

# Spectral Characteristics of the Electric Field Related to the Preliminary Breakdown Stage of Cloud-to-Ground Lightning Flashes

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**ABSTRACT:** The preliminary breakdown (PB) process is usually associated with some intra-cloud lightning discharge activity preceding the stepped leader (SL) phase of single or multiple cloud-to-ground (CG) flash and its first return stroke (RS) or RS and continuing current (CC) sequence, i.e., RS/CC component. On the basis of its electric field recordings in LF or HF range, the PB process can be well studied in the time domain. However, there are only few research works dealing with the power spectrum density (PSD) analysis of such important lightning pre-discharge incidents. Hence, the PSD designation of PB episodes can give some additional information about their frequency characteristics that seems to be very useful and convenient computer procedure for an exact examination of complex pulse structures of different PB stages and following lightning strokes. In this paper we have presented the PSD spectrogram patterns obtained for four selected PB stages preceding different types of CG flashes. These flash events were detected by the Local Lightning Detection Network (LLDN) operated in the region of Warsaw during thunderstorm seasons in 2009 with six measuring stations and in 2013 with two measuring stations only. From the extended E-field records database gathered by the LLDN stations we were able to select only 10 cases of single or multiple CG flashes with distinct PB stage followed by their first RS or RS/CC component. Besides their overall statistics, the most interesting four examples of PSD spectrograms of the considered PB stage together with following CG strokes were presented in detail. The obtained average value of PB stage parameters are:  $2.2 \pm 0.5$  ms for its duration,  $20.5 \pm 14.7$  ms for the time interval between the PB stage and the following first CG stroke, while the frequency range of the PB train pulses was changing from  $3.5 \pm 2.0$  kHz to  $21.6 \pm 2.4$  kHz, and the absolute value of PB spectral amplitude was  $30.5 \pm 9.7$  dB/Hz. We note that distinct differences in dynamic spectra properties of PB and the first RS or RS/CC flash stroke may be applied for developing more efficient and precise computer discrimination procedures that could be used for the better and more reliable detection of the first RS or RS/CC component of CG flash incidents by a new type of lightning location system.

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## **INTRODUCTION**

Preliminary breakdown, often referred to as initial breakdown, was effectively studied by different groups of scientists [e. g., Clarence and Malan 1957, Kitagawa and Brook 1960, Beasley et al. 1982, Gomes et al. 1998, Gomes and Corray 2004, Mäkelä et al. 2008, Nag and Rakov 2009, Baharudin et al. 2012]. Our primary aim of this work was to find and show to what extent the PB stage and following lightning CG strokes occurring during thunderstorms in Warsaw region can be well represented and recognized in the frequency domain by designation of their PSD spectrograms. To the best of our knowledge, this is the first attempt of this kind performed in countries of central Europe. For this purpose we have used extended electric field recordings database gathered during the field campaign of the Local Lightning Detection Network (LLDN) set up in Warsaw region in 2009 and its limited measurement action in 2013. Besides delivering an extended database of E-field recordings with frequency range up to 50 kHz of different CG flash strokes, measurement capability of the LLDN system has also given us a possibility to evaluate in post-time analysis their thundercloud electric charge sources and locations in the 3D domain. The six measuring stations (A, B, C, D, E and F) of the LLDN were located in Warsaw region and were equipped with dedicated setups consisting of E-field antennae, triggering circuit, backup memory and commercial GPS receiver (see Fig. 1). More detailed information on the configuration and performance features of the LLDN can be found in the papers by Baranski et al. [2011] and Baranski et al. [2012].

In this paper we have presented in the form of a combined time-frequency-signal power domain four selected examples of the performed PSD analysis for different CG flash events, when their pronounced PB stage was followed by first CG lightning stroke incidents. Similar studies were done recently by Baranski et al. [2007], Maslowski et al. [2011], Karnas et al. [2013] and more currently by Karnas and Maslowski [2014]. Alike PSD spectrograms, but only in frequency domain and with higher frequency range from 0.2 to 20 MHz were previously reported by Willet et al. [1990].

Our transformation of the particular E-field record to relevant PSD spectrogram form was done with application of the Short-Time Fourier Transform (STFT) available in a powerful signal processing toolbox of Matlab. The comprehensive description of used algorithms was given by Oppenheim and Schaffer [1989], and Cohen [1995].

## **ANALYSIS OF PRELIMINARY BREAKDOWN STAGE PRECEDING DIFFERENT TYPES OF CG FLASHES AND DISCUSSION OF THE RESULTS**

Since June 2009, when the LLDN has started its field measurement action in Warsaw region with full configuration of six independent stations, only ten E-field records can be selected when the distinct PB stage and following first CG lightning stroke have been clearly distinguished. Six of such cases were collected during the field campaign in Warsaw region in 2009. The rest were recognized from limited number of the LLDN stations used for operation in the years from 2010 to 2013 and therefore only those records from the station E were taken into final considerations.

Among 10 cases of purely detected PB stages, five were associated with the following first negative RS of four multiple (i.e., three discrete and one hybrid) and one single CG flash, two were preceding negative RS/CC component of one multiple and one single CG flash, the next two were involved in

subsequent initiation of three bipolar CG flashes (i.e., a single negative RS jump combined with following positive one and that were separated by a few millisecond time span) and only one was connected to single positive CG stroke.

Some important time, amplitude, frequency and PSD spectrogram parameters were evaluated for such collection of the PB events and were presented in Tab. 1. It is worth to note that values of the time domain parameters of the PB episode listed in Tab. 1 (see rows 1-4) are well fitted to their value ranges reported by other researchers [e.g., Rakov and Uman 2003].

Four selected examples of the PB events occurring during different thunderstorms in Warsaw region and associated with different types of following CG flashes were chosen for illustration and taken into consideration to present some their characteristic features and interdependencies. Hence, their relevant PSD spectrograms have been evaluated and given in Figs. 3-5. The PSD designation was done with application of the Matlab build-in functions. Taking into account that the sampling frequency of used ADC unit was 50 kHz, the obtained PSD analysis was limited up to 25 kHz according to the Nyquist criteria. A 128-point time window with 120-point overlap was set to the STFT procedure. An additional interpolation was applied to get smoother PSD plots.

In Fig. 2 we have shown the exemplary PB stage that was followed by one RS and three RS/CC components of multiple CG flash detected by the LLDN during thunderstorm approaching to Warsaw on 30 June, 2009. Moreover, we can notice that some characteristic M changes and their E-field variations are superimposed on the particular CC stage recordings. This case and other PSD spectra related to different types of multiple CG flashes detected by the LLDN in Warsaw region were also reported by Maslowski et al. [2011].

The dominant negative polarity of PB pulses preceding the first also negative RS change of CG flash was the most frequent case recorded by us and reported by other researchers [e. g., Rakov and Uman 2003]. For the case presented in Fig. 2, the time interval between PB stage and 1RS was 17.8 ms and was close to the geometric mean value for all of the considered cases (see Tab. 1). The PSD stripe for this PB incident was scattered between several frequencies. The most intense E-field emission part of the PB pulse train was concentrated about three frequencies, i.e., 8 kHz, 14 kHz and 21 kHz. From direct time and signal power relation between E-field records of this PB stage and the corresponding shape of the obtained PSD stripe we can see that the evaluated bottom spectral frequency of PB pulse train corresponds well to the average frequency of PB pulses observed in their E-field recordings (see panel c and d in Fig. 2).

The next PB stage incident we have analyzed was also preceding multiple CG flash (see Fig. 3). But this time such a flash was composed from two small RS followed immediately by large CC change. All these flash components were detected successfully by the LLDN in Warsaw during thunderstorm observed on 25 June 2009. The BIL (Breakdown-Intermediate-Leader) model of initial breakdown [Clarence and Malan 1957] can be fitted to this case very well. It was the only case where the amplitude of the PB stage was greater than for 1RS/CC jump (see panel c in Fig. 3), which was clearly reflected by strong/intense PSD stripe for such PB event in comparison to those indicated by following RS/CC stroke changes.

An unique positive single CG flash event with preceding PB stage and another type of complex and strong intra-cloud (IC) activity is presented in Fig. 4. We have noted that the time characteristic of this PB stage were quite different from the ones occurring in two previously analyzed cases. The time interval

between PB and 1RS was only 5.5 ms, that is the minimum value in our database. On the other hand, the time duration of this PB stage was 1.4 ms and was the greatest one in our observations. The considered PB stage has displayed the clear BIL structure with all B, I and L changes that were distinctly pronounced and recognized in our E-field recordings (see panel d in Fig. 4).

On the left side of our extended in time E-field record shown in panel (d) in Fig. 4 some additional intense and powerful IC discharges activity can be noticed. This activity has been manifested by the single and strong bipolar pulse occurring at 10:17:48.0260 UT and preceded by another pulse train similar to that recognized as the PB stage before positive RS incident. It is very likely that such IC activity represented by our E-field recordings may be an evidence for occurrence in Poland of a rare compact intra-cloud discharge (CID) event recently studied by Nag et al. [2010]. We have noted that the CID lightning event was also followed by a kind of pre-discharge pulse train similar to the PB one and its phase B, and occurring later before a positive CG flash with single stroke.

Much higher signal power indicated by the PSD stripe/line for positive RS incident (see panel c in Fig. 4) in comparison to that obtained for negative RS flash component (see panel c in Fig. 2) is due to the meaningful difference of the horizontal distance, i. e., 25.6 km against 4.3 km from the measuring station E for particular evaluated charge source of the each considered RS event.

The fourth selected case of the PB stage was preceding three so-called complex lightning discharge events (CLDEs) not frequently observed in Poland and previously described by Baranski and Bodzak [2006]. This time each of the recorded CLDE consisted of a distinct negative and positive jump of two E-field changes of bipolar CG flash, that were separated by the time interval of the order of 1 ms. Such polarity change of two lightning strokes could mean that the first RS transferred to ground a large negative charge coming from the extended negative charge layer of a thundercloud while the second positive one, with smaller E-field amplitude than the first RS, would be an evidence of subsequent positive charge transfer to ground from a small and lower positive charge center (LPCC) imbedded in negative charge layer. This suggestion/scenario was partly confirmed by the PERUN lightning detection system routinely operated in Poland. According to the PERUN detection, all three negative RS components of three bipolar flashes shown in panel (b) in Fig. 5 have been distinguished as three following CG strokes of one multiple negative CG flash located at a distance range of 46 km, 47 km and 45 km from our measuring station E, respectively, and having the estimated peak current -12.6 kA, -23 kA and -18.7 kA, respectively. However, none of positive RS changes of the considered three CLDEs were properly identified by the PERUN system.

The diffuse structure of the PSD stripes corresponding to three bipolar CG flashes presented in panels (a) and (c) in Fig. 5 together with their low level of signal power within the frequency range from 5 kHz to 20 kHz was caused by the great distance of these flashes, i.e., of the order of 50 km range from our recording station E in comparison to the other three cases shown in Figs. 2-4.

## CONCLUSIONS

Several cases of E-field records representing different types of CG lightning flashes activity in Warsaw region were selected from the LLDN database for the examination of possible occurrence of their preceding pre-discharge preliminary breakdown process and evaluation of the corresponding PSD

spectrogram parameters. These chosen cases including single, multiple or complex/bipolar CG discharges with RS or RS/CC signatures of different polarities were presented together with their preceding PB stages. The selected exemplary E-field recordings were transformed to combined time-frequency domain with application of the Short-Time Fourier Transform. As a result, the corresponding PSD spectrograms were obtained for each pronounced lightning incidents noted during the considered examples. Some their characteristic parameters were listed on the basis of data gathered during the field campaign of LLDN in Warsaw region in 2009 and limited measurement action in 2013. It is worth noting that distinct spectral stripes of PB stage were significantly different from the following ones and associated with first or subsequent lightning strokes of CG flashes. Usually, there were no low frequency components (up to 5 kHz) for the PB spectrogram stripe/line compared to the ones representing RS or RS/CC flash components. On the other hand, the PSD spectrogram stripe/line of PB stage preceding positive RS was much more intense and steady, and had no distinct minimum frequency, as compared to the one appearing before negative RS or RS/CC components of CG flash. In other recorded cases of negative RSs the characteristic spectrogram stripes/lines of their preceding PB stages were scattered in the frequency domain. Our analysis has also shown that the signal amplitude ratio between the PB stage and the first RS was strongly dependent on the distance range of evaluated lightning strike point from the measuring station. For greater distances this ratio was lower because the breakdown pulses were also attenuated. However, in one recorded case (see Fig. 3) the E-field amplitude of PB stage is higher than this one for following 1RS/CC flash component. It could be a result of much closer space location of thundercloud PB electric charge sources related to measuring stations of the LLDN than the one obtained for charge source of the considered 1RS/CC flash component. As now, any determination of space locations of electric charge sources involved in a thundercloud PB process is beyond of present measurement ability of our LLDN set up in Warsaw region.

The PSD spectrogram designation is a good alternative for the time domain analysis of different short-lasting pre-discharge and lightning stroke incidents. There is a great potential in using of the FFT-based methods for computer processing of different E-field signatures related to diverse patterns of CG and IC lightning discharge activity inside a thundercloud. However, further investigations of different kind of fast pre-discharge CG flash events in the VLF-LF-HF ranges are strongly needed in order to elaborate and unify some computer procedures useful for obtaining important parameters of PB stage from its PSD spectrograms. In this way we could obtain the relevant computer discrimination criteria for reliable detection of different kinds of lightning strokes and their preceding PB stages.

## **ACKNOWLEDGMENTS**

This work was partially supported by grant No. COST/204/2006 from Polish Ministry of Science and High Education for setting up the LLDN system in Warsaw region.

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Figure 1. One of six E-field antennae devices used by the LLDN in Warsaw region (panel a) and general view of measuring station E located on the roof of Space Research Centre building (panel b).

Table 1. The value ranges of time, amplitude, frequency and PSD spectrogram parameters of recorded ten PB stage events. The values of PB parameters given in rows 1-4 are obtained from E-field signatures of PB stages. The rest rows (5-10) are indicated these values obtained from the relevant PSD analysis of PB stages.

Parameter	Minimum value	Maximum value	Arithmetic mean	Geometric mean	Standard deviation
PB duration from E-field, ms	0.3	2.5	1.3	1.0	±0.8
PB amplitude, V/m	2	42.7	11.7	7.8	±12.2
PB to 1RS amplitude ratio, %	5.5	170	47.9	23.2	±61.1
Time span from PB to 1RS, ms	5.5	45.9	20.5	15.6	±14.7
PB duration from PSD, ms	1.4	2.6	2.2	2.1	±0.5
PB amplitude, dB/Hz	-42.0	-16.3	-30.5	-29.0	±9.7
PB min. frequency, kHz	0.7	7.3	3.5	2.8	±2.0
PB max. frequency, kHz	15.1	23.2	21.6	21.5	±2.4
1RS amplitude, dB/Hz	-39.2	-4.4	-24.3	-20.6	±12.1
1RS max. frequency, kHz	9.5	23.1	20.8	20.2	±4.0

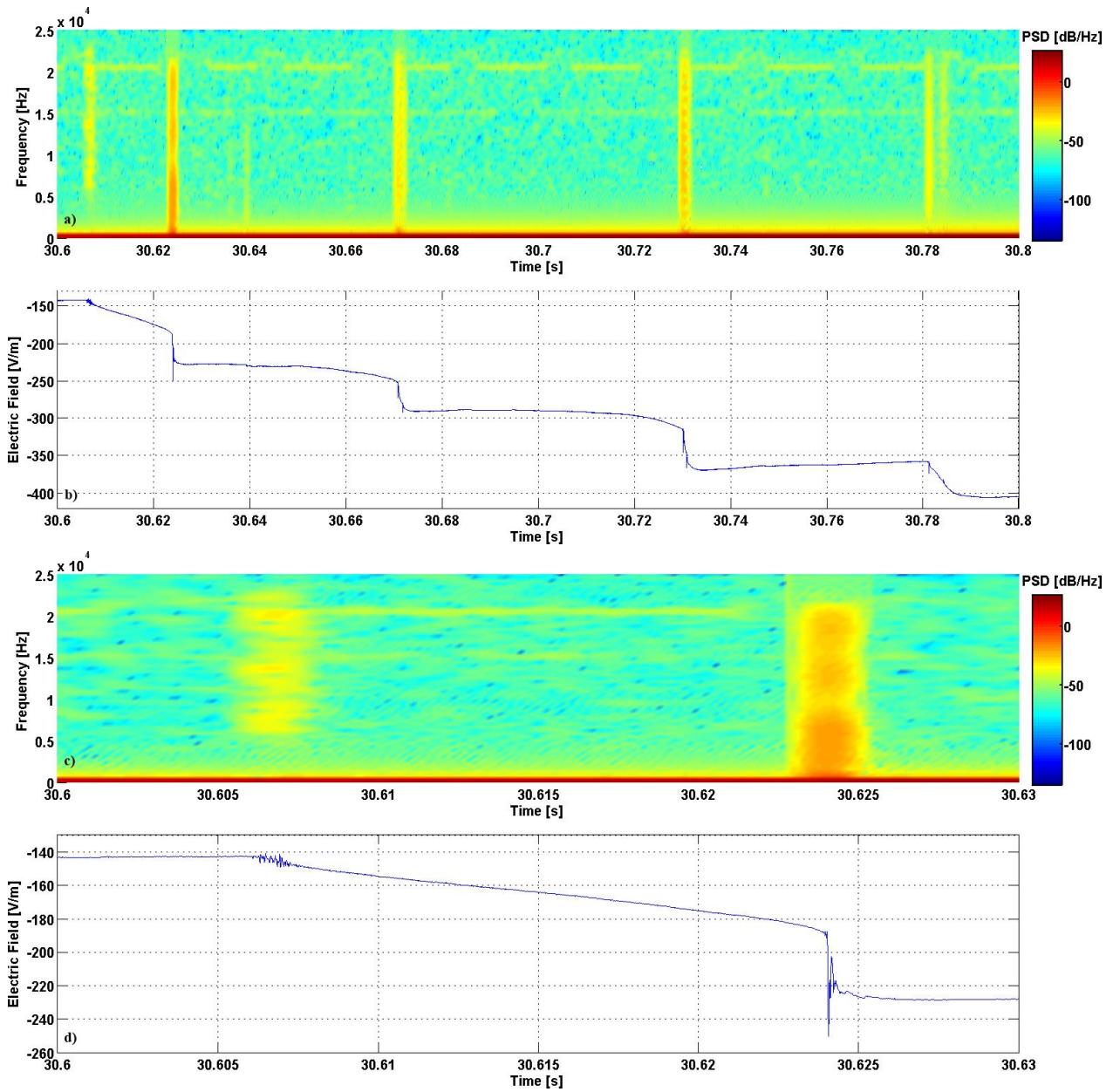


Figure 2. The PSD spectrogram of multiple negative cloud-to-ground flash with four strokes recorded in Warsaw region on 30 June 2009. Panel (a) presents the spectrogram view of PSD for the time period from 20:41:30.6 to 20:41:30.8 UT and panel (b) the corresponding part of the E-field record from station E of the LLDN. In panel (c) the 30 ms time window/zoom of PSD spectrogram taken from panel (a) is shown, which is obeying only the PB stage with the first RS. Panel (d) gives the corresponding simultaneous part of E-field record that represented these two lightning flash incidents from panel (c).



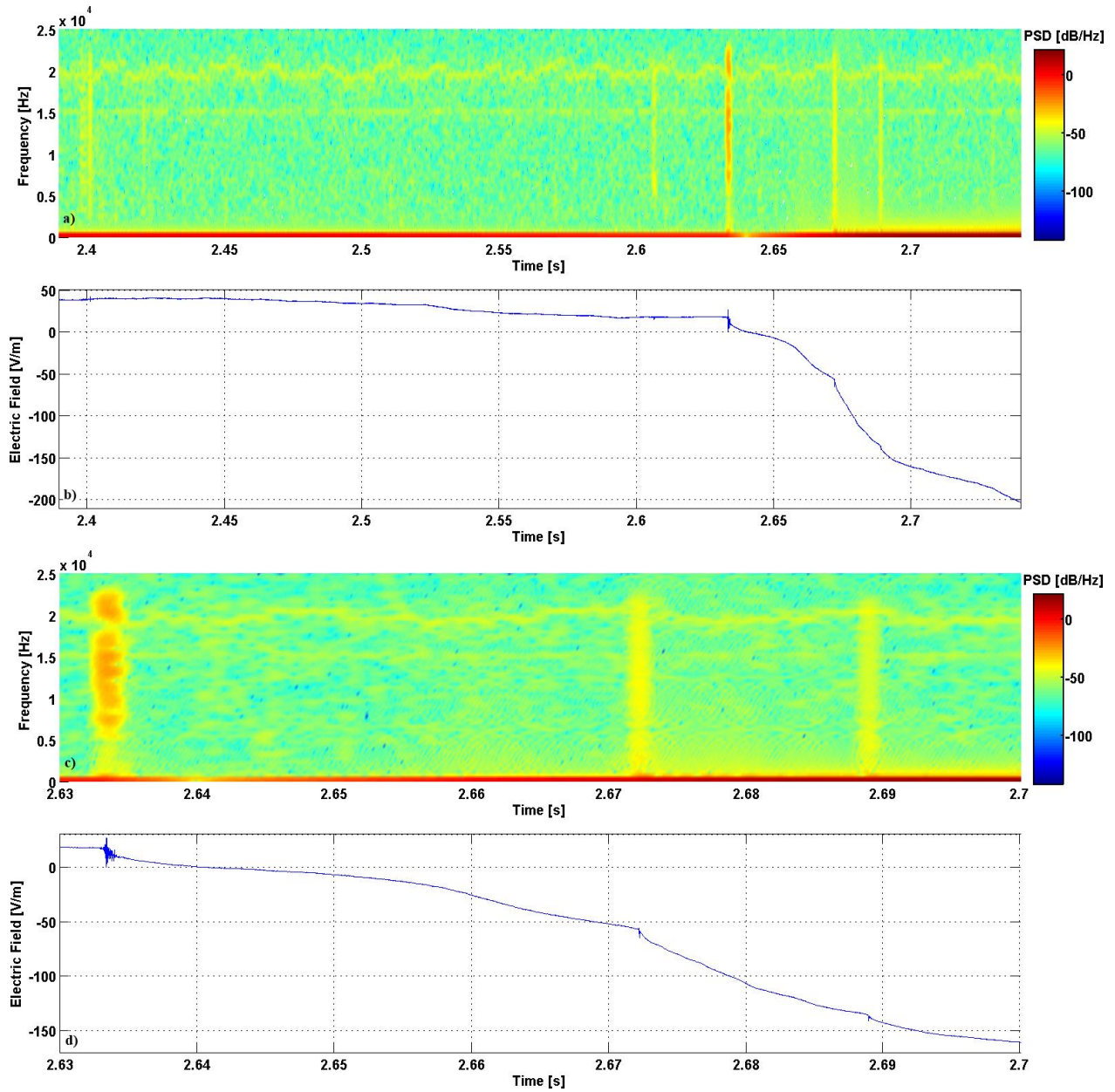


Figure 3. The PSD spectrogram of PB stage preceding multiple negative CG flash with two RS/CC strokes recorded in Warsaw region on 25 June 2009. Panel (a) presents the spectrogram view of PSD for the time period from 17:15:02.63 to 17:15:02.75 UT and panel (b) the corresponding part of the E-field record from station E of the LLDN. In panel (c) the 70 ms time window/zoom of PSD spectrogram cut off from panel (a) is shown, which is obeying only the PB stage with following two RS/CC flash incidents. Panel (d) gives the corresponding simultaneous part of E-field record that represented the same three lightning events from panel (c).

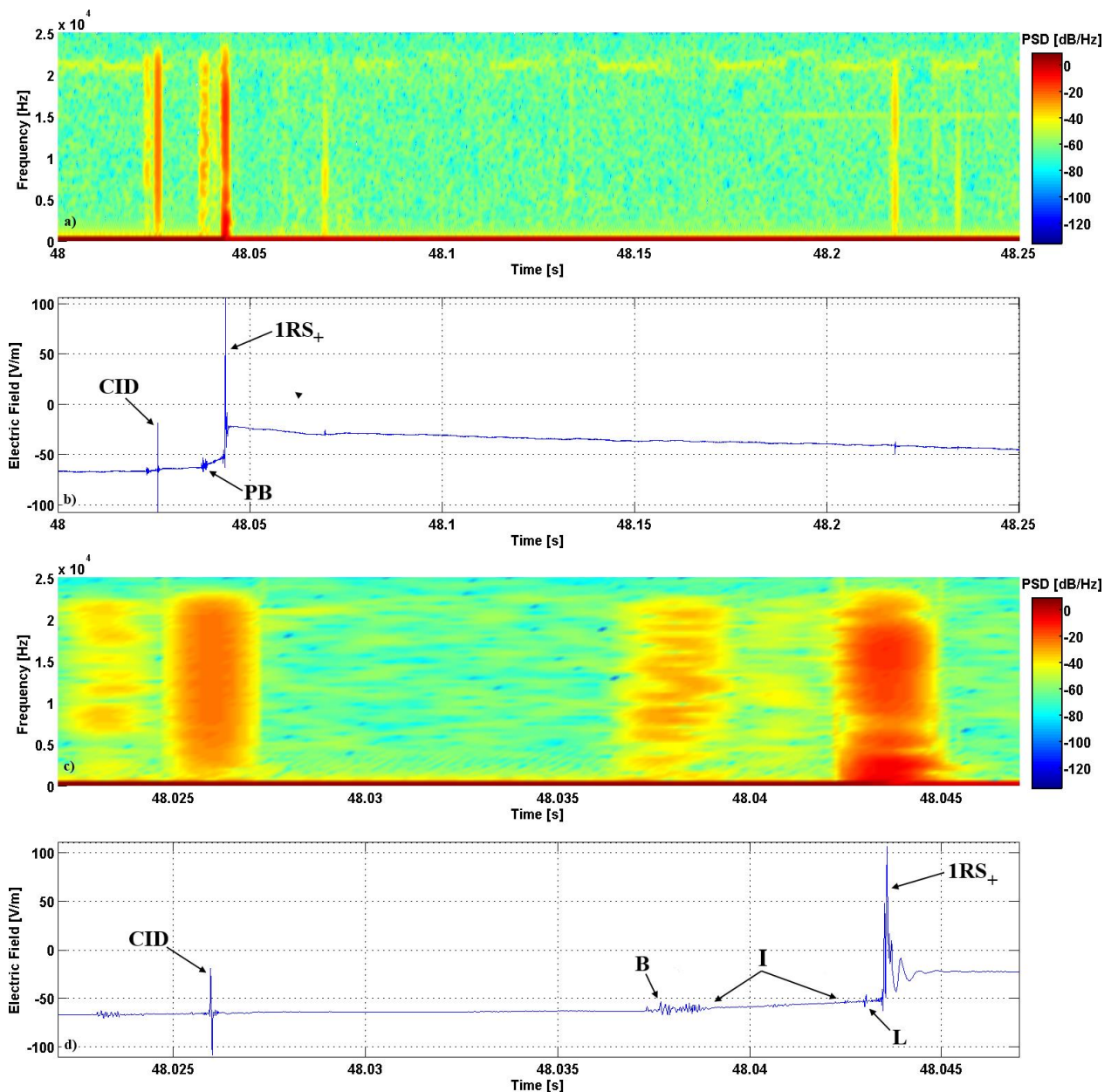


Figure 4. The case of PB activity preceding the positive return stroke in single CG flash. The obtained PSD spectrogram of these two lightning processes is given for the time span of 250 ms in panel (a). The corresponding simultaneous E-field changes shown in panel (b) were recorded by the station E, i.e., one station of the LLDN system in Warsaw region on 10 July 2009 from 10:17:48.00 to 10:17:48.25 UT. The same lightning incidents as those from panel (a) and (b) are presented in panel (c) and (d), respectively, but with the relevant time scale extension through the selected 30 ms time window depicting in more details some pronounced and complex intra-cloud lightning activity before the occurrence of positive RS.

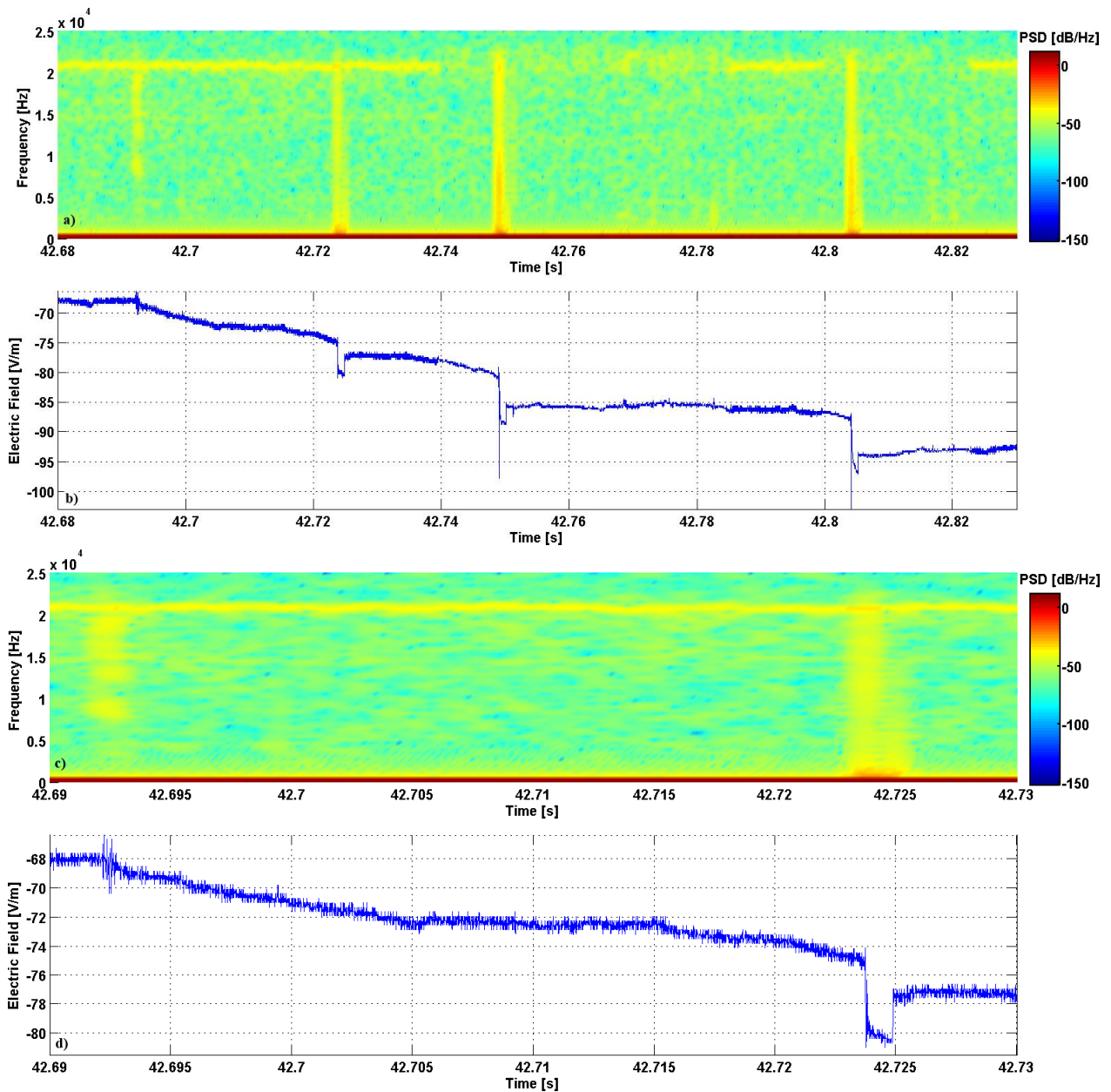


Figure 5. The PSD spectrogram of PB stage preceding three complex lightning discharge events (CLDEs), each consisting of single negative and positive RS component of bipolar CG flash that were separated by the time interval of the order of 1 ms and were recorded in Warsaw region on 10 October 2013. Panel (a) presents the spectrogram view of PSD for the time period from 13:51:42.680 to 13:51:42.830 UT and panel (b) the corresponding part of the E-field record from station E of the LLDN. In panel (c) the 40 ms time window/zoom of PSD spectrogram cut off from panel (a) is shown, it is obeying only the PB stage with the following first CLDE. Panel (d) gives the corresponding simultaneous part of E-field record that represented the same time window as displayed in panel (c).