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Microwave radio emissions of negative cloud-to-ground lightning flashes

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ABSTRACT

We report preliminary results of a new observational study of microwave-frequency electromagnetic radiation that is emitted by lightning discharge processes. Radiation was observed with a ceramic patch antenna and a digital radio receiver tuned to a center frequency of 1.63 GHz and a bandwidth of 2 MHz. The recorded radiation waveforms are compared with data collected by the Oklahoma Lightning Mapping Array (OKLMA) lightning mapping system and the co-located Earth Networks Total Lightning Network (ENTLN) broadband electric field antenna. Microwave radiation was observed to occur during preliminary breakdown, negative stepped leader breakdown, negative dart leader breakdown, and return strokes. Characteristic radiation signatures were observed, including trains of individually resolvable impulses during breakdown and brief but intense trains of noise-like bursts during return strokes.

1. Introduction

Lightning is an important manifestation of severe weather, causing a significant portion of severe weather damage. The state of the understanding of lightning is broad and in some instances detailed, but numerous questions remain. Current research involving lightning physics is focused on understanding of processes such as initiation, positive and negative leader breakdown, dart leader breakdown, and runaway breakdown. One of the most important means of studying lightning processes has been observations of the resultant electromagnetic emissions, especially at radio frequencies (RF). There are numerous studies, too numerous to list here, that detail observations made from near DC through VHF and lower UHF frequencies. The reader may refer to the text by Rakov and Uman (2003) for a thorough review of these studies. At frequencies above about 1 GHz, however, there are relatively few studies.

The part of the RF spectrum ranging from 1 GHz up to about 10 GHz is still relatively transparent in heavy precipitation environments (Janssen, 1993), so there exists a potential for observing lightning processes at these frequencies. Based on a theoretical analysis, Cooray and Cooray (2011) have reported that the electron avalanche, a fundamental process of electrical discharges, is capable of generating significant radiation in the microwave band. The earliest observational studies at microwave frequencies include those by Ligda (1956) who reported observations of RF impulses at 10 GHz, and by Atlas (1959) who reported observations of RF impulses at 1.2 and 2.8 GHz. Brook and Kitagawa (1964) reported observations at 0.85 GHz with a bandwidth of 200 kHz, reporting radiation coincident with negative stepped leader, return stroke, dart leaders, K changes, and IC discharges. Stepped leaders were shown to generate strong impulsive radiation with easily discernible pulses, while dart leaders were also seen to radiate strongly but with the pulses often overlapping. Return strokes were also seen to radiate strongly, but not all of the time. IC discharge activity was also observed to emit radiation, and was often seen to radiate more strongly than during CG discharges. Oetzel and Pierce (1968) reported observations of RF impulses at 11 GHz, 90 MHz, and VLF, showing that nearly all microwave emissions occur as a few brief impulses during some, but not all, return strokes. The radiation pulses were shown to be only a few microseconds in duration. Radiation was also observed in

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association with leader breakdown, with an intensity that was an order of magnitude weaker than that of the accompanying return strokes. Kosarev et al. (1970) reported observations at 0.7 GHz, 0.9 GHz and 1.3 GHz with a 1 MHz bandwidth using omnidirectional dipole antennas, showing bursts of radiation at 0.7 and 0.9 GHz with durations in the order of 10 ms. Radiation was detected at 1.3 GHz, but was considered insufficient for analysis. Rust et al. (1979) reported observations at 2.2 GHz and a bandwidth of 500 kHz using a high-gain parabolic antenna, showing impulsive activity during leader breakdown, return strokes and dart leaders. Le Boulch et al. (1987) reported observations at 900 MHz and 4.6 GHz and a bandwidth of 128 kHz, showing radiation during some (but not all) return strokes. Due to the relatively narrow bandwidth of the receiver, impulse width could not be resolved. Most recently, Yoshida (2008) reported observations at VHF and at 2.9 GHz with a bandwidth of 500 kHz using a standard gain horn antenna. Analysis of a single flash that was initiated on a tall radio tower showed radiation associated with an upward-propagating positive leader, subsequent dart leader/return stroke sequences, and late intracloud breakdown activity. The initial upward positive leader was observed to generate impulsive radiation at both VHF and microwave frequencies, as were the dart leaders. The return strokes were observed to be quiet in the VHF band while generating a strong burst of radiation at 2.9 GHz with the burst showing a much higher impulse frequency than during the leader breakdown. A period of impulsive activity was also observed during a continuing current phase that was associated with intracloud activity. At the higher end of the microwave spectrum, Fedorov et al. (2001) observed radiation at 37.5 GHz with a 1 MHz bandwidth using a high-gain dish antenna. Impulse trains were detected in conjunction with the passage of a lightning channel through the beam, but it was unclear whether the radiation was generated by leader breakdown or by the return stroke.

Upon review of these studies, it is clear that various lightning discharge processes radiate well at microwave frequencies. Given the impulsive nature of this radiation, it is important to note that all of these studies involved receiver bandwidths less than 1 MHz. Such bandwidths limit the time resolution of impulse width to about 1 μs, limiting the ability to observe impulses whose pulse width is much less. Observations of dE/dt waveforms by Murray et al. (2005), and of UHF radiation by Labaune et al. (1987) and Bondiou et al. (1987) show that a significant fraction of impulses have pulse widths in the order of tens of nanoseconds. The existence of such narrow impulses suggests that the ability to detect impulsive radiation from lightning may be greatly enhanced by a suitable increase in receiver bandwidth. It was suggested by Oetzel and Pierce (1968) that lightning-generated radiation at frequencies above 200 MHz could not be observed using omnidirectional antennas and available receivers. They also suggested that receiver bandwidths greater than a few hundred kilohertz would be unnecessary for resolving individual impulses. Possibly because of these expectations, most studies at microwave frequencies have been conducted using highly directional antennas and relatively narrow bandwidths. However, given improvements in modern receiver noise figures and the low cost for digitizing signals with wide bandwidths, it is reasonable to explore the possibility of using omnidirectional antennas in order to observe lightning discharge processes at microwave frequencies. We expect that with a sufficiently low receiver noise figure and wide receiver bandwidth, it will be possible to map the impulsive radiation generated by lightning at microwave frequencies using both time-of-arrival and interferometry techniques. The observations reported in this paper represent the first iteration of our effort, and support these expectations.

2. Observational apparatus

A diagram of the apparatus is shown in Fig. 1.

The apparatus consisted of a roof-mounted antenna, LNA and filter connected via shielded coaxial cable to a nearby digital radio receiver system. A commercially available GPS ceramic patch antenna, shown in the left-hand side of Fig. 2, was utilized for its cardioid antenna pattern and circular polarization. A cardioid radiation pattern exhibits maximum gain in the forward direction, with the gain falling off by approximately 10 dB at 90° from the forward direction. Circular polarization allows for non-preferential reception of all orientations of linearly polarized radiation, with overall attenuation of 3 dB. For the observations reported in this study, the antenna was vertically oriented and located at the top of the south-facing wall of the National Weather Center in Norman, OK, as shown in the right-hand side of Fig. 1.

The antenna was connected via a short hardline coaxial cable to a low noise amplifier with 23.5 dB gain and a noise figure just over 2 dB. The signal was filtered and then transported via coaxial cable to a nearby laboratory where it was again filtered, amplified and then fed into a digital radio receiver. The receiver was an Ettus Research USRP1 with a DBSRX2 direct-conversion front end, an analog-to-digital (A/D) converter, and a field-programmable gate array (FPGA) DSP processor. The daughter board amplified and mixed the received signal, generating both in-phase (I) and quadrature (Q) baseband components that were fed to the A/D converter where they were linearly sampled at a bit depth of 12 bits and a sampling rate of 64 MHz. The digitized I and Q signals were then passed to the FPGA processor where they were decimation low-pass filtered to a bandwidth of 2 MHz and then resampled at 2 MS/s and 16 bits. The resulting baseband I and Q signals were then passed by a USB 2.0 trans port to a host computer where they were stored on a hard drive for later analysis. In order to maintain accurate timing of the incoming signals, a GPS-disciplined IRIG-B signal was fed into a parallel channel of the USRP and was synchronously recorded as a time reference. The microwave signals were later demodulated to a magnitude waveform. The system was not calibrated, therefore it is not possible to attach an accurate value to the received signal amplitude. Further complicating this problem, the ceramic patch antenna was oriented upward but the flashes discussed in this paper were located at a range of lower elevation angles. Based on the given manufacturer specifications, the system had an estimated signal gain (not including antenna gain) of 72 dB and an estimated noise figure of 3–4 dB.

In order to interpret the microwave data, comparisons were made with a co-located Earth Networks Total Lightning Network (ENTLN) electric field waveform antenna and the Oklahoma Lightning Mapping Array (OKLMA) lightning mapping system. The ENTLN waveform antenna has a pass band of 1 Hz to 12 MHz, enabling the capture of both slow and fast electric field waveform records. It also has GPS timing, allowing precise