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# MILLIMETRIC ELECTROMAGNETIC RADIATION OF A LIGHTNING RETURN STROKE

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*The paper reports results of recording the pulsed microwave radiation of return lightning strokes using a high-time-resolution, 8-mm-wavelength radiometer. The procedure of recording pulsed radiations with millimetric wavelength is briefly described. The complex shape of the recorded pulses is shown to be due to the features of the current system within the antenna spot at the initial stage of a lightning return stroke.*

**Introduction.** Recently, microwave radiometry has been actively developed. Microwave devices are used in navigation and medicine, in solving problems of the ecology of the atmosphere, in remote probing, in detecting various objects by their thermal radiation and determining their parameters, etc. Millimetric waves have been used most widely in communication systems [1].

Lightning discharges are known to produce major noise for reception of radio radiation [2, 3]. Therefore, determining the shapes and parameters of the millimetric electromagnetic radiations of lightnings is an urgent problem.

The maximum energy of an electromagnetic pulse (EMP) of lightning is in the range of very low frequencies and corresponds to the return stroke stage. In this case, several discrete EMP are emitted, whose characteristics are related to lightning macroparameters [4–7].

With increase in frequency, the number of discharge pulses increases, and the maximum amplitude of the signal decreases. At a frequency of about 10 kHz and higher, the electric intensity varies with the frequency $\nu$ as $1/\nu^{\beta}$, where $\beta = 1$–$2$, depending on current variation and source geometry [5]. In the high-frequency region of the EMP spectrum, the stepped and arrow-like leaders are growing in importance in signal generation. Uman [4] gives results of measurements of the microwave radiation of lightning at frequencies of 0.42 and 0.85 GHz. This radiation was assumed to arise from air breakdown primarily in the main thunderstorm cloud and the lightning channel.

Thus, since the width of the expected pulse is of the order of 10 $\mu$sec and less, the millimetric microwave radiation of lightning can be recorded only by pulsed radiometers with a time constant of about 1 $\mu$sec and smaller. In the millimetric range there are four atmospheric spectral windows. Microwave radiation is attenuated in the rain, and the attenuation increases with decrease in wavelength. Therefore, to detect the lightning radiation, it is expedient to use the longest-wave spectral window with center corresponding to $\lambda \approx 8$ mm. If the signal level decreases with increase in frequency, the expected signal is weak. Hence, it is necessary to use a high-gain, narrow-beam antenna, which, however, considerably decreases the probability of recording, because the radiometer records a signal only when the source is within the antenna spot, which is very rare. Thus, the small duration, the low level of the signal, and the uncertain location of the source impede the recording of the millimetric microwave radiation of lightning. The present paper gives results of observations of the pulsed microwave radiations of lightning discharges using a high-time-resolution, millimetric-wave-band radiometer.

**Instrumentation and Recording Procedure.** For the experimental studies, we designed a radiometric complex consisting of a power unit, a control unit, a noise-compensated superheterodyne radiometer operating at a wavelength of 8 mm with a time constant of 1 $\mu$sec, and a horn-reflector optical-type antenna. The effective antenna

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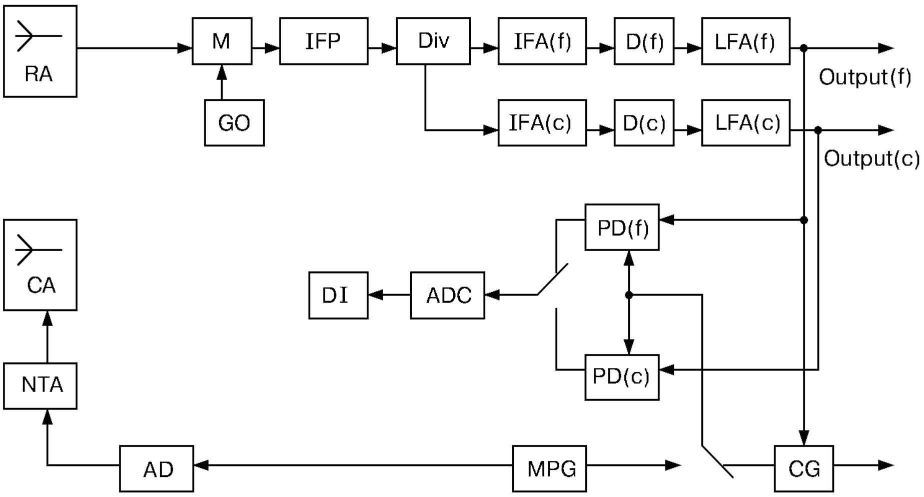

Fig. 1. Block diagram of the radiometer: RA is a reception antenna, GO is a Gunn oscillator ($\lambda \approx 8$ mm), M is a mixer, IFP is an intermediate-frequency preamplifier, Div is a signal divider into two channels (fine and coarse) with a tenfold amplitude ratio, IFA(f) and IFA(c) are the main intermediate-frequency amplifiers of the fine and coarse channels, respectively, D(f) and D(c) are the square-law detectors of the fine and coarse channels, respectively, LFA(f) and LFA(c) are the low-frequency amplifiers of the fine and coarse channels, respectively, PD(f) and PD(c) are the peak detectors of the fine and coarse channels, respectively, ADC is an analog-to-digital converter, DI are seven-segment indicators, CG is a clock generator with an amplitude selector, MPG is a master-pulse generator, AD is an avalanche diode, NTA is a noise temperature attenuator, and CA is a calibration antenna.

area was 0.12 $\text{m}^2$ with a half-power beam width of about 1.4°. The characteristics and a functional diagram of the radiometric complex are given in [8, 9]. A simplified block diagram of the radiometer is presented in Fig. 1.

The main purpose of the device is to record short electromagnetic pulses with a duration of 1 $\mu$sec up to 0.01 sec. Therefore, there is no output signal from slowly varying sources and noise (there is no steady component). The pulsed signal comes from the source to the reception antenna and is mixed in the mixer with the local heterodyne signal at a frequency of 37.5 GHz. The difference frequency in the range of 0.1 to 1.6 GHz is amplified in the intermediate-frequency preamplifier IFP, which does determine the intermediate frequency band. Thus, the receiver records the upper and lower lateral bands, and the total bandwidth of the recorded frequencies is 3.2 GHz. The output signal of the IFP is divided by the divider (Div) into two channels (fine and coarse) to increase the dynamic range of the device and is then transmitted to the main intermediate-frequency amplifiers IFA(f) and IFA(c). The amplified signal is detected by the square-law detectors D(f) and D(c), because the output signal must be proportional not to the electric intensity but to the electric-field power and, hence, temperature. Next, the signal is amplified by the low-frequency amplifiers LFA(f) and LFA(c) without a steady component, which determine the time constant of the device and the limiting duration of the recorded pulses. From the LFA outputs, the signal is transmitted to the peak detectors PD(f) and PD(c), which store the maximum magnitude of the pulse received, and then to the analog-to-digital converter ADC and the digital indicator DI. A switch is used to record the readings of the fine or coarse channels. The peak detectors are activated by the master-pulse generator MPG or the clock generator CG with an amplitude selector. The CG generates a clock pulse when the threshold level of the output signal from the fine channel is exceeded, and this activates the peak detectors. Because there is no steady component in the present device, the calibration signal should be pulses of necessary duration. This is achieved by controlling the noise source of the avalanche diode AD using the MPG. The necessary noise temperature is set by the pin-diode noise-temperature attenuator NTA. The radiometer is supplied with analog outputs of the fine and coarse channels to connect peripheral recorders and a clock-pulse output for activating the peripheral recorders.

The instrumentation designed was used in preliminary laboratory experiments on recording the pulsed microwave radiation generated by a high-energy electron current, laser flash, explosion of wires, and air breakdown by a high-voltage discharge. A procedure for estimating the spectral intensity of microwave radiation from a known current pulse of the source was designed and tested [8–11].

TABLE 1

| Date and time of event (year/month/day/hour/min) | $T_{\text{eff}}$, rel. units | $L$, km | $T_{\text{a}}$, K |
|---|---|---|---|
| 96/07/28/14/08 | 30 | — | 600 |
| 96/08/03/18/12 | 52 | ≈3 | 1900 |
| 96/08/03/18/13 | 65 | ≈3 | 2700 |
| 96/08/03/19/09 | 61 | — | 2500 |
| 97/08/07/01/08 | 42 | — | 1300 |
| 97/08/07/01/10 | 133 | ≈0.35 | 6800 |
| 97/08/07/01/17 | 66 | ≈0.9 | 2800 |
| 97/08/07/01/19 | 68 | ≈0.9 | 2900 |
| 98/07/27/15/39 | 29 | — | 500 |
| 98/08/10/17/21 | 31 | — | 600 |
| 99/08/20/16/07 | 40 | ≈5 | 1200 |
| 99/08/20/16/09 | 38 | ≈5 | 1100 |

Experiments on recording the pulsed microwave radiation of lightnings were begun in 1996. The experimental procedure was as follows. The antenna system was placed at a height of about 3 m, and during recording, it was at rest or continuously rotated. In the last case, the antenna spot continuously moved over the thunderstorm cloud. In field measurements, the maximum pulse level of the vertically polarized radiation was recorded by two recording channels (coarse and fine).

The recorded effective temperature of the radiometer is

$$T_{\text{eff}} = T_{\text{a}} + T_{\text{n}},$$

where $T_{\text{a}} = I_\nu S_{\text{eff}}/(2k)$ is the antenna temperature, $I_\nu$ is the spectral intensity, $S_{\text{eff}}$ is the effective antenna area, $k$ is the Boltzmann coefficient, and $T_{\text{n}}$ is the effective noise temperature of the radiometer. For the fine channel, $T_{\text{n}} \approx 1200$ K.

Simultaneously at short waves, the radio signal from the lightning was recorded and observations of the optical signal were carried out. The distance to the source was estimated from the delay of the acoustic signal with respect to the radio signal from the lightning stroke with allowance for the direction of reception of the microwave radiation. In 1996, in seven events of lightning strokes with no rain at the site of observation, the readings of the radiometer from a thunderstorm cloud exceeded background values. The main recording results are given in [12].

In summer, 1997, these experiments were continued by a modified procedure (recording of microwave radiation from return stroke channels). Maximum signal level was expected because peak currents correspond to exactly this stage. A high metal object was chosen beforehand at approximately 900 m from the site of recording. The antenna was directed to the area above the object, and the dimension of the antenna spot was approximately 40 m. Six close lightnings were recorded, and at 1:10 a.m. on August 7, 1997, the signal source came nearer (discharge to the top of an oak occurred) but was directed similarly. Data of recording with the fine channel switched on are given in Table 1. It should be noted that the recording of August 7, 1997 was carried out through a wet glass 3.5 mm thick during a cloudburst. The distance to the source was determined by measuring the distance to the site of the lightning stroke.

Laboratory studies of the transmission of 8-millimeter radiation through a wet glass 3.5 mm thick were performed more recently. In this case, the transmittance was 0.2, the absorption coefficient was 0.4, and the reflectivity was 0.4.

In 1998–1999, primarily the shape and duration of microwave radiation of lightning were recorded. Only on August 20, 1999, did we record two distinct signals of almost identical shape from the upper part of the lightning return stroke channel. The signals were observed at distances of about 5 km or less. Each signal had a complex shape and consisted of a series of single pulses with duration exceeding 5 $\mu$sec, which were partly imposed on each other (Fig. 2a). The total duration was approximately 60 $\mu$sec. In both cases, the second rather than the first pulse had the largest amplitude. The amplitude of the second pulse was approximately four times larger than that of the initial pulse. The complex shape of the signal is apparently explained by the fact that the branching lightning channel of complex geometry was within the antenna spot at the moment of recording. For comparison, Fig. 2b gives the shape of the signal from a single discharge in air. In Fig. 2, the antenna temperature in relative unities is plotted on the ordinate (the value of 100 corresponds to about 6000 K). The signals were recorded through an

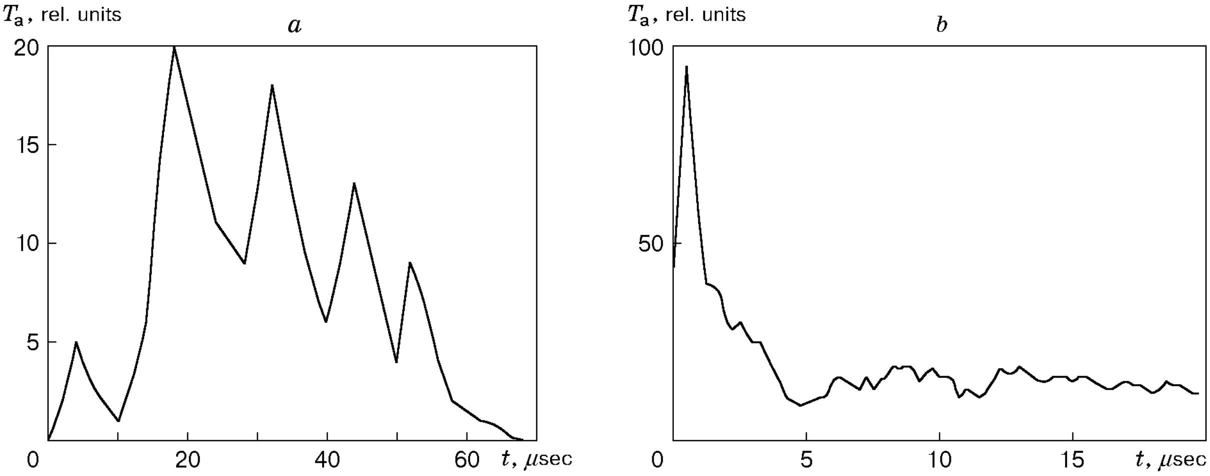

Fig. 2. Intensities of the microwave radiation of a lightning discharge (a) and a high-voltage discharge in air (b) versus time.

open window at the moments of light flash from a thunderstorm cloud which moves to the northeast in the absence of rain at the site of observation. The antenna was directed to the cloud at an angle of about 45°. An increase in the background level (by about 10%) from the thunderstorm cloud was revealed even in the absence of a visible lightning discharge. This is apparently due to discharges in the interior of the cloud, which are not accompanied by light flashes.

**Discussion of Results.** If, with increase in the signal frequency, the maximum intensity amplitude decreases in inverse proportion to the frequency [4], the spectral intensity and the antenna temperature decrease in inverse proportion to the square of the frequency. According to theoretical results, such dependence of coherent radiation can be due to sharp changes of the initial electron current at the current pulse front. To obtain a rough theoretical estimate of the lightning microwave radiation level, we use the procedure proposed in [10] to estimate a coherent signal from a high-energy electron flow. Using this procedure, Gorbachev et al. [9] obtained a formula for the maximum antenna temperature of a radiometer (in Kelvin)

$$T_{\mathrm{a}} = \alpha F I^2 S_{\mathrm{eff}}/(L^2 t_i \omega^2),$$

where $\alpha$ is the proportionality factor (in the SI system, $\alpha = 4.3 \cdot 10^{22}$), $L$ [m] is the distance to the source, $I$ [A] is the current strength, $t_i$ [sec] is the characteristic time of current variation, $\omega$ [sec $^{-1}$] is the circular frequency of microwave radiation, $S_{\mathrm{eff}}$ [m$^2$] is the effective antenna area, and $F$ is the attenuation factor.

With allowance for the data of [4], we assume for rough estimates that the current value in a return stroke channel is 10–20 kA and the characteristic time of current variation is approximately 40 $\mu$sec. Then, for the present antenna at a distance of about 0.9 km, with allowance for signal attenuation by a cloudburst (for rain intensity of 80 mm/h, the attenuation is about 20 dB/km), we obtain an antenna temperature of $T_{\mathrm{a}} = 4700$–19,000 K. This value agrees in order of magnitude with the data of the experiment performed at 1:17 a.m. on August 7, 1997, considering signal attenuation in glass. For comparison, we note that according to the data of [4], the antenna temperature calculated from the maximum electric intensity of the vertically polarized radiation of lightning and extrapolated to a frequency of 37 GHz is thousand degrees at a distance of about 0.9 km with allowance for signal attenuation by a cloudburst.

Thus, it is believed that lightning discharges generate millimetric microwave radiation. At distances of about several kilometers, the maximum spectral intensity of this radiation corresponds to an antenna temperature of several thousand degrees. With allowance for the antenna parameters, the maximum spectral radiation intensity is more than $10^7$ Jy [1 Jy = $10^{-26}$ W/(m$^2 \cdot$ Hz)]. The signal duration is 20–60 $\mu$sec. In our opinion, the recorded signals are due to current pulses that arise from a return stroke in the conducting channel. For reception of millimetric waves, lightnings are radio interference only at distances less than 5 km.

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