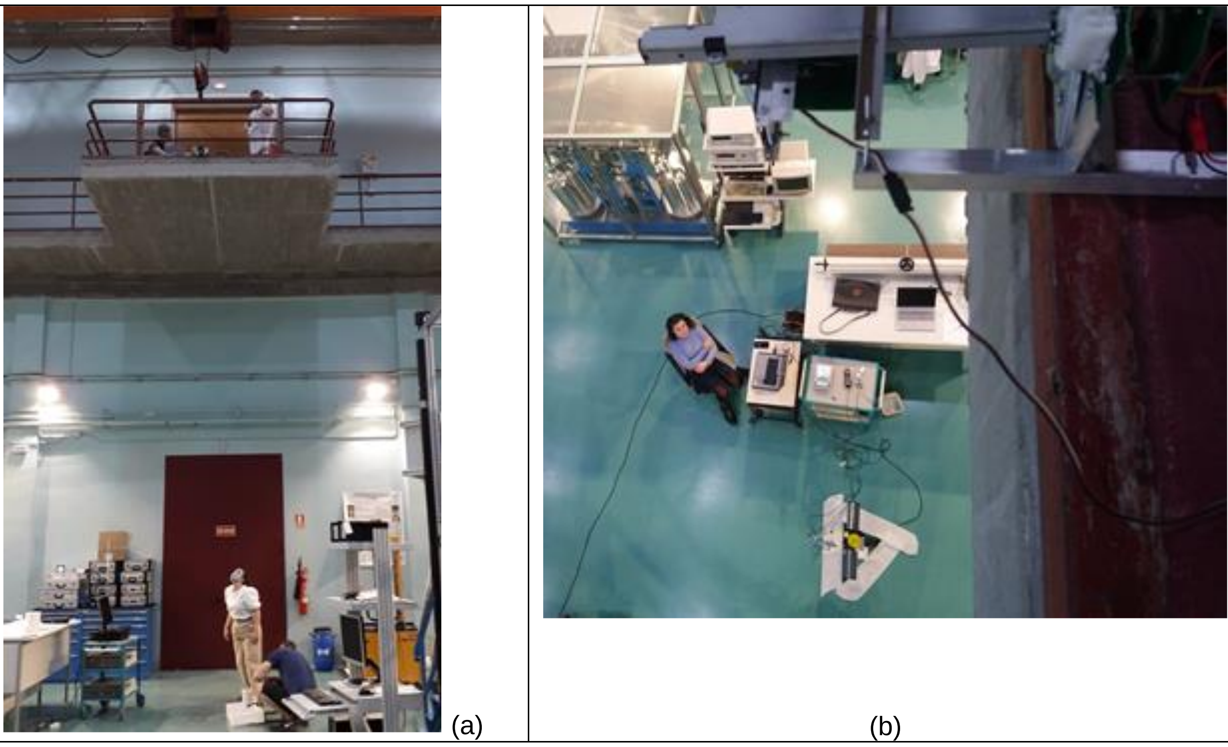
Lessons learnt from the experiments performed in Payerne and Vigna di Valle are that calibration procedures for NCGs should be limited to the controlled laboratory environment. Indeed, the experienced wind and atmospheric humidity conditions proved to be challenging for both rain generators developed within the project. Ambient characteristics especially impact on the production (detachment) of the smallest drops and their fall trajectory (deviation from the vertical) towards the instrument sensing area. Also, for the largest drops, the relevant release height that is necessary to reach a significant portion of the terminal velocity would require tall temporary support structures, whose installation and management is tough in field conditions.
It is therefore recommended that calibration is only performed in the laboratory, while limited verification tests to check that the instrument does not deviate significantly from the original calibration, must be limited in the field to few intermediate drop sizes (in the order of 2-3 mm in diameter) and in low wind and humidity conditions.

In addition to this, some non-catching rain gauges were calibrated at CEM using the rain generator designed and assembled by SMD as standard.

The non-catching gauge under study is an optical gauge (OTT2 Parsivel). This instrument was calibrated at laboratory conditions, 20 ºC ± 1 ºC and < 50 % RH, and three different distances between the drop generator and the sensitive area of the instruments. These distances are 2.2 m, 4.2 m and 6.4 m. Figure 11 shows different views of the calibration performed with the drop generator at a 6.4 and 4.2 m height.

Special attention was paid to fit each generated drop into the sensing area of the rain gauges. Before performing the measurements, the optimal relative position between the drop generator and the rain gauge was determined by reaching the maximum rain intensity reading in the rain gauge.

In order to increase the measurements comparison reliability, a constant measuring time interval of 10 min was defined for all the measurements.



(a) (b)

Figure 11: Laboratory configuration for the calibration performed with the drop generator (a) at a height of 6.4 m, (b) at a height of 6.4 m with a view from the platform where the drop generator is placed.

The OTT2 Parsivel was calibrated following the procedure already described in previous paragraphs. For this calibration, disdrometer data every 10 s were considered. Figure 12 shows the average of all disdrometer rain intensity readings for different reference rain intensities generated by the SMD drop generator and for several distances between the drop generator and the sensitive area of the non-catching instruments. The bars represent the standard deviation of the non-catching instrument readings at each calibration point. The calculated reference values of the rain intensity generated by the drop generator depends on the sensitive area of the non-catching instruments and these values are in Table 5 for the different configurations of the drop generator. These reference values are derived from the drop size, drop generation rate (determined in the calibration of the drop generator at 20 ºC) and considering the collecting area is 180 mm x 30 mm for the OTT2 Parsivel, as it is indicated in its manual.

Table 5: Reference conditions in the calibration of the OTT2 Parsivel.

Reference drop characteristics from initial calibration (20 ºC)	Reference generated rain intensity (mm/h)
2.8 drops/s, ø4.5 mm	86.7
12.4 drops/s, ø4.1 mm	189,7
3.4 drops/s, ø2.6 mm	21.2
8.5 drops/s, ø2.4 mm	40.3
2.2 drops/s, ø3.6 mm	34.9
5.0 drops/s, ø3.2 mm	57.8
2.4 drops/s, ø4.9 mm	99.2
10.1 drops/s, ø4.6 mm	352.9
5.0 drops/s, ø2.5 mm	27.2
11.3 drops/s, ø2.2 mm	40.0

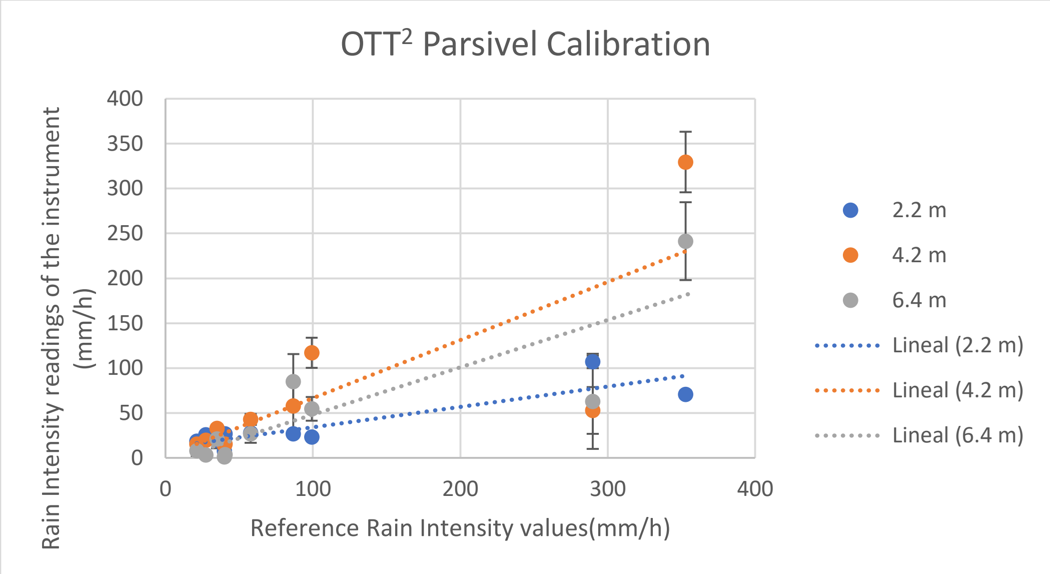
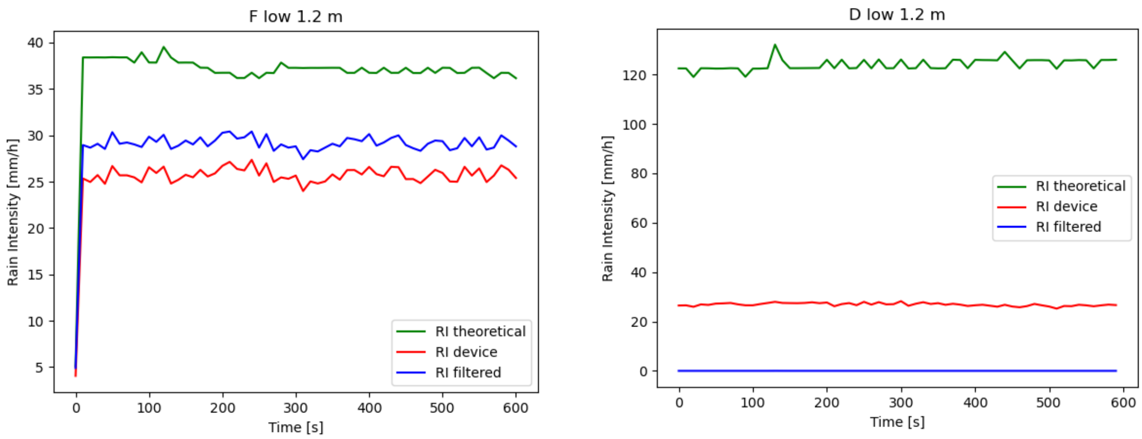


Figure 12: Calibration of OTT2 Parsivel at different distances between the drop generator and the sensitive area of the non-catching instrument.

Figure 12 shows that a distance of 2.2 m between the drop generator and the non-catching instrument is not high enough to perform a correct calibration, this is due the drops are unable to reach the appropriate terminal velocity and these drops are not correctly detected by the OTT2 Parsivel. An increase of the quality of the calibration with the distance is expected, but this is in contradiction with Figure 12, where the calibration at 4.2 m seems better than the calibration at 6.4 m. Two reasons explain this behaviour. On one side, the drops generated at 4.2 m reach a velocity value very close to the appropriate terminal velocity, needed for correct readings and calculations performed by the OTT2 Parsivel. On the other side, the drops generated at 6.4 m are more disperse when they reach the level of the sensitive area of the instruments, and some of them don't cross the sensitive area. This means that some drops are not detected by the instrument and, as a consequence, the readings of the instrument are lower than the rain intensity generated at the drop generator. This is confirmed by Figure 13, which shows the rain intensity as given by the device, in red, computed with the DSD after filtering particles detected at a ± 50 % of the terminal velocity, in blue, and from the theorical drop size using the number of detected particles, in green.



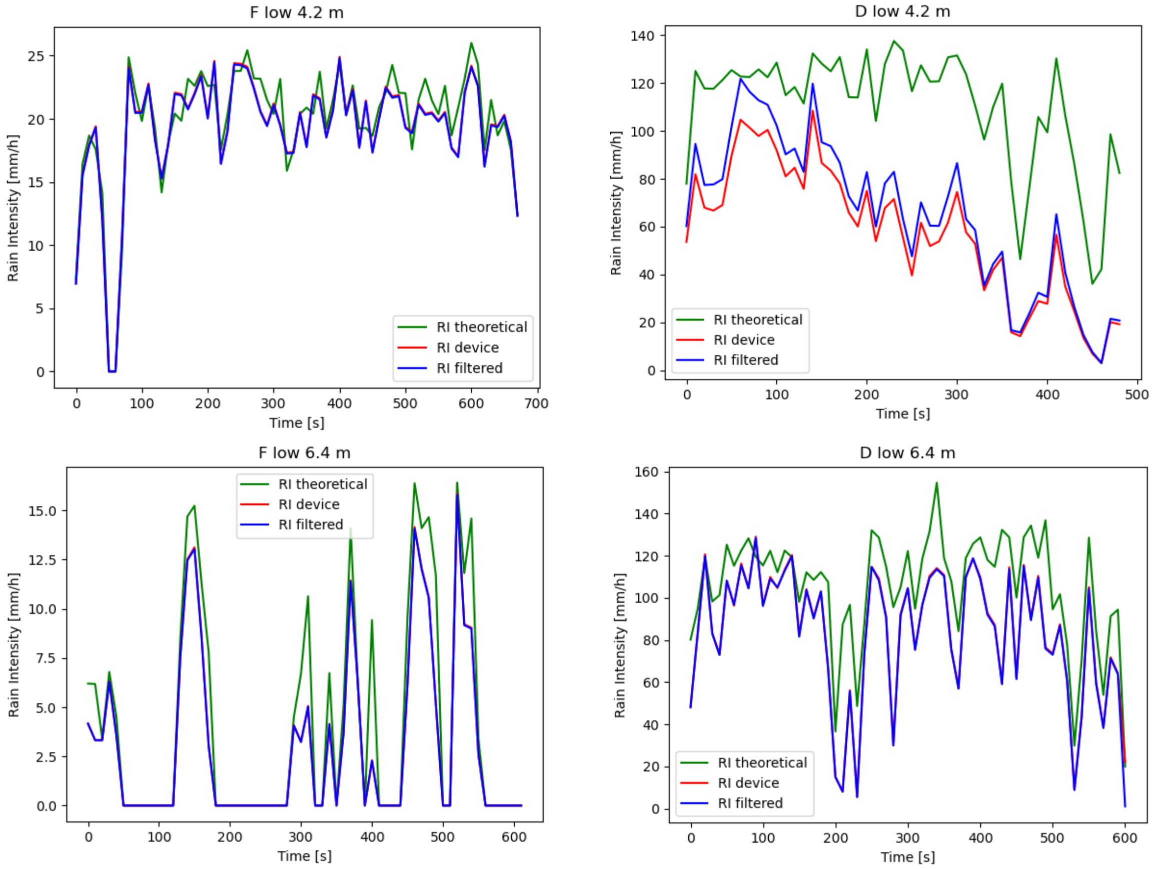


Figure 13: Rain intensity from the device (in red), from the DSD filtered (in blue) and from the theorical drop size (in green) for the 10 minutes of measurements, for F nozzle at low speed (5 drops/s, 2.5 mm) on the left, and for the D nozzle at low speed (2.8 drops/s, 4.5 mm) on the right. The first line is in the climatic chamber (1.2 m), the second one for the gas laboratory (4.2 m) and the last one for the force laboratory (6.4 m).

We can see that at 6.4 m, the device rain intensity curve and the filtered one are superposed at this scale. For the F nozzle (2.5 mm drops), the differences between the theorical curve and the two other ones can be explained by a non-negligible number of particles detected at a size lower than the characterized size (a peak of more than 60 particles at 2.125 mm for a characterized size of 2.5 mm). The higher number of particles detected, and the larger diameter of drops might explain larger differences for the D nozzle (4.5 mm drops). The differences between the device rain intensity and the computed rain intensity from the DSD for the D nozzle at 4.2 m can be explained by filtering/algorithm. Since we are using the raw data from the device, we might have used, for the computation of rain intensity, some drops that have been discarded by the device for its computation of this value.

RMG2, whose activities – performed at INRiM – can be linked to this objective, was focused on optimising some of the technical features of raindrop generators developed by the parent project. Two key achievements have been produced: a) the evaluation of the drop dispersion from different heights allowed to transfer the knowledge for the infield campaign that followed during the parent project lifetime and improve the positioning and structure for the in-field use and b) a clear distinction between validation and calibration of non-catching rain gauges was also presented.

Key Outputs and Conclusions:

Three types of non-catching precipitation gauges were calibrated, using a drop generator previously calibrated and characterized for different air temperature conditions. SMD gathered measurements from laboratory test which were included in the first-step quantitative assessment for the uncertainty budget of one type of rain gauge. Analysis of the measurements was made and reported in the accuracy assessment through evaluation of quantities of influence. Based on the results, the first recommendation for proper calibration was made, i.e., limiting the drop rate, calibration as close as possible to the height for obtaining the drop terminal velocity, and using manufacturer information about the rain intensity computation in the device under test.

A model for the calibration uncertainty of non-catching precipitation gauges was proposed and detailed, based on separating uncertainty components into blocks. This gives a flexibility on designing a calibration procedure by combining different blocks (i.e., changing the drop generator or the type of instrument). The main filtering component is related to final velocity of the falling drops, and this might be a major concern when developing an easy to implement calibration procedure.

Further to the laboratory validation, field testing of instruments was performed at the experimental field test sites of Payerne – Switzerland, and Vigna di Valle – Italy, thanks to the availability and support of Météo Suisse and the Italian Meteorological Service, respectively. In Payerne, at the end of March 2022, two rain generators (DG1 and DG2) were mounted used for the verification of the installed Thies laser disdrometer, while in Vigna di Valle, in June 2022, only the DG2 was used for the verification of the Biral light scatter disdrometer. It has been concluded that calibration procedures for NCGs should be limited to the controlled laboratory environment. Indeed, the experienced wind and atmospheric humidity conditions proved to be challenging for both rain generators developed within the project. It is therefore recommended that calibration is only performed in the laboratory, while limited verification tests to check that the instrument does not deviate significantly from the original calibration, must be limited in the field to few intermediate drop sizes (in the order of 2-3 mm in diameter) and in low wind and humidity conditions.

Objective #3 - To validate the calibration methods and uncertainty budgets developed via an appropriate laboratory comparison involving the test calibration of different non-catching precipitation gauges - was successfully achieved.

Objective 4: “To provide a substantial metrological contribution to CEN/TC 318 (Hydrometry) /WG12 (Rainfall Intensity) and the ISO/TC 113 (Hydrometry) committees on the development of a technical specification or standard on precipitation measurement using non-catching type instruments, following the identified research needs submitted by CEN/TC 318 under the STAIR-EMPIR agreement. This will include the provision of a technical report with guidelines on recommended traceable calibration methods to measure atmospheric liquid precipitation using non catching instruments and recommendations for incorporation of this information into future standards or technical specifications at the earliest opportunity”.

A technical report, including a draft procedure for the traceable calibration of non-catching precipitation measuring instruments, was prepared by the consortium, and provided to CEN/TC 318 (Hydrometry)/WG12 (Rainfall intensity). The document contains the description of a recommended traceable calibration method for consideration in the development of future standards.

The traceable calibration procedure proposed in the report summarises the results of the work performed in various steps of the project, including the analysis of the state-of-the-art about the calibration of non-catching precipitation gauges, the design, construction and testing of rain generators, the assessment of the model uncertainty for precipitation measurements using non-catching instruments, and the laboratory and field testing of the procedure using different sample gauges. All the issues encountered, and the obtained results, contributed to raise the confidence that the proposed procedure is suitable for the traceable calibration of non-catching precipitation measuring instruments in the laboratory. Field verification using the proposed procedure is only recommended for those specific and limited cases, where instruments cannot be removed from the field installation.

The first step in the procedure is the definition of the characteristics of a suitable drop generator, able to release drops of the desired size (diameter) at a sufficient release height above the instrument sensing area, to ensure enough vertical fall distance of the released drops and a sufficient (possibly close to terminal) fall velocity.

Essential elements of the drop generator are:

- a drop formation and detachment device able to produce, on demand, drops of a predetermined size, having equivolumetric diameters in the range between 0.5 mm and 6 mm;

- a verification device, using and independent measurement principle, able to detect the released drops in flight along their fall trajectory and to determine their actual size and fall velocity before they reach the sensing area or volume of the instrument under test;

- in case the instrument under test does not interfere with the drop trajectory (e.g., employs an optical principle), a gravimetric device (usually a weighing system) able to check the total mass delivered through a given sequence of drops.

The drop generator used for calibration shall have an expanded uncertainty of less than 1%, calculated with a coverage factor equal to 1.28. This number shall be certified with explicit traceability to the international standards by means of extensive characterisation that shall be demonstrated and documented.

The proposed procedure is as follows:

Calibration of non-catching precipitation measuring instruments shall be performed by generating a controlled set of water drops and letting them fall from a sufficient height over the sensing area (or volume) of the instrument under test. The drop size and fall velocity shall be determined by means of an extensive characterisation of the drop generator and their uncertainty assessed and traced back to the international system of units (Baire et al., 2022). When triggered by the generated drops, the reading of the instrument shall be recorded and compared with the known drop characteristics.

Water drops of at least three different diameters in the range 0.5 mm – 6 mm shall be generated

(it is advisable to generate five different diameters, including those at the limits of the above range)

The release height above the sensing area of the instrument under test shall be such that at least 50% of the terminal velocity is achieved when the drop reaches the sensing area (or volume) of the instrument (this requirement means that at least 0.063 m are used for a drop with diameter 0.5 mm and at least 2.1 m for a drop with diameter 6 mm).

It is recommended that the size and fall velocity of each generated drop are measured immediately before or after they reach the instrument under test by means of an independent measurement method (gravimetric, photogrammetric, etc.)

Drops should be released in different positions over the sensing area (or volume) of the instrument under test, to cover both the central and peripheral measurement regions (a minimum of 5-6 different positions is recommended, depending on the instrument geometry)

Enough drops should be released to allow statistical significance of the results (at least 30 drops per each position) and the mean and coefficient of variation of each set of drops shall be used to assess the performance of the instrument under test.

Objective 5: "To collaborate with CEN/TC 318 and ISO/TC 113, and the relevant WMO-CIMO* (World Meteorological Organisation-Commission for instruments and Methods of Observation) Expert Teams and end users of the standards (e.g., national meteorological services, manufacturers of environmental measurement instruments) to ensure that the outputs of the project are aligned with their needs and in a form that can be incorporated into standards at the earliest opportunity".

Collaboration with the CEN/TC 318 materialised with the approval within the same TC of a new work item (NWI) for a European norm entitled "Hydrometry - Measurement of precipitation intensity - Metrological requirements and test methods for non-catching type rain gauges". This new work item was approved last February 2022, and it was activated based on the proposal submitted by the Italian national normative body (UNI) after suggestion from the INCIPIT partners and approved by 15 countries in a balloting process. A second document was prepared and submitted to the same CEN TC318, to support the proposal of a new work item (NWI) for a Technical Report entitled "Calibration and accuracy on non-catching precipitation measurement instruments", approved in February 2022.

The preparation of the two documents concludes the pre-normative activities of the INCIPIT project and both are submitted to CEN in response to the specific testing and measurement needs for non-catching instruments that were expressed in October 2017 by CEN TC318 to EURAMET, through the cooperation programme between STAIR (the joint CEN CENELEC strategic Working Group supporting standardization in research and innovation) and EMPIR. Those needs had been also presented at the 3rd STAIR EMPIR workshop "From metrology research to standardization", held at the CEN CENELEC Meeting Centre, Brussels, 10 October 2017.

Key Output and Conclusions:

Based on the proposal from Prof. Lanza (UNIGE) the chair of WG12, CEN TC 318 "Hydrometry" decided to maintain the working group 12 (Rainfall Intensity) to analyse the results of this project. Therefore, the proposals for calibration procedures developed by the present project now have an appropriate committee to transform the information into normative. A report for WG 12 was presented, and a NWI for a Technical Report was proposed with the title "Measurement of rainfall intensity - Calibration methods and performance assessment of non-catching instruments". The proposal for a European Standard on the same subject was also approved. This activity was also performed at the national level within the mirror committee of the Italian national standardization body (UNI).

In July 2021, a meeting of the Italian UNI/TC 055 "Metrology of flow, pressure and temperature" (decision n. 7), formulated two NWI proposals for a European Technical Report (CEN/TR) and a European Norm (EN) about non-catching precipitation measurement instruments, to be submitted for balloting within the UNI/TC 055 WG/02, so that they could be transmitted to CEN CEN/TC 318 "Hydrometry". The proposal was approved in the national balloting closed on September 1st, 2021.

The two new work item proposals were submitted to CEN/TC 318 by the Secretary of the Italian Mirror Committee UNI CT055 on September 10th, 2021. After balloting among the member countries, the two proposals for a European Standard and a Technical Report were approved and included in the work programme of CEN/TC 318 with the titles: a) EN "Hydrometry - Measurement of precipitation intensity - Metrological requirements and test methods for non-catching type rain gauges" and b) TR "Calibration and accuracy of non-catching precipitation measurement instruments".

Objectives #4 (and #5) were successfully achieved. The engagement with committees was constant throughout the project. Standard and regulatory activities were performed at the European scale, and therefore first addressed to CEN/TC 318 as an initial step towards further extension at the global scale (ISO/TC 113). CEN has agreements in force with ISO and the WMO in order to address the development of standards on similar topics, to avoid duplications.

Last, the chair of CEN/TC 318 is an active member of ISO/TC 113 and will keep that committee aware and informed of the normative steps activated within CEN on this subject.

5 Impact

Dissemination activities included:

a) A training course, attended by ~ 20 people of mixed origin (researchers, technicians, end-users) by UNIGE on the working principles, measurement processes, use and calibration of different typologies of rain gauges (including non-catching ones). This training went beyond the planned expectation, since it was held at one of the most important meteorological sites for measurement of precipitation, linked with the WMO (see "News Stories"). This allowed the course to be extended to practical aspects, with detailed field analysis of such kind of instruments and the way they are compared.

b) The project website was hosted by the MeteoMet main website, since it already attracted a wide size of audience, due to its history and impact. https://www.meteomet.org/incipit

c) The project and its objectives were presented during the environmental and climate session of the international conference CIM 2019 held in Paris in September 2019, under a talk with titled as: "INCIPIT: it started to rain". Other International Conferences included the 2019 United Nations Framework Convention on Climate Change and the European Geosciences Union General Assembly 2020.

d) The closing meeting was organized and hosted at the University of Genova, one of the WMO Lead Centres "B. Castelli" on precipitation intensity measurement.

Furthermore, three Research Mobility Grants (RMGs) have been linked to this project. The main achievements of the RMG1 are summed up in a scientific report on numerical simulation of free-falling water droplets using COMSOL Multiphysics. First the researcher reviewed the literature on natural rain drops and determined the main expected characteristics such as size, shape and velocity. Then, based on fluid mechanics principles RMG1 described the forces acting on a free-falling drop and the factors that affect its shape during fall. This theoretical study was the basis of the development of a numerical model implemented in COMSOL Multiphysics. After optimization, the numerical model was used to run simulations of drop shape changes during free fall for different drop sizes (ranging from 0.5 to 5.8 mm). In addition, RMG1 calculated, using different available experimental models, the minimal fall distance needed before reaching final velocity. This information was used in INCIPIT project during the experimental in lab campaign to set-up the height of the rain generator with respect to the measuring instrument.

RMG2 was focused on optimising some of the technical features of raindrop generators developed by the parent project. Two key achievements have been produced: a) the evaluation of the drop dispersion from different heights allowed to transfer the knowledge for the infield campaign that followed during the parent project lifetime and improve the positioning and structure for the in-field use and b) a clear distinction between validation and calibration of non-catching rain gauges was also presented.

RMG3 has been cancelled due to logistic and travel difficulties during the COVID-19 pandemic.

Impact on industrial and other user communities

The main industrial sector that will benefit is the hydro-meteorological equipment industry. The calibration procedure and guidance developed in this project will enable manufacturers to certify the performance of non-catching type instruments based on standard procedures. This will respond to the needs of national meteorological services for maintenance-free instrumentation and fully automated weather stations. Manufacturers of laboratory equipment for instrument calibration will be able to provide calibration devices for non-catching type instruments that are compliant with a standardised procedure and possibly included in a European standard. As a result, users of precipitation gauges, particularly national meteorological services will be able to make decisions about the suitability and performance of equipment based on more robust and reliable information.

Impact on the metrology and scientific communities

The inclusion of the traceability of modern precipitation devices, which is of utmost importance in climate analysis, environmental monitoring and early warnings, will support the growing interest in metrology for environment. The climate community, represented by the relevant WMO Technical Commissions and Standing Committees and by the GCOS with its GSRN, will benefit from improved knowledge on data quality in precipitation records. Data series and standard measurements, which are mainly based on temperature records at present, are extending the focus to other observables. Precipitation is the most important observable after temperature, and the GSRN will design standard climate observing stations in part on the basis of the traceability achievable and uncertainty of the instruments selected. This project's outputs have therefore contributed to better addressing the definition of traceability in precipitation measurements and instrumental quality and uncertainty. The projects outputs have been disseminated and promoted to the end users, the metrology and wider scientific community via peer-reviewed papers and presentations at key international conferences.

Impact on relevant standards

The project prepared a Technical Report on the calibration and accuracy of non-catching precipitation instruments and submitted it to CEN/TC 318 – via WG12 – for adoption as a New Work Item (NWI). The project's outputs have also had an impact on the standardisation activities of ISO/TC 113 (Hydrometry), where a standard on precipitation measurements has been recently developed, though not yet addressing non-catching instrument. Two New Work Item proposals were submitted to CEN TC318 by UNI (Italy) for a Technical Report on "Calibration and accuracy of non-catching precipitation measurement instruments" and for a European Norm on "Hydrometry – Measurement of precipitation intensity – Metrological requirements and test methods for non-catching type rain gauges". These were both accepted to be included in the work programme, with a good participation.

Under the Vienna agreement between CEN and ISO, impact is expected in the form of a proposal to adopt both the Technical Report and the Standard submitted to CEN. Finally, a proposal was submitted to the WMO Editorial Board to include recommendations about non-catching instruments in the Guide WMO-Nr. 8, following the results of this project.

This submitted report on best practice made an outstanding and noteworthy contribution to the issue of comparability and traceability of the measurements coming from non-catching rain gauges, which are increasingly being used in meteorological stations, as data quality and comparability are key factors in the accurate determination of rainfall intensity and will matter even more as these instruments will be of more widespread use.

WMO recognised the impact of project "INCIPIT" as well, as a pre-normative endeavour that will contribute to the standardization of methods and best practices of calibration, maintenance and usage of these instruments. It has been confirmed that these submitted documents on best practices and procedures for the calibration of non-catching precipitation gauges, and their uncertainty evaluation, will be taken into account (as a contribution to the revision of the) for inclusion in WMO GIMO (Guide to Instruments and Methods of Observation) n°8.

This is a first step to activate accelerated adoption by ISO as per the Genève agreement (WMO & ISO) in the form of an ISO standard.

Early Outreach and uptake

During the project lifetime, a field test was made on instruments actually operating in a meteorological network. That was the calibration campaign at the MeteoSwiss operational site in Payerne. Following the results of the campaign, procedure and calibration results, the Measuring Technology Division confirmed that the measurement results provided by this instrument are now made traceable to standards, raising the quality of the data products. The system is now operating in this meteorological network and given the benefit of being calibrated, it raises its role to reference instrument among non-catching rain gauges. This is in particular relevant, because non-catching type instruments show multiple advantages when used operationally, and they are meant to be used intensively in the near future. Among others, they show significant lower maintenance costs compared to traditional rain gauges (tipping bucket or weighing gauge). The generated output offers also additional possibilities, with for instance the drop size and fall velocity distribution, which is not available with traditional gauges. Moreover, the same procedure will be applied to other similar instruments now contributing to our numerical weather predictions and to climate data series, should a rain generator be available, such as those developed by the INCIPIT project.

Longer-term economic, social and environmental impacts

Wider impact from the project is expected on companies operating in the fields of hydro-meteorological warnings, water resources management, flood control, and agriculture. These companies generally provide services based on the monitoring of hydro-meteorological variables (precipitation, flow rate, evaporation, etc.) and the processing of the related measurements to support end users' decisions, even in real time, about the configuration of industrial systems including water diversions, dam overflows, weirs, hydropower turbines, etc. Due to their intrinsic features, non-catching instruments require less maintenance, and the absence of mechanical and moving parts makes them more stable devices for field use, impacting on the required calibration and check intervals, and resulting in reduced maintenance costs for hydro-meteorological agencies and users. The use of calibrated non-catching type instruments to measure liquid precipitation would improve the management capabilities of the users, since decisions would be based on traceable measurements obtained at a lower operational cost than the present networks of catching-type instruments.

Based on a general lack of traceability and data quality in historical observations, the Global Climate Observing System (GCS) is preparing the creation of the GCOS Surface Reference Network (GSRN). During its first meeting the newly formed WMO Commission for Infrastructures approved the creation of the GSRN under its Decision 4.1.1(4)/1 (INFCOM-1), "Development of a draft implementation plan for the GCOS Surface Reference Network". There, *"a set of high-quality long-term fiducial reference measurements of Essential Climate Variables (ECV)* is recommended to *enable future generations to make rigorous assessments of future climate change and variability.* Non-catching gauges will offer more reliable data and are relatively immune to maintenance and mechanical drifts and shocks, thus becoming a more robust candidate for long term data series recording. The calibration procedures and guidance developed by this project are therefore expected to benefit climate science through the GCOS and other similar initiatives, by enabling better environmental and climate data and analysis.

Non-catching instruments are suited to operation in unmanned meteorological stations, e.g., those far from urban settlements or in remote areas and in harsh environments. These remote stations are needed to monitor the whole territory of hydrological basins, whose headwater area is generally located in mountainous or impervious regions, in order to provide improved coverage and completeness of information about incoming precipitation. More reliable early warnings would therefore make it possible to promptly inform weather services, civil protection agencies and the general population about the risk of floods and especially flash floods, which evolve rapidly and have a strong potential for disruption. The accuracy of such data and information is vital for issuing effective and timely warnings, resulting in increased safety for citizens and extended lead time for warnings, with a potential to save lives and properties in case of extreme events.

6 List of publications

1. Lanza, L. G., Merlone, A., Cauteruccio, A., Chinchella, E., Stagnaro, M., Dobre, M., Garcia Izquierdo, M. C., Nielsen, J., Kjeldsen, H., Roulet, Y. A., Coppa, G., Musacchio, C., Bordianu, C., & Parrondo, M. (2021). Calibration of non-catching precipitation measurement instruments: A review. *Meteorological Applications*, 28(3), e2002. https://doi.org/10.1002/met.2002
2. Chinchella, E.; Cauteruccio, A.; Stagnaro, M.; Lanza, L.G. Investigation of the Wind-Induced Airflow Pattern Near the Thies LPM Precipitation Gauge. Sensors 2021, 21, 4880. https://doi.org/10.3390/s21144880.
3. Baire, Q., Dobre, M., Piette, A.S., Lanza, L.G., Cauteruccio, A., Chinchella, E., Merlone, A., Kjeldsen, H., Nielsen, J., Friis Østergaard, P, Parrondo, M., Garcia Izquierdo, C. (2022). Calibration uncertainty of non-catching precipitation gauges. *Sensors*, 6413 22(17). DOI: 10.3390/S22176413

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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