PRECIPITATION TYPE AND RAINFALL INTENSITY FROM THE PLUDIX DISDROMETER DURING THE WASSERKUPPE CAMPAIGN

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1. INTRODUCTION

Pludix is an X-band disdrometer based on the Doppler principle, providing information on the drop size distribution (DSD) and rainfall intensity (R). In the past few years the instrument has been involved in various measuring campaigns (e.g. Caracciolo et. al., 2006), testing its performances in R and DSD measurements, and comparing it with other disdrometers of different operating principles. The instrument has shown good capabilities in both R and DSD estimations. This work describes, for the first time, the research done to determine the capabilities and limitations of Pludix also as a Present Weather Sensor (PWS). Twelve precipitation codes are selected in liquid, mixed and solid precipitation. Pludix is compared with the reference observations of a human observer (hereinafter HO) during a two-year campaign held at the Wasserkuppe weather station – Germany (Bloemink and Lanzinger, 2005). Moreover Pludix is compared with other PW instruments present at the site: the Vaisala FD12P-PWS (V1.83 1999-11-19, SN: 30301) and the optical disdrometer Parsivel M300 (PMTech). The Parsivel M300 used here (Löffler-Mang and Joss, 2000) was produced by PMTech (Germany) and is no longer on the market. The instrument has been completely redesigned in hardware and software and it is now produced by OTT (Germany) under the name "OTT Parsivel". We also test the performance of Pludix in measuring rainfall intensity, comparing it with the other sensors for some significant events. Finally, some drop size spectra analyses for Pludix and the optical disdrometer Parsivel are shown.

2. INSTRUMENTS SET-UP AND METHODOLOGY

Pludix (referred to as Plx in the following tables and figures) is compared with FD12P, Parsivel (referred to as Pars) and human observations during a campaign held at the Wasserkuppe weather station, located in central Germany at an height of 950 m (asl). The instruments are all collocated within a field of about 50 m^2, with Pludix and Parsivel almost neighbours.

Pludix is a rain-gauge/disdrometer based on the analysis of an X-band (9.5 GHz) continuous wave radar signal backscattered by hydrometeors (Prodi et. al., 2000). The shape of the power spectrum in the 0-1024 Hz frequency range has various characteristics, depending on the different precipitation types. Twelve precipitation codes, according to WMO-4680, are considered by analysing the characteristics of the power spectrum in terms of maximum intensity, maximum location in the frequency range and spectrum amplitude. The precipitation types corresponding to the selected codes are: rain (codes 61, 62, 63 – rain not freezing slight, moderate, heavy), snow (codes 71,72,73 – snow slight, moderate, heavy), hail (codes 93, 96 – thunderstorm slight or moderate, heavy with hail), ice crystals (code 78), mixed precipitation (codes 67, 68 - rain and snow slight, moderate or heavy), no significant weather observed (code 00). The Pludix data consist also of number of raindrops n_i of diameter D_i in 21 categories, ranging in size from 0.8 to 7.0 mm, with a constant step of 0.3 mm. The rainfall rate in mm/h is computed from the DSD information. All data are given in 1-minute time intervals.

The reference at Wasserkuppe consists of data from various sources (Bloemink and Lanzinger, 2005). The HO is located about 100 m from the instruments, reporting PW 24 hrs/day with a 1-minute time resolution. A number of instruments report precipitation intensity, 2m temperature, 2m relative humidity, 2m wind speed and dew point temperature.

The FD12P measures the scattering of light of a small volume of the atmosphere. If there are precipitation particles present in this volume, they lead to peaks in the scattered light (FD12P Interface Control Document, 2007). The peaks are related to particle size. Separately, the FD12P has a capacitive sensor (DRD 12) that measures the water content of the precipitation. Combining these two quantities leads to a discrimination between large particles with low water content (i.e. snow) and small particles with high water content (rain). Fine tuning is done by choosing appropriate limits for, for instance, mixed precipitation, hail and freezing rain. In addition, temperature constraints, maximum particle size and a selection algorithm to determine the most significant precipitation type, are used. Every 15 seconds, an “instant” precipitation type is given (among other parameters). Here, the information on the precipitation intensity in mm/h and the fifty-two codes supported by the WMO code table 4680 are used.

Parsivel is a laser-based optical system; a laser sensor produces a horizontal strip of light (Parsivel M300, PMTech Manual, 2002). Precipitation particles passing through the laser beam block off a portion of the beam corresponding to their diameter, thus reducing the output voltage. To determine the particle speed, the duration of the signal is measured. The size range of liquid precipitation particles is 0.2-5mm, the size range of solid precipitation is 0.2-25mm (32 classes), the velocity range is 0.2-20 m/s (32 classes). From particle size and speed, different parameters are derived. We use information on the rain intensity R in mm/h, the DSD in $mm^{-1}m^{-3}$ and the precipitation type (eighteen WMO-4680 precipitation codes). All data are given in 30-seconds time intervals.

Two years of data are analysed (from December 2000 to December 2002); in this period, more than 300 precipitation events were selected, in terms of both liquid and solid precipitation, allowing for a good evaluation of Pludix capabilities. All data are synchronized in 1-minute time intervals, leading to a maximum of 1440 measurements per day. The HO precipitation type, reported in the WMO code 4677, is changed into code 4680 (automatic observation) to match with the output of the other instruments. Differences in Pludix ground noise are observed passing from autumn to summer months, determining the necessity to consider different precipitation type identification criteria for the different seasons.

3. RESULTS AND DISCUSSION

3.1 determination of the capabilities of Pludix as a PWS

Tab. 1 shows the percentage of agreement/disagreement between Pludix and HO (taken as the truth) for the twelve WMO-4680 codes considered by Pludix for the two years of data. The results show that Pludix performs quite well in distinguishing the precipitation type, and is generally in agreement with the HO, especially for the rain codes (codes 61, 62 and 63). The percentage of agreement for codes 62 and 63 grows to 51% and 73%, respectively, during the summer months (June, July and August). Consider now the codes grouped by precipitation type. When HO gives code 61, Pludix gives a rain code in 31.67% of cases. When HO gives code 62, Pludix gives a rain code in 76.69% of cases. When HO gives code 63, Pludix gives a rain code in 81.51% of cases. When HO gives code 67, Pludix gives a mixed code in 12.8% of cases (a rain code in 17.46% of cases, a snow code in 16.99% of cases). When HO gives code 68, Pludix gives a mixed code in 16.11% of cases (a rain code in 43.89% of cases, a snow code in 34.99% of cases). When HO gives code 71, Pludix gives a snow code in 13.85% of cases. When HO gives code 72, Pludix gives a snow code in 42.52% of cases.

Percentage of agreement/disagreement Plx-HO (taken as the truth) – Codes 4680													
	61	**62**	**63**	**67**	**68**	**71**	**72**	**73**	**78**	**93**	**96**	**00**	**other**
61	17.99	13.10	0.58	4.30	0.01	0.29	0.33	0.43	3.45	0.08	0.02	58.61	0.80
62	23.58	48.59	4.52	5.53	0.05	0.20	0.72	0.54	1.05	0.81	0.29	13.01	1.09
63	3.36	30.25	47.90	0.84	0	0	0	0	0	3.36	3.36	10.92	0
67	8.54	6.73	2.19	12.39	0.41	3.83	6.24	6.92	1.44	0	0	48.25	3.05
68	5.56	32.22	6.11	14.44	1.67	1.11	19.44	14.44	0	0.56	0	2.22	2.22
71	5.29	0.19	0.05	5.12	0.02	6.03	4.67	3.15	6.07	0	0	67.64	1.78
72	6.68	0.56	0.24	10.22	0.01	18.03	14.90	9.59	3.26	0	0	33.85	2.66
78	5.63	0.01	0	1.20	0	0.60	0.50	0.11	9.00	0	0	82.50	0.43
00	2.76	0.04	0.02	2.06	0	0.52	0.40	0.47	3.68	0	0	89.17	0.89
other	4.35	1.72	0.20	3.10	0	0.51	0.25	0.30	5.35	0.02	0.03	83.50	0.67
Counts													
HO	55684	10923	119	6390	180	32719	6800	0	7142	0	0	129567	225857
Plx	29140	17170	1536	15934	61	5501	4344	3747	21836	180	105	371605	4222

Tab. 1: Percentage of agreement/disagreement between Pludix and HO (taken as truth) for the 12 WMO-4680 codes considered by Pludix. Two years of data are considered.

Consider now the percentage of agreement/disagreement between Pludix and the other instruments (taken as the truth) for the twelve codes considered by Pludix for the two years of data (Tab. 2).

Agreement/disagreement % Plx-HO (taken as the truth) – Codes 4680					
	liquid	**mixed**	**solid**	**no rain**	**other**
liquid	39.40	4.52	4.17	51.06	0.85
mixed	18.20	12.89	18.89	46.99	3.03
solid	5.82	5.28	22.20	64.99	1.70
no rain	2.82	2.06	5.06	89.17	0.89
Agreement/disagreement % Plx-FD12P (taken as the truth) – Codes 4680					
	liquid	**mixed**	**solid**	**no rain**	**other**
liquid	45.18	5.59	4.50	43.69	1.04
mixed	12.09	9.99	24.08	51.92	1.92
solid	5.33	4.53	22.31	66.31	1.51
no rain	3.27	2.08	5.73	87.90	1.02
Agreement/disagreement % Plx-Pars (taken as the truth) – Codes 4680					
	liquid	**mixed**	**solid**	**no rain**	**other**
liquid	55.37	8.49	2.58	32.23	1.33
mixed	9.61	4.93	17.40	66.79	1.26
solid	5.51	1.90	31.99	58.99	1.61
no rain	3.35	2.26	7.33	86.35	0.70

Tab. 2: Percentage of agreement-disagreement between Pludix and the other sensors taken as the truth for precipitation categories. Two years of data are considered.

Pludix performs quite well in the case of liquid precipitation, and is in good agreement with Parsivel for solid precipitation. The percentage of agreement with HO for the rain, mixed and solid category grows to 47%, 17% and 28%, respectively, during autumn, winter and summer months. Note that the Pludix percentage of agreement in the case of mixed precipitation is low, and in these situations our instrument detects a high percentage of solid precipitation. This is probably due to the fact that in the case of mixed precipitation the refraction index is the one of water (the maximum intensity is high) but the terminal velocity (therefore the frequency) is that of snow; therefore Pludix identifies a snow code instead of a mixed code.

In the following analysis we show that Pludix works better than the others in the case of rain (see also Sect. 3.2). The two years of data are considered. When Pludix gives code 61 consider how many minutes the other three sensors give code 62 or 63 (Fig. 1a). The HO always reports a temperature between 0-15°C during these minutes. Code 63 is probably wrong because R is always below 5 mm/h. When Pludix gives code 63, consider how many minutes the other three sensors give code 61 or 62 (Fig. 1b). The HO always reports a temperature between 0-20°C during these minutes. The rainfall rate is over 10 mm/h for a high percentage of minutes, indicating that the code 63 indicated by Pludix is probably the most reliable.

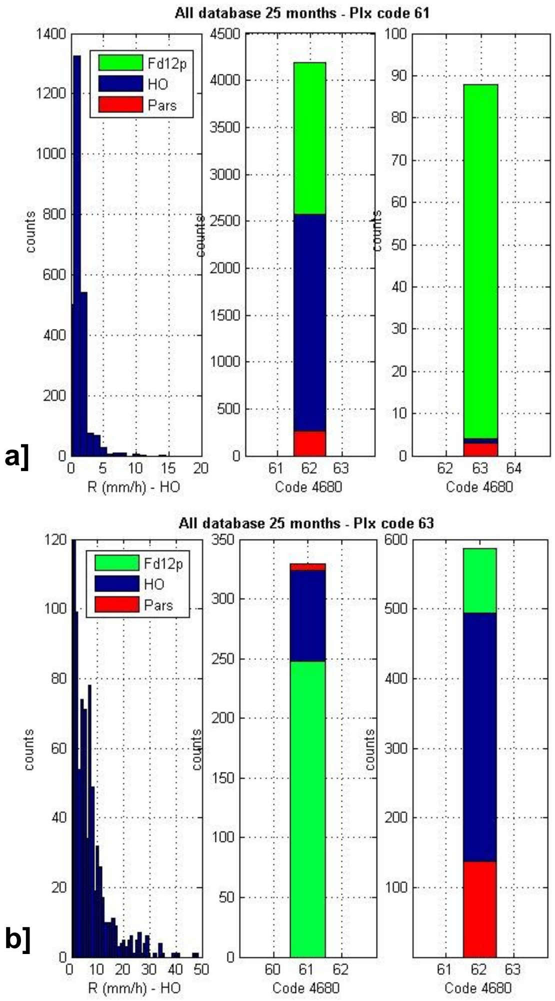
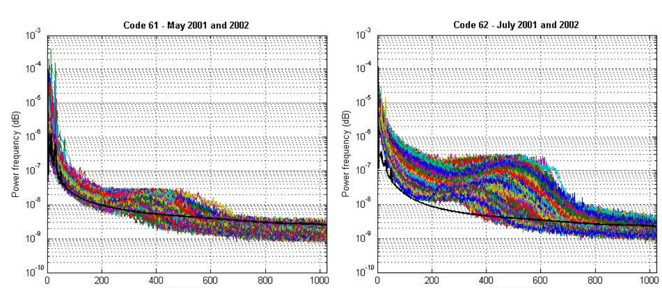


Fig. 1: **a]** HO rainfall rate (mm/h), HO temperature (°C), HO, FD12P and Parsivel WMO-4680 codes 62 and 63 when Pludix gives code 61; **b]** HO rainfall rate (mm/h), HO temperature (°C), HO, FD12P and Parsivel WMO-4680 codes 61 and 62 when Pludix gives code 63. Two years of data are considered.

Fig. 2 shows the 1-minute power spectra of Pludix for some coincident minutes in which Pludix is in agreement with HO for some of the 12 Pludix selected codes (except code 93, not reported by HO). These figures are considered as reference for a subsequent analysis. The frequency interval is divided into three parts: the snow band between 0-200Hz; the rain band between 200-600Hz; the hail band over 600Hz. It is important to point out that these values are indicative. For the rain band (codes 61, 62 and 63), the power spectrum has a characteristic maximum whose frequency is higher as rain intensity grows; the maximum location in the frequency band also usually grows as the rain intensity grows. Moreover the heavy precipitation usually has relatively flattened spectra, with narrow and emphasized maxima at higher frequencies, often with an irregular shape. The presence of heavy rain with hail (codes 93 and 96) is indicated by the high frequency part of the spectrum, with one or more peaks over 550 Hz. The presence of snow (codes 71, 72 and 73) is indicated by a bell-shaped spectra, with a maximum totally in the lower part of the spectrum (below 200 Hz). The bell is usually quite narrow, indicating rather similar terminal snowflake velocities. The maximum is sometimes shifted toward higher or lower frequencies, in the case of higher or lower terminal fall velocities, respectively. The case of rain and snow (codes 67 and 68) is very similar to the rain-snow cases. There is a bell-shaped spectrum of the snow and a hyperbolic extension toward the high frequencies of the rain. More often a single maximum is present, usually at low-medium frequencies, in the transition zone between rain and snow. The presence in the atmosphere of frozen hydrometeors with low terminal velocities gives rise to peaks in the lower part of the spectrum (below 50 Hz). This bristle-like spectrum indicates a superposition of almost monodisperse size distributions of ice crystals (code 78).



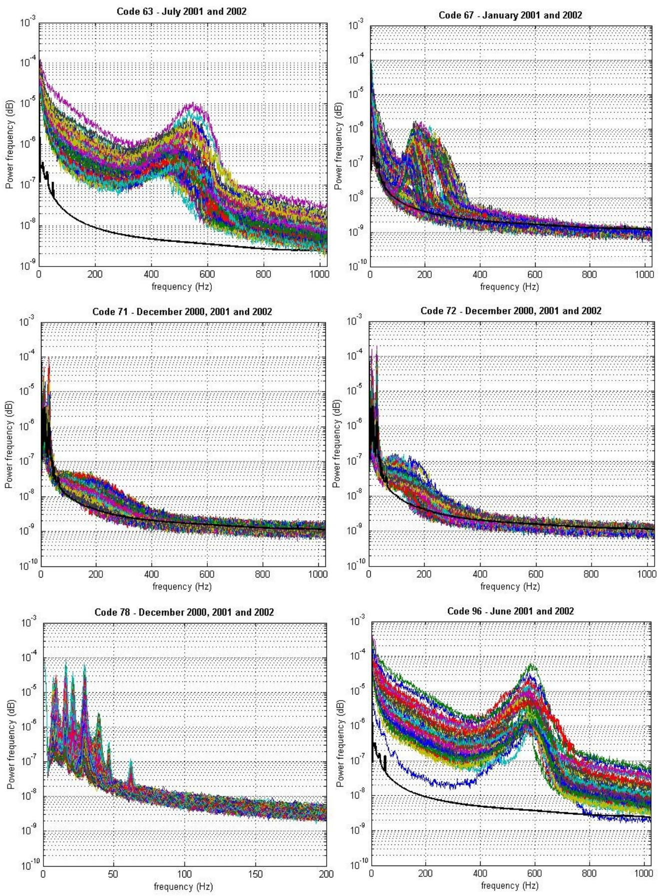
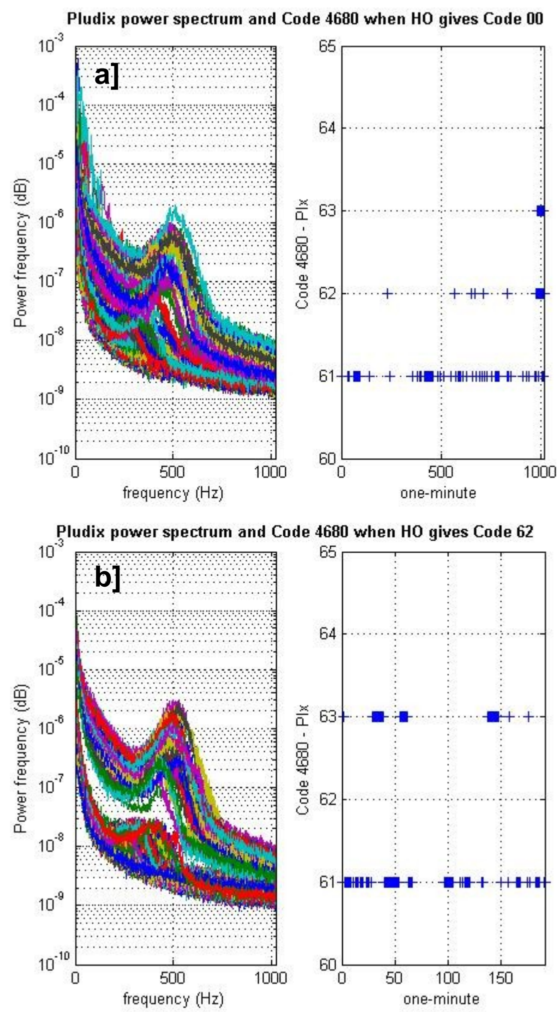


Fig. 2: Typical meteorological situations detected by Pludix in Wasserkuppe from December 2000 to December 2002.

The following analysis shows that Pludix detects some situations (especially rain, rain-shower with hail, ice crystals) that the HO does not detect (Fig. 3). The two years of data are considered. The situations of agreement between HO and Pludix are discarded. When HO gives code 00, Pludix gives rain codes (see, for example, Fig 3a showing the August spectra, where Pludix gives 0.8% of code 61, 0.2% of code 62, 0.1% of code 63). When HO gives code 62, Pludix gives a different rain code. For example in May (Fig. 3b), in 17.9% of cases Pludix gives code 61 and in 8.1% of cases it gives code 63. In December (Fig. 3c), when HO gives code 71, Pludix gives in 8% of cases code 67, in 4% of cases code 72, in 2% of cases code 73 and in 8% of cases code 78. In December (Fig. 3d), when HO gives code 72, Pludix gives in 14.62% of cases code 67 and in 21.82% of cases code 71. It is supposed that Pludix performs better than HO in these cases; in fact it can be seen that the spectra shown in Fig. 3 are similar to the ones shown in Fig. 2, where Pludix is in agreement with the HO for the corresponding codes.

Consider now again Tab. 1. Code 78 is not well detected by Pludix because its spectrum is quite similar to the ground noise (low percentage agreement with HO). Codes 61 and 71 are not well detected because our instrument is less sensitive to these slight precipitations; moreover the HO samples on a large measurement volume, while Pludix samples on a small measurement volume (about 3 m high and 1 m wide above it). When the HO gives codes 61 and 71, Pludix gives code 00 in a high percentage (see Tab. 1).



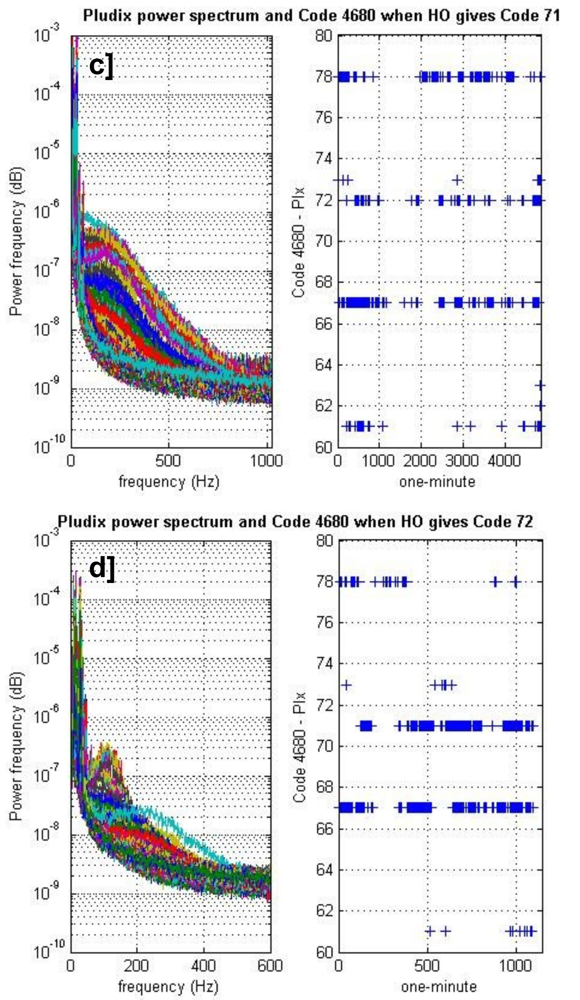


Fig. 3: Pludix power spectrum and WMO-4680 code when HO gives code 00 (August) **a]**; code 62 (May) **b]**; code 71 (December) **c]**; code 72 (December) **d]**.

Consider Fig. 4, in which we analyse the HO rainfall rate (mm/h), temperature (°C) and WMO-4677 codes when Pludix detects no significant weather observed (code 00) for all the two years of data. The HO detects a high percentage of fog/ice fog (codes from 40 to 50) and drizzle (codes from 50 to 60), of difficult identification with Pludix, because of the low terminal velocities. Also FD12P provides an high percentage of fog and drizzle situations (not shown). The agreement is better between Pludix and Parsivel. During the fog/drizzle situations reported by HO, Pludix provides the code 00 in 84.51% of cases.

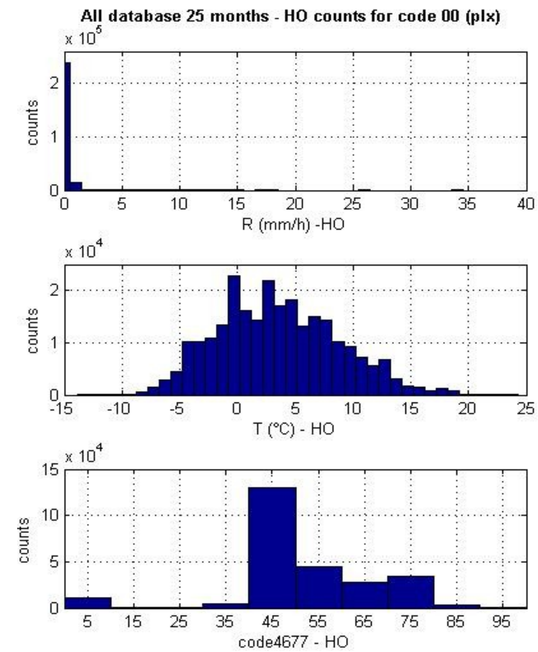


Fig. 4: HO rainfall rate (mm/h), temperature (°C) and WMO-4677 code when Pludix provides code 00. Two years of data are considered.

Consider now only the twelve Pludix selected codes and convert the HO WMO-4677 into 4680. When Pludix gives code 00 observe the percentage of minutes in which the other three sensors give the twelve codes (Tab. 3). The two years of data are taken into account. A good percentage of agreement is seen in the case of code 00 between Pludix and the other three sensors (especially Parsivel). There is a percentage of cases in which the other sensors (especially HO and FD12P) detect codes 61 and 71.

Percentage of frequency of the 12 codes when Plx provides code 00			
WMO4680	**HO**	**FD12P**	**PARS**
61	8.78	8.23	3.49
62	0.38	0.88	0.03
63	0	0.04	0
67	0.83	0.46	3.33
68	0	0.02	0.08
71	5.96	6.55	0.01
72	0.62	1.16	0.31
73	0	2.76	0
78	1.58	0.23	0
93	0	0	0
96	0	0	0
00	31.09	22.69	83.22

Tab. 3: Percentage of frequency of the 12 WMO-4680 codes for HO, FD12P and Parsivel, when Pludix provides code 00. Two years of data are considered.

Therefore, the codes that Pludix recognizes with more difficulty are WMO-4680 61 and 71, corresponding to WMO-4677 60-61 and 70-71 for HO (codes 60 and 70 are intermittent precipitation, codes 61 and 71 are continuous precipitation). The HO is able to detect intermittent precipitation because of its large sample volume, while Pludix, looking over a few cubic meters above it, provides code 00 for these minutes. Tab. 4 shows situations in which Pludix gives code 00 and HO gives different WMO-4677 codes. The two years of data are considered. The HO provides an intermittent rain code 60 in a maximum of 56.6% of cases during winter; the percentages are smaller for the snow situation.

HO WMO-4677 codes when Pludix gives code 00. Total Percentage (two years of data)							
60	**61**	**62**	**63**	**70**	**71**	**72**	**73**
36.4	63.6	10.6	89.4	25.3	74.7	29.2	70.8
Winter							
60	**61**	**62**	**63**	**70**	**71**	**72**	**73**
56.6	43.4	0	100	32.5	67.5	0	100
Spring							
60	**61**	**62**	**63**	**70**	**71**	**72**	**73**
50.1	49.9	0	100	25.8	74.2	0	100
Summer							
60	**61**	**62**	**63**	**70**	**71**	**72**	**73**
48.9	51.1	4.5	95.5	0	100	59.3	40.7
Autumn							
60	**61**	**62**	**63**	**70**	**71**	**72**	**73**
54.2	45.8	0	100	14.9	85.1	0	100

Tab. 4: HO WMO-4677 codes when Pludix gives code 00. Codes 60-61: rain not freezing intermittent or continuous slight; Codes 62-63: rain not freezing intermittent or continuous moderate; Codes 70-71: intermittent or continuous fall of snowflakes slight; Codes 72-73: intermittent or continuous fall of snowflakes moderate. Two years of data are considered.

3.2 comparison between the different instruments in terms of rainfall intensity

Considering all the 1-minute coincident measurements in all the database and only the minutes in which the HO provides rain codes (WMO-4680: 61, 62 and 63), the correlation coefficients between the rainfall rate estimation (mm/h) of HO and the other sensors are: HO-Pludix 0.61, HO-Parsivel 0.46, HO-FD12P 0.59. Thus, Pludix works better in the case of rain. Fig. 5 shows a rain event taken as representative. A good agreement is seen both in rainfall rate values and in WMO-4680 codes among the four instruments.

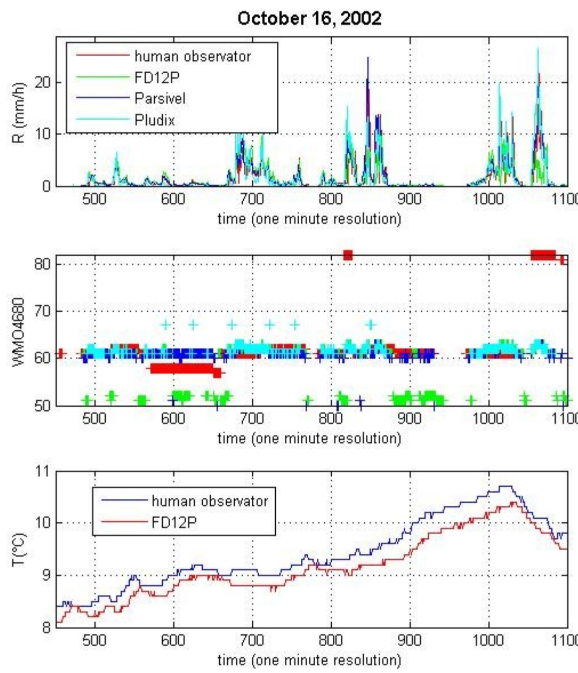


Fig. 5: 1-minute time evolution of R (mm/h), WMO-4680 code and T (°C) for the 16 October, 2002 event in Wasserkuppe.

3.3 comparison between Pludix and Parsivel for different precipitation events

In this section we test the performances of Pludix in PW identification and DSD measurement, comparing it with Parsivel. One rain event, one snow event and one hail event taken as representative are considered.

The rain event of 10 August, 2002

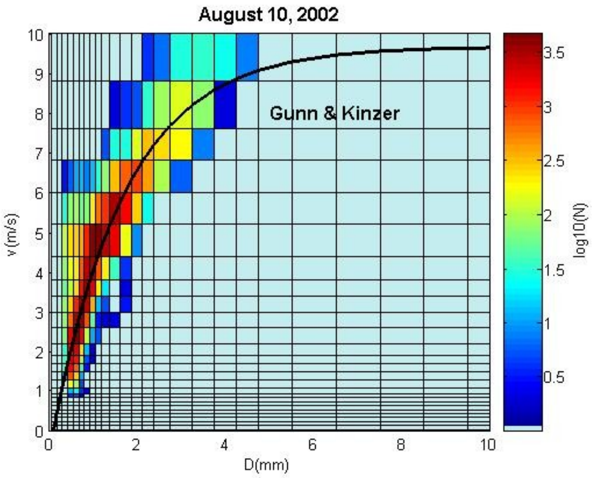


Fig. 6: Parsivel v-D histograms for the 10 August 2002 rain event. The solid line is the Gunn and Kinzer (1949) curve.

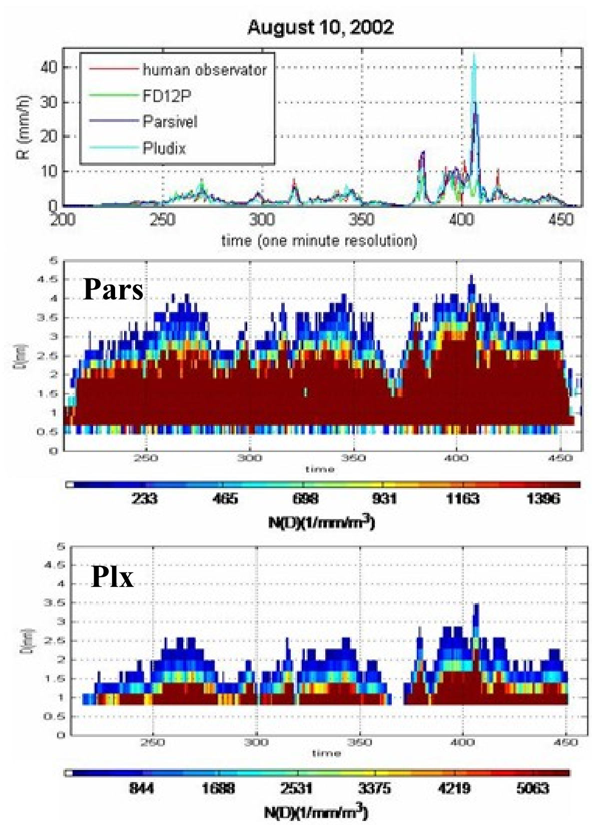


Fig. 7: Rainfall rate time series for the 10 August 2002 rain event for the four instruments; DSDs time series for the 10 August 2002 event for Parsivel and Pludix

Fig. 6 shows the velocity-diameter histogram derived from Parsivel data; N is the number of drops in each 32 velocity and 32 diameter classes. For this event the v-D relationship follows very well the Gunn and Kinzer (1949) relationship for water droplets in stagnant air at sea level: $v(D) = 9.65 - 10.3\exp(-0.6D)$ - D in mm, v in m/s. For this event Pludix shows the characteristic spectra of rain (not shown). Fig. 7 shows the 1-minute rainfall rate evolution for the event for the four instruments and the 1-minute DSD evolution for Parsivel and Pludix. The four instruments are in good agreement in the R estimation. The DSDs derived from Parsivel and Pludix show a good agreement in the mid-diameter range (1<D<3 mm), with a higher concentration of small drops in the first Pludix diameter classes.

The snow event of 24 February, 2001

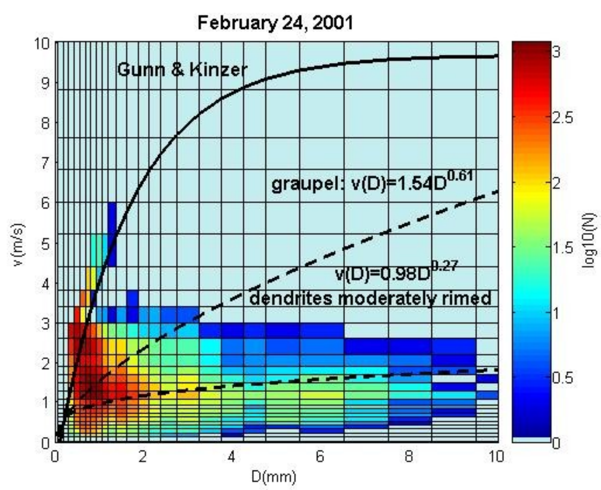


Fig. 8: Parsivel v-D histograms for the 24 February 2001 snow event. The solid line is the Gunn and Kinzer (1949) curve. The dashed lines are two empirical fits for graupel and snowflakes (Pruppacher and Klett, 1998).

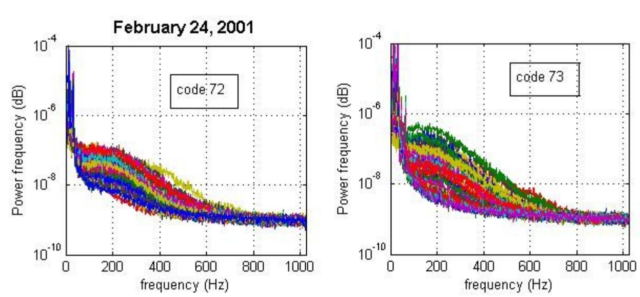


Fig. 9: Pludix power spectra for the 24 February 2001 snow event for the minutes characterized by codes 72 and 73.

Fig. 8 shows the v-D histogram derived from Parsivel data. It can be seen that for this event the v-D relationship is very far from the Gunn and Kinzer (1949) relationship for water droplets, while it follows two of the empirical fits derived for graupel and snow-flakes of different riming degree and consisting of different crystal types (Pruppacher and Klett, 1998). For this event Pludix identifies WMO-4680 snow codes (71, 72 and 73). Fig. 9 shows the Pludix power spectra for the event for the minutes characterized by codes 72 and 73.

The hail event of 05 June, 2002

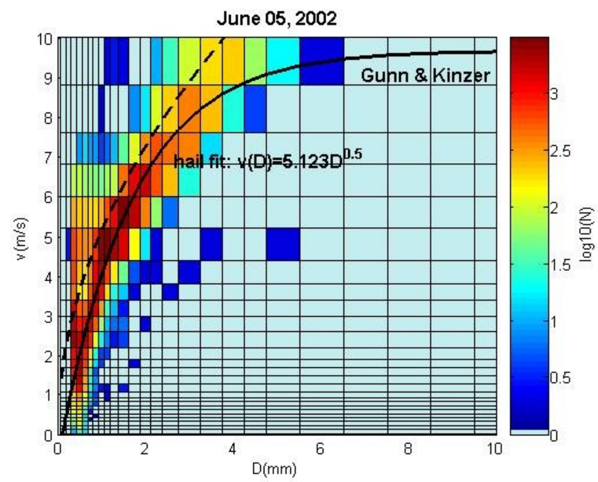


Fig. 10: Parsivel v-D histograms for the 05 June 2002 rain-hail event. The solid line is the Gunn and Kinzer (1949) curve. The dashed line is an empirical fit for hail (Pruppacher and Klett, 1998).

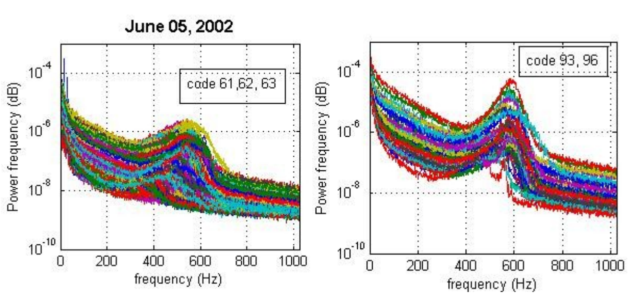


Fig. 11: Pludix power spectra for the 05 June 2002 rain-hail event for the minutes characterized by rain and hail codes.

The 05 June 2002 events is characterized by a rain shower with R>50mm/h (R reported by HO). The v-D relationship derived from Parsivel (Fig. 10) is not far from the Gunn and Kinzer (1949) relationship for water droplets, but it also follows quite well the empirical fit derived for hail (Pruppacher and Klett, 1998). For this event, Pludix identifies WMO-4680 rain codes (61, 62, 63) and for some minutes hail codes (93, 96). Fig. 11 shows the Pludix power spectra for the event for the minutes characterized by the rain and hail codes.

4. CONCLUSIONS

The principle aim of the present work was to determine the capabilities and limitations of Pludix as a PWS. Twelve precipitation codes are selected according to the WMO-4680 table: 3 rain codes, 3 snow codes, 2 hail codes, 1 code for ice crystals, 2 mixed precipitation codes, 1 no significant weather observed code.

The comparison of Pludix with the reference observations of a human observer and with other two PW instruments shows good capabilities of our instrument in detecting the precipitation type, especially the rain. In some situations Pludix works better than the other instruments in the case of rain. Moreover, it detects some situations (especially rain, rain-shower with hail, ice crystals) that the HO does not detect. Codes 61 and 71 are not well detected by Pludix, since it is less sensitive to such slight precipitations; also, the HO samples on a large measurement volume, while Pludix samples on a small measurement volume (about 3 m high and 1 m wide above it). In addition, the HO, due to its large sample volume is able to detect intermittent precipitation.

The test of the performances of Pludix in measuring the rainfall intensity shows that it works better than the other instruments (it has the higher correlation coefficient with HO). Pludix also shows a good agreement with Parsivel in detecting rain, snow and hail situations.

In the future, we are planning to refine the criteria for the PW codes presented here, and eventually introduce new PW codes.

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