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THE WMO FIELD INTERCOMPARISON OF RAINFALL INTENSITY (RI) GAUGES in Vigna di Valle (ITALY), October 2007- April 2009: relevant aspects and results.

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ABSTRACT

The WMO Field Intercomparison of Rainfall Intensity (FI-RI) Gauges was conducted from 1 October 2007 to 30 April 2009, in the Centre of Meteorological Experimentations (ReSMA) of the Italian Meteorological Service, in Vigna di Valle, Italy. It was organized following the request of users and the recommendations of CIMO-XIV. In view of the very high variability of the rainfall intensity, measurements at a 1-minute time scale are crucial to enable proper measures be taken to mitigate the impact of severe weather events and save lives, property and infrastructures. The main objective of the FI-RI was to intercompare the performance of in-situ rainfall intensity instruments of different measuring principles, with special consideration given to high rainfall intensities. Further objectives were to offer advice on improvements of instruments and precipitation measurements. This intercomparison hosted 25 different rainfall intensity gauges. The majority of these instruments were catching type gauges comprising tipping-bucket gauges, weighing gauges and one water level gauge. Non-catching rain gauges were represented by optical and impact disdrometers, one optical/capacitive gauge and one microwave radar gauge. In the field, all gauges were compared with a RI composite working reference consisting of a set of three reference rain gauges in a standard pit. This paper is dedicated to the summary of relevant aspects and results of the FI-RI and, in particular, offers a discussion on the proposed recommendations and possible developments in the standardization of RI measurements and laboratory calibration procedures at the international level in order to obtain homogeneous and compatible data sets.

Keywords: rainfall intensity, WMO Intercomparison, rain gauges,

1. Introduction

Background

The attention paid to accuracy and reliability in rainfall measurements is currently increasing, following the increased recognition of scientific and practical issues related to the assessment of possible climatic trends, the mitigation of natural disasters (e.g. storms and floods), the hindering of desertification, etc. A reliable quantitative knowledge of the liquid atmospheric precipitation at a specific site on the territory, or over more or less extended regions (catchment basins), is indeed fundamental to a number of investigation threads, especially within the atmospheric and hydrological applications.

Rainfall is the forcing input of the land phase of the hydrological cycle. The knowledge of rainfall, its variability and the observed/expected patterns of rain events in space and time, are of paramount importance for most meteorological and hydrological studies, and a large number of consequences of such studies are exploited in the everyday technical operation. Traditionally, the volume of rainfall received by a collector through an orifice of known surface area in a given period of time is assumed as the reference variable, namely the rainfall depth. Under the restrictive hypothesis that rainfall is constant over the accumulation period, a derived variable – the rainfall rate, or intensity – can be easily calculated. Precipitation intensity is defined (*WMO, 1992a*) as the amount of precipitation collected per unit time interval. According to this definition, precipitation intensity data can be derived from the measurement of precipitation amount using an ordinary precipitation gauge. In that sense, precipitation intensity is a secondary parameter, derived from the primary parameter precipitation amount. However, precipitation intensity can also be measured directly. For instance, using a gauge and measuring the flow of the captured water, or the increase of collected water as a function of time. A number of measurement techniques for the determination of the amount of precipitation are based on these direct intensity measurements by integrating the measured intensity over a certain time interval.

Nowadays the requirements are tighter and applications increasingly require enhanced quality in rainfall intensity (RI) measurements. The interpretation of rainfall patterns, rainfall event modelling and forecasting efforts, everyday meteorological and engineering applications, etc., are all based on the analysis of rainfall intensity arrays that are recorded at very fine intervals in time (1 or 5 minutes). Therefore the relevance of rainfall intensity measurements is dramatically increased and very high values of such "new" variable are recorded, due to the shortening of the reference time frame. Moreover, the design and management of urban drainage systems, flash flood forecasting and mitigation, transport safety measures, and in general most of the applications where rainfall data are sought in real-time, call for enhanced resolution in time (and space) of such information, even down to the scale of one minute in many cases.

The World Meteorological Organisation (WMO) recognised these emerging needs and promoted a first Expert Meeting on Rainfall Intensity (*WMO, 2001*) already in 2001 in Bratislava (Slovakia), a location where great part of the activities developed within WMO about atmospheric precipitation had been held in previous years (see e.g. *Sevruk, 1982*; *Sevruk and Hamon, 1984; Sevruk and Klemm, 1989*). The convened experts defined the rainfall intensity and the related reference accuracy and resolution. Following the recommendations of the meeting, the Joint CIMO Expert Team on Surface-Based Instrument Intercomparison and Calibration Methods (ET-SBII&CM) and the International Organizing Committee (IOC) on Surface-Based Instrument Intercomparison, according to the CIMO Plan of WMO Intercomparisons, organized at first a Laboratory Intercomparison, followed by a Field Intercomparison both of rainfall intensity gauges. The Laboratory Intercomparison (2004-2005) was held at the recognised laboratories of Météo France, KNMI (The Netherlands), and the University of Genoa (Italy). The results are available on the WMO Web site, and were published elsewhere (*Lanza, 2005a, b; Lanza and Stagi, 2008*). The developed procedure for laboratory calibration of catchment type RI gauges and the reference instruments to be used for Field RI Intercomparison initiatives have become recommendations of the fourteenth session of the WMO Commission for Instruments and Methods of Observation (*WMO, 2007a*). The subsequent WMO Field Intercomparison of Rainfall Intensity Gauges that is the focus of this paper on the 1 October 2007 and ended on the 30 April 2009. The results are available on the WMO Web site, and were published elsewhere (*Vuerich et al., 2009*). The campaign was hosted, upon invitation of the Permanent Representative of Italy, at the Centre of Meteorological Experimentations (ReSMA) of the Italian Meteorological Service, in Vigna di Valle, Italy.

The history of instrument intercomparisons in the case of rainfall measurements dates back significantly in the last centuries (*Goodison et al., 1998; Poncelet, 1959; Sevruk et al., 2009; Sevruk, 1982; Sevruk and Hamon, 1984; Sevruk and Klemm, 1989; Stow, 1871; Struzer, 1971; for a summary see Vuerich et al. 2009***)**. This is in line with the well-established awareness of the relevance of intercomparison in atmospheric sciences, since Father Francesco Denza, member of the Italian Meteorological Society, already stated in 1872 that "… in order that meteorological studies produce advantages for human beings … it is not only necessary to have lots of observatories and observations/measurements be done with intelligence and accuracy, but it is moreover requested a meteorological investigation with same methodology and with well compared instruments".

Previous international rain gauges intercomparison efforts were however focused on accumulated amounts of precipitation, low intensity events (including solid precipitation) and sometimes only on qualitative RI information (light, moderate, heavy). The latest international intercomparison effort had the objective to assess and compare quantification and catching errors of both catching and non-catching type of rainfall intensity measuring instruments with the emphasis on high rainfall intensity.

Objectives

The main objective of the field intercomparison is to test the performance of rainfall intensity measuring instruments especially in high RI conditions. The objective of data analysis is to provide guidance on improving the homogeneity of long-term records of rainfall with special consideration given to high rainfall intensity. Further objectives are also to offer advice for RI uncertainty determination and for improving RI rain gauges measurements accuracy; to provide guidance material for further improvements in the area of Intercomparisons and to draft recommendations for consideration by the WMO-CIMO; to compare RI measurements in field conditions of non-catching type rain sensors with respect to catching type rain gauges.

In terms of accuracy, both laboratory and field RI Intercomparisons have contributed to a quantitative evaluation of measuring errors and the achievable accuracy in RI measurements.

2. Procedures and methods

Intercomparison site, standards and references

The in-FIeld RI intercomparison (FI-RI) site adopted was positioned at the Centre of Meteorological Experimentation of the Italian Air Force Met Service, in Vigna di Valle (ITALY) (Fig.1). It is a flat, green grass area of 400 m^2, equipped with 34 acquisition concrete platforms, evenly distributed, and 4 central acquisition pits, close to each other, specifically used for the installation and acquisition of the FI-RI "**working reference gauges**" - a group of 4 recommended RI gauges. A total number of 26 different RI gauges were installed on dedicated ground platforms; 13 additional meteorological sensors for monitoring environmental conditions were installed on 6 ground platforms; at the centre of the area, the 4 "working reference gauges" were inserted in a 4-fold RRGP – Reference Rain Gauge Pit (collectors at ground level), according to the standard EN13798:2002 (revised 2010) "Specifications for a reference rain gauge pit" (Fig. 2) adopted for this Intercomparison. All recommended standards contained in the CIMO guide (*WMO, 2008a*), concerning precipitation measurements, instruments installation and procedures for conducting the Intercomparison, were adopted and inspected during two Expert Meetings (*WMO 2007a/b*). All standard procedures and equipment recommended for meteorological data acquisition were adopted with care as part of a general quality assurance framework (*WMO 2008a).* A full description of the intercomparison site, a general description of rainfall intensity gauges, their measurement principles, uncertainty sources and measurements errors are provided in *Vuerich et al., 2009*.

Fig.1 – Intercomparison site – Vigna di Valle (ITALY).

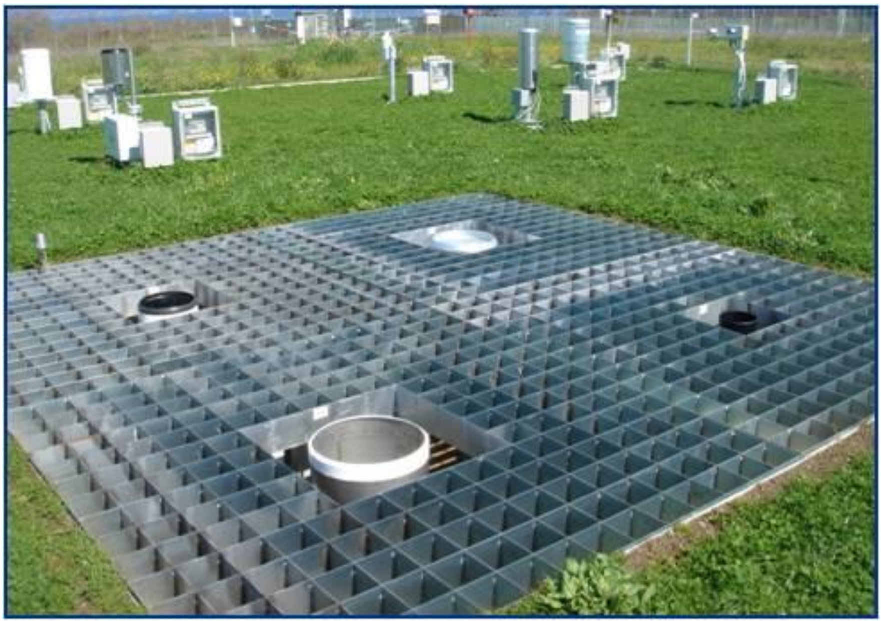


Fig.2 – 4-fold RRGP – The 4 working reference RI gauges.

A reference can be defined as a virtual device based on a set of measuring instruments and, according to VIM (the Vocabulary in Metrology), a working reference is a calibrated set of instruments used for controlling/make comparison with measuring instruments. For this Field Intercomparison of RI a set of gauges was recommended and the combined analysis of the reference gauges will provide the best possible estimation of RI in the field, giving their demonstrated performance during the previous Laboratory Intercomparison (2004-2005) (*Lanza at al., 2005b*). For minimizing the weather related catching errors, the working reference rain gauges were inserted in a RRGP (*WMO, 2005*).

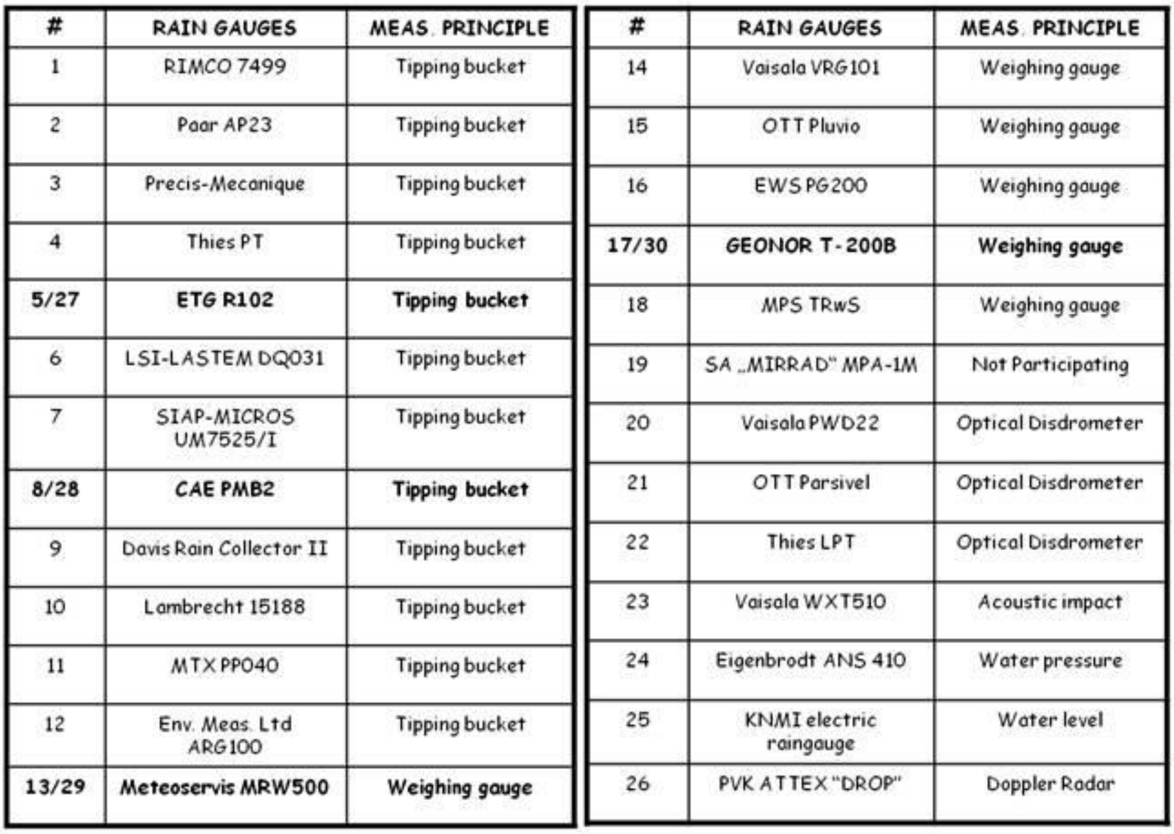
Gauges are typically mounted at some distance above the ground to reduce debris (dust, needles and leaves) being blown into the orifice. A standing gauge acts as a disturbance to the air flow. This wind-induced effect has been known from more than one century and it is described as *JEVONS effect* (1861) (*see Koschmieder, 1934*). The effect of flow deflection and the associated eddies and turbulence around the gauge cause some of the rain drops (particularly smaller ones) to miss the orifice area. The resulting rainfall catch error depends on the ambient wind speed, the rainfall drop size distribution (DSD) and the gauge design. The buried or "sunken" gauge (e.g. *Koschmider, 1934* and *Sieck et al., 2007)* is expected to show a higher rainfall reading than the gauge above the ground, with differences potentially 10% or more, when both instruments work perfectly and accurately. The effect is enhanced in snowfall. In the case of the RRGP, the influence of the form of the rain gauge on the air currents disappears. The influence of the necessary catchment surface on the air currents in its vicinity is reduced to a minimum through the fact that this surface lies in the layer with the least air movement. Moreover, the influence of the turbulent vertical movements is likewise reduced to a minimum, since these disappear at the earth's surface.

Instrument selection and general criteria

Participation in the intercomparison was accepted based on the following conditions: a) Only in situ, both catchment and non-catchment, RI instruments that are currently being used in national networks or being considered for use in national networks were included; b) Only instruments that are capable of measuring rainfall intensities as high as 200 mm/h at a time resolution of 1 minute were accepted (*WMO, 2005*). Because the number of instruments proposed exceeded the capacity of the field site, the instruments for participation were selected based on the following additional criteria (*WMO 2007b*): a) Instruments were selected to cover a variety of measurement principles; b) Preference was given to new promising measuring principles; c) Preference was given to instruments that were widely used; d) For those equipment tested in the WMO laboratory intercomparison, results of the laboratory tests were taken into consideration.

For selecting reference gauges, corrected tipping bucket rain gauges (TBRG) and weighing gauges (WG) with the shortest step response and the lowest uncertainty were used as working reference instruments (*WMO, 2007a*). Previous requirements (*WMO, 2005*) were additionally applied in selection of the reference gauges: a) Uncertainty of the gauge in laboratory tests must satisfy the WMO requirement of +/- 5 % over the range of rain intensities expected at the test site, i.e. 2 - 400 mm/h; b) Minimum resolution of 0.1 mm; c) Time delay less than 1 minute; d) Correction of a tipping bucket gauge should be applied on each tip, rather than delivering an extra pulse (catching type).

According to the above-mentioned requirements for participating instruments, the list in Table 1 reports all selected instruments and the corresponding measuring principle.



#	RAIN GAUGES	MEAS. PRINCIPLE
1	RIMCO 7499	Tipping bucket
2	Paar AP23	Tipping bucket
3	Precis-Mecanique	Tipping bucket
4	Thies PT	Tipping bucket
5/27	**ETG R102**	**Tipping bucket**
6	LSI-LASTEM DQ031	Tipping bucket
7	SIAP-MICROS UM7525/I	Tipping bucket
8/28	**CAE PMB2**	**Tipping bucket**
9	Davis Rain Collector II	Tipping bucket
10	Lambrecht 15188	Tipping bucket
11	MTX PP040	Tipping bucket
12	Env. Meas. Ltd ARG100	Tipping bucket
13/29	**Meteoservis MRW500**	**Weighing gauge**
14	Vaisala VRG101	Weighing gauge
15	OTT Pluvio	Weighing gauge
16	EWS PG200	Weighing gauge
17/30	**GEONOR T-200B**	**Weighing gauge**
18	MPS TRwS	Weighing gauge
19	SA „MIRRAD" MPA-1M	Not Participating
20	Vaisala PWD22	Optical Disdrometer
21	OTT Parsivel	Optical Disdrometer
22	Thies LPT	Optical Disdrometer
23	Vaisala WXT510	Acoustic impact
24	Eigenbrodt ANS 410	Water pressure
25	KNMI electric raingauge	Water level
26	PVK ATTEX "DROP"	Doppler Radar

Table 1 – WMO Field Intercomparison of RI – The list of participating instruments

According to the above-mentioned requirements for reference instruments, rain gauges ETG-R102(#5/#27), CAE-PMB2(#8/#28), Meteoservises-MRW500 (#13/#29) and GEONOR-T200B (#17/#30) were selected as "working reference gauges" and inserted in the RRGPs (Fig.2). The four instruments that were installed as reference gauges in the pits, were also installed in the open field in order to quantify the effect of wind losses.

All participants were also requested to calibrate their instruments against any suitable recognized standard before shipment and to provide appropriate calibration certificates.

Participants provided their assistance for installation and during the Intercomparison, allowing the test to be carried out properly (a Participants Meeting was held in Vigna di Valle, on 21-22 May 2008).

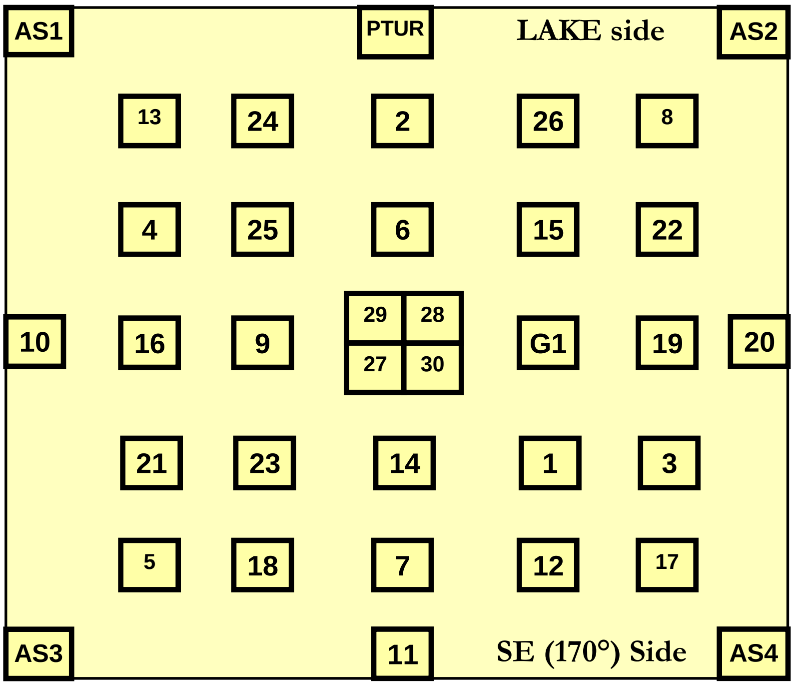
The environmental conditions were monitored by the following ancillary sensors:

- 4 propeller-vane anemometers mod. Young 05106 installed at the site corners;
- 4 wetness sensors mod. Vaisala DRD11A installed at the site corners;
- 1 Temperature/Relative Humidity sensor mod. Rotronic M101A, 1 atmospheric pressure sensor mod. Young 61020L and 1 global irradiance sensor mod. Lycor 200X all installed on a side position ground platform;

- 1 ultrasonic anemometer mod. Gill Windsonic installed on a ground platform close to the 4-fold RRGP.

Positioning and installation procedures

All gauges and ancillary sensors (wind, wetness) were installed at 1 m height. Other ancillary sensors (T, RH, solar radiation, atmospheric pressure) were installed at CIMO standard heights. Agreed positioning of the 30 participating rainfall intensity gauges and the 13 ancillary sensors are displayed in Fig. 3 (*see WMO, 2007b*).



1	**RIMCO 7499 (TB)**
2	**Paar AP23 (TB)**
3	**Précis-Mecanique (TB)**
4	**Thies PT (TB)**
5/27	**ETG R102 A, B (TB)**
6	**LSI DQO31 (TB)**
7	**SIAP UM7525/I (TB)**
8/28	**CAE PMB2 A, B (TB)**
9	**Davis Rain collector II (TB)**
10	**Lambrecht 15188 (TB)**
11	**PP040 MTX (TB)**
12	**ARG100 Env. Meas. Ltd (TB)**
13/29	**MRW500 A, B (WG)**
14	**Vaisala VRG101 (WG)**
15	**Ott PLUVIO (WG)**
16	**EWS PG200 (WG)**
17/30	**GEONOR T-200B3 A, B (WG)**
18	**MPS TRwS (WG)**
19	**SA „MIRRAD“ MPA-1M (WG)**
20	**Vaisala PWD22 (optical)**
21	**Ott PARSIVEL (OD)**
22	**Thies LPM (OD)**
23	**Vaisala WXT510 (acoustic)**
24	**Eigenbrodt ANS 410 (pressure)**
25	**KNMI electrical raingauge (level)**
26	**PVK ATTEX "DROP" (Radar)**

ANCILLARY SENSORS

G1	**Gill windsonic (IMS-ReSMA)**
ASn	**4 Young 05106 wind sensors + 4 Vaisala DRD11A Rain detectors (USA)**
PTUR	**RotronicM101A Temp/RH + Young 61020-L Press + Lycor200X rad. (IMS-ReSMA)**

Fig.3 – WMO Field Intercomparison: Instruments Positioning

The following criteria for positioning were applied (*WMO, 2007b*): a) Almost random distribution of gauges with different measuring principles; b) No clustering of large gauges in order to prevent mutual disturbance of the wind field.

A decision was taken to exclude windshields to provide uniform measurements from all gauges (*WMO, 2007b*).

Instruments calibration

Twenty catching type instruments, including the four rain gauges selected as reference instruments, were calibrated in the laboratory before their final installation at the Field Intercomparison site. The WMO recognized laboratory at the University of Genoa performed the calibration using the same standard tests in constant flow regimes adopted for the previously held WMO Laboratory Intercomparison of RI Gauges *Lanza et al.,2005b).*

Further tests were performed to investigate the dynamic performance of the involved instruments at the resolution of one minute, through the evaluation of the step response to a step input (time constant) which is a measure of the instrument stability and ability to detect rapid changes of the input signal (similar to the natural phenomenon).

The objectives of this Laboratory Calibration of the Intercomparison were to single out the quantification errors associated with each instrument, to determine the measurement uncertainty and to help to understand the results obtained in the field during the subsequent phase.

All gauges of the catching type were also tested using a portable calibration device after installation, simulating ordinary calibration inspections in the field (Field Calibration).

The laboratory calibration procedure (*Vuerich et al., 2009*) was based on the generation of a constant water flow from a suitable hydraulic device (see Fig. 4) within the range of operational use declared by the instrument's manufacturer. Water is conveyed to the funnel of the instrument under test in order to simulate a constant rainfall intensity. The flow is measured by weighing the water over a given period of time. The output of the instrument under test is measured at regular periods of time or when a pulse occurs. The two measurements are compared in order to assess the difference between the actual flow of water conveyed through the instrument and the "rainfall intensity" measured by the instrument itself. The relative difference between each measured and actual "rainfall intensity" figure is assumed as the relative error of the instrument for the given reference flow rate.

Tests are extended to cover the one-minute resolution instrument behaviour rather than just focusing on the average response under a constant reference flow rate, thus providing better insights into the measurement performance of such instruments. This was also due to the fact that, during the measurements in the field, the one-minute resolution rainfall intensity is considered under real outdoors conditions.

The objective is to perform tests at least at seven reference flow rates, at 2, 20, 50, 90, 130, 170, 200 mm·h-1. Alternatively, if the higher rainfall intensities are of utmost importance, the whole range of operation declared by the manufacturer may be also investigated.

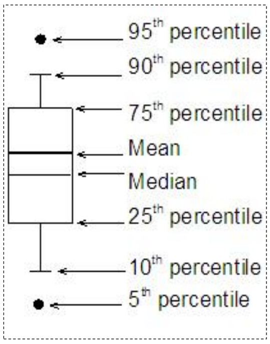
The reference intensities could be adjusted to the set-point within the following precision limits:

- 1.5 – 4 $\mathrm{mm \cdot h^{-1}}$, at 2 $\mathrm{mm \cdot h^{-1}}$;
- 15 – 25 $\mathrm{mm \cdot h^{-1}}$, at 20 $\mathrm{mm \cdot h^{-1}}$; and
- ± 10 % at higher intensities.

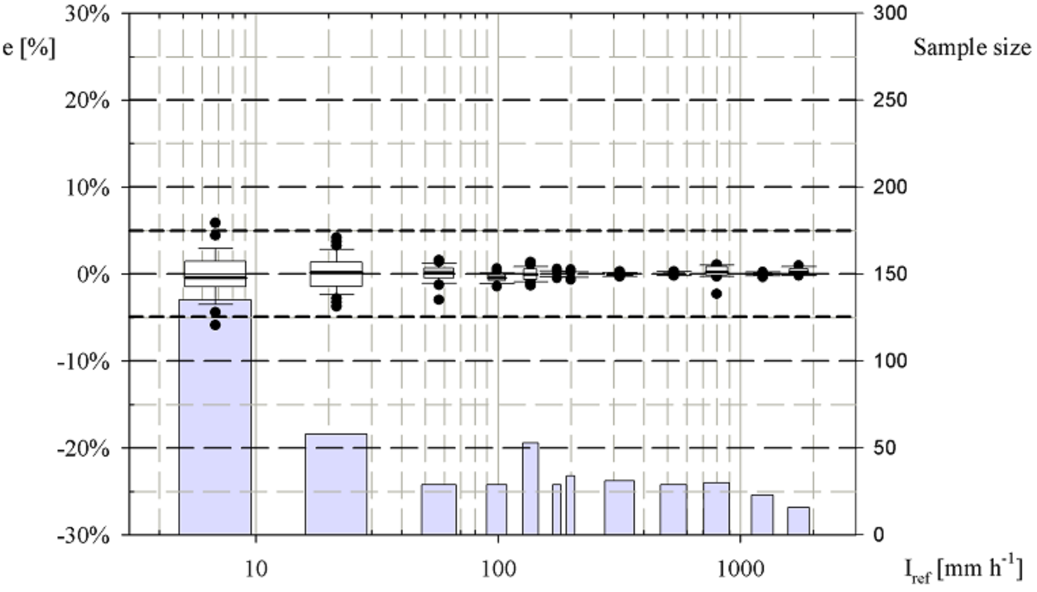
The uncertainty of the laboratory device, expressed as relative expanded uncertainty (95% confidence level), is 0,45% of RI flow generated. Tests were performed at one minute resolution for a variable duration that was tuned to the individual instrument and the reference flow rate used. The average errors were obtained by discarding the minimum and the maximum value obtained for each reference flow rate, then evaluating the arithmetic mean of the remaining errors and reference intensity values. The average values were used to derive the error and correction curves.

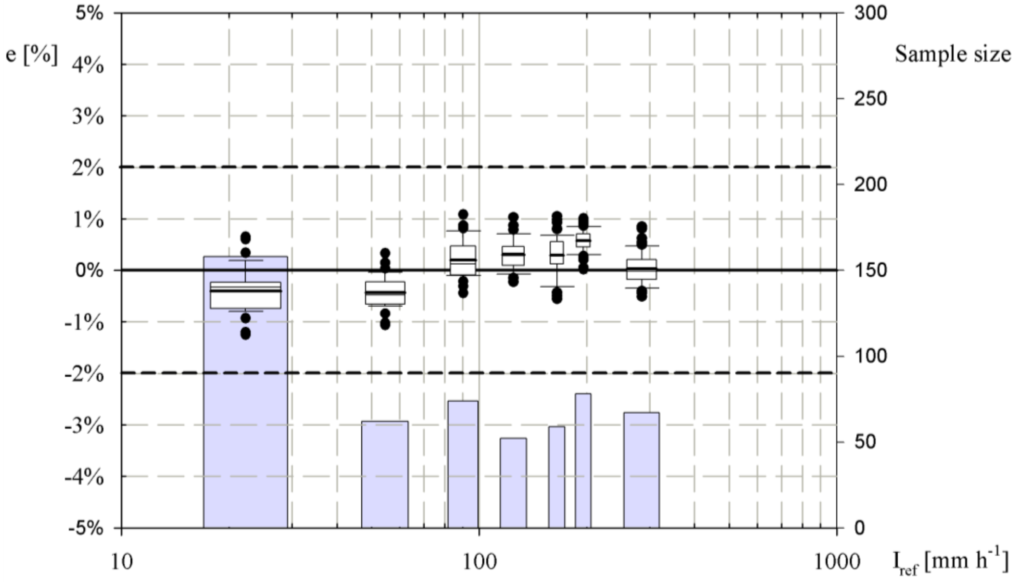
Fig. 4: The Qualification Module for Rainfall Intensity Measurement Instruments developed at the University of Genova, and used in the laboratory calibrations.

The results of laboratory tests may be shown using different graphs. Two different plots were proposed (*Vuerich et al. 2009*): the *constant flow response plot*, where the relative error for each single gauge is plotted versus the laboratory reference intensity, and the *step response plot*, where the ratio I_{meas}(measured RI) / I_{ref} (laboratory reference RI) is plotted versus time.

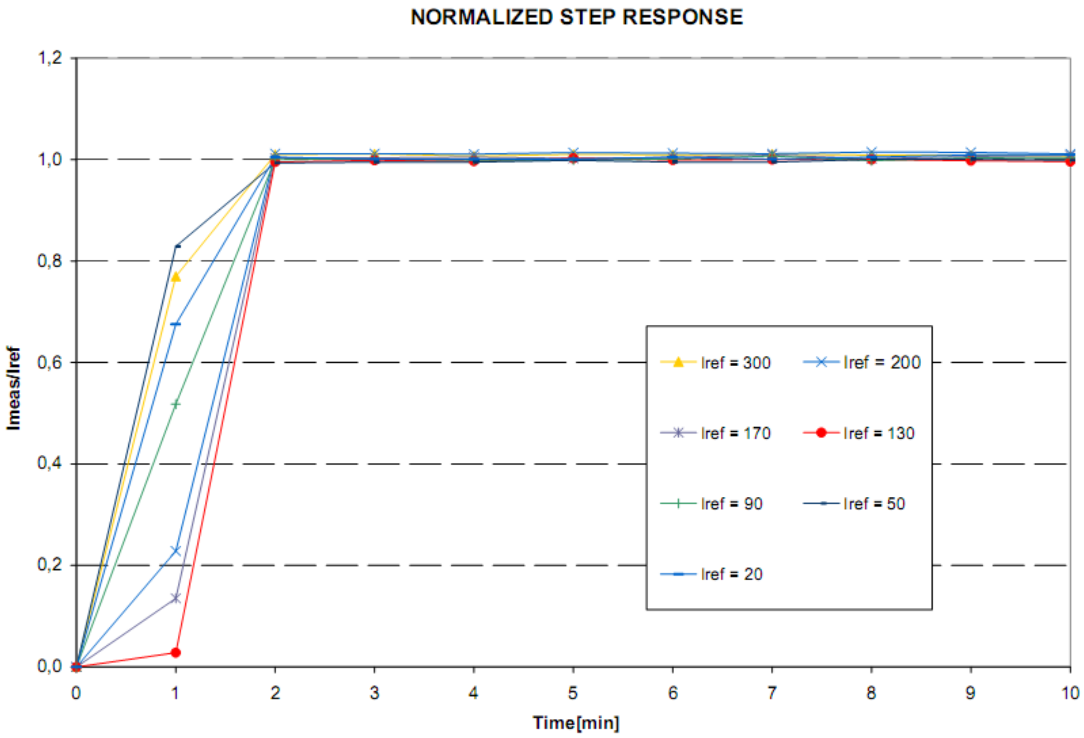


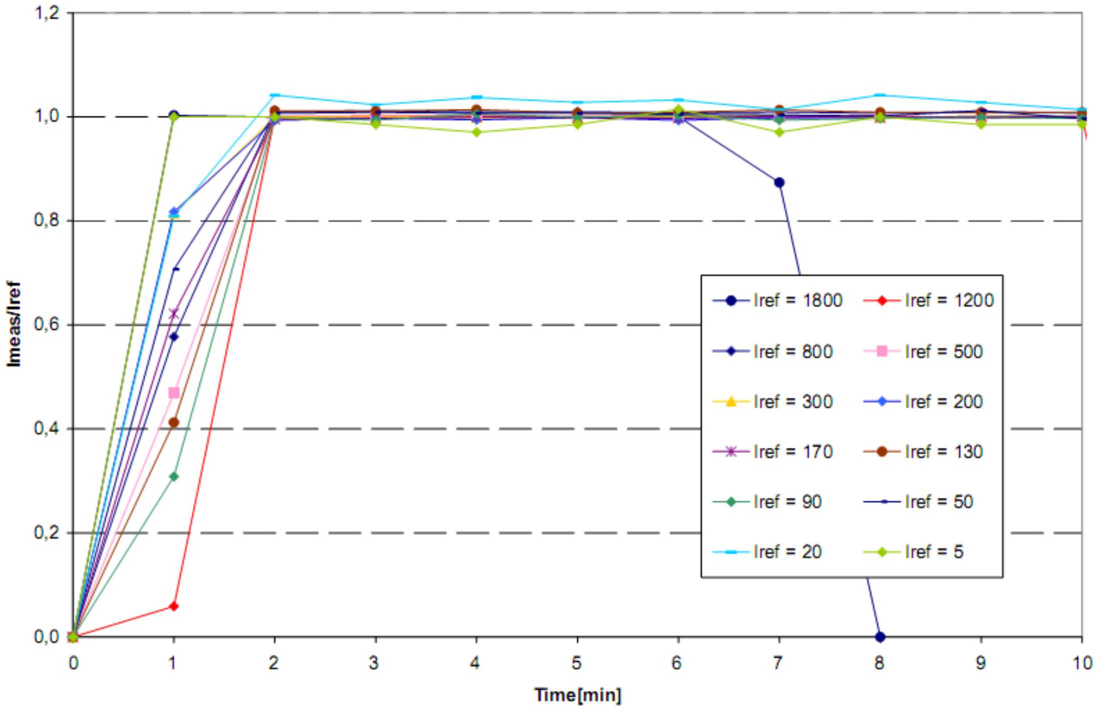
The constant flow response is presented in the form of superimposed box-plot and vertical bars, respectively reporting the one-minute variability of the observed instruments performances and the size of the sample used for calculation of the statistics at each reference intensity. Box plots synthetically indicate the values obtained for the mean (solid line), median (thin line), 25-75th percentiles (box limits), 10-90th percentiles (whisker caps) and outliers (black circles) per each series of one-minute data obtained during the tests. The shaded vertical bars indicate the sample size according to the scale reported on the right hand side of the graph.





The step response reflects the time behaviour of the gauge to a sudden increase of RI from 0 mm/h to a given RI as indicated in the graph. The step response is presented in the form of superimposed and normalized response curves corresponding to different laboratory reference RI. In the following examples, the observed behaviour of the first minute is not reliable, being affected by non synchronization effects between the internal clock and the laboratory acquisition system, and should be neglected.





The Laboratory of the University of Genoa designed a portable field calibrator to perform field calibrations tests of all catching type rain gauges (*Vuerich et al., 2009*). The field calibration was part of a Quality Assurance plan. The main purpose of this activity was to verify the operational status of rain gauges, to detect malfunctions, output anomalies and calibration drifts throughout time. These calibrations provided valuable insight to data analysis and data interpretation. The field calibration is based on the same principles as laboratory calibration using the generation of constant rainfall intensity within the range of operational use (stationary flow).

The laboratory calibration of the RI Field Intercomparison proved to be essential in providing basic information on the behaviour of the catching type instruments. The laboratory tests were performed at the resolution of one minute, so that the spreading of the errors around their average value could also be evaluated. The derived calibration curves were not applied to the output data obtained in the field from the individual gauges, since only the manufacturer's calibration was allowed for the Intercomparison purposes. As for the reference rain gauges, to be installed in the pit, calibration curves were provided to assess the residual quantification errors and their spreading as a function of the rainfall intensity. For all other catching type gauges the curves will be useful to assess the potential improvement that can be attained by any possible additional hardware and/or software correction that the manufacturer might decide to implement for better accuracy.

The field calibrator is composed of a cylindrical water tank, of about 6500 g of capacity, a combination of air intakes and output nozzles, for different rainfall intensities, and an electronic system to calculate the emptying time (see Fig. 5). According to the rain gauges collector size and the value of rainfall intensity chosen for the calibration, the suitable combination of air intakes and nozzles must be selected. By opening the top tap and the bottom nozzle, a constant flow starts to be conveyed to the funnel of the rain gauge and, through the time of emptying and the conversion table (volume-time-intensity), it is possible to retrieve the RI produced within the instrument uncertainty reported below. Air intakes provide the pressure compensation, thus keeping a constant push.

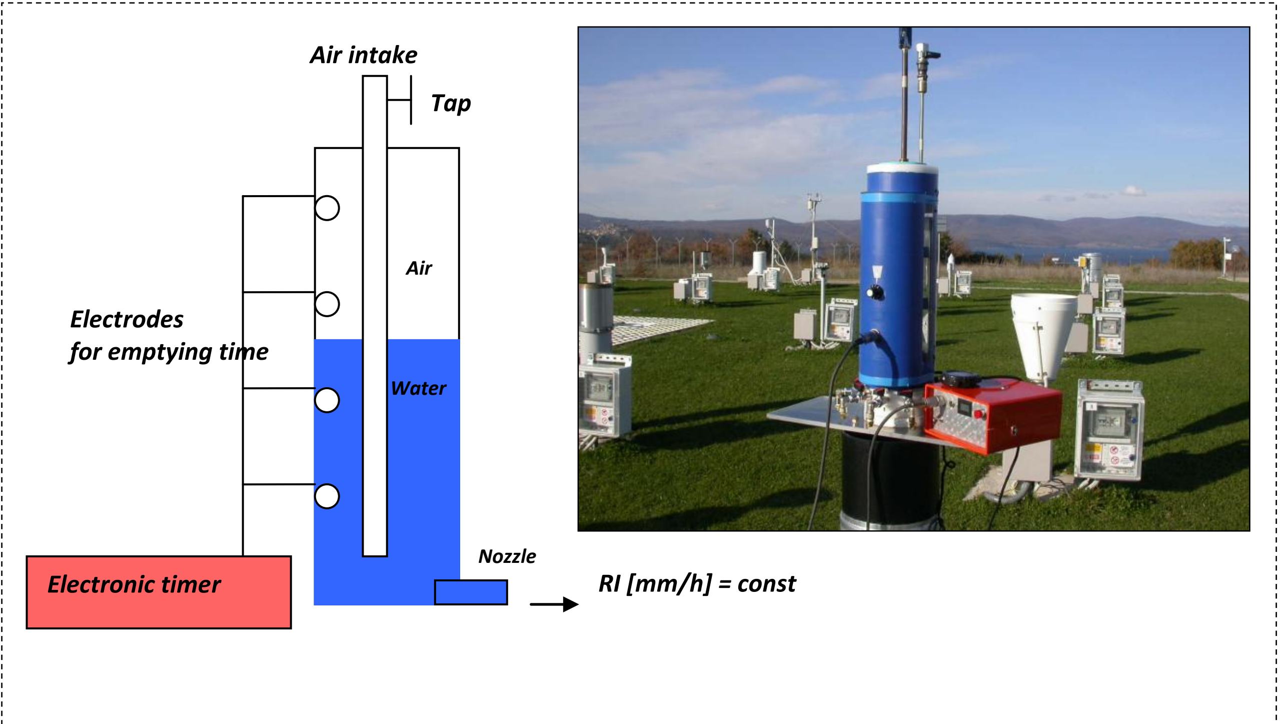


Fig. 5: The Portable Field Calibrator: the simplified scheme and the field setup during the Field Calibration at Vigna di Valle, Italy.

From the operational viewpoint the portable field calibrator permits rapid tests due to its very simple operation. The calibrator does not contain any sophisticated components, therefore, it provides cost effective solution for metrological verification of rainfall intensity instruments.

The repeatability of the field calibrator (and its accuracy) was assessed in a laboratory before the operational use. The uncertainty for each rain gauge collector size was expressed as relative expanded uncertainty (Urel) in relation to the statistical coverage interval. The 95% confidence level (k=2) was used and leaded to the following values:

Rain gauges collector size	*1000 cm^2*	*500 cm^2*	*400 cm^2*	*325 cm^2*	*200 cm^2*
$U_{rel}(RI_{ref})$ %	**1,0**	**1,5**	**0,4**	**1,8**	**1,8**

For each field calibration, several test series were done to investigate possible reasons of suspect malfunctioning or doubtful data, for at least 25-30 data points (1-MIN RI). All tests were performed in environmental conditions without precipitation or fog and with low wind speed (to avoid dynamic pressure perturbations to air intakes).

Data acquisition, processing and quality control

The data acquisition (DAQ) system chosen was a Campbell Scientific CR1000 data-logger equipped with peripherals suitable serial and analogue signals. A complete description of the DAQ is provided in *Vuerich et al. 2009*. The DAQ system was programmed for performing direct measurements (for switch closure gauges, vibrating wire rain gauges, pulse emitting rain gauges, wind monitoring sensors, temperature/RH sensors, etc.) and serial output acquisition for string emitting rain gauges. The clock of the CR1000 was the official timestamp used for optimal synchronization, especially relevant for the evaluation of 1-minute data. The acquisition for rain gauges consisted of a record of raw data from the rain gauges with a sampling time of 10 seconds or 1 minute, depending on the output time interval of the rain gauges. In case the RI (rainfall rate at 1 minute) was not directly provided as an output of the measurement, a transfer function given by the manufacturers was applied to derive RI at 1-min time resolution. The acquisition of ancillary sensors consisted of a record of raw data with a sampling time of 10 seconds.

The raw data contain all data delivered by the sensors, including diagnostic data, and they were processed in near-real time by the Automatic Quality Control (AQC) implemented on a separated CPU. The AQC procedures were implemented before the intercomparison and they checked files coming from DAQ, namely the RI raw data and the 1-min RI data, in order to provide quality checked 1-minute RI data, quality checked 1-minute ancillary data and QC information (e.g. flags, suspect data, erroneous data, etc.) to be used for data analysis and evaluation of results (available, valid data) (*for details see Vuerich et al., 2009*).

The focus of the RI Intercomparison was on liquid precipitation. For this reason only liquid precipitation events were evaluated. The identification of the precipitation type was based on information provided by the meteorological station of Vigna di Valle.

The following metadata were used to improve the interpretation of the Intercomparison results:

a) RI output, response time, time delays and factory's calibration certificate and procedures (if any) according to all operating manuals of selected instruments;

b) Results of the laboratory phase;

c) Record of all actions performed and observations made concerning the functionality of the instruments in a form of an electronic logbook operated by local staff;

d) Special observations recorded by the meteorological station, especially during precipitation events.

Summary of available data

The Field Intercomparison has been continuously managed for 18 months in all weather conditions. According QC daily reports produced by the AQC, the total availability of valid data was 98.2%. The number of precipitation events (collected in quality checked-valid daily files) was **162** (156 events with rain and 6 events with hail and mixed rain/hail). The following selection criteria were also applied to precipitation daily events in order to obtain the best dataset for the purpose of the Field RI Intercomparison:

1. The events used for the analysis were chosen among those that occurred during the period from 13 May 2008 to 30 April 2009. Problems of rain gauges data synchronization and other critical malfunctions where all solved before 13 May 2008. The event of the 30 October 2007 was the only one included (the highest rainfall rate event) that occurred during the period with the problem of synchronization;
2. The events used to retrieve the weights for the calculation of the reference RI had to be characterized by rainfall data with at least 2 consecutive minutes with $RI_{1min}>6$ mm/h (isolated point/events or those with $RI_{1min} < 6$ mm/h were discarded).
3. The events used for the RI data analysis had to be characterized by rainfall data with at least 2 consecutive minutes and $RI_{1min}>12$ mm/h.

According to first criterion, the number of daily events considered for the Field Intercomparison was **85**. This was the basis for the "**reduced**" Field Intercomparison (FI) **dataset (synchronized data)**. According to the second criterion, **79** events (out of 85) were used for the **calculation of reference RI**. According to the third criterion, **43** events (out of 79) were used for the **data analysis** of all rain gauges.

The rainfall accumulated over the intercomparison period was 1325 mm and the Table 2 shows the 43 maxima values of reference rainfall intensity (RI) recorded in each event used for data analysis, sorted from higher to lower RI values.

Nr	*Date*	*Max [mm/h]*	*Nr*	*Date*	*Max [mm/h]*	*Nr*	*Date*	*Max [mm/h]*	*Nr*	*Date*	*Max [mm/h]*
1	04/11/2008	195,1	12	05/12/2009	69,8	23	31/10/2008	37,5	34	24/01/2009	23,7
2	20/05/2008	152,4	13	22/05/2008	63,5	24	06/12/2009	36,1	35	04/03/2009	23,2
3	28/11/2009	112,7	14	13/05/2008	62,1	25	10/12/2009	34,8	36	20/01/2009	22,2
4	28/10/2008	108,9	15	06/06/2008	61,7	26	29/11/2009	33,6	37	07/02/2009	20,8
5	30/11/2009	107,9	16	01/11/2008	54,9	27	27/04/2009	31,3	38	18/02/2009	17,9
6	23/04/2009	84,4	17	16/12/2009	52,4	28	28/04/2009	29,2	39	10/02/2009	17,4
7	07/01/2009	78,8	18	08/09/2008	47,0	29	24/11/2008	27,8	40	31/03/2009	16,6
8	15/12/2009	75,8	19	01/01/2009	43,9	30	12/11/2008	26,3	41	15/01/2009	13,7
9	15/09/2008	75,4	20	26/01/2009	42,3	31	11/12/2009	26,3	42	14/12/2008	13,6
10	02/03/2009	73,2	21	29/10/2008	39,1	32	01/04/2009	25,8	43	05/03/2009	12,3
11	30/10/2008	72,3	22	27/07/2008	38,3	33	29/03/2009	24,2			

3. Data analysis

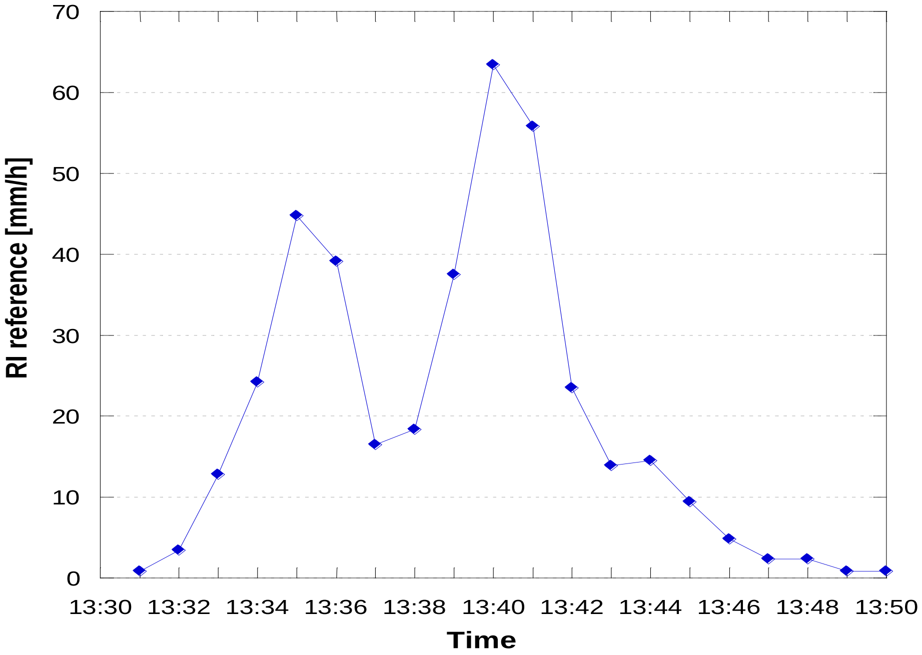
In order to perform the best intercomparison of rainfall intensity instruments in the field conditions, it was necessary to develop the appropriate tools, to compare different instrumental responses during a wide range of rainfall events.

Therefore it was necessary to find a specific statistical approach, taking into account the complex nature of the observed phenomenon. The analysis of the 1-minute RI data was done through different steps:

a) First a reliable 1-min working RI reference made up from the four reference rain gauges installed in the pit was determined.
b) Each rain gauge data were analysed in comparison with the calculated 1-min RI reference, and its performance and possible relation with weather conditions were evaluated.

In order to determine the most appropriate way of analyzing the data, a representative group of RI events was studied first to test different procedures. A method developed in this way was applied to all the intercomparison selected events.

To illustrate the high temporal variability of RI and the difficulties related to the comparison of 1-minute data from all rain gauges, an example of rainfall intensity versus time is shown below.



Reference value

The RI reference is the best estimation of the 1-minute RI true value that can be obtained from the working reference gauges inside the RRGP, which are two corrected tipping bucket rain gauges (TBRG with correction algorithm) and two weighing gauges (WG) with the shortest step response and the highest accuracy obtained from the WMO Laboratory Intercomparison results (2004-2005).

The determination of a reference value of the rainfall intensity is fundamental for defining the baseline for the intercomparison. Since there are four instruments that were chosen as RI reference gauges, it was necessary to define how to convert their readings into to a **RI composite working reference value**. The best estimation of a RI composite working reference can be done using two different methods:

1. The use of the dynamic response of the set of reference gauges;
2. The statistical evaluation of the experimental data.

The first method requires specific laboratory or field tests with several step function inputs in a suitable range of RI to determine experimentally the step response function and the time constant of each instrument. The static characteristics of an instrument and measurements of the output must be made for different values of the input. During the transition from one static state to another, as during a precipitation event, the system becomes dynamic. The step response function of each reference rain gauge applied in field conditions would provide the best estimate of the 1-minute RI value within a tolerance that is a combination of the uncertainties evaluated experimentally in the laboratory through a standard procedure. The accuracy of some catching-type rain gauges could depend on their response to dynamic characteristics of the natural phenomenon of precipitation. This method was discarded because little information was available about the time constant of each instrument and its influence on the overall accuracy of the reference.

The second method consists of a statistical evaluation and was used for the estimation of a RI composite working reference, as follows:

The statistical evaluation of the 1-minute RI reference is made using a **Weighted Average** obtained from the rainfall intensities measured by the four references:

$$RI_{ref} = \frac{\sum_i \mu_i RI_i}{\sum_i \mu_i}$$

where μ_i is the weight of the reference rain gauge *i* (*i* = R102-ETG, PMB2-CAE, MRW500-METEOSERVIS, T200B-GEONOR). Calculation of weights is the most challenging issue. As it will be shown in the following graphs which represent high RI events in October 2008, a purely statistical evaluation is not sufficient, because it is necessary to take into account effects related both to dynamic internal characteristics and the possible lack of synchronization on 1-minute time base. For this reason the weights were calculated taking into account both a global statistical parameter, obtained from the whole data set, and also the evaluation of each single event from which the average is calculated:

$$\mu_i = \frac{S_i^{-1} \cdot F_i}{\sum_i S_i^{-1} \cdot F_i}$$

where $S_i = \sum_{k \neq i} \sigma_{ik}$ with *k* = R102-ETG, PMB2-CAE, MRW500-METEOSERVIS, T200B-GEONOR but $k \neq i$; σ_{ik} are 3 statistical parameters calculated for each reference gauge *i* compared to the other references rain gauges in RRGP throughout the database of all precipitation events as:

$$\sigma^2{}_{ik} = \frac{\sum_{j=1}^{N} (RI_j^i - RI_j^k)^2}{N}$$

where:

- RI_j^i the *j* th 1-min intensity measured by the reference rain gauge *i* in the RRGP,
- RI_j^k the *j* th 1-min intensity measured by the reference rain gauge *k* in the RRGP,
- *N* the number of experimental (1-minute RI) data of all the events.

The evaluation of each single event is introduced in the weights μ_i through the factor F_i, which is a "gross" parameter determined on the basis of a detailed examination of the RI data for that event. This parameter can be 1 or 0, it is 1 if the reference rain gauge under examination is not evidently affected by 1-minute lack of synchronization or high dynamic oscillation, otherwise it is 0, which means that pit gauge for that particular event is excluded from the calculation of the reference intensity.

Therefore after the examination of the laboratory/field tests for the response function determination, these functions could be used for accurately estimation of composite RI reference. The calculation of the *F* parameter can be more appropriate and the calculation of weights is a combination of a statistical and physical component.

The calculation of the statistical parameters S_i, according to the above-mentioned procedures, gives the following values:

S_{R102}^{-1}	S_{PMB2}^{-1}	S_{MRW500}^{-1}	S_{T200B}^{-1}
0.172	**0.192**	**0.226**	**0.238**

Looking at the values obtained for the S^{-1} parameter, it was found that the behaviour of the four reference rain gauges is such that their weights should be almost the same in the calculation of the RI composite working reference. The strongest difference is given instead by the other parameter *F* that is related to the behaviour of the instrument during each rainfall event.

In order to develop the best method for the calculation of the 1-min RI composite working reference, a selection of rainfall events was performed according to the criteria described in the summary of available data. Eleven 1-min RI events matching the requirements were selected from the complete database for the following analysis. These RI events represent the best example of the application of the statistical method described above and they show the effect of the 1-minute lack of synchronization and dynamic behaviour. This approach and the corresponding preliminary results were presented during the Sixth reduced Session of the WMO CIMO ET/IOC meeting (*WMO, 2008b*), for evaluation and approval, and during the WMO CIMO TECO METEOREX, held in St. Petersburg in November 2008 (*Vuerich et al., 2008*).

In order to analyze the behaviour of the four reference gauges in the considered rainfall events, the relative differences (RD) between the measured rainfall intensities and the RI composite working references on 1 minute time scale were computed as follows:

$$RD_i = \frac{RI_i - RI_{ref}}{RI_{ref}} \cdot 100\% \quad .$$

RD_i were plotted versus a non-scaled ascending series of 1-minute RI composite working reference values calculated as the weighted averages of the RRGPs 1-minute measured intensities of the events (namely event #1 to #11), as shown in Fig. 6, 7, 8.

The calculated weighted average is obtained assuming that all the instruments in the pit did not have synchronization or dynamical problems, therefore the *F* parameter is equal to 1 for all the instruments and events. In this case the weights are:

μ_{R102}	μ_{PMB2}	μ_{MRW500}	μ_{T200B}
0.27	**0.25**	**0.23**	**0.25**

Figure 6 illustrates that the R102-ETG and T200B-GEONOR gauges have a relative difference in most cases of ±20 %; in particular the R102 sensor is well within this limit, whereas the T200B-GEONOR shows wider variations. The PMB2-CAE and MRW500-METEOSERVIS gauges on the other hand show a different situation, because they have very high relative differences with big variation compared to the other two gauges.

After a detailed examination of events #1 to #11 it was concluded that in event #3 the PMB2-CAE reference gauge was strongly affected by 1-minute non-synchronization that did not permit a good estimation of composite working RI reference (relative differences of the four references are too high on average). To minimize the RD, the PMB2-CAE gauge was excluded in event #3 (F_{PMB2}=0). In events #1, 2, 4, 5, 6, 7, 8, 9, 10 and 11 this instrument was perfectly synchronized and the *F* parameter is set to 1. Unfortunately the MRW500-METEOSERVIS gauge, which is always synchronized, has shown an anomalous behaviour due to 1 minute oscillating step response that had not been observed during the previous Laboratory Intercomparison (*Lanza et al. 2005b*). According to manufacturer, these oscillations were caused by the time beats between the rain gauge sampling period of 16 s and the output readout period of 60 s. Thus they were due to the fact that the measurement interval of 60 s did not coincide with the multiple of the sampling interval of 16 s of the rain gauge. Therefore, in all events this gauge was excluded from the calculation because its 1-min RI clearly deteriorated the accuracy of a RI composite working reference estimation.

During event #6, the R102-ETG gauge did not work properly; therefore *F* was set to 0 for R102-ETG in this event. This is a typical “event based” criterion to assign the value of the “gross” parameter.

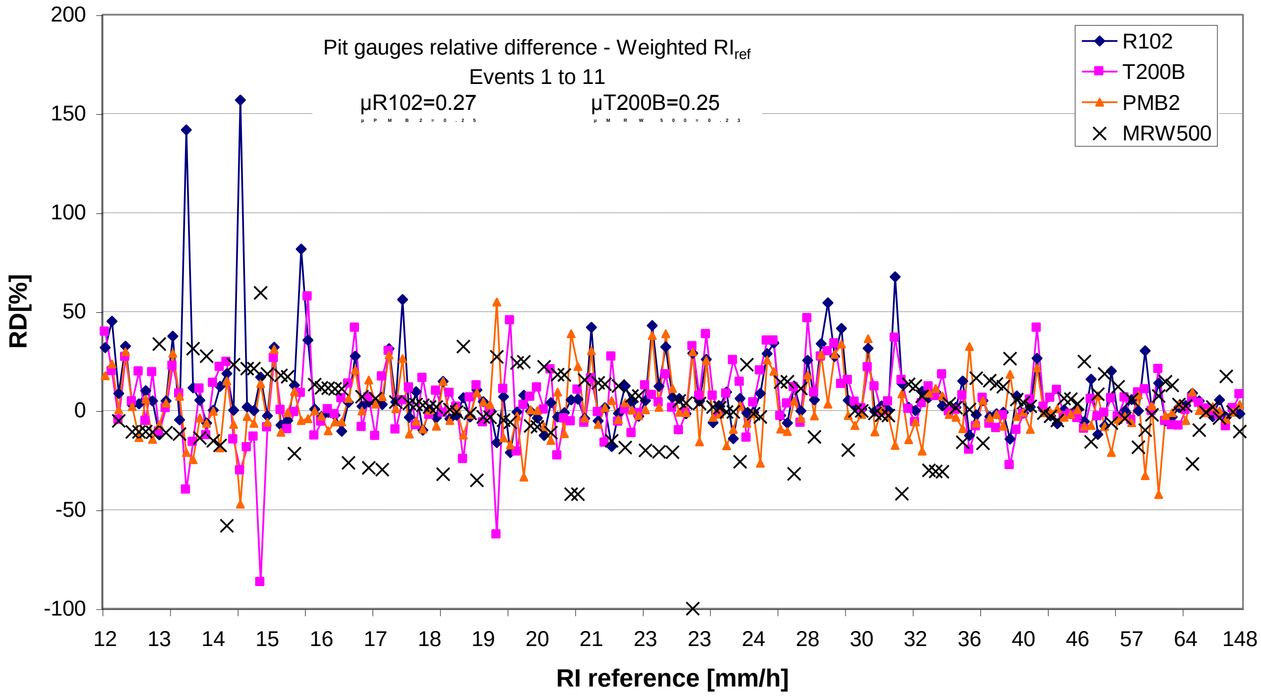


Fig. 6: RI relative difference of each working pit gauge with respect to the calculated composite working RI reference; the weights for the RI average are computed with $F_{R102} = F_{PMB2} = F_{MRW500} = F_{T200B} = 1$ for all the events.

The result of the RI reference calculated is shown in Fig. 7. In this graph, the *F* parameters for event 1, 2, 4, 5, 7, 8, 9, 10, 11 are $F_{R102} = F_{PMB2} = F_{T200B} = 1$ and $F_{MRW500} = 0$; for event 3 $F_{R102} = F_{T200B} = 1$ and $F_{PMB2} = F_{MRW500} = 0$; for event 6 $F_{PMB2} = F_{T200B} = 1$ and $F_{R102} = F_{MRW500} = 0$.

In this case the RI reference is not affected by the wide variations of MRW500-METEOSERVIS and by the lack of synchronization of PMB2-CAE in event #3. It is evident that the effect on the RD of R102-ETG and T200B-GEONOR gauges is dominant and it becomes smaller and decreases when RI increases. The RD of R102-ETG and T200B-GEONOR reduces to about 10%. Looking at the RI data without the PMB2 RD values of rainfall event #3, as shown in Fig. 31, it is evident that when the PMB2-CAE is synchronized it shows very good agreement with R102-ETG and T200B-GEONOR; with a RD in the range of ± 10%. Note also the higher the intensity the better the agreement. Some RD values corresponding to a larger variation of T200B-GEONOR gauge can be explained through the Laboratory tests results, where it was seen that the response time of this instrument is around 1 minute.

A very useful tool for the evaluation of the effects of non-synchronization and dynamical behaviour is the representation of the relative difference RD compared to the 1-minute RI reference variation:

$$\Delta = RI_{ref}(t) - RI_{ref}(t - 1\text{min})$$

This parameter can be used to investigate a possible dependence of RD on the variation of the rainfall intensity on 1-minute time scale, for example a study of dynamic effects due to the transition from one state to another during a precipitation event.

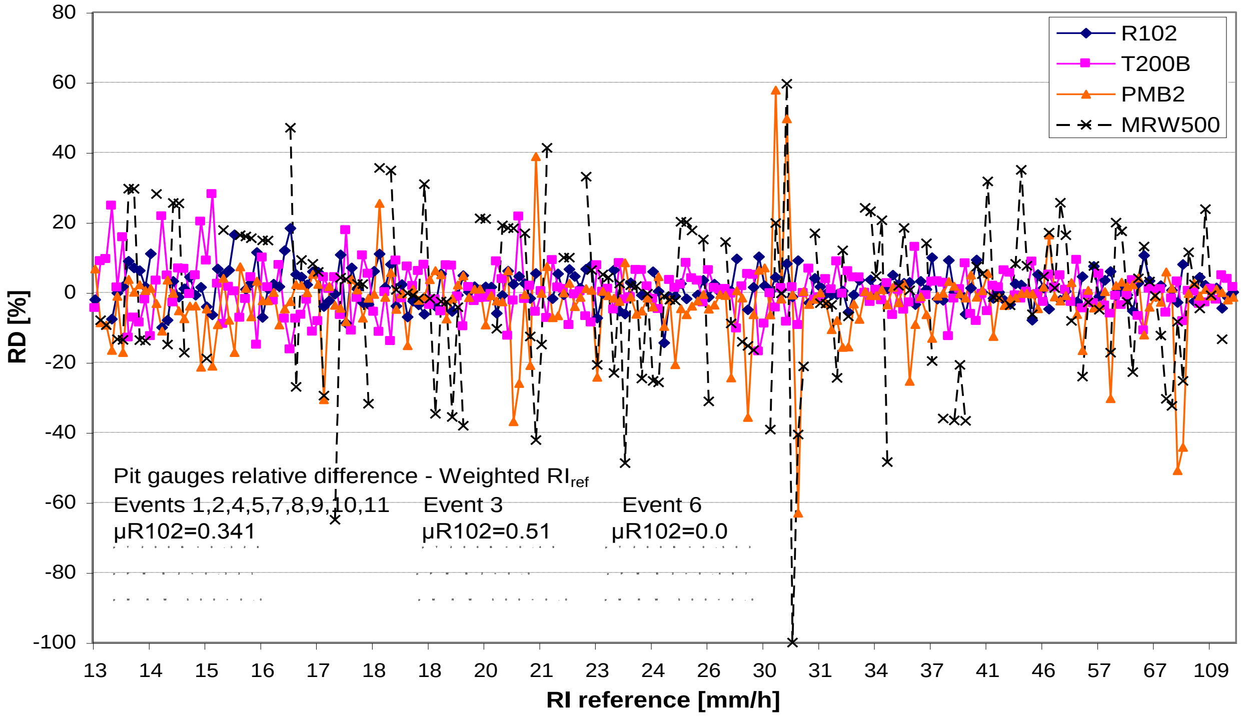


Fig. 7: RI relative difference: the weights for the RI average are computed with F_{R102} = F_{PMB2} =F_{T200B} =1 for events 1, 2, 4, 5, 7, 8, 9, 10, 11; F_{PMB2} = F_{MRW500} =0 and F_{R102} = F_{T200B} =1 for event 3 and F_{R102} = F_{MRW500} =0 and F_{PMB2} = F_{T200B} =1 for event 6. Note that x-axis is non-linear.

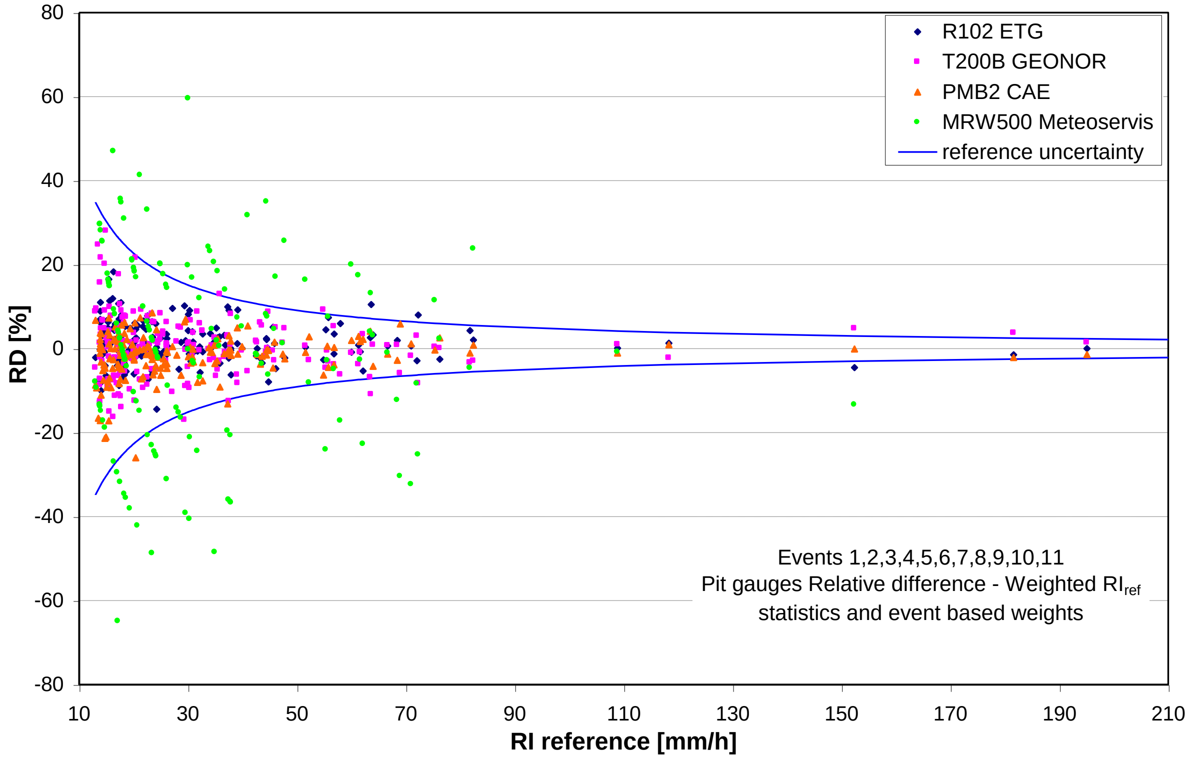


Fig. 8: RI relative difference: the weights for the RI average are computed with F_{R102} = F_{PMB2} = F_{T200B} =1 for events 1, 2, 4, 5, 7, 8, 9, 10, 11, F_{PMB2} = F_{MRW500} =0 and F_{R102} = F_{T200B} =1 for event 3 and and F_{R102} = F_{MRW500} =0 and F_{PMB2} = F_{T200B} =1 for event 6. Data points of PMB2 gauge for event 3 are not represented. (For reference uncertainty, see following sections).

Considering Fig. 9 and 10 it is evident that R102-ETG and T200B-GEONOR do not show particular dependence on the RI variation parameter, therefore these two gauges represent the most reliable set of references through the evaluated events.

The distribution of RD experimental points for PMB2-CAE reference gauge shows a diagonal distribution in event #3 (Fig. 11), otherwise RD does not show particular dependence on the Δ variations for the other events. During event #3, when Δ > 0 then RD< 0 (RI_{PMB2} has not yet increased compared to the RI composite working reference) and when Δ < 0 then RD> 0 (RI_{PMB2} has not yet started decreasing compared to RI composite working reference); the transmission of the 1-min data from the instrument is delayed compared to the data acquisition timestamp. PMB2 represents the most reliable gauge for the four events (even better then R102-ETG and T200B-GEONOR) as graphs show, but it cannot be weighted for event #3 due to an evident non-synchronization on 1-minute time scale. This is confirmed by a detailed examination of raw data timestamp and can be explained by the data acquisition method; at the time when event #3 occurred, PMB2-CAE was set to automatic data transmission but the procedure to synchronize its internal clock with the main clock of the DAQ system was not in operation.

The distribution of experimental points of RD for gauge MRW500-METEOSERVIS (Fig. 12) does not show a dependence on RI variation but the values in Fig. 12 are very scattered due to a 1-minute oscillating step response which does not permit an accurate RI measurement or a RI composite working reference determination on a 1-minute time scale. Moreover, the low resolution of this gauge on 1-minute precipitation negatively affects the comparison between the four pit gauges.

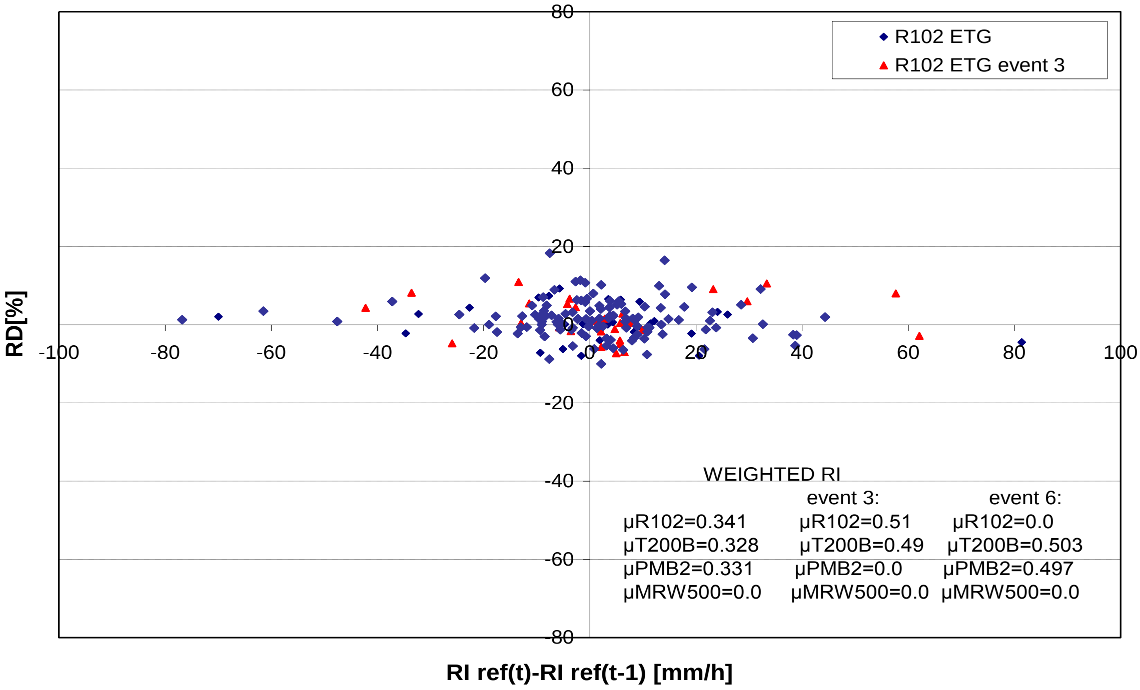


Fig. 9: Relative difference of R102-ETG compared to time variation of RI reference.

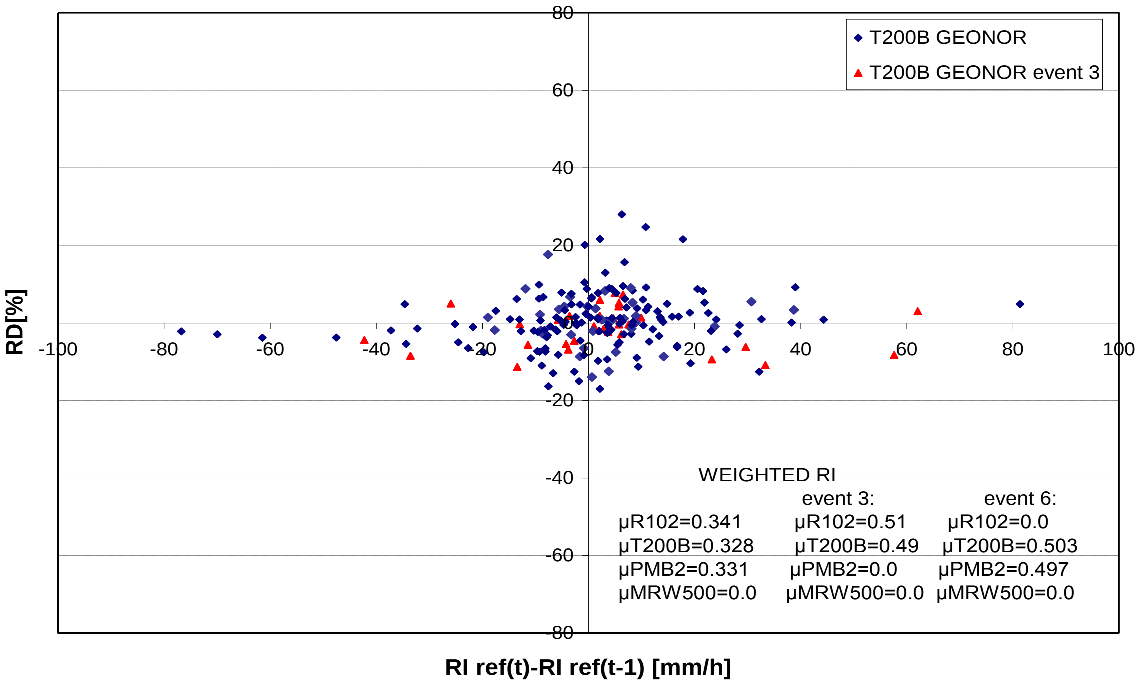


Fig. 10: Relative difference of T200B-GEONOR compared to time variation of RI reference.

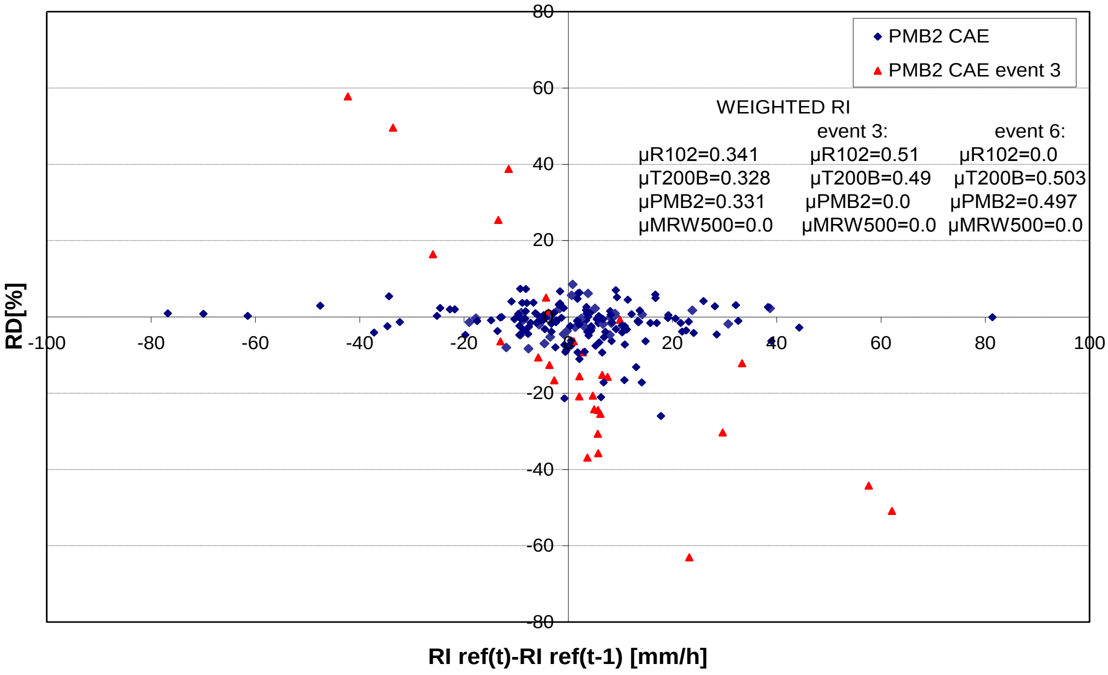


Fig. 11: Relative difference of PMB2-CAE compared to time variation of RI reference.

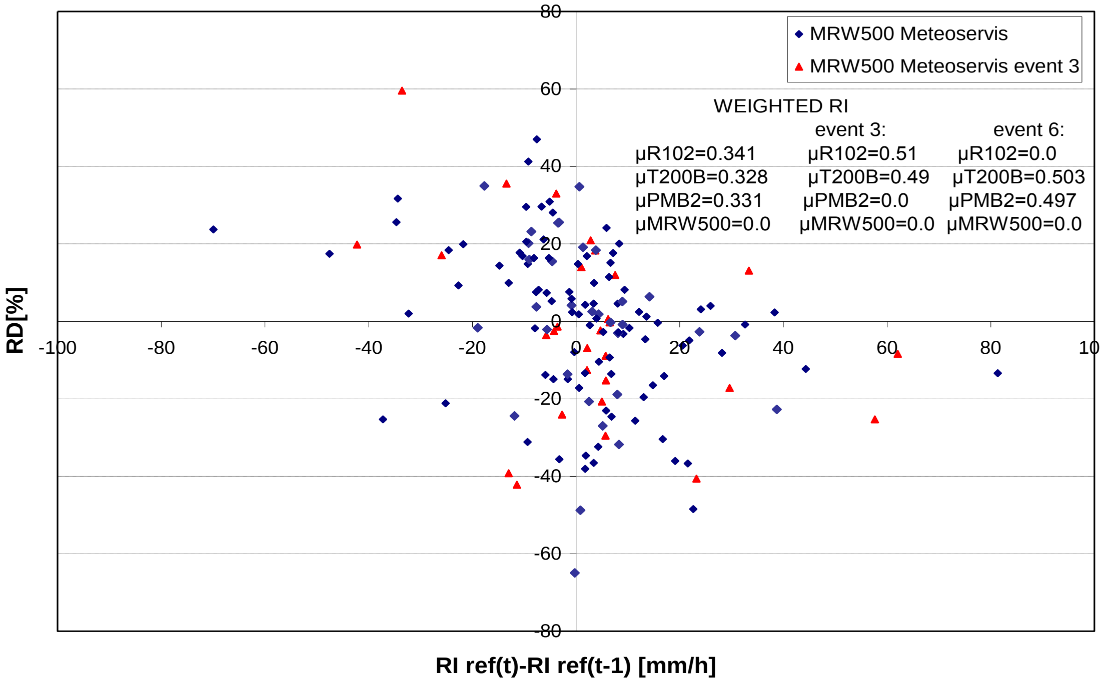


Fig. 12: Relative difference of MRW500-METEOSERVIS compared to time variation of RI reference.

The analysis of the laboratory calibrations on 1-min time basis performed during the preliminary phase of this intercomparison confirms the large dispersion of data due to the above-mentioned oscillating step response. This effect was not seen during the previous WMO Laboratory Intercomparison and explains why the MRW500-METEOSERVIS was at that time selected for participating to the reference group. Therefore the CIMO ET/IOC decided to exclude the MWR500-METEOSERVIS pit rain gauge from the calculation of the 1-min RI composite working reference (*see WMO 2008b: Chapter 3.3.2 and 3.3.3, Final Report of the sixth session of the Expert Team Meeting CIMO-ET-IOC-SBII, Vigna di Valle (Italy) 15-17 September 2008*).

Uncertainty of the reference

The method described above permits to calculate 1-minute RI composite working reference as the best estimation of the 1-minute RI true value. The evaluation of the uncertainty of this reference value is very complex because the physical contributions due to the dynamics of the instruments, their response functions and environmental related effects are not known, therefore, in order to evaluate the uncertainty of the calculated RI composite working reference**,** it was decided to proceed as follows:

A normal distribution of the deviations of the rainfall intensity measurements of the pit gauges is assumed and the standard deviation of the distribution with respect to the reference intensity is calculated according to $\sigma=[\sum(RI-RI_{ref})^2/N]^{1/2}$, where the sum is extended for all the RI>12 mm/h of the three reference gauges. It is common practice in metrology to express the uncertainty as "expanded uncertainty" in relation to the "statistical coverage interval", therefore the 95% confidence level, or k=2, is used for all measurements. Since the measurement uncertainty is assumed to be independent on the rainfall intensity, the RI reference expanded uncertainty (95%) is calculated as $U(RI_{ref})= 2\sigma$. The relative uncertainty (k=2) is thus $u_{rel}(RI_{ref})= (U(RI_{ref}) \ / \ RI_{ref})\cdot 100$ and it is plotted in Fig. 13. The 95% of all experimental points are inside the uncertainty limits and the formula to calculate the relative uncertainty of the reference intensity is a function of RI.

The results were extended to the representative dataset of the intercomparison (see Summary of available data) in order to calculate the values of the weights for the RI composite working reference and to determine the uncertainty of such reference (Relative uncertainty reported Fig. 13). For the 1-

minute data, the calculated uncertainty is **$U(RI_{ref})$= 4.3 mm/h**. (For details on the extended table of weights' value see *Vuerich et al. 2009*).

In Fig. 13, where the relative difference RD between the pit gauges' RI is represented as a function of the reference intensity, it is evident that the dispersion of data is higher for RI below 30 mm/h, where there is also the effect of short and sudden rainfall events. The response of the instruments in fact is not instantaneous, moreover the initial status of tipping buckets is very important, because some water could have remained in the bucket. When the intensity of the precipitation event increases, the dispersion reduces and it is very low for high intensity rate.

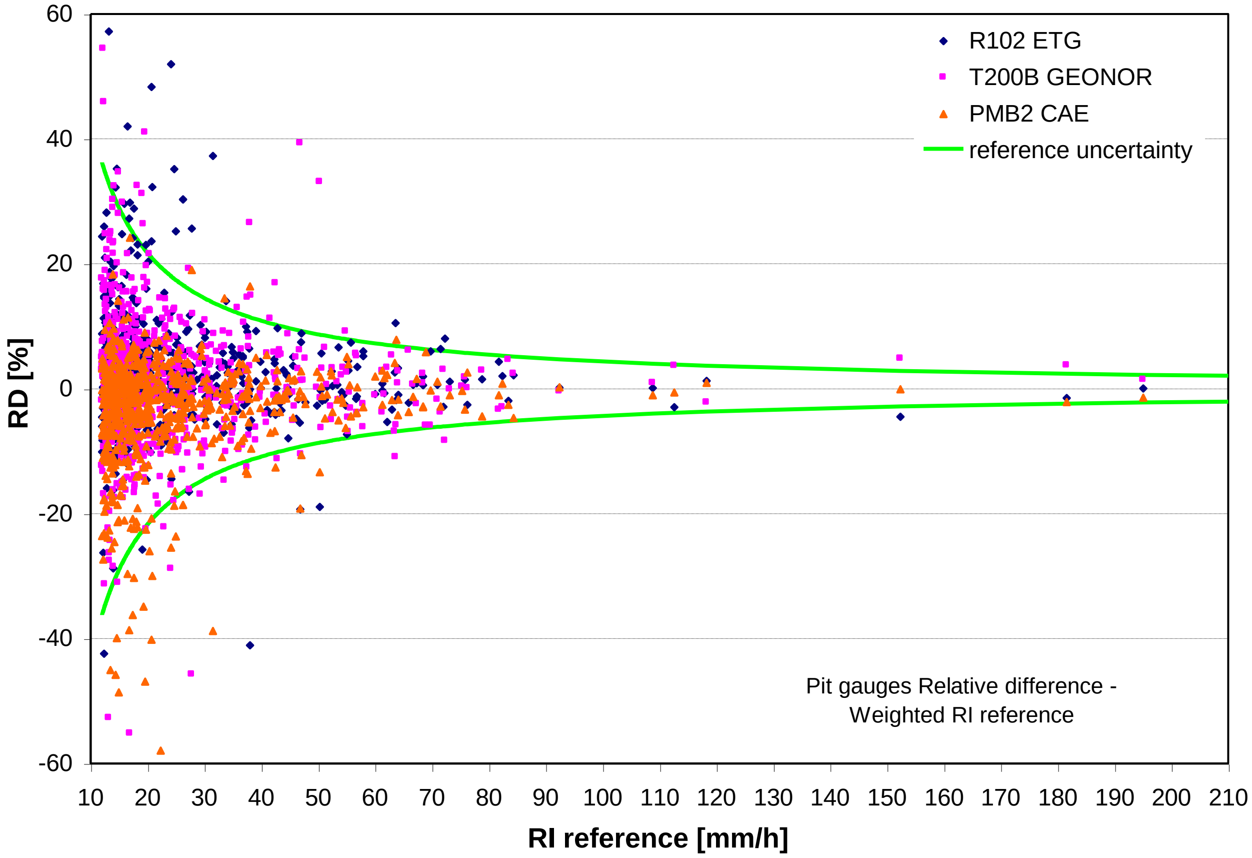


Fig. 13: RI relative difference: the weights for the RI average are computed from the whole dataset of events. Green lines delimit the region which includes the 95% of the experimental points according to u(RIref)= (2 σ/ RIref)·100.

Tolerance region

In order to compare the gauges to the reference and to assess their agreement with the user uncertainty requirement, a tolerance region was established. For the calculation of the tolerance region we assumed the WMO required measurement uncertainty, of 5% for each rainfall intensity gauge according to CIMO Guide (*WMO, 2008a, Part I, Chap.1, Annex 1.B*). The tolerance region is composed of this 5% uncertainty and of the uncertainty of the reference, thus its value is finally calculated as: $[u_{rel}(RI_{ref})^2+5^2]^{1/2}$ [%]. To show the results of the intercomparison, the tolerance region is represented by upper and lower lines which are drawn in the plots of the "*Results and discussion*" section. . The limits of performance of measuring devices are determined both by the characteristics of the devices and by the natural variability of the element to be measured. The tolerance region represents an indication of these limits. The required performance for RI measurements (required uncertainty) stated in the CIMO Guide (*WMO, 2008a*) is 5% above 2 mm/h. Due to the uncertainty of the reference, such a performance cannot be demonstrated, except for high RI values. The results of this intercomparison could provide advice on the achievable RI measurement uncertainty.

Synchronization

During the period of the intercomparison campaign, the problem of the synchronization between the internal clock of some rain gauges and the clock of the DAQ system was one of the hardest and most important to solve.

In order to compare the 1-minute RI data of all instruments, a synchronization of ±10 s was required, in other words the internal clock of the instrument should be within ±10 s compared to the DAQ system timestamp (nominal timestamp). If the difference/delay between the instrument's data output time and the nominal timestamp exceeds the required ±10 s time interval, the corresponding 1-minute RI is like the one shown for gauge B in Fig. 14, thus the result cannot be correctly compared to synchronized gauges.

In Fig. 14, 1-minute rainfall intensity curves of three sample gauges A, B and C are plotted versus time. For gauge A the difference/delay between the data output time and the nominal timestamp (i.e., hh:mm:00) is up to 6 seconds (case of PLUVIO-OTT). In this way gauge A can be always considered synchronized with the DAQ system. Gauge B internally updates data every minute but in this example the difference/delay between the data output time and the nominal timestamp is 30 seconds (hh:mm:30). Therefore, the comparison of the data for past precipitation events (i.e. non-synchronized PMB2-CAE) shows large differences due to this delay. For gauge C the difference/delay between the data output time and the nominal timestamp is equal to 0 (case of T200B-GEONOR). In this way gauge C is always perfectly synchronized with the DAQ system. This example demonstrates the problem to compare RI data of non synchronized rain gauges on 1-minute time basis. Moreover, an automatic post-synchronization of gauge B data is not possible, because the gauge B data output is shifted by 30 seconds. The lack of synchronization causes a different RI distribution in time, so it is impossible to compare rainfall intensities evaluated on the nominal timestamp. This effect is difficult to be detected by 1-minute data and the shift between data output and DAQ clock could be variable with time, so Intercomparison raw data (available every 10 s) should be firstly checked before applying the proper synchronization procedure. It is not realistic to find and apply the right "forward-backward shifting" of all gauges data for all precipitation events. The only way to obtain a correct synchronization of the data on 1-minute is automatically and periodically synchronizing the internal clock of those gauges which show that problem by sending synchronization commands at least once a day through the DAQ system.

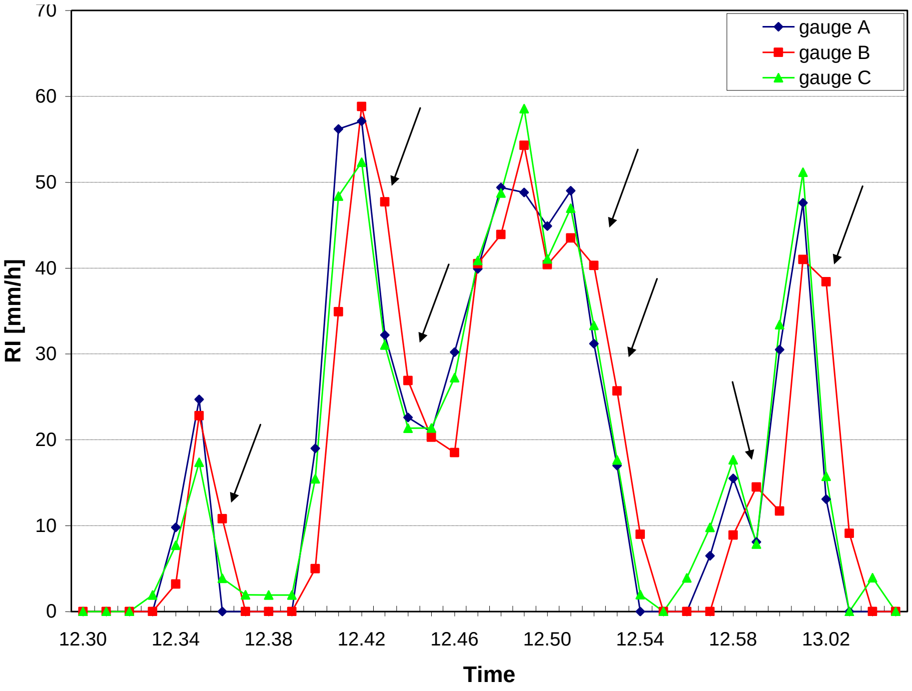


Fig. 14 Gauge A and C are synchronized with the DAQ system clock; gauge B has a delay exceeding 10 seconds. Arrows indicate sample points of B with large difference due to non-synchronized data points of gauge B.

In the period from October to December 2007, the following rain gauges had shown the effects of non-synchronization, thus affecting the Intercomparison results: R102-ETG, PMB2-CAE, DQA031-LSI LASTEM, UMB7525/I-SIAP-MICROS, VRG101-VAISALA, PWD22-VAISALA, TRwS-MPS, LPM-THIES, ANS 410/H-EIGENBRODT, LCR "DROP"-PVK ATTEX. From January to May 2008 much effort was dedicated to the attempt of performing the best automatic synchronization throughout the DAQ system of the above-mentioned instruments. It was decided to perform the Intercomparison data analysis only on synchronized data (period after May 2008). However, for statistical reasons and only for pit gauges, the calculation of the weights μ for the determination of the RI reference was extended to all events, therefore the *F* parameter was introduced for a correct calculation of the 1-min RI composite working reference, in order to take into account the problem of synchronization by manually selecting only synchronized pit gauge data for each precipitation event (the operation was performed only for R102-ETG and PMB2-CAE reference pit gauges).

A further consideration must be done for the TBRG-SC gauges (R102-ETG, PMB2-CAE, UMB7525/I-SIAP-MICROS): their data had delay of 1 minute (factory set up, documented by manufacturers). This delay is not a lack of synchronization as the problem described above: after proper clock synchronization they must be further shifted by 1 minute backwards, in order to perform a correct comparison. During the Field Intercomparison, it was possible to apply a clock synchronization procedure by the DAQ system but not a 1 minute backward shift: the 1 minute shift was carried out by "a posterior" procedure before data analysis.

In Fig. 15, the precipitation event measured by the reference pit gauges on 30 October 2007 is presented. It shows a clear example of non-synchronized 1-minute RI data, in particular for PMB2-CAE rain gauge. MRW500-METEOSERVIS and T200B-GEONOR are perfectly synchronized, so their 1-min RI timestamps must be considered as the nominal timestamp. The R102-ETG is synchronized within 10 s of nominal timestamp (hh:mm:00) but RI data required a further backward shifted by 1 minute. The PMB2-CAE is not synchronized and RI data are shifted by 1 minute and 40 seconds with no possibility to apply a correct synchronization procedure and with no possibility to correctly compare its results to the others (in particular see the second peak intensity).

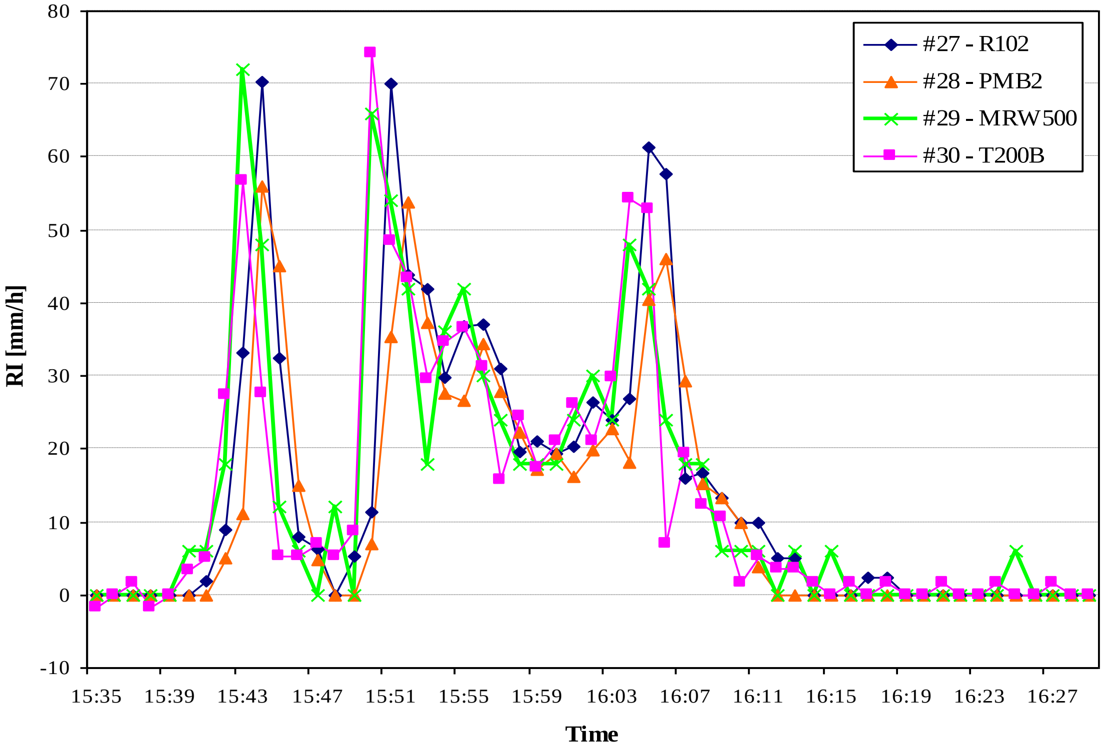


Fig. 15: Example of rainfall event: rainfall intensity measured by the working reference gauges.

Results and discussion

The following section is dedicated to the general results of the comparison between the RI measured by the rain gauges and the RI composite working reference. Rain gauges are grouped according to the physical principle of measurement, to show the differences in the 1-min measurement related to these principles (Fig. 16-22). Additional and more specific plots about laboratory calibration and field measurements are reported in *Vuerich et al. 2009*).

The plots reported in Fig. 16-22 represent the trend of each instrument compared to RI composite working reference, where the trend line is obtained from a power law fitting of the experimental data:

$$RI = a \cdot RI_{ref}^{\ b}$$

where *a* and *b* are constants. The corresponding best fit equations are reported on each plot. In order to assess the **accuracy of field measurements** compared to the reference, the lines of the tolerance region, calculated according to the procedure previously described, are represented in dashed lines on each plot. The best fit curves must be interpreted with their corresponding correlation coefficient (R^2).

For easier comparison, the instruments have been divided into seven groups according to the measurement principle, as indicated in the title of each plot. WG instruments are split in two groups for easier presentation of results.

Catching rain gauges

Fig. 16: Tipping Bucket Rain Gauges (TBRG)

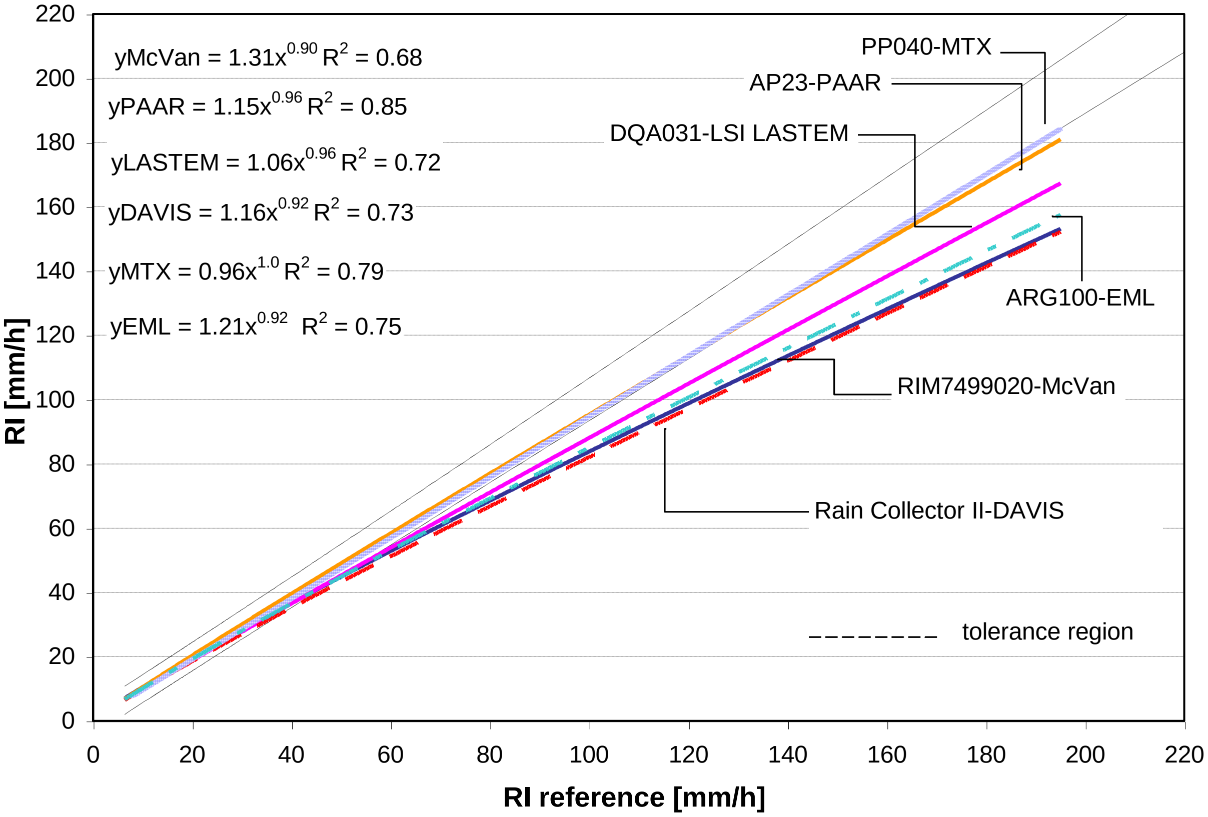


Fig. 17: Tipping-bucket rain gauges with correction algorithm (TBRG-SC)

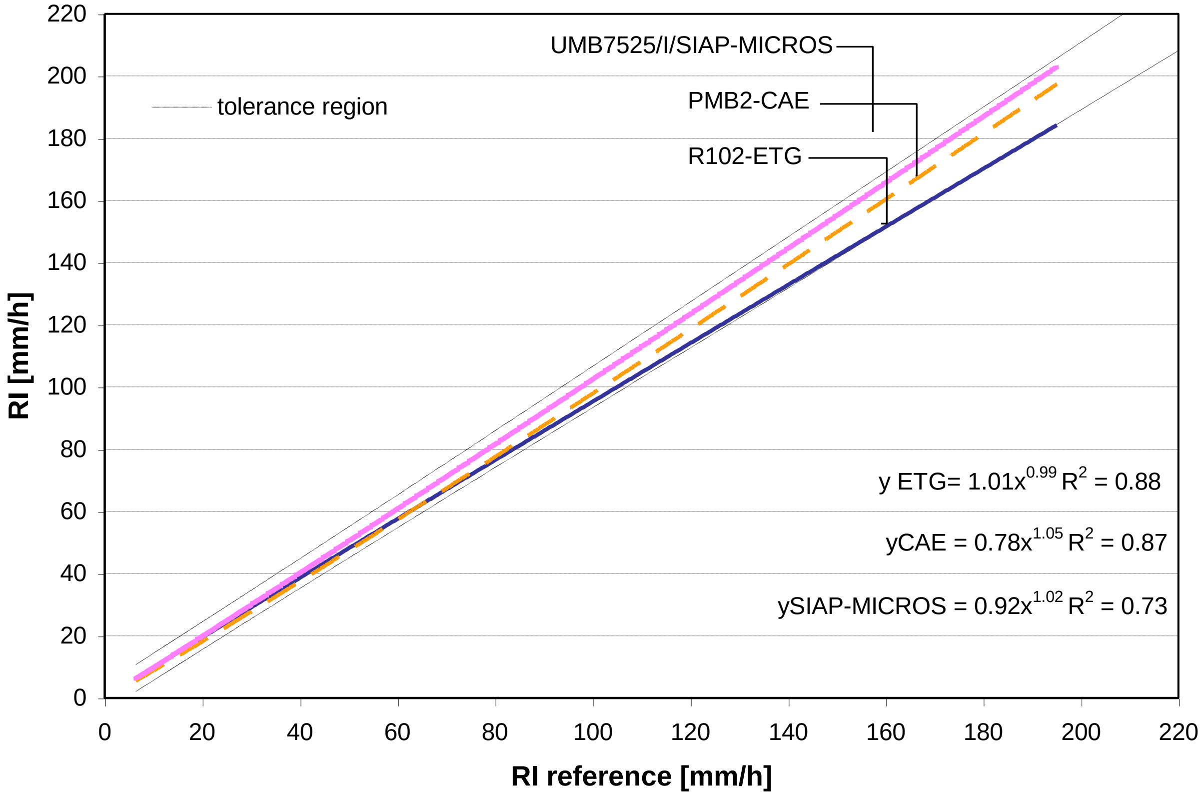


Fig. 18: Tipping-bucket rain gauges with extra pulse correction (TBRG-PC)

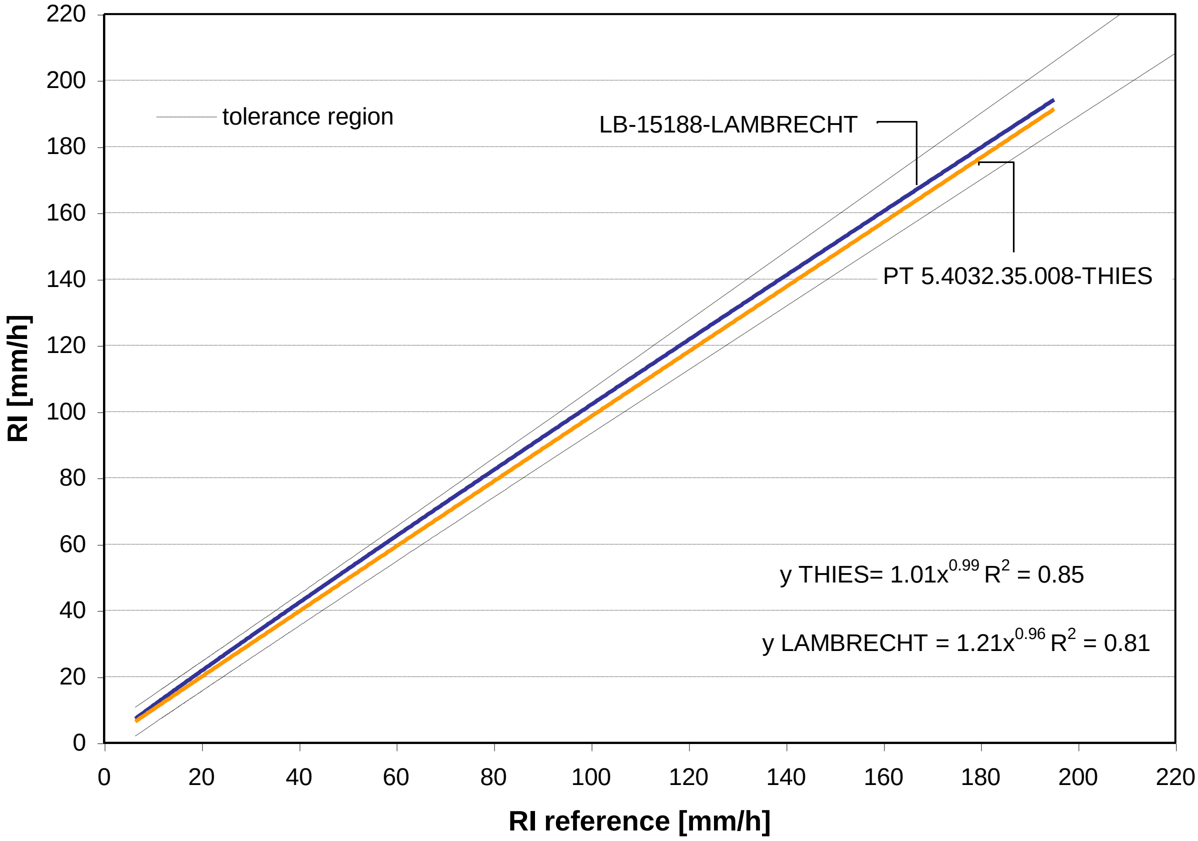


Fig 19: Tipping bucket rain gauges with mechanical corrections (TBRG-MC) and Level Measurement Rain Gauges (LRG)

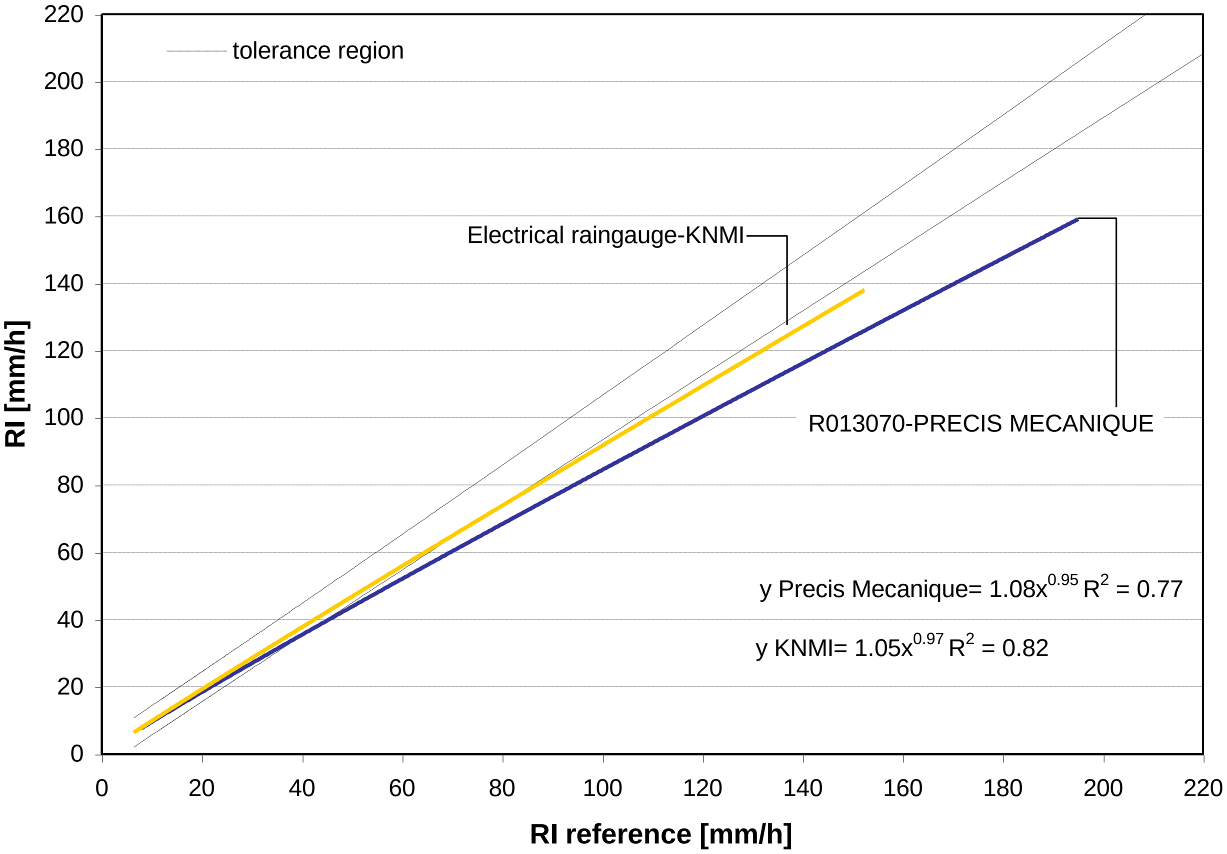


Fig. 20: Weighing rain gauges (WG)

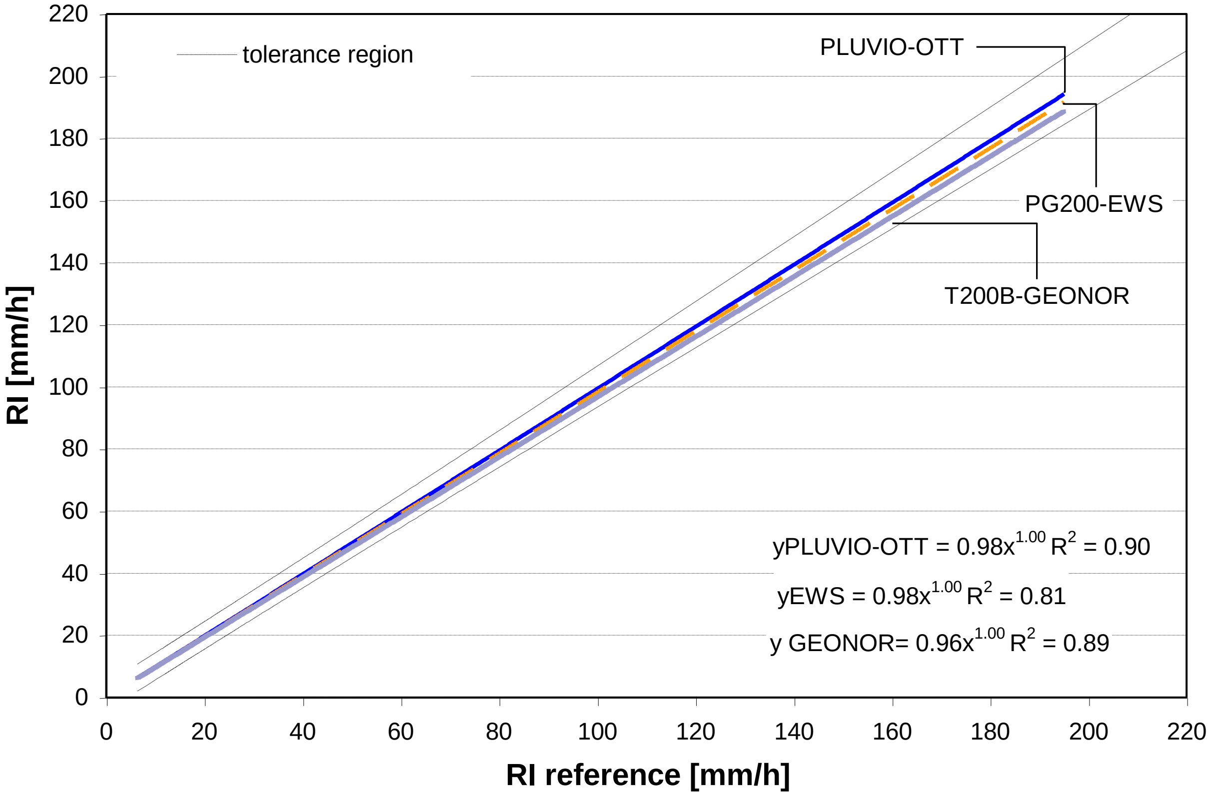
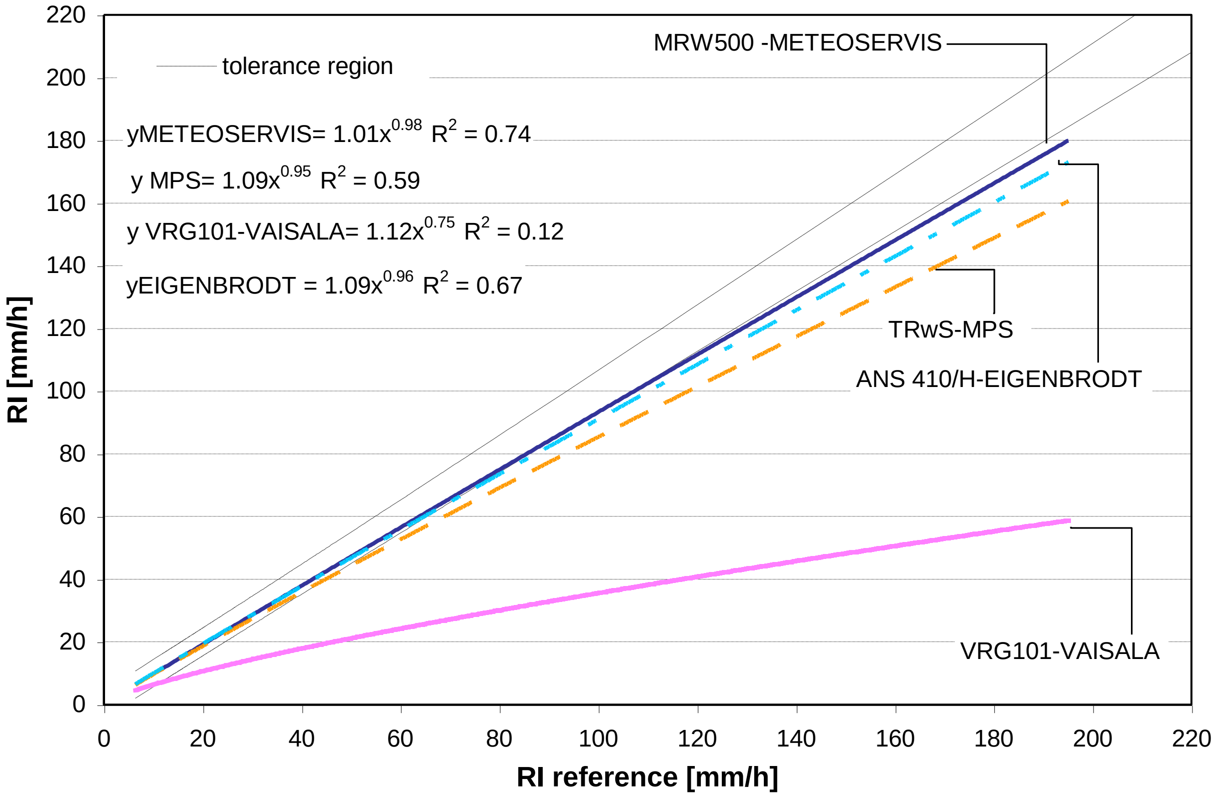
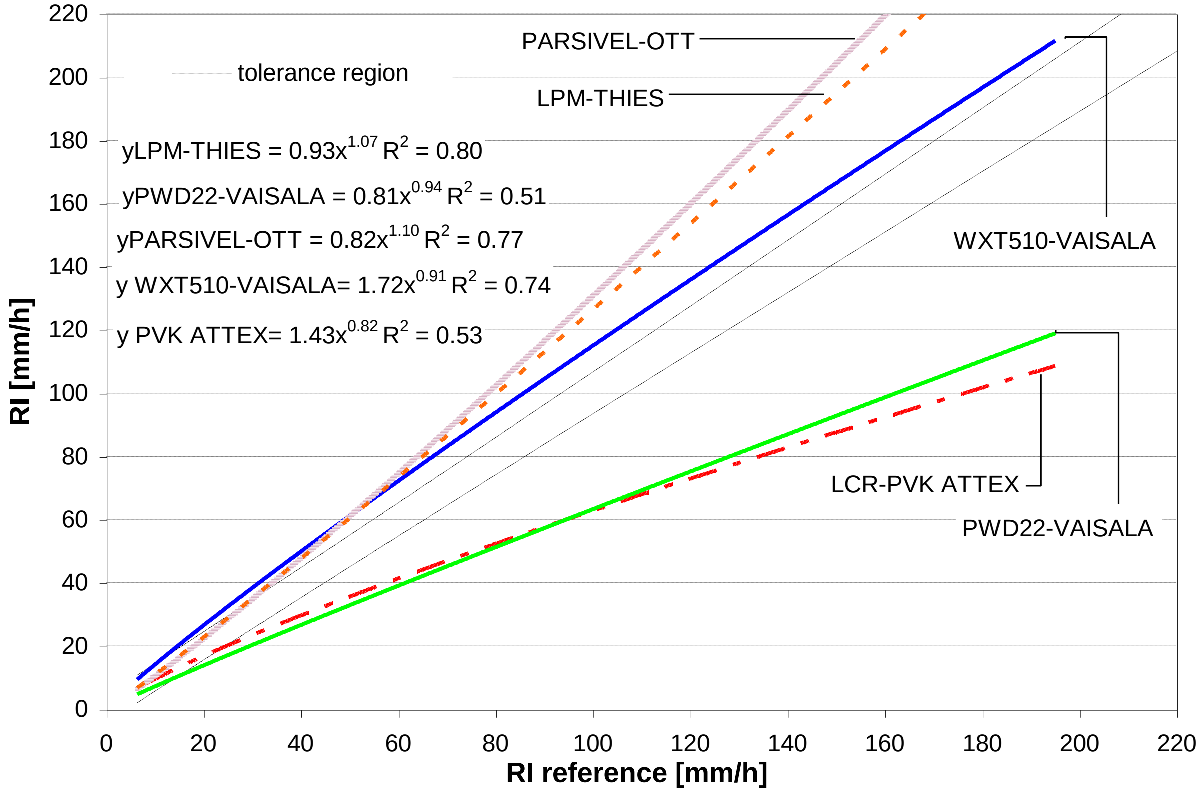


Fig. 21: Weighing rain gauges (WG)



Non-Catching precipitation sensors

Fig. 22



The previous figures, containing the power law fits and the tolerance region, can be used to compare the various rain gauges participating in the Field Intercomparison and the corresponding measurement techniques on 1-minute time scale. Through their evaluation it is possible to provide the following general conclusion: this comparison at one minute time scale in field conditions demonstrates the possibility to evaluate the performance of RI gauges. Additional remarks are provided below.

For Catching type rain gauges, the achievable accuracy of WG can be improved in field conditions by means of the reduction of the response time below 1-minute and by appropriate filtering methods.

With regard to tipping bucket rain gauges, the method applied by TBRG-SC confirms the possibility to improve the 1-min RI resolution and to provide accurate field measurements for the whole RI range experienced during the Intercomparison.

With regard to tipping bucket rain gauges, the method applied by TBRG-PC revealed the possibility to provide accurate field measurements at higher RI, even if the performance is limited by their resolution at lower RI.

The correlation coefficient R^2 of the best fit curve for VRG101-VAISALA is very low, so the fit is not representative of this sensor. The use of raw mass data, also available from the VRG101-VAISALA sensor, could improve the results. See *Vuerich et al., 2009* for more details.

For non catching type rain gauges, during the intercomparison period, the non-catching type rain gauges needed low maintenance and few periodic checks (especially for the impact disdrometers and the microwave radar), thus this kind of instruments is considered particularly suitable for automatic weather stations or generally unmanned meteorological stations. Moreover LPM-THIES, PWD22-VAISALA and PARSIVEL-OTT have the advantage to determine the type of precipitation, to distinguish between solid and liquid precipitation and to provide present weather information (METAR and SYNOP codes). For further investigations concerning these aspects, the observations of the Vigna di Valle H24 meteorological station are available to distinguish hail and rain events.

This intercomparison is the first WMO test bed where non-catching type rain sensors were compared to catching type rain gauges and to a pit RI composite working reference for the field measurement of 1-minute RI, however some analysis of RI was conducted during PREWIC Intercomparison (*Leroy et al., 2008a*)

The non-catching type rain gauges were calibrated by the manufacturers prior to the start of the intercomparison. However, since no standard calibration procedure exists which is suitable for all the involved non-catching gauges, it was not possible to perform laboratory and field calibrations of these instruments. Therefore factory calibration reports and information about calibration methods provided by manufacturers were the only sources of information available on the achievable accuracy of these instruments.

According to the results, WXT510-VAISALA, LCR “DROP”-PVK ATTEX and PWD22-VAISALA rain gauges show a non-linear behaviour compared to the RI reference in the full range or within some intensity ranges and their data are more spread than the data of other gauges. In particular: LCR “DROP”-PVK ATTEX shows a strong non-linearity above 80mm/h (1 min); WXT510-VAISALA tends to overestimate RI and has a larger spread of data above 50 mm/h. On 1 minute time scale, PWD22-VAISALA tends to underestimate RI, with large dispersion of data. On the other hand, PARSIVEL-OTT and LPM-THIES optical disdrometers show a lower spread of data, a more linear behavior in the full range and an overestimation trend. The R^2 correlation coefficients of the best fit curves for PWD22-VAISALA and LCR “DROP”-PVK ATTEX are very low, so the fits are not representative of these sensors.

This field Intercomparison has shown the need to improve calibration methods adopted for non-catching rain gauges for 1-minute RI measurements.

Wind effect

The wind effect study on the 1-minute RI measurements was performed through the comparison of identical instruments that are placed inside and outside the pit. It is important to examine possible wind induced errors only on identical instruments to avoid effects due to the different measurement principles, that are especially evident on 1-min time basis. In *Vuerich et al. 2009* a complete evaluation of wind conditions and related effects on RI measurement is provided whose conclusions are briefly reported here. The effect of the wind cannot be evaluated for low wind speed conditions because of the presence of the 1-min data dispersion mainly due to the differences of calibration between the two identical gauges. On the other hand, during this intercomparison only few rainfall events happened with moderate or strong wind (wind speed above 5 m/s) and their number do not permit a complete evaluation of wind induced losses. The reference pit gauges generally measured higher rainfall intensities than their identical gauges installed outside but a correlation/relationship between wind speed and 1-min RI reduction cannot be determined. Thus, the effect due to wind losses was impossible to be quantitatively estimated. Therefore, it can be said that, for low wind speeds, the Jevons effect weakly affected the field intercomparison RI measurement and, for moderate-strong winds (WS>5 m/s), it was more intense but without a feasible quantitative determination.

In conclusion, since a relevant effect of the wind did not appear in this intercomparison, we are able to affirm that the wind is not affecting in a significant way the outer instruments compared to those installed in the pit, and in any case the possible wind induced effects have already been considered in the tolerance region reported for each gauges. Therefore it is reasonable to compare all the instruments without wind shields.

4. Conclusions

The Field Intercomparison of Rainfall Intensity Gauges held in Vigna di Valle, Italy, was the first intercomparison of quantitative rainfall intensity measurements in field conditions and one of the most extensive in terms of the number of instruments involved.

The Vigna di Valle intercomparison site confirmed its suitability for hosting this field intercomparison due to its climatology (the maximum rainfall intensity recorded was 195 mm/h) as well as its innovative and versatile design. The latter permitted a flexible set-up of the data acquisition system in order to comply with the various output protocols of the participating instruments and allowed for time synchronization of the measurements which was fundamental for the correct data interpretation.

Laboratory tests on the participating catching-type rain gauges were performed to assess their accuracy prior to their installation in the field, based on the procedures developed during the previous WMO Laboratory Intercomparison of Rainfall Intensity Gauges. These tests were innovative since the analysis was performed at one minute time resolution. Operating in the laboratory at such a high resolution introduced some difficulties since the noise was enhanced. The laboratory simulation of high rainfall rates at a one minute resolution provided a better understanding of the intrinsic performance of the various instruments and of their ability to measure high rainfall intensity rates.

For the best quality instruments, the **achievable measurement uncertainty in laboratory**, under constant flow conditions, was found to be **5% above 2 mm/h and 2% above 10 mm/h**.

The field calibrations of catching type rain gauges was regularly performed and was based on the same method and principles as the laboratory tests. It confirmed the general stability of the instruments' calibration status, as no significant calibration drifts were detected.

It was the first time that four reference rain gauges in a standard pit were used to derive a rainfall intensity composite working reference. During the Intercomparison period, a resolution of the Technical Committee 318 ("Hydrometry") of CEN (European Commission for Normalization) was adopted in order to revise the current standard ISO/EN13798:2002 (Reference Rain Gauge Pit) to take into consideration the experiences gained during this intercomparison. The outcome of the enquiry of the proposed revision by the European Members was published on 18th June 2009 by CEN, reporting no objections. The revised document would become the new ISO/EN13798 standard, and would be available in summer 2010. Following the publication of this standard, the relevant WMO regulatory material should be updated.

One of the most challenging aspects of the Intercomparison was the definition of a 1-minute field reference precipitation intensity. The reference rainfall intensity was calculated with weighted values of individual gauges in the pit and its uncertainty was evaluated. This procedure confirmed the suitability of R102-ETG, PMB2-CAE and T200B-GEONOR for the calculation of the reference.

The results of the intercomparison confirmed the feasibility to measure and compare rainfall intensities on a one minute time scale as required by users and recommended by CIMO and provided information on the achievable measurement uncertainties.

The rainfall intensity is highly variable from minute to minute. The correlation between two successive 1-minute rainfall intensity measurements is very low and much lower than the correlation between two different instruments that are well synchronized. Therefore, the time synchronization of the instruments is crucial to inter-compare their measurements and to design the measurement systems.

The wind effect was found to have a minor influence on the results primarily due to the low wind speeds observed during the precipitation events.

In **field conditions**, the **uncertainty of** the rainfall intensity composite working **reference** in the pit was evaluated to be **4.3 mm/h**. Consequently, the **relative uncertainty of the reference was found to be below 5% only for intensities above 90 mm/h**. Below 90 mm/h, the relative uncertainty of the reference values was higher than the 5% required measurement uncertainty provided in the CIMO Guide.

The Meeting of Participants and Local Staff (Vigna di Valle, 21-22 May 2008) was fundamental for the success of the intercomparison. In particular, it allowed to confirm that the rain gauges were operated according to the recommended procedures and permitted to achieve the best possible data quality and instrument synchronization.

As previously found in the Laboratory Intercomparison, corrected Tipping Bucket Rain Gauges (TBRGs) performed better than uncorrected ones. The correction could be achieved either by electronically adding an extra pulse or by software based correction. The present laboratory and field results confirmed that software correction is the most appropriate method for the correction of TBRGs. Very good results with respect to linearity, resolution enhancement and noise reduction could be achieved.

Catching gauges that do not use a funnel are sensitive to external factors, like wind and splash, which could affect the measurements. As a consequence, their noise level is generally increased in comparison to gauges using a funnel. The necessary filter algorithms for noise reduction could introduce a delay, longer time constants or other effects on the RI output. However, proper techniques could be used to reduce the noise in the measurements without introducing a delay and/or a longer time constant.

Some rain gauges provided output data telegrams containing additional values (e.g. raw mass) that could be used to improve the RI measurements.

The best performing weighing gauges and TBRGs were found to be linear over their measurement range. However, weighing gauges generally cover a wider range.

None of the non-catching rain gauges agreed well with the reference.

Disdrometers tended to overestimate the rainfall intensity. Despite their very different calibration procedures, they agreed better to each other than to the reference. This indicated that they had a good degree of precision but were not as accurate as conventional gauges.

The microwave radar and the optical / capacitive sensors tended to underestimate the rainfall intensity.

For this intercomparison quality control and synchronization procedures were developed to ensure the high quality of the intercomparison data. These one-minute data would be available for further analysis.

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