Bursts of Pulses in Lightning Electromagnetic Radiation: Observations and Implications for Lightning Test Standards

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***Abstract*— Bursts of regular microsecond-scale electric field pulses produced by three multiple-stroke cloud-to-ground discharges (a total of 2782 pulses) and by three cloud discharges (a total of 1436 pulses), all recorded within 20 km or so at the NASA Kennedy Space Center, are analyzed. The regular pulse bursts are similar in both cloud-to-ground and cloud discharges. A burst is characterized by some tens of pulses, each having a total width of a few microseconds, with an average interpulse interval of 6–7 μs. Pulse peaks in cloud-to-ground discharges are approximately two orders of magnitude smaller than return-stroke initial field peaks in the same flash. In both cloud and ground discharges, there is a tendency for the bursts to occur in the latter stages of a discharge, and positive and negative pulse polarities are about equally probable. Many bursts were found to be associated with the latter part of K changes while one pronounced M change appeared to be initiated by a regular pulse burst. The observed regular pulse bursts exhibit some similarity to the "multiple burst" (component H) of the standard lightning environment for the design and testing of aerospace vehicles [1]. Overall, neither the present definition of the H component given in [1] nor its newly proposed revision appears to be based on adequate experimental data.**

I. Introduction

KRIDER *et al.* [2], hereafter called KRN, observed regular sequences or bursts of microsecond-scale, essentially unipolar pulses in a large fraction of the electric and magnetic fields produced by distant lightning in both Florida and Arizona. In the following, we will summarize the observations of KRN.

1) The waveshape of the individual pulses within a burst is essentially the same in both electric and magnetic field records, as expected for radiation field waveforms.
2) Electric field pulses recorded in Florida at a distance of 50 km or more had amplitudes of the order of 1 V/m. Magnetic field pulses recorded in Arizona within 50 km or so had amplitudes of typically 5 nWb/m^2. We estimate from these values that the pulse amplitudes in both locations were about an order of magnitude smaller than the corresponding initial field peaks of the return strokes in ground flashes at comparable distances (e.g., Uman [3]). The data of KRN are likely to be biased toward larger amplitudes since they used triggered field measuring systems with relatively short oscilloscope sweeps.
3) Each burst had a typical duration of 100–400 μs, with the mean time intervals between individual pulses in a burst being 6.1 μs in Florida and 5.1 μs in Arizona; thus, we infer that the typical number of pulses per burst was between 15 and 80.
4) The initial half cycle of a pulse had a full width at half maximum of typically 0.75 μs with a total duration of typically 1–2 μs, and was followed by a relatively small and more slowly varying overshoot.
5) Pulse bursts often began with the largest pulses, the pulse amplitude decreasing with time.

Based on their observations that 1) the pulse bursts tended to occur toward the end of the intracloud discharges, where K changes are known to occur (e.g., Ogawa and Brook [4]), and 2) the waveshape of the pulses was similar to that produced by steps in the stepped leader process, KRN suggest that the bursts are due to "an intracloud dart-stepped leader process," possibly associated with K recoil streamers [4] developing in the previously formed channels. The amplitude spectrum of a typical regular pulse burst had a peak near 200 kHz. The rise times of individual pulses were reported in KRN to be sometimes at the measuring system limit of 0.1 μs, suggesting that higher frequencies than observed might be present in the source. The latter observation, taken together with the high repetition rate of the pulses, indicates that these pulses, although relatively small in magnitude, are capable of causing interference or upset to sensitive electronic systems. Regular pulse bursts similar to those observed by KRN were also reported by Muller-Hillebrand [5, Fig. 14] from lightning magnetic field measurements made in Switzerland.

The pulse bursts observed by KRN are generally similar in both the number of pulses per burst and the interpulse intervals to the "multiple burst" (component H) of the standard lightning environment for the design and testing of aerospace vehicles [1]. The H component consists of 24 pulse bursts, each containing 20 pulses (similar to KRN's bursts) separated

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by 10–50 μs (somewhat larger than in KRN's bursts); that is, the burst duration is 200–1000 μs. The individual bursts are separated by 10–200 ms over a period of up to 2 s. Pulses within a burst, characterized in terms of current, are defined to have peak of 10 kA, a relatively low value compared to other components of the standard lightning environment (200 kA for the first return-stroke peak and 100 kA for the subsequent return-stroke peak), a risetime of 240 ns, and a decay time to half-peak value of 4 μs [1]. Besides [1], the multiple burst described above is adopted as part of the standard lightning environment in the following documents (listed as given in [1]):

1) SAE Committee Report, SAE AE4L-83-3, Rev. B, "Recommended Draft Advisory Circular on Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning," Appendix III;
2) DOT/FAA/CT-89/22, "Aircraft Lightning Protection Handbook;"
3) US MIL-STD-1795A, "Lightning Protection of Aerospace Vehicles and Hardware;"
4) NASA STS 07636, Rev. A, "Space Shuttle Lightning Criteria."

Since KRN used triggered field-measuring systems with 200 μs oscilloscope sweeps, they could not adequately determine the position of the bursts within the overall flash record or the relation of the bursts to K changes or to any other known lightning processes. Further, KRN present results only for intracloud lightning flashes, although they do state that bursts of pulses were observed in about 10% of the cloud-to-ground flashes in their data set. Again, this fraction is probably biased by a relatively high trigger threshold.

The present study represents an extension of the research of KRN to cloud-to-ground discharges, and it includes a comparison of the characteristics of the regular pulse bursts in ground and in cloud flashes. In contrast to KRN, we are able to examine the relation of the regular pulse bursts in both cloud-to-ground and cloud discharges to various lightning processes by making use of our continuous flash records. Additionally, we comment on the relation of the observed regular pulse bursts to the H component of the standard lightning testing environment [1].

II. Data and Results

The electric field records of three multiple-stroke cloud-to-ground discharges and of three cloud discharges, all six discharges recorded in August 1991, in four different storms at the NASA Kennedy Space Center (KSC), are analyzed here. The three cloud flashes analyzed were previously studied by Villanueva *et al.* [6], primarily for the position of the larger microsecond-scale pulses within a flash, these being found to occur preferentially early in the flash. No reliable information on the distance to the discharges is available; however, judging from the overall field waveforms the distances were likely greater than 5 km and less than 20 km. The data can be viewed as a random sample from a large data set acquired using a multiple-channel 12 b digitizing system characterized by a 500 ns sampling interval with individual record lengths up to a few seconds [7]. Two channels of the digitizer were used, each fed from a flat-plate antenna via an integrating amplifier and a low-pass, anti-aliasing filter. One integrating amplifier had a decay time constant of about 10 s so as to reproduce faithfully the relatively slow, predominantly electrostatic, field changes. Following the terminology introduced by Kitagawa and Brook [8], we call this system configuration a "slow antenna." The other integrating amplifier had a decay time constant of about 150 μs and usually a much higher gain so as to accentuate the microsecond-scale, predominantly radiation field, variations. Following Kitagawa and Brook [8], we call the latter system configuration a "fast antenna." The system noise level was as low as ± 1 bit (about 5 mV on a 5 V scale). This system had an upper frequency response of about 1 MHz so that we could not reliably measure the detailed characteristics of individual pulses, but it enabled us to determine the relation of the regular pulse bursts to various lightning processes identifiable in the electric field records. No smoothing was applied to any records involved in this study. Only those pulse bursts that contained more than five pulses separated by time intervals shorter than 30 μs or so are included in this analysis (the interpulse intervals in KRN do not exceed 20 μs).

A summary of the pertinent information on the three ground flashes analyzed is presented in Table I and on the three cloud flashes in Table II. Examples of regular pulse bursts in ground flashes are shown in Figs. 1–4, and in cloud flashes in Figs. 5 and 6. Overall electric field record of cloud flash 9 123 164 is shown in Fig. 1(a) of [6].

A. Cloud-to-Ground Flashes

The microsecond-scale pulse burst in Figs. 1 and 2 occurs in the latter portion of a ramplike millisecond-scale field change characteristic of a K change (Kitagawa and Brook [8]; Thottappillil *et al.* [9]), while the bursts in Figs. 3 and 4 appear to be associated with a hook-shaped field change characteristic of an M component (Malan and Schonland [10]; Thottappillil *et al.* [9]). In the "slow antenna" trace in Fig. 1(a), no regular pulse burst is seen because of insufficient gain. What is seen instead is a small ramp characteristic of the K process in both ground and cloud flashes. In the "fast antenna" trace in Fig. 1(b), the ramp is distorted due to the system decay times being comparable to the duration of the ramp; but a pulse burst is readily observable in the later portion of the ramp. Fig. 2(a) and (b) show two portions of the burst on an expanded time scale [350 μs versus 2 ms in Fig. 1(a) and (b)]. In about 40% of all the cases in Table I the bursts were associated with ramplike field changes similar to that illustrated in Fig. 1(a) and (b) and typically occurred in the second half of the ramp, as seen in Fig. 1(b).

In 55% of the cases there was no detectable relatively slow field change associated with the burst, although an existing ramp might have been too small to be detected with the instrumentation gain used. Evidence for this view is given in the discussion of cloud flashes found in the next section. Further, one should not attach too much significance to the percentages given above since the detectability of relatively slow, predominantly electrostatic field changes depends on the

TABLE I
CHARACTERISTICS OF PULSE BURSTS IN THREE GROUND FLASHES

Flash ID (digits 3 through 5 indicate the Julian day)	Time (EDT)	Number of Strokes	Number of Pulse Bursts			Characterization of Bursts		
			Only +	Only -	Total	Average Burst Duration, μs	Average Number of Pulses	Average Inter-Pulse Interval, μs
9122246	18:41:17	7	15	20	35	173	30	6.1
91231107	14:40:44	9	21	12	34*	192	28	7.3
91231111	14:44:53	3	10	10	20	235	39	6.1

* One burst shows polarity reversal.

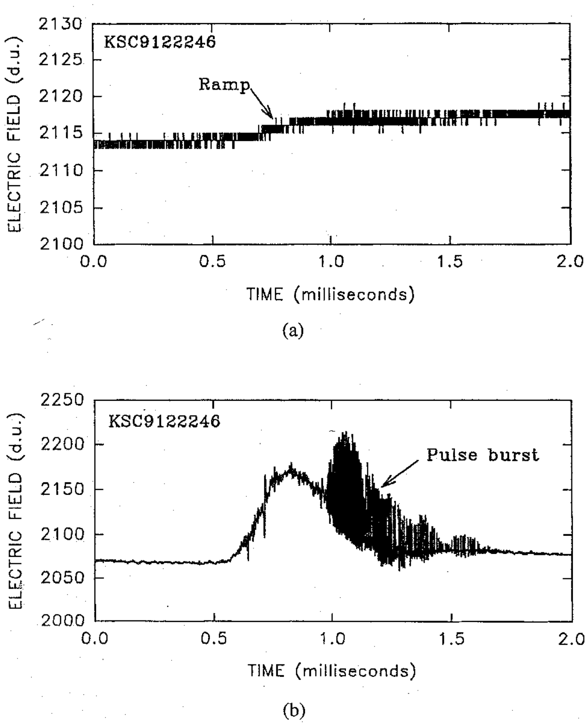

Fig. 1. A regular burst of microsecond-scale pulses associated with a ramp-like millisecond-scale field change (K-change) in a ground flash; (a) Low gain, decay time constant of 10 s ("slow antenna" trace); (b) High gain, decay time constant of 150 μs ("fast antenna" trace). The pulse burst is shown on an expanded time scale in Fig. 2. Here and in the following figures "d.u." denotes digitizer units.

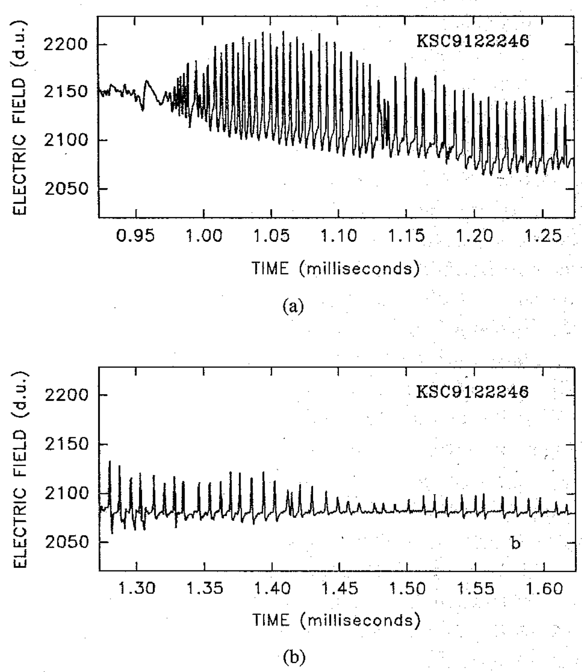

Fig. 2. Same as Fig. 1(b) but displayed on an expanded time scale (50 μs per division). End of time scale in Fig. 2(a) is the beginning of time scale in Fig. 2(b). Positive field change deflects downward (atmospheric electricity sign convention).

location (orientation and distance) of the lightning channel with respect to the observer, in addition to the amount of charge transferred. Note that many ramps do not contain detectable regular pulse bursts, although some contain irregular pulse activity, consistent with the observation of Rakov *et al.* [11].

In the second example, shown in Figs. 3 and 4, one of the bursts culminates in a hook-shaped field change characteristic of an M component, the lightning process that occurs after some return strokes and is accompanied by a brightening of the faintly luminous channel to ground. Note from Fig. 3(a) and (b) that pulses in that burst [also shown in Fig. 4(b)] are large enough to appear in both the "fast antenna" and "slow antenna" outputs (the trailing edge of the field "hook" is saturated (clipped) in the higher-gain "fast antenna" trace). The large pulse in Fig. 4(b), which marks the end of the regular pulse activity and is immediately followed by the field hook (see Fig. 3), is a typical feature of the hook-shaped M-component field changes (see Rakov *et al.* [11]). The amplitude of this pulse is larger than that of one of the smaller return-stroke

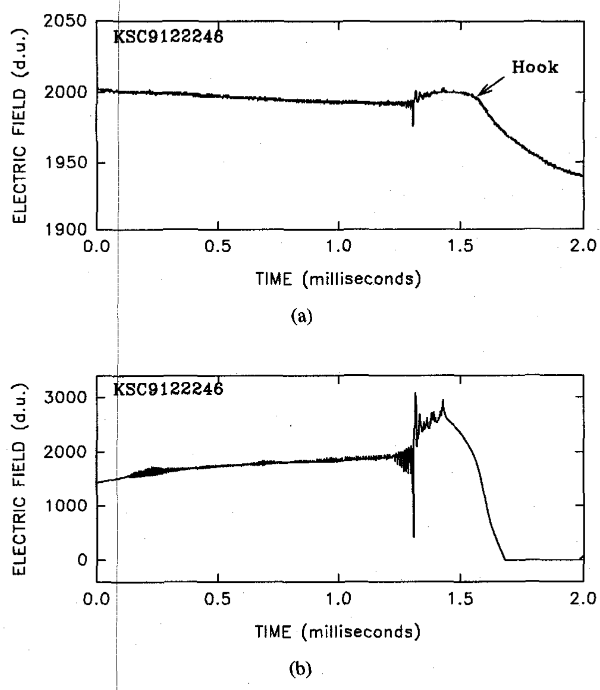

Fig. 3. Regular bursts of microsecond-scale pulses associated with a hook-shaped millisecond-scale field change (M-change); (a) Low gain, decay time constant of 10 s ("slow antenna" trace); (b) High gain, decay time constant of 150 μs ("fast antenna" trace). The pulses are shown on an expanded time scale in Fig. 4.

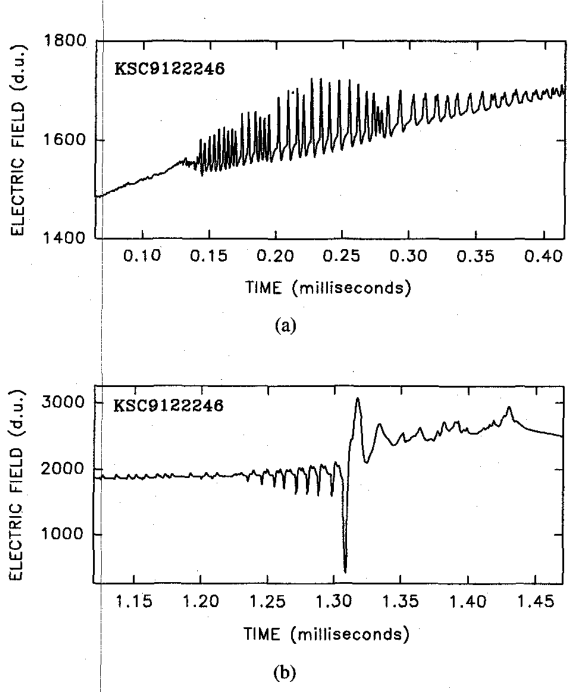

Fig. 4. Two fragments of the field record shown in Fig. 3(b) but on an expanded time scale (50 μs per division). Positive field change deflects downward (atmospheric electricity sign convention).

pulses in the same flash. Note the different polarities of the pulses preceding the large pulse in Fig. 4(b) [also compare the polarities of the pulses in Fig. 4(a) and (b)].

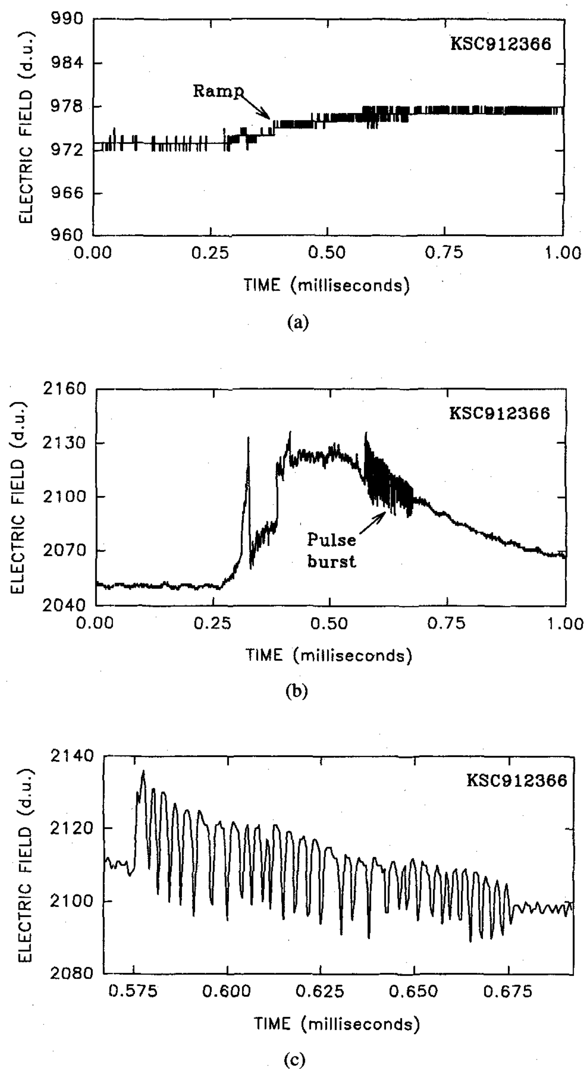

Fig. 5. A regular burst of microsecond-scale pulses associated with a ramp-like millisecond-scale field change (K-change) in a cloud flash; (a) Low gain, decay time constant of 10 s ("slow antenna" trace); (b) High gain, decay time constant of 150 μs ("fast antenna" trace); (c) Portion of (b) showing the regular pulse burst on an expanded time scale (25 μs per division). Positive field change deflects downward (atmospheric electricity sign convention).

As evident from Table I, there are on average 28–39 pulses per burst in the three ground flashes analyzed. The average interpulse interval varies from 6.1–7.3 μs, and the average burst duration from 173–235 μs. Usually all pulses within a burst have the same polarity. Positive and negative pulse polarities are about equally probable. Pulse peaks are approximately two orders of magnitude smaller than return-stroke initial field peaks in the same flash.

Following are some observations regarding the position of the regular pulse bursts with respect to return-stroke pulses in the ground flashes. Except for the bursts apparently associated with one pronounced M component hook (see Figs. 3 and 4), there is usually a delay in excess of 10 ms between the preceding return stroke and the pulse burst. Further, the bursts show a clear tendency not to occur before the first stroke or

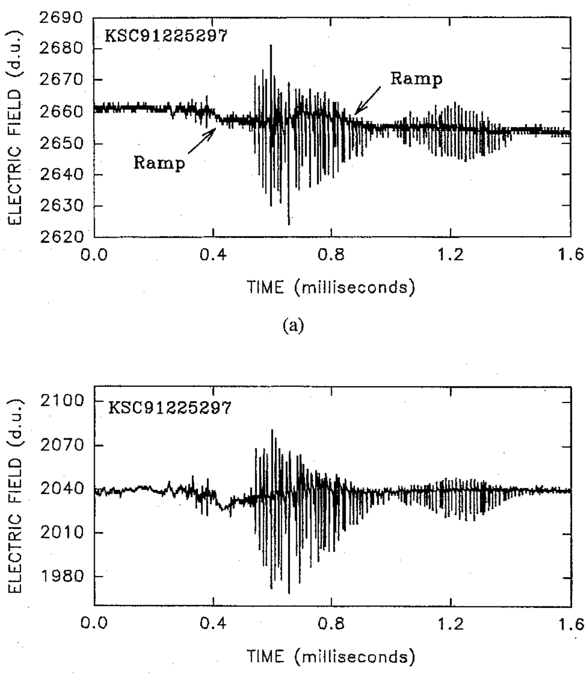

Fig. 6. A sequence of two regular pulse bursts associated with small ramplike field changes (K-changes) in a cloud discharge; (a) Decay time constant of 10 s ("slow antenna" trace); (b) Decay time constant of 150 μs ("fast antenna" trace). Note that the gain for Fig. 6(a) is about an order of magnitude higher than for Fig. 5(a), while the gain for Figs. 6(b) and 5(b) is the same. Positive field change deflects downward (atmospheric electricity sign convention).

between the first and second strokes. In the two ground flashes containing 7 and 9 strokes (see Table I), the occurrence of bursts after the fourth stroke gradually decreases. Note that the pulse bursts shown in Figs. 3 and 4 occurred during the time that continuing current flowed in the channel to ground.

B. Cloud Flashes

In cloud flashes, the relation of the regular pulse bursts to the relatively slow field changes is similar to that found for ground flashes: that is, many bursts occur in the latter part of electric field ramps characteristic of K processes, as illustrated in Figs. 5 and 6, but the majority of bursts occur when there is no detectable relatively slow field change. Note that, as opposed to the ground-flash data for which the gain of each of the two systems ("slow antenna" and "fast antenna") was the same for all three flashes, the gain for Fig. 6(a) is about an order of magnitude higher than for Fig. 5(a), while the gain for Figs. 5(b) and 6(b) is the same. It follows that if the signal shown in Fig. 6(a) were recorded using the same gain as that used to record the signal in Fig. 5(a), the two small ramps seen in Fig. 6(a) would not be discernible. Thus, we speculate that when regular pulse bursts cannot be related to relatively slow field changes, it is likely due to insufficient system gain, if not due to unfavorable orientation of the discharge channel with respect to the observer and/or relatively small charge transfer. The characteristics of the cloud-flash regular pulse bursts presented in Table II appear to be similar to those of the ground-flash bursts given in Table I: There are 18–24 pulses per burst; the average interpulse interval varies from 6.4–7.2 μs; and the average burst duration varies from 117–161 μs. Similar to ground flashes, in cloud discharges there is a tendency for the regular pulse bursts to occur in the latter stages of the discharge, a behavior that is consistent with the observations of KRN.

III. Discussion

A. General

We have seen that the characteristics of regular pulse bursts in the three ground flashes are similar to those in the three cloud flashes (compare Tables I and II), suggesting that the physical process which produces this field signature is probably not affected by the presence of a channel (or its remnants) to ground. Note that the regular pulse bursts shown in Figs. 3 and 4 occurred during the continuing-current stage of a lightning discharge to ground.

As stated in the introduction, regular pulse bursts have been observed in different geographical locations, including Switzerland, Florida (KSC), and Arizona. Further, the present authors have observed, but not analyzed, regular pulse bursts in natural lightning near Socorro, NM and in Gainesville, FL, and in lightning flashes triggered using the rocket-and-wire technique at Camp Blanding, FL. In the latter case, the lightning termination on ground was within 500 M or so of the measuring station, although the pulses probably emanated from the cloud discharge processes at altitudes of the order of several kilometers. Thus, it appears that the regular pulse bursts are a manifestation of some basic lightning process that occurs under different topographical and meteorological conditions in both naturally-occurring cloud and ground lightning, as well as in rocket-triggered lightning and, presumably, in aircraft-initiated lightning. This process probably occurs in all lightning discharges but has escaped registration in most previous lightning studies due to an insufficient measuring system gain, dynamic range, and/or time resolution.

B. Comparison with KRN

As seen from Tables I and II, the regular pulse bursts we analyze here (162 bursts containing a total of 4218 pulses) are very similar to those reported by KRN (a total of 1371 pulses in an unspecified number, probably some tens, of bursts). Indeed, in our six flashes the average duration of the burst varied from 117–235 μs, consistent with the typical burst duration of 100–400 μs reported in [2]. Further, the average interpulse intervals in our study varied from 6.1–7.3 μs, in agreement with the 6.1 μs found by KRN for Florida. However, KRN state that the pulse amplitudes often decrease during the burst, whereas we observed that the pulse amplitudes often first increase and then decrease, as seen in Figs. 2, 4(a), and 6. We also observed that the pulse repetition rate tends to decrease toward the end of the burst. In fact, the initial part of a burst often appears as an oscillation [see Fig. 2(a)], perhaps due to the insufficient upper frequency response of our system that

TABLE II
CHARACTERISTICS OF PULSE BURSTS IN THREE CLOUD FLASHES

Flash ID (digits 3 through 5 indicate the Julian day)	Time (EDT)	Number of Pulse Bursts			Characterization of Bursts		
		Only +	Only -	Total	Average Burst Duration, μs	Average Number of Pulses	Average Inter-Pulse Interval, μs
91225297	19:58:49	11	16	28*	161	18	6.8
9123164	13:59:42	3	5	8	133	24	6.4
912366	15:19:46	31	6	37	117	20	7.2

* One burst shows polarity reversal.

converted sharp and closely spaced pulses into an oscillatory signal. It is possible that KRN missed the initial, relatively low amplitude portion of the regular pulse bursts because that portion was below their system trigger threshold, and their system apparently recorded no data prior to the trigger. (The delay lines they usually employed to obtain pre-trigger data were omitted to provide the faster system response time of about 0.1 μs.)

The observation that the pulse bursts in both cloud and ground flashes appear to avoid the initial part of the discharge supports the view of KRN that these bursts are associated with processes in previously conditioned in-cloud sections of the lightning channel (as opposed to processes creating new channels), similar to a dart-stepped leader in a preexisting channel. Further, our data also support the hypothesis of KRN that the regular pulse bursts are related to K changes. Additionally, we found that the bursts tend to occur during the second half of K changes in both cloud and ground flashes.

C. Regular Pulse Bursts and Lightning Test Standards

The observed bursts of regular pulses analyzed above, as well as those studied in KRN, appear to be similar in the number of pulses per burst and the interpulse intervals to the "multiple burst" (component H), defined in terms of current, of the standard lightning environment for the design and testing of aerospace vehicles [1]; although in our data the intervals between the pulses are somewhat shorter (6.1–7.3 μs versus 10–50 μs in the standard lightning environment). We will now discuss the possible relation of the H component of the standard lightning environment [1] to the regular pulse bursts and to other radiation field signatures that are known to be produced by lightning. In doing so, we will refer to Table III in which all presently known lightning radiation field signatures, as recorded at ground, are summarized. Besides return strokes (the first row) and so-called isolated pulses (the last row), the pulses occur in sequences with submillisecond interpulse intervals. Leader pulses (rows 2 and 3) are presumably emitted by the lower portion of the channel to ground just prior to the initiation of a return stroke, while both initial breakdown pulses (rows 4 and 5) and regular pulse bursts (row 6) are produced by lightning processes occurring inside the cloud.

The typical microsecond-scale pulse structure of naturally-occurring ground discharges, as observed at ground, includes (e.g., [3]) an initial sequence of pulses (usually called preliminary breakdown pulses) followed, some tens of milliseconds later, by 3–5 relatively large return-stroke pulses spaced several tens of milliseconds apart. The initial pulses can have amplitudes comparable to that of the corresponding return-stroke pulses [7]. Just prior to the first return-stroke pulse and prior to some subsequent return-stroke pulses there are pulse sequences associated with stepped and dart-stepped leader processes, respectively. These pulse sequences last for some tens to some hundreds of microseconds, and the pulse amplitudes are one to two orders of magnitude smaller than the corresponding return-stroke pulse amplitude. The intervals between the return-stroke pulses, and the time interval of some tens of milliseconds or so following the last return-stroke pulse, contain the regular pulse bursts of relatively small amplitude studied here, and some other, usually irregular (see, for instance, [11]), pulse activity. The regular pulse bursts are very similar in their characteristics to the pulse sequences associated with dart-stepped leaders. Note that the relative amplitudes of pulses in ground discharges that will be "seen" by airborne vehicles can differ significantly from those observed at ground because of the difference in the position of the source with respect to the ground and the vehicle, as well as the variation of lightning current characteristics along the cloud-to-ground path.

The typical pulse structure that is observed in naturally-occurring cloud discharges ([6] and this study) includes an initial sequence (or sequences) of pulses of relatively large amplitude, spaced some hundreds of microseconds apart and occurring within the first several to a few tens of milliseconds, followed by a number of regular pulse bursts of significantly smaller amplitude, pulses within the burst being several microseconds apart with each burst lasting for some hundreds of microseconds. There are also microsecond-scale pulses with amplitudes appreciably lower than those of the initial pulses which are dispersed, as opposed to clustering in bursts,

TABLE III
CHARACTERIZATION OF RADIATION FIELD PULSES ASSOCIATED WITH VARIOUS LIGHTNING PROCESSES

Type of pulses	Dominant polarity (atmospheric electricity sign convention)	Typical total pulse duration, μs	Typical time interval between pulses, μs	Comments
Return stroke	Positive	30-90 (zero-crossing time)	60×10^3	3-5 pulses per flash
Stepped leader	Positive	1-2	15-25	Within 200 μs just prior to a return stroke
Dart-stepped leader	Positive	1-2	6-8	Within 200 μs just prior to a return stroke
Initial breakdown in ground flashes	Positive	20-40	70-130	At least several milliseconds before the first return stroke
Initial breakdown in cloud flashes	Negative	50-80	600-800	The largest pulses in a flash
Regular pulse burst in both cloud and ground flashes	Both polarities are about equally probable	1-2	5-7	Occur later in a flash; 20-40 pulses per burst
Isolated pulses (e.g., Willett et al., 1988 [17])	Negative	10-20	-	Reportedly not related to any known lightning process

Notes: 1. Polarity refers to polarity of the initial half cycle in the case of bipolar pulses.
2. Typical values are subjectively synthesized from our comprehensive literature search and from our unpublished experimental data.
3. As shown by Rakov et al. [11], there is no characteristic radiation pulse signature associated with lightning K and M processes.

throughout the flash [6]. Some of these smaller and often irregular pulses are associated with ramplike K field changes (see, for instance, Fig. 5). K changes typically occur in the latter part of the cloud flash and are separated by some tens of milliseconds.

We will examine next the information available in the literature on the aircraft measurements that apparently formed the basis for the definition of the H component [1], and then we will attempt to interpret those using Table III.

1) Aircraft Observations: The "multiple burst" in the standard lightning environment [1] is based on measurements of current taken during direct lightning strikes to an instrumented F-106B aircraft. Most of the data were obtained while the plane was flying through or near the tops of thunderstorm clouds where the ambient temperature was below $-40°$C. The majority of the direct strikes to the F-106B were apparently initiated by the aircraft itself and did not involve a channel to ground. Different sets of instrumentation with different settings were used in different years (1980–1986) of the project. It appears [12] that the current measurements which prompted the requirement for the multiple burst test were obtained in 1984. In that year, lightning current was measured at two locations: in the aircraft's nose boom (a slender metal extension projecting from the plane's nose), and at the tip of the vertical tail. The waveform recording instrumentation [13] included continuous analog tape recorders having a nominal frequency bandwidth of 400 Hz to 100 kHz and a multiple-channel 8 b digital transient recorder capable of taking about 2.6 ms of data per channel at a sampling interval of 40 ns (the shortest possible sampling interval was 5 ns). The gains of the transient recorder channels used to measure currents were set to capture pulses with amplitudes in the kiloampere range. The transient recorders were triggered by the signal from an electric-flux-density time-derivative sensor. Data from the transient recorder were transferred to an analog tape recorder for storage, the transfer time, during which the recorder was unavailable for data acquisition, being 19 s. Thus, the transient recorder could capture only a single, relatively narrow time window of data per flash, while the continuous recorders, due to their insufficient high-frequency response, did not allow the faithful reproduction of the amplitudes, shapes, and sometimes even polarity of microsecond-scale pulses (see, for instance, Fig. 11 of Mazur [14]). The maximum value of lightning current measured during the entire project, recorded with the so-called peak recorder, was 54 kA; however, in many cases no current was discernible on the kiloampere scale of the transient recorder after triggering by the field sensor (see, for instance, [13]). The latter observation might be indicative of the fact that induced effects (the triggering field signals) are caused by processes in remote sections of lightning channel, not necessarily accompanied by a current simultaneously flowing through the aircraft.

2) Interpretation of Aircraft Data: The pulse bursts representing the H component are claimed [1] to occur "randomly throughout a lightning flash;" that is, no distinction is made between pulses occurring at the beginning of the flash and pulses occurring later in the flash. As noted above, due to the 19 s dead time, only one burst per flash could be recorded with sufficient frequency response (using the transient recorder), and, therefore, the presence of other similar bursts in the flash was likely inferred from the continuous recorder data in which the pulse waveforms might be significantly distorted. Sequences of pulses occurring at the beginning of the flash are likely to be due to the initial channel formation processes. It is not clear what processes are responsible for the later pulse bursts that were reportedly [15] observed on the F-106B. To the best of our knowledge, only one measured current waveform (Fig. 3.27 in [12]), that apparently occurred at the beginning of the discharge, is specifically presented in the literature to substantiate the H component definition. Apparently one additional example, very similar to that in [12], is found in Fig. 11(b) of Mazur [14]. If aircraft-initiated lightning is similar to naturally-occurring lightning, then most of the later pulse bursts reportedly seen on the aircraft should have been the regular pulse bursts studied here and by KRN. On the other hand, it is not clear if these bursts would be recorded with the aircraft current sensors. Mazur and Moreau [16] specifically studied currents and fields during the latter stage of lightning strikes to the instrumented FAA CV-580 and French C-160 airplanes flying below 6 km (near 0°C). Using a tape recorder with a frequency bandwidth from d.c. to 500 kHz and an amplitude range from 10 A–1.6 kA, they observed sequences of current pulses, each pulse lasting for some hundreds of microseconds with interpulse intervals ranging from several hundreds of microseconds to several milliseconds. Mazur and Moreau [16] labeled these pulses "recoil streamers," the term introduced by Ogawa and Brook [4] to describe processes giving rise to K changes in naturally occurring lightning discharges. The amplitudes of the "recoil streamer" pulses are reported in [16] to be higher, within the upper measurement limit of 1.6 kA, than those of the initial breakdown pulses in the same flashes. From observations at ground, the initial breakdown pulses in natural cloud flashes are larger than the microsecond-scale pulses associated with K changes [6], in contrast with the pulse structure of aircraft-initiated lightning reported in [16]. Note that the initial current pulses measured on the F-106B flying near -40°C, which prompted the requirement for the multiple-burst test, exhibited amplitudes in excess of 10 kA [12]. The "recoil streamer" pulses observed by Mazur and Moreau [16] do not appear to match the H component definition [1] since they are characterized by 1) about an order of magnitude smaller peaks, 2) one to two orders of magnitude longer pulse duration, and 3) one to two orders of magnitude longer interpulse interval. It is possible that the in-flight data, on which the definition of the H component is based, represent a mix of measurements made during both the formation of new channels (initial breakdown pulses) and during the processes in previously formed channels (the regular pulse bursts studied here and by KRN). If this be the case, it is important to know the contribution of each of these processes to the mix, since the characteristics of the initial pulse sequences and regular pulse bursts are appreciably different, as delineated in Table III and in the description of the typical observed pulse structure of cloud lightning discharges given above.

3) Proposed Changes in the Lightning Test Standard: Recently, the SAE (Society of Automotive Engineers) Committee AE-4L (Lightning) and EUROCAE WG-31 have suggested a revision of the description of the "multiple burst" for the standard lightning environment [1]. These groups propose changing: 1) the number of pulse bursts per flash from 24 to 3, and 2) the interpulse intervals from 10–50 μs to 50–1000 μs, and c) the separation between bursts from 10–200 ms to 30–300 ms [18]. The number of pulses per burst and the characteristics of individual pulses will remain the same. It is unclear from [18] what the rationale is for such a radical revision. Although the change in the number of bursts per flash is emphasized in [18], there is a significant difference between the original definition and its proposed revision in terms of the interpulse interval which is proposed to be on average about 500 μs versus about 30 μs (on average) in the original definition. The proposed new multiple burst definition matches best the radiation field signatures of the initial breakdown in ground and cloud flashes while the original definition matches best the regular pulse bursts studied here and by KRN (see Table III). There exists, of course, the possibility that an aircraft creates specific conditions in the cloud, not present otherwise, conducive to a process different from any of the processes in the naturally occurring flashes that are listed in Table III. Clearly, more experimental data on the microsecond-scale pulse activity in the aircraft-measured lightning currents and in the lightning electromagnetic radiation are needed to allow an adequate definition of the H component of the standard lightning environment.

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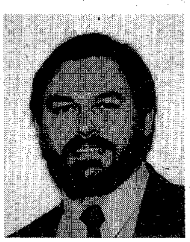

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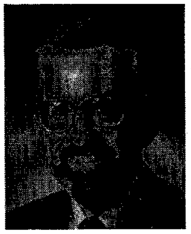

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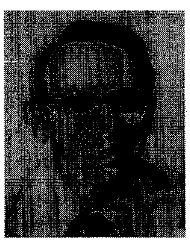
Glen R. Hoffman photograph and biography not available at the time of publication.

Michael W. Masters photograph and biography not available at the time of publication.



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