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Key Points:
- An average 5 mA current flows near ground prior to dart leader descent to ground
- No current "cutoff" is observed at ground between lightning strokes
- Ours is the most sensitive reported channel-base interstroke current measurement

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Does the lightning current go to zero between ground strokes? Is there a current "cutoff"?

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Abstract At the end of 120 prereturn stroke intervals in 27 lightning flashes triggered by rocket-and-wire in Florida, residual currents with an arithmetic mean of 5.3 mA (standard derivation 2.8 mA) were recorded. Average time constants of the current decay following return strokes were found to vary between 160 μs and 550 μs, increasing with decreasing current magnitude. These results represent the most sensitive measurements of interstroke lightning current to date, 2 to 3 orders of magnitude more sensitive than previously reported measurements, and contradict the common view found in the literature that there is a no current interval. Possible sources of the residual current are discussed.

1. Introduction

Negative-polarity cloud-to-ground lightning discharges have a typical overall duration of about 250 ms and are usually composed of three to five downward-leader/upward-return-stroke sequences, each sequence being separated by a period of tens of milliseconds [e.g., *Rakov and Uman*, 2003]. There is no consensus on why the charge transfer in negative cloud-to-ground discharges is intermittent via individual strokes rather than continuous. Return strokes following the first stroke, so-called subsequent strokes, are generally preceded by dart leaders which distribute negative cloud charge along the leader's path to ground (the path of the previous return stroke), that leader charge then being lowered to ground by the following upward propagating return stroke. Some researchers [e.g., *McEachron*, 1940; *Brook et al.*, 1962; *Loeb*, 1966] have argued that current must flow in the lightning channel between strokes to maintain the channel in a properly conditioned state to allow dart leader propagation. *Brook et al.* [1962] argue that 10 A could flow without being detectable by the remote photographic and electric field measurement techniques available in the 1960s. *Loeb* [1966] suggested that the interstroke channel was kept conducting by "nonluminous" ionizing waves associated with K changes. *Uman and Voshall* [1968] argued that no current flow was necessary between lightning strokes to keep the lightning channel conditioned for the dart leader because the elevated temperature of the defunct return stroke channel provides a preferred low-density path for breakdown, but the possibility of small current flow through the weakly conductive channel was not excluded.

Measurements made on actual lightning currents have set upper limits on the current that could be flowing between strokes. *McCann* [1944], in the United States, measured interstroke currents down to 0.1 A using a calibrated optical/photographic measurement system mounted on towers and buildings ranging in height from 22 to 178 meters. *Berger* [1967] observed interstroke currents down to his system's 1 A minimum detectable level on two instrumented towers in the mountains of Switzerland. *Fisher et al.* [1993] documented interstroke currents down to about 2 A in rocket-and-wire triggered lightning discharges in Alabama. Thus, from prior measurements, it is reasonable that the interstroke current generally falls to a value below 1 A prior to dart leader initiation.

It is also clear from direct lightning current measurements that dart leaders and the following return strokes can occasionally occur in channels carrying a steady current of a few amperes at ground [e.g., *Miki et al.*, 2005; *Flache et al.*, 2008; *Winn et al.*, 2012; *Rakov*, 2013; *Pilkey et al.*, 2013].

The prevailing view today, although unproven, is that the current between strokes generally decays to 0 A prior to dart leader propagation [e.g., *Fisher et al.*, 1993]. *Krehbiel et al.* [1979], based on their multistation electric field measurements, infer that channel cutoff occurs in the lower atmosphere, away from the source region in the cloud, and suggest that the negative resistance characteristic (increasing electric field with decreasing current) observed in laboratory arcs was important in causing this cutoff to occur. According to *Krehbiel* [1981], the characteristic "cutoff change" in his electric field records had a typical duration of 5 ms or less. *Heckman* [1992], interpreting rapid falls of radar reflectivity as indicative of a cutoff channel, observed that the lightning channel becomes cutoff on the order of a millisecond or less and also attributed the cutoff mechanism to the negative arc resistance. *Mazur and Ruhnke* [2014] review laboratory measurements and modeling of free-burning arcs and conclude that a free-burning arc should always have a negative resistance, whereas the measurements of *King* [1961] on laboratory arcs show a negative resistance region below about 100 A, and a positive resistance at higher current. *Williams and Heckman* [2012] give a thorough overview of evidence for current cutoff, highlighting discrepancies between the evidence and present theories of current cutoff.

If cutoff is to occur, the conductive, radiative, and convective power losses from a channel segment will exceed the power input to that segment. Heckman, using the negative resistance of an arc as a necessary factor, estimated the ability of the lightning channel to recover from disruptions, developing an arc instability model to explain current cutoff and multiple strokes in lightning [*Heckman*, 1992; *Williams*, 2006; *Williams and Heckman*, 2012]. An alternative qualitative explanation is given by *Mazur and Ruhnke* [1993, 2014] who attribute channel cutoff to electric field screening. As the channel propagates, charge is induced at the channel tip which reduces the electric field behind it. The geometry of a branched channel further reduces this aftward electric field, eventually choking off the channel.

The primary purpose of the present paper is to provide a more sensitive measurement of the lightning current between strokes than is available in the literature. We will show that there is a relatively smooth current decay to a final interstroke value having an average (arithmetic mean) of 5.3 mA, with the current decaying to essentially 0 mA 1 s to 11 s after the final stroke of each of the 27 triggered flashes studied.

2. Experiment

The data presented in this paper were collected during the summers of 2012 and 2013 at the International Center for Lightning Research and Testing (ICLRT) in north central Florida, 45 km northeast of the University of Florida campus. Rocket-and-wire triggered lightning is studied at the ICLRT via measurements of channel-base current, electromagnetic fields and their derivatives, energetic radiation, and optical measurements. The triggering process is discussed in *Rakov and Uman* [2003]. Small rockets trailing grounded Kevlar-clad copper wires were launched from a 4.3 m tall aluminum rocket launcher which was connected to ground through a current measurement box to three 12 m long copper-clad steel ground rods connected in parallel. In 2012, the strike object was a roughly 5 m by 5 m rectangular ring suspended 5.4 m above ground level, located over and electrically bonded to the rocket launcher. In 2013, the rectangular ring was replaced by a 1 cm radius vertical copper-clad steel rod bonded to the center of the rocket launcher and extending 1.5 m above the top of the launcher.

The channel-base current was measured using a T&M Research R-7000-10 1 mΩ current-viewing resistor (CVR) which has a flat frequency response from DC to 8 MHz. Note that *Berger* [1967] and *Fisher et al.* [1993] employed a similar measurement technique. The output voltage signal from the CVR was passed to four separate sets of electronics in order to measure current amplitudes ranging from 1 mA up to 60 kA. From least sensitive to most sensitive, the current measurements are called High (Hi), Low (Lo), Very Low (VL), and Extremely Low (XL). Negative charges flowing to ground or positive charges flowing up the channel are recorded as positive-polarity waveforms.

Signals from each measurement station were transmitted over fiber-optic cable to the shielded Launch Control trailer for digitization and storage. The analog Opticomm multimode fiber-optic links used in 2012 were replaced in 2013 with single-mode Terahertz Technologies Inc. (TTI) LTX-5515 signal transporters that digitized the analog signal at the launcher with 14 bit resolution at 100 MS s^{-1}, providing improved signal fidelity. The current measurement characteristics for 2012 and 2013 are summarized in Table 1.

The key instrument in this paper is the XL measurement which is sensitive to currents in the milliampere range via a three-stage amplifier gain of 5000 and which has its bandwidth limited to 160 Hz. The XL current data presented here were digitized at 50 kS s^{-1} and passed through a digital 1 kHz first-order low-pass Butterworth filter to reduce noise. The XL measurement amplifier uses chopper amplifiers to minimize input

Table 1. Summary of the Current Measurement Characteristics at the ICLRT in 2012 and 2013

	Hi	Lo	VL	XL
		2012		
Saturation level	60 kA	6 kA	250 A	250 mA
Noise floor	500 A	50 A	2 A	0.5 mA[a]
Resolution	13 A	2 A	70 mA	0.07 mA
Bandwidth	DC—8 MHz	DC—8 MHz	DC—8 MHz	DC—160 Hz
		2013		
Saturation level	50 kA	5 kA	200 A	200 mA
Noise floor	150 A	30 A	1 A	0.2 mA[a]
Resolution	3 A	300 mA	12 mA	0.01 mA
Bandwidth	DC—8 MHz	DC—8 MHz	DC—8 MHz	DC—160 Hz

[a]After being passed through a 1 kHz first-order low-pass Butterworth filter.

noise, allowing the small microvolt signal produced by the milliampere current through the milliohm shunt to be measured with high precision. The accuracy of the XL measurement was tested during fair weather by installing resistors in series with the CVR and measuring the current when a DC battery voltage was applied across it. Test currents of 5 mA and 15 mA agreed to within 1% of expected values, while the test of 1 mA agreed within 4% of the expected value, the reduction in accuracy being attributable to the smaller signal-to-noise ratio of the measurement. The accuracy of the XL measurement is also demonstrated by *Ngin et al*. [2013] who present XL measurement data in 2012 during the ascent of the trigger wire and find good agreement both with previously reported current measurements and with their simultaneous electric field measurements.

Instrumental time constants, the time needed for the output signal to reach e^{-1} of its final value in response to a step function rise or fall, were measured using a square wave generator with a 20 ns rise and fall time. The Hi, Lo, and VL electronics and both the Opticomm and TTI fiber-optic links adequately reproduced the 20 ns square wave risetime and fall time. The XL current measurement was saturated by the generator signal and exhibited a 1.2 ms to 2 ms time constant, increasing with input pulse width, as it recovered from saturation, which was longer than the expected decay time constant of 1 ms derived from its 160 Hz upper frequency response. This change in decay time constant was found to be due to a power supply which sagged during the saturation of the XL measurement, but which recovered to normal values within 10 ms of leaving saturation. XL current data presented here are taken at least 15 ms after leaving saturation to ensure they are not affected by this power supply distortion.

A small drift on the order of ±0.01 mA s^{-1} was observed on the XL current measurement in both 2012 and 2013 in both fair and foul weather, including during triggering attempts. The drift was characterized by a more-or-less linear slope over a period of seconds and was present only when the CVR was connected to the XL current measurement. The reason for this drift is unknown but is likely attributable to the interaction of the rocket launcher with the ambient environment. A separate drift attributable to the warm-up of the fiber-optic links was measured to be monotonic, consistent, and was on the order of 0.001 mA s^{-1}. Vertical offsets caused by these drifts were removed by averaging a 200 ms segment of the XL current waveform 5 s before each rocket launch and adopting that average value as the zero-current level. A second 200 ms segment was selected several seconds after the observed cessation of current flow, which occurred between 1 s and 11 s after the final return stroke, to determine the variation in the offset before and after each flash. The standard deviation of the 200 ms means was about 0.1 mA. The difference between the initial zero-current level and the final current level due to drift varied from 0 mA to 2.1 mA. The drift was subtracted from the data with the assumption that the drift was linear between the vertical offsets measured before and after the flash. Total offsets, due to both an initial offset present when turning on the measurement and the subsequent drift discussed above, had magnitudes of up to 135 mA.

High-speed video images of the triggered lightning channel in 2012 were recorded by a Phantom V711 operating at 10,000 frames per second with a 20 mm lens and in 2013 were recorded by a Photron SA 1.1 operating at 1000 frames per second with a 14 mm lens. Both cameras were located 430 m from the launcher.

3. Results

In 27 triggered lightning flashes, a total of 120 prereturn stroke currents were recorded. The data set includes 76 prereturn stroke intervals in 18 flashes in 2012 and 44 prereturn stroke intervals in 9 flashes in 2013. The

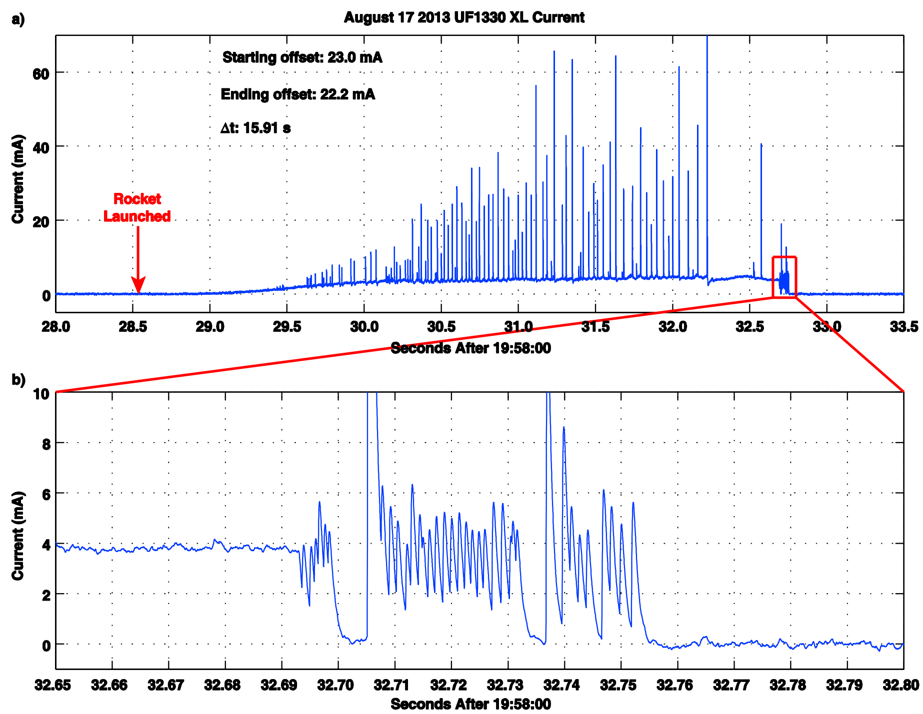

Figure 1. (a) A 5.5 s record of the 1 kHz low-pass filtered XL current from event UF1330 on 17 August 2013 where the trigger wire broke at the rocket launcher at about 32.693 s leaving the wire disconnected from the XL current measurement. (b) An expanded 0.15 s plot of the waveform around the time of the wire break. The starting and ending vertical offsets around this flash and the time (Δt) between where they were measured are also shown.

measured current dropped below 1 mA just prior to a return stroke in only seven of the 120 intervals (5.8%), with only one observed case where the current reached the 0 mA level. These seven intervals all occurred in data collected in 2012, while measured currents in 2013 never dropped below 5 mA. The average (standard deviation) current just prior to a return stroke was 3.7 (2.3) mA for the 76 intervals in 2012, 7.9 (1.7) mA for the 44 intervals in 2013, and 5.3 (2.8) mA overall. We confirm that the waveforms subsequent to these milliampere current measurements are return strokes by their fast risetimes, on the order of microseconds, distinguishing them from *M* components which occur superimposed on continuing currents and which have typical risetimes of hundreds of microseconds [e.g., *Rakov et al.*, 2001; *Rakov and Uman*, 2003].

Figure 1 shows the XL current measurement during flash UF1330 on 17 August 2013, in which the trigger wire broke at the launcher about 4.25 s after launch, leaving the wire disconnected from the current measurements during the remainder of the rocket ascent. The 4 mA current flowing prior to the wire disconnect is due to wire-charging current maintaining the grounded, ascending wire at zero potential [e.g., *Ngin et al.*, 2013]. Impulses recorded around the time of the wire break at 32.693 s are attributed to the bottom end of the trigger wire erratically contacting the rocket tubes. After periods without these impulses, around 32.700 s and 32.735 s, the subsequent impulses are larger than average, which can be explained as the trigger wire having accumulated more charge via polarization in the ambient electric field before again being discharged through the rocket tubes. Of most interest in these quiet periods is the observation that the XL current waveform exponentially decays to near 0 mA with a 1 ms time constant, its ideal instrumental response. This event clearly illustrates that the XL current measurement was functioning properly.

The XL current measurement during flash UF1310 on 14 June 2013 with eight return strokes is plotted in Figure 2. In this case, the current did not fall below 5 mA. Photron SA 1.1 high-speed video images, with its aperture set at f/11 and exposure time at 200 μs, show that the channel was clearly luminous prior to the first through fifth return strokes. The total frame luminosity between return strokes, found by summing the 8 bit pixel values of each 1024 × 640 pixel frame, is also shown. The average background luminosity was calculated at the end of the flash, and the higher luminosity levels are clipped to show the low-level luminosity in better detail. Evidently, there is no obvious relationship between luminosity and current flow at these small

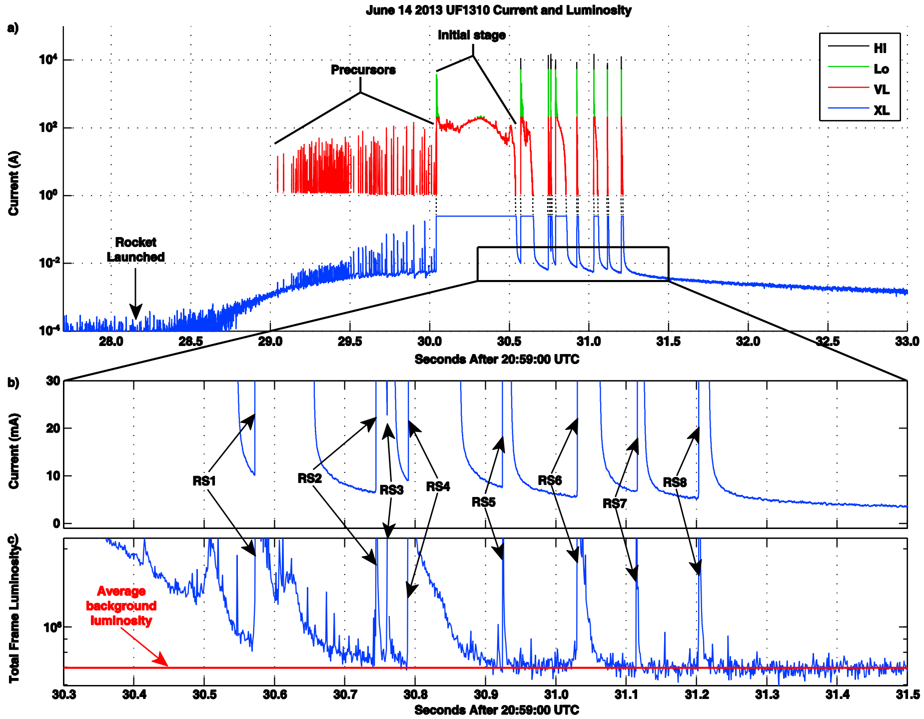

Figure 2. (a) A 5.3 s log-scale record of the four current measurements from event UF1310 on 14 June 2013. The precursors and the initial stage are labeled. Noise floors, except for the XL measurement, have been removed for clarity and where overlap occurs between current measurements, the more sensitive measurement is given priority. The gap below 10^0 A between the VL and XL current records is a current region not measured by our system. Dotted lines have been added in this region to aid in viewing the continuity between waveforms. Below is an expanded 1.2 s plot of (b) the XL current on a linear scale and (c) the total frame luminosity on a log scale. The current did not drop below 5 mA between return strokes in this event. XL measurement offsets before and after this event were −46.6 mA and −46.8 mA, respectively, and were measured 21.6 s apart.

milliampere levels. The channel luminosity is due to two effects: the channel's relatively slowly decaying temperature [e.g., *Uman and Voshall*, 1968] and the power input due to the residual current.

Decay time constants for the observed current during prereturn stroke intervals were calculated for the three least sensitive current ranges by fitting an exponential function to the measured current. The XL measurement was excluded because of its distortion due to power supply sag. The fit was applied over the total range of the individual Hi, Lo, and VL current measurements from current peak to noise floor. Events with a poor fit to the exponential function, having a correlation coefficient less than 0.9, and events with significant continuing current, those lasting longer than 10 ms [e.g., *Shindo and Uman*, 1989], were excluded, leaving 42 intervals where a decay time constant could be calculated on all three current levels. Decay time constants averaged (standard deviation) 160 (160) μs in the Hi current range, 180 (170) μs in the Lo range, and 550 (390) μs in the VL range. The decays on overlapping portions of current measurements, from 500 A to 5 kA (the bottom of the Hi range and the top of the Lo range) and from 50 A to 200 A (the bottom of the Lo range and the top of the VL range) were found to agree within 5%.

4. Discussion

The XL current measurements show that there is typically a current of 2 to 8 mA (average of 5.3 mA with a standard deviation of 2.8 mA for 120 intervals) flowing at the end of the prereturn stroke interval, with the current falling exponentially to the same level seen before the flash 1 s to 11 s after the final stroke of the flash. The source of this residual current is unknown. Also unknown is whether the current flows through the entire channel from cloud to ground, keeping it conditioned for a subsequent dart leader from the cloud charge, or if it is local, flowing only in a channel segment near ground. Potential sources of the residual current include (1) discharge of the launcher assembly, (2) displacement current from ambient electric field changes, (3) charge drift around and down the channel remnants, including from collapse of the corona envelope surrounding the lightning channel, and (4) local corona processes. These potential sources of current are discussed below.

The capacitance of the launcher can be modeled as that of a parallel-plate capacitor with a gap $d = 2$m, approximately the height of the bottom of the launcher above ground, and an area $A = 10\text{m}^2$, approximately the surface area of the launch tubes. The capacitance is then $C = \varepsilon_0 A/d \approx 40$ pF, where ε_0 is the permittivity of free space. The ground resistivity at the ICLRT is about 4000 Ω·m [*Mata et al*., 2000], so the resistance of three 12 m long ground rods connected in parallel at the ICLRT is about 300 Ω [e.g., *Michaels*, 2007]. The resistor-capacitor time constant of the launcher, a measure of how fast accumulated charge on the launcher will be discharged to ground, is then about 10 ns, too short to affect the millisecond-scale currents seen in the XL measurement.

Another potential source of the 5.3 mA average prereturn stroke current is displacement current through the launcher due to the changing ambient electric field between strokes. Effectively, the launcher acts as an electric field derivative antenna. The displacement current density J_D is given by $J_D = \varepsilon_0 \mathrm{d}E/\mathrm{d}t$ [e.g., *Balanis*, 2012] where dE/dt is the time derivative of the electric field. If the equivalent launcher area A (see above) through which the displacement current flows is 10 m^2, then the necessary electric field change to produce a 5 mA current flow ($J_D A$) would be about 60 MV $\text{m}^{-1}\,\text{s}^{-1}$. Electric fields measured 60 m to 100 m from the launcher exhibit variations less than 1 MV $\text{m}^{-1}\,\text{s}^{-1}$. *Miki et al*. [2002, Figure 6] show a 250 ms record of the vertical electric field measured 0.1 m from a lightning channel which exhibits variations of about 50 kV m^{-1} over about 20 ms between return strokes, producing an electric field derivative of roughly 2.5 MV $\text{m}^{-1}\,\text{s}^{-1}$, again too small to account for the 5.3 mA measured current via a displacement current. Thus, displacement current due to changing electric fields between strokes could be a potential source for, at least, a portion of the measured current flow between strokes but is unlikely to account for the entire observed prereturn stroke current.

Uman and Voshall [1968] modeled the thermodynamic evolution of the lightning channel after a return stroke and found that the channel can remain at a temperature near 4000 K for up to 10 ms for a 1 cm channel radius and for over 100 ms for over 4 cm channel radius. At 4000 K, the electrical conductivity σ of dry air at 1 atm is on the order of 1 S m^{-1} [*Yos*, 1963]. By Ohm's law, $J_C = IA_C^{-1} = \sigma E$, and assuming a lightning channel area $A_C = 10^{-4}\text{m}^2$ for a centimeter-scale channel radius through which conduction current density J_C flows, a current I of 5 mA would require an electric field E of only about 50 V m^{-1}. Foul weather electric fields at ground at the ICLRT are commonly 1 to 5 kV m^{-1}. At channel temperatures below 4000 K, *Yos* [1963] found a rapid decrease in channel conductivity, falling to 10^{-6} S m^{-1} at 2000 K, for example, so electric fields several orders of magnitude larger than 50 V m^{-1} would be required to cause the measured milliampere current to flow. Note that the calculations of electrical conductivity are for dry air and the addition of water vapor could alter the stated values. High-speed photographs by *Picone et al*. [1981] and *Colvin et al*. [1987] show significant turbulence in current-carrying channels in air, so the channel may cool somewhat more rapidly than predicted by *Uman and Voshall* [1968] which did not account for the effects of convection in cooling the channel. The results of *Uman and Voshall* [1968] are supported, however, by the modeling of *Latham* [1980] who also ignored convection but stated that it is, at most, equal to thermal conduction in removing heat from the channel.

Maslowski and Rakov [2009] present a model of the lightning channel corona sheath dynamics in which the corona sheath collapses to a nearly zero radius on the order of milliseconds, not inconsistent with the millisecond-scale current flow measured in this study.

The average currents prior to a return stroke measured in 2012, 3.7 mA, were smaller than those measured in 2013, 7.9 mA. None of the 44 measured prereturn stroke interval currents in 2013 fell below 5 mA, while 55 of the 76 intervals in 2012 dropped below 5 mA. The main differences between the two data sets are the different fiber-optic links, Opticomm links in 2012 and TTI links in 2013, and the different strike objects, a horizontal wire ring in 2012 and a vertical strike rod in 2013. Both fiber-optic links have good frequency response well above the 8 MHz upper limit of the current shunt and should not cause any difference in the signal between the 2 years. If the different strike objects influence the different currents measured in 2012 and 2013, it is unclear how. *Miki et al*. [2002] found that milliseconds after a return stroke, electric fields 0.1 m from the lightning channel typically fell below their 20 kV m^{-1} noise level. Corona currents from 1 cm radius

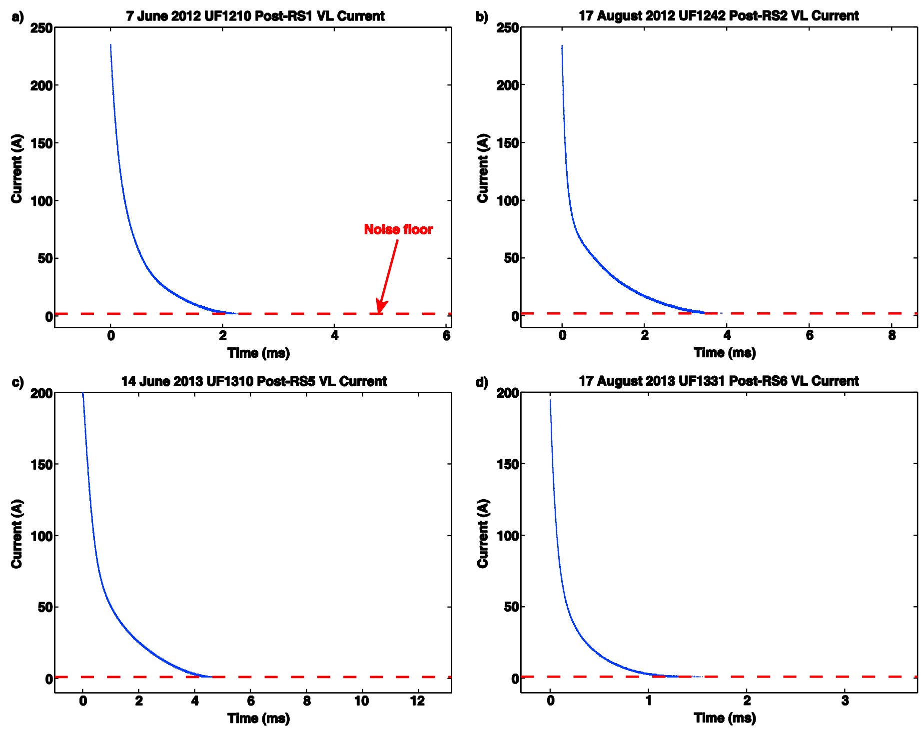

Figure 3. Typical VL current records without significant continuing current (having continuing currents lasting less than 10 ms) as they decay into the noise floor from (a) UF1210 on 7 June 20 2012 after the first return stroke, (b) UF1242 on 17 August 2012 after the second return stroke, (c) UF1310 on 14 June 2013 after the fifth return stroke, and (d) UF1331 on 17 August 2013 after the sixth return stroke. The horizontal dotted lines show the noise level of each measurement: 2 A for 2012 data and 1 A for 2013 data. Time zero was chosen to be the point where the VL waveform exits saturation.

rods in a 20 kV m^{-1} electric field are expected to be on the order of 10 to 100 μA [*Aleksandrov et al.*, 2005a, 2005b], too small to account for either the current at the end of the interstroke interval or the 4.2 mA discrepancy between the data sets from the 2 years.

Typical VL current waveforms for events without significant continuing current, those having continuing current durations less than 10 ms [e.g., *Shindo and Uman*, 1989], are shown in Figure 3. These waveforms, in the 2 A to 250 A range, include the transition region from positive to negative resistance near 100 A observed in laboratory arcs by *King* [1961]. These VL current waveforms, decreasing into the noise floor of 2 A in 2012 and 1 A in 2013, after the initial stage and after each return stroke, were observed to decay smoothly on a millisecond time scale. No evidence was observed of any significant change in the channel characteristics as might be expected from a transition from positive to negative resistance.

5. Summary

We have presented here channel-base current records that show a smooth decay to a milliampere-level current prior to a return stroke. In view of the above discussion, a possible source of the average 5.3 mA residual prereturn stroke current is current flow due to ambient electric fields in a lightning channel whose temperature is at or below 4000 K and still weakly conductive [*Yos*, 1963] at the end of the interstroke interval. The predicted interstroke channel temperature decay [*Uman and Voshall*, 1968] does not explain, however, the observation of current continuing to flow for 1 s to 11 s at the end of a triggered lightning flash, so the source of the observed milliampere current is still not definitively known.

Neither Heckman's arc instability model nor Mazur and Ruhnke's screening effect describe in detail the evolution of the channel during the modeled cutoff process. They both predict a reduction in current but do not specify the shape of that reduction nor how long it might take. Our measurement of current at the base of the lightning channel provides more information that may allow for further refinement of these models.

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References

Aleksandrov, N. L., E. M. Bazelyan, F. D'Alessandro, and Y. P. Raizer (2005a), Dependence of lightning rod efficacy on its geometric dimensions—A computer simulation, *J. Phys. D Appl. Phys.*, *38*(8), 1225–1238, doi:10.1088/0022-3727/38/8/021.

Aleksandrov, N. L., E. M. Bazelyan, and Y. P. Raizer (2005b), The effect of a corona discharge on a lightning attachment, *Plasma Phys. Rep.*, *31*(1), 75–91, doi:10.1134/1.1856709.

Balanis, C. A. (2012), *Advanced Engineering Electromagnetics*, 2nd ed., Wiley, New York.

Berger, K. (1967), Novel observations on lightning discharges: Results of research on Mount San Salvatore, *J. Franklin Inst.*, *283*(6), 478–525, doi:10.1016/0016-0032(67)90598-4.

Brook, M., N. Kitagawa, and E. J. Workman (1962), Quantitative study of strokes and continuing currents in lightning discharges to ground, *J. Geophys. Res.*, *67*(2), 649–659, doi:10.1029/JZ067i002p00649.

Colvin, J. D., C. K. Mitchell, J. R. Greig, D. P. Murphy, R. E. Pechacek, and M. Raleigh (1987), An empirical study of the nuclear explosion-induced lightning seen on IVY-MIKE, *J. Geophys. Res.*, *92*(D5), 5696–5712, doi:10.1029/JD092iD05p05696.

Fisher, R. J., G. H. Schnetzer, R. Thottappillil, V. A. Rakov, M. A. Uman, and J. D. Goldberg (1993), Parameters of triggered-lightning flashes in Florida and Alabama, *J. Geophys. Res.*, *98*(D12), 22,887–22,902, doi:10.1029/93JD02293.

Flache, D., V. A. Rakov, F. Heidler, W. Zischank, and R. Thottappillil (2008), Initial-stage pulses in upward lightning: Leader/return stroke versus M-component mode of charge transfer to ground, *Geophys. Res. Lett.*, *35*, L13812, doi:10.1029/2008GL034148.

Heckman, S. (1992), Why does a lightning flash have multiple strokes?, PhD dissertation, Mass. Inst. of Technol., Cambridge.

King, L. A. (1961), The voltage gradient of the free burning arc in air or nitrogen, Proc. of the Fifth International Conf. on Ionization Phenomena in Gases, *2*, 871–877.

Krehbiel, P. R. (1981), An analysis of the electric field change produced by lightning, PhD dissertation, New Mexico Inst. Of Mining and Technol., Socorro.

Krehbiel, P. R., M. Brook, and R. A. McCrory (1979), An analysis of the charge structure of lightning discharges to ground, *J. Geophys. Res.*, *84*(C5), 2432–2456, doi:10.1029/JC084iC05p02432.

Latham, D. J. (1980), A channel model for long arcs in air, *Phys. Fluids*, *23*(8), 1710–1715, doi:10.1063/1.863190.

Loeb, L. B. (1966), The mechanisms of stepped and dart leaders in cloud-to-ground lightning strokes, *J. Geophys. Res.*, *71*(20), 4711–4721, doi:10.1029/JZ071i020p04711.

Maslowski, G., and V. A. Rakov (2009), New insights into lightning return-stroke models with specified longitudinal current distribution, *IEEE Trans. Electromagn. Compat.*, *51*(3), 471–478, doi:10.1109/TEMC.2009.2017200.

Mata, C. T., M. I. Fernandez, V. A. Rakov, and M. A. Uman (2000), EMTP modeling of a triggered-lightning strike to the phase conductor of an overhead distribution line, *IEEE Trans. Power Delivery*, *15*(4), 1175–1181, doi:10.1109/61.891499.

Mazur, V., and L. H. Ruhnke (1993), Common physical processes in natural and artificially triggered lightning, *J. Geophys. Res.*, *98*(D7), 12,913–12,930, doi:10.1029/93JD00626.

Mazur, V., and L. H. Ruhnke (2014), The physical processes of current cutoff in lightning leaders, *J. Geophys. Res. Atmos.*, *119*, 2796–2810, doi:10.1002/2013JD020494.

McCann, G. D. (1944), The measurement of lightning currents in direct strokes, *Electr. Eng.*, *63*(12), 1157–1164, doi:10.1109/EE.1944.6440663.

McEachron, K. B. (1940), Wave shapes of successive lightning current peaks, *Electr. World*, *113*(6), 428–431.

Michaels, K (2007), Connection to Earth, in *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE Std 142-2007*, 161 pp., Institute of Electrical and Electronics Engineers, Inc., New York, doi:10.1109/IEEESTD.2007.4396963.

Miki, M., V. A. Rakov, K. J. Rambo, G. H. Schnetzer, and M. A. Uman (2002), Electric fields near triggered lightning channels measured with Pockels sensors, *J. Geophys. Res.*, *107*(D16), 4277, doi:10.1029/2001JD001087.

Miki, M., V. A. Rakov, T. Shindo, G. Diendorfer, M. Mair, F. Heidler, W. Zischank, M. A. Uman, R. Thottappillil, and D. Wang (2005), Initial stage in lightning initiated from tall objects and in rocket-triggered lightning, *J. Geophys. Res.*, *110*, D02109, doi:10.1029/2003JD004474.

Ngin, T., M. A. Uman, J. D. Hill, J. Pilkey, W. R. Gamerota, D. M. Jordan, and R. C. Olsen III (2013), Measurement and analysis of ground-level electric fields and wire-base current during the rocket-and-wire lightning triggering process, *J. Geophys. Res. Atmos.*, *118*, 10,041–10,055, doi:10.1002/jgrd.50774.

Picone, J. M., J. P. Boris, J. R. Greig, M. Raleigh, and R. F. Fernsler (1981), Convective cooling of lightning channels, *J. Atmos. Sci.*, *38*, 2056–2062, doi:10.1175/1520-0469(1981)038<2056:CCOLC>2.0.CO;2.

Pilkey, J. T., et al. (2013), Rocket-and-wire triggered lightning in 2012 tropical storm Debby in the absence of natural lightning, *J. Geophys. Res. Atmos.*, *118*, 13,158–13,174, doi:10.1002/2013JD020501.

Rakov, V. A. (2013), The physics of lightning, *Surv. Geophys.*, *34*(6), 701–729, doi:10.1007/s10712-013-9230-6.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge Univ. Press, New York.

Rakov, V. A., D. E. Crawford, K. J. Rambo, G. H. Schnetzer, M. A. Uman, and R. Thottappillil (2001), M-component mode of charge transfer to ground in lightning discharges, *J. Geophys. Res.*, *106*(D19), 22,817–22,831, doi:10.1029/2000JD000243.

Shindo, T., and M. A. Uman (1989), Continuing current in negative cloud-to-ground lightning, *J. Geophys. Res.*, *94*(D4), 5189–5198, doi:10.1029/JD094iD04p05189.

Uman, M. A., and R. E. Voshall (1968), Time interval between lightning strokes and the initiation of dart leaders, *J. Geophys. Res.*, *73*(2), 497–506, doi:10.1029/JB073i002p00497.

Williams, E. (2006), Problems in lightning physics - the role of polarity asymmetry, *Plasma Sources Sci. Technol.*, *15*, S91–S108, doi:10.1088/0963-0252/15/2/S12.

Williams, E., and S. Heckman (2012), Polarity asymmetry in lightning leaders: The evolution of ideas on lightning behavior from strikes to aircraft, *J. Aerospace Lab*, *5*, 28–33.

Winn, W. P., E. M. Eastvedt, J. J. Trueblood, K. B. Eack, H. E. Edens, G. D. Aulich, S. J. Hunyady, and W. C. Murray (2012), Luminous pulses during triggered lightning, *J. Geophys. Res.*, *117*, D10204, doi:10.1029/2011JD017105.

Yos, J. M. (1963), Transport properties of nitrogen, hydrogen, oxygen and air to 30000 K, Technical Memorandum RAD-TM-63-7, Research and Advanced Development Division AVCO Corporation, Wilmington, Mass.