Time variability in rainfall events observed by Pludix

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Abstract. Pludix is a raingage-disdrometer based on the analysis of an X-band Continuous Wave radar signal backscattered by hydrometeors. The Doppler shift of the individual falling particle, which is supposed to randomly cross the radar volume, is detected. The 2048 readings of the signal are inverted to generate a hydrometeor size distribution subdivided into 21 bands. Pludix operates integrating 60-sec. backscattered signal and so it provides a more detailed information with respect to the classical tipping bucket rain gage. Moreover it's possible to detect the actual rainfall rate as an indirect product.

Since September 1999 the instrument has been in operation aside with a tipping bucket and a weighting scale rain gauge downtown Bologna. More than 200 rainfall events have been detected and subgroup of 21 events has been investigated. The spectral intensity of the signal is analysed with different algorithms for both time variability and precipitation type.

A network of Pludix seems to be the right tool for investigating the space variability of rain in addition to time variability.

1 Introduction

Measurements of rainfall rate is a crucial issue for the study of the water cycle, the climate change and a number of practical applications from agriculture to water resource management, to mitigation of risks of floods. Most common instruments are tipping bucket rain gauges. The additional information of rain drop size distribution is also of great importance and it can be estimated by disdrometers, instrument based on different physical principles which have specific inconvenience and generally high costs.

Recently efforts have been simultaneously made to develop instruments based on low power radar signals combining both capabilities. Pludix (Prodi, et al., 1999) is one of these. In the first paragraph a brief instrument description will be given, then a series of rainfall events with Pludix and tipping bucket rain gauges simultaneously operated downtown Bologna will be investigated with the aim of studying their time variability, both in rainfall rate and raindrop size distribution.

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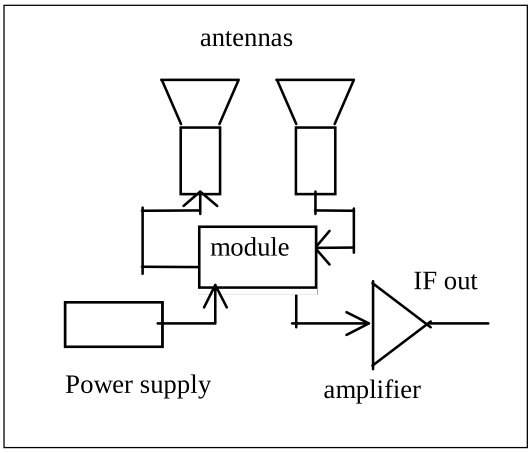

Fig. 1. Schematic description of Pludix structure

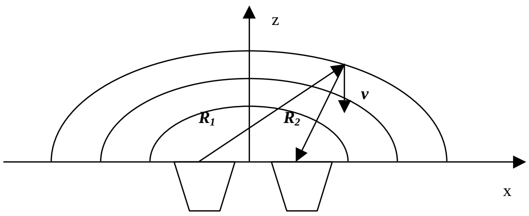

Fig. 2: Pludix Antennas and equipahese surfaces.

2 Instrument description

Pludix is a system composed by different units: the sensor, the signal processing unit and the data communication unit. The sensor is an X band continuous wave, low power (10 mW), Doppler Radar, operating at a frequency of 9.5 GHz.

A sketch of the disdrometer is shown in Fig. 1 and its geometry of operation in Fig.2. The transmitting and receiving antennas are very close to each other and the volume of measurement is immediately above them, larger for the largest obstacles.

2.1 Drop size distribution and rainfall rate from CW backscattered signal

Pludix is based on the well known electromagnetic Doppler effect. The target (an hydrometeor) move vertically, in dynamic equilibrium, toward the instrument, with constant velocity. When it enters the measurement volume it produces a signal which frequency is a function of its velocity. Actually the frequency depends on the velocity with which the object crosses the equi-phase surfaces, the surfaces made by the points having $R_1 + R_2 = \text{const}$ (Fig. 2).

A semi-empirical relationship has been used for rain and different relationships should be used for the different ice hydrometeors (hail and snow); it's possible to get a direct analytical link between vertical velocity and equivalent diameter. For raindrops it has been used the Gunn/Kinzer relationship (Atlas et al., 1973):

$$v(D) = 9.65 - 10.3e^{-0.6D} \tag{1}$$

where D is in mm, and v is in m/s.

Falling speed is considered in a model with complete absence of wind. Due to the Pludix position (few tens of centimetres from the ground) it's correct to assume that Pludix is not affected by winds, by the fact that vertical velocity is one order of magnitude lower than the horizontal one (Arya, 1988).

The physical characteristics of hydrometeors affecting the output signal are the backscattering cross section σ and the fall velocity v. Both are related to size, phase (liquid, solid, mixed) and composition (water, air) of hydrometeors. The knowledge of σ and v as a function of D is needed to generate an inversion algorithm which associates the output signal to the characteristics of precipitation.

From the frequency analysis of signal we have information on the sizes, which are v dependent.

From the power response, related to σ, we have information on the precipitation intensity.

N(D), the hydrometeor size distribution, is the direct final result. Once v(D) is known and for the case of rain the rainfall intensity is indirectly determined.

To correctly estimate the instrument response to a natural precipitation and determine the drop size distribution, measurements on monodisperse droplets are performed in controlled conditions and a calibration procedure is constructed.

If we consider a natural rain as a superposition of monodisperse rains, its spectral intensity S_{real} is:

$$S_{real} = \int_{D\min}^{D\max} N(D)\, S_{mon}(D)\, dD \tag{2}$$

with S_{mon} the spectral intensity generated by a monodisperse rain of diameter D, divided by the number of drops which has caused it, and N(D) is the distribution function, i.e. the relative contribution of that size to the real spectral intensity S_{real} .

If we discretize in frequency and diameter the above equation we have:

$$S_{fi} \approx C_{\{fi,Dj\}}\, N_{\{Dj\}} \tag{3}$$

where N is a column vector with elements the number of drops per unit volume in diameter interval D_j.

C is the matrix of the contributions to power of monodisperse drops of diameters D_j (column index) at frequencies f_i (row index), divided by the average number of monodisperse drops.

The normalized contribution of a monodisperse rain of a given diameter is an "average signal", i.e. it has the average characteristics from the drop falling in various regions of the measurement volume.

2.2 General characteristics

Signal processing unit synchronises, elaborates, and stores signals. Data communication unit interacts with different external units, granting connections to the system.

This kind of configuration makes Pludix a completely independent instrumentation, suitable for operation in remote areas and severe meteorological conditions.

Measurement data can be recorded in real time. Two dedicated software procedures have been developed in order to handle both connection and data processing.

2.3 Related software

A presentation of software data processing interface is shown in Figs 3 to 6. Each stored data file contains binary data, which are converted mainly into graphs and numerical integrated data. Every file is sub-divided into cycles, and each of them is 60 sec. long. In each figure, first diagram shows the mean backscattered power in any cycle, with in abscissa the cycle and in ordinate the power retrieved (mW). The second graph describes the spectral power (i.e., power transformed with FFT), of the selected cycle in function of frequency. This curve is divided into three parts, in which only in the median (light grey line) we find presence of rain. This is very useful to roughly discriminate region in which backscattered signal is caused by the presence of snow (left black line), or hail (right black line). Y-axis is in dB (10dB/div), and X-axis is in Hz (100Hz/div). The third diagram (on the left) shows the histogram of the spectral power just discussed divided in selected frequency bands (Y-axis is in mW, X-axis represents the bands). The fourth one (on the right) is the conversion of the power divided by band into a size distribution (Y-axis is in number of droplets/m^3mm, X-axis represents the corresponding diameter bands). The diagram on the bottom shows the time evolution of retrieved rain rate for each cycle (Y-axis is in mm/h, X-axis represents the cycle) superimposed with the temporal evolution of tipping bucket measurements (light grey, only in Fig. 3 and 4). Each file can be divided in shorter parts to better distinguish the period where precipitation occurs.

3 Event classification and discussion

The rainfall events have been selected from about 200 recorded episodes in the time period from February to May 2000. A preliminary classification of selected groups has been performed using internal criteria since radar data were not available and synoptic situation too long to deal with for the many episodes. These criteria resulted from a combination of maximum rainfall intensity and raindrop size distribution. The four classes were:

- stratiform rain (rain rate intensity less than 10 mm/h, total number of droplets larger than 3.5 mm less than

10% total detected droplets);
- convective rain (rain rate greater than 10 mm/h);
- mixed rain (both previous criteria are satisfied during the event evolution);
- heavy rain with hail (presence of signal greater than -15dB and relative maximum in the hail zone).

Once this classification has been determined, time evolutions of intensity and drop size distributions are investigated and discussed.

3.1 Stratiform rain

During winter most of precipitation are represented by stratiform rain, with a lifetime varying from few minutes to tens of hours. Time variation of rainfall rate is low, rain consists of medium and small droplets, and usually the Marshall/Palmer (MP) size distribution is a fair good approach.

In Table 1 rainfall rates recorded by Pludix are shown, compared to the tipping bucket measurements. Lifetime ranges from some tenth of minutes up to two hours. Rainfall rate derivatives reach 7 mm/h/min, but stays at an average of 2.6 mm/h/min, then we could consider this trend as typical of stratiform rain dynamics.

Table 1. Stratiform events recorded in Bologna (Italy), during February-May 2000

File name	Integrated tipping bucket	Integrated Pludix	Time length	Max RR growing rate (>0)	Max RR falling rate (<0)
	mm	mm	min.	mm/h/min	mm/h/min
20212	2.88	2.03	128	5	5
30117	2.04	2.10	107	3	2.5
32400	2.52	2.25	110	1	1
32910	1.56	1.29	58	2	2
40100	.96	.59	36	2	2
40300	1.44	1.11	33	1	1
40609	1.08	.85	21	3	3
40900	2.28	1.52	157	1	1
42400	1.56	1.33	24	7	5
50700	.84	.86	78	1	1

Fig. 3 shows one recorded cycle within an event (third one in table 1). In the second diagram from the top, only maxima in the middle region (light grey) are present. Spectral power and MP size distribution (small diagrams) shows only low-frequency components. Moreover, in the right diagram, the MP histogram is parallel to the corresponding logarithmic analytical expression. Both histograms are truncated, because of the absence of large droplets. Finally, the last diagram shows that the event corresponds to a low precipitation cycle (<5 mm/h).

3.2 Mixed rain

With the term "mixed (stratiform-convective) rain" we considered three events with such hybrid features, with a background of stratiform rain on which low intensity convective episodes are suggested. Table 2 shows Pludix data compared to tipping bucket recording. In these events rainfall rate changes are more frequent and intense and rainfall intensities are higher, while lifetime of each event tends to be the same as for stratiform rain. MP size distribution is still followed, but we can find episodes which don't match it. Neither a more complex theoretical size distribution could better fit (3-parameter Gamma distribution, Ulbrich, 1983), showing instead a multi-modal behaviour (Waldvogel, 1974).

Table 2. Mixed events recorded in Bologna (Italy), during February-May 2000

File name	Integrated tipping bucket	Integrated Pludix	Time length	Max RR growing rate (>0)	Max RR falling rate (<0)
	mm	mm	min.	mm/h/min	mm/h/min
40200	.72	1.11	24	4	4
41700	.6	.91	14	5	3
42800	6.0	5.26	80	5	5

Table 3. Convective events recorded in Bologna (Italy), during February-May 2000

File name	Integrated tipping bucket	Integrated Pludix	Time length	Max RR growing rate (>0)	Max RR falling rate (<0)
	mm	mm	min.	mm/h/min	mm/h/min
30200	0.6	.70	6	15	7.5
32813	15.72	10.3	71	12	20
32900	1.44	1.62	11	20	20
41100	4.92	5.06	59	15	12
42900	.84	.93	17	15	15
50200	1.56	5.879	4	150	50
50214	3.84	21.88	7	300	200
51000	2.28	9.11	8	100	50

Fig. 4 shows one recorded cycle within an event (the third one in table 2). The second diagram from the top, the spectral power, shows the presence of large droplets (maximum over 500 Hz, light grey region). Spectral power histogram shows a more spread shape, because of the action of larger droplets on backscattered signal. As well as in the mixed cycle, MP model cannot correctly represent the real size distribution; the histogram of the right diagram doesn't follow the dark straight line (analytical MP expression). In fact a multi-modal behaviour in the real size distribution is present. The histogram is not truncated, because of the presence of largest drops. Finally, the last diagram shows that the event corresponds to a medium intensity precipitation cycle (<25 mm/h).

3.3 Convective rain

Most of convective episodes are detected during spring. Dynamics are totally different from the other events. Table 3 shows numerical data of Pludix and those of tipping bucket. We can note first a strong difference in some integrated values of rainfall between the two instruments. From the recorded downloads of tipping bucket we could deduce that during heavy rains the tipping bucket reaches its overflow, while Pludix is still recording.

A second feature is the very short lifetime of all the recorded events, less than 20 minutes in the 75% of events.

The third feature is the steep rainfall rate change in some episodes, with minimum value of 12 mm/h/min. Especially in convective episodes it's difficult to fit in an analytical size distribution model (see fig. 5) due to the presence of a large number of degrees of freedom to correctly describe the phenomena, e.g. drop break-up and local presence of turbulence in the lowest boundary layer (Ulbrich, 1983).

3.4 Heavy rain and hail

In the whole period an event with presence of hail with rain

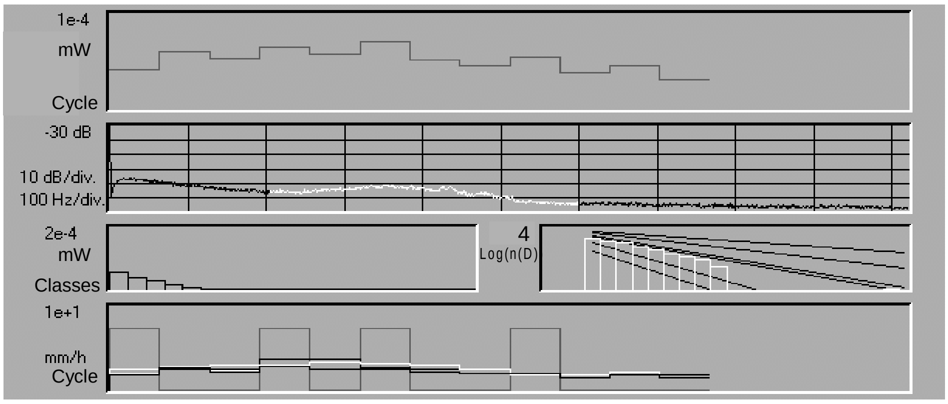

Fig 3. Stratiform rain as viewed by Pludix Elaboration Software

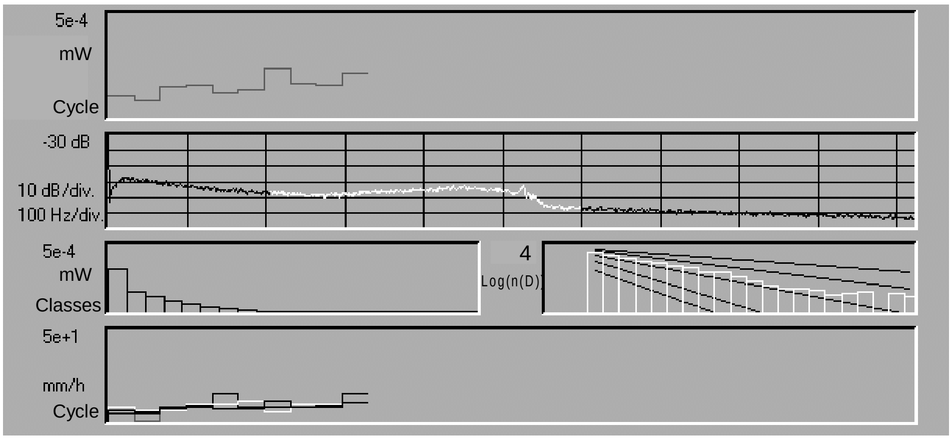

Fig 4. Mixed rain as viewed by Pludix Elaboration Software.

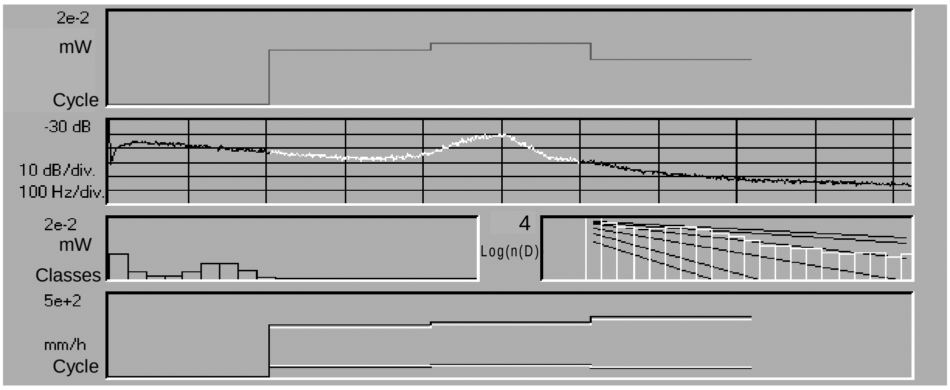

Fig 5. Convective rain as viewed by Pludix Elaboration Software.

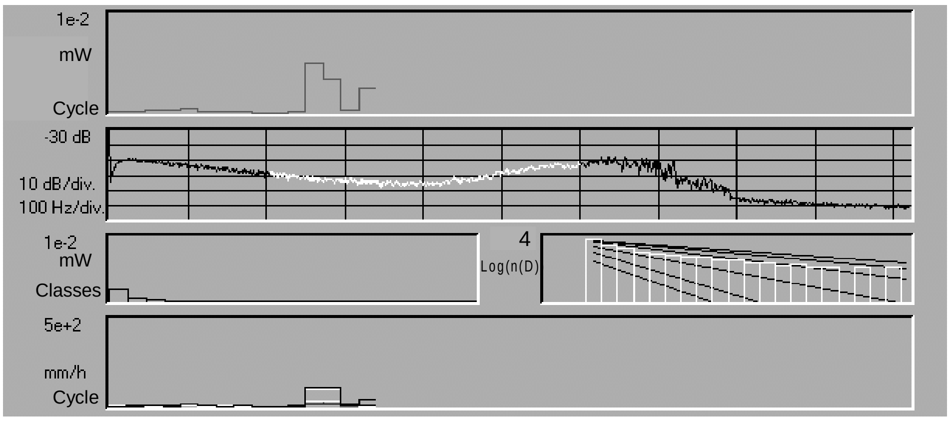

Fig 6. Hailfall episode as viewed by Pludix Elaboration Software. Bologna, may 2nd, 2000.

is recorded (may 2nd, 2000). The event has a very short lifetime, and a fast dynamics. Because Pludix was set to rain detection, it's not correct to talk about 'rainfall': the graphs, which are calibrated to analyse rain signal, don't detect this hydrometeors, but in the spectral power diagram shows a very high signal in the black right part (hail) (see Fig. 6).

However, it's possible to set Pludix to the conversion of hail (or snow) data, considering that the technical and theoretical approaches are the same to that used for rain. All

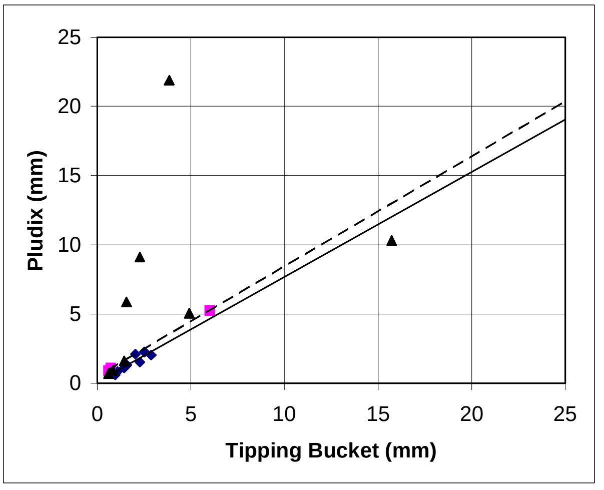

Fig 7. Comparison between tipping bucket recorded integrated rainfall and Pludix. Triangles are convective episodes, squares are mixed, and polygons are stratiform. Dashed line is the linear regression of stratiform events, dotted line is the same for mixed rainfall.

what's concerning the size distribution and dimension data here recorded, has no physical significance, because they belong to a frequency range typical of rain, instead of hail.

4 Conclusions

Correlation between Pludix data and tipping bucket data is shown in Fig. 7. For stratiform and mixed rain we can find a fair good correspondence; for convective episodes, part of them follows quite well the trend of the previous two groups, while others follow another well-defined trend. It's crucial to note that latter which deviates from the correct trend, is made by all the episodes in which the tipping bucket was in overflow.

For all events the correspondence among the recorded data by Pludix and by the traditional tipping bucket is fairly good, and similar to what Sheppard and Joe (1994) obtained with a similar instrument. So to the advantage of more information on falling precipitation (size distribution, time evolution, presence of mixed phases, etc.) a fairly good precision on rainfall rate is added.

Because of the oddity of hail and snow events in Bologna, this study has been mostly limited to the rainfall detection. The same concepts are easily extended to any other type of hydrometeors (hail, graupel, snow etc.). At the moment, however, it' s possible, even if the system is set to rain detection, to discriminate in real time an event with snow, hail, or rain, or events with mixed hydrometeors.

Finally, considering the possibility to operate Pludix in real time, and having the opportunity to transfer recorded remote data in any time, the system is particularly suitable for simultaneous control on large remote areas, letting the operator investigate space variability as well as time-variability of the event.

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