Subionospheric propagation and peak currents of preliminary breakdown pulses before negative cloud-to-ground lightning discharges

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Abstract We analyze broadband electromagnetic measurements of pulse sequences occurring prior to first return strokes of negative cloud-to-ground lightning flashes. Signals generated by lightning discharges were recorded close to the thunderstorm by a magnetic field receiver and traveled up to 600 km to three distant electric field receivers. We found that amplitudes of observed preliminary breakdown pulses, as well as amplitudes of the corresponding return strokes, are attenuated approximately by 2 dB/100 km when propagating in the Earth-ionosphere waveguide over mountainous terrain. Propagation simulations show that there is a significant contribution of the sky wave signals in the waveforms observed beyond 500 km from their source. The estimated peak currents of the largest preliminary breakdown pulses reach over 60 kA. Such current pulses propagating through in-cloud lightning leader channels in a strong electric field may be able to initiate terrestrial gamma ray flashes.

1. Introduction

Even though the very first stage of the development of lightning discharges has been intensely studied and modeled by different groups of researchers [e.g., Stolzenburg et al., 2013, 2014; Gurevich et al., 2013; Marshall et al., 2014a, 2014b, 2015; Karunarathne et al., 2013, 2014; Kolmašová et al., 2014; da Silva and Pasko, 2015], the in-cloud processes leading to the initiation of lightning flashes are still not fully understood. The initiation of both cloud-to-ground (CG) and intracloud (IC) lightning flashes is usually signalized by the presence of sequences of bipolar pulses in the electromagnetic records, reported for the first time by Clarence and Malan [1957]. The pulses have been given various names in different studies: characteristic pulses, initial breakdown pulses, or preliminary breakdown pulses. We will use the term preliminary breakdown pulses (PBPs) throughout this study. A sequence of predominantly bipolar PBPs usually lasts from a few milliseconds to several tens of milliseconds, occurring probably prior to all first return strokes (RS) of negative CG flashes [Marshall et al., 2014a]. The largest pulses in the sequence have the same initial polarity as the following first RSs. The peak-to-peak amplitude of the largest PBPs seems to be dependent on the geographic latitude and can be sometimes comparable to the amplitude of the corresponding RSs [Gomes et al., 1998; Baharudin et al., 2012a; Marshall et al., 2014a]. The time separation between the initial PBP and the first return stroke usually reaches several tens of milliseconds. Extremely short PBP-RS time intervals, such as 1 ms, were usually observed not only during winter thunderstorms [Brook, 1992; Wu et al., 2013] but, unexpectedly, also during a summer thunderstorm [Kolmašová et al., 2014].

The true origin of the PBPs in lightning discharges remains unexplained. Clarence and Malan [1957] hypothesized that the PBPs are produced by a vertical in-cloud discharge between the main negative and the lower positive charge centers. This hypothesis is consistent by the simultaneous optical and electromagnetic observation reported by Stolzenburg et al. [2013], but they unfortunately had no information on the location of the charge centers. The vertical motion of pulses, attributed to a vertical motion of negative charges in the cloud, was also confirmed by Karunarathne et al. [2013] based on a measurement of a network of electric field sensors. Using the modified transmission line model with downward moving current pulse Karunarathne et al. [2014] succeeded to
reproduce the shapes of measured bipolar PBPs. da Silva and Pasko [2015] recently proposed a new physical mechanism explaining the source of both PBPs and narrow bipolar events (NBEs), which are believed to be the strongest sources of radio frequency radiation from lightning [Le Vine, 1980]. da Silva and Pasko [2015] used a generalization of electrostatic and transmission line approximations and showed that bipolar pulses can be a manifestation of a stepwise elongation of the in-cloud negative leader in the thunderstorm electric field. A new simple analytical model describing both bipolar and unipolar pulses was introduced by Kašpar et al., [2015].

Radio emissions associated with NBEs and other IC discharges have been detected with radio receiver on board the FORTE satellite [Light and Jacobson, 2002; Jacobson and Shao, 2002; Jacobson and Heavner, 2005; Jacobson and Light, 2012]. It was also shown that the NBE radio emission can propagate in the Earth-ionosphere waveguide and can be recorded on the ground hundreds of kilometers from the source [Smith et al., 1999].

The importance of the investigation of the preliminary breakdown stage of the lightning flashes was stressed by the hypothesis introduced by Marshall et al. [2013] that the pulses occurring during the development of IC lightning discharges have the potential to cause terrestrial gamma ray flashes (TGFs) of atmospheric origin [Fishman et al., 1994]. This hypothesis was supported by Cummer et al. [2014] who analyzed the reflected multipath propagation of low-frequency radio emissions associated with TGFs. They succeeded to directly measure the TGF source altitude, and they found it inside the thundercloud between the two main charge centers. In another study Stanley et al. [2006] reported a possible link between TGFs and positive IC discharges with normalized amplitudes of 3.4 V/m or greater at 100 km range.

The above listed results indicate that remote analysis of electromagnetic signals radiated by a developing lightning flash is a useful way to investigate the in-cloud processes related to lightning initiation. The propagation effects, as ionospheric reflections (illustrated in Figure 1a) and additional attenuation of signals propagating over the finitely conductive surface, need to be taken into account during this analysis. In the present study we analyze properties of magnetic and electric field pulse sequences occurring prior to the first return strokes of negative lightning flashes in order to evaluate effects of their propagation in the Earth-ionosphere waveguide and to characterize their source currents. We analyze 10 sequences of pulses measured at different distances from 9 to 600 km, during a night thunderstorm which occurred close to Rustrel, France, on 11 October 2012 from 19:02 to 21:23 UT. In section 2 we introduce our instrumentation, and in section 3 we describe the data set. In section 4 we investigate the propagation attenuation and source peak currents, and in section 5 we describe results of the finite difference time domain (FDTD) simulations of the measured signals propagated in the Earth-ionosphere waveguide. In section 6 we discuss the results.

2. Instrumentation

For the magnetic field measurements we use a shielded loop antenna connected to a ground-based version of a broadband (5 kHz–37 MHz) analyzer [Kolmašová and Santolík, 2013] which was developed for the TARANIS spacecraft [Blanc et al., 2007]. The sampling rate is 80 MHz. The analyzer is placed on the summit of La Grande Montagne (1028 m, 43.94°N, 5.48°E) close to Rustrel, France, at an external measurement site of the Laboratoire Souterrain à Bas Bruit (LSBB).

For the electric field measurements we use vertical dipole whip antennas connected to receivers sampling at 12.5 MHz. The frequency band of the receivers goes from a few hundred hertz to 5 MHz. Identical receivers are placed at three locations in France (see Figure 1b) located northward from Rustrel at 321 km, 431 km, and 577 km, respectively, called F1, F2, and F3. A detailed description of the instrumentation is given by Farges and Blanc [2011].

GPS receivers connected to all receivers are used for the time assignment of our measurements with an accuracy better than 10 μs. Locations, peak currents, and polarities of analyzed return strokes are provided by the French lightning location network MÉTÉORAGE.

3. Data Set

All analyzed prestroke pulses and following first return strokes were recorded on 11 October 2012. Our data-set is based on 15 sequences of magnetic field preliminary breakdown pulses and their corresponding negative cloud-to-ground return strokes selected by Kolmašová et al. [2014] who used the magnetic field data from LSBB and electric field data from the F2 station to analyze the duration of the prestroke process and
PBP/RS peak amplitude ratios. Here we analyze the propagation of these pulses by including the records from other distant receivers. After removing narrowband interferences caused by strong radio transmitters, we reduce the data set down to 10 events by imposing the condition that all cases must have distinguishable PBPs in the waveforms recorded by all three distant electric field receivers.

The return strokes following these PBP sequences were reported by MÉTÉORAGE at distances from 9 to 30 km to the LSBB station, at distances from 306 to 335 km to the F1 station, at distances from 415 to 446 km to the F2 station, and at distances from 563 to 592 km to the F3 station. The zone where the analyzed events occurred is marked by a white circle in Figure 1b. Using the MÉTÉORAGE time assignment of the individual return strokes and the time of the onsets of the respective return stroke peaks in the analyzed electric field waveforms we have estimated the propagation delay. We have found that radiated signals traveled within 2% of the speed of light. This deviation is consistent with the accuracy of our estimations of the return stroke onsets.

Figure 1c gives an example of the magnetic field waveform showing a return stroke with a peak current of –97 kA localized by MÉTÉORAGE at a distance of 28 km from the LSBB station at 20:30:03.24582 UT. The data records of all four stations are time shifted by the respective propagation delays from the source lightning localized by MÉTÉORAGE at 20:30:03.24582 UT.
contains the corresponding pre-stroke PBP sequence. Figures 1d and 1e, respectively, show the details of the same PBP sequence and return stroke pulse measured by distant electric field receivers. All the data have been time shifted backward by the speed-of-light propagation delay. Note that both the polarity and absolute value of the received horizontal component of the magnetic field depend on the relative orientation the antenna with respect to the discharge position. For the vertical electric field component we use the atmospheric electricity sign convention for the measurement of electric field (positive polarity downward). The initial positive polarity of the electric field return stroke pulse is then consistent with the negative cloud-to-ground flash.

We have found that both the first and the largest preliminary breakdown pulses are bipolar in all cases of our magnetic field measurements. Example is given in Figure 1c where the arrow shows the PBP with the largest peak-to-peak amplitude. This dominant pulse is also present in all electric field records in Figure 1d. However, for the more distant F2 and F3 stations, different pulses reach the largest relative amplitudes within the train although the original dominant pulse is still well traceable in all the records. For the 10 flashes, the time separation from the first detected PBP to the corresponding return stroke varies from 0.9 ms to 3.1 ms with a mean value of 2.6 ms; for example, the time separation in Figure 1c is 2.4 ms. For individual discharges this value is always conserved (within experimental uncertainties) in the data records from four different distances. These observations suggest that the propagation speed of PBP is, not surprisingly, the same as for the return stroke pulses but that the propagation effects can cause changes of individual waveform shapes measured at large distances.

4. Subionospheric Propagation of Lightning Generated Signals

To analyze the propagation of PBPs, we have always selected the largest PBP in each sequence using the magnetic field records at close distance. The ratio of the peak-to-peak amplitudes of these dominant magnetic field PBPs and the corresponding return strokes varies from 13.5% to 46.1% with the mean value of 28% for all ten events. We have found that this original dominant magnetic field PBP remained to be the largest pulse in all ten F1 records, but only in 5 cases from ten F2 records, and 2 cases from ten distant F3 records. However, when we trace the original dominant pulses to larger distances, their statistical properties remain approximately the same in all sequences from the individual electric field receivers. The ratio of the traced positive pulse amplitudes to the corresponding RS positive pulse amplitudes varies from 12.9% to 48.1% with a mean value of 27% for F1 sequences, from 13.8% to 50.9% with a mean value of 30% for F2 sequences, and from 10.6% to 38.7% with a mean value of 23% for F3 sequences.

Examples in Figure 1 show that the electric field amplitudes of both the RS pulse and the dominant PBP are decreasing with the distance from the source lightning stroke, as it can be expected. This behavior is demonstrated for all 10 events in Figures 2a and 2b. Amplitudes of the positive peaks were estimated manually from the F1, F2, and F3 records. The results are shown in Figures 2a and 2b as solid dots with error bars representing the noise in the recorded waveforms at a level of $\sigma_E = 0.1$ V/m. The particular events are denoted by letters A–J and ordered according to the RS peak current from the MÉTÉORAGE data. The example case from Figure 1 is shown here as event D.

With this data set, we have used a nonlinear least squares method to estimate parameters of a model of the electric field amplitude $E$ at a horizontal distance $d$ from the source, based on the planar geometry of emitted radiation,

$$E = \frac{A}{D} 10^{-\alpha D}, \quad D = d/100 \text{ km},$$

where the coefficient $A$ (in V/m) represents the electric field amplitude at a distance of 100 km from the source lightning. $\alpha \times 20$ dB gives the amplitude attenuation in decibels per 100 km, representing a simplified form of the wave propagation constant [e.g., Fullekrug et al., 2009]. The resulting nonlinear fits for all 10 analyzed RS pulses are plotted as solid lines in Figure 2a. Estimated values of attenuation (Figure 2c) vary from 1.74 dB/100 km to 2.30 dB/100 km, with a mean value of 2.15 dB/100 km. Figure 2c also confirms that attenuation does not depend on the RS peak current reported by MÉTÉORAGE. Similar fits of the model from equation (1) but for the dominant PBPs are shown by solid lines in Figure 2b. The obtained attenuation (Figure 2d) has the same mean value of 2.15 dB/100 km as for the RS results but varies in a larger interval from 1.25 dB/100 km to 2.94 dB/100 km. The nonlinear least squares procedure also gives us the standard deviations for the attenuation (solid lines in Figures 2c and 2d) with relative values of 4–13% for the RS peaks and 11–76% for the PBP peaks.
The estimated amplitude $A$ of the RS peaks at a distance of 100 km from the lightning (Figure 2e) varies from 24 to 91 V/m. Its relative standard deviation is about 5%, exceptionally reaching up to 10%. In theory, this amplitude should be linearly proportional to the peak current which generates the observed electromagnetic signal [Uman and McLain, 1970, Kašpar et al., 2015]. We experimentally obtain this linear trend between the RS peak current $I$ reported by MÉTÉORAGE and the amplitude $A$ of the RS peaks by linear least squares fit (dashed line in Figure 2e) as

$$\frac{A}{I} = 0.499\pm 0.008 \text{ V m}^{-1} \text{ kA}^{-1}$$

Figure 2. (a) Amplitudes of the RS pulses and (b) the corresponding dominant PBPs as a function of the distance from the source lightning stroke. Measured values (dots) and nonlinear least squares fits (lines) of the model from equation (1) are denoted by letters A–J and color coded from magenta to red according to the increasing RS peak current reported by MÉTÉORAGE for the 10 cases. (c) Attenuation per 100 km versus the RS peak current for the RS pulses and (d) the corresponding dominant PBPs, dashed lines represent the mean values. (e) RS pulse amplitude at 100 km versus the RS peak current, dashed line shows a linear least squares fit. (f) Estimated PBP peak currents versus the RS peak currents. The arrows indicate cases F and J where the dominant PBP remained the largest one during the propagation. Vertical lines represent estimates of standard deviations in all panels.
This relation gives us a unique opportunity to estimate the in-cloud peak currents, related to the observed PBP amplitudes. The amplitude $A$ for the PBPs at a distance of 100 km is generally smaller than for RSs; it varies from 5 to 32 V/m, with a larger relative standard deviation of 29% which can also be as small as 11%, and as large as 48%. By combining these results with the coefficient $A/I$ from equation (2) under the assumption that this coefficient is also valid for PBPs, we obtain estimates of PBP source currents shown in Figure 2f. The estimated PBP peak currents vary from 9 to 64 kA, with relative standard deviations from 11% to 49%. The obtained PBP peak currents do not show any obvious correlation with the peak currents of the corresponding return strokes. The highest PBP current is observed with the highest RS current, otherwise we do not see any clear dependence of the PBP currents on the corresponding RS currents. Two PBP currents indicated by arrows are the most reliable ones, as the dominant PBP remained the largest one during the propagation in these two cases.

5. Propagation Effects on the Waveform Shape

The RS waveforms in Figure 1e are clearly composed of two peaks. The first peak (G) is a ground wave; the second peak (S) represents "sky waves" reflected from the lower edge of the ionosphere. Estimated delays $\tau$ between the G and S peaks are $\tau = 118, 142, \text{and} 178 \mu s$, for the F3, F2, and F1 stations which, respectively, are at $d = 569, 422,$ and 309 km from the source lightning. Very simple geometrical considerations of specular reflection for the S wave then give an estimate for the effective ionospheric height

$$h = \frac{1}{2} \sqrt{(d + \tau c)^2 - \left(2R_E \sin \left(\frac{d}{2R_E}\right)\right)^2 - R_E \left(1 - \cos \left(\frac{d}{2R_E}\right)\right)},$$

where $R_E$ is the Earth’s radius and $c$ is the light speed. This gives us reasonable estimates of $h$ between 93 and 96 km for the three stations while neglecting the height of the source return stroke above the ground.

The PBP waveforms in Figure 1d have their sources inside the thundercloud and are thus formed by a ground wave G and two sky waves S1, and S2 (Figure 1a). We use the FDTD method introduced by Hu and Cummer [2006] in order to investigate how the ionospheric reflections contribute to the observed waveforms. The model was developed for simulations of the lightning generated electromagnetic signals that propagate long distances and for which ionospheric reflections are important. The ionosphere is regarded as inhomogeneous cold plasma with the Earth’s magnetic field superposed. The Earth curvature corrections are also included in the model.

We have selected the case from Figure 1 for the simulation (event D in Figure 2). This event occurred at a distance of 28 km from the magnetic field receiver, and we assume that the magnetic field is dominated by the radiation field from the source. Then the source current moment can be obtained by the time integration of the magnetic field waveform. This source waveform is used as input to the FDTD simulation for a realistic nighttime ionosphere. We assume a source at 4 km altitude (estimated by the Lightning Mapping Array [Kolmašová et al., 2014]) to compute the electric field propagation impulse responses at 309, 422, and 569 km range. We model two sets of impulse responses; the first set includes all the ionospheric reflections and the second set includes the ground wave only (with the ionosphere removed from the simulation). Then we convolve these impulse responses with the source waveform and compute simulated waveforms at the three distances. The source current moment waveform, however, includes the effect of a 5 kHz high-pass filter, which is incorporated in the magnetic field receiver hardware. We therefore filter the measured distant electric field in the same way in order to be able to compare it with the model.

Figure 3a shows the modeling results for the most distant receiver (F3) where the propagation effects are most visible. The waveforms in Figure 3a start by the sequence of preliminary breakdown pulses and end with the return stroke. The detail of the return stroke pulse in Figure 3b shows that the measured (blue) and simulated (green) ground wave pulses are initially in nearly perfect agreement, as well as the red pulse which also includes simulated reflections. The measured first ionospheric reflection then remains in agreement only with the red simulated waveform, although the simulation predicts a wider pulse. Figures 3c and 3d, respectively, zoom in on the PBP in-cloud part of the discharge waveforms from F3 and F1 stations. There is a noticeable difference between the red and green curves, which means that some of the energy in the observed signal originates in the sky wave. It is evident that the red waveform which includes the ionospheric reflections is clearly a better reproduction of the measurement than the green one which represents only the ground wave, especially at the most distant F3 receiver.
6. Summary and Discussion

We have recorded 10 sequences of preliminary breakdown pulses and corresponding return strokes by four receivers placed at different distances from the studied lightning discharges. Using the lightning location networks and according to the initial polarity of the RS peaks in the electric field records all of them were identified as the first negative cloud-to-ground lightning discharges. When we compare the waveforms of individual prestroke sequences measured at different distances, we can recognize very similar pulse patterns.
in all measured waveforms, up to a distance of 600 km from the source lightning. Such a distant observation of PBPs is reported, to our knowledge, for the first time.

We analyze the attenuation of the return stroke peaks and the dominant PBP peak during their travel to the distant electric field receivers. The radiative part of the electric field generated by a lightning discharge would be inversely proportional to the distance between the source discharge and the receiver if the wave propagated above an infinitely conductive surface [Uman et al., 1975]. We have found that the peak amplitudes of both the RS pulses and the largest PBPs were attenuated substantially faster. This demonstrates that the signals are affected by propagation over a finitely conducting ground, with an average attenuation of 2.15 dB/100 km for both RS pulses and PBPs. This is higher than the results of Cooray [1987] who reported that the RS peaks can be attenuated by 25% when propagating 200 km above the ground with a low conductivity of 0.002 S/m (~1.25 dB/100 km). A possible reason could be that high-frequency parts of the radiated signal can be attenuated faster [Chapman and Macario, 1956; Chapman et al., 1966; Le Vine et al., 1986; Cooray, 1987; Cooray et al., 2000]. However, we found that the attenuation remained roughly the same when we applied the digital low-pass filtering with cutoff frequencies of 35 kHz or 350 kHz on electric field waveforms. Our average attenuation is also higher than the radio wave propagation constant for 100-kHz transmitter signal and nighttime ionosphere (~5 dB/Mm) reported by Fullekrug et al. [2009] probably due to lower conductivity of a mountainous propagation path.

Idone et al. [1993] introduced an exponential model, $E = E_0 D^{-C}$, for the electric fields radiated by triggered lightning discharges and propagating over lossy ground. They found an exponent $C$ of 1.13 to match best their Florida observation. A model with the same value of the exponent $C$ was also used by Cummins et al. [1998]. Using the model of Idone et al. [1993], we have obtained the exponents $C$ close to 2 for both RS and PBP peaks. This high value indicates that the radiated fields in our study are attenuated faster than in the Florida case, most probably due to less conductive propagation paths. We consider our model to be more realistic compared the model of Idone et al. [1993] which, in our case, gives unrealistic field values at distances closer than 100 km from the source discharge.

A larger spread of the obtained values of attenuation of PBPs originates in the propagation effects, as the pulse shapes are influenced by the slightly delayed sky waves belonging to immediately preceding ground wave pulses. The FDTD simulation shows that there is a significant contribution of the sky wave signals in the PBP waveforms observed beyond 500 km from their source. This also explains our observation that the original dominant PBP did not remain to be the largest pulse in a substantial fraction of electric field records at large distances from the source lightning. Even though the method of the estimation of the PBP peak currents is probably influenced by these propagation changes of the waveform pattern, our model from equation (1) is still well consistent with the measurements. It must be noted, however, that extrapolation of relation (2) from RS pulses to PBPs might be questionable. According to the transmission line model [Karunarathne et al., 2013, 2014; Kašpar et al., 2015], the peak amplitude also increases with the propagation speed of the source current pulse which might be larger for the RS peaks than for the PBPs. This would lead to underestimation of the PBP peak currents. Nevertheless, our PBP peak current estimates of 9-64 kA are roughly consistent with the source peak currents from the modeling of PBPs by da Silva and Pasko [2015]. Similarly, Karunarathne et al. [2014] obtained pulse peak currents ranging from 16 to 154 kA in their PBP models.

Our data set consisting of 10 events is insufficient for deriving more general conclusions and an extended data set of PBP sequences recorded in different conditions is needed for further analysis of the in-cloud processes. All the analyzed PBP sequences belong to atypical lightning flashes, which started at a very low altitude (3–4 km) having unusually fast (10⁶ m/s) stepped leaders [Kolmašová et al., 2014]. The observed maximum PBP amplitudes reaching 32 V/m at 100 km are also more than twice larger comparing to the data of Marshall et al. [2014a, 2014b]. However, this first observation of PBPs far from their source thundercloud, together with our observation of the presence of ionospherically reflected waves in the distant records indicate that PBPs may have sufficient energy to escape the Earth-ionosphere waveguide and be detected by satellite radio receivers. The in-cloud currents up to 60 kA which we estimate for the preliminary breakdown stage of lightning flashes form pulses with a typical duration of a few tens of microseconds. Total charge on the order of 1 C is therefore moved in each current pulse over a distance of 300–1500 m [Stolzenburg et al., 2013]. A burst of such current pulses propagating in a strong in-cloud electric field might be capable to initiate terrestrial gamma ray flashes [Cummer et al., 2014; Marshall et al., 2013; Stanley et al., 2006; Carlson et al., 2009].
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