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Very low frequency sferic bursts, sprites, and their association with lightning activity

R. A. Marshall,[1] U. S. Inan,[1] and W. A. Lyons[2]

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[1] Recent observations have revealed the occurrence of burst-like VLF activity, lasting from tens of milliseconds up to a few seconds, associated with the onset of many sprites. These "sferic bursts" are thought to be due to the horizontal in-cloud component of lightning activity, since they have been observed to propagate only short distances (a few hundred kilometers) in the Earth-ionosphere waveguide and are generally not reported by lightning detection networks. The possible involvement of in-cloud lightning in sprite production has been previously suggested on the basis of the observed long delays and spatial displacement between causative cloud-to-ground (CG) discharges and sprite events. In this work, we investigate the association between sprites and sferic bursts using VLF data and a large set of sprite observations between 1995 and 2000. We compare the occurrence of sferic bursts in association with sprites for thousands of observations through many different dates and thunderstorms. Results indicate that sprite-causative CGs are more commonly found in association with bursts of sferic activity than those CG discharges without sprites and that, furthermore, the distribution of sferic burst VLF energy is significantly higher for sprite-associated events. We further investigate the source of these bursts by comparing VLF data to Lightning Mapping Array (LMA) data of VHF pulses due to lightning. Such comparisons show that most sferic burst events can be explained as radiation from the horizonal in-cloud components of +CG lightning, as detected by the LMA.

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1. Introduction

[2] Sprites are the most-studied member of a category of phenomena known as Transient Luminous Events (TLEs) that occur above the stratiform region of energetic thunderstorms [e.g., *Lyons*, 1996]. They occur in the altitude range of 40 – 90 km above large positive cloud-to-ground (+CG) discharges [e.g., *Sentman et al.*, 1995], although it must be noted that (1) a few sprites have been associated with negative cloud-to-ground (−CG) discharges [*Barrington-Leigh et al.*, 1999; *Williams et al.*, 2007] and (2) sprites have been seen to be displaced from the CG by up to 50 km [*Wescott et al.*, 1998]. Furthermore, while most sprites occur within a few to tens of milliseconds after the causative +CG [*Sao Sabbas et al.*, 2003], some have been seen to have delays up to 200 ms or more [*Bell et al.*, 1998; *Mika et al.*, 2005].

[3] Sprites are caused by a quasi-electrostatic (QE) field generated above thunderclouds by the removal of positive charge by a +CG discharge, leaving a downward-pointing QE field between the conducting ionosphere and the cloud top [e.g., *Pasko et al.*, 1997]. It has been suggested [*Valdivia et al.*, 1997; *van der Velde et al.*, 2006] that the contribution of the in-cloud component of a CG discharge to the production of sprites may explain these long-delayed sprites (in this paper, we will refer to this activity for brevity as in-cloud activity, not to be confused with well-documented intracloud lightning, which is generally taken as "cloud only" lightning, never reaching the ground). *van der Velde et al.* [2006] showed that long-delayed sprites are often accompanied by bursts of very low frequency (VLF) sferic activity, referred to as "sferic clusters" [*Johnson and Inan*, 2000] or "sferic bursts" herein (we have chosen the latter nomenclature due to the fact that such bursts do not exhibit properties of a set of individual sferics; rather, they appear as a burst of continuous VLF activity). *Johnson and Inan* [2000] associated these sferic bursts with in-cloud lightning on the basis of the observations that (1) they do not propagate to great distances in the Earth-Ionosphere (EI) waveguide, typical of horizontal sources, and (2) they are not reported by the National Lightning Detection Network (NLDN), which, until April 2006, reported only CG discharges.

[4] *Johnson and Inan* [2000] also showed a one-to-one correspondence between sferic bursts and early/fast VLF perturbations. These "early/fast events" are perturbations to VLF transmitter signals propagating in the Earth-Ionosphere (E-I) waveguide, caused by conductivity changes in the lower ionosphere due to lightning. These perturbations

[1] STAR Laboratory, Stanford University, Stanford, California, USA.
[2] FMA Research, Inc., Fort Collins, Colorado, USA.

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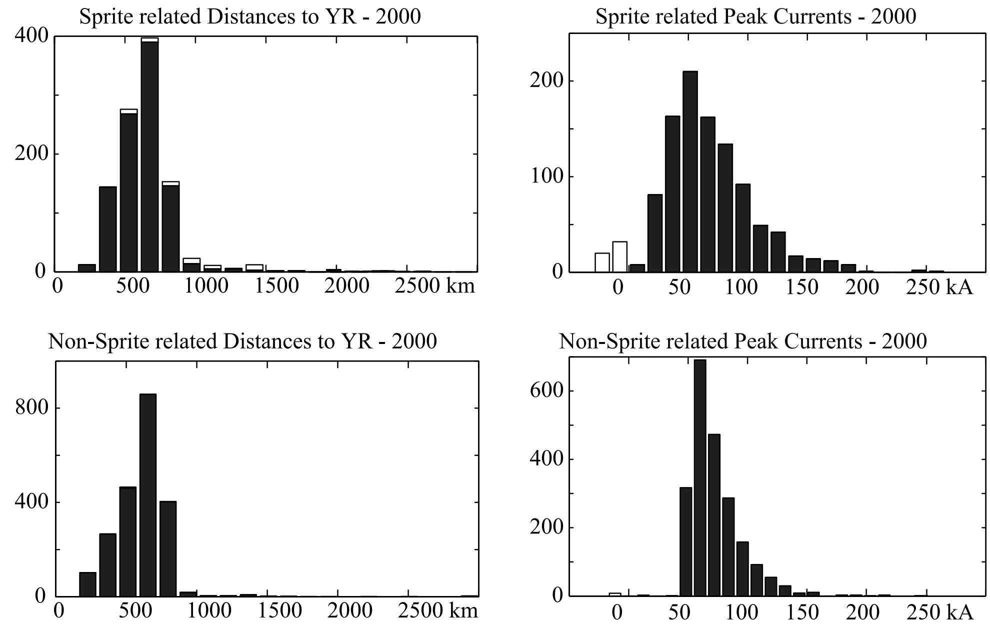

Figure 1. Distributions of peak currents and distances to the receiver for sprite and non-sprite NLDN CGs, showing no preference for sprite-related events.

occur within 20 ms of the causative CG lightning (“early”) and rise to their full perturbation within 20 ms (“fast”), noting that the 20 ms threshold is due to the 50 Hz data resolution used to classify them [*Inan et al.*, 1995]. More recently, a new class of events has been discovered, which are still “early” but rise to their full perturbation over a few hundred milliseconds, and these have been labeled “early/slow” [*Haldoupis et al.*, 2006]. Noting that the occurrence of sprites and both types of “early” events have been shown to be strongly correlated [*Haldoupis et al.*, 2004; *Marshall et al.*, 2006], in this paper we investigate the relationship between sprites and sferic bursts using a large data set in order to establish the connection between these phenomena on a statistical basis.

[5] It is important to realize that in prior publications on sferic bursts [*Johnson and Inan*, 2000; *Ohkubo et al.*, 2005; *van der Velde et al.*, 2006], the identification of sferic bursts as signatures of in-cloud lightning was based on the two observations stated above from *Johnson and Inan* [2000]. *van der Velde et al.* [2006] attempted to show a correlation between sferic bursts and VHF sources reported by a SAFIR 2-D interferometric lightning mapping system, but did not find agreement in time. VHF sources are important in this context since *Stanley* [2000] showed that they were correlated in time with spider lightning lasting up to a few seconds. In this paper, we present data from hundreds of sprites that were observed near the New Mexico Tech Lightning Mapping Array (LMA) during its deployment in the summer of 2000; this deployment was part of the very productive STEPS program [*Lang et al.*, 2004]. Our study thus provides the most complete correlation of sprite, VLF, and LMA activity to date.

2. Description of the VLF Data

[6] VLF data were recorded at Yucca Ridge Field Station (YRFS) near Fort Collins, CO, during most summers from 1995–2000; in this paper we focus on data during 1995, 1996, 1998, and 2000, as these provided the best overlap in the optical sprite data and VLF data. Data were collected by two orthogonal 1-meter square magnetic loop antennas, oriented in the north-south and east-west directions. The VLF receiver had a flat frequency response from ~10 Hz up to 30 kHz. The data from the two antennas were originally recorded on Betamax tapes with PCM coding on two data video channels, and with IRIG-B timing on the audio channel. The data have been recently converted to DVDs, the process of which involves filtering the analog readout from the Betamax channels with a 4-pole hardware low-pass filter with cutoff at 15 kHz, and redigitizing the data with a sampling rate of 33.3 kHz and 16-bit resolution.

[7] In total, about 6000 sferics were analyzed for burst activity. About 2000 of these had associated sprites, optically confirmed from YRFS in 1995, 1996, 1998, and 2000. Sprite-associated sferics were located by searching through VLF broadband data for known, archived optical observation times of sprites. Non-sprite associated sferics were located by searching for all non-sprite associated +CGs greater than 50 kA, as reported by NLDN, within the periods of sprite observations and within 1000 km of YR. They are also confirmed to be within the field-of-view of the cameras while operating. While the choice of positive CGs only and the large 50 kA threshold unfortunately restricts the data set, it is necessary to reduce the number of cases, and limits us to the comparison of sprite-producing and non-sprite-producing large +CGs. In Figure 1, the peak currents of sprite-associated and non-sprite associated NLDN strokes are shown in histograms to show that there is no peak current bias in favor of sprite-associated sferics. Also in Figure 1, the distances of each NLDN stroke to YR is shown, again showing no bias. A few errors (shown in open boxes) are due to the search algorithm occasionally finding the wrong NLDN stroke (often when no +CG was

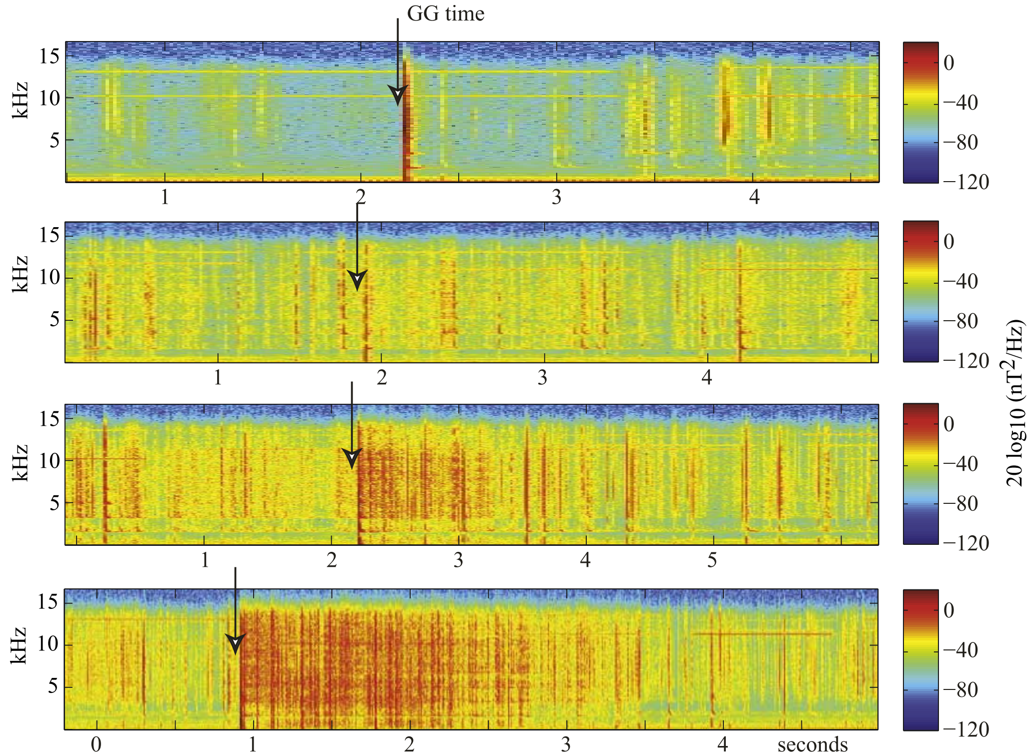

Figure 2. Examples of sferic bursts. The arrows show the time of the CG discharge. Each of these cases is associated with a sprite.

reported by NLDN, or where a larger +CG was found within 1 s of the sprite-causative CG).

3. Results: Sprite Correlations

[8] Figure 2 shows four examples of VLF sferic bursts. Each of these examples occurred in association with a sprite, where the causative CG is located with the arrows. These examples show the wide variability in the VLF sferic bursts, and the fact that sprites can sometimes occur without any VLF burst activity at all. However, we shall see below that most sprites are found in association with burst activity.

[9] In order to make a quantitative comparison of events, we measure the energy in each sferic event. Four time points are located on each event: (1) the start of the burst activity, (2) the start of the CG-induced sferic, (3) the end of the sferic, and (4) the end of the burst. Note here that we define the "sferic" as being only the return stroke component of the VLF signature, whereas the "sferic burst" refers to the long-duration activity seen in Figure 2. Within each of the three resulting sections, energy is calculated by evaluating the average power of a hamming-windowed periodogram. The total energy is then calculated by simple addition after multiplying with the respective time intervals. To normalize the energy values and to allow comparison of events from different days and times, background noise is subtracted by taking average noise power samples every five minutes. We then add the pre-CG (1 $\rightarrow$ 2) and post-CG (3 $\rightarrow$ 4) energy and combine the north/south and east/west component vectors, a procedure equivalent to removing the CG-induced sferic itself from the calculation. The results are given below in Figure 3 by year, and show a marked difference in energies, about a factor of 5, between sprite-related and non-sprite-related events (note the shift in the distributions, as marked by the green arrows). In comparison, the sferic energy (2 $\rightarrow$ 3) in each case shows little difference between sprite-related and non-sprite related events (vertical green arrows), indicating that the data are not biased by sferic intensity.

[10] While *van der Velde et al.* [2006] reported no cases of sprite-associated sferic bursts that lasted longer than 250 ms, in our data set there are many such events, lasting up to 3 s in some cases, consistent with observations of in-cloud lightning using VHF time-of-arrival (TOA) techniques, as discussed later. Figure 4 shows distributions of burst times leading up to and following the CG, for both sprite and non-sprite cases. It is evident that sprites are generally associated with much longer duration bursts, and that the burst activity following the CG is generally much more prominent in events with associated sprites. While the total energy of the burst, as in Figure 3, is higher for sprite cases, we see that this is in part due to the fact that the duration is longer.

4. In-Cloud Sources of VLF Bursts

[11] It has been speculated [*Johnson and Inan*, 2000; *van der Velde et al.*, 2006] that these VLF sferic bursts are caused by in-cloud lightning activity. However, previously no convincing comparisons have been made between such VLF sferic bursts and measurements of in-cloud activity. Here we show correlations between sferic bursts and in-

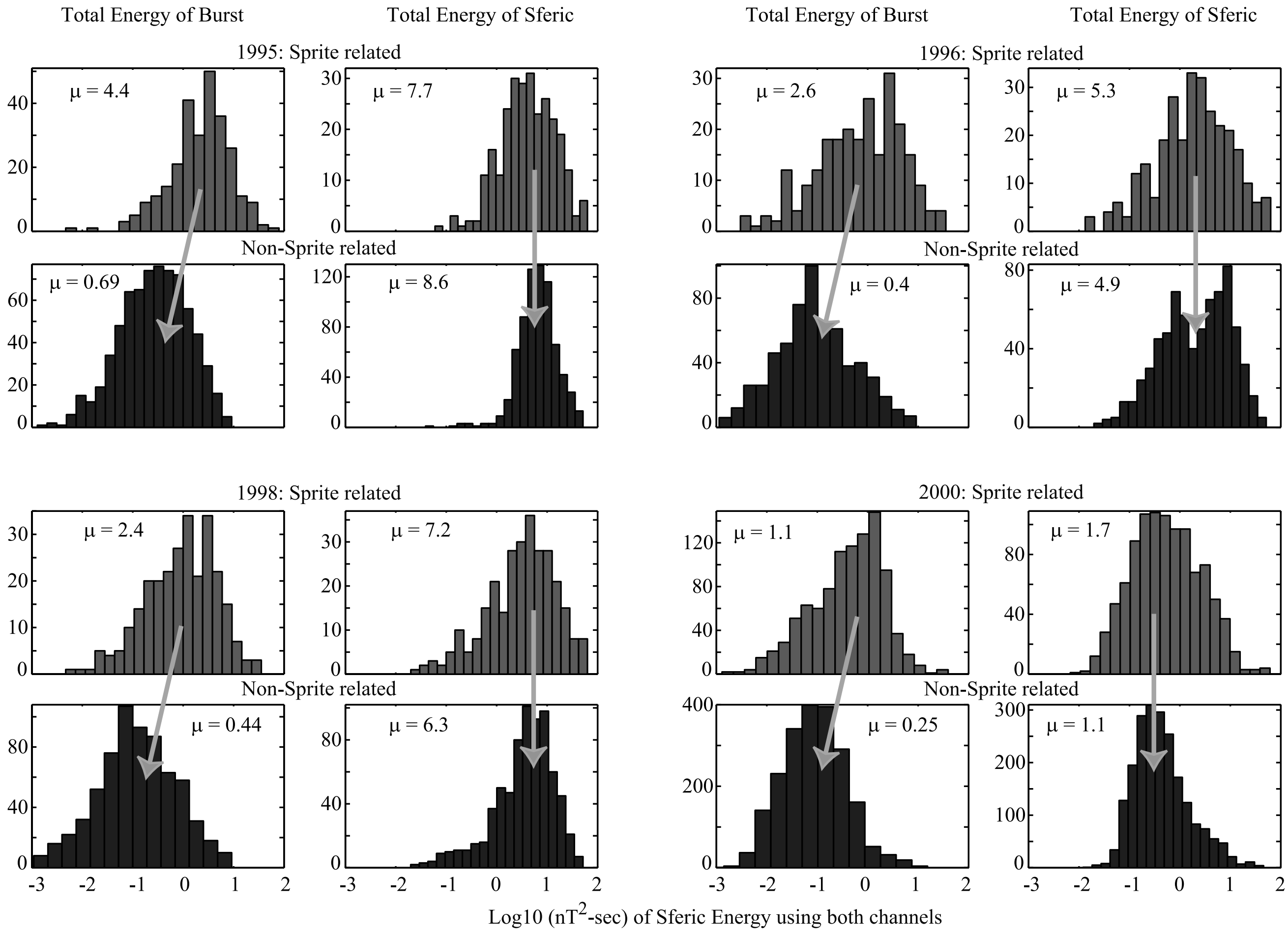

Figure 3. Distributions of sferic energy for each year. Histograms are of the energy of either the sferic only or the burst activity outside the sferic. The clear shift in each histogram from sprite to non-sprite cases demonstrates the interrelationship. μ refers to the mean of each distribution.

cloud activity, as measured by the New Mexico Tech LMA, deployed near the Colorado/Kansas border in the summer of 2000 [e.g., *Thomas et al.*, 2000]. LMA data were not available for the other summers of sprite and VLF data discussed above.

[12] We wish to emphasize again that the "in-cloud" lightning activity we are referring to is actually most often the in-cloud horizontal component of CG discharges, rather than typical intracloud lightning which never touches ground. Indeed, all of the cases analyzed in the previous section and in this section were associated with +CGs. As such, if the correlations outlined below hold, the results in Figure 3 can be interpreted as a measure of the horizontal in-cloud activity associated with the parent CG for each case. We use the term "in-cloud" for brevity, but realize that the CG is still integral to the discussion.

[13] Data from the LMA are established by the reception of a pulse at a minimum of six locations (four for 3-D location and time, and two for redundancy), and source locations are calculated using time-of-arrival (TOA) differences. Uncertainties for the three direction components at 200 km are ~60 m (azimuth), ~1500 m (range), and ~1500 m (altitude) [*Thomas et al.*, 2004, Figure 12]. Given that a 1.5 km uncertainty is far more significant for altitude (which usually ranges from 0–20 km), latitude/longitude positions are generally considered accurate to about 200 km, and altitudes to about 100 km (P. Krehbiel, private communication, 2006).

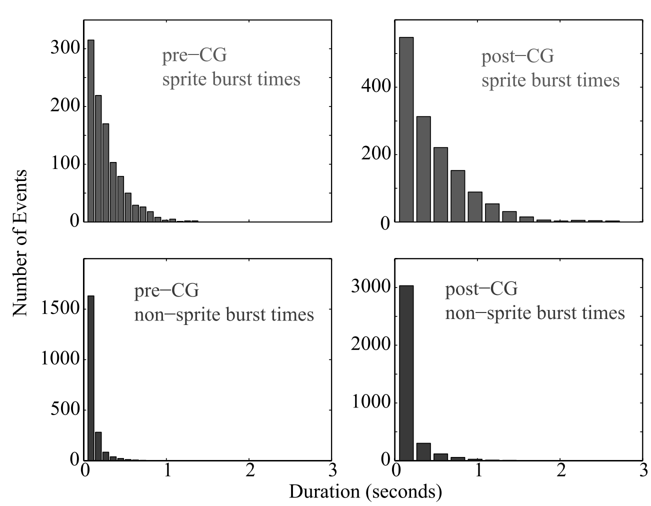

Figure 4. Distributions of durations of sferic bursts, for sprite- and non-sprite-related bursts, pre- and post-CG.

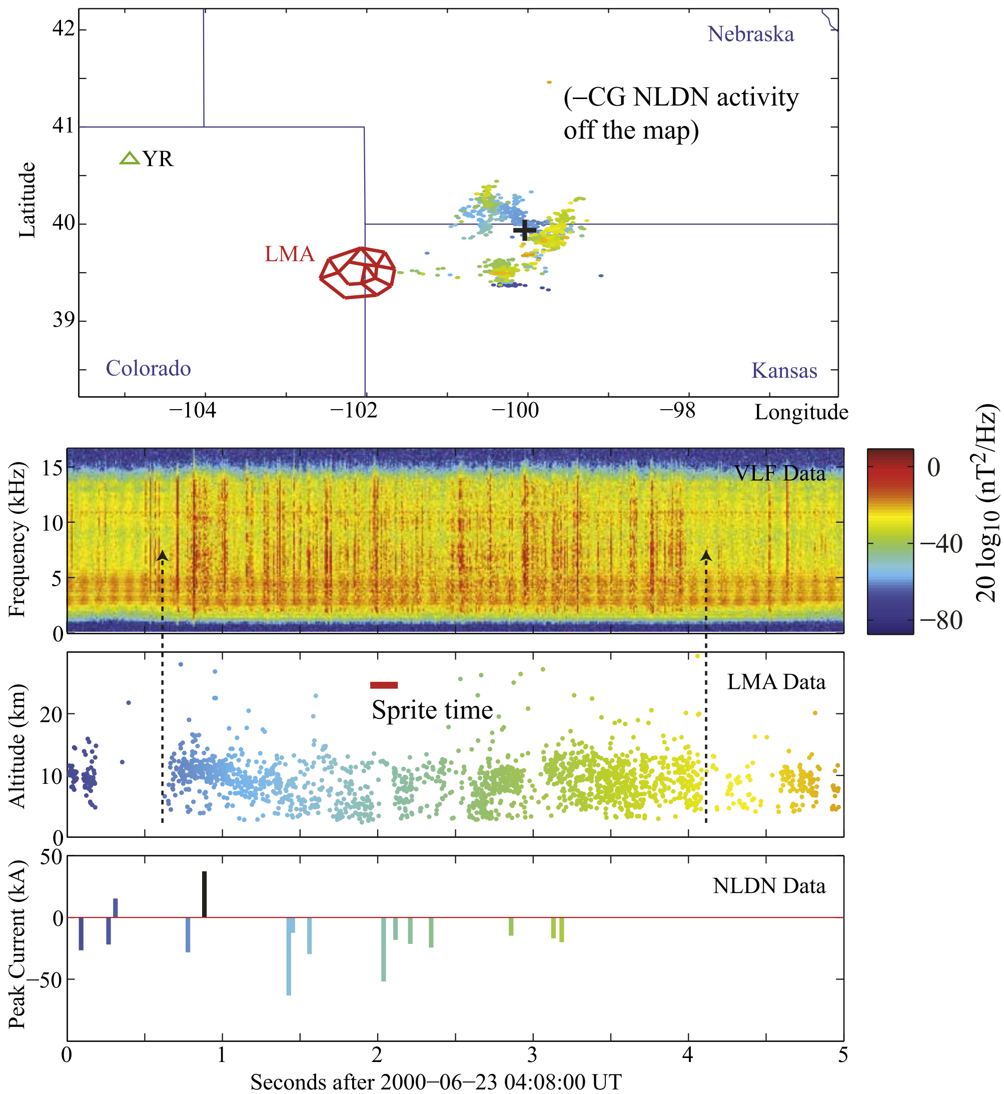

Figure 5. Example of VLF, NLDN, and LMA data together for a sprite case. The large +CG (shown in black) caused a sprite halo at 04:08:00.908 UT, followed by a sprite at 04:08:01.108 UT; VLF data show the causative sferic as well as burst activity lasting about 3.5 s. LMA data during the same time and location corroborate the 3.5 s period of in-cloud activity. This example has a correlation peak (described in the text) of 0.863. In this case, the NLDN -CG activity was off the map shown.

[14] Figure 5 shows an example of LMA data together with VLF and NLDN data for a sprite case. The LMA data shown here are the decimated data available through the New Mexico Tech Web site, which have a time resolution of 0.4 ms. This example clearly shows a strong correlation between LMA and VLF burst data, as both show a distinct, continuous burst of activity lasting about 3.5 s.

[15] We observe LMA activity during sprite times, although this part of the study does not account for sprite occurrence; these times are simply used for convenience, since we have already compiled the VLF data above. Of over 1000 sprites observed in the summer of 2000, when the LMA was operational, 373 sprite times had corresponding LMA data available. Of these, 154 correspond to storms within ∼200 km of the LMA, where 2-D latitude/longitude data are reliable. Figure 5 shows a good example of the association between the LMA and the VLF burst activity. The color scale of the LMA data progresses from blue to red in time, so that pulses can be tracked in time on the corresponding map. Figure 6 shows another example with exceptional association.

[16] In Figure 6, it is evident that the VLF burst activity is almost perfectly correlated with the LMA data, even at times when no NLDN strokes were reported. Note specifically the burst from 5–6 s on this plot; no NLDN stroke was reported, but one must take into account the 85–90% efficiency of NLDN for +CGs. However, VLF data were analyzed for this time period from Palmer Station, Antarctica, and no sferics were found in this time period coming from the United States sector. This comparison shows that in-cloud activity, as measured by the LMA, can explain many cases of VLF burst activity; and that in turn, the VLF bursts can provide a measurement of in-cloud activity.

[17] Note that since amplitudes of the individual LMA pulses are not available, quantitative rules for these correlations cannot be established. However, a metric has been

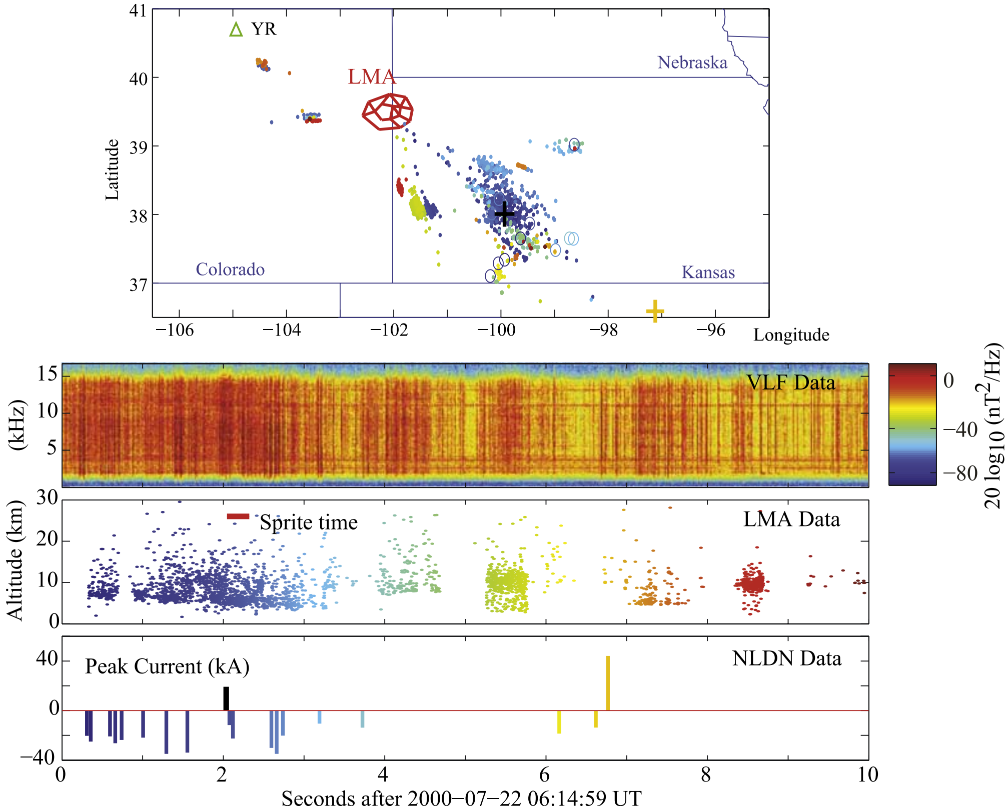

Figure 6. A second example of VLF, NLDN, and LMA data together for a sprite case. In this case the correlation between VLF and LMA data is very strong, even explaining VLF activity where there is no NLDN (seconds 5–6). On the map, −CG discharges are shown as circles.

created to attempt to quantify the association between the LMA data and the VLF activity. Taking into account only the 154 cases that are near enough to the LMA for data to be reliable, we use the following analysis:

[18] VLF data are first rectified, then integrated in 100 ms time segments, to yield a time trace of VLF "energy" similar to those shown by *Johnson and Inan* [2000]. Next, LMA pulses are counted in 100 ms bins, creating a time histogram of LMA activity. Both of these traces are then normalized. The two normalized traces are shown in Figure 7 for the data in Figure 6. The middle five seconds (centered around the sprite time) of the traces are then cross-correlated; the peak of the cross-correlation, occurring at zero-lag, is recorded. The distribution of all of these peaks are shown in the bottom panel of Figure 7. For comparison, the correlation peaks for each of the example figures are shown. The relatively low correlation in Figure 6 (and 7) can be attributed to lack of amplitude data for the LMA, and thus the effect of simply counting the pulses, as can be seen by the discrepancy in amplitude around 5–6 and 8–9 s. For further comparison, correlations were calculated for the storm of 2 July 2000, occurring in South Dakota, some ~750 km from the LMA and ~600 km from Yucca Ridge, for each of about 400 sprites. At this range, the LMA would not be expected to receive many pulses from the storm. VLF burst activity was prominent in the data, and no other large storms occurred within 1000 km of the VLF receiver that might contribute to the burst activity. Results show a mean

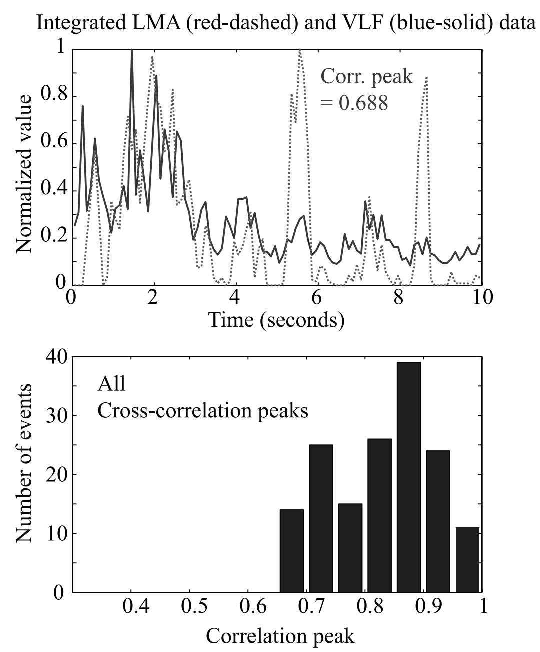

Figure 7. (top) Normalized running integrals of VLF and LMA data from Figure 6. (bottom) Histogram of correlation peaks for the dates discussed in the text. Note that for the case shown, the correlation peak is weak, despite the visual correlation; this is possibly due to the lack of amplitude data with which to scale the LMA integration.

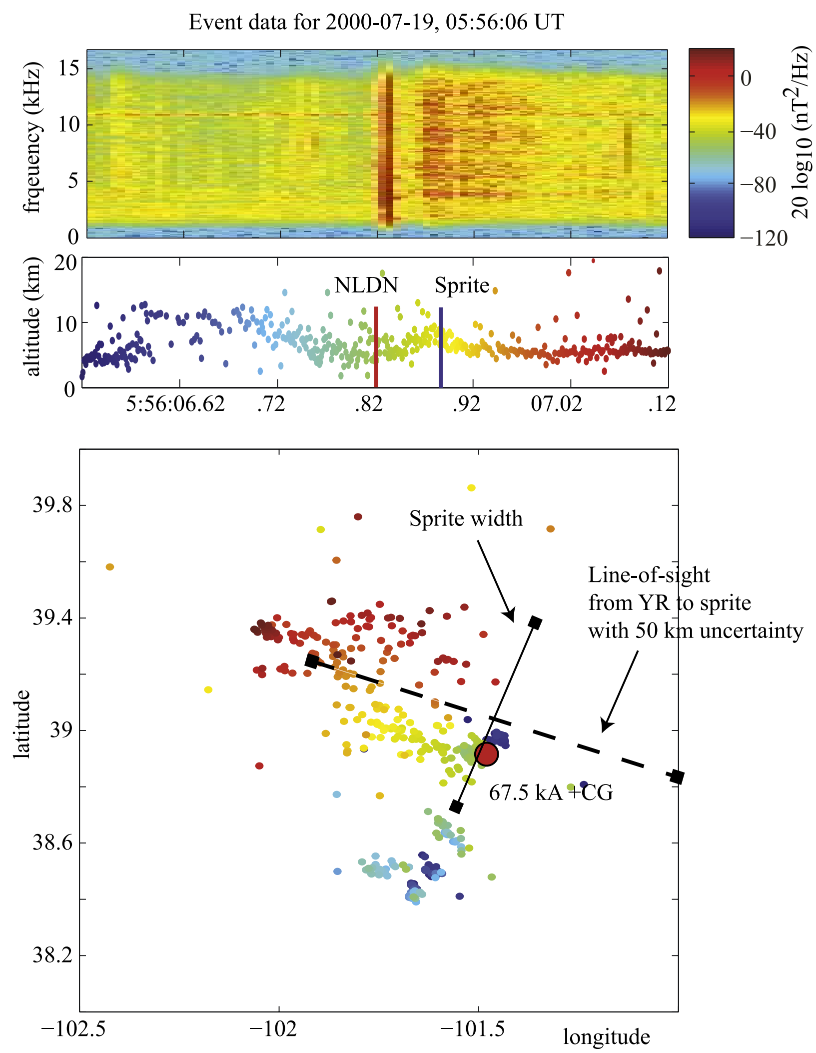

Figure 8. An example of LMA and VLF sferic burst data demonstrating the tendril-like structure of the in-cloud lightning. This example has a correlation peak (described in the text) of 0.824.

correlation peak of 0.53 with a standard deviation of 0.1. When compared with the distribution in Figure 7, this demonstrates that when the LMA data is reliable, it is undeniably associated with VLF burst activity.

[19] Further examination of the LMA activity leads to some insight into the nature of the VLF sferic bursts. Figure 8 shows an example including a zoomed-in view of the 2-D latitude/longitude positions of the LMA pulses, using the undecimated data (80 μs resolution). With the color scale progressing from blue to red in time, we can see that from the time of the CG, LMA pulses were observed originating from progressively farther from the CG, fanning out where the red pulses are seen; this activity strongly resembles the "spider" lightning reported by *Mazur et al.* [1998]. The black dashed line shows where the sprite occurred as observed from Yucca Ridge, taking into account the ±50 km uncertainty.

[20] This example shows evidence that the LMA and VLF data are both recording signatures of the CG-associated in-cloud horizontal lightning activity. This in-cloud activity likely serves to tap the large positive charge reservoir of the convective system [*Williams*, 1998; *Lyons et al.*, 2003]. In this way, the burst activity is actually a signature of the processes by which large amounts of charge are removed from the thundercloud in a +CG, leading to a large charge moment change; and in turn, since sprites require large charge moment changes [e.g., *Cummer and Inan*, 2000], the VLF burst can be interpreted as the signature of cloud processes that often lead to sprite occurrence. Furthermore, the statistics in Figure 1 show that sprite events have much longer burst durations; this long-duration in-cloud lightning activity could also be related to the large charge moment change through the long continuing current that has been associated with sprites [*Reising et al.*, 1996]. In a similar vein, these longer-duration bursts most likely reach a greater distance into the cloud, and these longer channels will likely to radiate stronger in the VLF, appearing as stronger bursts. In this way the duration and the average power of these bursts should be intertwined. Figure 9 shows a scatter plot of the burst durations versus the average power in the sferic burst for all sprite-related cases in 2000. While the result is

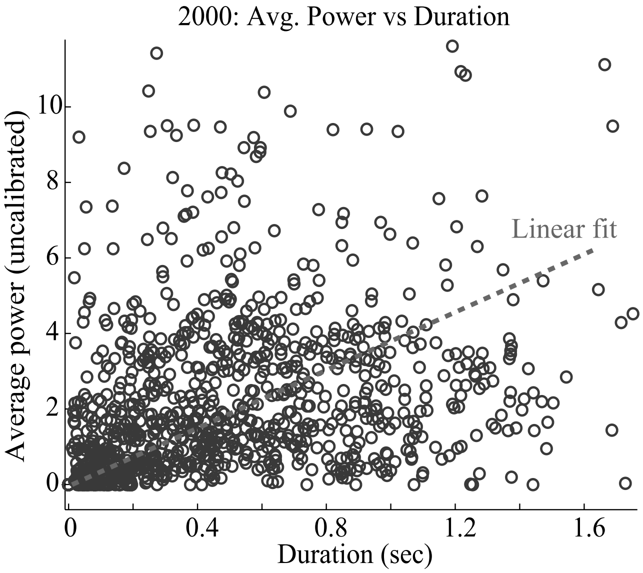

Figure 9. Sferic burst average power versus burst duration. We see that a weak trend exists where bursts of longer duration have higher average power, possible evidence that longer-duration bursts have longer channels and thus radiate stronger at VLF frequencies.

obviously quite noisy, one can discern a general trend that higher burst power correlates with longer duration.

5. In-Cloud Processes Leading to Sferic Bursts

[21] The sferic burst data presented here give some insight into the types of in-cloud activity detected by VLF methods. *Proctor et al.* [1988] showed the differences between "pulses" and "Q-noise" in lightning, having durations of 1 μs and 40–400 μs, respectively. *Mazur et al.* [1997] showed that Time-of-Arrival (TOA) detection systems for VHF activity are more sensitive to the individual fast pulses, while Interferometric (ITF) detection systems are more sensitive to the long-duration Q-trains. Furthermore, *Mazur et al.* [1997] showed that the Q-trains, as detected by ITF, occur at altitudes significantly lower than pulses, with means of 5 km and 9 km, respectively. Note that spider lightning, often thought to be active in sprite initiation [e.g., *Stanley*, 2000], occurs at altitudes of 4–6 km [*Lyons et al.*, 2003]. The LMA, used in this study, is a TOA system.

[22] Recently it has been shown that the LMA can often observe impulsive components following CG discharges [*Shao and Krehbiel*, 1996; *Thomas et al.*, 2004]. The example in Figures 1 and 2 of *Thomas et al.* [2004] shows how the LMA can detect in-cloud components of CG discharges, of precisely the type of dendritic structure thought to be responsible for continuing currents [*Reising et al.*, 1996]. *van der Velde et al.* [2006] used an interferometric SAFIR system, which has a 100 μs resolution [*van der Velde et al.*, 2006, and references therein], and it was noted that the activity reported by the SAFIR system did not correlate well with the VLF burst activity.

[23] *Mazur et al.* [1998] noted that spider lightning is often luminous for hundreds of milliseconds, due to continuing current; it is likely that the radiation from this continuing current is what is measured by the VLF receiver. The coincident observations from the LMA are evidence of fast leader processes also occurring over hundreds of milliseconds. It is possible, then, that sprite-producing "spider" lightning does not exhibit the Q-train type of pulses that are well mapped by interferometric systems such as SAFIR.

6. Summary

[24] Bursts of radio activity observed in VLF data almost always accompany the parent CG lightning of sprites. However, many non-sprite-producing +CGs are also accompanied by burst activity, so that burst activity does not provide a unique identifier for sprites. The correlation between sprites and burst activity shows that the in-cloud component of the cloud-to-ground lightning discharge has a significant role in sprite production. Note that the CG component of the discharge is still a requirement for sprite production; no sprites have been confirmed without CG causation. It may thus be that in-cloud activity is responsible for enhancing the QE field above the thundercloud, raising it above the breakdown threshold and causing a sprite to occur that would not have otherwise. This is most likely if the in-cloud activity acts to tap the positive charge reservoir of the cloud and enhance the charge moment through continuing current.

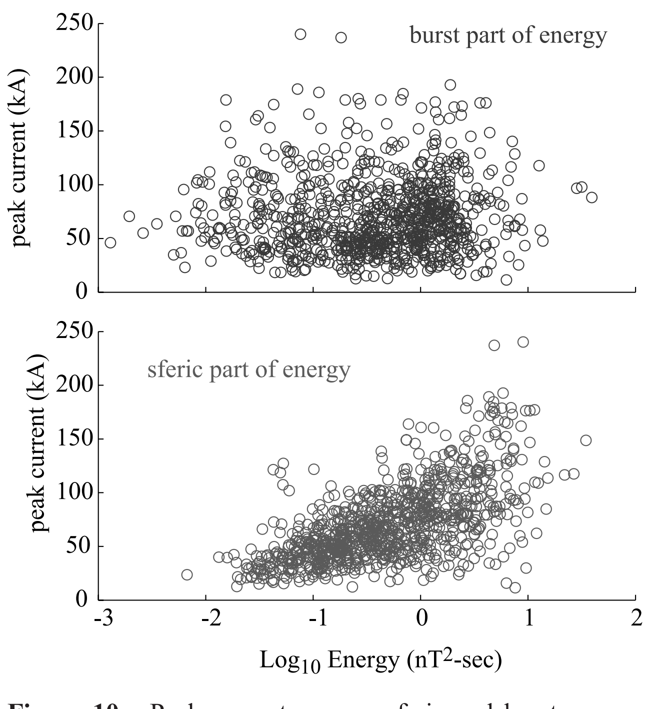

Figure 10. Peak currents versus sferic and burst energy. For the sferic, a trend appears that disallows large peak currents with small energy; however, in the burst cases, large peak currents may be accompanied by small burst energy, showing that for larger discharges, burst energy is not required to initiate a sprite (though charge moment is still very important).

[25] Figure 10 shows a scatter plot of burst energy versus the peak current of the sprite-causative CG. The trend is evident: in the sferic energy (bottom plot), a clear slope shows that there are no cases of large peak currents with small burst energy. But in the energy content of the burst (top plot), such cases do occur. It thus appears that the larger peak current strokes (which presumably, and statistically, have larger charge moments) do not always *require* large sferic bursts (i.e., in-cloud activity) for sprites to occur. Or, viewed conversely, small peak current strokes, when accompanied by burst activity, can produce sprites. The non-sprite-producing cases (not shown) show the same trend in both the sferic and burst parts of the energy distributions.

[26] The comparison of VLF burst examples with LMA data shows a strong correlation and thus evidence that these VLF sferic bursts are signatures of horizontal in-cloud lightning activity. Given the arguments above (that this in-cloud lightning activity, when associated with a +CG, constitutes the in-cloud component of continuing current that taps the positive charge reservoir, leading to larger charge moments), these sferic bursts provide an identifier for large charge moment cloud-to-ground lightning strokes, and thus a good measure of sprite occurrence without optical observations.

[27] **Acknowledgments.** This work was supported by a Texas Instruments Stanford Graduate Fellowship and by the Office of Naval Research (N00014-03-1-0333) and the National Science Foundation (ATM-0551174). Partial support to FMA Research was provided by the National Science Foundation (ATM-0221512). The authors wish to thank Ken Cummins and John Cramer of Vaisala, Inc., for access to NLDN lightning data and Bill Rison and Paul Krehbiel for access to the New Mexico Tech LMA data and helpful discussions thereof.

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U. S. Inan and R. A. Marshall, Space, Telecommunications and Radioscience Laboratory, Stanford University, 350 Serra Mall, Room 306, Stanford, CA 94305, USA. (ram80@stanford.edu)

W. A. Lyons, FMA Research, Inc., 46050 Weld County Road 13, Fort Collins, CO 80524, USA.