Comparison of sprite initiation altitudes between observations and models

W. R. Gamerota,[1,2] S. A. Cummer,[1] J. Li,[1] H. C. Stenbaek-Nielsen,[3] R. K. Haaland,[4] and M. G. McHarg[5]

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[1] Simultaneous analyses of measured sprite initiation altitudes with predicted initiation altitudes from simulations enable an examination of our understanding of the sprite initiation mechanism and the modeling techniques to simulate this mesospheric electrical phenomenon. In this work, we selected a subset of sprites optically observed from Langmuir Laboratory, NM; locations near Las Vegas, NM, in 2007 and near Portales, NM, in 2008; and a Duke University field station. The sprites were observed by high-speed imaging with time resolutions of at least 1 ms and by low light level imagers. Sprite initiation altitudes were determined by triangulation between Langmuir Laboratory and either Portales or Las Vegas, while star field analysis determined the approximate measured initiation altitudes for Duke observations. These video observations were coordinated with electromagnetic field measurements from Yucca Ridge Field Station and Duke University, respectively. With a 2-D finite difference time domain model, we simulated the lightning-driven electric fields and predict the likely altitude of sprite initiation and compare these findings with the measured initiation altitude of each sprite analyzed. Of 20 discrete sprite events analyzed, both the measured and the simulation-predicted initiation altitudes indicate that long-delayed sprites tend to initiate at lower altitude. The average discrepancy between the measurements and the simulation results is 0.35 km with a standard deviation of 3.6 km. This consistency not only confirms previous results about the relationship between sprite initiation altitude and time delay but also helps to develop confidence in the models to reveal the sprite physics.

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1. Introduction

[2] Sprites are high-altitude optical emissions produced by a subset of cloud-to-ground (CG) lightning discharges. Most sprites occur between 40 and 90 km above thunderstorms as a result of conventional electric breakdown in the upper atmosphere [*Sentman et al.*, 1995; *Lyons*, 1996; *Pasko et al.*, 1997, 1998]. Since they were first documented in 1989 [*Franz et al.*, 1990], sprites have been regularly photographed and videoed by observers around the world [*Stanley et al.*, 1999; *Cummer et al.*, 2006; *McHarg et al.*, 2007; *Su et al.*, 2002]. Sprite analysis has advanced to the point where we may now estimate the lightning-driven electric field at a particular location above a thundercloud for a specific time by combining measurements of lightning-radiated electromagnetic fields and numerical models. *Hu et al.* [2007] reported the electric fields required to initiate short-delayed sprites, which initiate within several ms after their parent lightning discharge. They reported lightning-driven background electric fields of about 0.2 E_k, 0.3–0.5 E_k and above 0.5 E_k to initiate dim, typical and bright sprites, respectively, where E_k is the local air breakdown field. These electric fields are driven by the lightning return stroke and subsequent continuing current. *Li et al.* [2008] have reported that the electric fields required to initiate long-delayed sprites, which initiate a few tens to hundreds ms after their parent discharge, are comparable to those for short-delayed sprites. However, the fields for long-delayed sprite initiation are primarily driven by the continuing current and depend more strongly on the nonlinear processes of heating and ionization. All these results are essentially consistent with the conventional air breakdown model

[1]Electrical and Computer Engineering Department, Pratt School of Engineering, Duke University, Durham, North Carolina, USA.
[2]Now at Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA.
[3]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[4]Department of Physics and Engineering, Fort Lewis College, Durango, Colorado, USA.
[5]Department of Physics, United States Air Force Academy, Colorado Springs, Colorado, USA.

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[*Pasko et al.*, 1997]. It should be mentioned that the fields reported above are the lightning-driven background fields at sprite locations by assuming a smooth ionosphere profile. Inhomogeneities, like irregularities and ionization patches, are not included. These inhomogeneities, which are required to initiate streamers, will enhance the local fields [*Ebert et al.*, 2006]. Thus the lightning-driven background fields are expected to be less than E_k, although a local electric field has to exceed E_k to initiate an air breakdown. Additionally, *Li et al.* [2008] also reported that the initiation altitudes of long-delayed sprites should be lower compared with short-delayed sprites. *Stenbaek-Nielsen et al.* [2010] accurately measured the sprite initiation altitudes with triangulation.

[3] Measuring sprite initiation altitudes is an effective way to test the above initiation mechanisms and to confirm previous studies. Initial sprite video observations involved charge-coupled device (CCD) sensors in digital cameras. This method was useful for determining the altitude range and color of sprites, but not for determining finer sprite structures [*Sentman et al.*, 1995; *Wescott et al.*, 1998]. *Stanley et al.* [1999] first demonstrated the value of using high-speed video to confirm the accuracy of sprite modeling, specifically for sprite streamers measured with 1 ms time resolution. This technique is then widely applied to measure the sprite dynamics including the initiation altitude and propagation properties [*Cummer et al.*, 2006; *McHarg et al.*, 2007; *Li and Cummer*, 2009; *Stenbaek-Nielsen and McHarg*, 2008; *Stenbaek-Nielsen et al.*, 2010].

[4] The goal of this work is to test our understanding of the physics behind sprite initiation. We test our model for inferring electric fields above a thunderstorm and our understanding of the physics of sprite initiation. Specifically, we compare the measured altitude from two data sets with the predicted simulation altitude from our own data analysis to confirm results reported by *Li et al.* [2008] and *Stenbaek-Nielsen et al.* [2010]. We report and analyze in detail two sets of sprite events for which we have both high-speed optical and electromagnetic radiation observations. One set is from 23 June 2007 and 3 July 2008 with video observations from Langmuir Laboratory, NM; Las Vegas, NM (2007 data); and Portales, NM (2008 data), and electromagnetic radiation measurements from Yucca Ridge Field Station near Fort Collins, Colorado. The other set is from 3 June 2009 with both optical and electromagnetic observations from Duke University. For each sprite sequence detected, we first extract the lightning source current moment waveform from remote measured lightning-radiated magnetic fields [*Cummer and Inan*, 1997, 2000; *Cummer*, 2003]. We then compute the electric fields above the lightning discharge using a finite difference time domain (FDTD) model [*Hu and Cummer*, 2006]. At the time of sprite initiation, we compare the measured initiation altitudes from high-speed images with the simulation-predicted altitudes. For 15 discrete sprite events captured at Langmuir Laboratory, NM, and 5 events captured at Duke University, NC, the simulation-predicted initiation altitudes agree well with the measured initiation altitudes with an average difference of 0.35 km and a standard deviation of 3.6 km. At the time and location of sprite initiation, the local electric fields vary from 0.13 E_k to 0.51 E_k, completely falling into the field range reported in previous studies. Additionally, both measurements and simulation predictions indicate that long-delayed sprites tend to initiate at a lower altitude comparing with short-delayed sprites. All these results further confirm the conventional air breakdown model and the initiation mechanism for both short-delayed and long-delayed sprites.

2. Instrumentation and Method of Analysis

[5] In this work, our data set combines simultaneous measurements of high-speed sprite optical emissions and broadband lightning-radiated electromagnetic fields. The reported sprite events were recorded in the southwest United States and at Duke University. Optical observations in the southwest United States were made from Langmuir Laboratory, NM (33.975°N, −107.181°E), from Las Vegas, NM (35.555°N, −105.080°E) and from Portales, NM (34.121°N, −103.196°E). At all three sites the Watec 902H2 video cameras were used with GPS timing to facilitate triangulation of sprite location and altitude. The cameras had a field of view of 31 × 23° in 2007 and 21 × 16° in 2008 due to different lenses applied. The site at Las Vegas, NM, was overcast during the events presented from 2008. High-speed video observations were made from Langmuir using two intensified Phantom-7 cameras with GPS timing. The frame rates used varied from 10,000 to 16,000 frames per second (fps). For the events presented here the image exposure time was gated to 50 microseconds (corresponding to 20,000 fps continuous recording). The intensifier on the Phantom camera has a P-24 phosphor with a decay time constant of a few nanoseconds so there is no persistence between successive images. Details about the data and triangulation procedures are given by *Stenbaek-Nielsen et al.* [2010].

[6] At the Duke site, two cameras were used to record the optical emissions from sprite events on 3 June 2009. First, a Watec 902H2 Ultimate monochrome low light level camera capable of imaging near infrared visibility was used to capture a field of view (50° wide) that included background stars and the horizon with an image size of 720 × 480 pixels. The high-speed camera was a Vision Research Phantom 4.2 high-speed imager coupled to an ITT Gen III image intensifier with spectral response from 450 to 900 nm. The phosphor persistence of this intensifier was measured to have a half-life of 0.35–0.70 ms, depending on the source brightness [*Cummer et al.*, 2006]. For the five events captured on the Phantom, images were captured at 500, 1000, and 2000 frames per second with a constant image size of 512 × 512 pixels and field of view 7.16° wide. An external GPS-synchronized IRIGB time code computes an integration time and the camera stamps this time onto each image with a time accuracy of 10 microseconds.

[7] From the high-speed images recorded, the initiation of sprites was defined by the first visible light in downward streamers, which initiate first after the parent lightning discharge [*Stanley et al.*, 1999; *Cummer et al.*, 2006; *McHarg et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008]. For the sprites detected over the southwest United States, the initiation altitude was determined by triangulation between observations from multiple stations. For the sprites detected at the Duke site, we determine sprite altitudes by applying the star field analysis. The elevation angle of sprites can be interpolated from the locations of the known stars appearing

on the images. Sprite altitudes can be estimated by knowing their elevation angle and the distance to the observation site. Due to the single station measurement, we made the assumption that each sprite was directly above their parent lightning discharge recognizing that the unknown horizontal offset between sprites and their parent lightning, typically a few tens of km [*Wescott et al.*, 2001], can introduce some uncertainties in the altitude estimation. For the sprites recorded at the Duke site the lightning strikes were about 350 km away, and an offset of ±10 km would correspond to an altitude uncertainty of ±3 km [*Haaland et al.*, 2008; *Li and Cummer*, 2009].

[8] The broadband low-frequency electromagnetic radiation data were collected from two sites: Yucca Ridge Field Station and Duke University. At Yucca Ridge Field Station (40.702°N, −105.031°E), one pair of magnetic field sensors, built by Quasar Federal Systems, Inc., measured the vector horizontal magnetic fields in geographic north and east directions. The frequency range covers from a few Hz up to 25 kHz. At the Duke University field site (35.864°N, −79.101°E), two pairs of magnetic induction coils record the horizontal magnetic fields in the ULF range (0.1–500 Hz, built by EMI, Inc.) and VLF range (100 Hz–25 kHz, custom designed). More details of these sensing systems are given by *Cummer et al.* [2006] and *Li et al.* [2008]. Additionally, the National Lightning Detection Network (NLDN) provides locations of the sprite-producing lightning discharges. The vector magnetic fields and the known location allow us to determine the azimuthal magnetic field defined by a cylindrical coordinate system with the origin at the location of the lightning discharge.

[9] As mentioned in the introduction, we extract the lightning source current moment waveform from the azimuth magnetic field using a deconvolution technique described by *Cummer and Inan* [1997, 2000] and *Cummer* [2003]. With this current moment waveform, we are able to estimate the electric fields above a source lightning discharge as a function of time and altitude with a 2-D FDTD model [*Hu and Cummer*, 2006]. The nonlinear processes, like heating and ionization, have been included in this model [*Pasko et al.*, 1997]. In this work, the simulation domain was set to 100 km (radial direction) × 100 km (vertical direction) in a 2-D cylindrical coordinate. Another 40 km and 80 km thick perfect matched layers were set on top and at the outer surface of the computation domain to adequately absorb the radiated EM waves. The grid size has been chosen as 1000 or 500 m, which have been confirmed to provide reliable results with a convergence test. The model takes the lightning current moment waveform as the input and is capable to compute the true electric as a function of time at every grid location in the computation domain. In this work, we are interested in the locations directly above the lightning discharge. We then normalize the electric fields at these locations against the air-breakdown field at different altitudes (E/E_k). At a given sprite delay time, the downward streamer should appear first at the location of the maximum normalized electric field. This location is referred to as the simulation-predicted altitudes in the following text. In this work, one of the main tasks is to compare the measured altitudes and the simulation predictions, which can reveal the accuracy of the modeling technique and the physics behind the initiation of sprites.

3. Results

3.1. Triangulated Events

[10] We began with 30 discrete sprite events observed over the southwestern United States on 23 June 2007 and 3 July 2008 for which we had observations from three sites in New Mexico, Langmuir, Las Vegas (2007 data), and Portales (2008 data). Of these 30 events, 21 had a clearly identifiable onset for which the onset altitude could be determined by triangulation. Of these 21 events, we had the necessary low-frequency data for 18. These 18 discrete sprite events are found in 7 sprite sequences, which may contain a single or multiple sprites at different time delays after their parent lightning discharge. Sprite current, which is the current flow in the body of a sprite [*Cummer et al.*, 1998], was detected in 3 out of 18 events. In our magnetic field measurements, the radiation of the sprite current is superposed on the lightning-radiated magnetic fields. To avoid the interference caused by the sprite current, we ignored three discrete sprite events occurred after sprite current. For one event occurring on 23 June 2007 we were able to successfully use Duke ULF data for the analysis, and for events on 3 July 2008 we used ELF data from Yucca Ridge Field Station because the Duke data were missing. With the results from the FDTD simulation, plots were then developed that illustrate the measured triangulated altitudes and the predicted altitudes.

[11] The time delay between the parent lightning discharge and sprite initiation is determined by simultaneous measurements of lightning-radiated magnetic fields and sprite optical emissions. A correction to the time delay was made to account for the different propagation time to the location of optical measurements and the location of the field observations. With high-speed images and broadband magnetic field measurements, the accuracy of this time delay is in the order of submillisecond.

[12] Figure 1 illustrates measurements for the single event on 23 June 2007 occurring at 0510:10.601 UT initiated by a positive lightning cloud-to-ground stroke. Figure 1a shows the azimuthal (tangential) magnetic field measured by the Duke ULF system. The time is labeled from the lightning return stroke. Figure 1b shows the extracted lightning source current moment waveform and total charge moment change. The sprite initiated 2.5 ms after the lightning return stroke. At this time, the total charge moment change is 352 C km. According to *Hu et al.* [2002], this charge moment change is large enough to initiate typical short-delayed sprites. We then use the extracted current moment waveform as an input to the aforementioned 2-D FDTD model. Figure 1c shows the vertical normalized electric fields above the lightning discharge as a function of time and altitude between 65 and 90 km. The color intensity represents the amplitude of the normalized electric fields. The measured sprite initiation altitude is represented by the red dot, which is at 80 km altitude and 2.5 ms after the lightning return stroke. The predicted sprite initiation altitude, which is defined to be the altitude of the maximum normalized electric field, is 79 km

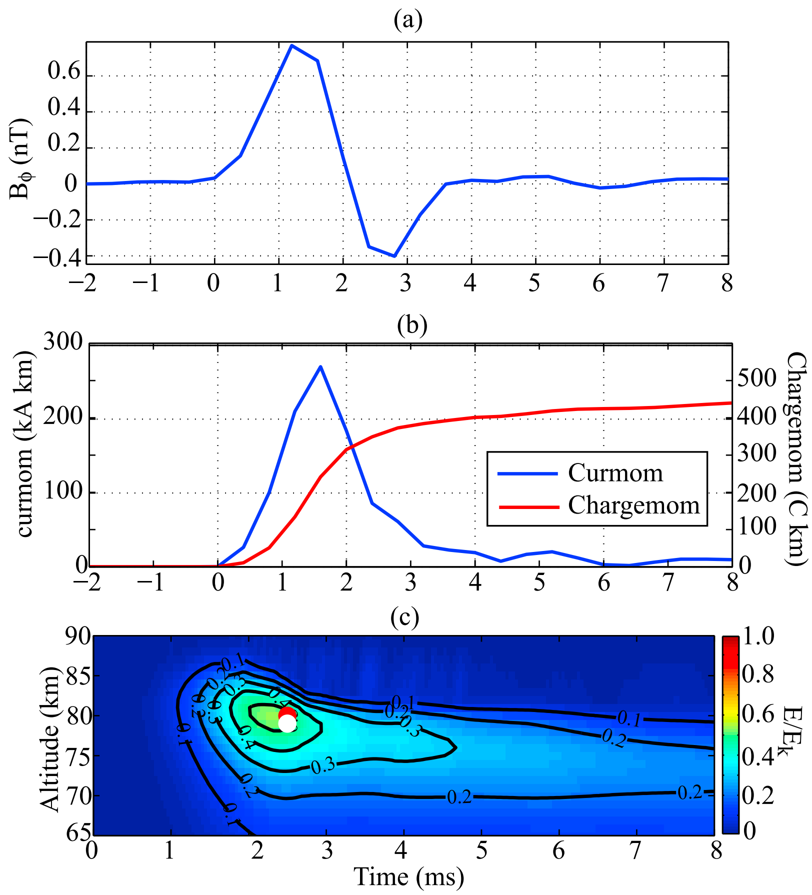

Figure 1. Simulated electric fields for a sprite event detected on 23 June 2007, 0510:10 UT. (a) The azimuthal magnetic field at Duke University. (b) The extracted current moment waveform and total charge moment waveform for the event. (c) Time-space plot of simulated normalized electric fields directly above the lightning discharge. At the time of sprite initiation (2.5 ms), the measured initiation altitude (80 km) and simulation-predicted initiation altitude (79 km) are represented by the red and white dots, respectively.

altitude at 2.5 ms and plotted as a white dot. In Figures 2–5, red dots are used for the measured sprite initiation altitude and white dots are used for the simulation-predicted initiation altitudes. For this event, the simulation-predicted initiation altitude agrees very well with the measured value. The predicted maximum normalized electric field (2.5 ms, 79 km) is 0.51, which is also in good agreement with the reported electric fields for typical short-delayed sprites [*Hu et al.*, 2007].

[13] In addition to a short-delayed sprite, we also compare the initiation altitudes for sprite sequences containing multiple sprite elements initiated at different time delays produced by a single lightning discharge. Previous studies have revealed that the initiation mechanism of long-delayed sprites is more complicated than that of short-delayed sprites. Intense continuing current, rather than the lightning return stroke [*Cummer and Füllekrug*, 2001; *Li et al.*, 2008], is the primary driver for those long-delayed sprites. The increase of continuing current (slow intensification [*Li et al.*, 2008] or lightning M component [*Rakov et al.*, 1995]) can significantly increase the chance of delayed sprite initiation due to the nonlinear processes of heating and ionization [*Asano et al.*, 2009]. Figure 2 shows a sprite sequence containing 3 single sprite elements initiated at 35.3, 66.4 and 66.5 ms after the lightning return stroke. Figure 2a shows the extracted current moment waveform and the total charge moment change history derived from the lightning-radiated magnetic fields. Figure 2b shows the normalized electric fields above the lightning discharge as a function of time and altitudes from numerical simulations. Figure 2c shows the high-speed images recorded at 16,000 fps. The images on the left show the development of the first downward streamer. The images on the right show the entire sprite elements at the stage of maximum brightness. In this event, the total charge moment change provided by the lightning return stroke is 190 C km and created a high field region with a normalized field 0.3 within a few ms after the lightning discharge and at the altitude close to 80 km. According to previous studies [*Hu et al.*, 2007; *Li et al.*, 2008], this total charge moment change and the field quantity may or may not initiate a sprite immediately. After the lightning return stroke, the continuing current is about 20 kA km. From ~20 ms to ~40 ms, this continuing current increases to 40 kA km, signifying the slow intensification. At 35.3 ms, the first sprite element initiated following this slow intensification and appeared at the leading edge of the

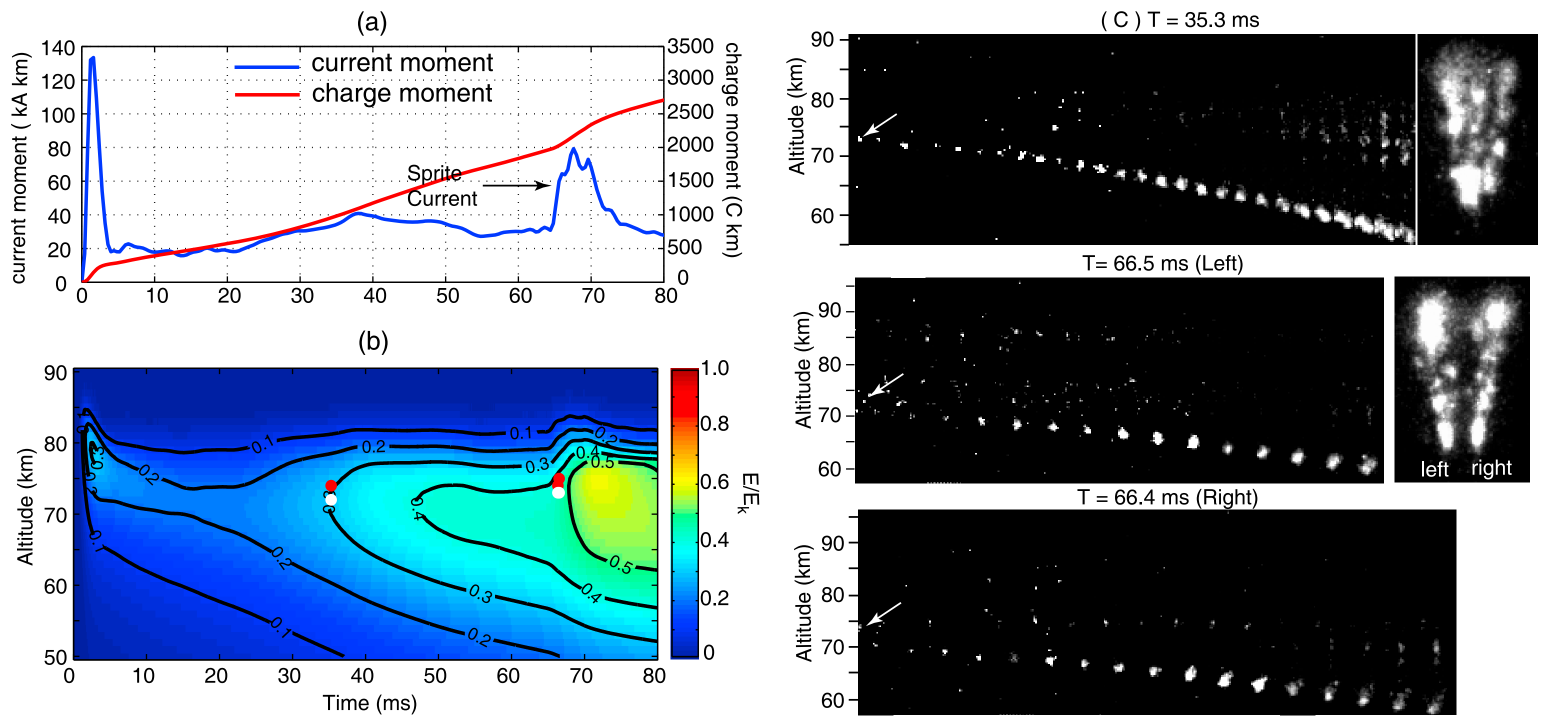

Figure 2. Example of a sprite sequence detected on 3 July 2008, 0737:31 UT. (a) Extracted lightning source current moment waveform. (b) Inferred electric fields above the lightning discharge. The measured and the simulation-predicted sprite initiation altitudes are represented by the red and white dots, respectively. (c) High-speed images recorded at 16,000 fps. The images on the left show the initiation and development of the first downward streamer. The images on the right show the sprite elements at their maximum brightness.

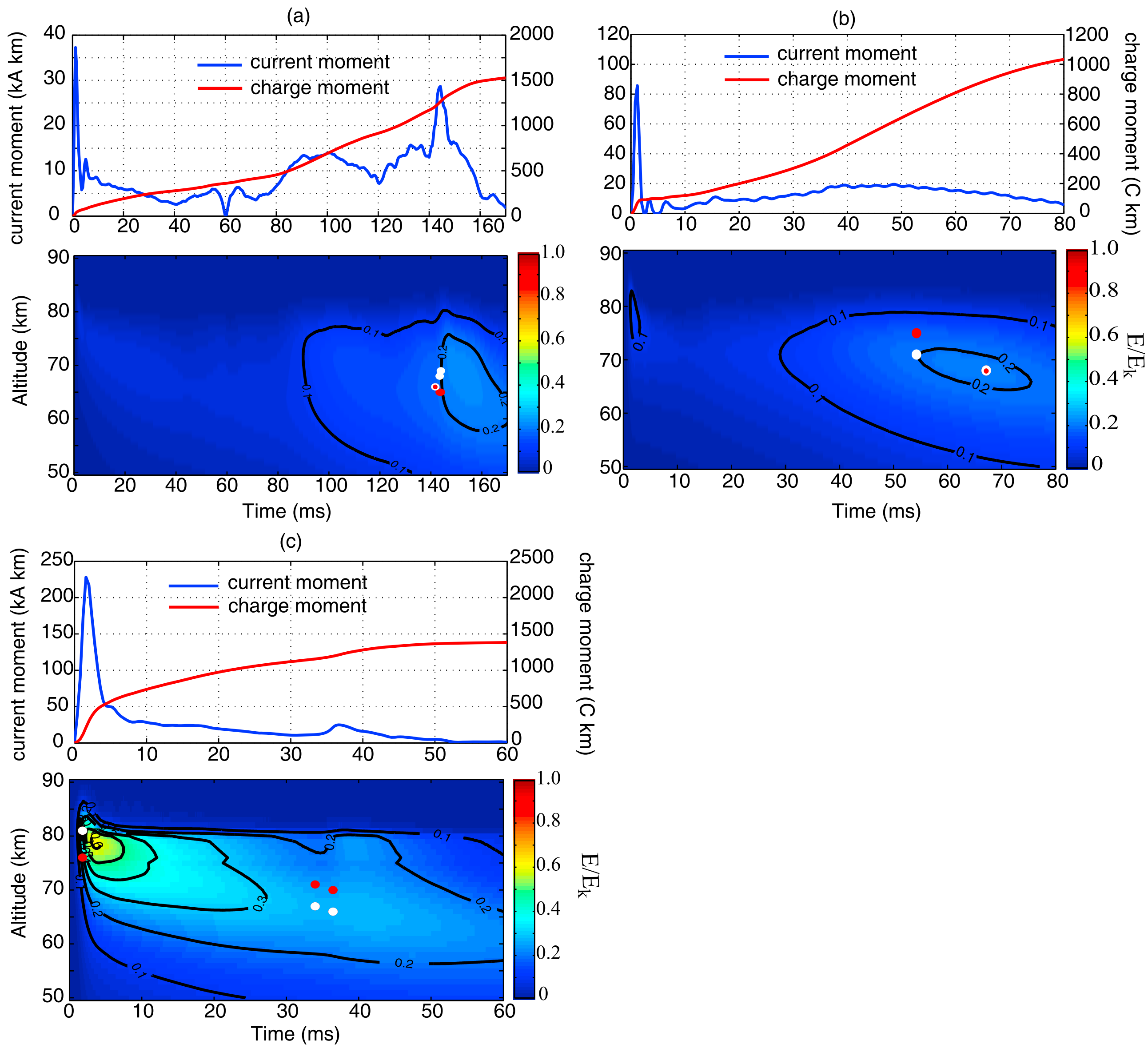

Figure 3. Extracted lightning source current moment waveform and simulated electric fields above the lightning discharge for sprite events on 3 July 2008. (a) Sprite event detected at 0728:26 UT. (b) Sprite event at 0855:11 UT. (c) Sprite event at 0722:04 UT. For each event, at the top are shown the lightning source current moment waveform and the total charge moment change history. At the bottom are shown the simulated electric fields above the lightning discharge. The measured and the simulation-predicted sprite initiation altitudes are represented by the red and white dots, respectively.

second high field island in the space-time plot. The measured initiation altitude is 74 km. In the space-time plot, the maximum normalized field appeared at 72 km with field value of 0.3 E_k. After that, the electric fields continue to increase due to the intense continuing current. Another two sprite elements occurred at around 66 ms. They both initiated at 74 km altitude but at slightly different times. At the time of sprite initiation, the maximum normalized electric field appears at 73 km with 0.45 E_k, which is consistent with results reported by *Li et al.* [2008] for typical long delayed sprites. During the development of the two sprite elements, a sprite current has been detected in the extracted current moment waveform. At the stage of full development, the brightness of these two elements is comparable to that of the first element. The triangulated centers of these two elements are 21.9 km (left) and 22.8 km (right) away from the center of the first element. Thus there might be some overlapping between these sprites. Comparing with the field of 0.3 E_k to initiate the first sprite element, the electric field to initiate the two later elements is 50% higher. Thus the detected sprite current after 66 ms might be associated with this higher initiation field. In this example, the field quantity for sprite initiation and the role of slow intensification agree well with the long-delayed sprite process described by *Li et al.* [2008].

[14] Figure 3 shows the measured and predicted initiation altitudes for sprite elements in other three sprite sequences. For each sprite sequence, the top panel shows the extracted

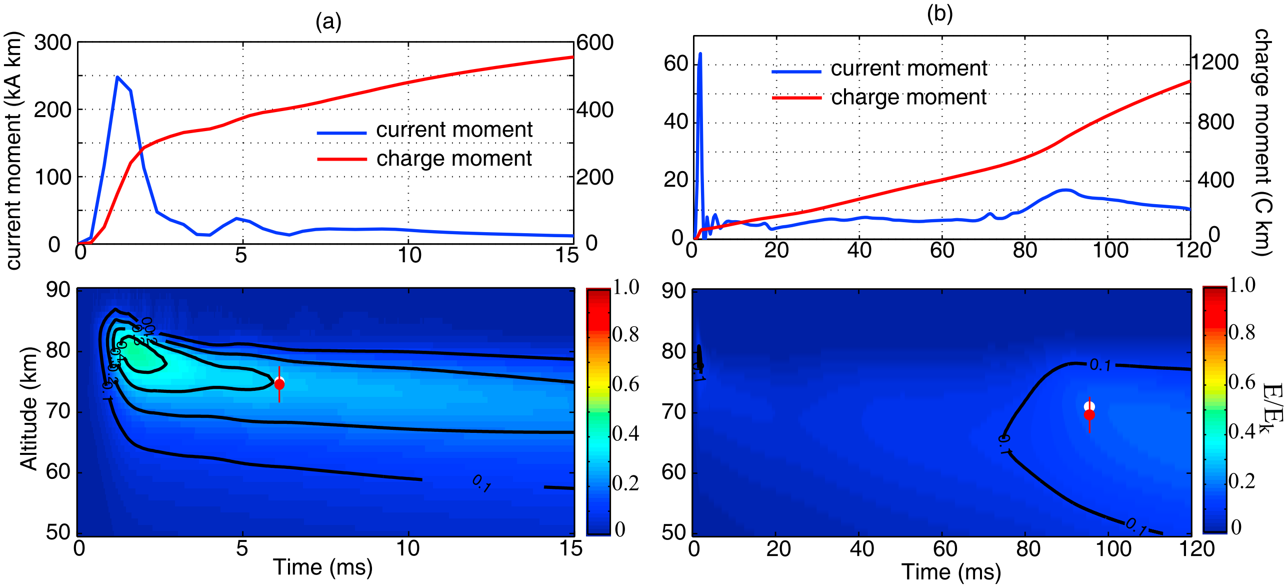

Figure 4. FDTD results for three events recorded on 3 June 2009 (a) at 0404:51 UT and (b) at 0339:58 UT.

current moment waveform and the total charge moment change history derived from the lightning-radiated magnetic fields. The bottom panel shows the normalized electric fields above the lightning discharge. In Figure 3a, three sprite elements occurred at 141.80, 143.48 and 143.96 ms following the lightning return stroke. In this event, the electric field caused by the lightning return stroke is small (0.08 E_k) due to a small charge moment change of 60 C km, which is not big enough to initiate a sprite. After the return stroke, the continuing current gradually decays from 10 kA km to 5 kA km. During this period, the normalized electric field decreases. From 70 ms to about 100 ms, the continuing current slowly increases by a factor of two and the electric field increases as the continuing current. From 120 ms to about 140 ms, the continuing current further increases from ~7.5 kA km to ~15 kA km, which is the slow intensification. The sprite initiated immediately following this slow intensification and appeared at the leading edge of the high field island in the space-time plot. A second peak in the current moment waveform after the sprite initiation could be a sprite current. At the time of sprite initiation, the maximum normalized electric fields increase to ~0.2 for each sprite element in the plot. This value lies in the range empirically observed [*Hu et al.*, 2007; *Li et al.*, 2008] to initiate dim sprites. The result of this event further confirms the roles of continuing current in long-delayed sprite initiation. The corresponding measured and simulation-predicted initiation altitudes of these sprites are 66 and 66 km, 65 and 68 km, and 65 and 69 km. Although these discrepancies are greater than that for the short-delayed sprite explained in Figure 1, there are now more complicated processes like heating and ionization involved [*Pasko et al.*, 1997]. Thus, the measured and predicted values are still in good agreement.

[15] Figure 3b shows the results for two distinct sprite elements that occurred more than 50 ms following a different parent lightning discharge. In the plot of the normalized electric field, two space-time regions of high field are observed. The first one at ~2 ms is caused by the lightning return stroke. Again, a 120 C km charge moment change provided by the return stroke is not big enough to initiate a sprite immediately. The continuing current increases at 30 ms and to its maximum value of 20 kA km at about 40 ms. At the same time, the normalized electric fields increase to form a second high field region and reach the maximum value after 50 ms. Similar to the long delayed sprites shown in Figures 2 and 3a, the sprite again appeared at the leading edge of the high field island. This event clearly shows that the normalized electric field in the second region is greater than the first one, and thus long-delayed sprites are more likely to occur. The corresponding measured and predicted altitudes are 75 and 71 km, and 68 and 68 km. The maximum normalized electric fields are close to 0.2.

[16] A more complicated sprite sequence is shown in Figure 3c, which includes both short-delayed and long-delayed sprites. In this event, the lightning return stroke provides about 500 C km charge moment change, which is enough to produce a short-delayed sprite. Thus the first sprite initiates at about 2 ms after the return stroke. The measured and simulation-predicted altitudes agree within 3 km for this sprite element. After the return stroke, the electric fields decrease due to the decrease of the continuing current. Two sprite elements occurred around 35 ms after the return stroke. Different from the long-delayed events shown above, we did not observe an increase of the continuing current before the initiation of these long-delayed sprites. However, the measured and predicted altitudes still agree within 4 km and the normalized electric field (~0.27) is within the range to initiate dim to typical sprites. For the sprite events in Figure 3c, both the measured and simulation-predicted altitudes clearly show that the initiation altitude of the short-delayed sprite is higher than the following long-delayed sprites. This is consistent with the results reported by *Li et al.* [2008].

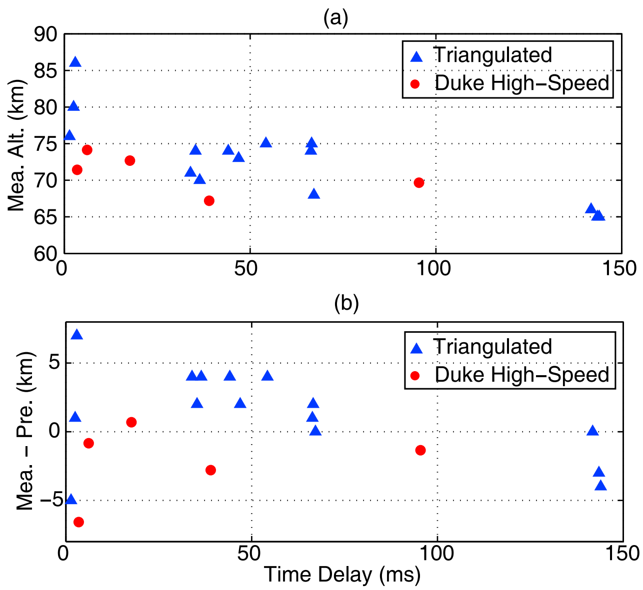

Figure 5. Data results from triangulated and Duke high-speed events. (a) Measured altitudes of all events analyzed. (b) The discrepancy between measured and predicted initiation altitudes.

[17] For the 5 sprite sequences shown in Figure 1, Figure 2 and Figure 3, although the lightning return stroke amplitude, the continuing current level and the time delay of sprite initiation are all different, the measured and simulation-predicted altitudes agree well in general. This indicates that our model truly reflects the mechanism and the electric fields to initiate both short-delayed and long-delayed sprites. The measured altitudes for all triangulated events as well as the differences comparing with simulation predictions will be shown in Figure 5 following the discussion of the Duke high-speed observations.

3.2. Events From Duke High-Speed Video

[18] On 3 June 2009, the high-speed camera at Duke captured five sprites produced by thunderstorms between 300 and 400 km away from our observation site. Although these events were captured at different locations with different systems when compared with the triangulated events, the mechanisms are very similar. Figure 4 shows the same quantities as Figure 3 for one short-delayed and one long-delayed sprite detected at the Duke station. In addition to markers indicating initiation altitudes, there is a vertical bar centered on the measured altitude indicating an uncertainty of ±3 km, as mentioned in section 2.

[19] Figure 4a shows the simulation result for a sprite that occurred 340 km from Duke. The sprite initiated 6.1 ms after the return stroke at 74.6 ± 3 km altitude estimated from high-speed images while the simulation altitude is predicted at 75 km. To the time of sprite initiation, the total charge moment change provided by the lightning discharge is about 400 C km, which is capable to initiate short-delayed sprite. The maximum normalized electric field is about 0.3.

[20] Figure 4b shows the simulation result for a long-delayed sprite that occurred 95.5 ms after the lightning return stroke. Similar to the long-delayed event in Figure 2a, the lightning return stroke provided a total charge moment change less than 100 C km, which is not enough to initiate a sprite immediately. After the lightning return stroke, the continuing current is about 7 kA km to 75 ms. From 75 ms to the time of sprite initiation, the continuing current gradually increases by a factor of two, which is the slow intensification. Accordingly, the electric field increases during this period. At the time of sprite initiation, the measured and simulation-predicted altitudes are 69.7 ± 3 km and 71 km. The maximum normalized electric field at sprite time and location is 0.17.

[21] For four of the five events observed at Duke University, the simulation-predicted altitudes agree very well with the estimated initiation altitudes within 3 km. One event had the maximum discrepancy of 7 km. This sprite initiated 3.5 ms after the parent lightning discharge. The measured and predicted altitudes are 71 km and 78 km, respectively. The 71 km initiation altitude seems low for a short delayed sprite and could be underestimated due to a large offset between the lightning discharge and the sprite.

3.3. Summary of Measurements

[22] We next summarize all the 20 discrete sprite events in cumulative plots shown in Figure 5. Figure 5a illustrates the measured altitudes for each event. Analysis of the plot reveals that shorter delayed sprites generally initiate at greater altitudes than sprites with a larger time delay, which is what we expect from *Li et al.* [2008] and surmised by *Stenbaek-Nielsen et al.* [2010]. Figure 5b illustrates the discrepancy, which is defined by the difference between the measured and the simulation-predicted altitude. It seems that the predictions are lower for the sprites with ~30–50 ms delay and higher for those with more than 100 ms delay. However, most of the discrepancies of these events are below 4 km. Considering the noise in the magnetic field measurements and therefore in the extracted lightning current source, the agreement is still in reasonable range. For all the 20 discrete sprite events, the average discrepancy is 0.35 km with a standard deviation of 3.6 km. The mean value of the absolute discrepancy is 2.76 km. Despite different time delays, lightning return stroke amplitudes, and continuing current levels, the predicted altitudes agree well with the measurements. This indicates that the predictions by combining lightning measurements and numerical simulations truly reflect sprite initiation mechanism. Furthermore, the normalized electric field at sprite initiation varies from 0.13 to 0.51, which is consistent with the electric fields reported by *Hu et al.* [2007] and *Li et al.* [2008].

4. Summary

[23] In this work, we combined high-speed measurements of sprite optical emissions and the lightning-radiated magnetic fields. Combining these measurements with numerical simulations enable us to infer the lightning-driven electric fields at sprite initiation locations. We reported and analyzed in detail two sets of 15 sprite events detected in the southwest United States and 5 events detected at Duke University. The time delay of these events varies from a few ms to more than 100 ms. We then compared the measured sprite initiation altitudes with predictions by combining lightning magnetic field measurements and numerical simulations. Independent of time delays, lightning return stroke

amplitudes, and continuing current levels, the observed and predicted values agree well with an average discrepancy of 0.35 km and a standard deviation of 3.6 km. The mean value of the absolute discrepancy is 2.76 km. The normalized electric fields at the time and location of sprite initiation vary from 0.13 to 0.51, which are consistent with previous results reported by *Hu et al.* [2007] and *Li et al.* [2008] for short-delayed and long-delayed sprites, respectively. For sprites initiated more than several tens of ms from the lightning return stroke, an increase of the continuing current is often detected proceeding the sprite initiation. Due to the nonlinear heating and ionization effects, these slow intensifications (or lightning M components) significantly increase the local electric fields and form a high field island in the space-time plot. Long delayed sprites usually occurred at the leading edge of this high field island. However, not all the long-delayed sprites follow such an increase of the continuing current level. This indicates that other factors, like local ionization and irregularities at sprite locations, may also contribute to sprite initiation. Our results also show that short-delayed sprites generally initiate at greater altitudes than sprites with longer time delays, which confirms the results in previous studies. The consistency of the simulation results with the measurements and previous studies revealed that our approach is physically reasonable and reliably revealed the initiation mechanism for both short-delayed and long-delayed sprites. This lays the foundation for increased understanding of sprites.

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S. A. Cummer and J. Li, Electrical and Computer Engineering Department, Pratt School of Engineering, Duke University, 305 Teer Engineering Bldg., PO Box 90271, Durham, NC 27708-0271, USA.

W. R. Gamerota, Department of Electrical and Computer Engineering, University of Florida, 216 Larsen Hall, Gainesville, FL 32611-6200, USA.

R. K. Haaland, Department of Physics and Engineering, Fort Lewis College, 1000 Rim Dr., Durango, CO 81301, USA.

M. G. McHarg, Department of Physics, United States Air Force Academy, Colorado Springs, CO 80840, USA.

H. C. Stenbaek-Nielsen, Geophysical Institute, University of Alaska Fairbanks, 903 N. Koyukuk Dr., Fairbanks, AK 99775-7320, USA.