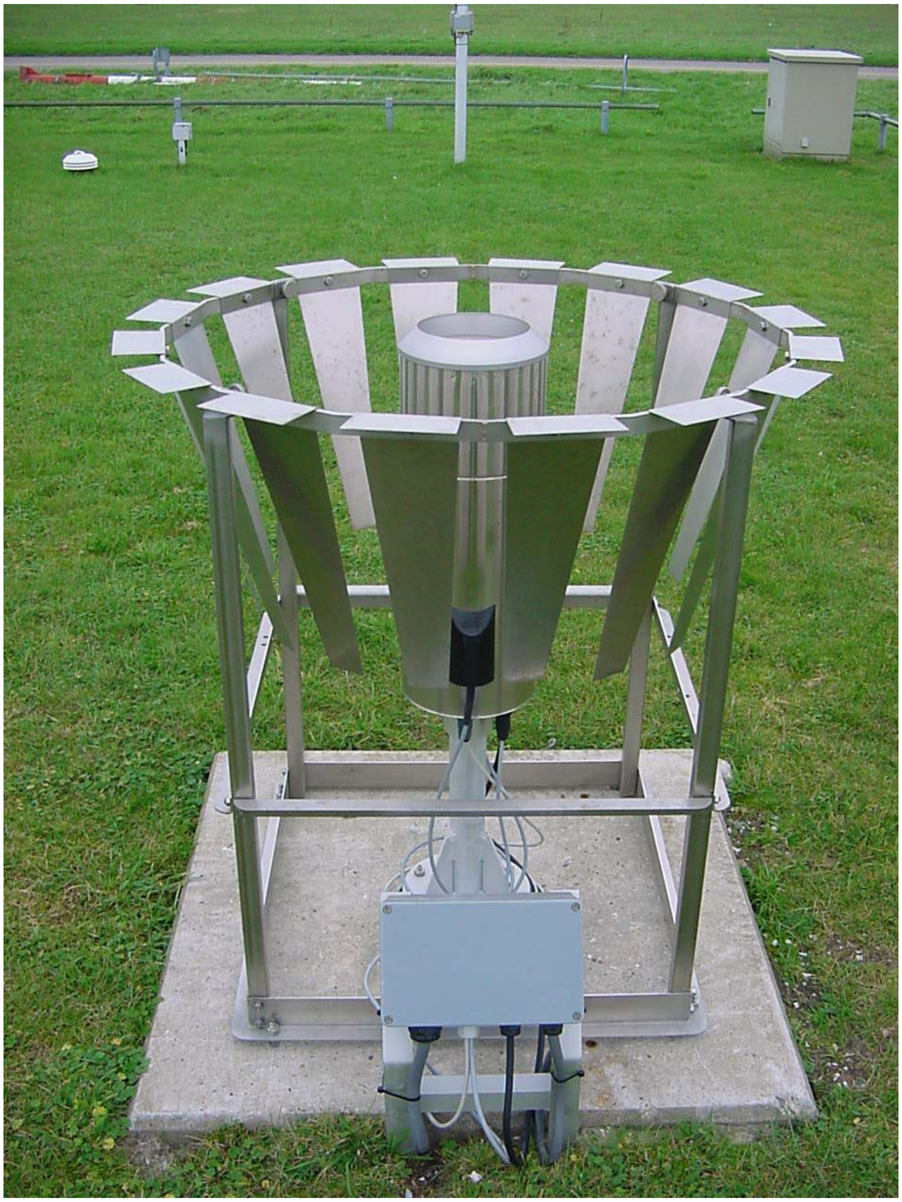
Precipitation amount and intensity measurements with the Ott Pluvio



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1. Introduction

The Royal Netherlands Meteorological Institute (KNMI) performs routine precipitation amount measurements at nearly all its automated weather stations and also on the meteorological sites of the Royal Dutch Air force. An electronic precipitation gauge that has been developed by KNMI performs these measurements automatically. The design of this sensor originates from 1991 and since then it has undergone no changes. The sensor is of the so-called float type and determines the precipitation intensity by the change of the water level in a reservoir as measured by a potentiometer per time interval. A more detailed description of the KNMI precipitation gauge is given in Wauben (2004).

The KNMI precipitation gauge has some shortcomings as a result of which KNMI is interested in the performance of new sensors suitable for precipitation amount measurements. The shortcomings are:

- The gauge gives faulty precipitation reports. This is a result of the sensor being very sensitive due the requirements regarding precipitation detection. As a consequence the KNMI gauge is susceptible to faulty reports. This occurs at sunny days, probably due to uni-directional heating of the gauge, and results in isolated faulty precipitation reports up to about 0.018mm/h.
- The gauge often requires additional maintenance since the sensor is sensitive to contamination due to debris falling into the funnel. This debris can prevent or delay the precipitation reaching the reservoir, and hence can lead to losses due to evaporation of the precipitation in the collector. In addition, the debris can, by blocking the shutter, cause a leakage after emptying the reservoir. The sensor interface checks for this and reports an alarm when the level in the reservoir decreases too fast when the shutter is closed.
- The gauge reports solid precipitation with some delay. The solid precipitation falling into the funnel has to be melted before the gauge can register it. For this purpose the funnel is heated, but this heating cannot be too large because that would result in a loss by evaporation.

Figure 1 shows an example of the faulty precipitation reports of the KNMI rain gauge (top) and the delayed registration of solid precipitation (bottom). Both figures show daily plots of the 1-minute averaged precipitation intensity measured by the KNMI precipitation gauge, the Vaisala FD12P present weather sensor and the Ott Pluvio precipitation sensor in De Bilt. The precipitation intensity values of the three sensors are plotted with a vertical offset in order to separate the curves. The precipitation duration measured by an Eigenbrodt precipitation detector is indicated in the figure as well. On July 22, 2001 all sensors report some precipitation at midnight, but later that day the precipitation detector observes no precipitation. The Pluvio and the present weather sensor agree, but the KNMI precipitation gauge reports several precipitation events around local noon. These reports under sunny conditions are mostly isolated events of 0.006mm/h, the resolution of the KNMI precipitation gauge. In the current operational data processing in the central 10-minute database these faulty cases are ‘corrected’ to zero. Also the current operational precipitation duration determination, which since the end of 2001 is performed by the KNMI precipitation gauge instead of the Eigenbrodt precipitation detector, requires at least 2 12-second intervals with precipitation in the past 5 minutes in order that it considers the interval with precipitation. The measurements of December 30, 2000 shown in the bottom panel of Figure 1 are performed during snow. Clearly the KNMI precipitation gauge reports precipitation whereas the other 3 sensors indicate that the precipitation already stopped. This occurs e.g. between 2 and 3UT and around 8UT. This is the result of snow accumulated in the collector that slowly melts and is reported as precipitation. The measurements show that this can lead to a delay of more than one hour. The measurements of the Pluvio were performed using an old software version that sometimes gave faulty precipitation reports, e.g. the reports between 18 and 20UT. This occurred mainly when the heater in the rim of the Pluvio sensor was in use.

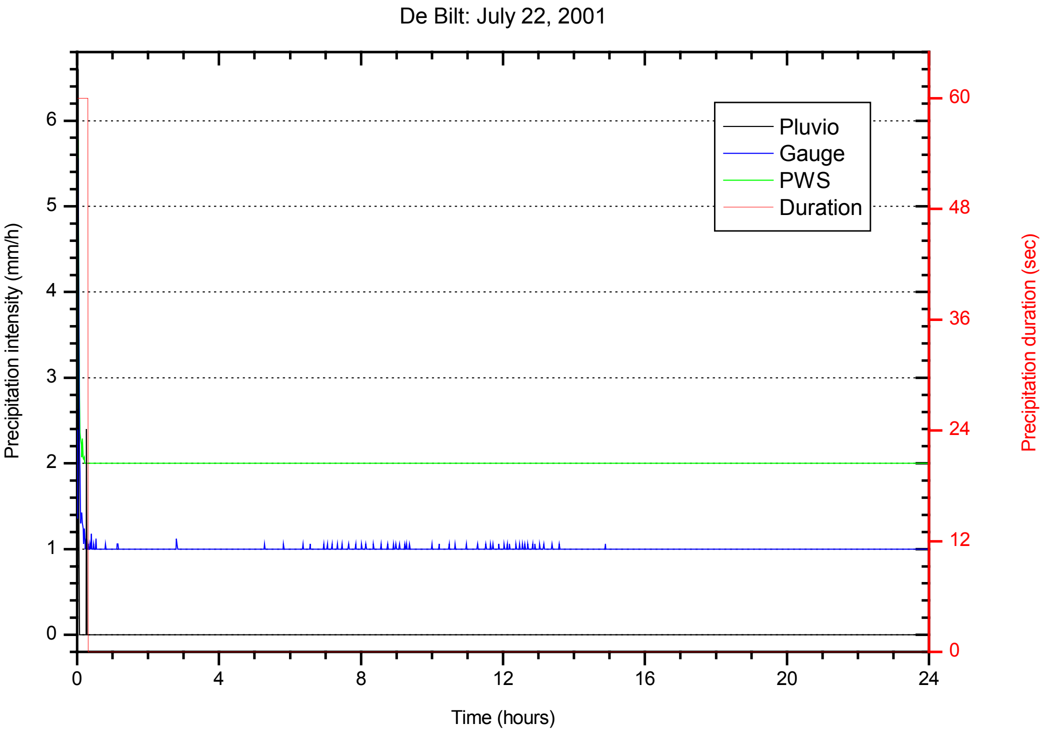

Figure 1: Daily plots of 1-minute precipitation intensity (mm/h) observed by the KNMI gauge, the Pluvio and the present weather sensor. The precipitation duration as reported by a precipitation detector is also shown. The top panel shows a typical example for a sunny day with faulty precipitation reports by the KNMI precipitation gauge; the lower panel shows the results for a day with solid precipitation.

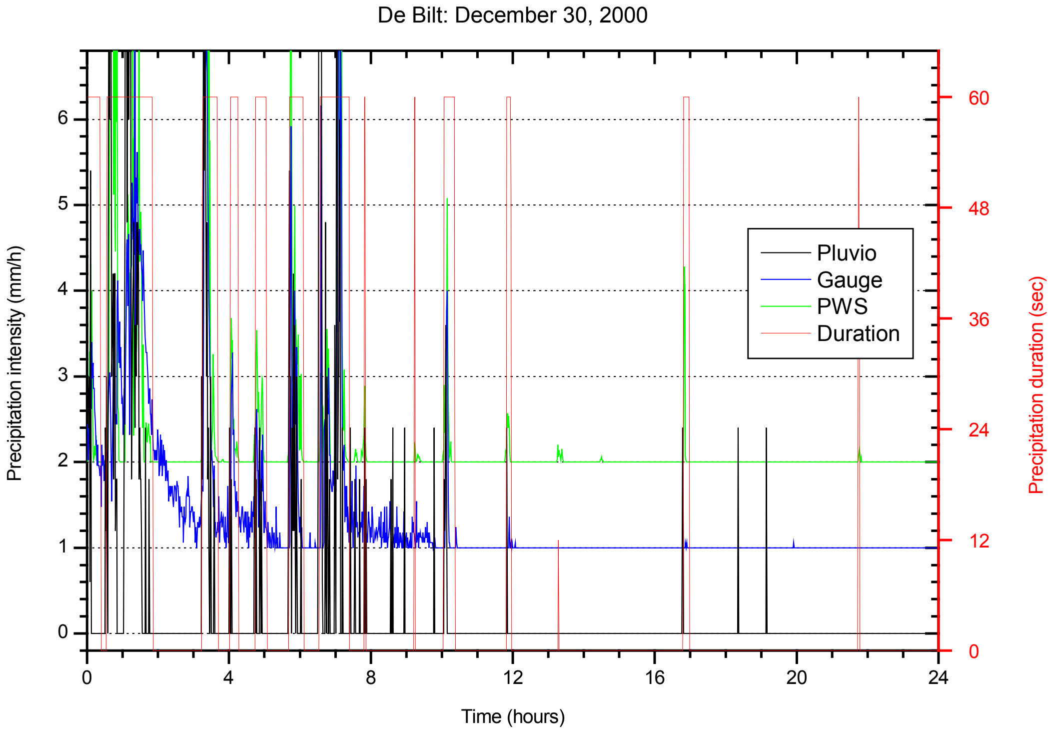

Figure 1: Lower panel.

As a result of the shortcomings of the KNMI precipitation gauge mentioned above, KNMI performed tests with the new Pluvio precipitation sensor from Ott Hydrometrie. The sensor is of the weighing type and hence could be less susceptible to contamination and will detect solid precipitation directly. Tests with the Ott Pluvio performed by e.g. the Deutscher Wetterdienst (Dibbern, 1999) and the U.S. Geological Survey (Gordon, 2003) suggested that the sensor could be a good alternative for the KNMI precipitation gauge. KNMI decided to test the new Pluvio precipitation sensor and to compare the results with that of the KNMI precipitation gauge. The tests are performed in the laboratory as well as during 1-year field trails performed at the KNMI test site in De Bilt and the coastal station at De Kooy. The aim of the tests performed with the Pluvio by KNMI is to investigate how the precipitation amount and intensity measurements of the Pluvio and the KNMI precipitation gauge compare in order to indicate whether the Pluvio is suitable for being considered for operational use by KNMI.

2. Precipitation sensors

In this section a brief description of the precipitation sensors considered in this investigation is given. First the operational precipitation gauge used by KNMI is discussed as well as the precipitation detectors. Next some details are given of the Pluvio precipitation sensor. Lastly the main differences are addressed.

2.1. KNMI precipitation sensors

KNMI uses an electronic precipitation gauge that has been developed indoors for the precipitation amount measurements at automated weather stations. The KNMI precipitation gauge is of the so-called float type and determines the precipitation amount and intensity from the observed change of the water level in a reservoir. More details are given in Wauben (2004). The sensor has been designed for measuring precipitation amounts with a 2% full-scale accuracy and a resolution of 0.006mm/h. The smallest reporting interval is 12 seconds, although generally the 10-minute averaged intensity is the basic quantity that is used for the calculation of hourly and daily precipitation sums.

Originally the precipitation gauge was operated in combination with an Eigenbrodt precipitation detector. The detector was used for determination of the precipitation duration. Furthermore, the results of the precipitation gauge and precipitation detector where combined in the coding of the meteorological reports in order to overcome faulty and inconsistent sensor readings. In 2001 KNMI ended the precipitation duration measurements by precipitation detectors and since then the precipitation gauge is used to determine the precipitation duration as well, although the gauge is less sensitive than the detectors. The sensor interface (Bijma, 1995) determines the presence of precipitation every 12 seconds by checking if the gauge reported at least 2 precipitation events in the past 5 minutes with an averaged intensity exceeding 0.05mm/h. The rain gauge being less sensitive compared to the precipitation detector, reports less precipitation events, but the summed precipitation duration is overall the same for both sensors when using the algorithm for the precipitation gauge mentioned above.

At locations where KNMI operates a so-called Present Weather Sensor (PWS), the FD12P sensor of Vaisala, the precipitation duration is determined from this sensor. Specifically, the sensor interface of the FD12P considers a 12-second interval having precipitation when the running 1-minute averaged precipitation intensity reported by the sensor is above 0.03mm/h. This threshold was determined by tuning of the precipitation duration to the duration reported by the Eigenbrodt (cf. Kuik, 2001).

2.2. Pluvio precipitation sensor

The Pluvio precipitation sensor of Ott Hydrometrie determines the precipitation amount and intensity based on the weighing principle (Ott Hydrometry, 2000). The sensor is of the so-called Hellmann form (cf. WMO, 1989) with a housing diameter of 210mm and a height of 570mm (cf. Figure 2). The collecting area is 200cm^2. The rim of sensor has a width of 30mm and falls off outwards with an angle of 40°. The collecting ring is heated in order to avoid snowcaps. The precipitation falls directly into a collector with a capacity of 250mm and is measured by an electronic weighing cell. The load cell is hermetically sealed against atmospheric pressure and contamination. The resolution of the sensor is 0.01mm and the maximum reported precipitation intensity is 50mm/min. The absolute measuring error is less than 0.04mm (for a 10mm precipitation amount) and the long-term (12months) stability is better than 0.06mm. The operating temperature range of the Pluvio is –30 to +45°C. The Pluvio precipitation sensor is supplied with an integrated data logger that allows data transmission via a serial protocol (RS232 and RS422). The data telegram gives amongst other information the actual collector contents (mm); the 1-minute averaged precipitation intensity (mm/min); the 6-second averaged ambient temperature measured within the sensor (°C); and status information such as whether the housing of the sensor is closed, or the collector contents is above 80%, or the calculated precipitation intensity is deemed to be not due to precipitation, and reports the quality of the measurement. The sensor uses a filtering algorithm for calculating the precipitation intensity. The algorithm uses the raw 6-seconds measurements of the sensor and eliminates the wind effect and also compensates any temperature dependence of the weight measurements. The precipitation intensity in the output telegram is updated once a minute. The algorithm can introduce a delay of maximally 90 seconds. The sensor employs a detection threshold of 0.03mm over the last 20 minutes. This means that the sensor will not report precipitation amounts less than 0.03mm in 20 minutes (i.e. averaged intensities less than 0.09mm/h). Starting precipitation will be reported when 0.03mm is exceeded. Higher precipitation amounts are reported with a 0.01mm resolution, as are small precipitation amounts once the 0.03mm level is exceeded in a 20-minute time interval.

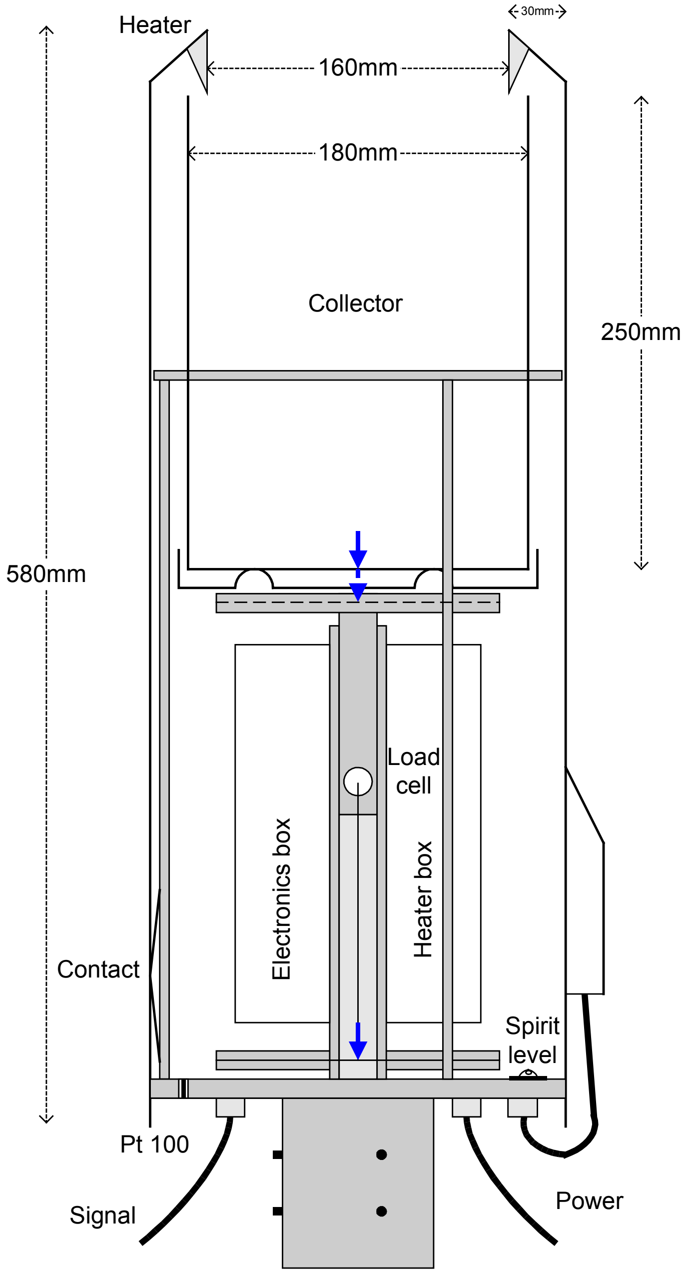

Figure 2: Schematic drawing of the Pluvio precipitation sensor from Ott with an indication of the main sensor parts and its dimensions.

2.3. Comparison of sensors

An overview of the main sensor characteristics for both precipitation sensors is given in Table 1. The reported specifications for both sensors meet the criteria of WMO (WMO, 1996). Comparison of the main characteristics of the Pluvio precipitation sensor and the KNMI electronic precipitation gauge already point out some interesting differences. The Pluvio precipitation sensor will measure solid precipitation without delay since the precipitation that has passed the orifice will directly fall into the collector bucket and will be measured. This will overcome the delays and possible evaporation losses the KNMI precipitation gauge might experience during solid precipitation. However, the filtering algorithm of the Pluvio can give a delay of maximally 90 seconds. A further advantage of the Pluvio precipitation sensor is that the sensor is less sensitive to contamination. In case any contamination by insects, leaves, dust, bird excrements, etc. falls in the collector, it could result in a faulty precipitation event -although the sensor filters out the very low (less than 0.03mm in 20minutes) and very high (more than 50mm per minute) contributions- but it will not lead to sensor failures. A Pluvio sensor is available with an automatic emptying mechanism in an extended 1m high housing. This sensor automatically empties the collector when it is nearly full. However, tests performed by KNMI showed that the emptying occurred only when the collector was almost full. KNMI did not select that version of the sensor for further tests because of the potential danger of wind-induced overflow and/or splash out of precipitation. Therefore KNMI has no experience regarding possible contamination or blocking of the emptying mechanism. Another advantage of the Pluvio is that it can easily be calibrated by using a set of reference weights whereas the KNMI precipitation gauge of the float type involves the use off fixed (weighed) amounts of water.

Drawbacks of the Pluvio sensor are the lesser sensitivity compared to the KNMI precipitation gauge and the additional maintenance required for emptying the bucket and the required application of a saline solution to the collector at the start of the winter season in order to prevent deformation or damage. The reduced sensitivity of the Pluvio makes the sensor less suitable for the determination of precipitation duration as is illustrated in Figure 3, which shows the measured precipitation intensities for all 3 sensors during a day with a long period of continues light snow. The precipitation reports of the Pluvio come generally as individual events whenever the threshold of 0.03mm (0.03/min=1.8mm/h) is exceeded, whereas the KNMI precipitation gauge and the PWS almost continuously report precipitation. Note that the Eigenbrodt precipitation detector, which at that time was in use in De Bilt, also gives significantly lower precipitation duration. The total daily precipitation amounts measured by the 3 sensors are 2.6, 2.1 and 1.7mm for Pluvio, gauge and PWS, respectively. The differences in the daily precipitation amount reported by the Pluvio and the KNMI gauge could be caused by evaporation of precipitation in the collector of the gauge.

Table 1: An overview of the general characteristics of the Pluvio precipitation sensor and the KNMI precipitation gauge.

Parameter	***Pluvio***	***KNMI gauge***
Range	0 … 10mm/min	0 …10mm
Accuracy	±0.04mm@10mm	±2% full scale
Reproducibility	±0.04mm@10mm	within ±1% full scale
Long-term stability (1yr)	±0.06mm@10mm	within ±2% full scale
Resolution	0.01mm/h	0.006mm/h
Sensitivity	0.03mm/20min	0.001mm/10min
Maximum intensity	600mm/h	300mm/h
Averaging time	30-90sec[1]	12sec
Collector content	0-200mm	1-11mm
Temperature range	–30 … +45°C	–25 … +40°C
MTBF	3500h[2]	26500h[3]
Calibration interval	+1year	36months
Maintenance	1 p.a. antifreeze 2-3 p.a. emptying	Covering of orifice during mowing
Collector area	200cm^2±0.5%	400cm^2±0.5%
Diameter sensor	210mm	226-284mm
Height sensor	570mm	610mm
Weight	6kg	19kg
Voltage sensor	12VDC	24VAC
Power usage sensor	<1.8W	3.6W
Voltage heater	24VAC	24VAC
Power usage heater	70W	115W
Communication interface	RS232/RS485	Frequency output

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[1] Depending on the variability of the raw weight measurements the averaging time may be as high as 400sec.

[2] During the field test one sensor was operated over the period February 2001 to August 2003 resulting in a MTBF of 22000h.

[3] Calculated from the error reports of 35 operational KNMI precipitation gauges for the period March 2000 to June 2004. Note that cases of contamination and cases where the quality of the measurements was seriously doubted, although inspection and pre-calibration did not reveal any problems, are included.

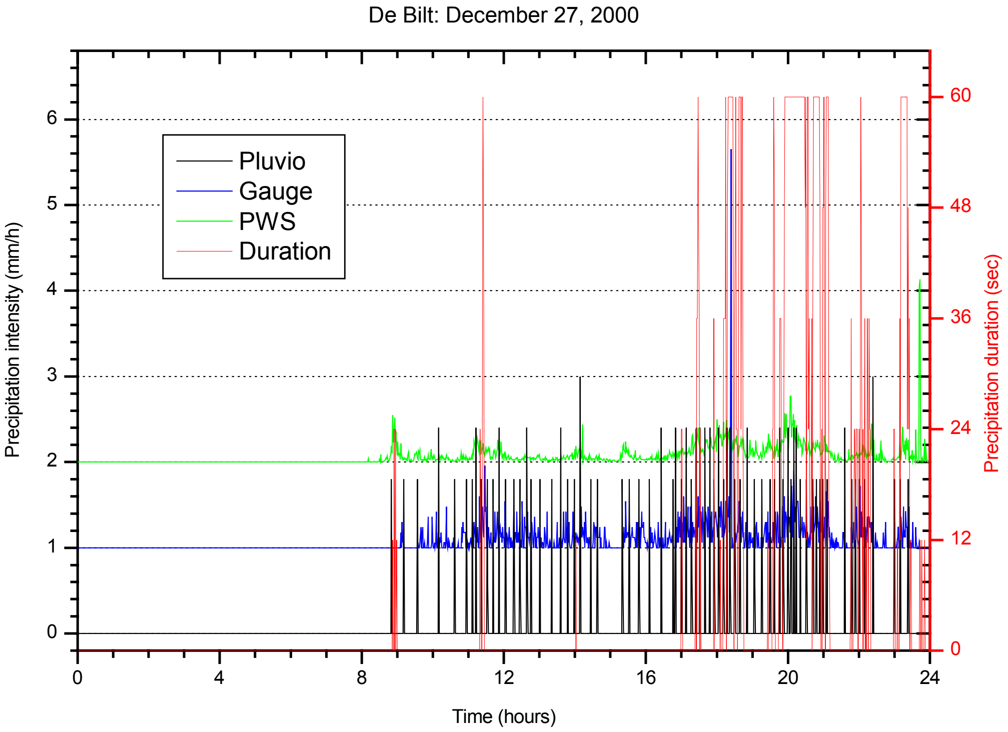

Figure 3: Daily plot of 1-minute precipitation intensity (mm/h) measured by the KNMI gauge, the Pluvio and the present weather sensor on December 27, 2000 in De Bilt. The results illustrate the measurements during a long period with low precipitation intensities.

3. Laboratory tests

In this section the results of the laboratory tests are discussed. These tests consist of tests where: (a) precipitation is simulated by pumping an adjustable rate of water in the collector; (b) the behavior of the sensor is investigated in a temperature chamber; (c) the check of the calibration at the start and at the end of the field test. The results of these tests are discussed in the next sections. At all times the tests were performed by using calibrated weights or by comparison with a calibrated balance. The data-acquisition of the Pluvio data telegrams was always performed with the software package that was also used during the field tests.

3.1. Preliminary tests

The Pluvio precipitation sensor was first subjected to some indoor tests. These tests started in 1999. The Pluvio sensor that was considered at that time did not include the data logger but used a pulse output. Furthermore the sensor was equipped with the automatic emptying mechanism. Tests were performed with an adjustable pump and a balance so that the amount of water pumped into the collector of the Pluvio could be regulated and determined. The results of these tests will not be discussed in detail here because since then changes were made to the sensor/software and finally KNMI selected the Pluvio sensor with the data logger and serial interface and without the automatic emptying mechanism for further tests including a 1-year field test. The results of the preliminary tests performed at KNMI were:

- The automatic emptying did not work satisfactory. Emptying occurred only when the collector was almost full. Hence there is a potential danger of wind-induced overflow or of splashing out during precipitation events. This problem remained even after the manufacturer made some modifications to the emptying mechanism. KNMI decided to perform further tests with the Pluvio without the automatic emptying mechanism.
- Sometimes the pulsed output of the sensor bounced and reported wrong precipitation rates. The serial output does not have this problem.
- At first the sensor could reach its upper limit so that it did not report any additional precipitation anymore. The manufacturer solved this problem by a readjustment of the sensor.
- The sensor at some intervals did not report precipitation although water was constantly pumped into the collector. The manufacturer solved this problem.
- Some test results at first looked strange, but could be explained by the, at that time undocumented, features of the software. These were the minimum reporting threshold of 0.03mm in 20 minutes and the delay in the reported precipitation intensity and sum generally up to 90 seconds, but of maximally 5 minutes at noisy situations e.g. during high wind turbulence.
- The test results showed generally good agreement, but at low precipitation rates the effect of evaporation have to be taken into account. Sometimes too large discrepancies were observed related to problems mentioned above or that were induced by the wind, leading to vibration and variations of the measured weight. The

latter problem was improved in a new software release. But even then, preliminary results of the field test showed that the problem was not entirely solved. There also remained some faulty sensor reports of precipitation during periods when the heater of the rim was in use. A clear example of this is given in Figure 4, which shows the 1-minute averaged precipitation amounts measured by the 3 precipitation sensors in De Bilt. The figure also indicates by the blue symbols the status of the heater of the rim of the Pluvio. The Pluvio shows several cases of faulty precipitation reports, but not around noon when the heater was not switched on.

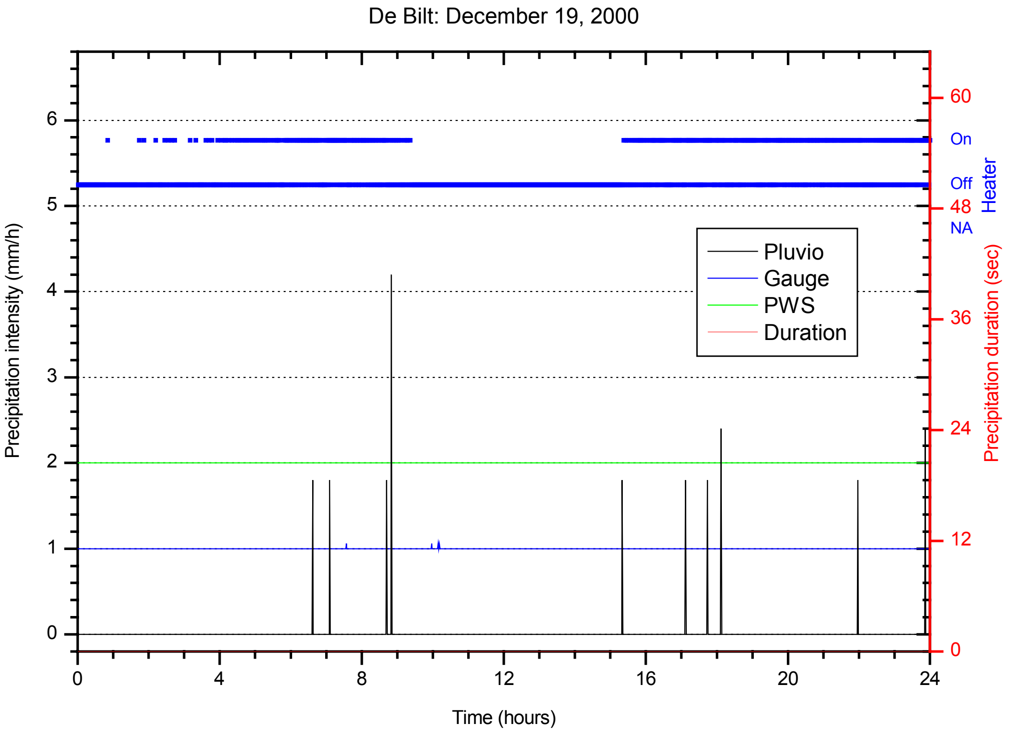

Figure 4: Daily plot of 1-minute precipitation intensity (mm/h) measured by the KNMI gauge, the Pluvio and the present weather sensor on December 19, 2000 in De Bilt illustrating the former faulty reports by the Pluvio during periods when the heater was on.

The results described in the remaining part of the report are based on the Pluvio precipitation sensor without the automatic emptying mechanism and equipped with the Ott-log data logger. These results were all obtained after a software upgrade (release 2.13) that was performed end of January 2001.

3.2. Temperature tests

A Pluvio sensor was subjected to a temperature test in the climate chamber of KNMI. These tests were performed in October 2003 with sensor 391 after completion of field test. Note that both field tests were mainly performed with sensor 391, which therefore was used outdoors for more than 2 years, whereas the other sensor was used outdoors for nearly 6 months, and during the rest of the time it was in storage. During the temperature tests an empty collector was used in order to eliminate any effects by evaporation. The temperature of the climate chamber was changed manually in steps while the Pluvio sensor was polled continuously every 12 seconds. After setting a new temperature of the climate chamber, the chamber takes some time in order to reach the new temperature, while the temperature of the Pluvio lags behind. A new temperature setting was set after the Pluvio temperature reached the setting of the chamber and was stable. During this process the temperature of the chamber was not logged and the relative humidity not forced. No condensation was observed during the tests. The relative humidity of the chamber was noted before a change was made to a new setting. The climate chamber operates a fan when the temperature is adjusted. This gave a wind flow over the orifice of the Pluvio that can be seen in the quality parameter. However, in such situations the quality parameter was maximally 40 and the measurements are considered valid. An overview of the temperature tests is given in Table 2.

Table 2: Results of the temperature tests with a Pluvio precipitation sensor 391. Listed as a function of time is the relative humidity at which a newly set chamber temperature was reached and the temperature gradient and quality parameter when a faulty message or precipitation event was reported by the Pluvio.

Time	***Temperature***	***Information***	***Comment***
8:45	Chamber at +21°C	RH=30%	Start at room temperature
9:09	Sensor at 10°C	ΔT_{sensor}=0.9°C/min	Sensor reported 0.07mm with Q=013
9:10	Sensor at 9°C	ΔT_{sensor}=0.9°C/min	Sensor reported 0.01mm with Q=011
9:20	Sensor at 1°C	ΔT_{sensor}=0.75°C/min	Sensor reported 0.06mm with Q=022
9:34	Sensor at –8°C	ΔT_{sensor}=0.5°C/min	Sensor reported 0.06mm with Q=025
10:59	Chamber at –20°C	RH=75%	
12:07	Chamber at –10°C	RH=90%	
13:19	Chamber at 0°C	RH=95%	
14:46	Chamber at 10°C	RH=95%	
16:04	Chamber at 20°C	RH=75%	
17:07	Chamber at 30°C	RH=40%	
18:27	Sensor at 44°C	ΔT_{sensor}=0.1°C/min	Sensor reported 0.06mm with Q=214*
18:40	Chamber at 45°C	RH=15%	Chamber switch off/open
19:06	Sensor at 39°C	ΔT_{sensor}=–0.2°C/min	Sensor reported 0.11mm with Q=013
7:10	Chamber at +25°C	RH=30%	Start at room temperature
7:36	Sensor at 10°C	ΔT_{sensor}=1.0°C/min	Sensor reported 0.03mm with Q=012
7:37	Sensor at 9°C	ΔT_{sensor}=0.9°C/min	Sensor reported 0.01mm with Q=015
7:49	Sensor at –0°C	ΔT_{sensor}=0.5°C/min	Sensor reported 0.06mm with Q=007
9:14	Chamber at –10°C	RH=59%	
10:28	Chamber at +5°C	RH=95%	Chamber switch off/open

The tests showed that the Pluvio sensor reported some small amounts off faulty precipitation when cooling from room to freezing temperature. The cases occurred around 10°C and 0°C. However, the rate of change in during these tests of maximally about 1°C per minute was very large. The changes in temperature of the sensor observed during the field test at De Bilt were between –3.0°C/10min and +3.5°C/10min and at De Kooy between –2.7°C/10min and +2.8°C/10min. According to the specifications of the

Pluvio the sensor has been subjected to a temperature gradient of 2.5°C/hour and should have a temperature coefficient within ±0.005mm/°C. Since the sensor uses a reporting threshold of 0.03mm/20min, a temperature gradient of ±6°C/20min and hence ±3°C/10min should not result in faulty precipitation results. This maximally allowable gradient is near the maximum temperature gradient observed during the field test. A future temperature test should be performed around such a temperature gradient.

One further interesting point is that when the temperature of the sensor slowly increased above 44°C the sensor also reported faulty precipitation. However, this corresponds with a situation where the sensor reports a bad quality. Even when the chamber was switched off so that ventilation stopped and the chamber was opened to allow the temperature to drop the quality remained poor, but without further faulty precipitation events. Only when the temperature of the sensor dropped below 40°C the sensor resumed normal operation, but at 39.4°C another faulty precipitation event occurred. It should be noted that such faulty precipitation events did not occur during the field tests. The maximum temperature reported by the sensor during the field test at De Bilt and De Kooy was, respectively, 35.7 and 33.3°C. The maximum observed sensor temperature of 35.7°C is about 5 degrees below the maximum operating temperature of the sensor. This seems acceptable for use in the Netherlands, but could cause a problem in warmer regions.

3.3. Calibration checks

The manufacturer performed a calibration at KNMI at the end of January 2001, i.e. before the upgraded Pluvio sensors were placed in the field. The calibration uses a weight of 0.45kg, which corresponds to an empty collector bucket, and a weight of 4kg, which corresponds to 200mm precipitation i.e. 80% level of collector, and an alignment tool that places the weight exactly in the middle. Before the calibration, as well as during the checks that were performed later, the sensor itself was aligned using the spirit level on the instrument. Furthermore, the calibration and the checks were performed at a constant room temperature and there was no wind disturbance. The quality parameter reported by the sensor is checked during the calibration and any measurement with a quality value 20 above is disregarded. During the calibration a linear correction is applied to the weight measurement. Only a relative calibration of the weight increase is required for the precipitation calibration. However, the absolute calibration should not be too far off, because otherwise the warning limit when the collector bucket is 80% full is not good anymore. After the calibration the same weights, in fact 2 weights of 2kg were used, were used to check the results. Adding 2kg to the empty collector resulted in an increase of the collector contents of 99.99 and 100.05mm for sensors 389 and 391, respectively. Adding 4kg corresponded with amount of 199.95 and 200.01mm for sensors 389 and 391, respectively. Hence the check gave results within ±0.05mm when adding 100 or 200mm. These results are within the specification of the manufacturer, i.e. a linearity of ±0.02mm and an accuracy of ±0.04mm when adding 10mm.

Table 3: Results of the weight calibration check of both Pluvio precipitation sensors after the field test. Reported is the change in container content with respect to the empty collector for weights of 0, 1, 2, 3, and 4kg, and the change with respect to these weights when adding 20 and 50g. Note that 1kg corresponds to 50mm.

Weight (g)	***Change 391 (mm)***	***Change 389 (mm)***
0	0.00	0.00
+20	1.00	1.00
+50	2.50	2.50
1000	50.035	50.02
+20	1.00	1.00
+50	2.50	2.50
2000	100.00	100.005
+20	1.00	1.00
+50	2.50	2.50
3000	149.935	149.965
+20	1.00	1.01
+50	2.49	2.49
4000	199.915	199.92
+20	0.99	1.00
+50	2.49	2.48

Some more checks of the calibration were performed by KNMI in October 2003 after the field tests were completed. For that purpose the sensors were placed in the calibration facilities of KNMI and different weights were used. The calibrated balance of the laboratory with an accuracy of 0.1g was used to measure the weights before and after they were placed in the collector. The weights considered were 0, 1, 2, 3 and 4kg, and with each of these weights in the collector small weights of 20 and 50g were added. The tests were performed at room temperatures between 21.5 and 22.7°C. During the test the Pluvio precipitation sensor was polled by a PC every 12 seconds and the data telegram stored. After changing the weights at least 2 minutes waiting time was inserted so that the sensor reports the correct new collector content. The weights were placed directly in the collector. When the 4kg weight was placed as much a possible to one side of the collector, the change in the collector content of 200mm was reduced by –0.1mm, but by placing the weight by eye as good as possible in the center the reproducibility of the container contents was ±0.02mm. The results of the tests are given in Table 3. The table shows that for all five collector contents between 0kg (empty) and 4kg (80% full) considered, the addition of 1 and 2.5mm is accurate within ±0.01mm, i.e. the resolution of the Pluvio. Only at 4kg+50g for sensor 389 the difference is –0.02mm. The container contents measurements of 1, 2, 3 and 4kg give a small difference, which can almost by explained by a difference in the slope. At 100mm (2kg) the measurements are correct, but for 50mm (1kg) the Pluvio gives slightly larger values of about +0.03mm, whereas for 150mm (3kg) and 200mm (4kg) the Pluvio results are, respectively, lower by about –0.05 and –0.08mm. However, all these differences are within the stated long-term accuracy of ±0.06mm when adding 10mm, and the accuracy required by WMO (1996), i.e. ±0.1mm for precipitation sums less than 5mm and ±2% for larger amounts. The uncertainty requirements for precipitation intensity measurements as proposed by a WMO expert meeting (WMO, 2001) are also met by the sensor, as is the minimum time resolution of 1 minute. The proposed range for intensity measurements of 0.02 to 2000mm/h is not met by the sensor, which has a range of 0.1 to 600mm/h. However, the intensity range of 0.02 to 0.2mm/h is required for precipitation detection for present weather observations only, and intensities higher than 300mm/h do not occur in the Netherlands and are also not reported by the KNMI gauge.

4. Field test setup

The field tests with the Pluvio precipitation sensor have been performed between February 1, 2001 and May 16, 2002 in De Bilt and between May 25, 2002 and August 11, 2003 in De Kooy. At both locations the Pluvio was placed on the measurement field in a windscreen, whereas the KNMI precipitation gauge was installed in the so-called English setup. The windscreen used in this study is of the so-called Tretyakov type (Dover and Winans, 2002) and is manufactured by Ott. The Pluvio sensor is placed in the center of the screen such that the rim at the sensor is at the same level as the windscreen. Both the screen and the Pluvio are placed on a concrete slab and are aligned horizontally. Details of the English setup and a comparison between precipitation amounts and intensities obtained with KNMI precipitation gauges in the English setup and on the measurement field within an Ott screen are given in Wauben (2004). The data of the operational KNMI precipitation gauge was acquired through the meteorological network. However, during the period of the field test a change was made to a new meteorological network on November 20, 2002. Up to November 2002 10-minute data was acquired in the time window H+05 tot H+15 etc. whereas the new network uses H+00 to H+10, hence there is a change of 5 minutes in the time window. Furthermore, before November 2002 the climatological KLIM report was made manually every hour with data up to H-10, where the observer could alter the sensor values, but afterwards the KLIM report was made fully automatic at H+00. In addition, the KLIM precipitation data before November 2001 also used the results of the precipitation detector in order to correct faulty precipitation reports by the gauge and detect situations with traces of precipitation. The situation at De Bilt is further complicated because the KLIM reports at that site were already fully automated between July and November 2002, but using the old measurement network with a time window closing at H-05. The data stored is the 10-minute averaged precipitation intensity of the KNMI gauge, the precipitation duration, and some additional parameters like the 10meter wind speed and direction, ambient temperature and humidity. Furthermore, precipitation intensity data from a Vaisala FD12P present weather sensor was archived.

The Pluvio precipitation sensor of Ott was connected to a PC and polled every 12 seconds. The data telegrams in combination with a time stamp of the PC were stored in daily files. Since the PC was connected to the network, the data could easily be accessed and was processed on a weekly basis, in order to verify the correct operation of the sensor. During the field test in de Bilt using Pluvio sensor 391 this worked nicely. However, during the field test in De Kooy the data-acquisition encountered some problems. When Pluvio sensor number 389 was installed in De Kooy between November 7, 2001 and May 17, 2002 this resulted in frequent gaps in the Pluvio data-acquisition. Since the setup was identical as in De Bilt, the sensor and data-acquisition PC in De Kooy were replaced with those used at De Bilt. However, shortly after it turned out that the connection between the sensor in the field and the PC was bad. The data-acquisition improved after the connection was fixed, but still the PC encountered some problems with the data-acquisition and timing. The PC in De Kooy had to be restarted regularly in order to minimize data loss as a result of this problem.

4.1 Setup De Bilt

The first field test was performed at the measurement field on the premises of the KNMI headquarters in De Bilt located in the middle of the Netherlands. The setup for the field test in De Bilt was nearly the same as during the test of the Ott windscreen. A description of the site can therefore be found in Wauben (2004). A picture of the setup in De Bilt is shown in Figure 5. The Pluvio precipitation sensor was placed on the measurement field about 30 meters to the South-Southeast of the KNMI precipitation gauges of the station De Bilt Operational (WMO number 06260). The orifice of the Pluvio was located 1m above the measurement field and the sensor was placed within an Ott windscreen at the same level. Figure 5 shows a picture of the Pluvio and the KNMI precipitation gauge setup at the measurement field in De Bilt. The present weather sensor of De Bilt Operational is located about 30m South-Southwest of the precipitation gauge such that the 3 precipitation sensors roughly form an equilateral triangle. Additional meteorological information such as the ambient temperature and relative humidity is measured approximately in the center of this triangle (note that the Stevenson screen in Figure 5 is not used for this purpose). The wind information, however, comes from the operational 20-meter mast that is located about 250m to the East since the measurement field at De Bilt itself is obstructed by trees and bushes in the vicinity.

Figure 5: The Pluvio precipitation sensor on the measurement field during the field test in De Bilt. In the background the so-called English setup containing the operational KNMI precipitation gauge is visible to the North-Northwest.

4.2 Setup De Kooy

The second field test was performed at the coastal station De Kooy (WMO number 06235) that is located in the Northwest part of the Netherlands. The geographical location of De Kooy is 52°55' North 04°47'East and the elevation is 1m above MSL. The measurement field at De Kooy is located on a Navy Airbase and is about 1km from Lake IJsselmeer, which is to the East. For the duration of the field test a Pluvio precipitation sensor was installed on the measurement field within an Ott windscreen. Figure 6 shows a picture of the Pluvio setup in De Kooy. The measurement field also houses the operational KNMI precipitation gauge in the so-called English setup that is located 11m North of the Pluvio. The temperature and humidity sensors are also located at the measurement field in the Northeast corner. The present weather sensor and wind sensor are located on the other side of the runway. The present weather sensor is located about 290m northwest of the measurement field and the 10-meter wind mast is located 465m to the North. The layout of the measurement field and the airbase with an indication of the position of the relevant sensors is given in Figure 7. The only obstruction in the neighborhood of the measurement field in De Kooy is the 15-meter tower 110m Southeast of the field. The helicopter platforms are situated 100m Northeast and 150m South of the measurement field.

Figure 6: Picture of the Pluvio precipitation sensor on the measurement field during the field test in De Kooy. In the foreground the so-called English setup containing the operational KNMI precipitation gauge is visible and in the background the helicopter platforms and buildings to the South of the measurement field.

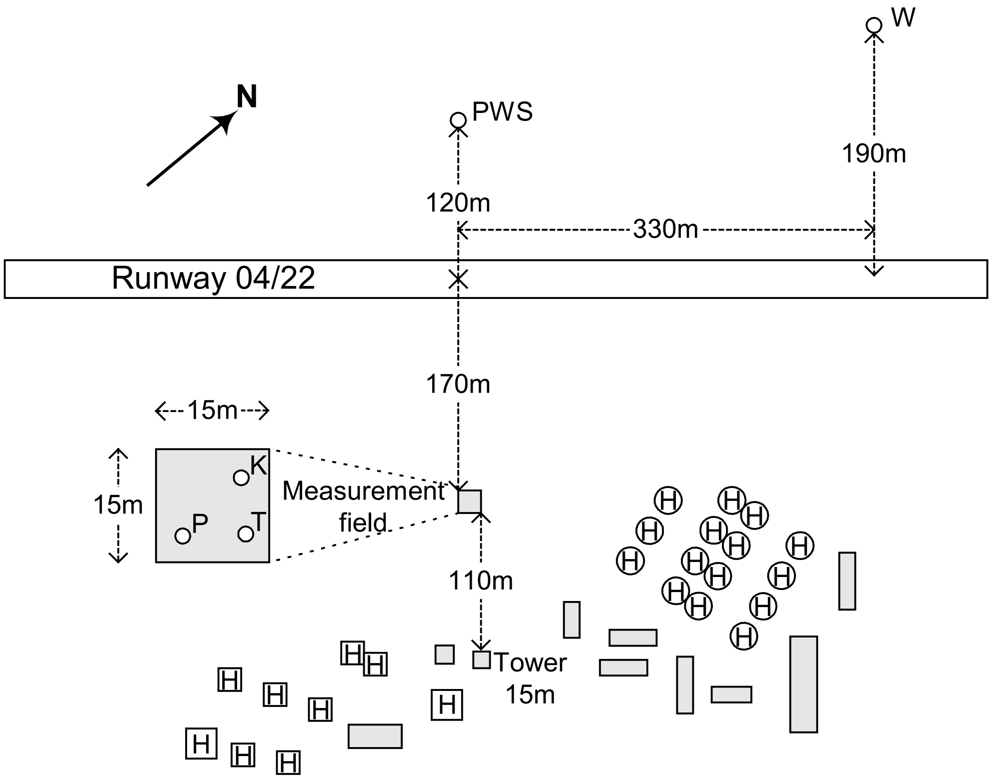

Figure 7: Sketch of the measurement site in de Kooy with the locations of the relevant sensors and obstructions in the surroundings. Circles indicate the positions of the KNMI gauge (K), the Pluvio (P) and the present weather sensor (PWS). The location of the temperature and humidity sensors (T) and the wind mast (W) is also shown. The wind mast is 465m from the measurement field.

5. Results for De Bilt

In this section the results for the field test at De Bilt for the period February 1, 2001 to May 16, 2002 are discussed. The comparison considers only those 10-minute intervals were the precipitation measurements of all three precipitation sensors are available and valid. Intervals where data of one or more of the sensors are missing are ignored. For the comparison in this paper these omitted intervals do not matter. However, the rejections affect the total sums reported in this paper, which should therefore not be taken for the actual daily, monthly and annual precipitation amounts. Note that the missing data was largely caused by gaps in the data acquisition and maintenance of one of the sensors.

During the field test in De Bilt the Pluvio operated correctly. The sensor reported no warnings or errors, except the messages when the heater was on, the collector was more than 80% filled or the housing was removed for maintenance. The collector of the Pluvio was emptied on 3 occasions namely on February 12, 2001, shortly after the field test started using the latest software version, on September 20 and on December 31, 2001. The autumn of 2001 was very wet, more than 200mm precipitation was registered in De Bilt in September 2001 alone, so that the collector had to be emptied twice within a 3 months period. During summer conditions the rate of evaporation is such that the collector does not easily fill up completely. The collector is mostly nearly empty during summer.

5.1 Comparison raw sensor data with validated hourly data

Monthly sums of the precipitation amounts obtained by all 3 sensors are given in the bottom panel of Figure 8 and compared to the summed hourly climatological data as obtained by the climatological department. Monthly differences in percentage are shown in the upper part. The numerical values have also been listed in Table 4. In this section only those hours are considered where all 10-minute intervals of all 3 sensors have valid readings. Since the time window between sensor data and KLIM is shifted 5 minutes, the hourly value requires 7 valid 10-minute intervals. Furthermore, if an hourly value is rejected and the first 10-minute interval reports precipitation then the previous hour is also disregarded. Similarly the next hour is disregarded in case the previous hour is rejected and the last 10-minute interval reported precipitation. This procedure ensures that no precipitation reported in a climatological report is considered without a valid sensor reading in the corresponding interval.

The monthly results show that the sums for KNMI gauge and the KLIM data are quite close, i.e. within ±1mm or in the range –1 to 2%, as could be expected, since the KLIM data are mainly based on the sensor reading from the KNMI gauge. However, Figure 8 also shows some striking features between the KNMI gauge and KLIM for June and July 2001. In these 2 months large differences between KNMI gauge and KLIM occur that could be ascribed to faulty sensor readings on particular days (cf. e.g. Figure 9). The KNMI gauge reported faulty precipitation for several hours on June 22, 2001 with intensities up to about 6mm/h leading to a daily of 7.5mm. On July 12, 2001 the KNMI gauge gives no precipitation readings during 3 precipitation events in the second half of the day so that the KNMI gauge reports only 1mm of precipitation compared to the 6mm reported by the other sensors. The status information reported by the KNMI gauge did not indicate any problems during these 2 situations. Furthermore, the KNMI gauge in both cases returned to normal operation shortly afterwards without human intervention. More suspicious events can be found in the raw sensor data by scanning the daily plot. For example on July 7 the KNMI gauge reports a single 10-minute averaged precipitation intensity of 36mm/h although the other sensors did not report higher values than about 10mm/h. During the field test 2 different KNMI gauges were in use at De Bilt. The replacement of the KNMI gauge occurred on June 25, 2001, because of a leaking shutter. The second gauge remained in use for the rest of the field test. The pre-calibration check of this gauge after replacement for routine maintenance and recalibration showed that it still was within ±1% of the reference.

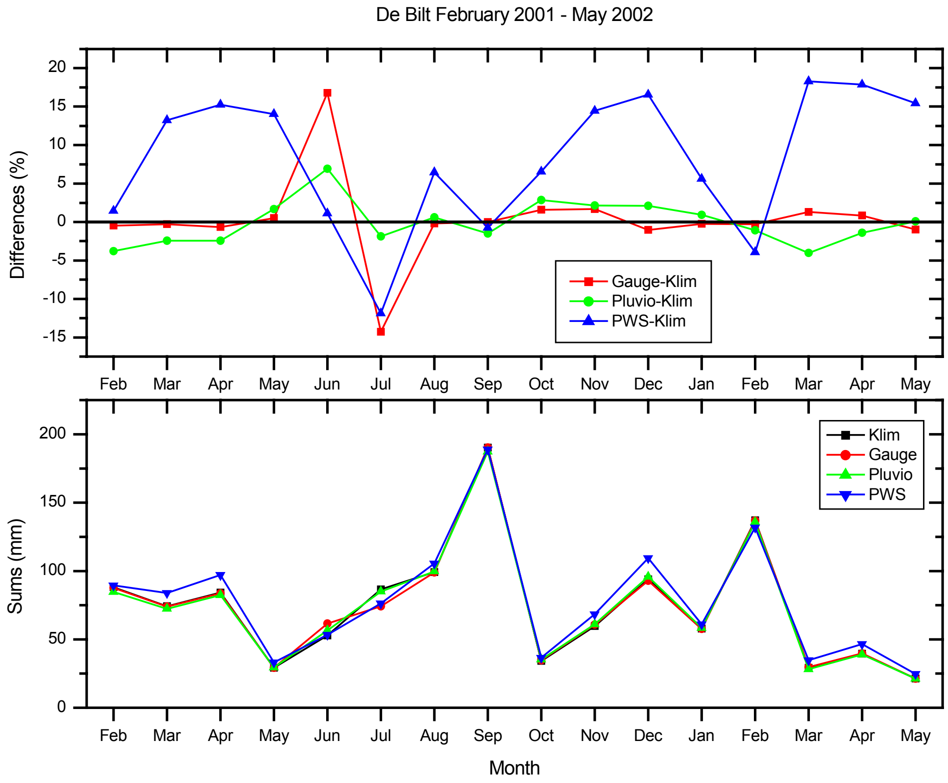

Figure 8: Monthly precipitation amounts for De Bilt using the 'raw' 10-minute sensor data for all hours where valid data of the three precipitation sensors is available. The results are compared to the validated hourly results from the climatological department.

The differences between Pluvio and KLIM are generally larger than those for the KNMI gauge, and range between –3 and 2mm or –4 and 3%. This could be expected when comparing the results for 2 different types of precipitation sensors during a field test. On a daily basis the precipitation amounts between the Pluvio and the climatological data are generally within ±0.5mm. On September 19, 2001 the Pluvio reports about 1.5mm less precipitation than the KNMI gauge. This can be traced to some 10-minute intervals within an extensive period of precipitation where the Pluvio reports less precipitation than the KNMI gauge, whereas in the other 10-minute intervals the reported precipitation intensities compare very well. A similar situation also occurred on February 8, 2001. The differences between the total amounts reported by KNMI gauge and Pluvio are almost identical i.e. –5mm or about –0.4%.

The monthly and daily precipitation amounts for the present weather sensor show larger differences. Generally the precipitation amounts reported by the PWS are higher than those of the other sensors. KNMI does not use the PWS for the determination of precipitation amounts, but for precipitation detection, and for the determination of precipitation type and visibility. However, in this paper the PWS is included because it can be useful for precipitation detection and the discrimination of faulty events by the other sensors. Furthermore, comparison with the PWS can reveal differences in the behavior of the other 2 precipitation sensors. Note also that a PWS was available at both test sites. The same PWS was in operation during the entire period of the field test in De Bilt.

Table 4: Monthly sums and differences between the precipitation amounts reported by the Vaisala PWS, the KNMI gauge, the Ott Pluvio, and the validated climatological sum for the field test in De Bilt. All hours are considered where valid precipitation data of all three sensors is available.

Month	***Sum (mm)***				***# valid hours***	***Difference (mm)***		***Difference (%)***	
	PWS	***Gauge***	***Pluvio***	***Klim***		***Ga–Kl***	***Pl–Kl***	***Ga–Kl***	***Pl–Kl***
0201	89.4	87.7	84.8	88.1	592	–0.41	–3.35	–0.47	–3.80
0301	84.0	74.0	72.4	74.2	735	–0.22	–1.81	–0.29	–2.44
0401	97.2	83.7	82.3	84.3	675	–0.55	–2.05	–0.66	–2.43
0501	33.2	29.2	29.6	29.1	739	0.14	0.49	0.49	1.68
0601	53.4	61.7	56.5	52.8	705	8.87	3.66	16.80	6.93
0701	76.3	74.3	85.0	86.6	737	–12.34	–1.63	–14.25	–1.88
0801	105.6	99.0	99.8	99.2	723	–0.20	0.61	–0.20	0.61
0901	188.9	190.3	187.4	190.3	704	–0.04	–2.90	–0.02	–1.52
1001	36.5	34.8	35.3	34.3	704	0.54	0.98	1.58	2.86
1101	68.3	60.7	61.0	59.7	655	0.99	1.29	1.66	2.16
1201	109.5	93.0	95.9	93.9	743	–0.95	1.96	–1.01	2.09
0102	61.1	57.6	58.3	57.8	719	–0.15	0.53	–0.26	0.92
0202	131.8	136.8	135.7	137.2	663	–0.40	–1.46	–0.29	–1.06
0302	34.7	29.7	28.1	29.3	718	0.38	–1.18	1.29	–4.03
0402	46.6	39.8	39.0	39.5	700	0.34	–0.55	0.85	–1.39
0502	24.7	21.2	21.4	21.4	360	–0.21	0.02	–0.98	0.09
Total	**1241.0**	**1173.5**	**1172.3**	**1177.7**	**10872**	**–4.22**	**–5.38**	**–0.36**	**–0.46**

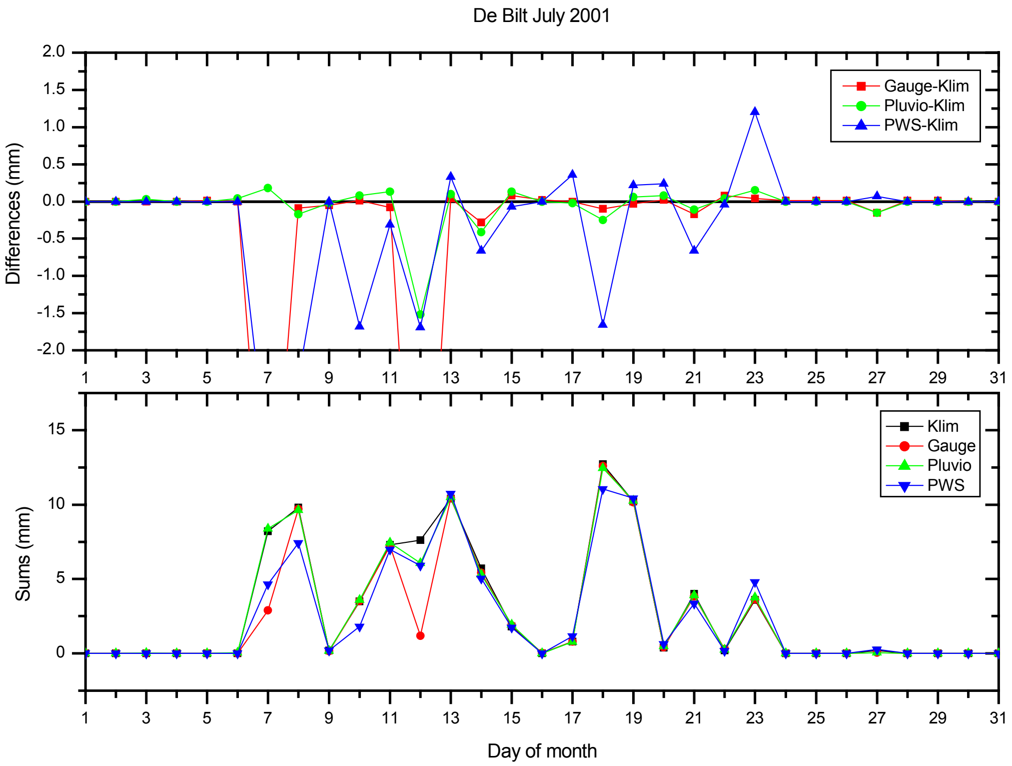

Figure 9: Daily precipitation amounts for July and September 2001 using the ‘raw’ 10-minute data for all intervals where data of the three precipitation sensors of Gauge, Pluvio and PWS are available. The results are compared to the validated hourly Klim results from the climatological department.

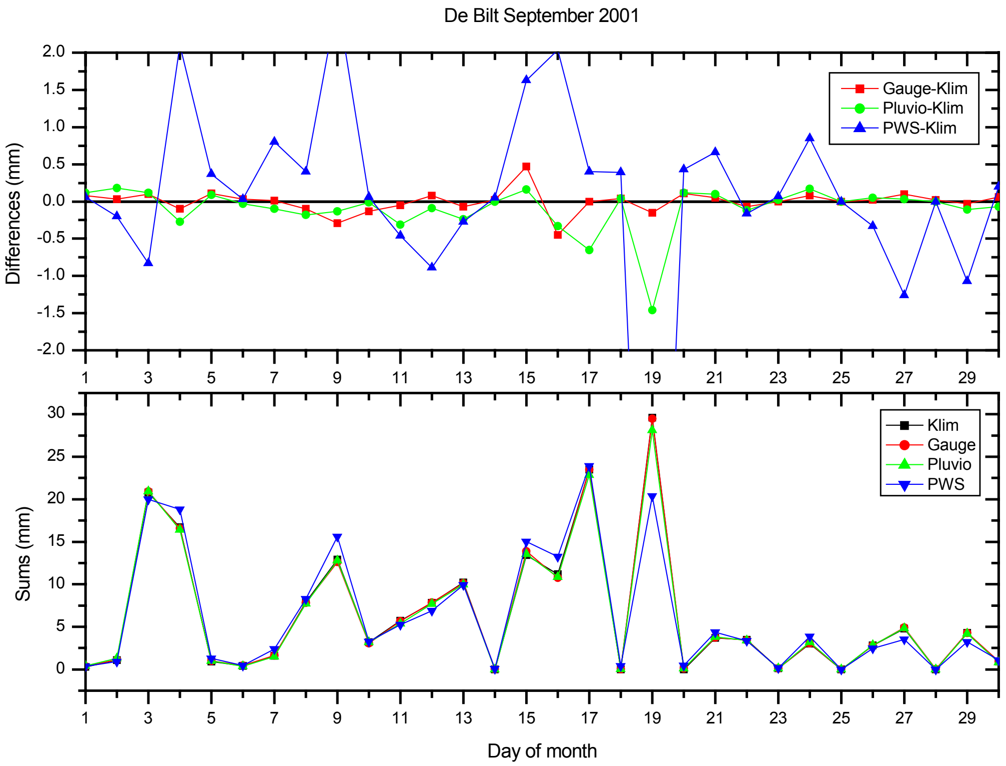

Figure 9: Continued.

5.2 Comparison after rejection of faulty data

The previous section showed that several instances could be indicated where sensor readings were obviously faulty. In this section a data rejection mechanism is considered in order to filter the data set for such cases. The rejection criteria applied to the 10-minute precipitation data are:

(i) The results of all three sensors need to be available. If the data of one is missing, the other 2 sensors will also be rejected. This way the same situations will be considered when comparing any 2 sensors with one another.

(ii) All 10-minute intervals are rejected where the difference between the precipitation amounts of any 2 sensors is larger than a threshold of 1mm, and also the difference between the sum including the sensor values of the previous and next interval is larger than 1mm (thus no compensation by adjoining intervals). In fact this correction only applies to the cases on June 15, June 22, July 7, and July 12 2001, mentioned above.

(iii) Intervals will be rejected where one sensor falsely reported precipitation. If the precipitation intensity of 1 sensor is above a certain threshold of 0.1mm/h, but the other 2 sensors do not report precipitation in that 10-minute interval, nor in the previous or next interval and also the precipitation detector (if available) did not detect any precipitation, than that interval is rejected.

(iv) Intervals will be rejected where one sensor falsely did not report precipitation. If the precipitation intensity of 1 sensor is zero in a certain 10-minute interval, as well as in the previous and next interval, but the other 2 sensors report precipitation above a certain threshold of 0.1mm/h in the 10-minute interval under consideration and the precipitation detector (if available) reports precipitation, than that interval is rejected.

(v) Within a period of precipitation no gaps with missing data are allowed. Due to spatial and temporal differences, a precipitation event can be partly assigned to different 10-minute intervals for different sensors. Thus, in case of missing data all adjoining 10-minute intervals will be rejected where at least one of the sensors reported precipitation.

Table 5: As Table 4, but now only those hours are considered that remain after rejection of faulty sensor data (see text).

Month	***Sum (mm)***				***# valid hours***	***Differences (mm)***		***Differences (%)***	
	PWS	***Gauge***	***Pluvio***	***Klim***		***Ga–Kl***	***Pl–Kl***	***Ga–Kl***	***Pl–Kl***
0201	43.6	43.0	41.0	43.3	483	–0.28	–2.31	–0.65	–5.33
0301	65.1	66.2	65.5	66.7	684	–0.48	–1.19	–0.73	–1.78
0401	59.9	51.5	50.8	51.9	616	–0.41	–1.10	–0.79	–2.12
0501	23.4	20.6	20.9	20.5	707	0.10	0.43	0.48	2.10
0601	45.7	43.5	45.2	43.2	667	0.33	2.01	0.77	4.65
0701	42.2	45.8	46.4	46.0	673	–0.17	0.38	–0.36	0.83
0801	60.5	53.1	53.5	52.6	680	0.48	0.89	0.91	1.69
0901	167.3	167.0	164.6	167.2	635	–0.16	–2.57	–0.09	–1.54
1001	26.9	25.5	26.0	25.0	677	0.46	1.03	1.83	4.12
1101	50.8	46.4	46.5	45.5	603	0.85	0.98	1.88	2.15
1201	51.8	45.1	45.9	45.4	612	–0.31	0.53	–0.69	1.17
0102	57.7	55.2	55.5	55.4	694	–0.22	0.12	–0.40	0.22
0202	117.9	122.6	121.5	123.0	620	–0.38	–1.51	–0.31	–1.23
0302	20.7	18.1	17.8	17.9	665	0.17	–0.12	0.98	–0.67
0402	13.6	11.5	11.3	11.3	622	0.15	0.03	1.34	0.27
0502	16.9	13.8	13.9	13.8	334	0.00	0.14	0.01	1.01
Total	**863.9**	**828.8**	**826.4**	**828.7**	**9972**	**0.14**	**–2.26**	**0.02**	**–0.27**

The monthly sums of the precipitation amounts obtained by all 3 sensors after applying the above mention data rejection criteria are given in Table 5 and are compared to the summed hourly climatological data as obtained by the climatological department. As a result of the data rejection the number of valid hours decreases by 900 hours from 10,872 to 9972. This number is rather high because the rejection of a single sensor value for a 10-minute interval leads to the rejection of the entire hour, and possibly also to the rejection of adjoining hours. The total amount of precipitation after data rejection is about 70% the amount when considering all raw sensor data. After the filtering of faulty data, the agreement between the monthly precipitation amount reported by the KNMI gauge and the validated KLIM data improves. The large differences for June and July are not present anymore and the monthly differences are now within ±0.5mm. While the raw KNMI gauge values showed slightly lower values compared to the validated climatological data, the sensor amounts after data rejection agree are slightly higher. The agreement between the monthly precipitation amounts for Pluvio and the validated climatological data improves after data rejection, but not as much as the data for the KNMI gauge. Again, the data rejection leads overall to slightly higher precipitation sums reported by the sensor when compared to the climatological data. The agreement can be further improved by using stricter values for the rejection thresholds. However, it is then easily possible that correct sensor reading are erroneously rejected, and furthermore the number of intervals with precipitation will reduce significantly. It must be noted that often one cannot be sure that the rejected cases are really faulty.

Some details of the rejected cases are given next. The number of situations (case ii) where the reported 10-minute averaged precipitation intensities for the KNMI gauge and Pluvio differ more than 6mm/h is 12. These include the situations with faulty KNMI gauge or faulty Pluvio data discussed above. There are 50 situations (case iv) where the Pluvio does not report precipitation but the KNMI gauge and PWS do, whereas there are 57 of such situations for the KNMI gauge. Finally, the situations with faulty precipitation reports (case iii) are 13 for the Pluvio, and 75 for the KNMI gauge. Note that the faulty cases for the KNMI precipitation gauge during bright weather are not rejected, since that would require a very low threshold. The applied data rejection showed that overall the number of rejections of Pluvio and KNMI gauge data is generally the same. The number of faulty precipitation reports for the KNMI gauge exceeds that for the Pluvio.

5.3 Comparison of raw 10-minute data

The rejection of data considered in the previous section gives a slight improvement of the results. However, rejection of faulty data is a tricky business and leads to a rejection of many cases with precipitation. Since the rejection has little effect on the overall differences, particularly when expressed as relative numbers, and also when the differences are studied statistically, as presented below, the remaining part of this section deals with the comparison of raw 10-minute sensor readings. In this case the validated hourly climatological data are not considered and the comparison can be done directly on the 10-minute sensor data for all cases where the data for all 3 sensors is available. Furthermore, the 1-minute data of the Pluvio can be summed on the correct 10-minute time intervals on which the other sensor data was available in the old and new measurement networks.

The monthly precipitation amounts for PWS, KNMI gauge and Pluvio as well as their differences are given in Table 6. The number of 10-minute intervals included is also reported. Almost 98% of the data is used in the comparison. Hence 98% of the time the data-acquisition worked correctly and all three sensors reported valid readings. The monthly differences Pluvio-Gauge are generally within ±3mm or ±3% and show the same features as the results in Table 4 based on hourly data. The total precipitation sum of Pluvio and KNMI gauge differ 4mm or 0.3%. The differences PWS-Gauge show larger variations. The reported standard deviation shows higher relative values during summer months and lower values during winter months. This is probably related to the nature of precipitation with more showers during summer. The higher standard deviation values for the differences Pluvio-Gauge as compared to PWS-Gauge is probably related to the lower sensitivity of the Pluvio and the its reporting threshold. The behavior of the differences of these raw sensor data will be analyzed in more detail in the next section.

Table 6: As Table 4, but now all 10-minute intervals are considered where valid data of the KNMI precipitation gauge, the Pluvio and the PWS are available.

Month	***Sum (mm)***			***Number***		***Pluvio–Gauge***			***PWS–Gauge***		
	PWS	***Gauge***	***Pluvio***	***Total***	***Valid***	***Dif (mm)***	***Dif (%)***	***StD (%)***	***Dif (mm)***	***Dif (%)***	***StD (%)***
0201	89.6	87.9	85.0	4032	3577	–2.89	–3.29	0.61	1.75	1.99	0.63
0301	84.0	74.0	72.4	4464	4434	–1.59	–2.15	0.69	10.02	13.55	0.95
0401	97.3	84.0	82.5	4320	4086	–1.49	–1.78	0.77	13.38	15.93	0.87
0501	33.2	29.2	29.6	4464	4452	0.34	1.17	0.78	3.94	13.47	1.00
0601	54.4	62.5	57.4	4320	4269	–5.14	–8.22	1.26	–8.10	–12.96	1.49
0701	76.3	74.3	85.0	4464	4456	10.68	14.38	1.64	2.02	2.71	0.82
0801	122.8	113.7	113.9	4464	4376	0.17	0.15	2.02	9.06	7.97	1.02
0901	195.0	195.7	198.9	4320	4256	3.23	1.65	1.51	–0.71	–0.36	0.52
1001	36.5	34.8	35.3	4464	4244	0.44	1.26	0.65	1.70	4.87	0.31
1101	74.9	66.1	66.5	4320	4043	0.41	0.61	0.41	8.78	13.28	0.22
1201	109.5	93.0	95.9	4464	4463	2.91	3.13	0.48	16.52	17.77	0.34
0102	79.4	77.8	78.6	4464	4405	0.75	0.97	0.38	1.57	2.02	0.39
0202	134.0	138.9	137.8	4032	4000	–1.09	–0.78	0.50	–4.95	–3.56	0.31
0302	39.2	33.6	31.8	4464	4396	–1.81	–5.38	0.25	5.61	16.69	0.17
0402	57.6	49.6	48.6	4320	4298	–1.00	–2.02	0.26	7.95	16.02	0.17
0502	24.7	21.2	21.4	2304	2193	0.23	1.08	0.42	3.52	16.59	0.36
Total	**1308.4**	**1236.3**	**1240.5**	**67680**	**65948**	**4.18**	**0.34**	**0.97**	**72.06**	**5.83**	**0.67**

Some statistical information is derived from the raw 10-minute data considered above. The information is derived from the monthly, daily, hourly summed values as well as from the raw 10-minute values. In each case only those cases are considered where one of the three sensors reported precipitation. The results are derived using different time-intervals, because climatological records are often available on such intervals. The statistical information considered is the total number of cases involved, the mean of the differences, the average deviation of the differences, the standard deviation, the median of the differences and the 5 and 95 percentiles. Furthermore, the correlation coefficient of the precipitation amounts is reported and tests are performed in order to checked whether the precipitation amount distributions have the same mean, by applying the Student's T-test and the T-test for paired precipitation amounts; the same variance, by applying the F-test; and are generally the same, by applying the Kolmogorov-Smirnov test (cf. Press et al., 1992). The results are given in Table 7. The mean, deviation, median and percentiles of the differences generally decrease when the time interval is made smaller. However, these values are reported in absolute values (mm) and the amount of precipitation involved also decreases for smaller time intervals. In all situations the total precipitation amounts for PWS, KNMI gauge and Pluvio are 1308, 1236 and 1240mm, respectively. Table 7 shows that the results for Pluvio-Gauge are generally better than for PWS-Gauge.

The PWS-Gauge statistics are slightly better when the 10-minute data is considered directly. This is probably the result of the lower sensitivity of the Pluvio. The correlation coefficient between the precipitation amounts is generally good and is significant for all cases. The correlation is less when 10-minute is used and again the results for PWS compare better to the KNMI gauge than the Pluvio in that case. The T-test shows that the mean of the all three sensors and are the same in all cases, whereas the paired T-test shows agreement for all Pluvio-Gauge cases, but not for any of the PWS-Gauge cases. The F-test shows that the variances for hourly and 10-minute data differ significantly and KS-test only gives agreement for the monthly results.

Table 7: Statistical summary (in mm) of the differences between the precipitation amounts of the 3 sensors and the outcome of several tests obtained for De Bilt using various time-intervals.

Parameter	***Pluvio–Gauge***				***PWS–Gauge***			
	Monthly	***Daily***	***Hourly***	***10'***	***Monthly***	***Daily***	***Hourly***	***10'***
Number of cases	16	416	4097	14820	16	416	4097	14820
Mean	0.26	.010	.001	.000	4.50	.173	.018	.005
Average deviation	2.12	0.16	0.05	0.04	4.97	0.53	0.08	0.03
Standard deviation	3.44	0.63	0.18	0.15	6.39	1.11	0.22	0.11
Median	0.17	–0.00	–0.00	–0.00	3.52	0.02	–0.00	–0.00
5 percentile	–5.14	–0.29	–0.11	–0.10	–8.10	–0.92	–0.16	–0.07
95 percentile	3.23	0.24	0.11	0.09	13.38	1.72	0.20	0.08
Correlation coefficient	1.00	0.99	0.97	0.77	0.99	0.97	0.96	0.87
T-test for mean	Agree	Agree	Agree	Agree	Agree	Agree	Agree	Agree
Paired T-test for mean	Agree	Agree	Agree	Agree	Differ	Differ	Differ	Differ
F-test for variance	Agree	Agree	Differ	Differ	Agree	Agree	Differ	Differ
KS-test for distribution	Agree	Differ	Differ	Differ	Agree	Differ	Differ	Differ

5.3.1 Analysis of 10-minute precipitation intensity

Next the valid 10-minute precipitation intensity amounts for the 3 precipitation sensors are analyzed in more detail. This analysis is performed on all 10-minute measurements in the period February 1, 2001 to May 16, 2002 where at least one of the three sensors reported precipitation. The total number of 10-minute intervals involved is 14,820. A frequency distribution of the measured 10-minute precipitation intensity is shown in Figure 10 for each of the three sensors. The distribution is given in 0.1mm/h bins for intensities between 0 and 5mm/h. Above 5 mm/h the number of events involved per bin decreases below 10, and hence statistics are poor. Between 0 and 5mm/h the frequency distribution of the three sensors is generally the same. The number of cases for the PWS is slightly higher for intensities below 1mm/h. This is probably related to the higher sensitivity of this sensor compared to the other 2. The frequency distribution of the Pluvio shows regular peaks and dips. This is probably related to some sensor property, e.g. internal accuracy or reporting step, which produces a deviation from a smoothly decreasing number with increasing intensity. A lower number of Pluvio cases with very light precipitation intensity, which is related to the reporting threshold of 0.03mm/h, is not clearly visible in Figure 10. This is caused by the bin size of 0.1mm/h and the inclusion of the cases where Pluvio does not report any precipitation, but one of the other 2 sensors does. When the distribution for very light precipitation is constructed in more detail, then the lack of Pluvio cases with low precipitation intensity (below 0.18mm/h for 10-minute intervals) clearly shows up.

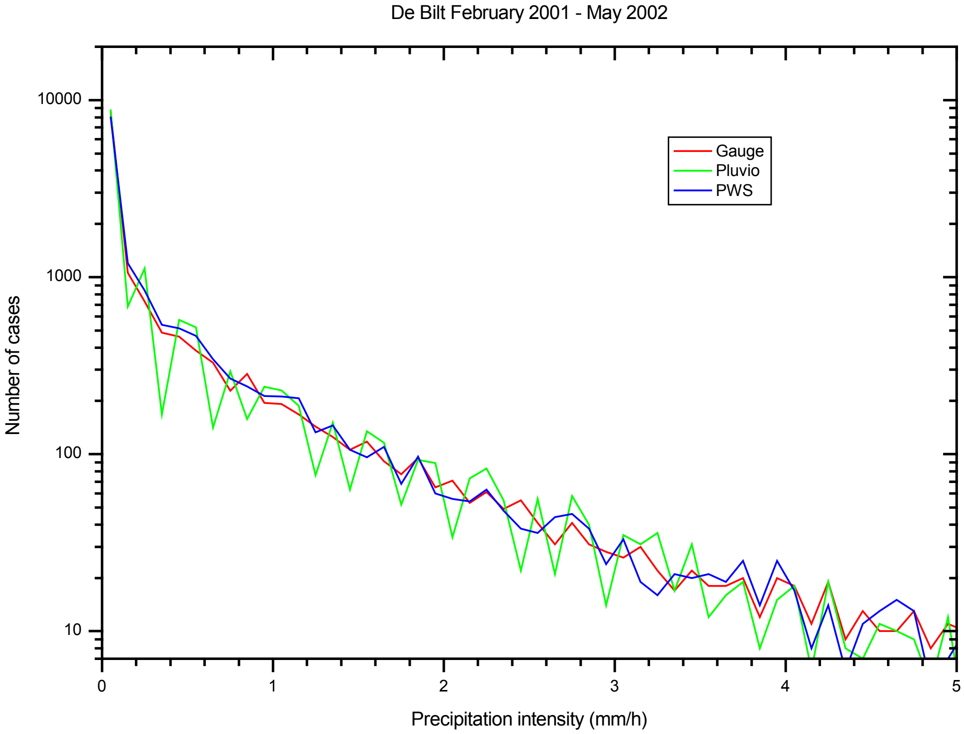

Figure 10: Frequency distributions of the raw 10-minute averaged precipitation intensity measurements for each sensor in De Bilt. The bin size is 0.1 mm/h. All valid cases are included where at least one of the sensors reports precipitation.

A histogram of the differences between the 10-minute intensity measurements of any 2 precipitation sensors is presented in Figure 11 using a bin size of 0.03mm/h. The histogram is plotted using a logarithmic scale. The histogram roughly resembles a Gaussian distribution. Both histograms peak at a difference of 0.00mm/h, where the bin for Pluvio–Gauge contains 41% of the cases and PWS-Gauge 33%. The number of cases within ±0.1mm/h is 66% for Pluvio-Gauge and 68% for PWS-Gauge. The number of cases in the bins for larger differences decreases exponentially. The histogram for PWS-Gauge shows more cases with positive than negative differences leading to the larger monthly sums for PWS compared to the KNMI gauge. The histogram for Pluvio-Gauge shows almost a constant value for differences between +0.03 and +0.18mm/h. This feature can probably be explained in terms of the reporting threshold of 0.03mm of the Pluvio. The cases with precipitation amounts of less than 0.03mm in 10 minutes, i.e. a 10-minute averaged intensity of less than 0.18mm/h, will be reported by the KNMI gauge, but not by the Pluvio. Such events add cases to the slightly negative bins of the histogram, as do faulty KNMI gauge readings. However, there are no or in any case less corresponding events adding cases to the slightly positive bins. As a result the number of cases with positive differences Pluvio-Gauge less than 0.18mm/h is reduced.

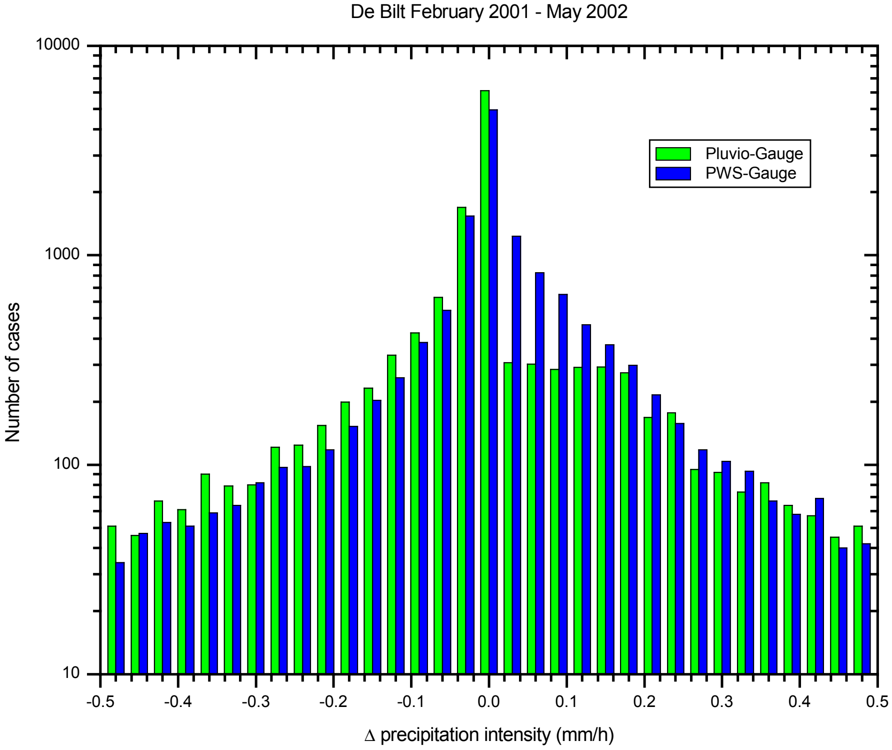

Figure 11: Histogram of the differences between the raw 10-minute averaged precipitation intensity measurements for any combination of 2 precipitation sensors during the field test in De Bilt. The bin size is 0.03 mm/h. All cases are included where at least one of the sensors reports precipitation.

5.3.2 Wind effect

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of wind speed. The measured wind speed at 20m is used. Again, the analysis is performed on all 10-minute measurements in the test period where the results for all three sensors are valid and at least one of the three sensors reported precipitation. In addition, the wind speed needs to be available. The differences are calculated for different wind speed bins in order to determine any wind speed effect. For that purpose the wind speed range is divided in 1m/s bins from 0 to 15m/s, where the last bin also contains all the cases with wind speeds above 15m/s. The averaged differences between the 10-minute precipitation intensities for 2 precipitation sensors per wind speed interval are given in Figure 12. The results are given as the percentage of the total precipitation amount per wind speed bin as measured by the KNMI gauge. The precipitation amount measured by the KNMI gauge and the total number of cases involved is also shown per wind speed bin. In addition, the number of so-called faulty cases, i.e. the cases where one precipitation sensor reports precipitation but the other 2 sensors do not report precipitation nor in the previous and in the next 10-minute interval if available, are given as the sensor only cases in Figure 12. First of all note that the behavior of the curves for Pluvio-Gauge and PWS-Gauge are generally the same. Between 1 and 8m/s the differences Pluvio-Gauge show no wind speed effect. The results above 8m/s are not shown because statistics is poor in that region. Below 1m/s the differences Pluvio-Gauge increase up to about 12%. A similar increase can be observed for PWS-Gauge. At low wind speeds the KNMI precipitation gauge reports less precipitation compared to the Pluvio and PWS. It is unlikely that this behavior is related to a wind effect, but it is probably the results of a phenomenon that particularly occurs at low wind speed. The number of faulty Gauge only events shows the same behavior as a function of the wind speed as the PWS only event. The number of Gauge only events is however much larger. The number of Pluvio only events is very small at all wind speeds.

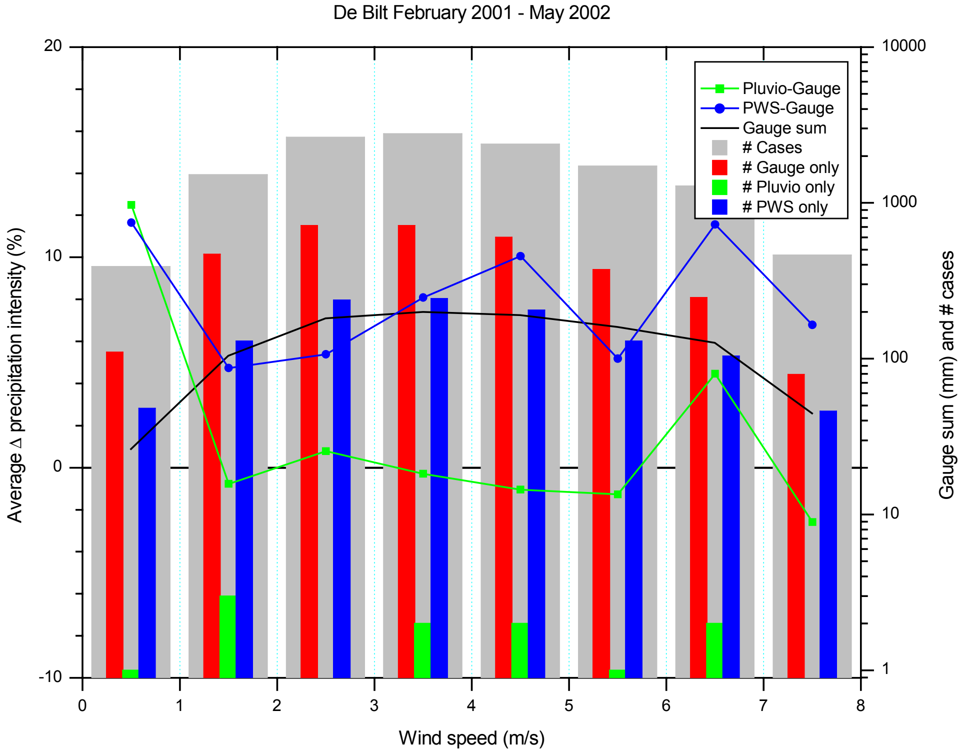

Figure 12: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the wind speed in bins of 1m/s for the field test in De Bilt. The results are presented as the percentage of the total precipitation amount per wind speed bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

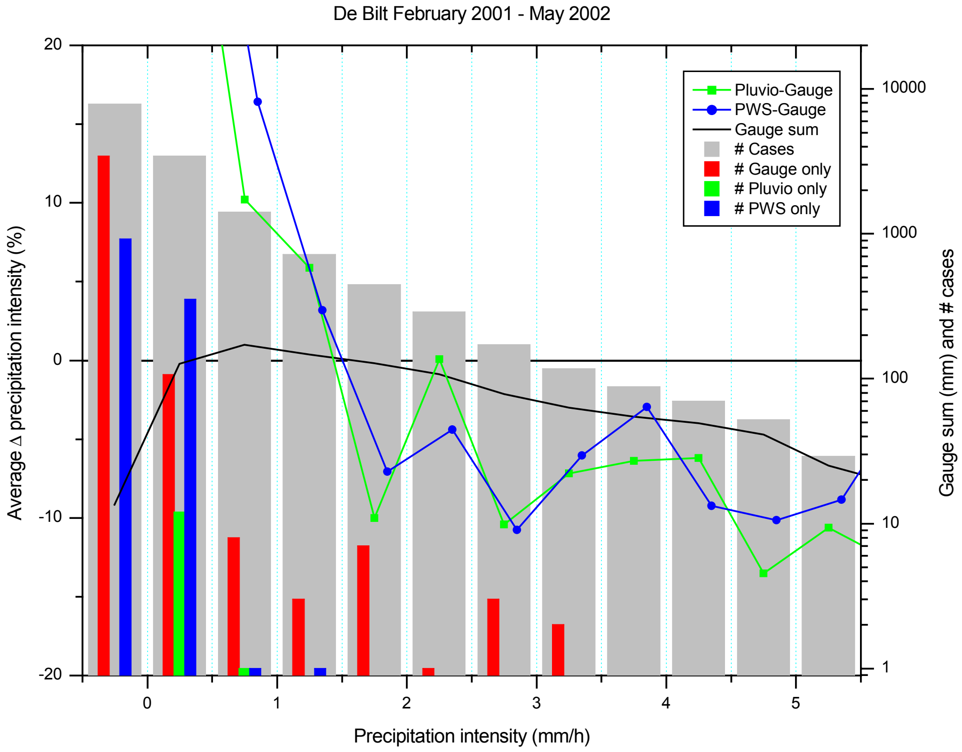

Figure 13: As Figure 12, but now the relative differences are given as a function of the precipitation intensity. The binning in steps of 0.5mm/h is performed on the intensity measured by the KNMI gauge. The first bin contains the cases with intensity less than 0.05mm/h. The number of faulty sensor only events is reported in the intensity bin derived from their own reported precipitation intensity.

Any wind speed effect also depends on the type of precipitation such as solid or liquid precipitation and the droplet size since small/light particles have a smaller fall velocity, and hence are more sensitive to the wind. The wind effect will be larger for snow compared to rain, but it will also be larger for smaller particles. The influence of droplet size will be investigated by analyzing the results as a function of the precipitation intensity, although this is not a real measure of the droplet size. Figure 13 shows the relative difference between the precipitation intensity measured by 2 precipitation sensors as a function of the precipitation intensity. The precipitation intensity is divided into bins of 0.5mm/h from 0 to 5.5 mm/h according to the intensity measured by the KNMI gauge. Situations with intensities higher than 5.5mm/h are not shown because the statistics are poor. Again, the curves for Pluvio-Gauge and PWS-Gauge show generally the same behavior. The first bin at zero contains the cases where the KNMI gauge reported precipitation intensities less than 0.05mm/h. This mainly consists of the ‘faulty’ cases when the KNMI gauge only reports traces of precipitation. Since the other 2 precipitation sensors report generally a higher intensity, if any, and the faulty cases of these 2 sensors are also added to this bin when calculating the relative differences, the relative difference at the first bin is large and positive. Note that Pluvio and PWS report faulty cases when the intensity of the sensor is below 1 and 1.5mm/h, respectively, whereas the KNMI gauge reports faulty cases up to 3.5mm/h. The differences Pluvio-Gauge and PWS-Gauge decrease with intensity between 0 and about 2mm/h. Above 2mm/h, the differences between Pluvio-Gauge and PWS-Gauge are generally about –5% to –10%. The behavior of the curves resembles the curves given by Nešpor and Sevruk (1999) obtained by numerical simulations. However, the curves are such that the measurements of the KNMI gauge in the so-called English setup seem to be affected by the wind effect. This is contrary to the results obtained by Wauben (2004) when comparing the measurements for 2 KNMI gauges, one placed in the English setup and the other on the measurement field surrounded by a windscreen. The results of that test showed that the measurements of the KNMI gauge on the measurement field were affected by the wind effect and underestimated precipitation at low intensities.

The above results seem to indicate that the Pluvio installed on the measurement field in a windscreen is not affected by the wind effect. If such an effect does exist, it must be masked by other error sources that occur when comparing different types of precipitation gauges (cf. WMO, 1994). The above results do not change when the analysis is performed using the filtered data as discussed in section 5.2. Since both the Pluvio and the PWS show the same general behavior, it could be concluded that the KNMI gauge seems in general to underestimate precipitation intensities below 1.5 mm/h and to overestimate intensities above 1.5mm/h. This could be caused by wetting and evaporation losses in the collector of the KNMI precipitation gauge. These losses are relatively largest at small precipitation intensities. The Pluvio and PWS measure precipitation more directly and it is therefore expected that these instruments will be less affected by wetting and evaporation losses.

5.3.3 Dependency on other meteorological variables

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of other meteorological variables. The results are affected by the general meteorological situation during the period of the test. This does not mean the general conditions, but specifically the situation during precipitation events. Hence, the results will be checked for a dependency on wind direction, the ambient temperature and the relative humidity. The total number of cases involved in this study is not sufficient in order to show the differences in a multiple parameter space.

First the relative differences are given as a function of the wind direction in Figure 14. The wind direction 0° corresponds to North, 90° to East, etc. The wind direction is the direction the wind is blowing from. The differences Pluvio-Gauge show hardly any dependence on wind direction. The peak near 0 degrees is caused by the faulty Pluvio cases for that direction. The difference PWS-Gauge shows generally positive values except for the directions 90-165 degrees (East to South southeast). This more or less coincides with the direction of the background luminance sensor. It could be that the differences are the result of the precipitation detector and optical measurement area of the PWS being the in wake of the background luminance sensor. The PWS largely overestimates precipitation during North to East wind directions. The reason for this is unknown. The smaller overestimation for the Northeast direction coincides with situations where the KNMI gauge reports a relatively large number of faulty cases.

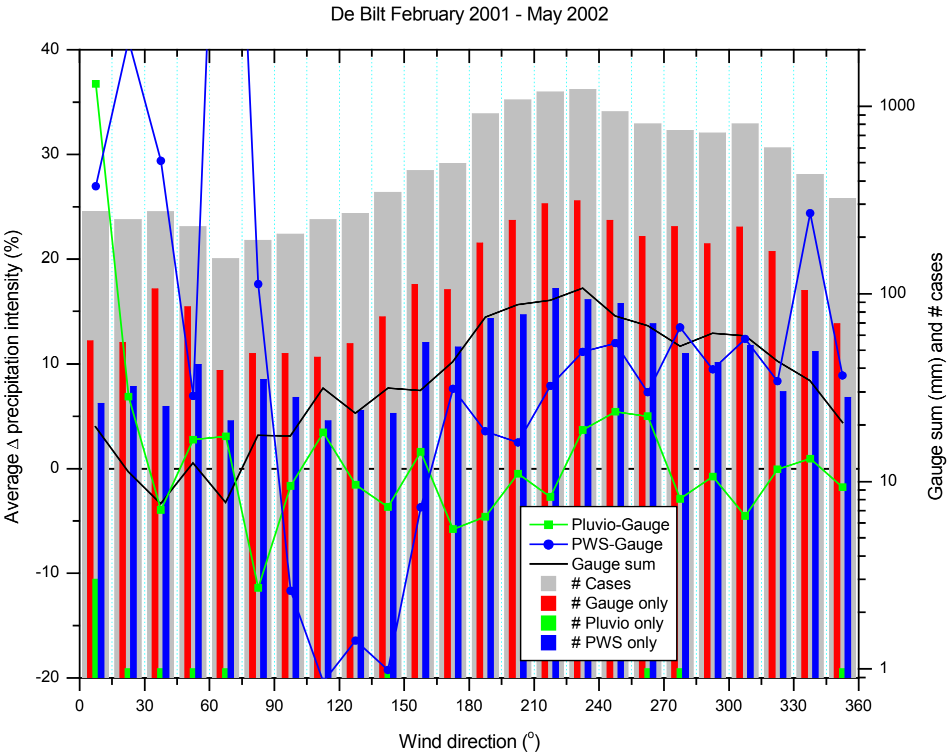

Figure 14: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the wind direction in bins of 15° during the field test in De Bilt. The results are presented as the percentage of the total precipitation amount per wind direction bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

The relative differences as a function of the ambient temperature are given in Figure 15. The size of the temperature bins is 2.5ºC. The curve Pluvio-Gauge shows hardly any dependence on the temperature except for temperatures above 15ºC where the differences Pluvio-Gauge gradually decrease below zero. This coincides with an increase of the faulty readings of the KNMI gauge at higher temperatures, although the amount of precipitation involved is small. However, this results in a significant overestimation of the otherwise small overall precipitation amount reported by the gauge in these conditions. The number of faulty PWS cases decreases significantly at high temperatures, whereas the Pluvio reports only some faulty cases between 2.5 and 12.5ºC. The sudden increase in the relative differences one but last bin is caused a single precipitation event reported by the Pluvio. A similar behavior can again be observed for the differences PWS-Gauge.

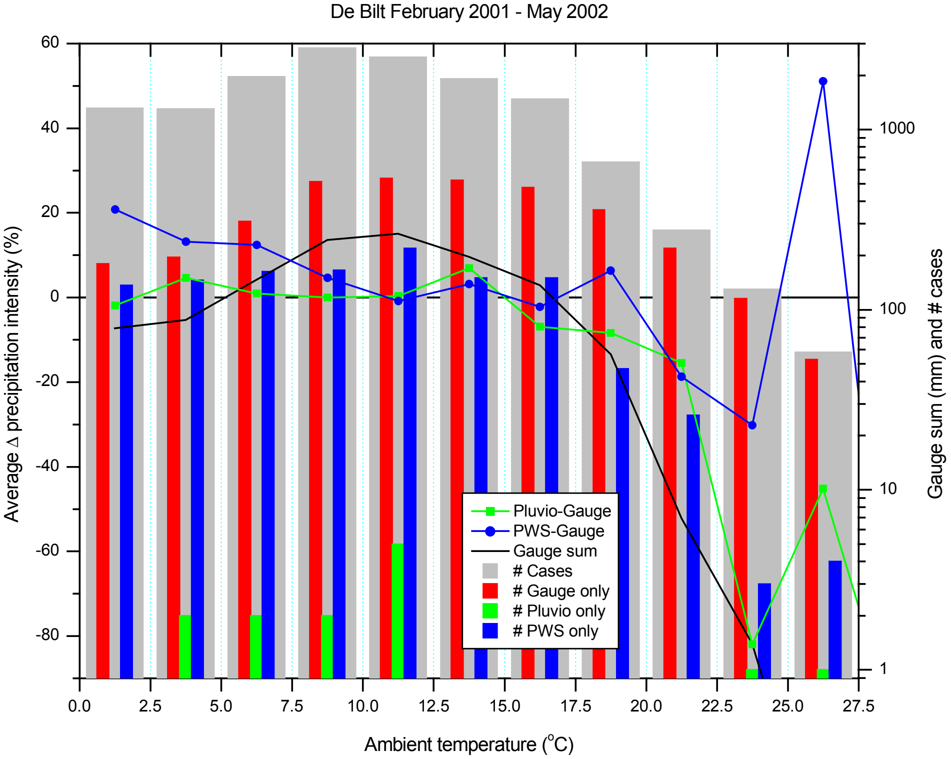

Figure 15: As Figure 14, but now the relative differences and number of cases are given as a function of the ambient temperature in bins of 2.5°.

Finally, Figure 16 shows the relative differences as a function of the relative humidity in bins of 5%. The curves show a clear dependence with relative humidity. The differences Pluvio-Gauge become gradually more negative for humidity values below 85%. For PWS-Gauge this negative trend starts below 75% relative humidity. This too, is mainly the result of the large number of faulty KNMI gauge readings at low humidity. The relative number of faulty PWS cases shows no increase at low humidity values and the few faulty Pluvio cases occur mainly at low and high humidity values. Note that the results as a function of ambient temperature and relative humidity show no evidence of evaporation losses of the KNMI gauge that seemed to be present when the differences were studied as a function of precipitation intensity (cf. Figure 13). However, at high temperatures precipitation events are generally more intense and are therefore less affected by evaporation and wetting losses.

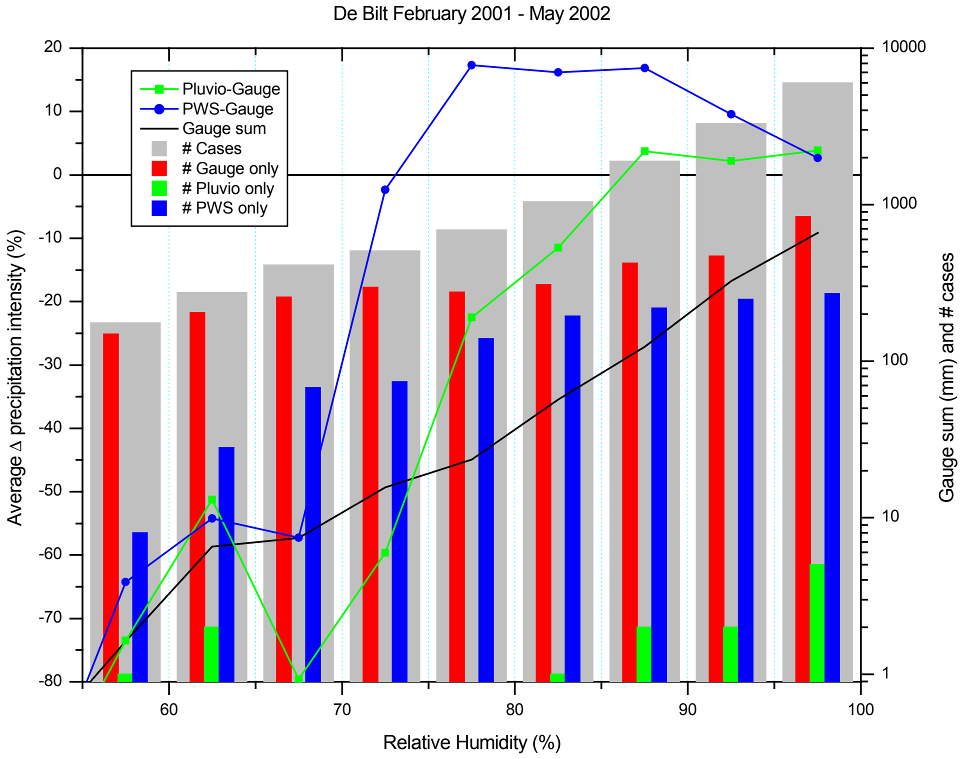

Figure 16: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the relative humidity in steps of 5% during the field test in De Bilt. The results are presented as the percentage of the total precipitation amount per relative humidity bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

5.3.4 Dependency on other parameters

Next the dependency of the observed differences between the precipitation sensors on other parameters is investigated. The parameters considered are: the collector content of the Pluvio; the quality parameter reported by the Pluvio; the temperature reported by the Pluvio; and the gradient of this temperature.

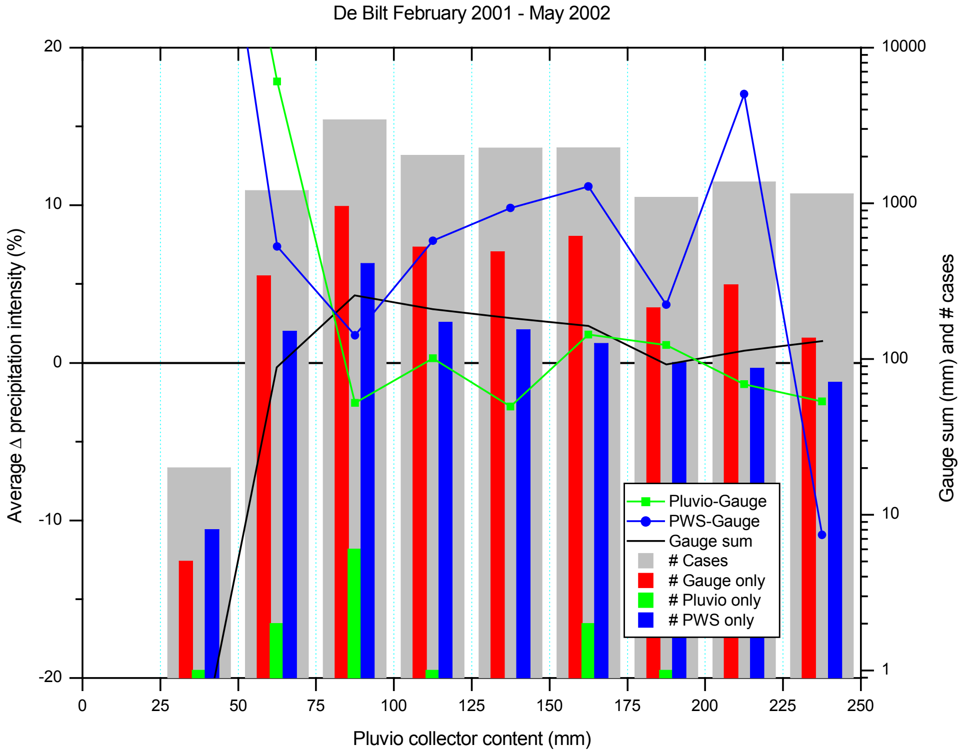

Figure 17: As Figure 16, but now the relative differences and number of cases are given as a function of the collector content of the Pluvio in bins of 25mm.

An analysis as a function of the collector content is considered in order to find out whether splash out when the collector of the Pluvio is nearly full plays a role. The relative differences between the measured precipitation amounts as a function of the collector content of the Pluvio are given in Figure 17. Figure 17 shows large relative differences between the PWS and Pluvio compared to the KNMI gauge when the collector is nearly empty. The number of cases and amount of precipitation involved is however small. During periods with sunny weather water evaporates from the collector, so that event with low collector content will generally occur during summer. During such periods the KNMI gauge is also more sensitive to faulty precipitation reports, but that cannot be observed in Figure 17. The Pluvio reports about 15mm more precipitation than the KNMI gauge when the collector contains less than 75mm. A small collector content, and hence a lighter collector makes it more sensitive to wind induced vibrations and possibly faulty precipitation report of the Pluvio, but this too is not confirmed by the Pluvio only precipitation numbers as a function of the collector contents. Furthermore, the strong increase in the differences for a nearly empty collector can also be observed in the difference PWS-Gauge. The Pluvio-Gauge curve shows a slight dependence on the collector content between 150 and 250mm. The curve decreases smoothly from 2 to –3%, but the differences of about 2mm per bin are of the same order of magnitude as the KNMI gauge only precipitation reports which also decrease slightly with collector contents. Hence any splash out losses of the Pluvio when the collector is nearly full are estimated to be less than 1%.

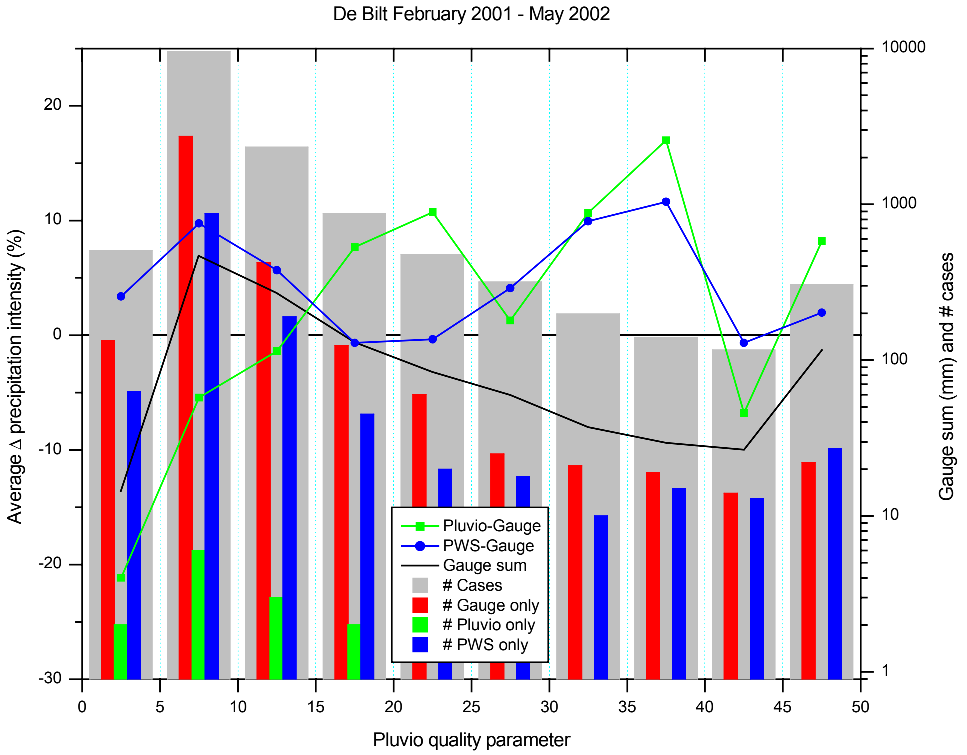

Figure 18: As Figure 16, but now the relative differences and number of cases are given as a function of the quality parameter of the Pluvio in bins of 5 units.

An analysis as a function of the quality parameter of the Pluvio is considered in order to find out whether differences can be explained in terms this parameter. The quality parameter generated by the Pluvio is based on raw 6 seconds weight measurements. Vibrations of the collector generated by the wind or precipitation can influence these raw measurements and lead to fluctuations of the raw weight measurement. The quality parameter is a dimensionless internal measure for these fluctuations. Ott considers a measurement with a quality parameter less than 20 a good measurement. Figure 18 shows that the largest differences occur when the quality parameter is below 10. The few faulty Pluvio cases also occur at low quality parameter values. However, the Pluvio measurements are considered good under these conditions. The differences can again be explained by the contribution of faulty KNMI gauge only precipitation events that occur mainly during sunny/calm conditions and hence a low quality parameter of the Pluvio. At quality parameters above 15 the Pluvio generally overestimates the precipitation amount reported by the KNMI gauge, although the few Pluvio only precipitation events hardly occur in this range.

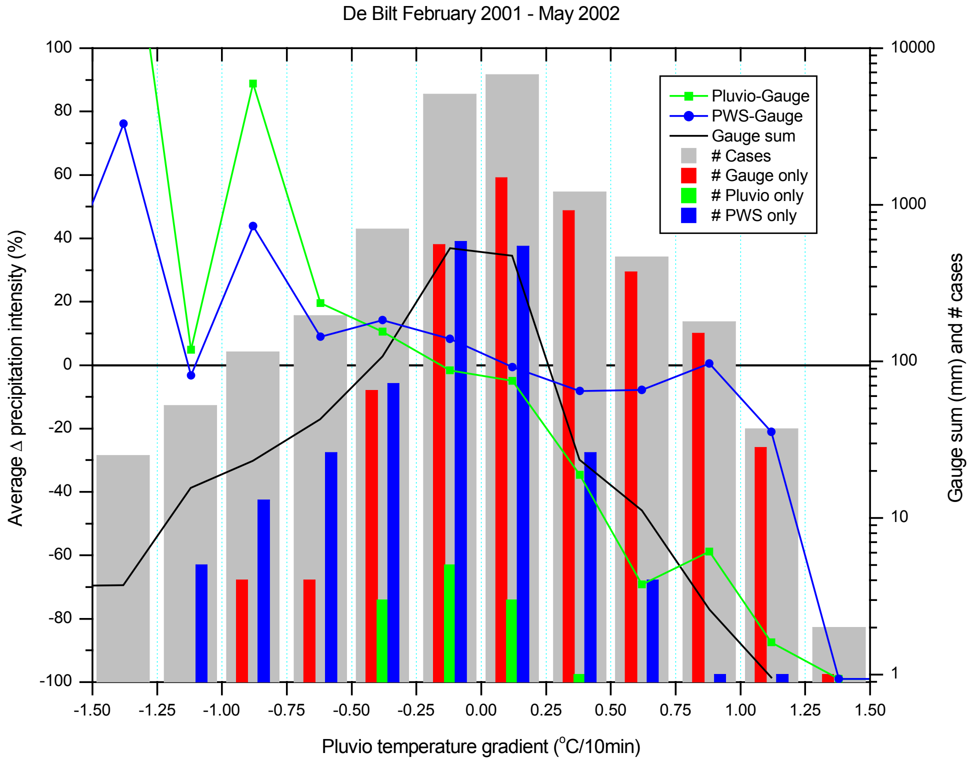

Figure 19: As Figure 16, but now the relative differences and number of cases are given as a function of the temperature gradient of the Pluvio in bins of 0.25°C/10min.

Finally, the differences are studied as a function of the temperature and temperature gradient as measured by the Pluvio. The results of the differences as a function of the temperature of the Pluvio are not shown because they give the same information as when the ambient temperature is used (cf. Figure 15). The differences as a function of the temperature gradient of the Pluvio are given in Figure 19. The temperature gradient is defined as the change in the 10-minute averaged temperature compared to the previous 10-minute interval. Figure 19 shows that for temperature gradients larger than 0.25ºC the number of KNMI gauge only precipitation events is relatively large. The number of gauge only event is, however, small when the temperature gradient is negative. All 12 cases where the Pluvio only reported precipitation with a total precipitation amount of 0.5mm occur within the temperature gradient range of –0.5ºC to +0.5ºC. Hence, no dependency on the temperature gradient can be observed in the results of the Pluvio. The general behavior of the curves Pluvio-Gauge and PWS-Gauge with the temperature gradient can partly be explained by the occurrences of faulty KNMI gauge only reports at gradients above 0.25ºC. Furthermore, it seems like the KNMI gauge shows a dependency on the temperature gradient, since the curves for Pluvio and PWS show the same behavior. This could be explained by the fact that when the temperature increases the amount of water in the reservoir of the KNMI gauge expands causing an overestimation of the observed precipitation amount. However, during the design of the KNMI gauge this aspect was considered and estimated to be negligible.

5.3.6 Faulty precipitation readings

The behavior of the faulty readings of the precipitation sensors is studied next in more detail. As mentioned before, a sensor reading is considered faulty when it reports precipitation in a 10-minute interval, but the other 2 sensors do not report precipitation in that 10-minute interval, nor (if available) in the previous or next interval. The number of cases and amount of precipitation when a sensor reported faulty precipitation and the number and amount when that sensor reported precipitation together with at least 1 of the other sensors is determined as a function of several parameters. It should be noted that the so-called faulty cases could also be the result of a higher sensitivity, other time constant or local differences. In general, the faulty readings for the field test in De Bilt showed no clear dependence on wind speed and direction (cf. Figure 12 and Figure 14). All cases with faulty readings for the PWS (1273 out of a total of 10178 precipitation reports) and Pluvio (13 of 6117) occur in the precipitation intensity bins below 1.5 and 1 mm/h and for the PWS occur mainly in the bin for traces of precipitation with intensity less than 0.05mm/h (cf. Figure 13). The faulty cases for the KNMI gauge also occur mainly for traces (3442 out of a total of 12672 precipitation reports), but some cases occur at higher intensity values up to 6mm/h.

Table 8 shows the faulty values as a function of the ambient temperature for each of the 3 precipitation sensors (cf. also Figure 15). Note that the number of cases differs slightly from the numbers reported above for the dependency on intensity. This is caused by selection since a valid temperature is required in Table 8. The results for PWS show that number of cases where the PWS only reports precipitation are generally much less than the number of cases where precipitation is simultaneously reported by other sensors. Only at ambient temperatures above 20ºC does the number of PWS only events exceed the number where precipitation is also reported by another sensor, however, the number of PWS only cases involved is only small. The situations where the PWS only reports precipitation are mainly the result of cases with light precipitation and the higher sensitivity of the PWS compared to the other 2 precipitation sensors. Furthermore, spatial differences and the faster response time of the PWS can lead to PWS only events at the start of precipitation. The results for the KNMI gauge show generally more cases where the gauge detects any precipitation. The number of Gauge only cases is much higher than for the other 2 sensors. Almost half of the cases is reported as gauge only events for temperatures above 10ºC and the gauge only cases exceed the other cases above 17.5ºC. These high numbers are caused by the faulty precipitation reports of the KNMI gauge during clear weather. The number of cases where the Pluvio reports precipitation is much lower compared to the other 2 sensors. This is the result of the reporting threshold used by the Pluvio. The amount of Pluvio only cases is negligible over the entire temperature range. The amount of precipitation involved in the gauge only cases is overall much smaller than the amount when the gauge reports precipitation together with another sensor. The amount of precipitation involved in the gauge only cases exceeds that for the PWS only cases at nearly all temperatures, but particularly between 12.5 and 25ºC, whereas the amount for Pluvio only is negligible, excepts for the isolated event at 25ºC which shows up in relative values because of the small amount of cases involved.

The faulty results as a function of the relative humidity occur generally at all relative humidity bins for the PWS, but the faulty cases for the KNMI gauge occur particularly at relative humidity values less than 85%, whereas the few faulty Pluvio occur mainly at low and at high relative humidity values (cf. Figure 16).

Table 8: Number of 10-minute intervals and the total precipitation amount (mm) where one sensor reported faulty precipitation or precipitation was reported simultaneously with at least one of the other sensors. The results are given as a function of the ambient temperature in bins of 2.5ºC and for each of the 3 precipitation sensors involved for the field test in De Bilt.

Temp. range	***PWS only***		***PWS&other***		***Gauge only***		***Gauge&other***		***Pluvio only***		***Pluvio&other***	
	#	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***
0-2.5	137	1.11	902	94.23	180	1.35	910	77.54	0	0.00	601	77.42
2.5-5	146	0.80	875	98.45	195	0.37	882	87.29	2	0.15	620	91.59
5-7.5	163	1.15	1366	163.23	309	0.53	1372	145.72	2	0.06	955	147.60
7.5-10	166	1.23	1937	253.92	513	1.02	2000	242.80	2	0.06	1335	243.86
10-12.5	219	1.48	1570	260.15	537	1.00	1627	262.83	5	0.20	1125	264.50
12.5-15	150	1.06	1096	201.63	523	4.43	1125	192.08	0	0.00	747	210.20
15-17.5	150	1.11	744	132.91	478	3.04	751	134.00	0	0.00	455	127.61
17.5-20	47	0.29	205	59.75	358	2.32	218	54.11	0	0.00	124	51.72
20-22.5	26	0.36	27	5.28	219	0.33	25	6.62	0	0.00	19	5.87
22.5-25	3	0.05	10	0.92	115	0.75	7	0.64	1	0.03	1	0.22
25-27.5	4	0.11	0	0.00	53	0.07	0	0.00	1	0.04	0	0.00
27.5-30	1	0.00	0	0.00	18	0.03	0	0.00	0	0.00	0	0.00
Total	**1212**	**8.74**	**8732**	**1270.46**	**3498**	**15.23**	**8917**	**1203.63**	**13**	**0.54**	**5982**	**1220.59**

The behavior of the faulty readings of the KNMI gauge during clear days is shown in more detail in Table 9, which shows the results as a function of the global radiation. The PWS and Pluvio show most faulty cases at low values of the global radiation. The ratio between the number of cases for sensor only and for sensor and at least one other sensor slightly increases for higher values of the global radiation for PWS and Pluvio. The number of faulty cases involved is, however, small. The KNMI gauge shows large numbers of faulty cases at all global radiation values, and these numbers for gauge only exceed the number of cases where the gauge and another sensor report precipitation when the global radiation is above 200W/m^2. The total amount of precipitation involved in these faulty cases is generally small. This clearly illustrates the faulty, low intensity readings of the KNMI gauge during clear days.

Table 9: Results as in Table 8, but now as a function of the global radiation in bins of 100W/m^2.

Global rad. range	**PWS only**		**PWS&other**		**Gauge only**		**Gauge&other**		**Pluvio only**		**Pluvio&other**	
	#	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**
0-100	1109	7.66	8067	1204.81	1339	7.49	8120	1142.98	8	0.35	5650	1153.86
100-200	106	0.76	499	58.95	338	1.12	512	49.80	2	0.06	286	54.04
200-300	31	0.32	168	14.30	336	1.37	198	9.13	1	0.06	79	10.76
300-400	10	0.08	48	2.75	298	1.49	70	1.25	0	0.00	22	2.99
400-500	5	0.03	25	0.75	268	1.43	48	0.61	1	0.03	8	1.32
500-600	3	0.01	11	0.81	237	0.40	21	0.30	0	0.00	6	0.32
600-700	1	0.00	4	1.44	200	0.35	11	2.33	0	0.00	0	0.00
700-800	0	0.00	7	0.18	209	1.35	14	0.19	0	0.00	2	0.27
800-900	0	0.00	3	0.23	182	0.25	17	0.05	0	0.00	1	0.11
>900	1	0.01	4	0.26	129	0.25	10	0.17	1	0.04	1	0.05
Total	**1266**	**8.86**	**8836**	**1284.47**	**3536**	**15.50**	**9021**	**1206.79**	**13**	**0.54**	**6055**	**1223.72**

The faulty sensor readings were also investigated as a function of the collector content of the Pluvio, the quality parameter of the Pluvio and the temperature gradient of the Pluvio. There is no clear correlation of the faulty reports with the collector content. The Pluvio seems to report more faulty report when the collector content is small. For a collector containing less then 100mm the faulty versus correct numbers are 9 and 1591 whereas above 100mm the numbers are 4 and 4513. It seems that, as could be expected, a lighter collector is more sensitive to e.g. wind induced or precipitation induced vibrations and hence faulty reports. The faulty cases show no dependency with the quality parameter of the Pluvio. Most cases with precipitation occur at low values for the quality parameter indicating a high quality of the Pluvio measurement. Nearly all faulty Pluvio cases occur when the Pluvio reports a good quality. As mentioned above, most faulty KNMI gauge cases occur when the temperature gradient is positive, whereas all faulty Pluvio cases occur within the temperature gradient range of –0.5ºC to +0.5ºC.

The available amount data does not allow a detailed analysis of the results as a function of several parameters.

5.3.6 Precipitation duration

The specifications of the Pluvio, in particular the threshold of 0.03mm in 20 minutes for reporting precipitation, already indicated that the Pluvio is not suitable for the determination of precipitation duration. This was clearly indicated during days with very light precipitation (cf. e.g. Figure 3). Also the internal update frequency and integration interval of 1-minute might be a problem in the determination of accurate precipitation duration from 1-minute precipitation intensities. This, however, turned out to be no problem in the precipitation duration determination for the PWS, using running 1-minute averaged precipitation intensity reports from the sensor. Although the Pluvio seems to be unsuitable for precipitation duration determination from the very start, the precipitation duration is determined from the reported 1-minute averaged intensity in order to give exact numbers. Each minute where the Pluvio reports precipitation intensity above zero generates 60 seconds of precipitation duration. In case the Pluvio does not report any precipitation in the previous or next minute, only 30 seconds of duration is assumed.

The comparison is done in 3 ways. Table 10 reports the monthly precipitation duration for the 3 sensors as well as for the hourly validated climatological data. The results for the KNMI gauge and the climatological data show good agreement, although the gauge generally reports higher values. Note that an Eigenbrodt precipitation detector measured the precipitation duration up to November 2001, and afterwards it was derived from the measurements of the precipitation gauge. The PWS generally reports higher monthly precipitation duration values than the KNMI gauge due the to higher sensitivity of the PWS, even though the sensor interface of the PWS uses a threshold of 0.03mm/h for each 1-minute averaged precipitation intensity for reporting precipitation duration. Only during some months does the gauge report larger values. In summer conditions this can be caused by faulty precipitation reports during clear days, in winter by extension of the period of precipitation as a result of melting solid precipitation (cf. Figure 1). Table 10 clearly shows that the precipitation duration derived from the Pluvio is much less compared to that of the other 2 sensors. The monthly underestimation ranges between a factor 3 to 5, and the total duration is less by a factor 3.5.

Table 10: Monthly precipitation duration derived from the PWS, KNMI gauge and Pluvio sensors and the validated hourly climatological values for De Bilt.

Month	***Precipitation duration (hours)***			
	PWS	***Gauge***	***Pluvio***	***Klim***
0201	107.2	90.1	23.5	92.8
0301	90.3	66.5	19.7	66.4
0401	77.1	72.9	21.9	69.5
0501	28.7	26.1	6.7	22.6
0601	31.4	33.9	9.9	30.8
0701	42.9	47.7	14.0	44.2
0801	43.0	46.8	14.8	42.7
0901	110.2	110.3	37.7	104.6
1001	35.5	30.7	9.0	28.7
1101	79.4	81.3	17.0	76.4
1201	106.8	113.8	27.9	109.8
0102	72.8	71.0	17.9	69.0
0202	111.3	117.3	40.0	113.2
0302	44.8	42.4	8.0	39.4
0402	60.0	57.5	11.6	56.0
0502	27.3	29.6	5.1	28.7
Total	**1068.6**	**1037.8**	**284.7**	**994.8**

Table 11 reports the number of hours with reported precipitation duration during the field test in De Bilt for each of the 3 precipitation sensors as well as for the validated hourly climatological data per month. The number of hours with valid data per month that are considered is also reported. The table also lists the number of hours where only traces of precipitation, i.e. an hourly sum less than 0.05mm, are reported. Table 10 shows large differences between gauge and the climatological values, with the gauge reporting fewer hours with precipitation. The PWS reports even fewer cases than the gauge. Taking into account the hours where only traces of precipitation are reported, shows that the differences between the climatological values, gauge and PWS are mainly caused by differences in these traces. The number of hours where the Pluvio reports precipitation is again much less than the number reported by the other sensors. This is also the case if the traces are taken into account.

Table 11: The number of hours where a precipitation sensor reported precipitation (duration) during the field test in De Bilt is given per month. The total number of valid hours considered and the number of hours reporting only traces of precipitation are also listed.

Month	***# hours***	***# hours with precipitation***				***# hours with traces***			
		PWS	***Gauge***	***Pluvio***	***Klim***	***PWS***	***Gauge***	***Pluvio***	***Klim***
0201	592	153	159	97	223	25	32	4	79
0301	735	136	134	73	230	31	41	3	126
0401	675	116	143	69	213	17	43	2	89
0501	739	49	66	21	84	10	33	2	41
0601	705	58	105	30	116	11	51	1	57
0701	737	77	118	42	158	14	58	2	71
0801	723	76	117	42	153	14	51	2	74
0901	704	176	235	108	303	30	85	3	125
1001	704	62	78	30	115	16	39	1	65
1101	655	121	146	74	215	24	48	4	102
1201	743	164	189	102	278	26	47	5	114
0102	719	110	116	69	174	24	32	2	75
0202	663	164	192	108	264	28	52	3	99
0302	718	64	87	33	102	8	38	0	49
0402	700	80	99	50	132	13	32	1	58
0502	360	38	64	26	88	4	26	1	47
Total	**10872**	**1649**	**2054**	**982**	**2848**	**299**	**713**	**42**	**1271**

Finally, the performance of the precipitation detection of the three sensors is studied in terms of the raw 10-minute averaged precipitation intensity data. This is done by means of 2-by-2 contingency matrices that show the agreement between precipitation reports of any set of precipitation sensors involved. The two cases considered in the contingency matrix are precipitation or not. Precipitation is defined as an event where the reported intensity is larger than zero. In addition, the contingency matrices are constructed by considering only events with intensities larger than 0.05mm/h as precipitating. The latter threshold is considered to get the score when ignoring the cases with traces of precipitation. The contingency matrices are given in Table 12 together with some relevant scores (cf. Kok, 2000). Comparison of the results of the PWS and KNMI gauge shows that the gauge has a POD of about 80% and a large false alarm rate of 36%. The FAR reduces to 10% when a threshold of 0.05mm/h is used for precipitation detection increasing the overall score from 54 to 75%. Comparison of the results of the PWS and Pluvio shows that the Pluvio has a POD of about 60% and a small false alarm rate of 2%. When a threshold of 0.05mm/h is used for precipitation detection the POD increases to 74% while the FAR increases to 6%. The overall CSI score of the Pluvio is 58% and 71%

for thresholds 0.00 and 0.05mm/h, respectively. When a threshold of 0.00mm/h is used for precipitation detection the results of the KNMI gauge and the Pluvio show large differences compared to the PWS. The KNMI gauge reports a large number of false alarms (36%) and the probability of detection for the Pluvio is only 59%. The overall score is better for the Pluvio. When a threshold of 0.05mm/h is used for precipitation detection the results of the KNMI gauge and the Pluvio compare equally well to the PWS. The gauge has a better POD whereas the Pluvio has a better FAR. Overall the results of the gauge are slightly better.

Table 12: Contingency matrices for the precipitation detection by all sets of precipitation sensors based on the 10-minute averaged precipitation readings and the corresponding scores. Results are given using a threshold for precipitation detection of 0.00mm/h and 0.05mm/h.

Contingency matrix				Scores
		Sensor		POD= Probability Of Detection = 100%*Hit/(Hit+Miss)
		Yes	No	FAR= False Alarm Rate = 100%*False/(False+Hit)
Ref	Yes	Hit	Miss	CSI= Critical Success Index = 100%*Hit/(Hit+Miss+False)
	No	False	None	BIAS= (Hit+False)/(Hit+Miss)

Threshold 0.00mm/h

		Gauge		Scores
				POD= 79.1
		Yes	No	FAR= 36.4
PWS	Yes	8055	2123	CSI= 54.4
	No	4617	51153	BIAS= 1.25

		Pluvio		Scores
				POD= 58.9
		Yes	No	FAR= 2.0
PWS	Yes	5995	4183	CSI= 58.2
	No	122	55648	BIAS= 0.60

		Pluvio		Scores
				POD= 47.3
		Yes	No	FAR= 2.0
Gauge	Yes	5994	6678	CSI= 46.8
	No	123	53153	BIAS= 0.48

Threshold 0.05mm/h

		Gauge		Scores
				POD= 81.5
		Yes	No	FAR= 10.0
PWS	Yes	6297	1426	CSI= 74.8
	No	700	57525	BIAS= 0.91

		Pluvio		Scores
				POD= 74.3
		Yes	No	FAR= 6.2
PWS	Yes	5737	1986	CSI= 70.8
	No	380	57845	BIAS= 0.79

		Pluvio		Scores
				POD= 81.5
		Yes	No	FAR= 6.7
Gauge	Yes	5705	1292	CSI= 77.0
	No	412	58539	BIAS= 0.87

6. Results for De Kooy and discussion

In this section the results for the field test at De Kooy for the period May 25, 2002 to August 11, 2003 are discussed. Again, the comparison considers only those 10-minute intervals were the precipitation measurements of all three precipitation sensors are available and valid. The missing data was largely caused by gaps in the data acquisition resulting from problems with the data-acquisition PC used for the Pluvio and a gap caused by a switch to the new measurement network.

During the field test in De Kooy the Pluvio operated technically correctly. The sensor, except the messages when the heater was on, the collector was more than 80% filled or the housing was removed for maintenance, reported only 1 warning for a system restart after a power failure on January 23, 2003. The collector of the Pluvio was emptied on 1 occasion namely on January 7, 2001. During summer conditions the rate of evaporation is such that the collector does not easily fill up completely. The collector is mostly nearly empty during summer.

6.1 Comparison raw sensor data with validated hourly data

Monthly sums of the precipitation amounts obtained by all 3 sensors are given in Figure 20 and compared to the summed hourly climatological data as obtained by the climatological department. Monthly differences in percentage are also shown. The numerical values have also been listed in Table 13. In this section only those hours are considered where all 10-minute intervals of all 3 sensors have valid readings. Since the time window between sensor data and KLIM is shifted 5 minutes, the hourly value requires 7 valid 10-minute intervals. Furthermore, if an hourly value is rejected and the first 10-minute interval reports precipitation then the previous hour is also disregarded. Similarly the next hour is disregarded in case the previous hour is rejected and the last 10-minute interval reported precipitation.

The monthly results show that the sums for KNMI gauge and the KLIM data are quite close, i.e. within ±1mm, as could be expected, since the KLIM data are mainly based on the sensor reading from the KNMI gauge. However, Figure 20 also shows some striking differences between the KNMI gauge and KLIM for July and August 2002 where the gauge reported respectively 5 and 11mm less precipitation than KLIM. Also in February 2003 the difference of 6mm between gauge and KLIM is large. In these cases the large differences between KNMI gauge and KLIM occur on specific days, namely July 21, August 4 and 20, 2002 and February 1, 2003. On these days, the sensor readings of the KNMI gauge show the same precipitation events and intensity variations as the results of the other sensors, but the magnitude during some precipitation events differs for some unknown reason. The status information reported by the KNMI gauge did not indicate any problems during these days. Furthermore, the differences are isolated events that disappeared without any intervention. During the field test 2 different KNMI gauges were in use at De Kooy. The pre-calibration check of these sensors after they were replaced for routine calibration showed that they still were within ±1% of the reference. The change of the KNMI gauge occurred on June 2, 2003. It is noteworthy that prior to the field test in April 2000 and March 2001 the previously used precipitation gauges at De Kooy were replaced as a result of user complaints of too low precipitation amounts. The pre-calibration check of these sensors indicated, however, no problems.

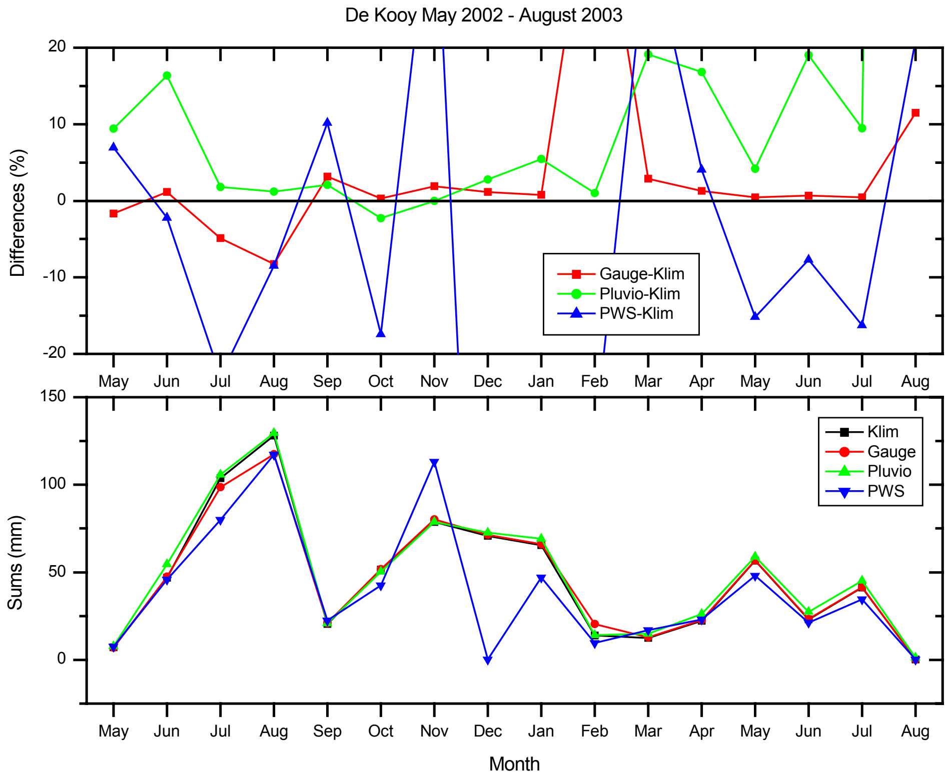

Figure 20: Monthly precipitation amounts for De Kooy using the ‘raw’ 10-minute data for all hours where valid data of the three precipitation sensors is available. The results are compared to the validated hourly results from the climatological department.

The differences between Pluvio and KLIM are generally larger than those for the KNMI gauge, and range between –1 and 8mm. This could be expected when comparing the results for 2 different types of precipitation sensors during a field test. Generally the Pluvio gives higher precipitation amounts than KLIM. However, the differences between Pluvio and KLIM for the field test in de Kooy are larger that for the test in De Bilt (cf. Table 4). Overall the differences between Pluvio and KLIM in De Kooy are 34mm or 4.5% compared to –5mm or –0.5% for De Bilt. The differences between KNMI gauge and KLIM for De Kooy and De Bilt are –4mm (–0.4%) and –4mm (–0.5%), respectively, and agree well.

On a daily basis the precipitation amounts between the Pluvio and the climatological data are generally within ±0.5mm. In the last week of June the daily differences are larger, but this is the result of a time difference caused by a faulty time stamp of the data acquisition PC. On July 21, 2002 the Pluvio reports about 1.7mm more precipitation than KLIM, whereas the KNMI gauge reports 5.5mm less than KLIM for some unknown reason. On December 24, 2002 the Pluvio reports 1.3mm excess of precipitation whereas KLIM and

KNMI gauge agree nicely. The daily results show 3 precipitation events, but the Pluvio also reports precipitation between the last 2 precipitation events. On December 22, 2002 and January 1, 2003 the daily Pluvio results exceed the KLIM sums by 1.0 and 1.5mm, respectively, whereas the gauge agrees with KLIM. On these 2 days the precipitation intensity results of Pluvio and gauge show the same behavior, but the results for Pluvio are higher. The previously mentioned differences cannot be compared to the results of the PWS, because these results where erroneously put to zero in the archiving process while making the transition to the new measurement network. The last day where the daily Pluvio and KLIM results differ more that 1mm is February 1, 2003. The Pluvio results are 1.7mm lower than KLIM, whereas the KNMI gauge reports 6.5mm too much. The results for the PWS report 1.6mm less than KLIM and agree well with the Pluvio results. Another striking feature that can be observed in the daily precipitation plots is that the Pluvio sometimes reports faulty precipitation events. The first noticeable faulty events were observed on March 12, 2003, but since then they have been observed on several days. Faulty precipitation events by the Pluvio have also frequently been observed by the DWD and the USGS (cf. Lanzinger, 2004 and Tumbusch, 2003).

The monthly and daily precipitation amounts for the present weather sensor show large differences. The overall results are mostly affected by the absence of PWS data in December 2002 and some adjoining days, when the PWS data were erroneously put to zero in the archiving process while making the transition to the new measurement network. The daily results show that the PWS sometimes overestimates the precipitation amount whereas on other days an underestimation can be observed. The daily differences can show large day-to-day fluctuations. The reasons for these large differences between PWS and the other precipitation sensors are unclear. The differences will, however, partly be affected by the large distance of about 300m between the PWS and the other 2 precipitation sensors. The same PWS was in operation during the entire period of the field test in De Kooy.

Table 13: Monthly sums and differences between the precipitation amounts reported by the Vaisala PWS, the KNMI gauge, the Ott Pluvio, and the validated sum for the field test in De Kooy. All hours are considered where valid precipitation data of all three sensors is available.

Month	*Sum (mm)*				*# valid hours*	*Differences (mm)*		*Differences (%)*	
	PWS	*Gauge*	*Pluvio*	*Klim*		*Ga-Kl*	*Pl-Kl*	*Ga-Kl*	*Pl-Kl*
0502	7.6	7.0	7.8	7.1	153	–0.12	0.67	–1.64	9.44
0602	45.9	47.4	54.6	46.9	713	0.53	7.67	1.13	16.35
0702	80.0	98.7	105.7	103.8	744	–5.05	1.89	–4.87	1.82
0802	117.2	117.4	129.5	128.0	568	–10.59	1.51	–8.27	1.18
0902	22.5	21.0	20.8	20.4	566	0.65	0.42	3.17	2.06
1002	42.6	51.8	50.4	51.6	577	0.16	–1.18	0.31	–2.29
1102	113.2	80.2	78.7	78.7	704	1.51	–0.03	1.91	–0.04
1202	0.1	71.5	72.7	70.7	741	0.82	1.96	1.16	2.77
0103	47.0	66.0	69.1	65.5	738	0.50	3.57	0.76	5.45
0203	9.5	20.4	14.0	13.9	594	6.47	0.14	46.58	1.01
0303	17.0	12.9	14.9	12.5	742	0.36	2.39	2.90	19.12
0403	23.2	22.6	26.1	22.3	658	0.29	3.75	1.29	16.82
0503	48.0	56.8	59.0	56.6	734	0.25	2.37	0.44	4.19
0603	21.3	23.3	27.5	23.1	627	0.16	4.39	0.69	19.00
0703	34.6	41.5	45.2	41.3	742	0.19	3.92	0.46	9.49
0803	0.2	0.2	1.1	0.2	263	0.02	0.90	11.50	450.00
Total	**629.8**	**738.8**	**776.9**	**742.6**	**9864**	**–3.84**	**34.35**	**–0.52**	**4.63**

6.2 Comparison after rejection of faulty data

The previous section showed that several instances could be indicated where sensor readings were obviously faulty. The data for De Kooy were also subjected to the data rejection mechanism as mentioned in section 5.2 for De Bilt. This data manipulation was, however, not considered useful for this study.

Another comparison was performed by considering only the data obtained for De Kooy in the period July 2002 to January 2003 and rejecting all other data. This interval was considered because the monthly results as given in Table 13 showed smaller differences between Pluvio and KLIM during this period. This alternative period also facilitated investigation of the fact that faulty Pluvio events, which were observed since March 2003, might have affected the results. However, the analysis of the results of De Kooy for the period July 2002 to January 2003 in graphs similar to the ones shown below for the entire period of the field test did not show any essential differences.

Table 14: As Table 13, but now the faulty sensor readings are omitted.

Month	**Sum (mm)**				**# valid hours**	**Differences (mm)**		**Differences (%)**	
	PWS	***Gauge***	***Pluvio***	***Klim***		***Ga-Kl***	***Pl-Kl***	***Ga-Kl***	***Pl-Kl***
0502	0.1	0.0	0.1	0.1	78	–0.07	–0.02	–73.00	–20.00
0602	4.1	4.4	5.3	4.4	368	0.01	0.86	0.23	19.55
0702	6.4	4.5	4.5	4.4	444	0.13	0.10	2.97	2.27
0802	1.5	1.4	1.3	1.4	390	–0.02	–0.13	–1.74	–9.29
0902	3.5	1.3	1.3	1.3	383	–0.03	0.03	–2.38	2.31
1002	1.3	1.7	1.7	1.7	332	0.02	0.04	1.14	2.35
1102	34.0	31.3	31.1	30.8	536	0.49	0.32	1.59	1.04
1202	0.1	64.2	65.8	63.5	681	0.66	2.25	1.04	3.54
0103	42.5	58.2	59.9	59.2	612	–1.04	0.74	–1.75	1.25
0203	9.2	19.0	12.1	13.0	539	5.97	–0.88	45.91	–6.77
0303	15.4	12.3	11.3	12.0	636	0.33	–0.69	2.76	–5.75
0403	21.8	21.6	21.5	21.4	546	0.22	0.11	1.03	0.51
0503	44.4	54.2	54.3	54.1	616	0.06	0.23	0.12	0.43
0603	18.1	21.2	20.9	21.2	503	0.01	–0.28	0.05	–1.32
0703	33.5	39.8	39.5	39.8	612	–0.05	–0.31	–0.11	–0.78
0803	0.2	0.2	0.3	0.2	229	–0.02	0.06	–12.00	30.00
Total	**236.0**	**335.2**	**330.9**	**328.5**	**7505**	**6.67**	**2.43**	**2.03**	**0.74**

Finally, a comparison has also been performed on the hourly data, but after elimination of the so-called faulty cases, i.e. the cases where one sensor reports precipitation but the other 2 sensors do not report any precipitation in that 10-nimute interval, nor (if available) in the previous or next interval. The corresponding monthly results are shown in Table 14. After this rejection the results of KNMI gauge, Pluvio and KLIM show a good overall agreement within 1 or 2 mm. Note that the overall difference of 7mm between KNMI gauge and KLIM is mainly caused by the 6mm difference in February. The number of cases (7505 versus 9864), and particularly the amount of precipitation involved (329 versus 743mm), is, however, largely reduced by this rejection scheme. This results in high values for the relative differences in some months. This rejection scheme will not be considered in the following analysis due to the large reduction in the number of cases with precipitation. Since the elimination of faulty cases improves the overall results considerably, the influence of the faulty cases will be studied in detail.

6.3 Comparison of raw 10-minute data

The remaining part of this section deals with the comparison of raw 10-minute sensor readings in a similar way as performed for De Bilt in section 5.3. The comparison will be done directly on the 10-minute sensor data for all cases where the data for all 3 sensors is available. Furthermore, the 1-minute data of the Pluvio can be summed on the correct 10-minute time intervals on which the other sensor data was available in the old and new measurement networks.

Table 15: As Table 6, but now for the field test in De Kooy.

Month	***Sum (mm)***			***Number***		***Pluvio-Gauge***			***PWS-Gauge***		
	PWS	***Gauge***	***Pluvio***	***Total***	***Valid***	***Dif (mm)***	***Dif (%)***	***StD (%)***	***Dif (mm)***	***Dif (%)***	***StD (%)***
0502	11.9	8.4	9.1	1152	948	0.70	8.31	0.14	3.55	42.27	1.06
0602	48.0	50.5	57.5	4320	4292	7.05	13.97	0.76	–2.45	–4.85	0.42
0702	80.0	98.7	105.7	4464	4464	6.94	7.03	1.30	–18.77	–19.01	1.40
0802	117.2	117.4	129.5	4464	3424	12.09	10.30	2.32	–0.26	–0.22	1.49
0902	22.6	21.2	20.9	4320	3433	–0.31	–1.46	0.10	1.37	6.48	0.65
1002	73.0	74.9	73.4	4464	3860	–1.59	–2.12	0.27	–1.93	–2.58	0.88
1102	113.2	80.3	78.7	4320	4259	–1.63	–2.03	0.94	32.88	40.95	1.45
1202	0.1	71.5	72.8	4464	4461	1.24	1.74	0.20	–71.43	–99.88	1.27
0103	47.0	66.0	69.1	4464	4451	3.07	4.66	0.41	–19.02	–28.83	1.05
0203	9.5	20.4	14.1	4032	3594	–6.30	–30.94	0.57	–10.83	–53.16	0.54
0303	17.0	12.9	15.0	4464	4462	2.10	16.31	0.23	4.09	31.80	1.10
0403	23.2	22.6	26.1	4320	3958	3.47	15.36	0.19	0.61	2.70	0.45
0503	48.0	56.9	59.0	4464	4414	2.11	3.71	0.21	–8.84	–15.55	0.75
0603	21.3	23.3	27.5	4320	3776	4.23	18.18	0.24	–1.94	–8.32	0.71
0703	34.6	41.5	45.2	4464	4461	3.73	8.99	0.42	–6.90	–16.63	0.90
0803	0.2	0.2	1.1	1584	1582	0.88	393.27	0.14	0.02	8.52	0.09
Total	**666.8**	**766.7**	**804.5**	**64080**	**59839**	**37.78**	**4.93**	**0.87**	**–99.87**	**–13.03**	**1.06**

The monthly precipitation amounts for PWS, KNMI gauge and Pluvio as well as their differences are given in Table 15. The number of 10-minute intervals included is also reported. About 93% of the data is used in the comparison. This availability number is less than for De Bilt, because the data-acquisition PC regularly experienced problems in De Kooy. The comparison between 10-minute KNMI gauge and Pluvio results shows generally the same results as the hourly given in Table 13. The monthly precipitation amounts of the PWS show very large differences with the gauge and Pluvio results and the differences vary largely from month tot month. The reason for the strange behavior of the results of the PWS is unknown, but could be related to the large spatial distance between the PWS and the other 2 precipitation sensors. However, when the faulty precipitation cases are rejected in the 10-minute data the overall agreement between Pluvio and KNMI gauge is 9mm (1%), but the agreement between PWS and gauge does not improve.

Some statistical information is reported in Table 16. The information is derived from the monthly, daily, hourly summed values as well as from the raw 10-minute values mentioned above. In each case only those cases are considered where one of the three sensors reported precipitation. The total amount of precipitation for PWS, KNMI gauge and Pluvio are 667, 767 and 804mm, respectively. Table 16 shows that the statistical results for De Kooy are generally worse than for De Bilt (cf. Table 7). The table also shows that the precipitation amounts for the PWS are much worse than the Pluvio results, particularly when dealing with monthly and daily time intervals. The various tests do not clearly show the better performance of the Pluvio compared to that of the PWS.

Table 16: As Table 7, but now for the precipitation amounts for De Kooy.

Parameter	***Pluvio–Gauge***				***PWS–Gauge***			
	Monthly	***Daily***	***Hourly***	***10’***	***Monthly***	***Daily***	***Hourly***	***10’***
Number of cases	16	359	2992	9331	16	359	2992	9331
Mean	2.36	0.11	0.01	0.00	–6.24	–0.28	–0.03	–0.01
Average deviation	3.01	0.24	0.06	0.03	12.29	1.09	0.16	0.06
Standard deviation	4.20	0.78	0.24	0.14	20.92	2.69	0.49	0.17
Median	2.10	0.03	0.00	–0.00	–1.94	-0.00	–0.00	–0.00
5 percentile	–6.30	–0.24	–0.08	–0.06	–71.43	–3.87	–0.49	–0.17
95 percentile	7.05	0.47	0.10	0.06	4.09	1.56	0.12	0.05
Correlation coefficient	1.00	0.98	0.96	0.89	0.83	0.79	0.81	0.80
T-test for mean	Agree	Agree	Agree	Agree	Agree	Agree	Agree	Differ
Paired T-test for mean	Differ	Differ	Differ	Differ	Agree	Agree	Differ	Differ
F-test for variance	Agree	Agree	Differ	Differ	Agree	Agree	Differ	Differ
KS-test for distribution	Agree	Differ	Differ	Differ	Agree	Agree	Differ	Differ

6.3.1 Analysis of 10-minute precipitation intensity

The valid 10-minute precipitation intensity amounts for the 3 precipitation sensors are analyzed in more detail. This analysis is performed on all 10-minute measurements in the period May 25, 2002 to August 11, 2003 where data of all three sensors is available and at least one of the three sensors reported precipitation. The total number of 10-minute intervals involved is 9331. A frequency distribution of the measured 10-minute precipitation intensity is shown in Figure 21 for each of the three sensors. The distribution is given in 0.1mm/h bins for intensities between 0 and 5mm/h. Above 5 mm/h the number of events involved per bin decreases below 10, and hence statistics are poor. Between 0 and 5mm/h the frequency distribution of the KNMI gauge and Pluvio is generally the same. The number of cases for the PWS, however, is lower for intensities between 0.2 and 2.5mm/h. This was not observed in the data for De Bilt (cf. Figure 10). Similarly as for De Bilt, the frequency distribution of the Pluvio during the field test in De Kooy shows regular peaks and dips.

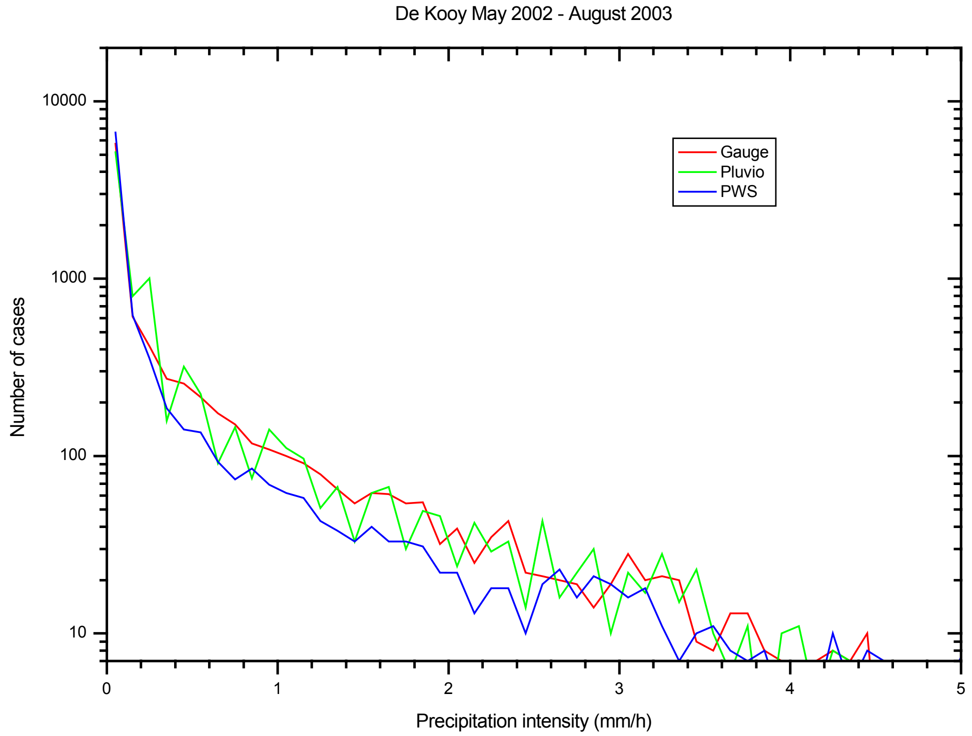

Figure 21: Frequency distributions of the raw 10-minute averaged precipitation intensity measurements for each sensor in De Kooy. The bin size is 0.1 mm/h. All valid cases are included where at least one of the sensors reports precipitation.

A histogram of the differences between the 10-minute intensity measurements of any 2 rain gauges is presented in Figure 22 using a bin size of 0.03mm/h. The histogram is plotted using a logarithmic scale. Both histograms peak at a difference of 0.00mm/h, where the bin for Pluvio-Gauge contains 34% of the cases and PWS-Gauge 37%. The number of cases within ±0.1mm/h is 61% for Pluvio-Gauge and 66% for PWS-Gauge. The number of cases in the bins for larger differences decreases exponentially. The histogram should resemble a Gaussian distribution, but both distributions are worse than for De Bilt (cf. Figure 11). The differences PWS-Gauge are not symmetric around zero since the PWS generally underestimates the precipitation amount. The histogram for Pluvio-Gauge shows again almost constant number of differences between +0.03 and +0.18mm/h caused by the reporting threshold of 0.03mm of the Pluvio. A new feature in the distribution of Pluvio-Gauge for De Kooy is the larger number of cases at differences of +0.18mm/h, +0.24mm/h, +0.30mm/h, …This is probably caused by faulty precipitation reports of the Pluvio of 0.03mm, 0.04mm, 0.05mm, … per 10-minute interval.

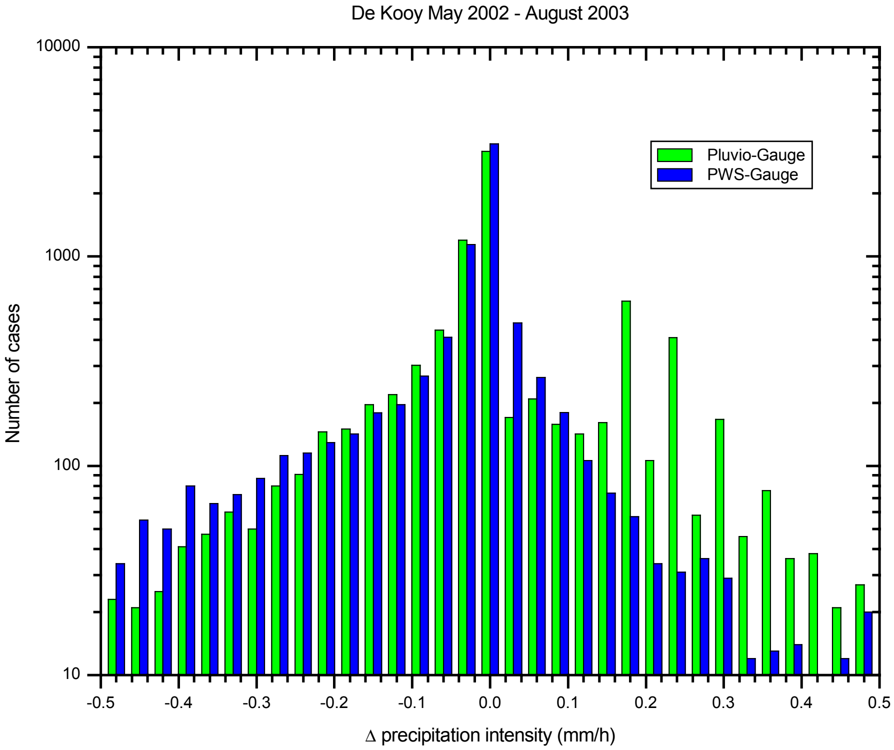

Figure 22: Histogram of the differences between the raw 10-minute averaged precipitation intensity measurements for any combination of 2 precipitation sensors during the field test in De Kooy. The bin size is 0.03 mm/h. All cases are included where at least one of the sensors reports precipitation.

6.3.2 Wind effect

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of wind speed. The measured wind speed at 10m is used. Note that the wind mast in De Kooy is located about 500m North of the measurement field. The averaged differences between the 10-minute precipitation intensities for 2 precipitation sensors per wind speed interval are given in Figure 23. The results are given as the percentage of the total precipitation amount per wind speed bin as measured by the KNMI gauge. The total precipitation amount measured by the KNMI gauge per wind speed bin and the total number of cases involved as well as the number of faulty precipitation reports per sensor are also shown in Figure 23. In contrast to the corresponding results for De Bilt (cf. Figure 12) the differences Pluvio-Gauge show a wind speed effect between 1 and 8 m/s. A linear fit to the data gives a slope of about 2.5%/ms^{-1}. The results above 8m/s are not considered because statistics is poor in that region, but in that region the differences Pluvio-Gauge decrease again. Figure 23 also shows that the number of faulty Pluvio cases increases between 3 and 8 m/s. The sign of the slope suggests that the KNMI gauge in the English setup reports less precipitation under high wind speed conditions compared to the Pluvio on the measurement field in a screen. This effect is opposite to the results obtained by comparing 2 KNMI precipitation gauges in a similar setup (Wauben 2004), where the gauge on the measurement field and within a windscreen reported less precipitation with increasing wind speed. The differences PWS-Gauge show a different behavior as a function of wind speed in the region 4 to 7 m/s. This is in contrast to the results for De Bilt, where Pluvio-Gauge and PWS-Gauge showed generally the same behavior as a function of wind speed (cf. Figure 12).

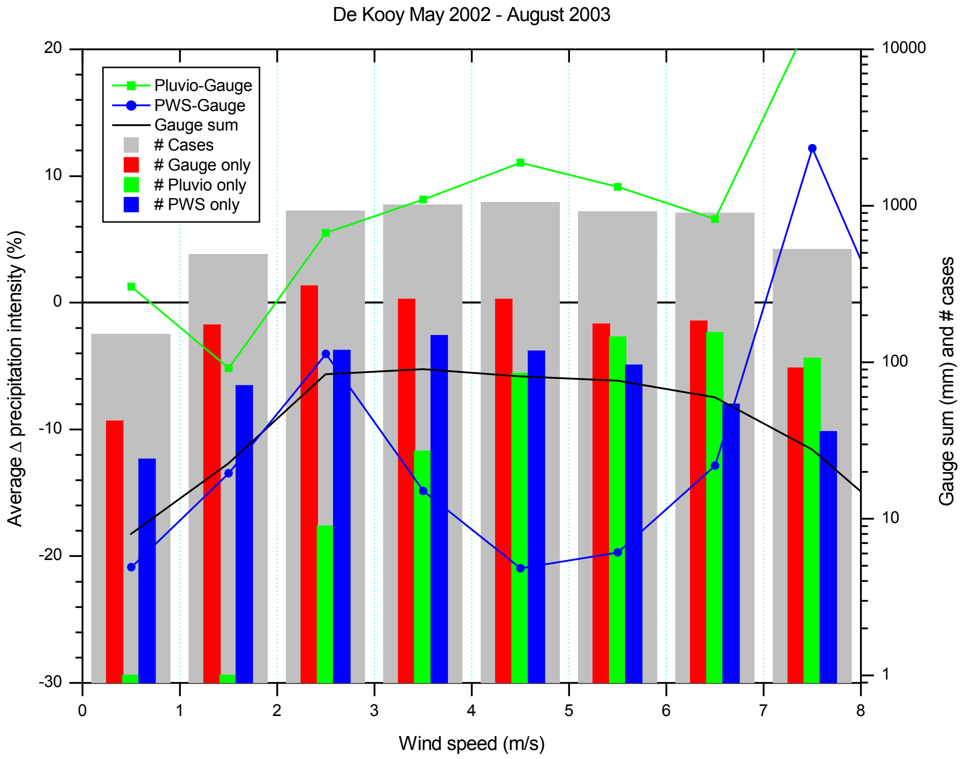

Figure 23: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the wind speed in bins of 1m/s for the field test in De Kooy. The results are presented as the percentage of the total precipitation amount per wind speed bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

The wind speed effect also depends on the type of precipitation and the droplet size since small/light particles have a smaller fall velocity and hence are more sensitive to the wind. The influence of droplet size is again investigated by analyzing the results as a function of the precipitation intensity. Figure 24 shows the relative difference between the precipitation intensity measured by 2 precipitation sensors as a function of the precipitation intensity. The precipitation intensity is divided into bins of 0.5mm/h from 0 to 5.5 mm/h according to the intensity measured by the KNMI gauge. Situations with intensities higher than 5.5mm/h are not shown because the statistics are poor. The first bin at zero contains the cases where the KNMI gauge reported precipitation intensities less than 0.05mm/h. For this bin the gauge reports a much lower precipitation amount than the Pluvio and PWS. The cases in this bin are dominated by the situations where one sensor only reports precipitation. Although the number of Gauge only cases is large (1956) the amount of precipitation involved is small (5.0mm). All faulty cases for PWS and Pluvio contributing to the relative differences occur in the first intensity bin of the KNMI gauge. Their number is less (812 and 776, respectively), but the amount of precipitation is higher (6 and 34mm, respectively). At the other intensity intervals the averaged differences Pluvio-Gauge are generally about –5% and do not show a clear dependency on intensity, and the averaged differences PWS-Gauge are about –15%, but shows large fluctuation. Unlike the results for De Bilt (cf. Figure 13) the differences show no gradual transition from positive to negative differences and hence do not resemble the curves given by Nešpor and Sevruk (1999) obtained by numerical simulations. The faulty cases for the KNMI gauge occur at intensities below 0.5mm/h, but faulty cases for PWS and Pluvio can be observed up to intensities of 2.5 and 4 mm/h, respectively. The Pluvio even reported a faulty case at 10.5 mm/h.

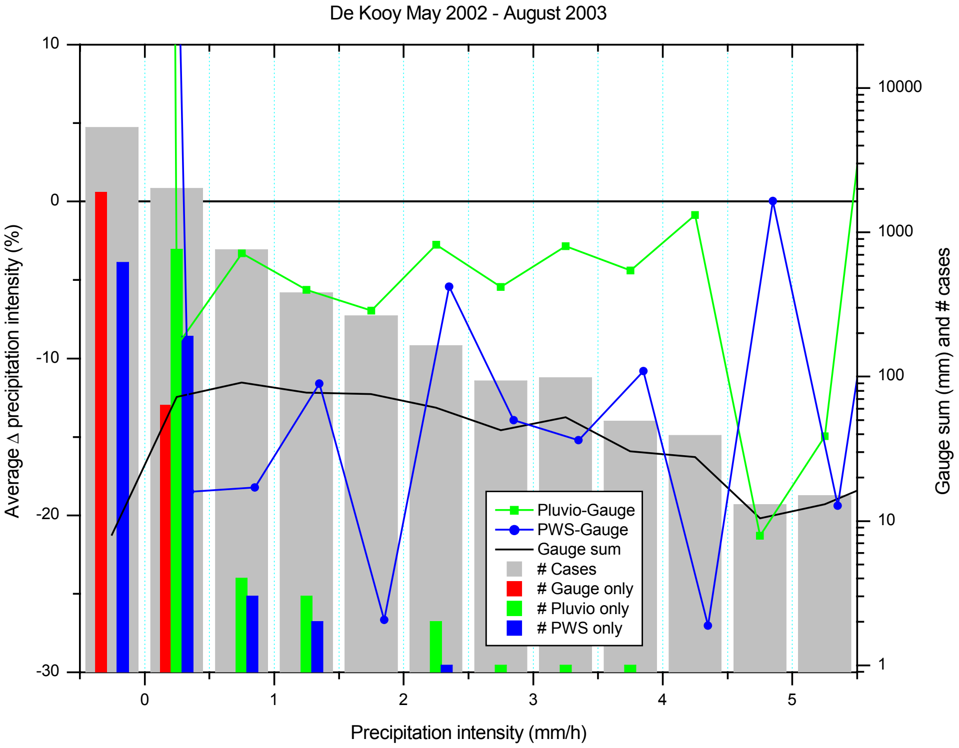

Figure 24: Relative differences between the 10-minute precipitation intensities measured by 2 sensors as a function of precipitation intensity for De Kooy. The binning in steps of 0.5mm/h is performed on the intensity measured by the KNMI gauge. The first bin contains the cases with intensity less than 0.05mm/h. The number of faulty sensor only events is reported in the intensity bin derived from their own reported precipitation intensity.

6.3.3 Dependency on other meteorological variables

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of other meteorological variables.

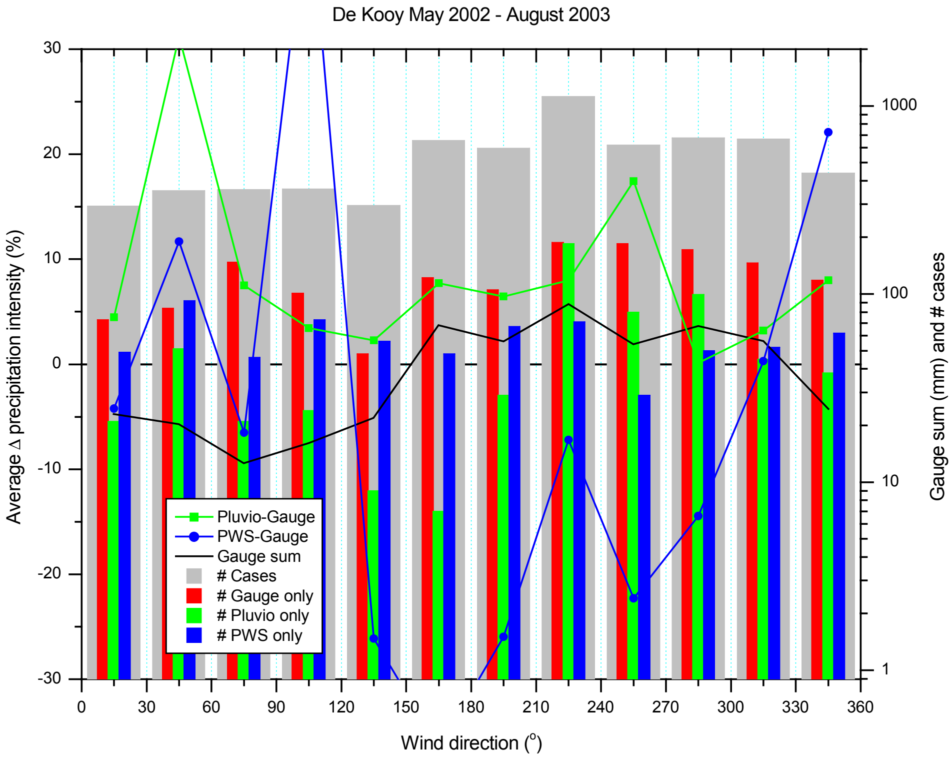

Figure 25: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the wind direction in bins of 15° during the field test in De Kooy. The results are presented as the percentage of the total precipitation amount per wind direction bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

First the relative differences are given as a function of the wind direction in Figure 25. The curves for De Kooy show more scatter than the corresponding results for De Bilt (cf. Figure 14). Therefore the bin size is increased to 30º. The averaged differences Pluvio-Gauge show again little dependency on wind direction. The differences PWS-Gauge show large variations as a function wind direction, but the general behavior (positive values between 0-90º with a dip around 60º, negative values between 120-180º and a positive peak between 330-360º) of the curve resembles the curve for De Bilt. This agreement corroborates that the differences are probably the result of the precipitation detector and optical measurement area of the PWS being the in wake of the background luminance sensor.

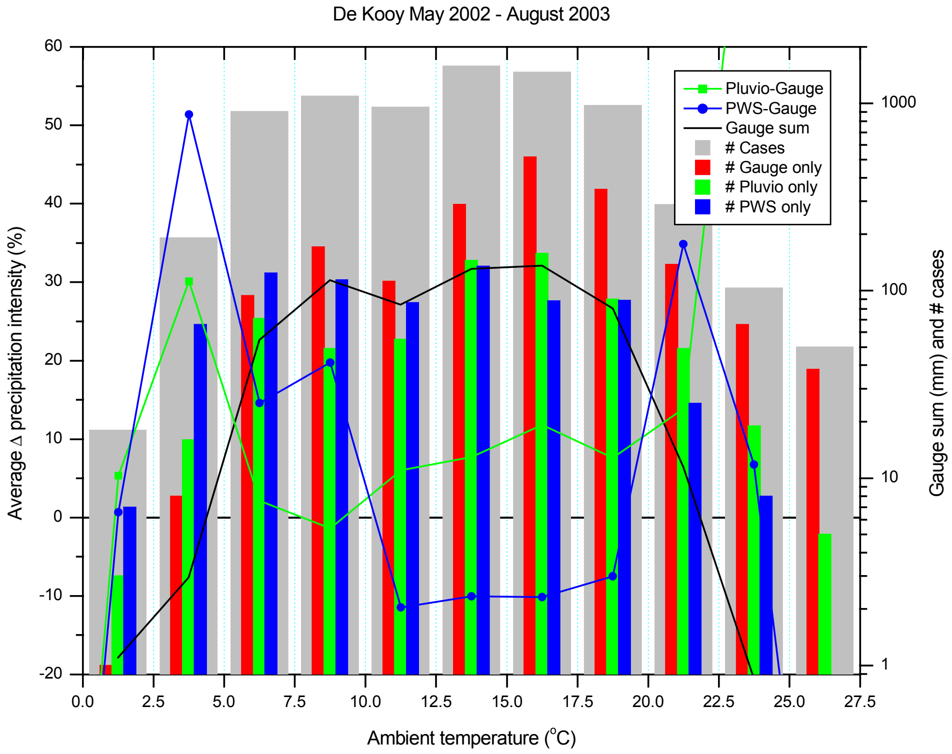

Figure 26: As Figure 25, but now the relative differences and number of cases are given as a function of the ambient temperature in bins of 2.5°.

The relative differences as a function of the ambient temperature are given in Figure 26. The averaged differences again show more variation than the corresponding results for De Bilt (cf. Figure 15). The curves Pluvio-Gauge and PWS-Gauge both show large positive differences between 0 and 7.5ºC, although the amount of precipitation involved is small. The relatively high number of faulty cases for the Pluvio and PWS as compared to the KNMI gauge could cause this. At ambient temperatures above 22.5ºC the curves for Pluvio-Gauge and PWS-Gauge show a different behavior with Pluvio reporting higher and PWS reporting lower amounts than the KNMI gauge, respectively. This is the result of the faulty readings of the KNMI gauge during clear days, and similar faulty readings, but having larger precipitation amounts, for the Pluvio.

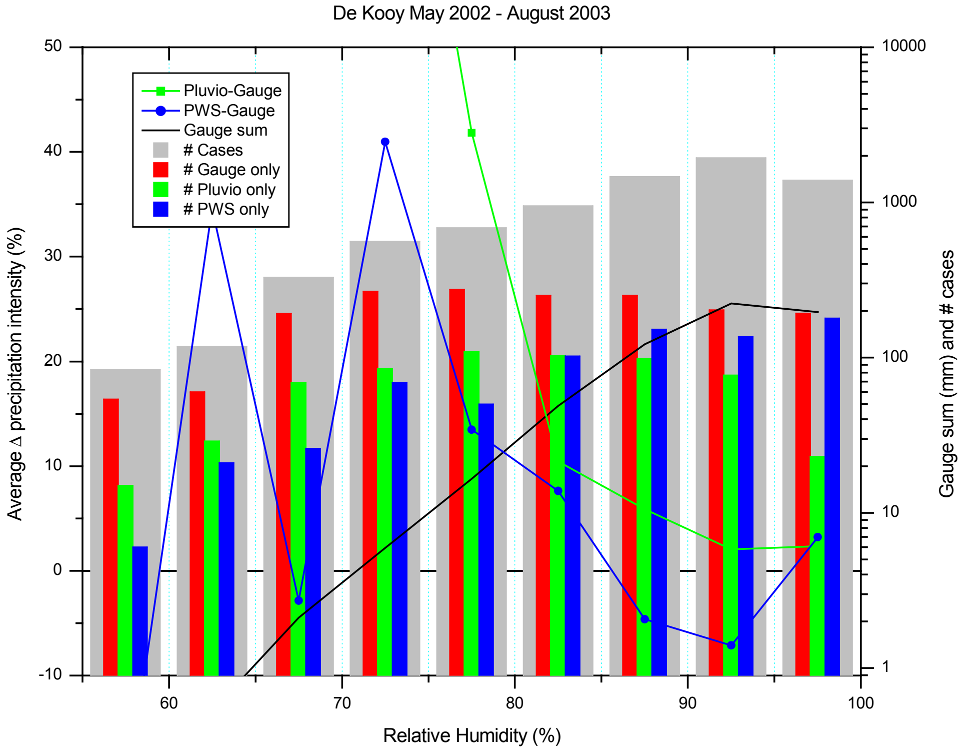

Figure 27: Averaged relative differences between the 10-minute precipitation intensities measured by 2 precipitation sensors as a function of the relative humidity in steps of 5% during the field test in De Kooy. The results are presented as the percentage of the total precipitation amount per relative humidity bin as measured by the KNMI gauge, which is indicated by the black line. The total number of cases involved is indicated by the histogram, as is the number of faulty sensor only events.

Finally, Figure 27 shows the relative differences as a function of the relative humidity in bins of 5%. A clear dependence with relative humidity can be observed. Again the curve Pluvio-Gauge shows a different behavior than the corresponding curves for De Bilt (cf. Figure 16), but now the same applies for the curves for PWS-Gauge as well. Again, this can partly be explained in terms of “faulty” sensor readings, which now also occur for the PWS. Although in the latter case it is probably also effected by the higher sensitivity of the PWS in combination with evaporation losses by the other sensors. The effect of the “faulty” sensor readings is discussed in more detail in section 6.3.5.

6.3.4 Dependency on other parameters

Next, the dependency of the observed differences on other parameters is investigated. The parameters considered are again the collector content of the Pluvio, the quality parameter reported by the Pluvio, and the gradient of the temperature reported by the Pluvio.

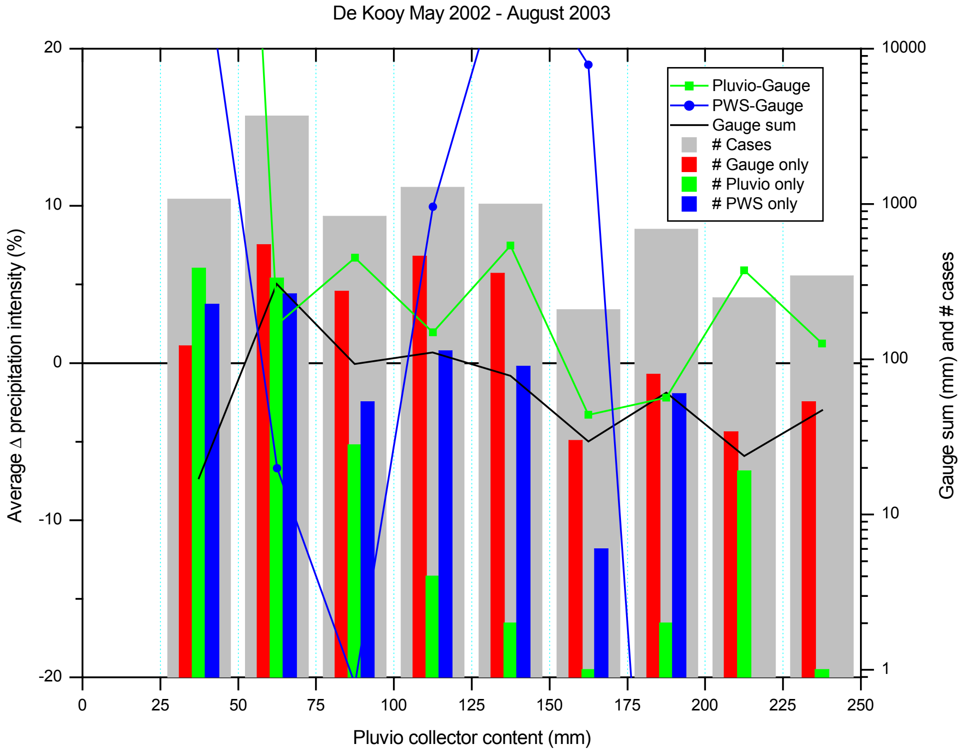

Figure 28: As Figure 27, but now the relative differences and number of cases are given as a function of the collector content of the Pluvio in bins of 25mm.

The relative differences between the measured precipitation amounts as a function of the collector contents of the Pluvio are given in Figure 28. Figure 28 shows large relative differences between the PWS and Pluvio compared to the KNMI gauge when the collector is nearly empty, as did the result for De Bilt (cf. Figure 17). The differences are now observed when the content is below 50mm, whereas at De Bilt it was observed up to 75mm. The Pluvio-Gauge curve shows no clear dependency on the collector content above 50mm and hence no indication of any splash-out losses of the Pluvio when the collector is nearly full. The curve PWS-Gauge shows large variation with the Pluvio collector content that were not observed in De Bilt.

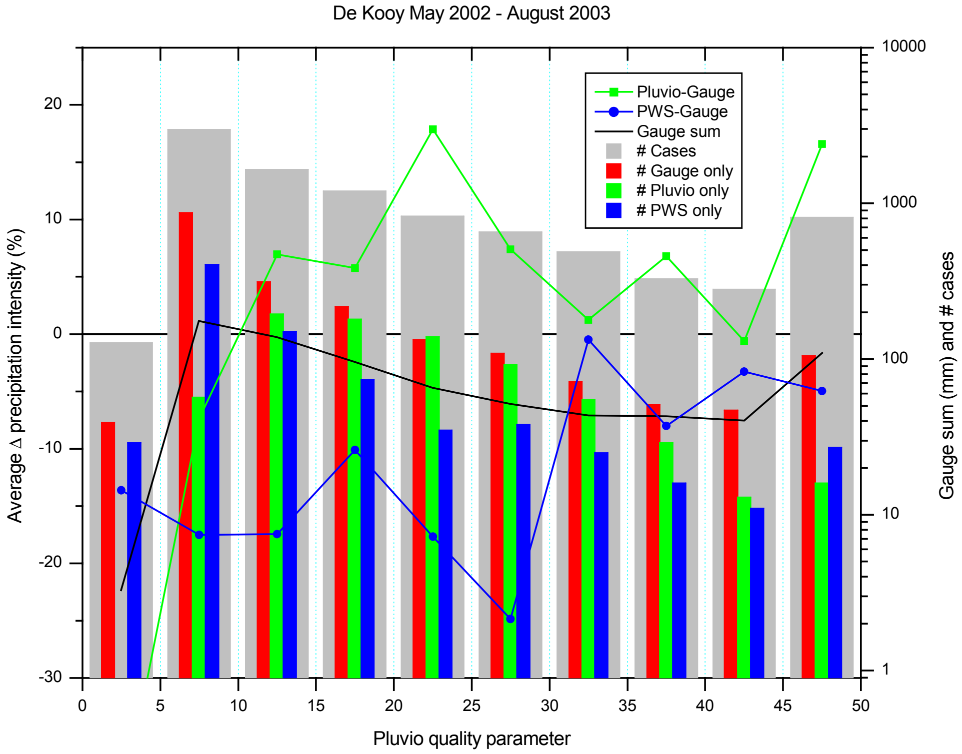

Figure 29: As Figure 27, but now the relative differences and number of cases are given as a function of the quality parameter of the Pluvio in bins of 5 units.

An analysis as a function of the quality parameter of the Pluvio is presented in Figure 29. The results now show good agreement with the corresponding results obtained for De Bilt (cf. Figure 18). The largest differences occur when the quality parameter is below 10 and hence can be considered good. At quality parameters above 15 the Pluvio generally overestimates the precipitation amount reported by the KNMI gauge. Faulty Pluvio only precipitation events occur in this range, but are not the sole cause of the overestimation. The PWS-Gauge differences for De Kooy, like for De Bilt, show no clear dependency with the quality parameter of the Pluvio.

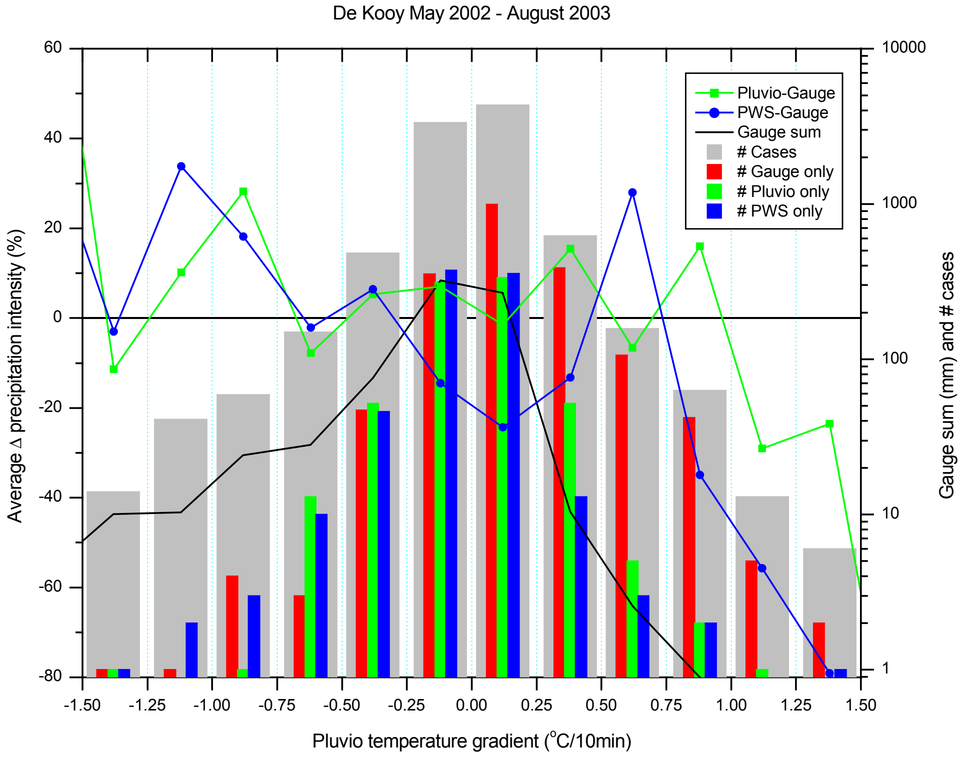

Figure 30: As Figure 27, but now the relative differences and number of cases are given as a function of the temperature gradient of the Pluvio in bins of 0.25°C/10min.

Finally, the differences as a function of the temperature gradient as measured by the Pluvio are given in Figure 30. Figure 30 shows again that for temperature gradients larger than 0.25ºC/10min the number of KNMI gauge only precipitation events is relatively large, but it is much less when the temperature gradient is negative. There are 775 cases where the Pluvio only reported precipitation. Of these cases 752 occur within the temperature gradient range of –0.5 to +0.5ºC/10min. Hence, the number of Pluvio only cases for De Kooy is much higher than for De Bilt, but these cases seem not related to observed temperature gradient. The general behavior of the curves Pluvio-Gauge and PWS-Gauge with the temperature gradient also differs from the corresponding results obtained for De Bilt (cf. Figure 19). The curves do not show any dependency on the temperature gradient, except when the gradient is larger than 1ºC/10min, but then the number of cases involved is only small.

6.3.5 Faulty precipitation readings

The behavior of the faulty readings of the precipitation sensors is next studied in more detail for De Kooy and compared with the results obtained for De Bilt (cf. sect. 5.3.6). For that purpose the number of cases when one sensor reported precipitation and the other 2 sensors did not report precipitation nor in the previous and next 10-minute interval (if available) is studied as a function of various parameters. The amount of faulty precipitation is determined as well. The number and amount when that sensor reported precipitation together with at least 1 of the other sensors is considered too. A major difference between the faulty Pluvio readings for De Bilt and De Kooy is that the number of faulty cases is much higher for De Kooy (776 out of a total of 4226 precipitation reports) than for De Bilt (13 out of 6117), and that some of these cases occur at higher intensity levels (cf. Figure 24). Most faulty Pluvio cases occur in the 0.05 to 0.5mm/h intensity bin. The results of the KNMI gauge also shows differences between De Kooy and De Bilt. The faulty cases for the KNMI gauge at De Kooy occur mainly for traces (1893 out of a total of 7042 precipitation reports), but some faulty cases (63) occur at the next intensity bin at 0.5mm/h, whereas for De Bilt the faulty cases occur up to 3.5mm/h (cf. Figure 13). The faulty readings for the PWS (812 out of a total of 5341 precipitation reports) occur mainly in the lowest precipitation intensity bins. The total amounts of precipitation included in the faulty cases at De Kooy are 5, 34 and 6mm for KNMI gauge, Pluvio and PWS, respectively, whereas for De Bilt the corresponding values are 16, 1 and 9mm. Since the Pluvio overestimates the total precipitation amount at De Kooy as measured by the KNMI gauge by about 38mm, the exclusion of the above mentioned “faulty” cases will reduced the overall difference by 29mm.

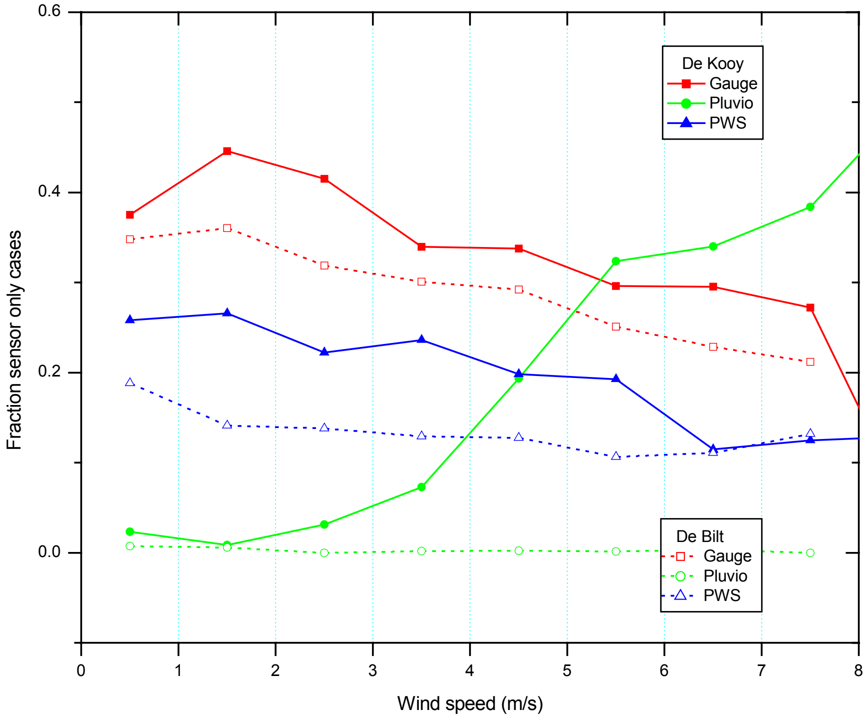

Figure 31: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation as a function of the observed wind speed in bins of 1m/s. The ratios are given for the 3 precipitation sensors involved and for the field test in De Bilt and in De Kooy.

Figure 31 shows details of the ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation as a function of the observed wind speed. The ratios are given for each precipitation sensors and for the field test in De Bilt and in De Kooy. In general, the faulty readings for the field test in De Bilt show no clear dependence on wind speed for all three sensors. The KNMI gauge and PWS also show no wind speed dependency at De Kooy, but the number of faulty cases is in general about 5% higher at De Kooy. The faulty Pluvio readings for De Kooy, however, show a clear dependency with wind speed, although the wind speeds considered are the same as for De Bilt. However, note that the wind speed is measured at 20m and 10m in De Bilt and De Kooy, respectively. The wind speed at 20m is about 12% higher than at 10m when a logarithmic vertical profile of the wind is assumed (cf. WMO, 1996). This cannot explain the observed differences between De Bilt and De Kooy.

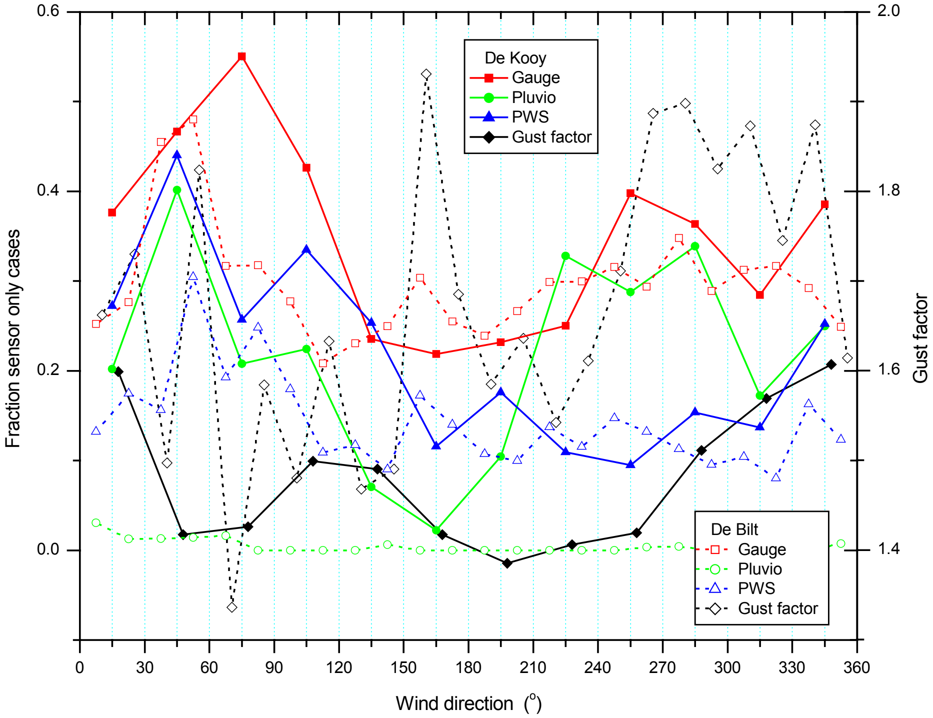

Figure 32: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the observed wind direction in bins of 15°. The ratios are given for the 3 precipitation sensors involved and for the field test in De Bilt and in De Kooy. The gust factor observed at De Bilt and De Kooy during precipitation events is also shown.

Figure 32 shows the behavior of the faulty readings as a function of the wind direction. The results for the Pluvio in De Bilt show no dependency on wind direction, but the results for De Kooy do. The faulty reading for the KNMI gauge and the PWS show some dependency on wind direction for De Bilt as well as for De Kooy. This dependency is more pronounced for De Kooy. The dependency on wind direction is roughly the same at De Kooy for all three sensors with a larger fraction of faulty cases between 0 to 120 degrees. The KNMI gauge and especially the Pluvio also show a large fraction of faulty cases between 220 and 300 degrees. Figure 32 also shows the so-called gust factor (ratio of wind gust and averaged wind speed per 10-minute interval) as a function of wind direction for all cases where one of the sensors reports precipitation. The gust factor is calculated when the averaged wind speed is above 0.5m/s, otherwise the gust factor is set to 1. The gust factor is a related to the upstream surface roughness and the gust duration (cf. Wieringa and Rijkoort, 1983). The curves for De Bilt and De Kooy show that the gust factor is higher for De Bilt compared to De Kooy, particularly in the directions between 180-330 degrees, i.e. the directions where the measurement field at De Bilt is shielded by nearby trees. As a result of the larger roughness the gust duration will be less and hence an induced wind effect will be shorter and should be more easily detectable by the Pluvio algorithm. However, the fraction of faulty Pluvio cases for De Kooy is not clearly anti-correlated to the observed gust factor. When the faulty cases are studied as a function of the gust factor, most faulty cases occur at gust factors below 1.75, but this holds also for the faulty cases of the other 2 precipitation sensors. So the gust factor range below 1.75 contains also the bulk of the faulty reports at clear days of the KNMI gauge and the light precipitation events of the PWS. Hence a possible relation between gust factor and faulty Pluvio reports is also affected by other meteorological parameters.

Table 17: Number of 10-minute intervals and the total precipitation amount (mm) where one sensor only reported faulty precipitation or precipitation was reported simultaneously with at least one of the other sensors. The results are given as a function of the ambient temperature in bins of 2.5ºC and for each of the 3 precipitation sensors involved for the field test in De Kooy.

Temp. range	***PWS only***		***PWS&other***		***Gauge only***		***Gauge&other***		***Pluvio only***		***Pluvio&other***	
	#	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***
0-2.5	7	0.07	7	1.04	1	0.00	6	1.10	3	0.10	2	1.06
2.5-5	66	0.44	96	4.03	8	0.03	70	2.92	16	0.53	48	3.31
5-7.5	124	0.86	495	61.60	94	0.30	547	54.20	71	2.59	367	53.07
7.5-10	114	2.29	611	133.69	171	0.51	674	113.04	49	1.76	463	110.25
10-12.5	86	0.26	595	74.35	112	0.28	613	84.00	55	2.03	387	87.34
12.5-15	135	0.56	820	117.23	289	0.52	874	130.42	145	6.53	547	134.48
15-17.5	88	0.45	572	121.80	515	0.85	597	135.19	158	10.07	426	142.02
17.5-20	89	0.49	386	73.82	348	0.62	375	79.72	90	3.14	244	83.30
20-22.5	25	0.16	65	15.26	138	0.21	50	11.23	49	1.81	40	11.21
22.5-25	8	0.08	7	0.83	66	0.10	8	0.75	19	0.63	8	1.01
25-27.5	0	0.00	1	0.08	38	0.05	6	0.18	5	0.19	4	0.31
27.5-30	0	0.00	0	0.00	8	0.01	8	0.01	3	0.09	6	0.21
Total	**742**	**5.66**	**3655**	**603.72**	**1788**	**3.47**	**3828**	**612.77**	**663**	**29.47**	**2542**	**627.57**

Table 17 and Figure 33 show the faulty values as a function of the ambient temperature for each of the 3 precipitation sensors. The faulty PWS cases for De Kooy show the same behavior as for de Bilt. However, in de Kooy the number of PWS only events does exceed the number where precipitation is also reported by another sensor not only at ambient temperatures above 20ºC, but also below 5ºC. However, the number of PWS only cases involved is only small. The results for the KNMI gauge show the same general behavior for De Bilt and De Kooy. The fraction of the faulty Pluvio reading was very low at De Bilt. The much higher values at De Kooy show a clear temperature dependency with higher numbers above 20ºC and below 5ºC. The temperature dependency of the faulty cases for PWS and Pluvio resemble each other very well. Considering the identical behavior of PWS and Pluvio, the faulty cases of PWS and Pluvio could in fact be events missed by the KNMI gauge due to solid and/or light precipitation below 5ºC and light precipitation above 20ºC that does not reach the collector as a result of sticking and/or evaporation in the collector. The large distance between PWS and Pluvio in De Kooy can then explain why these faulty cases turn up separately for PWS and Pluvio.

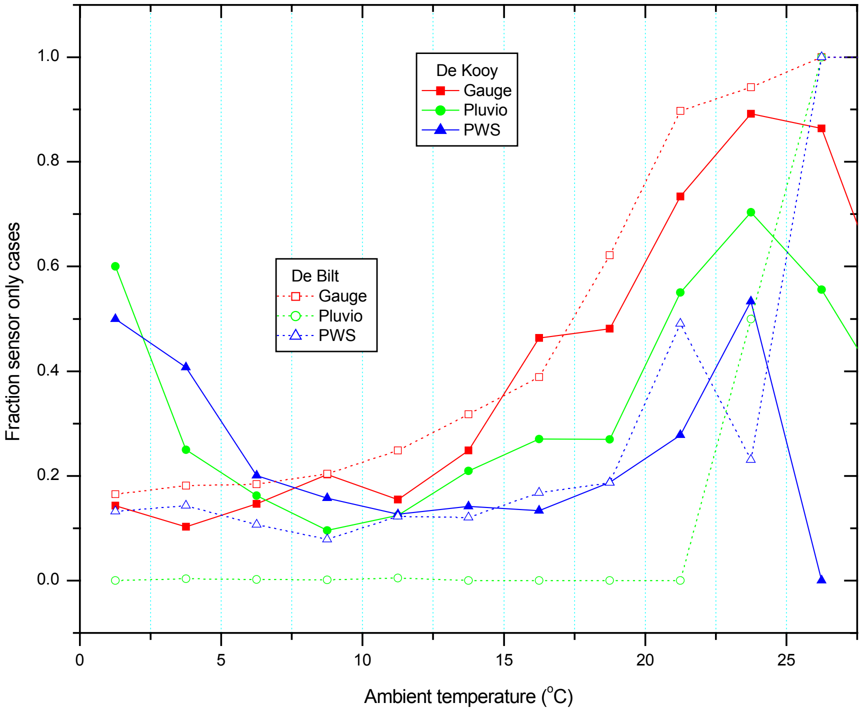

Figure 33: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the ambient temperature in bins of 2.5ºC.

The fraction of faulty results as a function of the relative humidity (cf. Figure 34) shows generally the same behaviors for all three sensors and at De Bilt and De Kooy. The Pluvio results at De Bilt, however, show a much lower fraction of faulty cases.

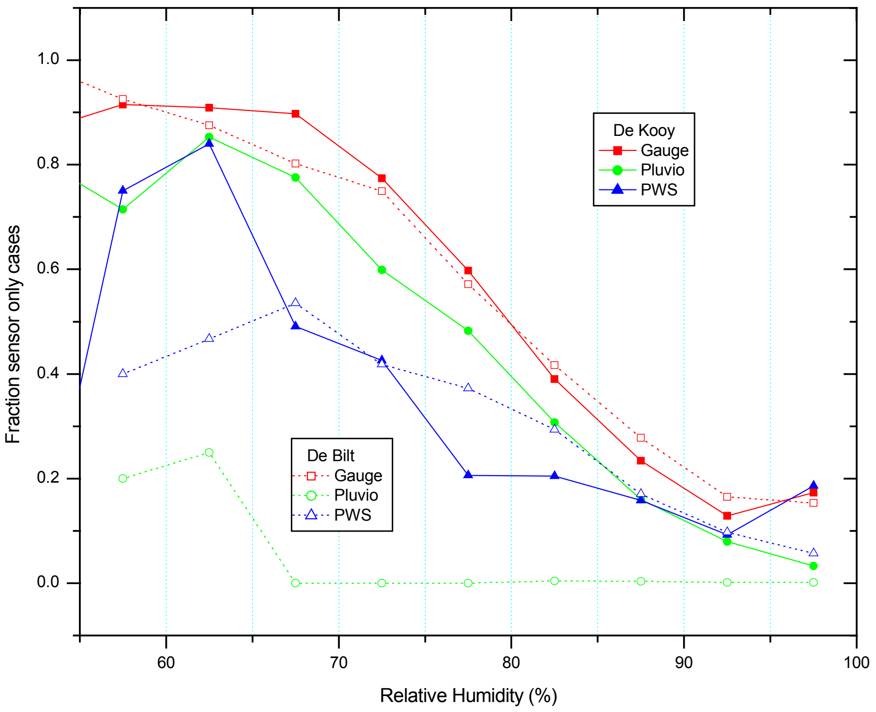

Figure 34: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the relative humidity in bins of 5%.

The behavior of the faulty readings of the KNMI gauge during clear days is shown in more detail in Table 18 and Figure 35, which shows the results as a function of the global radiation. All sensors show most faulty cases at low values of the global radiation, but the relative number increases for higher values of the global radiation for the KNMI gauge and only slightly for the PWS. The Pluvio faulty cases are again negligible for De Bilt, but are large and their relative number increases with global radiation for De Kooy.

Table 18: Number of 10-minute intervals and the total precipitation amount (mm) where one sensor only reported faulty precipitation or precipitation was reported simultaneously with at least one of the other sensors. The results are given as a function of the global radiation in bins of 100W/m^2 and for each of the 3 precipitation sensors involved for the field test in De Kooy.

Global rad. range	**PWS only**		**PWS&other**		**Gauge only**		**Gauge&other**		**Pluvio only**		**Pluvio&other**	
	#	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**	**#**	**Sum**
0-100	638	5.05	3185	547.86	528	1.55	3268	569.41	310	15.99	2239	586.80
100-200	59	0.40	315	37.46	187	0.34	318	28.78	62	2.81	180	26.22
200-300	28	0.14	91	13.93	169	0.25	102	11.24	47	1.72	59	10.11
300-400	4	0.00	32	1.98	165	0.23	48	1.22	57	2.19	17	1.47
400-500	7	0.04	11	0.33	140	0.25	26	0.37	34	1.35	14	0.83
500-600	4	0.01	8	0.46	143	0.20	22	0.55	34	1.26	10	0.84
600-700	0	0.00	5	0.65	143	0.19	12	0.58	38	1.35	4	0.53
700-800	2	0.01	3	0.13	141	0.22	18	0.15	45	1.56	7	0.21
800-900	0	0.00	4	0.04	125	0.16	8	0.06	28	0.94	10	0.39
>900	0	0.00	1	0.89	47	0.07	6	0.41	8	0.30	2	0.17
Total	**742**	**5.66**	**3655**	**603.72**	**1788**	**3.47**	**3828**	**612.77**	**663**	**29.47**	**2542**	**627.57**

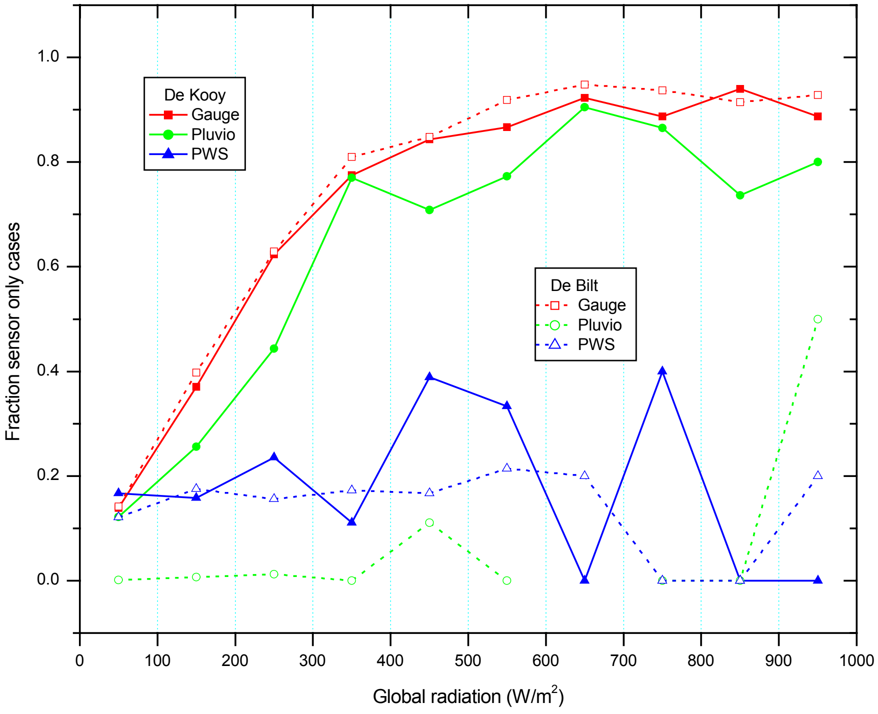

Figure 35: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the global radiation in bins of 100W/m^2.

The faulty sensor readings were also investigated as a function of the collector content of the Pluvio, the quality parameter of the Pluvio and the temperature gradient of the Pluvio. There is no clear correlation of the faulty reports with the collector content for PWS and KNMI gauge (cf. Figure 36). All sensors show a peak when the collector content is below 50mm, but the number of faulty cases involved is only small. The relative number of faulty cases reduces with increasing collector content when going into the wet season. The KNMI gauge and PWS in De Kooy shows a secondary peak when the collector is half full, but that is probably related to a particular meteorological situation. The Pluvio at De Bilt reported only a couple faulty reports at and showed no relation to the collector content. This dependence is clearly visible in the (relative) number of faulty cases for the Pluvio in De Kooy. This behavior could be expected since a lighter collector is more sensitive to e.g. wind induced vibrations and hence faulty reports. The faulty cases in De Kooy show also an increase when the collector is almost full. An explanation in terms of faulty reports by wind-induced ripples seems unlikely because at the largest collector content value the relative number of faulty cases is low again.

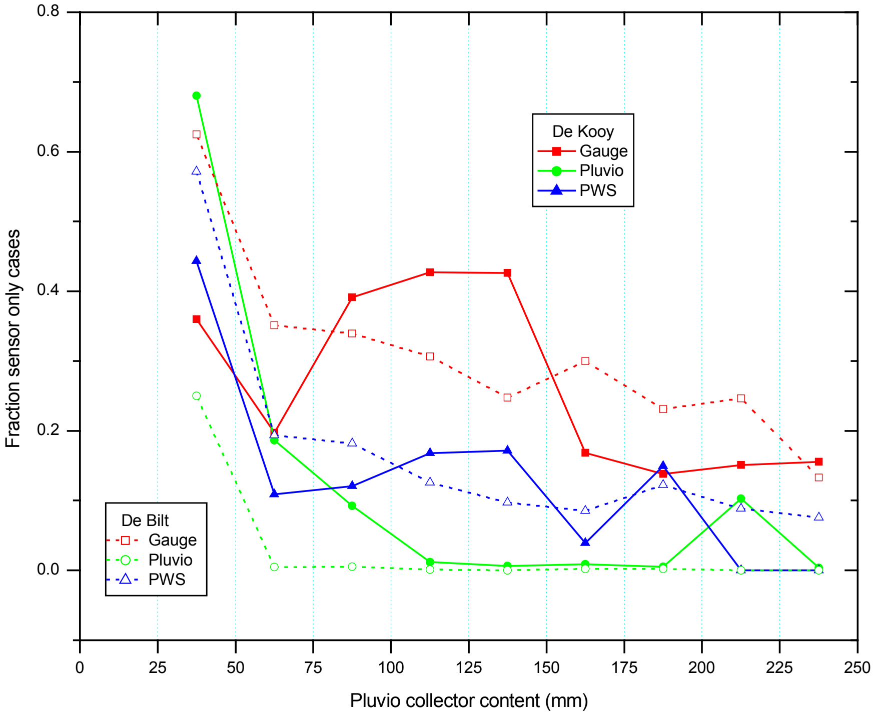

Figure 36: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the collector content of the Pluvio in bins of 25mm.

Figure 37 shows the relative number of faulty precipitation reports as a function of the quality parameter of the Pluvio. The curves for the KNMI gauge and the PWS show a gradual decrease with the quality parameter of the Pluvio with a similar behavior for the sensors at both locations. The faulty cases of the Pluvio show a different behavior as a function of the quality parameter reported by the Pluvio. The relative number does not generally increase with the quality parameter as one might expect for faulty Pluvio cases, but exhibits a broad peak around a Pluvio quality parameter value of about 25. The behavior is not present in the result for De Bilt, where most faulty Pluvio reports occurred at small quality parameter values.

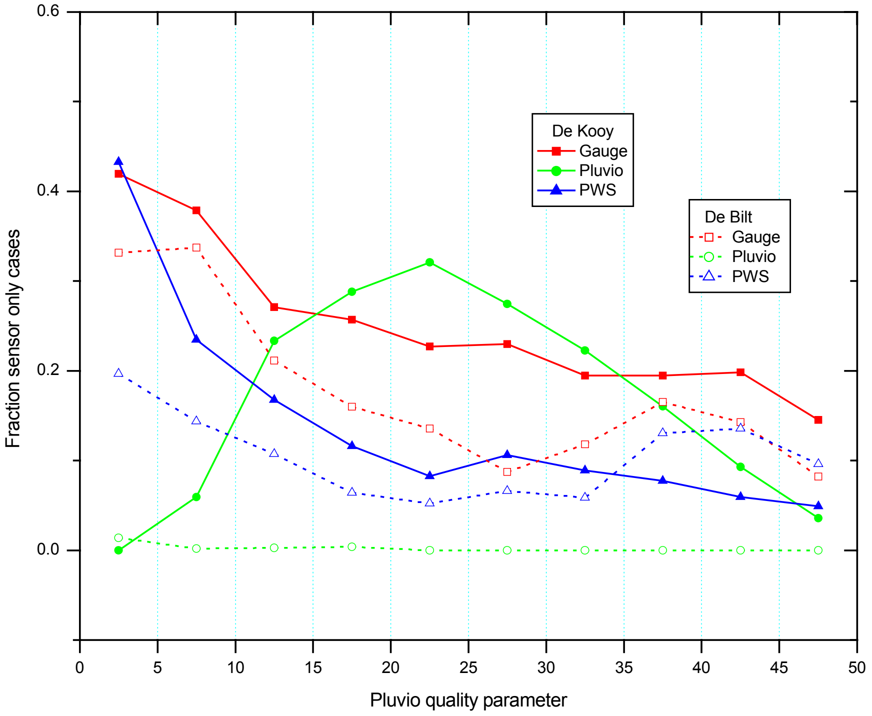

Figure 37: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the Pluvio quality parameter in bins of 5 units.

Figure 38 and Table 19 show the relative number of faulty precipitation reports as a function of the temperature gradient measured by the Pluvio. The KNMI gauge shows a steep increase in the relative number of faulty cases for positive temperature gradients above 0.25°/10min. The behavior of the curves for De Bilt and De Kooy is nearly identical. This can be explained in terms of faulty reports caused by expansion of the water volume in the reservoir. The number of faulty reports by the KNMI gauge also shows larger values at positive temperature gradients as compared to the corresponding negative gradients (cf. Table 19). The relative numbers shown in Figure 38 show this more pronounced because the number of cases where the gauge and another sensor report precipitation is smaller at positive gradients. The curves for the PWS at both locations also show good agreement. Both PWS sensors show a small gradual increase in the relative number of faulty cases from about 5% to 10% between a temperature gradient of –1.5 to 0.5º/10min. The faulty cases are concentrated around a zero gradient and the number of cases involved at larger gradients is only small. The general behavior of the relative results as a function of the temperature gradient is caused by a decrease in the number of cases where PWS and another sensor agree that precipitation occurred. The Pluvio shows again large differences between the results obtained at De Bilt and at De Kooy. De Bilt shows little dependency with the temperature gradient, the relative number of faulty cases for De Kooy peak between +0.25 and 0.50º/10min. Here too the number of cases showing agreement between sensors largely affects the relative number. Generally, the temperature is more or less constant during precipitation events, or else it will decrease. The number of faulty Pluvio cases themselves shows no clear dependency on temperature gradient.

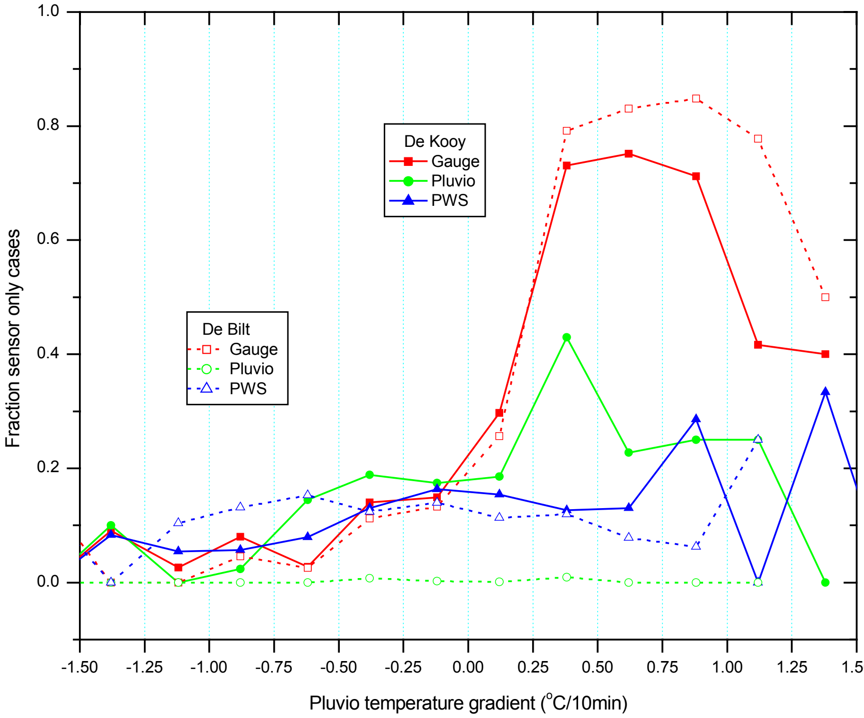

Figure 38: The ratio of the number of faulty sensor readings and the total number of sensor readings with precipitation is shown as a function of the temperature gradient measured by the Pluvio in bins of 0.25º/10min.

Table 19: Number of 10-minute intervals and the total precipitation amount (mm) where one sensor only reported faulty precipitation or precipitation was reported simultaneously with at least one of the other sensors. The results are given as a function of temperature gradient measured by the Pluvio in bins of 0.25ºC/10min and for each of the 3 precipitation sensors involved for the field test in De Kooy.

Temp. gradient range	***PWS only***		***PWS&other***		***Gauge only***		***Gauge&other***		***Pluvio only***		***Pluvio&other***	
	#	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***	***#***	***Sum***
–1.50, –1.25	1	0.00	11	9.77	1	0.00	10	10.07	1	0.03	9	8.89
–1.25, –1.00	2	0.02	35	13.81	1	0.00	37	10.33	0	0.00	31	11.38
–1.00, –0.75	3	0.01	50	28.45	4	0.01	46	24.06	1	0.04	41	30.82
–0.75, –0.50	10	0.05	116	27.46	3	0.00	107	28.10	13	1.11	77	24.79
–0.50, –0.25	46	0.28	307	80.36	47	0.11	288	75.67	52	3.02	224	76.77
–0.25, –0.00	374	3.73	1910	271.29	354	1.18	2016	320.63	314	14.40	1486	330.17
+0.00, +0.25	357	1.65	1960	201.17	997	2.67	2360	265.24	334	12.84	1468	251.01
+0.25, +0.50	13	0.05	90	8.99	388	0.67	143	9.76	52	2.05	69	9.98
+0.50, +0.75	3	0.04	20	3.26	106	0.17	35	2.41	5	0.21	17	2.20
+0.75, +1.00	2	0.02	5	0.56	42	0.11	17	0.78	2	0.09	6	0.94
+1.00, +1.25	0	0.00	4	0.27	5	0.02	7	0.59	1	0.04	3	0.39
+1.25, +1.50	1	0.00	2	0.05	2	0.01	3	0.23	0	0.00	1	0.18
Total	**812**	**5.85**	**4524**	**658.09**	**1953**	**4.95**	**5081**	**759.35**	**775**	**33.83**	**3445**	**767.90**

The available amount data does not allow a detailed analysis of the results as a function of several parameters.

6.3.6 Precipitation duration

Table 20 reports the monthly precipitation duration for the 3 sensors as well as for the hourly validated climatological data. The results for the KNMI gauge and the climatological data show good agreement, although the gauge generally reports higher values. Note that the precipitation duration was derived from the measurements of the precipitation gauge. The PWS generally reports lower monthly precipitation duration values than the KNMI gauge. This behavior is strange, considering the higher sensitivity of the PWS compared to the KNMI gauge and it also differs from the results obtained of De Bilt (cf. Table 10). The results for the Pluvio for De Kooy also clearly show that the precipitation duration derived from the Pluvio is much less compared to that of the other sensors. The monthly underestimation ranges between a factor of 2 to 7, and the total duration is less by a about a factor of 3.5.

Table 20: Monthly precipitation duration derived from the PWS, KNMI gauge and Pluvio sensors and the validated hourly climatological values for De Kooy.

Month	***Precipitation duration (hours)***			
	PWS	***Gauge***	***Pluvio***	***Klim***
0502	4.0	4.7	1.4	4.4
0602	32.0	36.2	12.9	33.1
0702	53.3	69.1	19.3	66.5
0802	32.2	33.4	15.3	31.3
0902	14.6	15.7	3.9	14.7
1002	35.4	48.5	9.8	44.2
1102	66.0	80.1	22.4	75.3
1202	65.7	76.8	21.1	72.2
0103	58.0	84.6	16.0	75.7
0203	16.0	29.2	2.9	19.4
0303	24.9	19.5	3.6	17.8
0403	21.8	23.4	6.5	21.8
0503	38.8	43.5	12.0	41.1
0603	15.4	13.1	5.1	11.7
0703	25.8	32.2	8.4	29.6
0803	0.4	0.4	0.3	0.3
Total	**504.3**	**610.4**	**160.7**	**559.1**

Table 21 reports the number of hours with reported precipitation duration during the field test in De Kooy for each of the 3 precipitation sensors as well as for the validated hourly climatological data per month. The number of hours with valid data per month that are considered is also reported. The table also lists the number of hours where only traces of precipitation, i.e. an hourly sum less than 0.05mm, are reported. Table 21 shows again large differences between gauge and the climatological values, with the gauge reporting fewer hours with precipitation. The numbers shows much better agreement when the reports of traces of precipitation are excluded. The number of traces of precipitation reported by the KNMI gauge reduces after November 2003. This does not coincide with a replacement of the sensor, nor can such a change be observed at De Bilt (cf. Table 11). The decrease of hours with traces of precipitation reported by the KNMI gauge occurs when the data is obtained via the new meteorological network. However, the new network acquires the same sensor data, but with a higher resolution, so that in fact a higher number of traces could be expected. The PWS reports fewer cases than the gauge for the first part of the field test, but since March 2003 it reports more cases then the gauge. The number of hours where the Pluvio reports precipitation is again much less than the number reported by the other sensors, but after March 2003 they are comparable to the number of cases reported by the KNMI gauge. This is also the case if the traces are taken into account.

Table 21: The number of hours where a precipitation sensor reported precipitation (duration) during the field test in De Kooy is given per month. The total number of valid hours considered and the number of hours reporting only traces of precipitation are also listed.

Month	**# hours**	**# hours with precipitation**				**# hours with traces**			
		PWS	**Gauge**	**Pluvio**	**Klim**	**PWS**	**Gauge**	**Pluvio**	**Klim**
0502	153	10	20	8	28	3	11	3	14
0602	713	60	114	60	120	18	69	15	63
0702	744	94	143	69	172	22	56	6	70
0802	568	54	90	31	103	14	50	1	54
0902	566	36	71	15	85	12	47	2	51
1002	577	86	128	42	170	31	53	3	75
1102	704	100	115	70	171	24	23	3	67
1202	741	34	95	72	156	34	10	2	67
0103	738	88	110	82	207	33	12	11	87
0203	594	39	44	24	84	17	9	4	42
0303	742	46	25	29	47	13	3	11	20
0403	658	44	34	37	78	14	7	10	42
0503	734	79	60	52	135	25	8	10	62
0603	627	31	19	32	59	11	5	14	38
0703	742	57	50	51	104	17	9	14	42
0803	263	1	6	5	4	1	6	2	3
Total	**9864**	**866**	**1133**	**684**	**1723**	**294**	**384**	**120**	**797**

Finally, the performance of the precipitation detection of the three sensors is studied by constructing 2-by-2 contingency matrices for precipitation detection from the 10-minute averaged precipitation intensity data by using a threshold of 0.00 and 0.05mm/h for precipitation detection (cf. Table 22). Comparison of the results of the PWS and KNMI gauge shows that the gauge has a POD of about 73% and a large false alarm rate of 44%. These results for De Kooy are worse than obtained for De Bilt, and the results, particularly the FAR, hardly improves when a threshold of 0.05mm/h is used for precipitation detection. In both cases the bias is larger than unity, hence the KNMI gauge reports more 10-minute intervals with precipitation. Comparison of the results of the PWS and Pluvio shows that the Pluvio has a POD of about 55% and a large FAR of 31% that even increases to 43% when a threshold of 0.05mm/h is used. Here too, the Pluvio always reports more cases with precipitation than the PWS. The overall CSI score of the KNMI gauge and Pluvio in De Kooy are always less than for De Bilt. This could be related to the large distance between the PWS and the other 2 precipitation sensors in De Kooy. Therefore the scores between the KNMI gauge and the Pluvio are also compared directly. The scores for gauge and Pluvio for De Kooy are, however, also worse than for De Bilt. In particular the FAR is high for De Kooy as a result of the large number of faulty Pluvio cases with intensity above 0.05mm/h.

Table 22: Contingency matrices for the precipitation detection by all sets of precipitation sensors based on the 10-minute averaged precipitation readings and the corresponding scores. Results are given using a threshold for precipitation detection of 0.00mm/h and 0.05mm/h.

Contingency matrix

		Sensor	
		Yes	No
Ref	Yes	Hit	Miss
	No	False	None

Scores

POD= Probability Of Detection = 100%*Hit/(Hit+Miss)
FAR= False Alarm Rate = 100%*False/(False+Hit)
CSI= Critical Success Index = 100%*Hit/(Hit+Miss+False)
BIAS= (Hit+False)/(Hit+Miss)

Threshold 0.00mm/h

		Gauge	
		Yes	No
PWS	Yes	3921	1420
	No	3121	51377

Scores
POD= 73.4
FAR= 44.3
CSI= 46.3
BIAS= 1.32

		Pluvio	
		Yes	No
PWS	Yes	2936	2405
	No	1290	53208

Scores
POD= 55.0
FAR= 30.5
CSI= 44.3
BIAS= 0.79

		Pluvio	
		Yes	No
Gauge	Yes	3174	3868
	No	1052	51745

Scores
POD= 45.1
FAR= 24.9
CSI= 39.2
BIAS= 0.60

Threshold 0.05mm/h

		Gauge	
		Yes	No
PWS	Yes	2660	550
	No	1343	55286

Scores
POD= 82.9
FAR= 33.6
CSI= 58.4
BIAS= 1.25

		Pluvio	
		Yes	No
PWS	Yes	2400	810
	No	1826	54803

Scores
POD= 74.8
FAR= 43.2
CSI= 47.7
BIAS= 1.32

		Pluvio	
		Yes	No
Gauge	Yes	3025	978
	No	1201	54635

Scores
POD= 75.6
FAR= 28.4
CSI= 58.1
BIAS= 1.06

7. Summary, conclusions and recommendations

7.1 Summary

The above analysis of the data of the Pluvio during the field test in De Bilt indicate that the results of the Pluvio compare generally very good with the results obtained by the KNMI precipitation gauge. The comparison of the measurements of the Pluvio on the observation field within a windscreen and the KNMI gauge in the so-called English setup do not show the wind effect, but this effect is probably masked by other error sources that occur when comparing 2 different types of precipitation sensors.

The differences between Pluvio and KNMI gauge show a dependency with precipitation intensity, with the Pluvio reporting higher precipitation amounts at intensities below 1.5 mm/h and lower values at higher precipitation rates. This signature has the opposite behavior as the wind effect that blows small droplets (low precipitation intensity) more efficiently over the orifice of a sensor in a windscreen, compared to the sensor in the English setup (cf. e.g. Wauben 2004). Possibly the differences are caused by wetting and evaporation losses in the KNMI gauge. This is corroborated by the fact that the results for the PWS closely follow the results for the Pluvio when both are compared to the KNMI gauge.

The results as a function of temperature or relative humidity reveal mainly differences caused by the faulty precipitation reports of the KNMI gauge during bright days. This effect also shows up when the results are plotted as a function of the temperature gradient. The faulty precipitation reports mainly occur at positive temperature gradients, during which the expansion of the water inside the reservoir of the KNMI gauge could result in faulty reports. Although the statistics is rather poor, the differences of the Pluvio and PWS compared to the KNMI gauge both show a similar negative slope with increasing temperature gradient. Again the differences seem to be the result of the KNMI precipitation gauge. Cooling will reduce the water level in the reservoir of the gauge and hence will cause the gauge to report lower precipitation intensities, whereas warming causes the gauge to report higher intensities.

The differences as a function of the collector content of the Pluvio show no evidence of splash out when the collector is nearly full. When the collector is nearly empty both Pluvio and PWS report more precipitation than the gauge. An empty collector is more susceptible to vibrations that could result in faulty reports by the Pluvio. However, the PWS shows the same behavior. Therefore the wetting and evaporation losses by the KNMI gauge mentioned above seem more likely.

The differences as a function of the quality parameter of the Pluvio show a slight positive slope for the differences between Pluvio and gauge, which cannot be observed in the differences between PWS and gauge. The overestimation of the precipitation intensities by the Pluvio for a quality parameter larger than 20 can be caused by erroneous results caused by vibration resulting from wind turbulence, temperature gradient or impact of precipitation itself. The occurrences of only a few faulty Pluvio reports and then only at low values for the quality parameter does no corroborate this.

The amount of data available and the number of parameters involved does not allow a detailed multi-parameter analysis.

Overall the results of the Pluvio compare rather well with those of the KNMI gauge for the field test in De Bilt, especially considering the 5% accuracy required by WMO. The differences that are observed can partly be caused by deficiencies in the KNMI gauge. The Pluvio is however not suitable for the determination of precipitation duration. For that purpose the usage of a precipitation detector should be considered. The use of separate sensors for the determination of precipitation amount a precipitation detection not only overcomes the compromises one has to make in the design when making an instrument for 2 different purposes including accurate overall sums and a high sensitivity, but furthermore the usage of 2 separate sensor makes it possible to perform online quality checks which is particularly useful for a meteorological parameter that shows large spatial differences.

The results of the Pluvio obtained during the field test in De Kooy show larger differences. Overall the differences are about 40mm (5%). The differences between the precipitation results obtained for each of the 3 sensors show no behavior indicating clearly the reason for this. Furthermore the differences between all 3 sensors show for some parameters a different behavior as for De Bilt, and this might be different for Pluvio and PWS. The differences between Pluvio and Gauge seem at least partly to be related to a larger number of faulty precipitation reports of the Pluvio. These faulty reports show a dependency on temperature and wind speed. However, it is not clear why the same instrument did not show this behavior during the field test in De Bilt under similar conditions. The differences can also not be explained in terms of differences in the gust factor caused by local condition.

7.2 Conclusions and recommendations

The comparison of the results obtained with the Pluvio precipitation sensor and the KNMI precipitation gauge during the field test in De Bilt showed that the Pluvio agrees within WMO requirements with the current operational KNMI gauge and in case of differences the Pluvio generally shows the same behavior as the results obtained with a present weather sensor. Based on the De Bilt results only the Pluvio proved to be a good alternative for the KNMI gauge. However, the results obtained during the field test in De Kooy showed many cases with faulty precipitation reports by the Pluvio and the observed differences between Pluvio and KNMI gauge are not corroborated by the PWS. The reason for the difference in performance at the test sites is unclear. Therefore the Pluvio precipitation sensor cannot be considered for operational use by KNMI at this moment.

The ways to proceed with the Pluvio are:

1. The sensor should be send back to the factory so that it can be checked. It could be that some mechanical change occurred to the instrument so that it did not work properly anymore after installation in De Kooy. This could, however, not be observed in the weight calibration of the sensor.
2. When the flied tests with the Pluvio described in this document started the same sensor and sensor software was used as the Deutscher Wetterdienst. By now the DWD, as a result of much experience with the sensor, is using a slightly modified version of the sensor and a newer software version (Lanzinger, 2004 and Zircher,

2004). KNMI should consider usage of this revised instrument especially when DWD is happy with the results. In any case, new field and laboratory tests would be necessary.

3. The new laboratory tests should check the temperature dependency of both Pluvio instruments using realistic temperature gradients as observed during the field tests. During the new field test the use of another Pluvio data format should be considered, which not only reports the derived precipitation intensity, but also reports the raw sensor weight data, that might be used by the manufacturer in order to investigate any problems in more detail.

A future field test should include more than one reference instrument and all the sensors considered in the test should be placed closely together. The results for De Kooy showed such variations and a different behavior from the results obtained at De Bilt that the correct operation of all three the sensors could be questioned. Furthermore the distance of the PWS and the wind mast to the Pluvio and KNMI gauge was too large at De Kooy. The situation was better during the field test in De Bilt, where the performance of each of the instruments also benefited by the proximity and a regular inspection. A future field test should preferably include at least 2 KNMI precipitation gauges (one in the English setup and another on the field within a windscreen, a PWS, 2 Pluvio sensors and a precipitation detector with all sensors are situated closely together. The raw data of all sensors should be acquired with a temporal resolution of at least a 1-minute and without being affected by changes to the measurement infrastructure network.

KNMI should consider the usage of a precipitation detector again. Presently optical detectors are available that seem to have acceptable maintenance intervals. Such a sensor is required in case precipitation duration measurements are to be continued for the users with the same level of sensitivity when a Pluvio is considered as the operational instrument for precipitation amount measurements. Furthermore, the field tests indicated that also the quality of the current precipitation measurements could benefit from such a sensor. Currently no on-line check of the precipitation measurements is performed by KNMI except for the internal sensor checks. A precipitation detector could easily have detected the cases of evidently faulty reports by the precipitation sensors that have been observed during the field tests.

KNMI should reconsider the necessity of replacement of the KNMI precipitation gauge. A modified design addressing the emptying mechanism, the potentiometer and the temperature compensation could possibly overcome the current problems with the sensor. Additionally, placing the gauge on the measurement field instead of in the English setup so that debris cannot get that easily into the collector could reduce the problems related with contamination. The faulty reports during clear days are mainly the result of the low detection limit of the sensor since it is also used for precipitation detection. When a separate detector measures precipitation duration, the gauge can be made less sensitive and/or validated on-line. Finally, the PWS could solely be used for the detection and reporting of the intensity of solid precipitation. Currently KNMI uses a combination of PWS and gauge data for reporting these weather phenomena that can lead to conflicts.

Lastly it is recommended that KNMI perform a study on the accuracy of the precipitation intensity measurements of the PWS. The intensity reported by the PWS is used operationally by KNMI for precipitation detection and the reporting of weather phenomena. The study should at least include a comparison of 10-minute intensity data obtained routinely for PWS and KNMI gauge at a dozen stations throughout the Netherlands. The results of the study can be used to set the intensity calibration factor of the PWS and to monitor its stability. However some effort should also be put on a calibration verification procedure such as dropping spheres of knows size through the optical measurement volume of the PWS in a laboratory.

8. References

Bijma, J.R.: XR1-SIAM Precipitation (in Dutch), Version 2.3, Instrumental Department, KNMI, De Bilt, 1995.

Dibbern, J.: Private communication, 1999.

Dover, J. and Winans, L.J.: Evaluation of Windshields for use in the Automated Surface Observing System (ASOS), Sixth Symposium on Integrated Observing Systems, AMS, 237, 2002.

Buishand, T.A. and Velds, C.A.: Precipitation and Evaporation (in Dutch), KNMI, De Bilt 1980.

Gordon, J.D.: Evaluation of Candidate Rain Gages for Upgrading Precipitation Measurements Tools for the National Atmospheric Deposition Program, Water-Resources Investigations Report 02-4302, U.S. Geological Survey, Denver, 2003.

Hooghart, J.C. et al.: From Penman to Makkink: a new calculation method for climatological evaporation values (in Dutch), Technical Report **TR 1988-111**, KNMI, De Bilt, 1988.

Kok, C.J.: On the Behaviour of a Few Popular Verification Scores in yes/no Forecasting, Scientific Report **WR 2000-04**, KNMI, De Bilt, 2000.

Kuik, F.: Precipitation Research 1998 (in Dutch), Internal Report **IR 2001-01**, KNMI, De Bilt, 2001.

Lanzinger, E.: Private communication, 2004.

Nešpor, V. and Sevruk, B.: Estimation of Wind-Induced Error of Rainfall Gauge Measurements Using a Numerical Simulation, *J. Atmos. Oceanic Tech.*, Vol. **16**, 450, 1999.

Ott Hydrometrie: Pluvio Precipitation Sensor DWD-Version (in German), User Manual, Ott Hydrometrie, 2000.

Ott Hydrometrie: Pluvio, Brochure, Ott Hydrometrie, 2002.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P.: Numerical Recipes in Fortran, Second Edition, Cambridge University Press, 1992.

Tumbusch, M.L.: Evaluation of Ott Pluvio Precipitation Gage versus Belfort Universal Precipitation Gage 5-780 for the National Atmospheric Deposition Program, Water-Resources Investigations Report 03-4167, U.S. Geological Survey, Carson City, 2003.

Wauben, W.M.F.: Precipitation amount and intensity measurements using a windscreen, Technical Report **TR 2004-262**, KNMI, De Bilt, 2004.

Wieringa, J. and Rijkoort P.J.: Wind Climate of the Netherlands (in Dutch), KNMI, De Bilt 1983.

WMO: Catalogue of National Standard Precipitation Gauges, (B. Sevruk and S. Klemm), Instruments and Observing methods Report No. **39**, WMO/TD-No. **313**, WMO, Geneva, 1989.

WMO: Guide to Hydrological Practices, Fifth edition, WMO-No. **168**, WMO, Geneva, 1994.

WMO: Guide to Meteorological Instruments and Methods of Observation, Sixth edition, WMO-No. **8**, WMO, Geneva, 1996.

WMO: WMO-CIMO Expert Meeting on Rainfall Intensity Measurements, Final Report, 23-25 April 2001, Bratislava, Slovakia, 2001.

Zircher, K.: Pluvio-DWD Modell 2004 (in German), Ott-Messtechnik, 2004.

Appendix: Evaporation

The Pluvio precipitation sensor measures the weight of the collector and reports the collector content in mm. Since the collector content is susceptible to evaporation, the Pluvio can also be used to determine evaporation. The evaporation of water from the Pluvio collector is illustrated in Figure 39 using the Pluvio measurements of June 25, 2001. The measured collector content of the Pluvio gradually decreases over this day from 74.26mm to 69.68mm, with the steepest decrease occurring around noon. The evaporation rate shown in the plot is derived by:

$$6\times\left(\mathrm{CC}_{k-1}-\mathrm{CC}_{k}\right)+\mathrm{NI}_{k},$$

with CC_k the collector content at 10-minute interval k in mm and NI_k the 10-minute averaged precipitation intensity in mm/h. The reporting resolution of the collector content of 0.01mm per 10-minute interval corresponds with a resolution of 0.06mm/h for the evaporation rate. The resolution clearly shows up as spikes in the evaporation rate, especially during nighttime. Figure 39 also shows that the evaporation rate is related to the observed ambient temperature and the amount of global radiation.

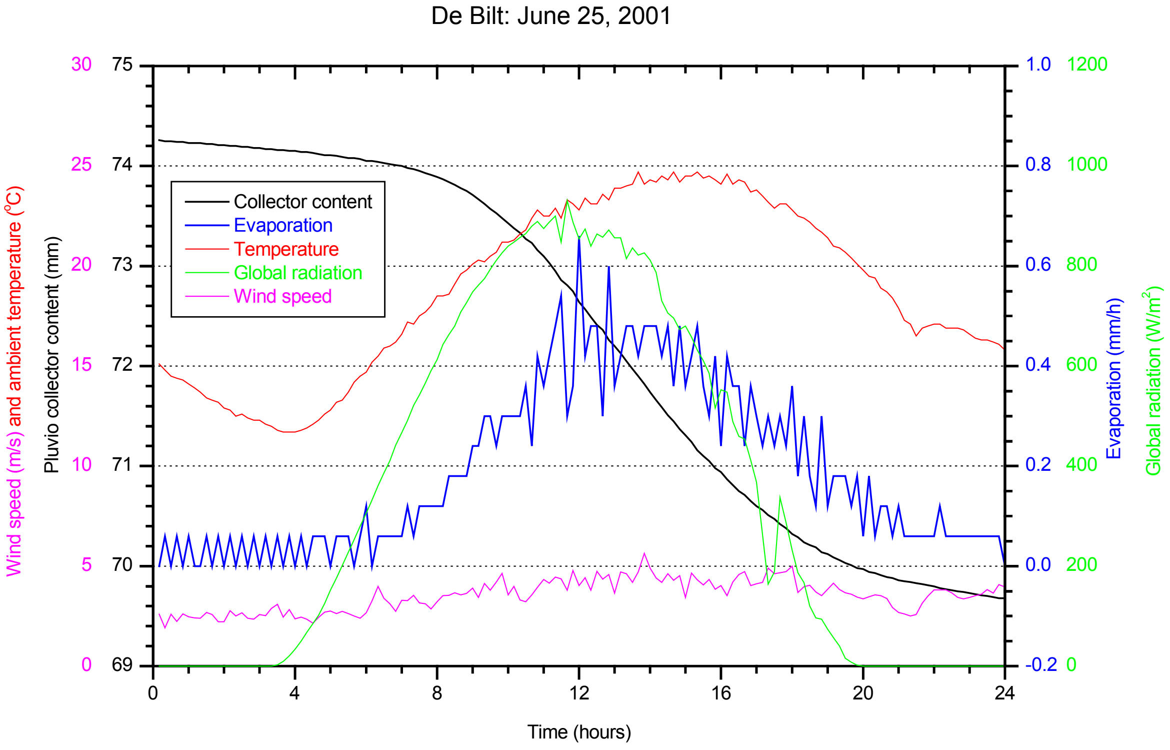

Figure 39: The Pluvio measurements of the collector content (black) and the derived evaporation rate (blue) performed at De Bilt on June 25, 2001. The behavior of several meteorological parameters is also shown for this clear day.

Figure 40 shows the collector content on a partially cloudy day with precipitation around noon. The evaporation rate is derived according to the above equation, but causes a large negative followed by a positive peak around the precipitation event. This effect is caused by the fact that the collector content and the precipitation reported by the Pluvio are not entirely consistent. Probably, the collector content and the precipitation amount are derived internally in the Pluvio by algorithms with different time scales. When the precipitation event, which is spread over 3 10-minute intervals, is considered as a whole, then the reported change in content (1.85mm) and precipitation amount (1.86mm) are nearly consistent and the difference of 0.01mm can be explained by evaporation (0.02mm/h), although this value is lower than the evaporation rate before and after the precipitation event. The results for July 15, 2001 also show a second precipitation event at about 20:30UT, but the other precipitation sensors did not report this event. Furthermore, Figure 40 also shows a slight increase in the reported collector content between 1 and 4UT without a corresponding precipitation intensity report. Since the other precipitation sensors did also not report any precipitation in this period, the increases is probably caused by the temperature dependency of the Pluvio and is correctly filtered out by the precipitation intensity algorithm used within the sensor.

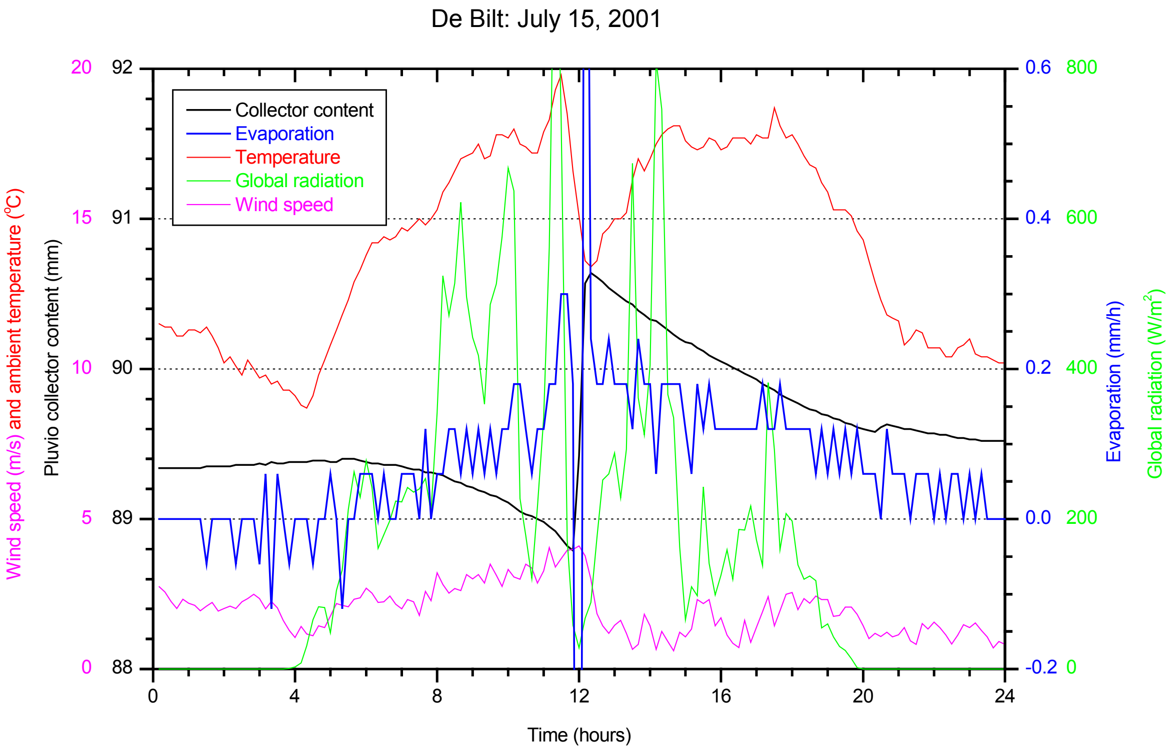
De Bilt: July 15, 2001

Figure 40: As Figure 39, but now for July 15, 2001 with a precipitation event.

Evaporation of an open water surface can be determined from energy conservation at the water/atmosphere interface. In e.g. a shallow lake the heat storage in the water can be ignored and the energy balance is expressed by (cf. e.g. Buishand and Velds, 1980):

$$R_n - LE - H = 0,$$

with R_n the net downward radiation at the surface, LE the latent heat flux, and H the sensible heat flux (all in W/m^{-2}). The net downward radiation can be measured, but it can also be derived form other meteorological parameters using the empirical relation:

$$R_n = 0.94 \times Q_g - \sigma T_a^{\,4} \times \left(0.47 - 0.067\sqrt{e}\right) \times \left(0.2 + 0.8 D_s\right),$$

where the first term is the incoming short-wave radiation with Q_g the global radiation (W/m^2), and the second term is the long-wave cooling with T_a the ambient temperature (K), e the water vapor pressure (hPa) and D_s the relative sunshine duration. The fluxes for latent heat and sensible heat can be written as:

$$LE = f(U) \times \left(e_s(T_0) - e\right) \text{ and } H = \gamma \times f(U) \times \left(T_0 - T_a\right)$$

with T_0 the water surface temperature (K), e_s the saturation vapor pressure (hPa), e the ambient vapor pressure (hPa) where $e = r \times e_s(Ta)$ with r the relative humidity, γ the psychometer constant and $f(U)$ the so-called wind function that can be described by the empirical relation:

$$f(U) = 4.4 + 1.82 \times U_{10},$$

with U_{10} the wind speed measured at 10 m (m/s). The above expressions can by further simplified by using the Taylor expansion:

$$e_s(T_0) \approx e_s(T_a) + s \times \left(T_0 - T_a\right), \text{ with } s = \left.\frac{de_s(T)}{dT}\right|_{T=Ta}.$$

The evaporation rate can then be expressed as:

$$LE = \frac{s \times R_n}{s + \gamma} + \frac{\gamma \times f(U) \times \left(e_s(T_a) - e\right)}{s + \gamma},$$

where the first term is a radiation term and the second determined by the wind speed and the saturation deficit. The latent heat flux LE is the product of L the latent heat of vaporization (2.5×10^{+6} J/kg) and E the evaporation rate (kg/m^{2}s). The evaporation rate can also be expressed in terms of mm/h by using the density of water ρ=10^3 kg/m^3. The evaporation is then given by:

$$E = \frac{3600 \times 1000}{\rho L}\left[\frac{s \times R_n}{s + \gamma} + \frac{\gamma \times f(U) \times \left(e_s(T_a) - e\right)}{s + \gamma}\right].$$

It should be noted that the evaporation rate of a bucket cannot directly be compared to the results obtained from commercially available evaporation pans. The main difference is that the water in the Pluvio collector is not freely exposed to sunshine, which will affect evaporation rate directly. Furthermore, shielding by the bucket will hinder the free exchange of the air directly above the water level, and hence will reduce evaporation. Finally, the water in the collector will also be contaminated by e.g. algae or leafs that affect evaporation, and the evaporation can only be measured as long as any water is left in the collector.

Next the dependency of the evaporation rate derived from the Pluvio on various parameters is studied in more detail. For that purpose the evaporation rate is calculated using the above relation, but the rate is only calculated for 10-minute intervals where:

- The collector content is valid and above a threshold of 60mm to assure that water is available for evaporation. This requirement also applies to the content of the previous 10-minute interval.

- The decrease in the collector content over the last 10-minute is less than 15mm in order to filter out events when the collector was manually emptied.
- The sensor reports no precipitation so that the above-mentioned inconsistency between collector content and precipitation amount cannot occur.

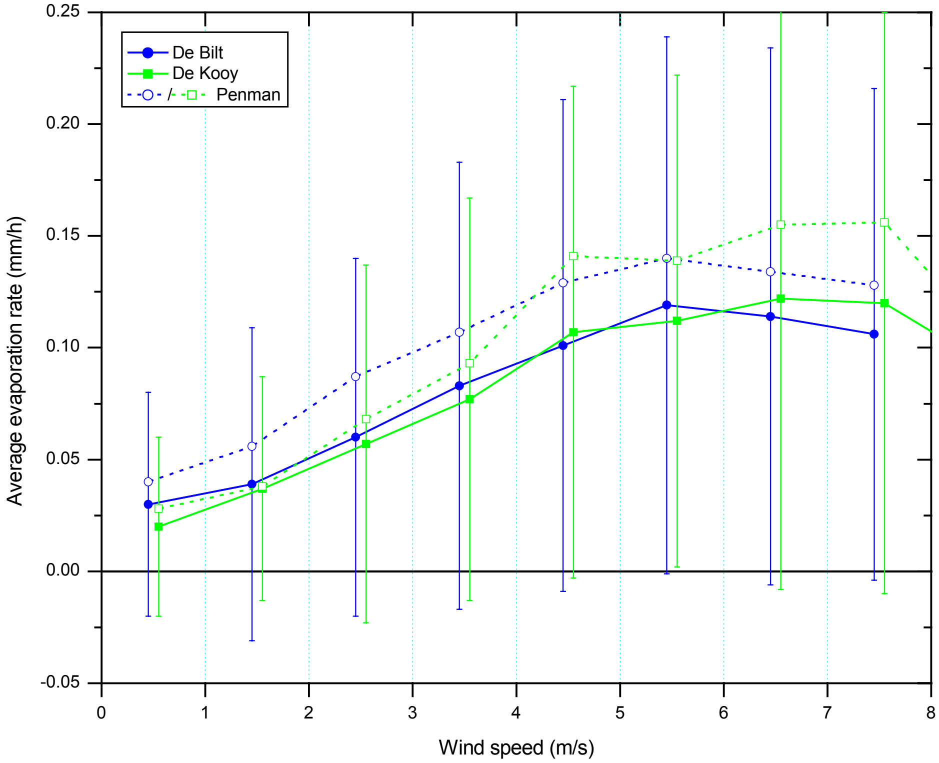

Figure 41: The average evaporation rate as a function of the wind speed in bins of 1m/s for field test data of De Bilt and De Kooy and the calculated evaporation rate using Penman' relation.

The evaporation rate is derived for the Pluvio data obtained during the field tests in De Bilt and De Kooy. The averaged evaporation is determined as a function of several meteorological parameters. Figure 41 shows the average evaporation rate as a function of the wind speed in bins of 1 m/s. The evaporation rate is shown for De Bilt and De Kooy separately together with the standard deviation. Both curves show a gradual increase of the evaporation rate with increasing wind speed at low wind speeds and nearly constant or slightly reducing evaporation rates at high wind speeds. The standard deviation of the measurements is relatively large. The figure also shows the evaporation rates calculated from other meteorological parameters by using the Penman relation reported above. The averaged evaporation measurements and the derived Penman evaporation rates for De Bilt and De Kooy show good agreement. The Penman evaporation shows an offset of about 0.02 to 0.03mm/h. The behavior of the measured and derived curves for De Bilt and De Kooy is, however, the same with De Bilt showing slightly larger evaporation rates than De Kooy except for wind speeds between 4 and 5m/s and above 6m/s.

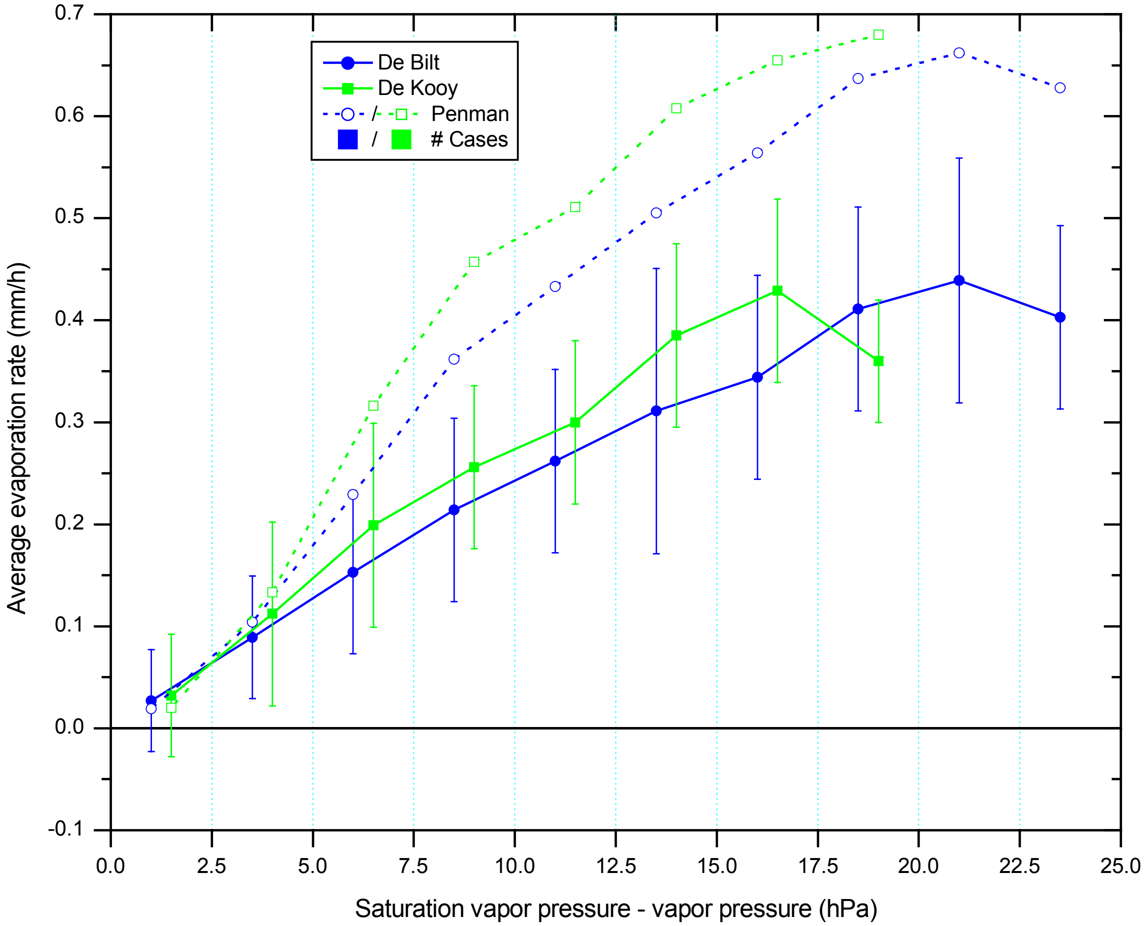

Figure 42: The average evaporation rate as a function of vapor pressure deficit in bins of 2.5hPa for field test data of De Bilt and De Kooy and the calculated evaporation rate using Penman' relation.

The averaged evaporation as a function of the vapor pressure deficit $e_s(Ta) - e$ is shown in Figure 42. The measured evaporation rates again show generally the same behavior as the Penman' results. Penman gives a slightly stronger dependency with the vapor pressure deficit. This is probably caused by a reduction in the free exchange of air for the Pluvio by shielding of the partly filled collector. As a result the evaporation will be less than could be expected for a freely exposed water surface.

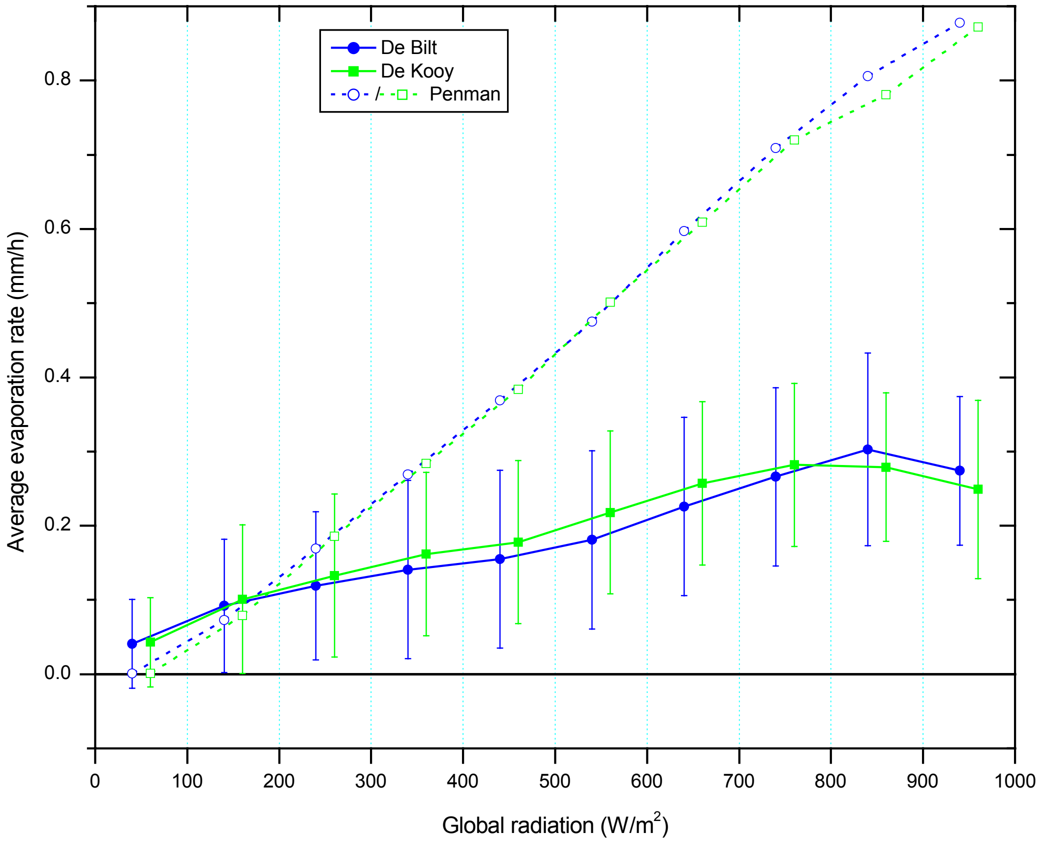

Figure 43: The average evaporation rate as a function of the global radiation in bins of 100W/m^2 for field test data of De Bilt and De Kooy and the calculated evaporation rate using Penman' relation.

Figure 43 shows the average evaporation rate as a function of the global radiation in bins of 100W/m^2. The evaporation rates show a gradual increase with increasing global radiation. The figure shows that the derived Penman evaporation rates are much higher than the observed evaporation rates. The difference of the slope of the evaporation rate as a function of the global radiation is nearly a factor of 4. The above-mentioned shading is the main cause for this difference in slope since the water in collector is not freely exposed to solar radiation.

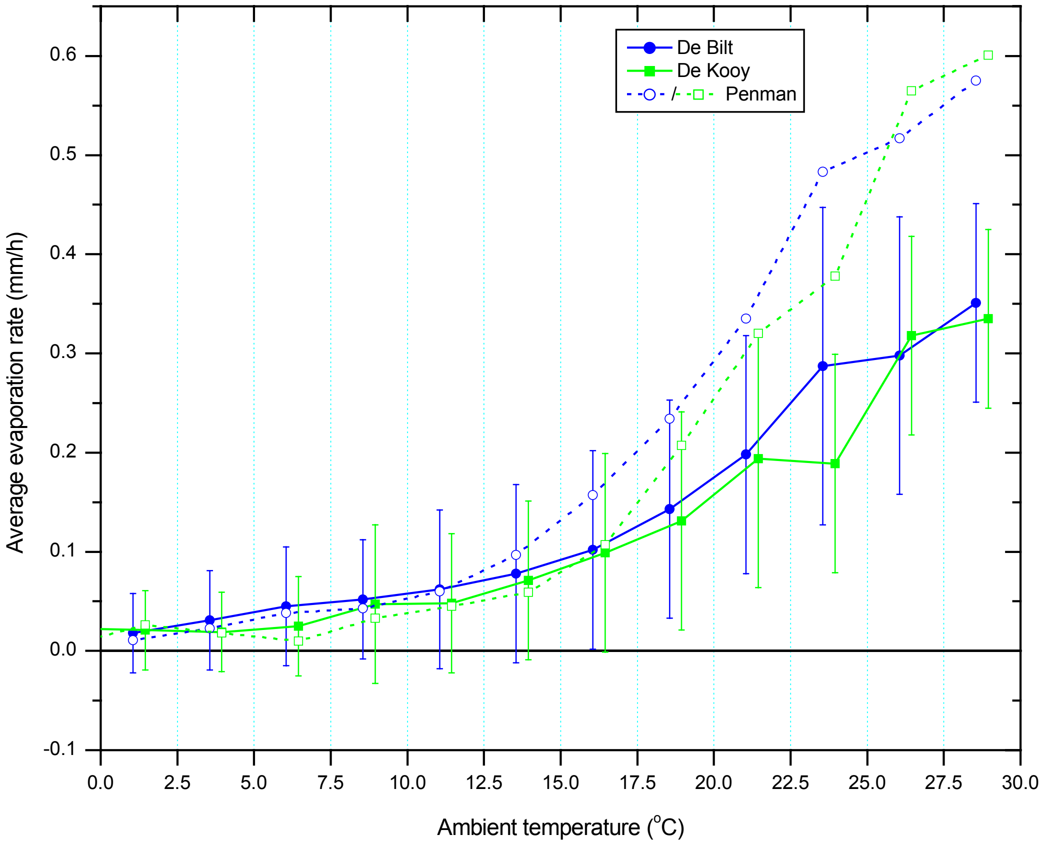

Figure 44: The average evaporation rate as a function of the ambient temperature in bins of 2.5°C for field test data of De Bilt and De Kooy and the calculated evaporation rate using Penman' relation.

In Figure 44 and Figure 45 the average evaporation rate is shown as a function of the ambient temperature in bins of 2.5°C and the relative humidity in bins of 5%, respectively. The evaporation rates show a gradual increase with increasing ambient temperature and decrease with increasing relative humidity. The differences between the measured and calculated evaporation rates are again large, although the behavior of the curves is generally correctly given by the Penman curves. The Penman curves generally underestimate the evaporation rates slightly for ambient temperatures below 12.5°C, whereas at higher temperatures the evaporation rates are overestimated. The evaporation rates as a function of relative humidity show a rather large difference between the results obtained for De Bilt and De Kooy. This difference is, however, also given by the Penman evaporation rates. The Penman curves overestimate the evaporation at low relative humidity values.

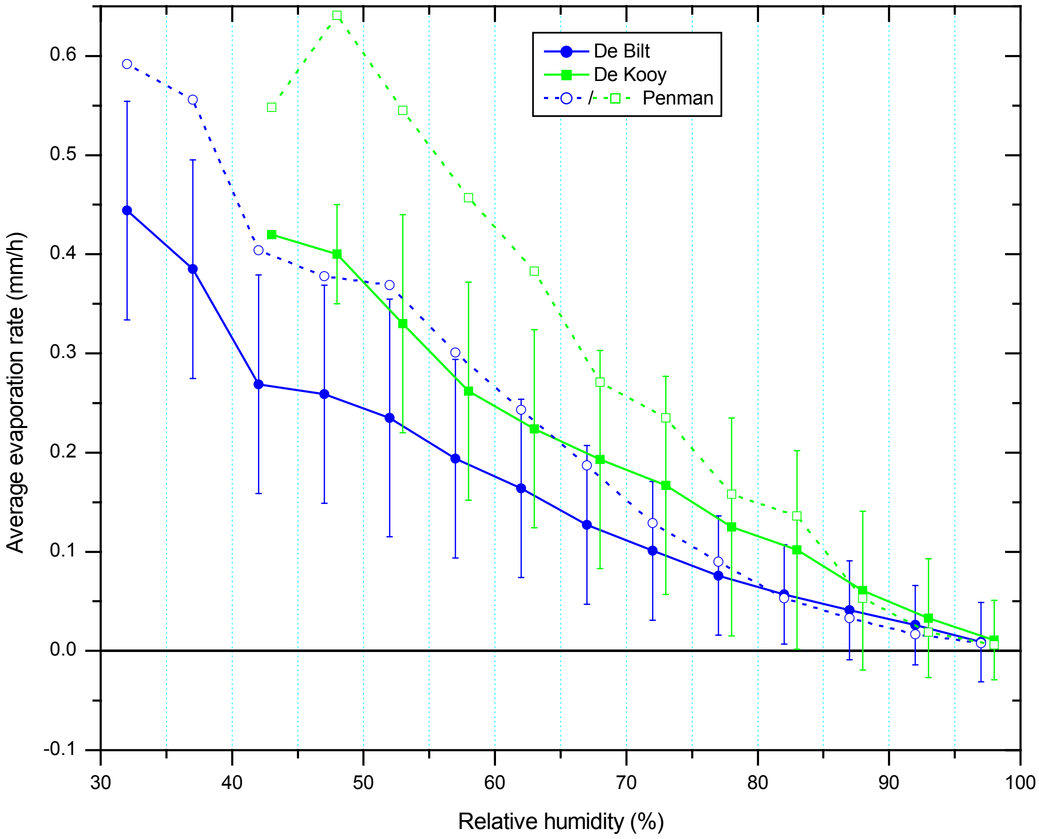

Figure 45: The average evaporation rate as a function of the relative humidity in bins of 5% for field test data of De Bilt and De Kooy and the calculated evaporation rate using Penman' relation.

In conclusion it is noted that although the weight measurements of the Pluvio show a clear sign of evaporation, this evaporation cannot directly be compared to the evaporation measured by commercially available evaporation pans. Furthermore, for agricultural purposes the parameter of interest is the so-called evapotranspiration from land covered with vegetation that is usually measured with so-called lysimeters. However, KNMI derives daily evapotranspiration values using the Makkink relation (Hooghart et al, 1988). Since the evaporation rates derived from the Pluvio weight measurements seem realistic they could possibly be considered for applying evaporation corrections to the derived precipitation intensity, particularly for low intensity rates. However, the relative humidity will generally be large in these situations, and hence the evaporation correction will be small.