

Sferic Clusters Associated with Early/Fast VLF Events

M. P. Johnson and U. S. Inan

STAR Laboratory, Stanford University, Stanford, CA 94305

Abstract. Characteristic subionospheric signal perturbations referred to as ‘early/fast’ VLF events are found to consistently be associated with the simultaneous occurrence of unusual clusters of radio atmospherics as observed in wide-band VLF data. A burst of sferic activity occurs at or before the onset of the early/fast events and lasts from several hundred milliseconds to several seconds. The cluster energy attenuates with distance more rapidly than cloud-to-ground (CG) lightning, suggesting that these clusters may be produced by intracloud (IC) lightning, and that the charge movement within the cloud may thus play a role in the causative mechanism of early/fast VLF events.

Introduction

‘Early/fast’ VLF events are characteristic changes in the amplitude and/or phase of a subionospheric VLF signal that exhibit a rapid onset (<20 ms, i.e., fast) followed by a relatively slow recovery (typically 10 to 100 s) and which occur within 20 ms of an associated radio atmospheric (i.e., early) [Inan *et al.*, 1993].

These VLF signal changes, indicative of changes in D region conductivity, exhibit a characteristic amplitude and/or phase perturbation signature that is unambiguously identifiable. The disturbance can be laterally displaced several wavelengths from the Great Circle Path (GCP) between the transmitter and receiver. A recent study has confirmed that early/fast events strongly scatter VLF signals largely in the forward direction, consistent with a disturbed region having a lateral extent of 90 ± 30 km [Johnson *et al.*, 1999].

In past observations, early/fast VLF events have been identified by their simultaneous (<20 ms) onset with respect to an associated radio atmospheric and sometimes also as CG discharges identified in National Lightning Detection Network (NLDN) data [Inan *et al.*, 1996a; and references therein]. In many cases, the associated sferics were observed in narrowband VLF data as singular impulsive peaks, allowing the identification of the event onset and supporting the concept of the ionospheric effect being produced by a single discharge. Those NLDN recorded flashes associated with early/fast VLF events are found to be positive and negative, ranging in recorded peak current intensities from 20 kA to 180 kA [Inan *et al.*, 1996b]. However, many events were observed without NLDN detected CG flashes but nevertheless with clear impulsive sferic signatures, interpreted as possible evidence of intracloud flashes. One common feature of early/fast observations reported in most past work has been that the associated sferics were observed at distances of >500 km from the lightning discharges in narrowband VLF channels tuned to known VLF transmitter frequencies.

Copyright 2000 by the American Geophysical Union.

Paper number 1999GL010757.
0094-8276/00/1999GL010757\$05.00

As a result, only the peak of the associated sferic energy which exceeded the transmitter signal level was detectable.

In this paper, we report broadband VLF measurements of sferics associated with early/fast VLF events, carried out within several hundred kilometers of the causative lightning. Within this range, several hundred millisecond clusters of sferics are consistently observed to accompany event onsets. The sferic clusters are found to attenuate with distance more rapidly than discrete sferics often associated with CG flashes, indicating that they are likely to be produced by quasi-horizontal (intracloud) current sources. Our results are consistent with the one previously reported broadband case of early/fast event associated sferics located nearby the source lightning discharges, in which case clusters remarkably similar to those reported here were observed during event onsets [Rodriguez *et al.*, 1992].

Description of the Data

The VLF data were collected during the summer of 1998 by a set of nine receivers with ~ 65 km spacing (Figure 1a) constituting the Holographic Array for Ionospheric Lightning research (HAIL) system [Johnson *et al.*, 1999]. NAA, the VLF transmitter used in this work, is located in Maine and radiates ~ 1 MW at 24.0 kHz.

At each receiver site, the wideband signal detected by a 1.7×1.7 m² magnetic loop antenna is bandpass filtered to a range of 9–45 kHz and sampled at 100 kHz with triggers provided by GPS timing. This broadband signal is subsequently rectified, averaged, and recorded with 20 ms resolution to constitute a ‘sferic channel’ in order to aid in the detection of occurrence times and durations of sferics radiated by lightning discharges. The receivers also digitally down-convert the individual VLF transmitter signals and record the demodulated amplitude and phase with 20 ms and 100 ms resolution, respectively, typically during 01:00 to 13:00 UT when most of the observed VLF paths are in the nighttime sector. In addition, VLF broadband receivers located near Fort Collins at the Yucca Ridge (YR) field station and at Stanford University (SU) were used for continuous broadband (~ 100 Hz to ~ 20 kHz) recordings from which individual sferics can be studied in detail.

Data from the National Lightning Detection Network provide the time, location, and peak current of most CG lightning discharges [Orville, 1994], and are used in this work to locate the discharges associated with the early/fast events. The entire NLDN dataset, covering the continental U.S., was included in the analysis.

Early/Fast Event Association with Sferic clusters

On seventeen days in August 1998, HAIL data clearly show early/fast event activity on the NAA signal at one or

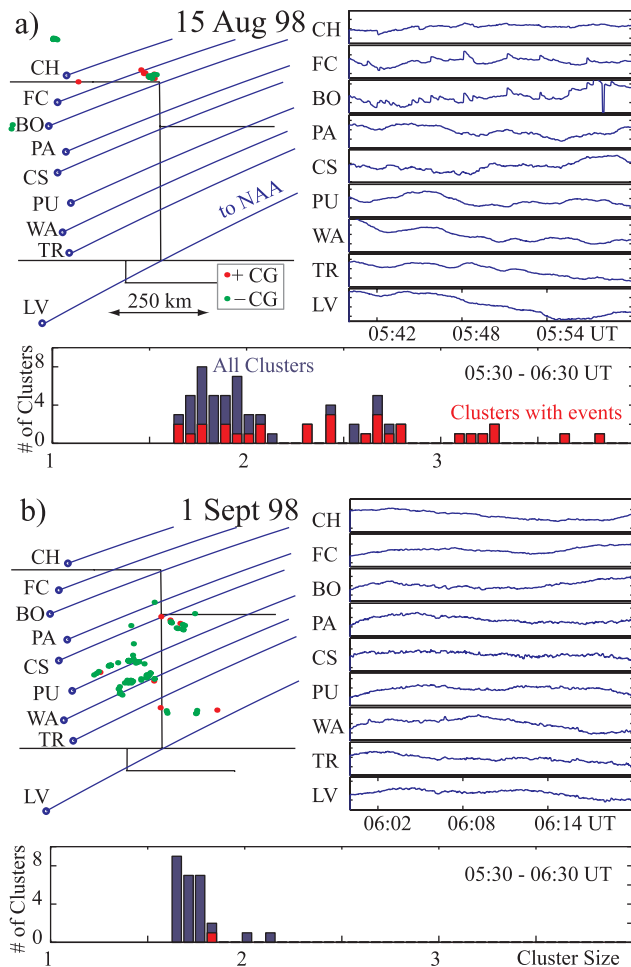


Figure 1. The location of lightning discharges for 20 minute periods on two different days are shown, along with the amplitude of the NAA transmitter received at 9 sites (all shown with a 3.5 dB range). (a) On 15 August 1998, early/fast events are observed at the FC and BO sites, and a histogram of cluster intensity shows large clusters that are preferentially associated with the events (histogram only shown clusters with more than 1.65 times the median sferic energy). (b) On 1 September 1998, lightning occurring with similar proximity to the array does not show many large clusters or early/fast VLF events.

more of the HAIL sites. Of these seventeen days, ten have records during which repeated (>10 in one hour) and clearly identifiable (>0.5 dB) early/fast events were observed.

In Figure 1, NLDN recorded CG lightning and the corresponding amplitude records from the HAIL receivers are shown for periods from two different days. On 15 August, several discharges located near the Northeast corner of Colorado occurred within 20 ms of early/fast events as recorded by two receivers with GCPs on either side of the lightning location. On 1 September, NLDN records a number of discharges with similar proximity to the array and similar peak currents, yet few early/fast events are observed.

Four early/fast events from the 15 August period as measured on the NAA-FC signal are labeled A-D in the top panel of Figure 2. Expanded views of these event onsets, spectrograms of the corresponding broadband data from YR, and NLDN recorded times of CG discharges are shown for each of the four events. Although NLDN only recorded

a CG at the onset of event D, each of the four events coincides with an unusually large cluster of sferic energy. In these and other cases of an event without an associated CG, based on the similarity of consecutive event signatures and sferic clusters, we nevertheless assume that the locations of the causative sferics are within the same thunderstorm.

Such large sferic clusters are found to occur predominantly in association with early/fast event onsets and may thus represent an inherent property of lightning episodes that produce ionospheric disturbances. In the 15 August case, this one-to-one association was observed to the degree that the early/fast VLF event onsets could be identified solely by inspection of the sferic data. In another case (not shown), during a period from 2 August 1998 from 05:00 to 05:30 UT, hundreds of CGs occurred within 500 km to the east of the HAIL array. During this period, only ~ 10 CGs were accompanied with sferic clusters, and these were also the only CGs associated with with early/fast events measured primarily at the PU receiver.

As exemplified by the 1 September case in Figure 1, there are many more lightning discharges than there are VLF events. During most periods of early/fast VLF event activity observed with the HAIL array, many NLDN recorded CGs in a localized storm are not associated with VLF events even if they occur within close proximity of one of the HAIL VLF paths, consistent with past findings [Inan *et al.*, 1993; Johnson *et al.*, 1999] that early/fast event occurrence or magnitude does not correlate well with NLDN peak current.

The high degree of sferic cluster variability is well illustrated in Figure 3, showing several early/fast events (labeled

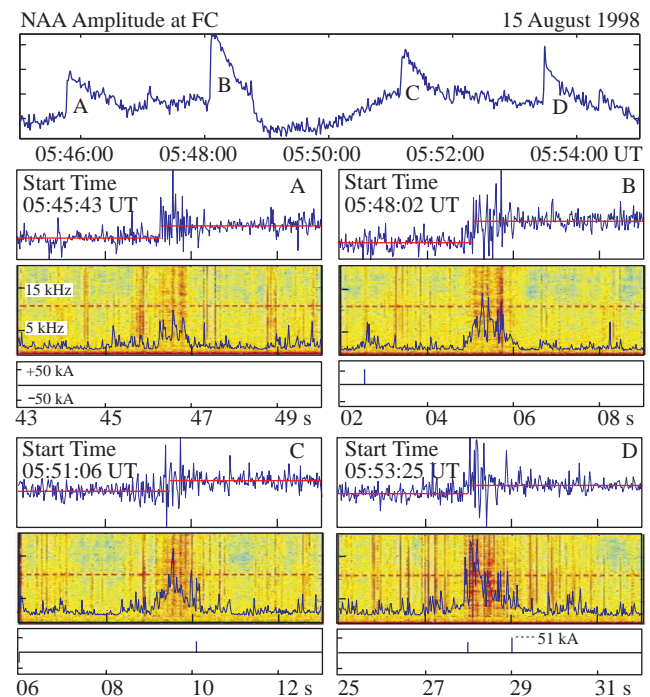


Figure 2. Top panel shows a sequence of four early/fast events labeled A-D measured on the NAA-FC path. Each of the four event onsets is shown below with the NLDN recorded discharges and the associated broadband spectrogram showing the sferic clusters (with integrated signal intensity superimposed). Events A-C have sferic energy at the event onset, but do not have an associated CG, suggesting that intracloud lightning was causative.

A–H) and associated clusters observed on 10 August 1998. These spectra were recorded at YR, ~ 300 km from the associated CG lightning activity.

Despite their variability in shape and duration, clusters all have an increased integrated intensity, and an algorithm has been designed to identify them. First, the sferic channel record is convolved with a test shape and normalized by its median value. Then, the largest output of the convolution record is selected from every few seconds, and only values above a threshold are selected as clusters. The blue histograms in Figure 1 are of this cluster intensity for a one hour period around the 20 minute periods shown (a cluster intensity of 4 represents 4 times the median integrated intensity, weighted by the test shape). The histogram of the subset of clusters associated with a VLF event above a certain threshold is superimposed in red. In Figure 1, the test shape was a 80 second unit step, with a 20 second interval, a normalized median threshold of 1.65, and an event threshold of 0.3 dB. Despite this very general algorithm used for both days in Figure 1, the results show that (i) there are relatively larger clusters seen on 15 August than on 1 September and (ii) nearly all of the large clusters are associated with early/fast events, and (iii) nearly all the early/fast events as associated with large clusters, suggesting a unique association. Although not shown for brevity, this algorithm yielded similar results for the 10 August period.

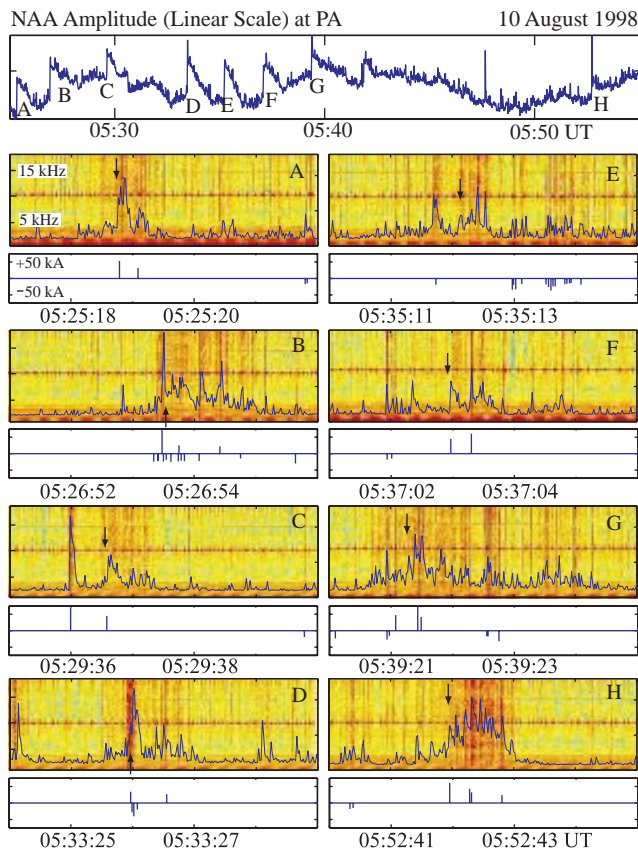


Figure 3. Eight early/fast events measured on the NAA-PA path, labeled A–H, are associated with sferic clusters showing a variety of shapes and durations. Some of the clusters are associated with NLDN recorded CGs while some are not. The time of the event onset is indicated with an arrow.

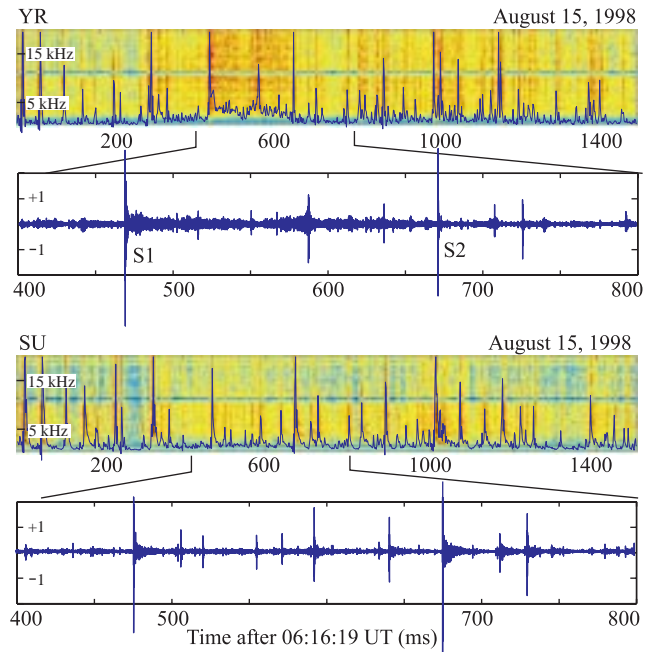


Figure 4. Spectrogram and normalized time domain data shown from YR, 200 km from the associated lightning discharge, with a cluster of sferic activity. Broadband data recorded at SU, some 1600 km farther from the lightning, demonstrates that the sferic cluster radiation has attenuated more rapidly than the individual atmospherics, consistent with quadrupole radiation from quasi-horizontal (intracloud) lighting.

Intracloud Lightning as the Source of Sferic clusters

A key property of these early/fast event associated sferic clusters is their relatively rapid attenuation with distance. This is illustrated in Figure 4, showing a sferic cluster associated with an early/fast event as observed at YR (200 km from the lightning) together with simultaneous spectra recorded at Stanford University (SU) (1800 km from the lightning). The associated time-domain waveforms are also shown on an expanded scale for a selected portion around the event onset. While the sferic cluster is clearly evident on the YR spectrogram, it is not visible at SU. In particular, the ~ 200 ms portion of the cluster is clearly evident in the YR time-domain waveform and detected intensity records from ~ 450 to ~ 650 ms. Noting that both the YR and SU time domain data are normalized so that the largest sferics have approximately the same amplitude, the intensity of the cluster of VLF energy (relative to the peak intensity of the largest sferics) is much larger at YR than at SU. It thus appears that the sferic cluster component of the VLF signal as observed at YR attenuated during its propagation between YR and SU significantly more than the discrete sferics.

This more rapid attenuation of the sferic cluster is consistent with an intracloud (quasi-horizontal) source, since the radiation pattern of a horizontal dipole above conducting ground exhibits a null at low elevation angles and thus preferentially launches waves that emanate from the antenna at relatively high angles [Jordan and Balmain, 1968; p. 641-644]. Considering propagating modes in the earth-ionosphere waveguide as a superposition of uniform plane waves, wave energy launched at such high elevation angles

preferentially excites higher order waveguide modes [Inan and Inan, 1999; p. 269-71], which in turn have higher attenuation rates [Wait, 1957]. Vertical discharges, in contrast, exhibit a maximum in their radiation pattern at low elevation angles, thereby preferentially exciting low order waveguide modes with substantially lower attenuation rates.

In past work involving measurements at distances >500 km from the active thunderstorm, singular sferics were always observed in association with early/fast event onsets, even when no associated CG flashes were identified by NLDN. Such 'causative' sferics may have been due to large quasi-vertical intracloud flashes that partially excite higher order modes. As an example, the sferics labeled S1 and S2 in Figure 4 both appear to attenuate by a similar amount at SU compared with YR; yet, only S1 was recorded by NLDN (with peak current of +30 kA) as a CG. Peak current correlates well with sferic intensity, and both appear to be of the same magnitude. Based on the fact that NLDN misses less than 10% percent of 30 kA flashes in the central U.S., S2 may have resulted from a quasi-vertical IC. On the other hand, these particularly complicated discharges may more often be discarded by the NLDN detection algorithm.

Although highly variable as indicated in Figure 3, the general character of the sferic clusters consists of persistent VLF energy lasting for a few hundred milliseconds followed by more impulsive clusters, consistent with other measurements of intracloud flashes. As an example, Figure 11 of Shao and Krehbiel [1996] shows a radar echo from an intracloud lightning flash demonstrating the continuous channel active portion of the flash lasting for ~200 ms followed by the so-called K burst of intermittent flashes lasting for another ~500 ms, with an overall shape remarkably similar to that of sferic bursts shown here. This similarity, the relatively high attenuation of the sferic cluster energy, the several hundred millisecond sustained radiation, and the lack of NLDN recorded CGs in every case all but excludes the cloud-to-ground channel as the sole radiator of the sferic clusters, strongly suggesting that the VLF energy of the clusters originates in intracloud lightning.

Summary and Discussion

Our results indicate that ionospheric disturbances that are detected as early/fast VLF events are exclusively produced by lightning episodes which include a large intracloud cluster. This exclusive association was missed in most past work due to the fact that 'causative' sferics were observed at locations distant from source discharges and in narrow-band channels tuned to VLF transmitter frequencies. Sferic clusters lasting ~ 1 s and exhibiting properties very similar to those shown here were observed in association with VLF perturbation events in one previous study involving broadband measurements at ~ 500 km from the active storm center [Rodriguez et al., 1992]. However, in that paper the authors did not recognize the clusters as a property of the causative lightning events and the exclusive nature of their association with early/fast events. This more general result constitutes our first insight into the specific nature of lightning discharges that lead to enhanced electrodynamic coupling between cloud tops and the lower ionosphere.

In view of the previously reported [Inan et al., 1995] association between Sprites and early/fast VLF events, it is

likely that at least a subset of such lightning episodes may be responsible for production of high altitude luminous glows known as Sprites. Possible involvement of intracloud discharges and horizontal charge motion in sprite producing lightning events has been suggested based on observed long delays between 'parent' CG discharges and sprite events [Bell et al., 1998], and the relatively poor correlation between vertical lightning charge moment change and Sprite intensity [Cummer and Stanley, 1999].

Acknowledgments. This work was supported under the National Science Foundation and the Office of Naval Research under grants ATM-9528173 and N00014-94-1-0100. The authors are indebted to the many high school teachers and students involved in the support of the HAIL array. We thank K. Cummins of Global Atmospheric, Inc. for allowing us to use the NLDN data.

References

- Boeck, W. L., O. H. Vaughan, R. J. Blakeslee, B. Vonnegut, and M. Brook, The role of space shuttle videotapes in the discovery of sprites, jets and elves, *J. of Atmos. and Solar-Terr. Phys.*, 60, 669-77, 1998.
- Cummer, S. A., and M. Stanley, Submillisecond resolution lightning currents and sprite development: observations and implications, *Geophys. Res. Lett.*, 26, 3205-08, 1999.
- Inan, U. S. and J. V. Rodriguez, VLF signatures of lightning-induced heating and ionization of the nighttime D region, *Geophys. Res. Lett.*, 20, 2355-58, 1993.
- Inan, U. S., T. F. Bell, V. P. Pasko, D. D. Sentman, E. M. Wescott, and W. A. Lyons, VLF signatures of ionospheric disturbances associated with sprites, *Geophys. Res. Lett.*, 22, 3461-64, 1995.
- Inan, U. S., A. Slingeland, and V. P. Pasko, VLF and LF signatures of mesospheric/lower ionospheric response to lightning discharges, *J. of Geophys. Res.*, 101, 5219-38, 1996a.
- Inan, U. S., V. P. Pasko, and T. F. Bell, Sustained heating of the ionosphere above thunderstorms as evidenced by 'early/fast' VLF events, *Geophys. Res. Lett.*, 23, 1067-70, 1996b.
- Inan, U. S. and A. S. Inan, *Electromagnetic Waves*, Prentice Hall, 1999.
- Jordan, E. C. and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, 2nd ed., Prentice Hall, 1968.
- Johnson, M. P., U. S. Inan, and S. J. Lev-Tov, Scattering pattern of lightning-induced ionospheric disturbances associated with early/fast VLF events, *Geophys. Res. Lett.*, 26, 2363-66, 1999.
- Orville, R.E., Cloud-to-Ground Lightning discharge characteristics in the contiguous United States: 1989-1991, *J. of Geophys. Res.*, 99, 10833-41, 1994.
- Rodriguez, J. V., U. S. Inan, Y. Q. Li, R. H. Holzworth, A. J. Smith, R. E. Orville, and T. J. Rosenberg, A case study of lightning, whistlers, and associated ionospheric effects during a substorm particle injection event, *J. of Geophys. Res.*, 97, 65-75, 1992.
- Shao, X. M. and P. R. Krehbiel, The spatial and temporal development of intracloud lightning, *J. of Geophys. Res.*, 101, 26641-68, 1996.
- Wait, J. R., The attenuation vs. frequency characteristics of VLF waves, *Proc. IRE*, 45, 768-71, 1957.

M. P. Johnson, STARLab, David Packard Bldg., Stanford, CA 94305.

(Received November 3, 1999; revised February 6, 2000; accepted February 9, 2000.)