

USING LABORATORY EXPERIMENTS TO IMPROVE RELIABILITY IN SOLID PRECIPITATION WEIGHING-GAUGE MEASUREMENTS

M. Colli^(1,4), L.G. Lanza^(1,4), R. Rasmussen⁽²⁾ and E. Vuerich^(3,4)

- ⁽¹⁾ University of Genova, Dep. of Civil, Chemical and Environmental Engineering,
Via Montallegro 1, 16145 Genoa, Italy, matteo.colli@unige.it, tel: (+39) 010 353
2031,
fax: (+39) 010 353 2481
- ⁽²⁾ National Center for Atmospheric Research, Research Application Laboratory,
Boulder, Colorado, USA
- ⁽³⁾ Italian Meteorological Service – Centre of Meteorological Experimentations
(ReSMA), km 20, 100 Braccianese Claudia, 00062 Bracciano (Rome), Italy
- ⁽⁴⁾ WMO/CIMO Lead Centre on Precipitation Intensity, Italy

ABSTRACT

Snowfall, drizzle and light rainfall events can often be hard to detect over a short-time resolution due to sampling limitations, wind/temperature effects and noise influencing the weighing-gauge measurements (Rasmussen et al., 2012). In many instances, the noise observed in the data sampling can be greater than the detectable signal from a real precipitation event. This is principally due to the daily variability of wind, also responsible for snowfall undercatch (Strangeways, 2004; Thériault et al., 2012), and environmental temperature (Duchon 2002; Duchon, 2008). Recent laboratory testing demonstrated the ability to reproduce some of these anomalies observed in precipitation measurements during field trial campaigns (Colli et al. 2012; Colli et al. 2013).

This work details the wind-free laboratory testing of some of the above-mentioned issues performed within the WMO Solid Precipitation Intercomparison Experiment (SPICE) to improve the measurement accuracy of the Geonor T-200b vibrating wire (VW) gauge and the OTT Pluvio2 weighing gauge (WG). The experiments examined the influence of environmental temperature oscillations the gauge sensors, as well as the snow capping issue and the potential problems associated with heating the gauges. Environmental chamber experiments were performed in two different sessions. The first one employed a low-rates liquid precipitation generator installed in the environmental chamber available at the Italian Air Force facility of Pratica di Mare Airport (Italy). The second session was carried out by using the snow machine available at the National Center for Atmospheric Research (Boulder, CO, USA) where controlled snowfall rates can be generated in a wind-free environment. In addition, the VW sensors showed high sensitivity to the non-perfectly static installation, a condition that occurs infield due to, e.g., wind-induced vibrations. This induces low precision of measurements performed at short time resolutions ($\Delta t \leq 5$ min) even in the field installations, emphasizing the need of a dedicated de-noising filter.

1) INTRODUCTION

The environmental errors are those caused by the impact of the weather conditions at the collector and other disturbing factors affecting the correct functioning of the gauge (not attributable to the instrumental characteristics). Typical environmental errors are caused by the gradients of atmospheric temperature, the wind speed and the solar radiation. A large part of the mentioned errors can be effectively reduced by adopting algorithms aimed at the advanced interpretation of the precipitation measurements. These are based on the information learned through laboratory, infield experimental campaigns or, more recently, numerical modelling activities. Still, the variable instrumental characteristics of different catching-type gauges enhance the non-homogeneity and would require dedicated analysis for the retrieval of a customized corrective method. In this scenario, the availability of comprehensive databases resulting from the WMO field and laboratory intercomparison experiments represent an important heritage to support those efforts. Significant improvements on environmental errors matter are also fostered by the availability of co-located ancillary data (horizontal wind speed, air humidity, environmental temperature and solar radiation) and precipitation types identification as performed in the recent WMO Rainfall Intensity Field Intercomparison and WMO Solid Precipitation InterComparison Experiment (SPICE).

This work details on environmental chamber testing of some of the above-mentioned issues performed within WMO SPICE to assess the solid precipitation measurement accuracy of the Geonor T-200b vibrating wire (VW) gauge and the OTT Pluvio2 weighing gauge (WG). Such experiments examine the influence of vibrations on the gauge sensors, as well as environment temperature sensitivity and snow capping. Potential problems associated with heating the gauges are also investigated.

2) UNCERTAINTIES DUE TO MECHANICAL VIBRATIONS AND SIGNAL NOISE

A first environmental chamber testing of precipitation gauge were performed on May 2012 by the Lead Centre of Precipitation Intensity for the WMO SPICE campaign. The investigation was focused on precipitation measurements obtained by the OTT PLUVIO2 and GEONOR T200B gauges under constant flow rates generations of an antifreeze liquid solution (with density approximated to distilled water). The results were presented during the 3rd SPICE IOC meeting and TECO 2012 (Colli et. al., 2012) remarking the relevance of the sensors noise on the quality of precipitation measurement. A sample of this issue is represented by the Fig. 1 vibrating wires (VW) measurements performed under a liquid precipitation rate equal to 1.2 mm/h and an environmental temperature T equal to 0 °C.

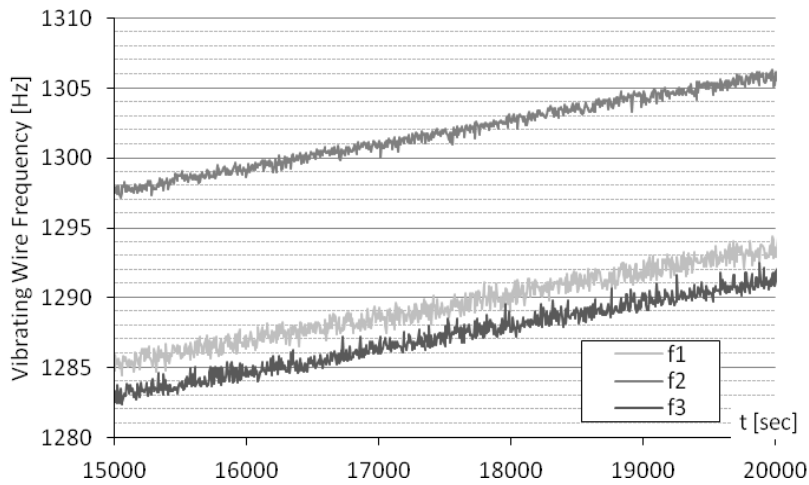


Fig. 1 Extract from the Lead Centre on Precipitation Intensity cold room tests (May 2012). The noise effect on three GEONOR T200B vibrating wires frequencies time series measured under a constant 1.2 mm/h liquid precipitation intensity.

It has been revealed that the noisy 6-seconds VWs signal significantly affects the repeatability of precipitation intensity observations even when calculated over periods that are longer than one-minute (the time resolution recommended by WMO). The distribution of the relative percentage error figures with an environment associated with solid precipitation ($T = -5^{\circ}\text{C}$) is shown in Fig. 2.

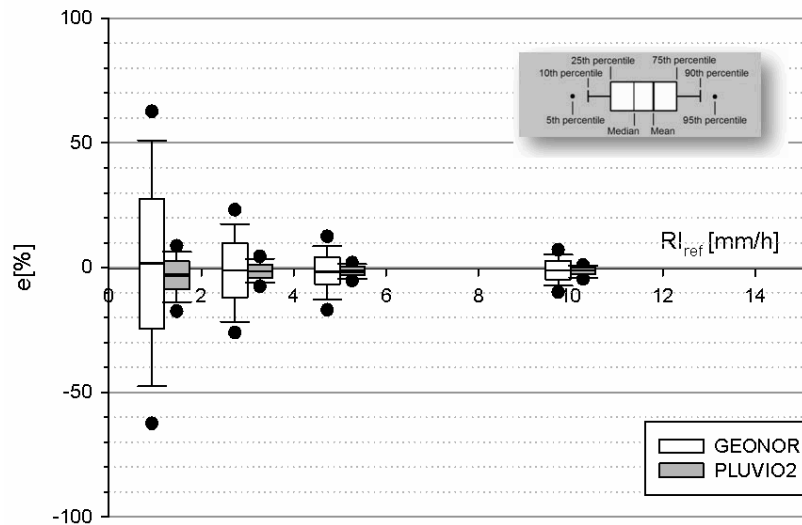


Fig. 2 Relative percentage error e of precipitation intensity RI measurements at two-minute resolution for the GEONOR T200B and OTT PLUVIO2 at the ambient temperature $T = -5^{\circ}\text{C}$.

A second controlled environment campaign was carried out at the NCAR Foothills Labs by using a snow-generation machine (Fig. 3) which is equipped with a milling cutter system for breaking a distilled water ice core into snowflakes as shown on the right snapshot.

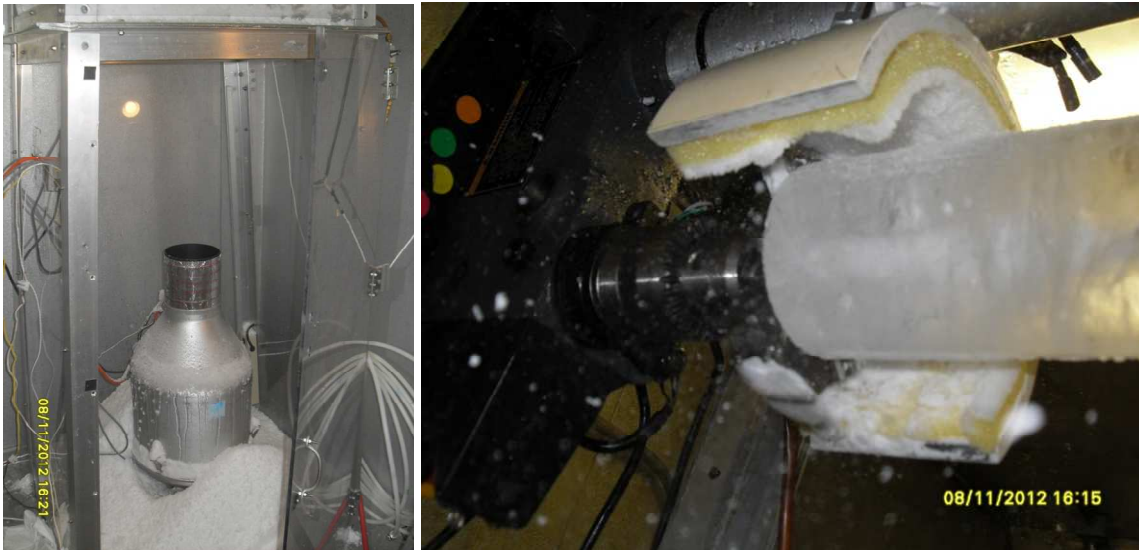


Fig. 3: a) (left picture) the GEONOR T200B in the snow-generation machine chamber; b) (right picture) particular of the snow flakes generation system fed by the distilled water ice core

Nine different combination of testing conditions were obtained by setting the cold room temperatures (T_{air}) around time-averaged values equal to -10, -5 and -2 °C and maintaining the snow-generation rates (SR) constant on 0.5, 1 and 2 mm/h of equivalent water. An excursion of the instantaneous cold room temperature values equal to +/- 2°C around the mean was observed and it's due to the latency of the cold room refrigeration system. Fig.4 shows a sample of the cold room and snowgauge orifice temperatures (grey scale time series) and the GEONOR T-200B VW frequencies f_i (colour time series) measured by realizing a SR value equal to 1 mm/h and $T_{air} = 10^\circ\text{C}$ in averaged terms.

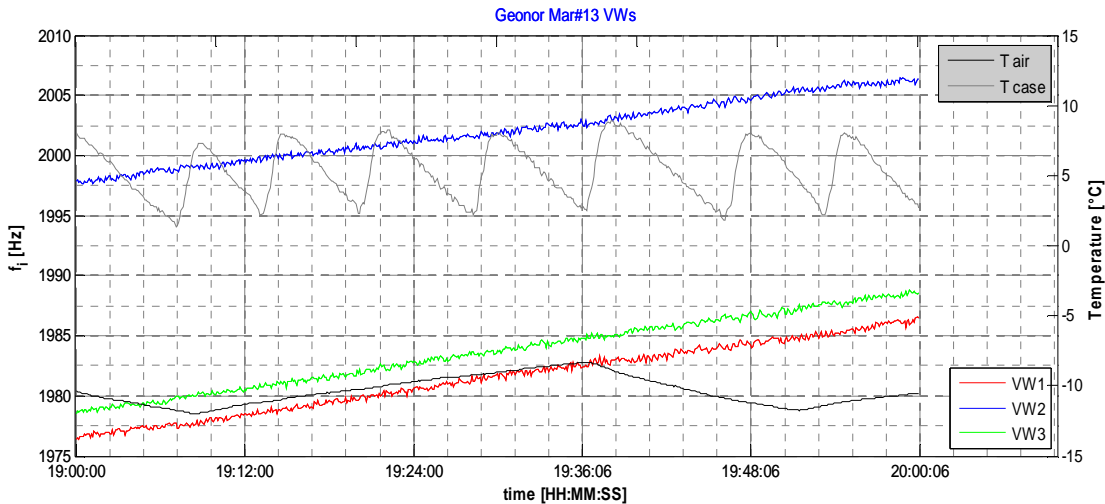


Fig. 4: Sample measurement set from a snow machine test with $\text{avg}(\text{SR})=1$ mm/h and $\text{avg}(T_{air})= 10^\circ\text{C}$. The plot includes three GEONOR T200B vibrating wires frequencies f_i (colored plots), the orifice T_{case} temperature and the cold room T_{air} environmental temperature (respectively light and dark grey).

The first evidence arising by the VW plots is the high noise of the frequency time series observed along the whole test duration. Once having excluded any signal disturbance of electrical nature by means of dedicated verifications the research was focused on the mechanical vibrations transmitted from the environment to the snowgauge under different testing conditions (Tab. 1). The modified standard uncertainty $u_{80\%}(f_{VW})$ of the vibrating wire signal recorded under no precipitation conditions is the parameter here considered for the quantification of the noise magnitude. This value is evaluated basing on the noisy data sample standard deviation under a no precipitation condition, representing the noise magnitude around the mean value, which is then multiplied by a scaling factor $k = 1.28$ in order to contain the 80% of the noise data population.

Five different installation situations were tested without precipitation:

- Outside the cold room
- Cold room installation
- Cold room installation with the snow machine motor activated
- Cold room installation with vibration damping legs
- Cold room installation with vibration damping legs and snow machine motor activated

Tab. 1 : Modified standard uncertainty $u_{80\%}$ of vibrating wires frequency and associated water accumulation measurement due to the noise induced by mechanical vibrations noise under different installation conditions

Cold chamber	Snowmachine ON	Damping legs	$u_{80\%}(f)$	$u_{80\%}(h)$
<i>[-]</i>	<i>[-]</i>	<i>[-]</i>	<i>[Hz]</i>	<i>[mm]</i>
			0.011	0.004
X			0.051	0.017
X	X		0.645	0.210
X		X	0.065	0.021
X	X	X	0.127	0.041

The installation of the VWs gauge within the cold room resulted in an increasing of the signal noise, $u_{80\%}(h)$ passes from 0.004 to 0.017 mm, which is not effectively reduced by the employment of vibration damping legs. The activation of the snow-generation machine caused a 0.210 mm modified standard uncertainty that is damped to 0.041 mm by the employment of rubber legs. Following these indications the VWs noise quantification activity was then extended to real world measurements recorded in case of wind at the Marshall field site as sampled on Fig.5. The main outcomes of such activity have been presented by Dr. Matteo Colli at the 4th IOC meeting (Colli, 2013).

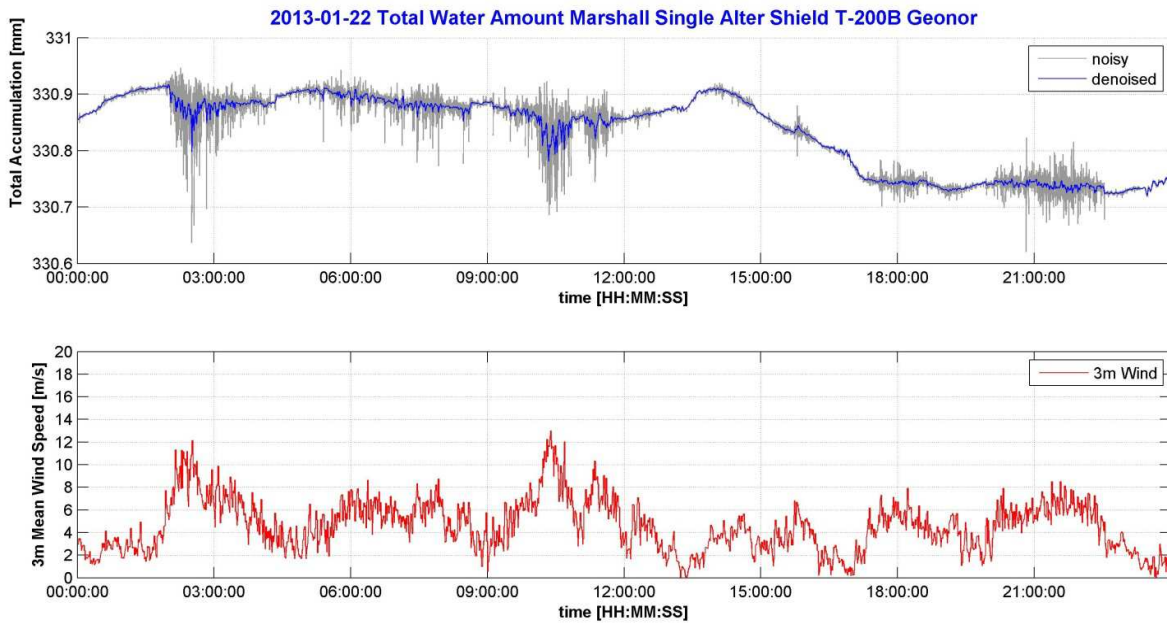


Fig. 5: Sample of the Marshall Single Alter shield GEONOR T200B total water accumulation (top plot) measured during a significant horizontal wind event (bottom plot) with no precipitation involved. The noisy behavior of the original 6-sec measurements (grey line) shows an evident correlation with the horizontal wind speed (red line) and could be effectively reduced by applying a de-noising technique.

Starting from the 3rd SPICE IOC meeting the noise-related effects have been extensively reported by the data analysis team leading to the decision to test various signal filtering techniques and then providing a unified methodology during the 4th SPICE IOC meeting.

3) FORMATION OF SNOW CAPPING

The formation of snow caps is one of the more challenging issue affecting the reliability of ground-based snowfall measurements as it requires the application of dedicated hardware components. The former generally consist of temperature probes and embedded heating systems of the gauge orifice, funnel and, in case of mechanical measuring principle, the sensor itself. The power requirements of the heaters, their working cycles management and possible interference with the snow measurements are all matters of today discussions.

The tested heating system for the GEONOR T200B orifice is manufactured by Marathon and composed by two silicone flexible blankets rated at 100 W AC. It's important to note that this configuration is different from the WMO SPICE reference heater which should work with a lower power requirement and DC electric current. Since the heating produced by the tested configuration is bigger than the SPICE one, it's valuable to consider the following results with reference purposes and to note that they constitute the best achievable performance in terms of snow capping but also the more relevant evaporation and heating plume effects observable in field. Furthermore, a slightly modified version of the CRN heating algorithm was used with the purpose of allowing the activation of the system for all the orifice temperature values $T_{orifice}$ falling below +2°C while preserving the original algorithm updating interval (equal to 1 min).

Differently from the GEONOR T200B case, the OTT PLUVIO2 comes with an embedded heating control system. During the present work the manufacturer system was activated and deactivated externally following modified version of the modified CRN algorithm and considering the actual orifice temperature as measured by an additional temperature probe installed on the purpose. The images showed on Fig. 6 and 7 compare the snow accumulation after 1 mm of water equivalent precipitation at different rates SR and environmental temperatures T_{air} . It's evident how the simulated snow tends to accumulate more conspicuously by increasing the temperature rather than snow rates. Meanwhile the tested GEONOR heater is able to avoid snow capping around the orifice rim even under the worst environmental conditions, a non-negligible accumulation of snow is observed on the Pluvio2 collection edge in case of temperature equal to 10°C irrespectively of the snow rates.



Fig. 6: Snow accumulation of the GEONOR T200B case after 1 mm of equivalent water. The gauge was equipped with an internal and an external AC heater stripe (100W)

managed by a modified CRN algorithm for three different environmental temperatures: a) $\text{avg}(T_{\text{air}}) = -10^{\circ}\text{C}$; b) $\text{avg}(T_{\text{air}}) = -5^{\circ}\text{C}$; c) $\text{avg}(T_{\text{air}}) = -2^{\circ}\text{C}$

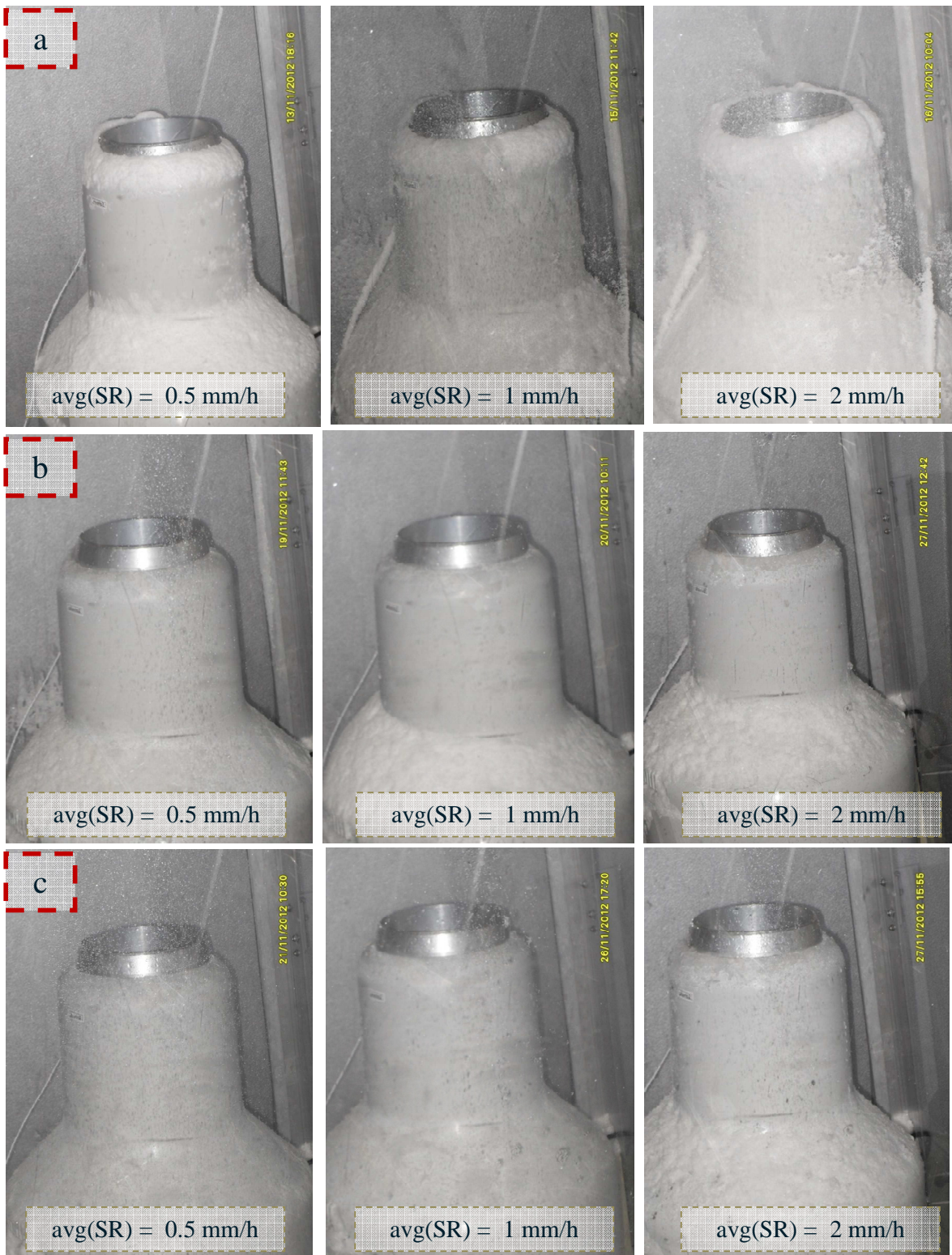


Fig. 7: Snow accumulation of the OTT Pluvio2 case 1 mm of equivalent water. The gauge was equipped with the manufacturer embedded heater, the activation and deactivation of such heating system was managed externally by the modified CRN algorithm for three

different environmental temperatures: a) $\text{avg}(T_{\text{air}}) = -10^{\circ}\text{C}$; b) $\text{avg}(T_{\text{air}}) = -5^{\circ}\text{C}$; c) $\text{avg}(T_{\text{air}}) = -2^{\circ}\text{C}$

It's important to stress the fact that such cold room investigations don't consider the wind contributes, the authors intention is to focus the tests on the heating related issues simplifying the interference of other environmental conditions such as horizontal wind speed, solar radiation and temperature gradients.

4) THE HEATING SYSTEM LATENCY

During the cold room testing particular attention was paid to the dynamic behaviour of the gauges orifice temperatures managed by the respective heating system, the CRN heating algorithm (applied to the GEONOR gauge) and the OTT algorithm.

The GEONOR T200B orifice temperature time serie T_{orifice} was sampled with a 0.5 Hz frequency and plotted together with the heater status (ON/OFF) and the environment temperature during a $\text{avg}(T_{\text{air}}) \approx -10^{\circ}\text{C}$ test, an example is shown in Fig. 8. The “saw-teeth” shaped oscillatory behavior of T_{orifice} is not influenced by the lower frequency fluctuations of T_{air} showing values that span from $+2^{\circ}\text{C}$ and $+9.6^{\circ}\text{C}$. The power requirement of the tested heaters along with the thermal conductivity of the GEONOR T200B collecting walls resulted in a variable waiting time dt_{off} , defined as the interval between two subsequent ON status, which could be approximated to 10 min meanwhile in all the observed situations the heater lasted on the activated status for only one minute.

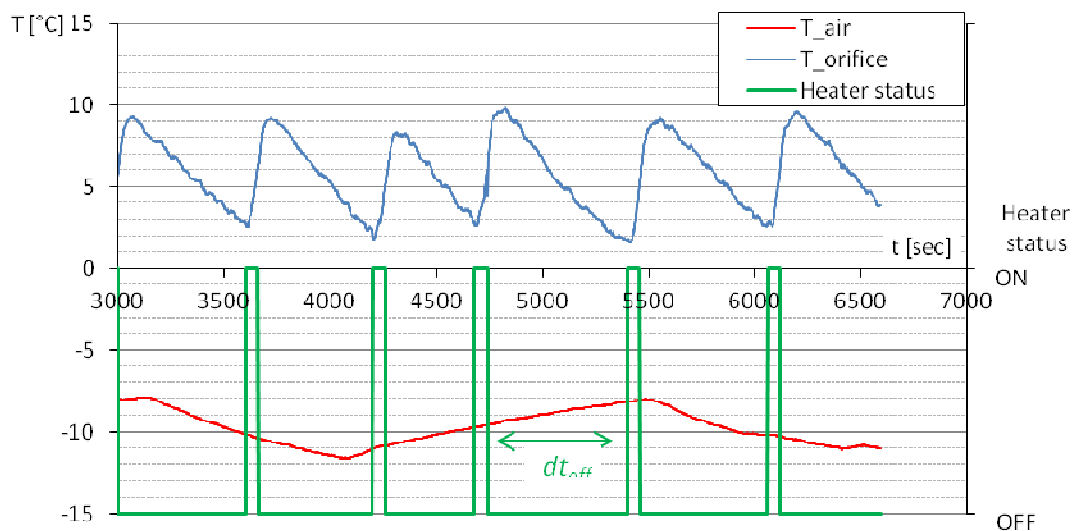


Fig. 8: GEONOR T200B orifice temperature T_{orifice} (blue line), environmental temperature T_{air} (red line) and heater status (green line) sampled with a 2 sec period during a cold room test.

In this situation the long duration of the deactivation phase dt_{off} and the high orifice temperature (the oscillation reach $+9.5^{\circ}\text{C}$) are ascribable to the refreshing time of the CRN algorithm which $\sim 10 \sim$

updates its status with a one minute resolution. Zooming the previous plot as shown in Fig. 9 is possible to verify that $T_{orifice}$ continues to increase up to 3 additional Celsius degrees with respect to the temperature reached at the end of the heater activation time.

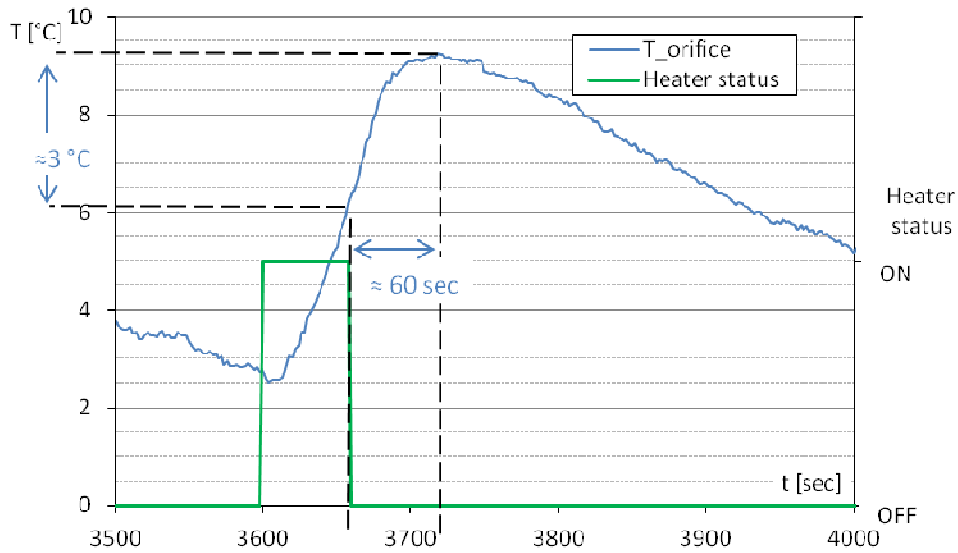


Fig. 9: Particular of the GEONOR T200B orifice temperature $T_{orifice}$ (blue line) and the heater status (green line) sampled with a 2 sec period during a cold room test.

Similarly to what showed in Fig.8 for the GEONOR snow gauge, further tests were carried out for the Pluvio2 heating system. The results revealed $T_{orifice}$ time series characterized by an oscillatory behaviour characterized by two constant main frequencies, as illustrated in Fig. 10.

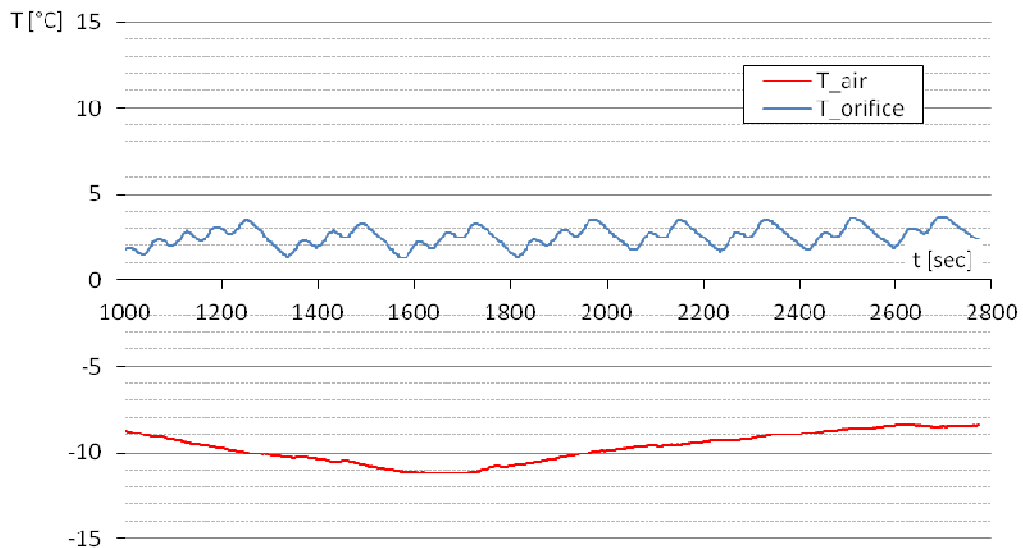


Fig. 10: OTT PLUVIO2 orifice temperature $T_{orifice}$ (blue line) and environmental temperature T_{air} (red line) sampled with a 2 sec period during a cold room test.

In this case the orifice temperature spans over only 2 °C due to the shorter response time of the heating system (composed by the heater hardware and the managing algorithm).

5) ON THE PRESENCE OF HEATING PLUMES

The environmental machine activity was also aimed at the detection of possible plumes realized above the orifice due to the temperature gradient between heated surfaces and the surrounding air. This effect, together with the evaporation of a limited number of collected snow particles which remain attached to the heated walls, would lead to an underestimate of the actual precipitation.

The first evidence of such underestimate was revealed during the snow machine testing by comparing the GEONOR T200B measurements made with the heating system deactivated and then switched on under the same snow rate conditions and temperature. The tests were repeated at least three times for each environmental condition and the evaluation of the snowfall rate underestimation was made using the relative percentage errors between SR measurements made with and without the heating system as follows:

$$e[\%] = \frac{SR_{heated} - SR_{unheated}}{SR_{unheated}}$$

The e values showed on Fig. 11 are referred to the GEONOR T200B measurements underestimation and the representation is subdivided for the three different tested environmental temperatures.

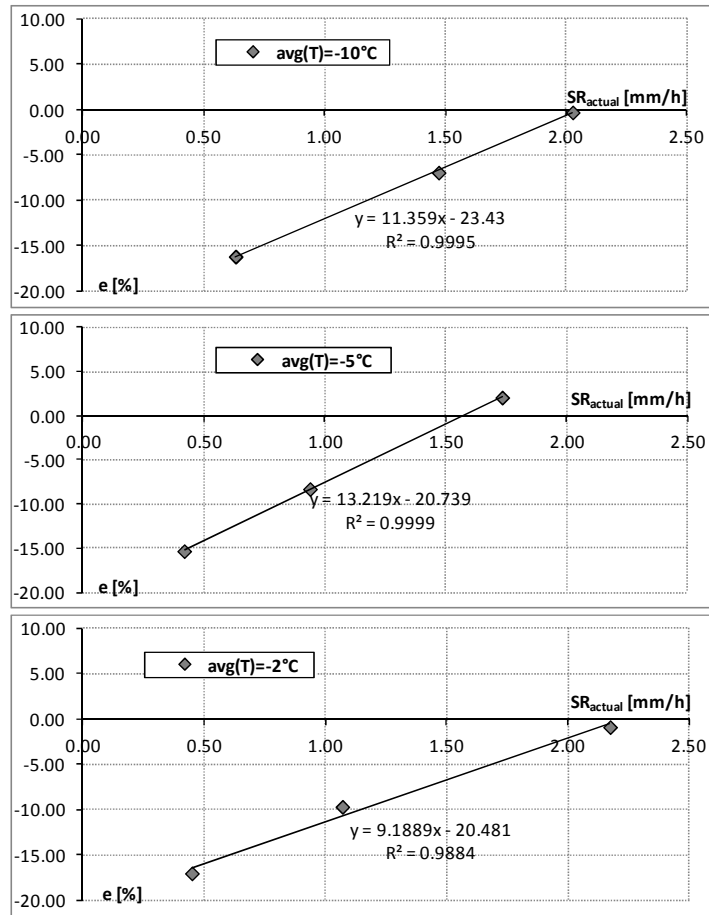


Fig. 11: Relative percentage errors e of the snow rates measurements made by the OTT PLUVIO2 with the heating system turned on. This value are observed with different reference snow rates SR_{actual} and averaged environment temperature $avg(T)$: -10 °C (top graph), -5 °C (center graph) and -2 °C (bottom graph).

Even if a clear dependence of e on the tested snow rate SR_{actual} is appreciable, it was not possible to define clearly the influence of the environmental temperature on the heater related errors and a certain experimental variability on the results must be taken into account. Anyway, the main indication provided by this investigation is the fact that, as the actual snow rate lies below 2 mm/h, an underestimation of the measurements related to the heating is observed and it could affect the measurement up to -15%. An example of the vibrating wires averaged total water accumulations measured before and after deactivating the heating system are plotted together with their linear fits on Fig. 12 showing the smaller rate of the heated case. The time series shown in the graph were observed by simulating an artificial snow rate approximated to 0.5 mm/h and an averaged air temperature equal to -5 °C. The same investigation on the OTT Pluvio2 errors has still to be completed because of problems occurred with the snow generation system.

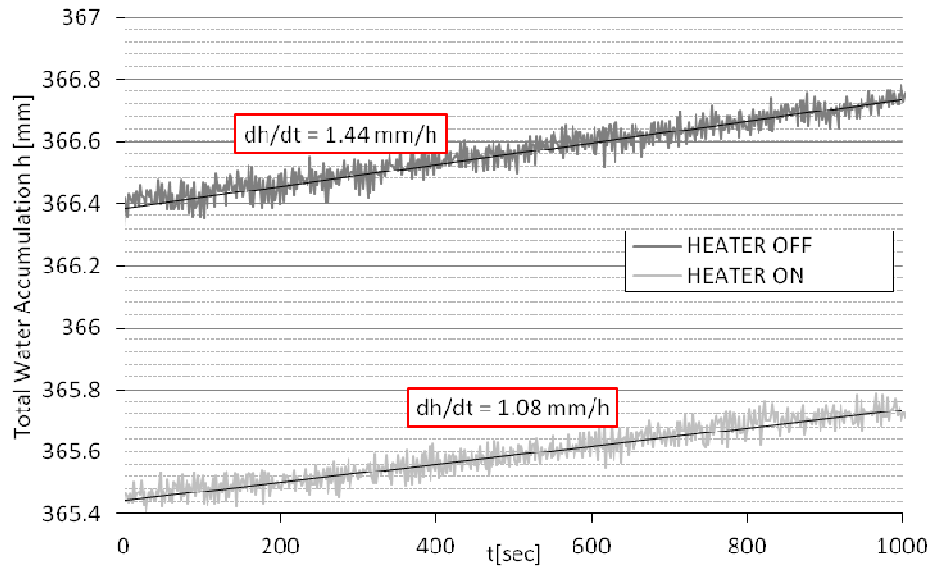


Fig. 12: GEONOR T200B total water accumulation measured before and after the deactivation of the heater from a sample test performed with $SR = 0.5 \text{ mm/h}$ and $T_{air} = -5^\circ\text{C}$

The next step of this work was to verify (or exclude) the existence of a plume above the heated orifice in order to find out the physical reason behind the observed errors. The task was addressed by installing an high frequency camera at the level of the snow gauges collecting section and a black panel on the background scene with white vertical reference rows and lighting up the air domain just above the orifice rims as show in Fig. 13. A case study of SR equal to 2 mm/h and a -10°C environmental temperature was shot with a movies duration larger than 30 sec.

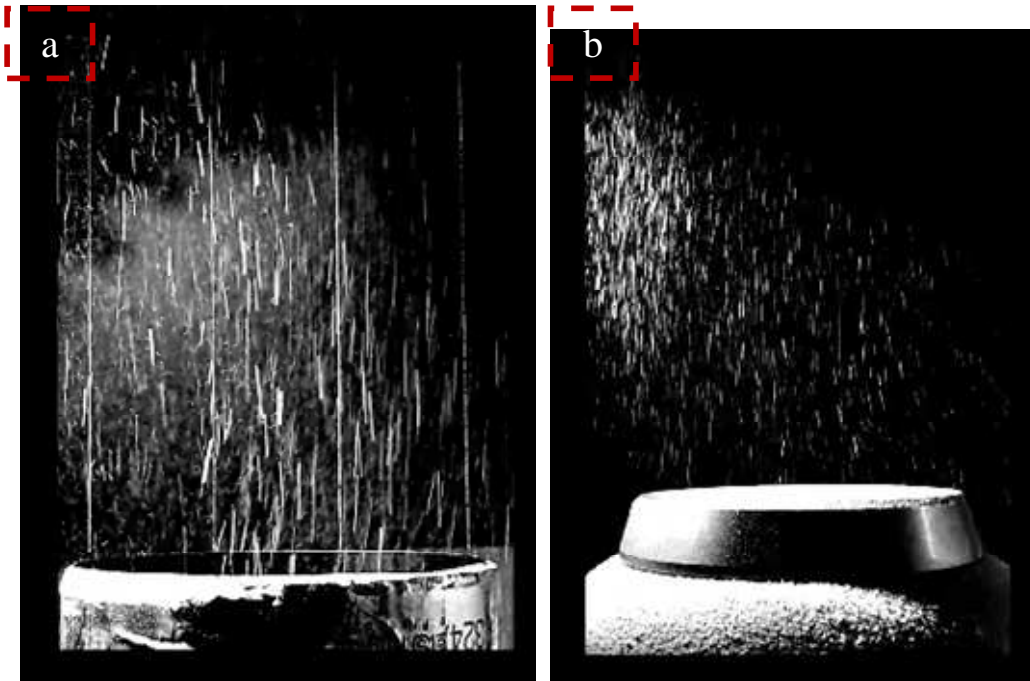


Fig. 13: Close views extracted from the movies shot above the orifice rims of the GEONOR T200B (figure a) and the OTT PLUVIO" (figure b) for the $SR=2\text{mm/h}$ and $\text{avg}(T_{\text{air}})=-10^{\circ}\text{C}$ case.

The two selected movies were discussed during the 4th SPICE IOC meeting (Colli et al., 2013) and no evidences of heated plumes or subsequent upward airflows were detected by tracking the falling snow flakes trajectories. It is worth mentioning that such experiment was carried out by adopting an high power-consuming heater for the GEONOR T200B, capable to realize higher values of orifice temperature than the system commonly installed on commercial gauges. As a consequence, it is possible to exclude relationships between the deformations of the snow particles trajectories and the infield heating conditions.

The last activity of this investigation should be the study of the last source of uncertainty directly ascribable to the usage of the heater: the evaporation of the melted snowflakes along the internal heated surfaces. This effect could impact appreciably on the GEONOR T200B measurements because of the size of its internal heated surface which is equal to 1655 cm^2 , more than four times the correspondent of the OTT PLUVIO2 size (382 cm^2).

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