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On the association of early/fast very low frequency perturbations with sprites and rare examples of VLF backscatter

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[1] Very low frequency (VLF) data recorded in the midwestern United States are compared with sprite observations on three different dates of high sprite activity between 1995 and 2000. Sprites are frequently seen to be correlated with ''early/fast'' events: perturbations of the amplitude and/or phase of a VLF transmitter signal propagating through the storm region. Unlike recent observations of Haldoupis et al. (2004), where a one-to-one relationship between forward scatter events and sprites was reported, only ~48% of sprites in our cases are accompanied by VLF perturbations, or, viewed conversely, ~61% of VLF perturbations are accompanied by sprites. The difference between the two data sets might be due to the relative location of the causative lightning along the VLF signal path (i.e., near transmitter or near receiver) in that mode coupling of the propagating VLF signal causes some perturbations to be undetectable at long distances from the disturbed region. In addition, there are quite a few cases of early/fast perturbations not accompanied by sprites, although not nearly the preponderance previously expected. In rare cases, observed VLF signal perturbations can only be explained by VLF backscatter from the sprite body because of the geometrical constraints that preclude other mechanisms, including forward scattering from elves or halos. However, such backscatter events are extremely rare and are found to occur only for the largest sprites in terms of their horizontal extent.

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1. Introduction

[2] Sudden amplitude/phase perturbations of subionospheric VLF signals have been associated with lightning since 1983 [*Armstrong*, 1983] and were studied extensively in the 1990s. These perturbations are indicative of direct effects of lightning on the ionosphere along the VLF propagation path [e.g., *Inan et al.*, 1991; *Taranenko et al.*, 1993a; *Taranenko et al.*, 1993b], as opposed to lightning-induced electron precipitation effects, in which whistler mode waves injected into the magnetosphere by lightning cause pitch angle scattering and thus precipitation of radiation belt electrons, causing density enhancements in the lower ionosphere detectable by subionospheric VLF waves. These direct events lack the onset delay resulting from whistler wave propagation along the magnetic fields lines (to magnetic equatorial interaction regions) and traveltime of the energetic particles (from the equator to the ionosphere) and thus must be explained by direct electrodynamic coupling effects in the Earth-ionosphere waveguide through which the VLF energy propagates. The physical mechanism of such events without onset delays, termed ''early/fast'' VLF events, have been under debate [*Inan et al.*, 1995, 1996a; *Dowden*, 1996; *Rodger*, 1999]. More recently, early/fast events have been associated with sprite halos [*Moore et al.*, 2003] through a full wave model that combines quasi-electrostatic (QE) heating and electromagnetic pulse (EMP) effects.

[3] Early/fast events have been correlated with the occurrence of sprites [*Inan et al.*, 1995], large luminous discharges occurring at altitudes from 40 to 90 km following intense lightning flashes [*Lyons*, 1994; *Sentman et al.*, 1995], and are typically associated with positive cloud-to-ground (+CG) discharges [*Lyons*, 1995; *Sentman et al.*, 1995; *Lyons*, 1996], typically those with large charge moments [*Cummer and Inan*, 2000; *Lyons et al.*, 2003; *Cummer and Lyons*, 2005]. Sprites are believed to be produced by QE heating of ambient electrons in the mesosphere [*Pasko et al.*, 1997], due to the quasi-static electric field that temporarily exists between the cloud and the ionosphere immediately after large lightning discharges.

[4] It has been shown that sprite halos involve changes in ionospheric density commensurate with the VLF signal perturbations typically observed, leading to the conclusion that early/fast VLF perturbations may be signatures of halos [*Moore et al.*, 2003]. Such considerations are based on the

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experimentally verified forward scattering of the VLF signal from a near-Gaussian-shaped perturbation, and thus would only lead to signal perturbations if the causative lightning flash is within ~100 km of the signal path [*Inan et al.*, 1995], consistent with most of the early/fast VLF data reported to date [e.g., *Inan et al.*, 1996b; *Johnson et al.*, 1999].

[5] On the other hand, *Dowden et al.* [1996] attribute direct subionospheric VLF signal perturbations to a different mechanism. In cases reported by these authors, the causative lightning strikes are ~300 km from the signal path, and are associated with sprites, so that the VLF signal perturbation is attributed to scattering from ionization in the sprite body that persists well beyond the optical sprite lifetime of a few tens of ms. This interpretation was further supported by *Hardman et al.* [1998] using an expanded data set. Furthermore, these authors suggest that such scattering occurs for nearly all sprites, so much so that observations of VLF perturbations can be used as a sprite detection method in the absence of optical data. Such scattering processes in the Earth-ionosphere waveguide have been modeled by *Rodger et al.* [1998], *Rodger and Nunn* [1999], and *Rodger et al.* [1999]. Additionally, *Corcuff* [1998] observed VLF perturbations in Europe that could only be attributed to a particularly large (~350 km) perturbed region, or to wide-angle scattering, though sprites were not conjectured as the source.

[6] In the summer of 2003, sprites were observed over France from the Pyrenees (see *Neubert et al.* [2005] for a description of the experiment). Simultaneously, VLF recordings were made at Nancay, France, and the University of Crete in Heraklion. Results of this experiment were reported by *Haldoupis et al.* [2004] and *Mika et al.* [2005]. In particular, *Haldoupis et al.* [2004] reported VLF perturbations in one-to-one association with sprites, while *Mika et al.* [2005] reported the possibility of rare examples of "backscatter" of VLF signals from the sprite body of the kind discussed by *Dowden et al.* [1996]. However, these events were observed ~150–200 km from the VLF receiver, and so it was concluded that they could be attributed to overlap of the density-enhanced region (i.e., the sprite halo) over the VLF signal path. These recent results motivated us to revisit previously unpublished results, in order to better quantify the association between sprites and early/fast events and to assess the conditions under which rare backscatter events may occur.

2. Case Studies

2.1. The 15 July 1995 Case

[7] During the summer of 1995, sprites were optically observed from Yucca Ridge Field Station (YRFS), near Fort Collins, CO, and a Stanford VLF receiver was located near the observing platform. This receiver recorded broadband data continuously from ~30 Hz to 30 kHz, and in addition, the broadband signals were bandpass-filtered in real time with ~200 Hz bandwidth around known transmitter signal frequencies, including the NAA (Cutler, Maine) signal at 24.0 kHz, NSS (Annapolis, Maryland) at 21.4 kHz, and NLK (Seattle, Washington) at 24.8 kHz, to produce amplitude data with time resolution of 20 ms. Furthermore, using real-time phase-coherent demodulation of the MSK-modulated signal, phase data is extracted from these signals at the same 20 ms time resolution.

[8] A total of 38 sprites were observed on 15 July 1995 between 0540 and 0740 UT, in a storm 300–500 km east of YRFS, as shown in Figure 1. For the purposes of VLF data comparison, these comprise 24 independent sprite "events", since in many cases up to 4 sprites are observed within a short time span of each other (<1 s) and cannot be distinguished in narrowband VLF data. Of these 24 optical events, 16 had corresponding VLF signal perturbations in amplitude and/or phase on the NAA and NSS great circle paths shown in Figure 1, based on a typical minimum detectable VLF event magnitude of 0.2 db in amplitude and ~3 degrees in phase (sometimes lower, depending on the noise level).

[9] In addition, during the time period of observations, 11 VLF perturbations were found on the NAA and NSS signal paths that were not accompanied with sprite observations. These perturbations are all associated with lightning flashes reported by the National Lightning Detection Network (NLDN) to be in the same region as the sprite-producing flashes, within the 20 ms time resolution of the narrowband VLF data. These events were tallied after eliminating those events for which the high-altitude regions above the causative CG lay outside the camera field of view at the time. Any sprites present would thus be well within the field of view of the cameras, but yet no sprites were detected.

[10] It is also important to note that sprite observations are frequently marred by clouds in the field of view, as was indeed the case for the July 1995 observations. In such cases, when sprite observations are ambiguous, VLF data are not used for the statistics.

[11] Associated with 5 of the sprite events were VLF signal perturbations on the NLK path, arriving at YR from the west, and not passing over the ionospheric region above the causative CG flashes as shown in Figure 1. Most of these were very small perturbations (~0.3 dB, where 0.2 dB is the threshold for event detection), and are observed simultaneously with larger perturbations on the NAA and NSS paths. An example is shown in Figure 2 at left, where a 2.0 dB perturbation is seen on the NSS amplitude signal, 0.7 dB on the NAA amplitude, and 1.0 dB on the NLK path; this being the largest such event. This particular perturbation occurred simultaneously with a series of 4 sprites within 600 ms of each other, resulting from 4 consecutive +CG flashes. The consecutive sprites were displaced from each other horizontally within the camera FOV, i.e., along a north-south line, noting that any displacement along an east-west line cannot be determined. In each of the other four cases of perturbations on the NLK paths, the associated sprite events were seen to be composed of a series of 2–4 sprites, displaced from each other in the plane of the camera FOV (along a north-south line). This observation suggests the establishment of a "grid" of ionization extending along a distance greater than the VLF wavelength, perpendicular to the NAA-YR and NSS-YR paths.

[12] Furthermore, we note that for 4 of the 5 events described above, perturbations were also observed on the NSS and/or NAA paths. In all four of these cases, the recovery times τ_r (defined as the time for the perturbation to recover from 90% of its perturbed value back to 10%) were only about half as long on the NLK path than they are on

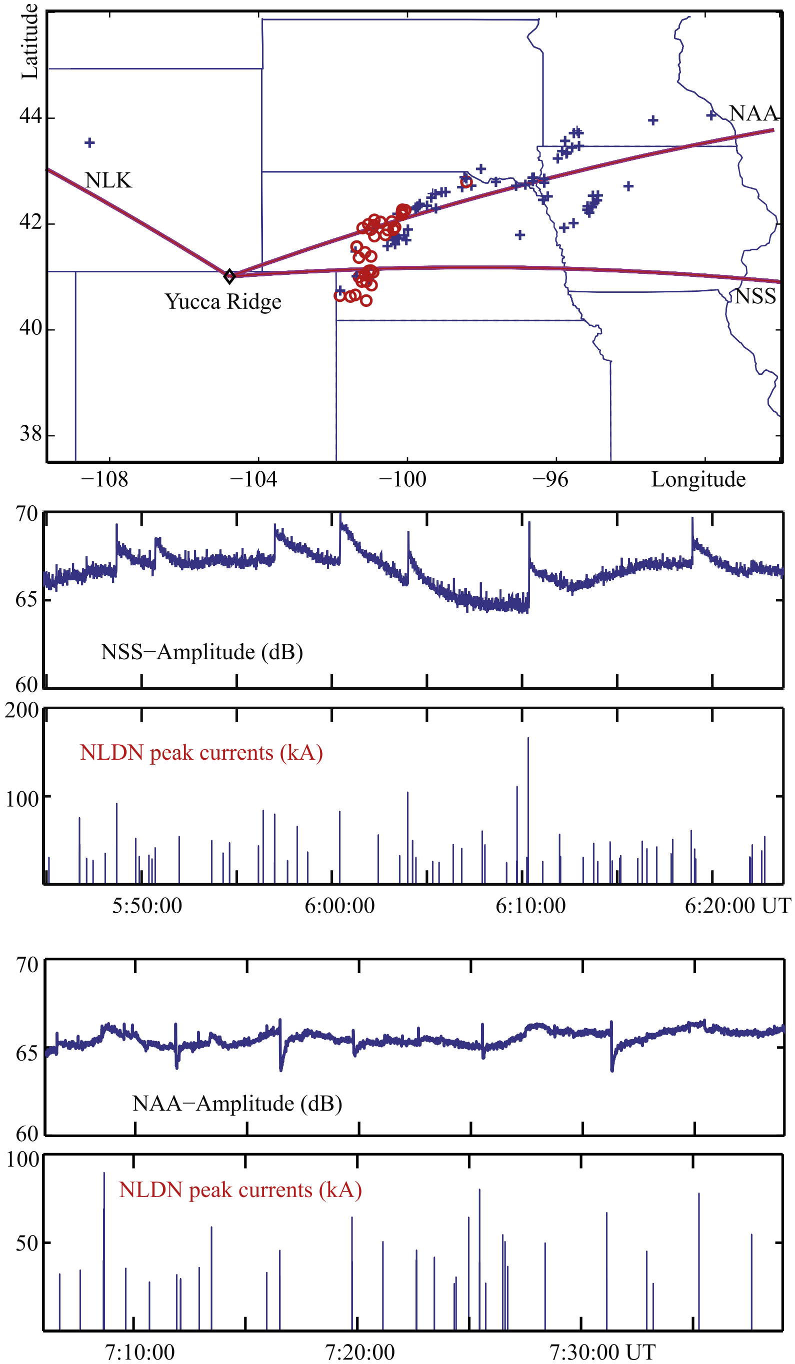

Figure 1. (top) Map of 15 July 1995 observations from 0530 to 0730 UT. The red circles indicate locations of sprite-inducing CGs; blue crosses indicate other +CGs > 50 kA. (middle and bottom) Data from two time periods during this day. The earlier events correspond to more southern part of the storm and hence occur on the NSS path; later events appear on NAA when +CGs occurred farther north.

the NSS or NAA paths (see Figure 2). Since the relaxation times for newly added secondary ionization drop rapidly with altitude [*Pasko and Inan*, 1994], this observation is consistent with the ionization that causes the perturbations on the NLK path being at lower altitude, providing further evidence that these particular perturbations may be caused by backscattering from the sprite body, while the perturbations on the NSS and the NAA paths may be forward scatter from sprite halos [*Moore et al.*, 2003]. It thus appears that while some configurations of sprites can backscatter VLF energy, the forward scattering from higher-altitude features (in the halo region) are typically dominant, as evidenced by the larger and longer lasting perturbations on the NAA-YR and NSS-YR paths.

[13] We note that the data presented here contain many of the same sprites analyzed by *Dowden et al.* [1996]. In that work, most of the sprites were reported to have corresponding "backscatter" events (perturbations to the

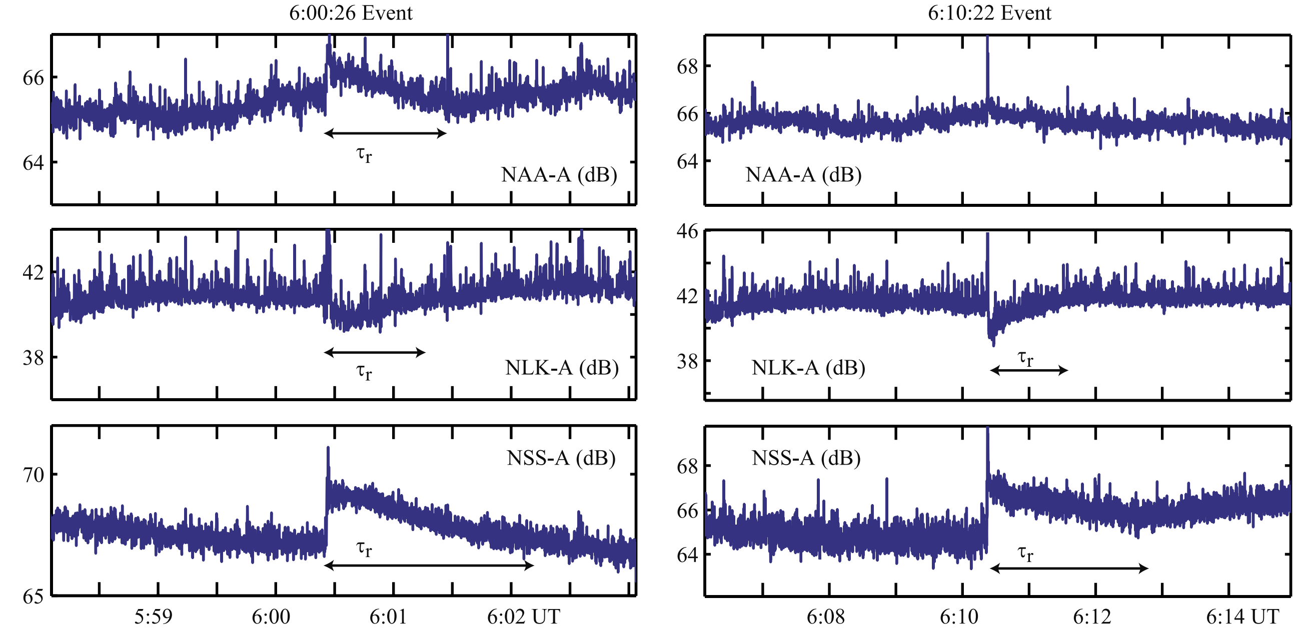

Figure 2. Example VLF perturbations from 15 July 1995 at 0600:26 UT and at 0610:22 UT. The first event followed a series of four +CGs located a minimum of 280 km east of YRFS, the largest of which was 91 kA. The strong perturbation on the NLK path is evidence of backscatter of VLF energy from the sprite body and of persistence in the conductivity enhancement created by the sprite. The longer recovery times on the NSS and NAA paths show that scattering also occurs from halo altitudes.

NLK signal path), contrary to the findings presented here. The major observational differences are that VLF observations by *Dowden et al.* [1996] were made from near Boulder, Colorado, while data presented here were recorded at Yucca Ridge, and that *Dowden et al.'s* [1996] measurements were made with 400 ms time resolution, while data herein were recorded with 20 ms resolution.

2.2. The 18 August 1999 Case

[14] On 18 August 1999, over 100 sprites were observed between 0230 UT and 0730 UT in a large storm to the Northeast of YRFS. At this time, the Stanford Holographic Array for Ionospheric Lightning research (HAIL) was in use. The HAIL array is a north-south aligned array of VLF receivers from Cheyenne, WY to Las Vegas, NM, designed to image in space and time the perturbed regions due to LEP and QE heating events [see *Johnson et al.*, 1999]. The array monitors the amplitude and phase of VLF transmitter signals from NAA, NLK, NAU (Puerto Rico) at 40.75 kHz, and NPM (Lualuaei, HI) at 21.4 kHz. Figure 3 shows the HAIL array and the location of the storm and sprite-producing CGs for this date.

[15] Figure 4 shows HAIL data from 0500 to 0600 UT for this day. Numerous large events are present, as well as a number of smaller events. It is evident upon comparison with the sprite times and NLDN data that many of these events correspond to sprite observations; however, once again, there are also many events do not have associated sprites.

[16] The 100+ sprites observed on this day can be categorized into 87 independent sprite events, according to the same criteria as the 1995 case. Of these, 56 were associated with VLF signal perturbations. Given that the HAIL array was used to bound the size of typical perturbation regions to ~150 km in diameter [*Johnson et al.*, 1999], it is evident that for this case study, the lack of events during sprite times cannot be attributed to the lack of VLF paths nearby, since no causative lightning flash was more than 32 km from any of the VLF paths being monitored. Another 71 VLF signal perturbations were observed that were not associated with sprites; 44 of those were verified to occur in association with lightning in the same region as the sprite-producing flashes, and within the camera field of view. Only 4 VLF signal perturbations were observed on the NLK paths; one example is shown in Figure 5. Of these 4 events, 2 events showed perturbations in amplitude and 3 showed phase perturbations (one event had both). However, the largest NLK signal amplitude and phase perturbations were only 0.4 dB and ~6 degrees, respectively; in comparison, large events on the NAA paths associated with sprites during this day exhibited changes of up to 2.0 dB in amplitude and 20 degrees in phase. Only a handful of events were seen on the NAU transmitter paths, all of which can be associated with forward scattering based on their locations with respect to the HAIL paths. No VLF perturbation events were detected on any of the NPM signal paths.

[17] Figure 6 shows a histogram of the VLF perturbation amplitudes for sprite-related and non-sprite-related VLF events. It is evident that sprite-related events are typically larger, and that the largest events always coincide with sprites. Overall, we find that the sprite-related events have an average perturbation of 0.71 dB, while non-sprite-related events have an average of 0.37 dB. This finding may simply indicate that the same characteristics of the parent lightning that control sprite occurrence (i.e., charge moment or the QE field that leads to heating of

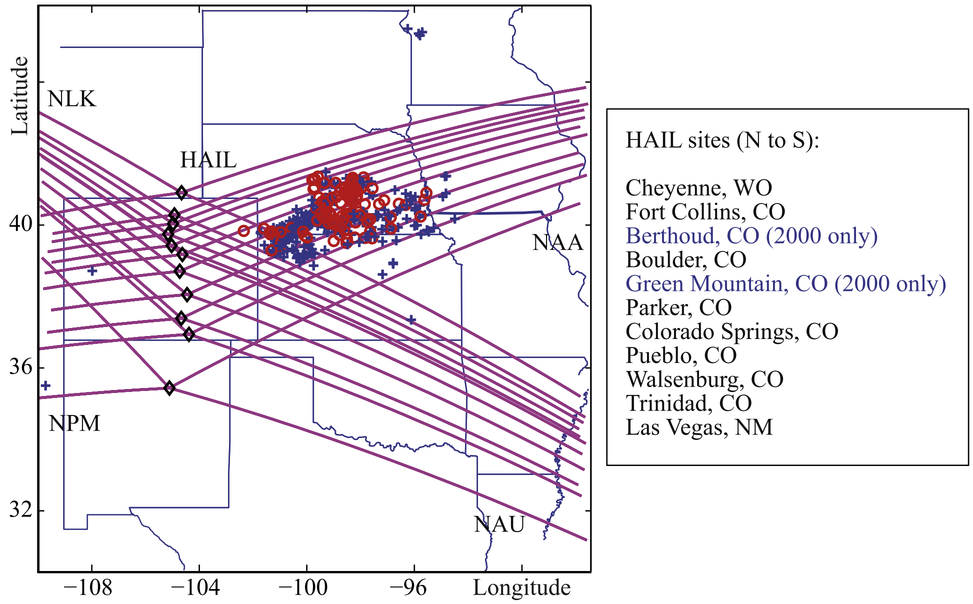

Figure 3. Map showing locations of sprites (circles) and other +CGs > 50 kA (crosses) for storm of 18 August 1999 from 0230 to 0730 UT. The HAIL paths from NLK, NAA, NAU, and NPM are also shown.

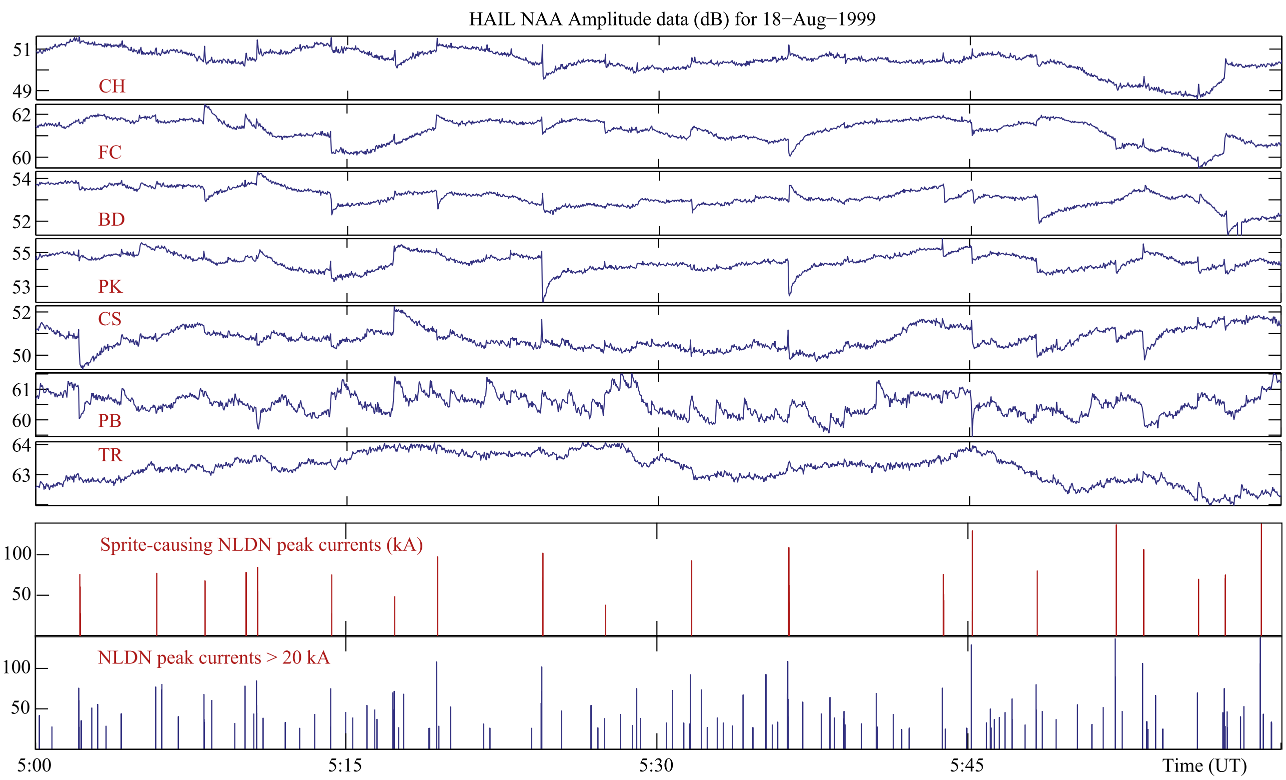

Figure 4. The 18 August 1999 narrowband VLF data from the HAIL array for a 1-hour period starting at 0500 UT. Plotted below the data are the lightning peak currents of sprite-causing CGs and of all CGs > 20 kA. It is evident from this figure that most but not all of the VLF perturbations in this time period are associated with sprites.

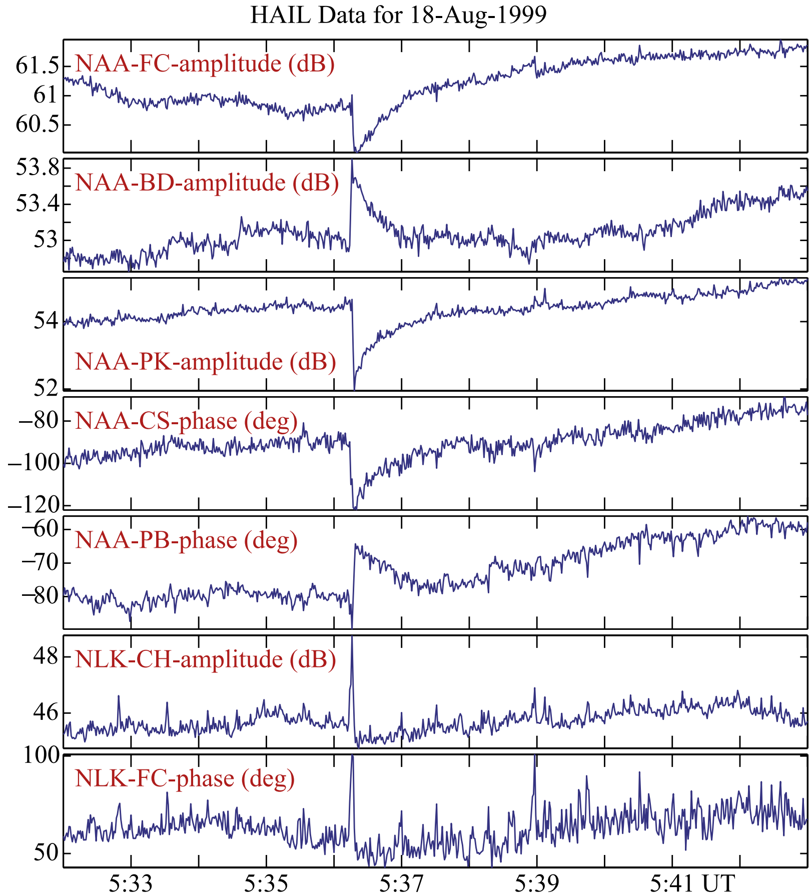

Figure 5. The 18 August 1999 narrowband VLF data for an event occurring at 0536 UT, in association with a sequence of five sprites. Large perturbations are seen in phase and amplitude on the NAA paths, and small perturbations are evident on the northmost (CH and FC) NLK paths.

ambient electrons [see *Cummer and Inan*, 2000]) also leads to the ionospheric disturbances that are signified by early/fast VLF perturbations.

2.3. July 2000

[18] Sprites were observed from YRFS on 9 nights in July 2000; here we present data from 8 of those nights. This data set provides a range of storm conditions to monitor, including large mesoscale convective systems displaced from the HAIL paths (2 July) or overlapping the HAIL paths (4 July), as well as smaller, or more distributed storms on the HAIL paths (6 July and 22 July).

[19] The locations of sprites and +CGs for 22 July 2000 relative to the HAIL array are shown in Figure 7. It is evident that most of the sprites occurred near the NAA-TR path; indeed, most of the VLF perturbations are seen on this path, as shown in Figure 8 for a 2-hour period. The overall statistics of sprites and early/fast events for July 2000 are shown in Table 1; 2 July 2000 is not included, since the storm was far from the HAIL paths. Overall, we find that of 151 sprites observed on the nights listed in Table 1, 53 had corresponding VLF perturbations, typically on the NAA-HAIL paths. Only 25 other VLF perturbations were found within the region covered by the camera field of view. Once again, we have clear evidence of sprites with and without corresponding VLF perturbations, and vice versa.

[20] On 2 July 2000 a large storm to the Northeast of YRFS produced a huge number of small sprites, as presented by *Gerken and Inan* [2004]. No perturbations were found on the NAA or NAU paths, as expected, since the storm was located more than 400 km (lateral distance) from

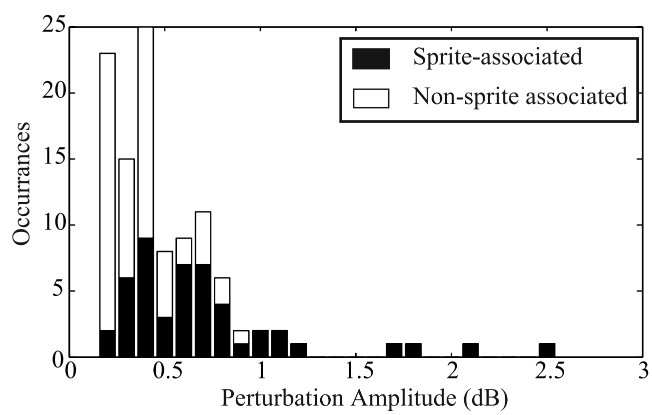

Figure 6. Perturbation amplitudes for sprite-associated and non-sprite-associated VLF perturbations of 18 August 1999. All of the largest perturbations are associated with sprites; the largest of the perturbations without sprites is 0.9 dB.

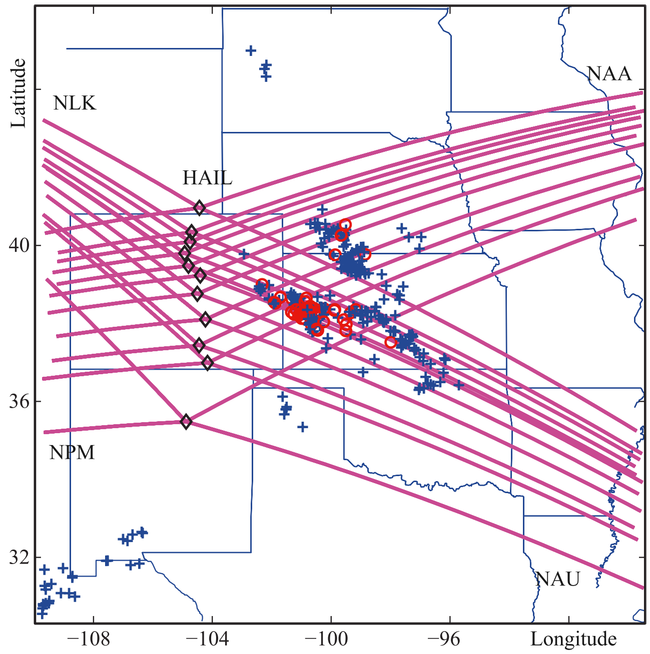

Figure 7. Map showing locations of sprites (circles) and other +CGs > 50 kA (crosses) for storm of 22 July 2000, from 0300 to 0700 UT. The HAIL paths from NLK, NAA, NAU, and NPM are also shown.

the nearest HAIL path. However, 9 VLF perturbations were found on the NLK paths, 5 of which were coincident with sprite-causative +CGs, while no CGs were found nearby in time for the other four VLF perturbation events, which could instead be attributed to lightning-induced electron precipitation events due to lightning in a storm near 31°N, 106°W to the southwest of the HAIL array, which coincidentally occurred within ~0.5 s of the sprite. Furthermore, upon comparison with sprite image data, it is found that these 5 events coincide with the largest sprites observed on this night, and that 4 of the 5 were composed of multiple sprites, extending laterally to tens of km. Figure 9 shows two of these sprites for comparison, along with a typical "reference" sprite for that night.

3. Discussion and Interpretation

3.1. VLF Backscatter From Sprites

[21] The 5 NLK perturbations on 15 July 1995 and the 4 such events on 18 August 1999 are suggestive of the possibility of scattering of VLF energy from the sprite body. In the 1995 cases, the causative +CGs occurred 280–330 km from the receiver at YRFS, a distance too great for the perturbations to be attributed to the QE-heated region (e.g., the sprite halo) overlapping the VLF signal path, since this region has been constrained to a radius of <100 km [*Johnson et al.*, 1999]. There remains the possibility that these perturbations were associated with EMP-induced conductivity changes in the ionosphere, associated with elves (which may have been below the camera sensitivity); since elves have observed radii extending to a maximum of 330 km [*Barrington-Leigh et al.*, 1999]. However, the 18 August 1999 NLK perturbations were all associated with +CGs 400–500 km from the receiver, and the 2 July 2000 events were >500 km distant. Furthermore,

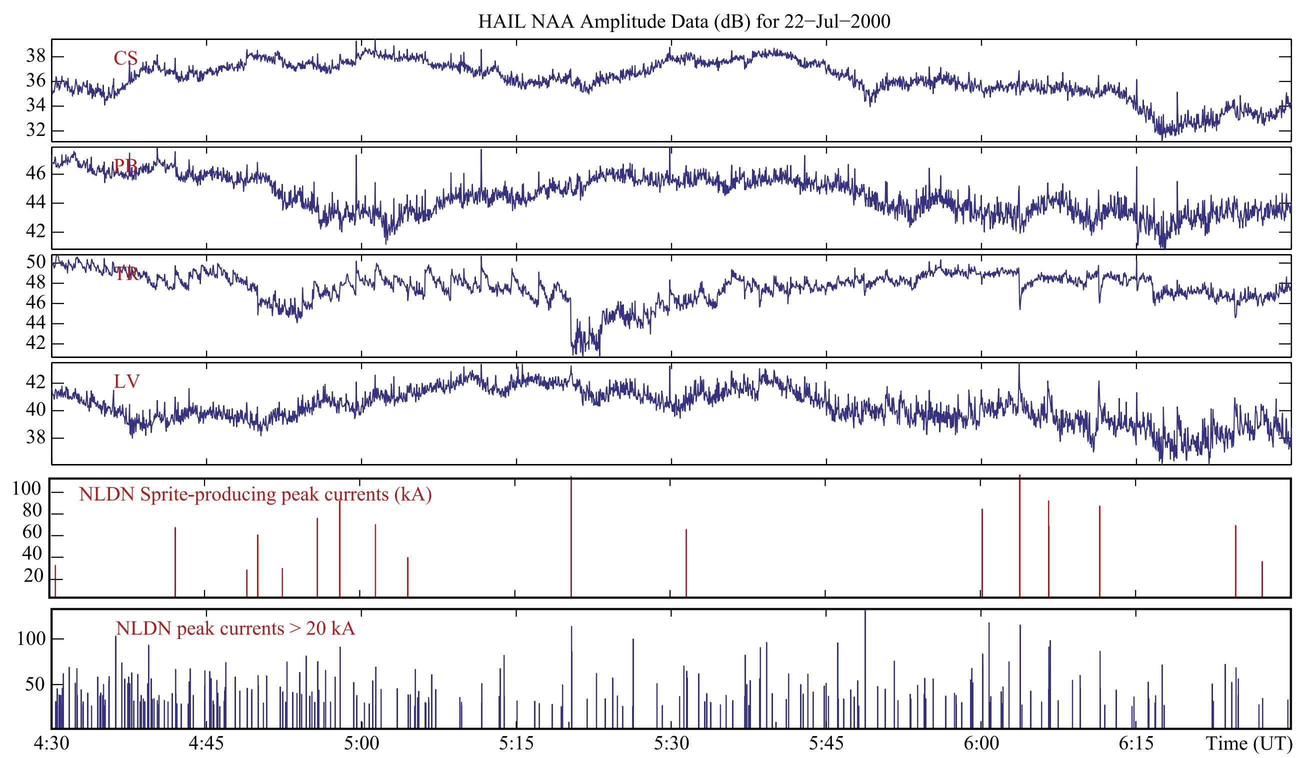

Figure 8. VLF narrowband data for a 2-hour period on 22 July 2000. Lightning data are plotted for sprite-causing CGs and for all CGs > 20 kA. A large number of small VLF perturbations are evident, and many are associated with sprite-causing CGs.

Table 1. Sprite/VLF Data for July 2000

Date	Sprites	Sprites With VLF	VLF Without Sprites
3 Jul	25	1	0
4 Jul	43	26	8
6 Jul	5	2	4
11 Jul	4	0	0
18 Jul	14	7	0
19 Jul	15	3	2
22 Jul	45	14	11

Taranenko et al. [1993a] predict ionization enhancements due to EMP at altitudes of 85–95 km, above the VLF reflection height, and in agreement with elve observations [*Fukunishi et al.*, 1996; *Barrington-Leigh et al.*, 2001]. In addition, current studies have shown very few isolated elves (i.e., those without accompanying sprites) to be associated with VLF perturbations [*Mika et al.*, 2006].

[22] Thus we are left with the possibility that at least some of the perturbations on the NLK signals are caused by scattering from the sprite features, as postulated by *Dowden et al.* [1996]. However, *Dowden et al.* [1996] claim that ''essentially all red sprites are associated with VLF [perturbations] irrespective of their displacement from the Great Circle Path,'' implying a one-to-one correspondence between sprites and VLF signal perturbations. The authors further claim that this fact can be used to detect the occurrence of sprites without optical data. However, the data presented here clearly show that this is not the case, that backscatter from sprites occurs very rarely, and that only very few sprites are associated with VLF perturbations when the sprite is >100 km from the VLF transmitter path.

[23] The fact that VLF backscatter events are extremely rare (9 such events out of more than 250 sprites analyzed) suggests that they might be associated with the largest sprites in terms of their horizontal extent, such that they create a large (compared to VLF wavelength) ''conductive grid'' for reflection of the VLF energy. In most of the backscatter cases reported here we find indeed that the backscatter perturbations are associated with multiple sprites. In this way, the sprites occurring in close succession set up a conductive grid (columns of ionization that decay over timescales of 10s of seconds) that is much larger than their individual size. This hypothesis also agrees with the sprites observed for 2 July 2000 and presented in Figure 9, which are horizontally expansive and are composed of multiple sprites. It is interesting that these events involve perturbations of the NLK signals but not of the NAA ones; in this case, due to the storm location, NAA perturbations could in principle also be attributed to wide-angle scattering from the sprite body and not forward scattering from the halo. The lack of NAA perturbations may be due to directional scattering; modeling results by *Rodger and Nunn* [1999] of scattering from a real distribution of sprite features showed a complex series of nulls and peaks in the angular scattering distribution; in addition, *Rodger et al.* [1999] showed similar nulls and peaks, on the order of ~100s of km, as a function of distance from the receiver, attributed to interfering waveguide modes.

[24] Figure 10 shows a correlation between sprite brightness and magnitude of VLF perturbation on the NAA or NSS signals. Since no forward scatter perturbations were observed on 2 July 2000 due it the storm location, data is shown only for the 1995 and 1999 cases. In Figure 10 the sprite brightness is defined by integrating the luminosity produced by the sprite over the entire pixel range of the image, where the pixel values range from 0 to 255, so that brightness is a factor of both luminosity and size. For the July 1995 and August 1999 cases, sprite brightness is weakly correlated with VLF perturbation amplitude. However, it is important to note that this analysis method suffers from the fact that larger lightning discharges will likely produce both larger sprites and larger early/fast events whatever the physical mechanism is for these perturbations, so that correlation itself does not provide evidence for scattering from the sprite body. We also see from Figure 10 that the rare ''backscatter'' events are, in most cases, associated with the brightest sprites, though not always with the largest perturbations, as is also evident in the 2 Jul 2000 data. Thus these backscatter events appear to be more closely linked to the sprite itself than to density enhancements at higher altitudes (e.g., sprite halo altitudes) in the ionosphere, which may be signified by the typical forward scatter signature of the NAA and NSS signals.

3.2. Correlation of Sprites With VLF Perturbations

[25] From the data presented above we conclude that VLF perturbations are not observed in a one-to-one relationship

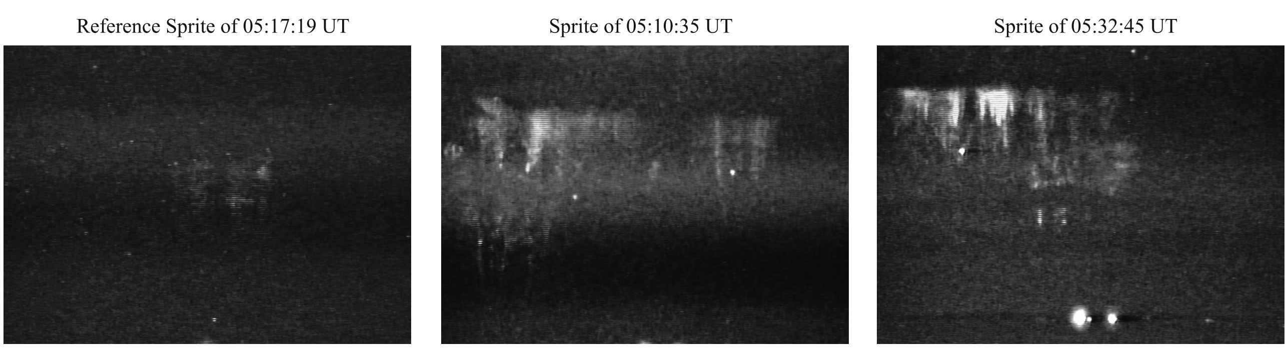

Figure 9. Large sprites observed on 2 July 2000. (left) A ''typical'' sprite for this night at 0517:19 UT. Most sprites are even smaller than this one. (middle and right) Sprite events for 0510:32 and 0532:45 UT. These events are image sums over a few sprites occurring within a few seconds of each other to show the spatial extent over the entire sprite event.

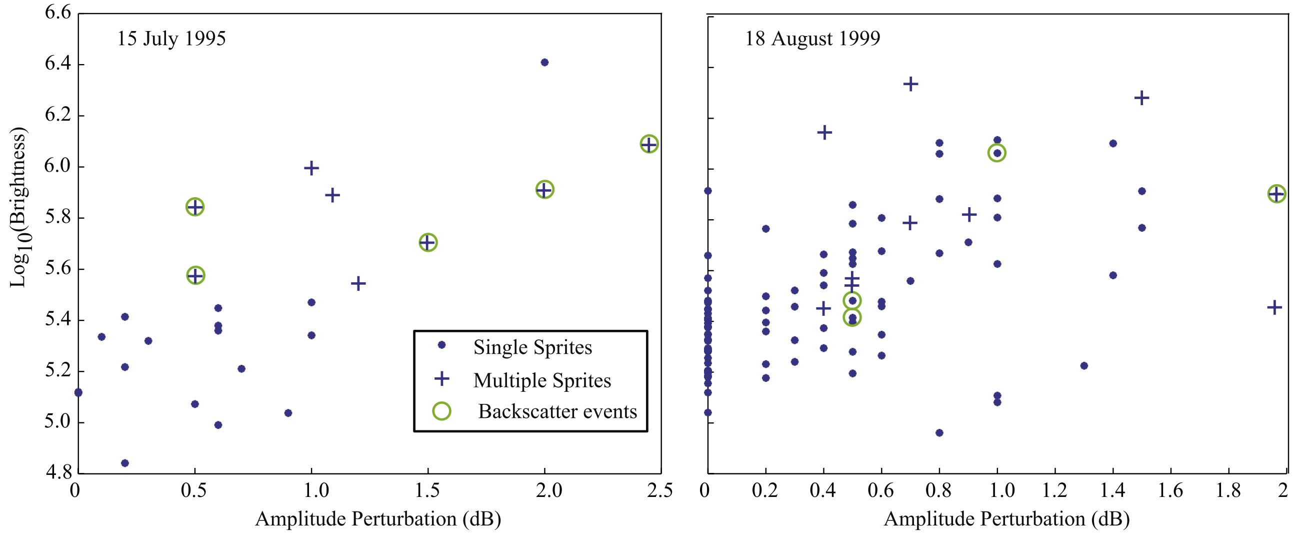

Figure 10. Sprite brightness versus VLF perturbation amplitude for the July 1995 and August 1999 cases. See the text for the meaning of the sprite "brightness."

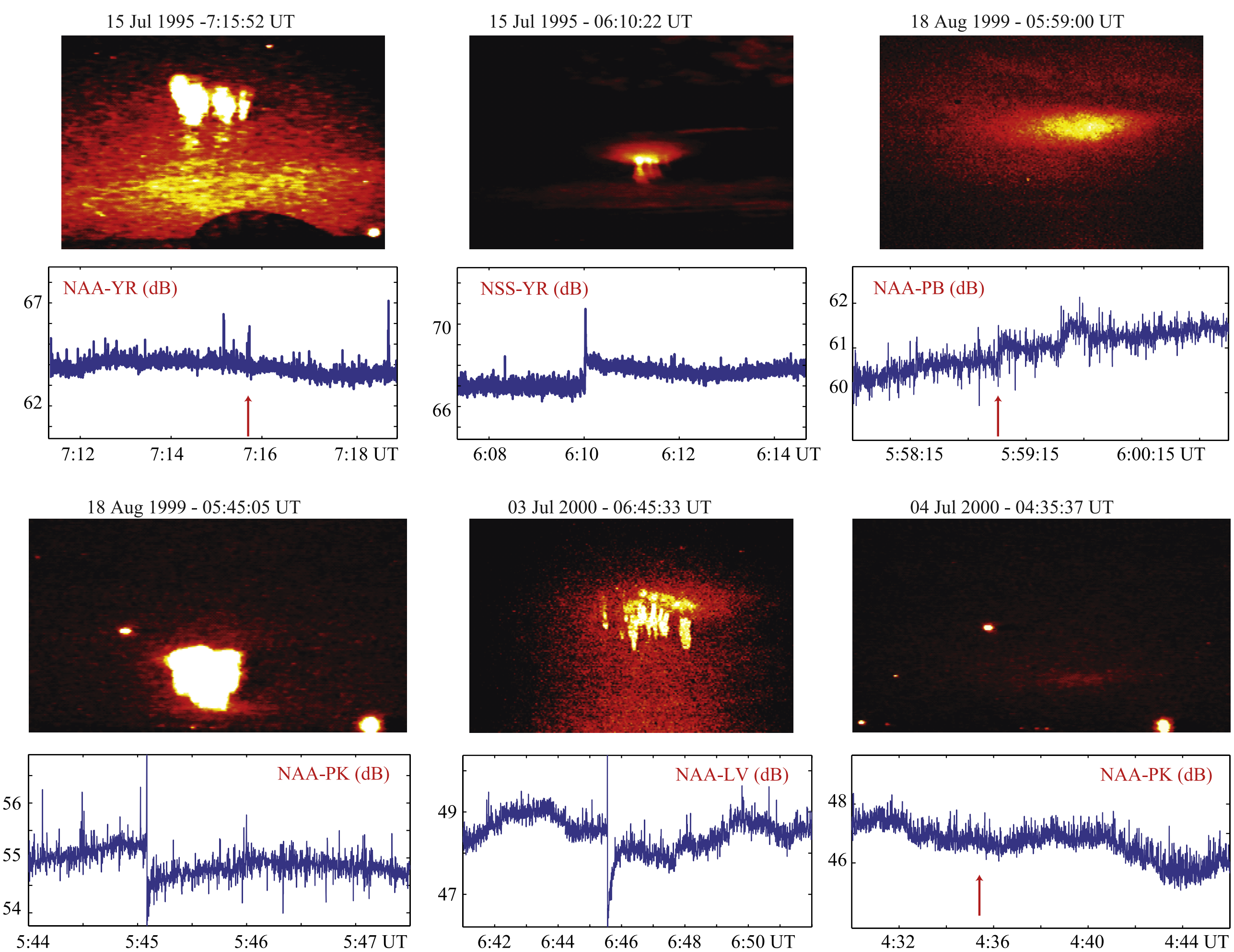

Figure 11. Examples of sprite/halo/VLF combinations. Clockwise from top left: a sprite with no halo and no VLF event; a sprite with halo and VLF event; a halo with no sprite, with a VLF event; a halo with no sprite and no VLF event; a sprite with halo and large VLF event; and a sprite with no halo and no VLF event. The images have been color contrasted to bring out the weak halos. Arrows in the VLF data point to the time of the sprite, except where obvious.

with sprites, so that the perturbations cannot be attributed exclusively to scattering from the sprite body. In the data set presented here, ~48% of sprites have associated VLF perturbations; or, when viewed conversely, ~61% of VLF perturbations are associated with sprites. This result may corroborate the postulate that VLF perturbations are associated with the mechanism of sprite halo production, and thus with the modeling results of *Moore et al.* [2003], since sprites are frequently observed with or without accompanying halos. Indeed, in the same data set, examples of sprite halos are observed without accompanying sprites, but with accompanying VLF perturbations. However, contrary to *Moore et al.'s* [2003] results, we also observe halos with and without associated VLF perturbations, and vice versa. The only exception is when sprites and halos are seen together; all such cases examined had associated VLF perturbations. Examples of each of the possible combinations in shown in Figure 11.

[26] While the lack of a one-to-one association between sprites and early/fast VLF perturbations in our data set appears to be inconsistent with the findings of *Haldoupis et al.* [2004], the difference between these may well be due to the fact that the disturbed ionospheric regions in the cases studied by *Haldoupis et al.* [2004] were much closer to the VLF transmitter. When the signal propagation from transmitter to receiver is broken into waveguide modes, the forward scattering of VLF energy from the ionospheric density perturbation may occur in one or only a few propagating modes. Over the course of the propagation path, energy may couple between modes, and over a long distance, the perturbation signature may be washed out through this coupling process. In the data presented by *Haldoupis et al.* [2004], the causative CGs were near the transmitter, and the receiver was some ~1000s of km away, so that only the largest perturbations would survive to the receiver; and, these largest perturbations (caused by the largest CGs, in terms of peak current and/or charge moment) would likely coincide with sprites, as shown in the data set presented here. Conversely, in our observations the causative CGs are close to the receivers (~100s of km away), so that even the smaller perturbations survive the distance to the receiver without being washed out in mode coupling, and these smaller perturbations may not have associated sprites.

[27] This scenario is contrary to the conclusions of *Haldoupis et al.* [2004], which related the one-to-one correspondence to the proximity of the perturbed region to the transmitter. Therein it was proposed that higher-order modes, which decay rapidly as they propagate away from the transmitter, could be more easily perturbed by the ionospheric density enhancement, and thus through mode coupling into lower-order, better propagating modes, the perturbation could survive to the VLF receiver some 1000s of km away. However, that postulate suggests that in data such as that presented here, where the perturbed region is farther from the transmitter, smaller events would not be seen, despite correlating with sprites, so that all VLF perturbations would be required to have corresponding sprites, although some sprites may not have detectable VLF events. In the data presented here, we clearly have examples of VLF perturbations without sprites, so that the rationale expressed by *Haldoupis et al.* [2004] is not likely to be the sole reason for the difference between the two data sets.

4. Summary

[28] We have presented data from three periods of sprite history that correlate with early/fast VLF event observations. The data show that when the geometry allows for the measurement of even the smallest density perturbations (i.e., when the receiver is <~500 km from the perturbation), they do not occur in one-to-one correlation with sprites. It has been shown that many sprites occur without coincident VLF signal perturbations, while in other cases, such early/fast events are seen without coincident sprites. We have also shown that only a very small subset of sprites show characteristics of VLF backscatter from the sprite body, and that all such cases correspond to multiple sprites or horizontally expansive sprites.

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