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An examination of superbolt-class lightning events observed by the FORTE satellite

Matt W. Kirkland

Space & Atmospheric Sciences Group
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

(mkirkland@lanl.gov)

Abstract

The silicon photodiode detector (PDD) on the FORTE satellite has observed over 600,000 optical events, attributed to lightning, during the first 19 months of operation. While the majority of these events have estimated peak optical powers >1 gigawatt at the source, several hundred events having peak optical powers >100 gigawatts have also been observed. These bright events fall within the range of peak optical powers of the so-called superbolts that were detected by the Vela satellites in the early 1970's. We examine the brightest optical events observed by FORTE in the context of data collected by from the National Lightning Detection Network (NLDN) and also of data from the RF payload on FORTE. We find that events having peak powers >100 gigawatts comprise the tail of the peak-amplitude and energy distributions for terrestrial lightning, are associated with both positive and negative cloud-to-ground events and are globally ubiquitous.

Introduction

The existence of very bright, satellite-detected optical signals was first reported by *Turman* [1977]. These bright optical events had estimated peak powers at the source of >100 gigawatts (GW), or greater than 100 times more powerful than ordinary satellite-detected lightning events. Turman dubbed these events "superbolts" and suggested that they were associated with large current, positive cloud-to-ground (CG) events [*Turman*, 1977, 1979]. *Uman* [1978] pointed out that negative CG events having large currents could also be responsible. *Turman* [1977] arbitrarily imposed a threshold of 3 terrawatts (TW) emitted at an isotropic source to reduce the number of bright events to a manageable level for comparison with meteorological data. For this subset of bright events having peak powers >3 TW at the source, Turman found that the bright optical signals contained on the order of a few gigajoules (GJ) of energy, or about 1000 times as much energy as a typical, satellite-detected lightning event. It was also noted that the bright optical pulses had a more symmetric pulse shape than their weaker counterparts. Turman estimated that events having peak powers at the source of >3 TW occured approximately once in every two million lightning events.

Unfortunately, data from satellite-borne silicon photodiodes, such as those flown aboard the Vela and Defense Meteorological Satellite Program satellites, have not been generally available to investigators to pursue the subject of superbolts further. Questions that might be asked include: Do bright events deserve a unique classification? Where do events of this magnitude typically occur? Can they be preferentially associated with a particular type or polarity (in the case of cloud-to-ground strokes) of lightning? Fortunately the data to address these questions is now available.

In August 1997 a small satellite called FORTE (Fast On-Orbit Recording of Transient Events) was launched into low Earth orbit (~825-km, circular). The satellite payload consists of RF and optical sensors that were designed by both Los Alamos and Sandia National Laboratories to trigger on and record transient RF and optical emissions, such as those emitted by lightning. The RF payload consists of two 22-MHz, tunable receivers and a single 100-MHz tunable receiver, all capable of collecting data over the HF and VHF bands (3-300 MHz). The RF payload and data have been described by *Jacobson et al.* [1998]. The optical payload consists of a silicon photodiode detector (PDD) that records the time history of optical events that trigger the photodiode system. *Kirkland et al.* [1998] has provided a description of the PDD instrument and an initial review of the PDD data. Also included in the optical payload is a planar array of charge-coupled devices (CCD) that serves as the lightning location sensor (LLS). The LLS pixel size maps to a 10-km x 10-km region on the Earth's surface, allowing for the geolocation of transient optical event to that level of precision. The LLS is almost identical in design to the optical transient detector (OTD) and lightning imaging sensor (LIS) flown in low Earth orbit by NASA (see http://thunder.msfc.nasa.gov/).

As of March 1999, FORTE has recorded over two million transient RF events, and over one million PDD events. While the vast majority of the PDD lightning events have relatively low peak powers (~1 GW, median value), the PDD has observed several hundred bright (>100 GW at an assumed isotropic source) optical events. In this paper we focus our attention on these bright optical events and attempt to address some of the questions mentioned above via a comparative study involving ground-based data from the national lightning detection network (NLDN), and the correlated RF data obtained from FORTE.

We first describe the PDD data-processing algorithms that are used to provide an initial rejection of marginal or irrelevant data and parameterization of the surviving PDD event data. We examine the PDD source peak power and energy parameter space, and also the general geographic locations of optically bright events. Next we examine the subset of bright optical events that correlate with NLDN-reported lightning events and draw inferences concerning the nature of the source of these bright events (i.e., intracloud versus cloud-to-ground versus positive or negative polarity). Finally, in an effort to understand the source of optically bright events, we examine two examples of VHF emissions recorded by FORTE RF receivers that correlate with optically bright events.

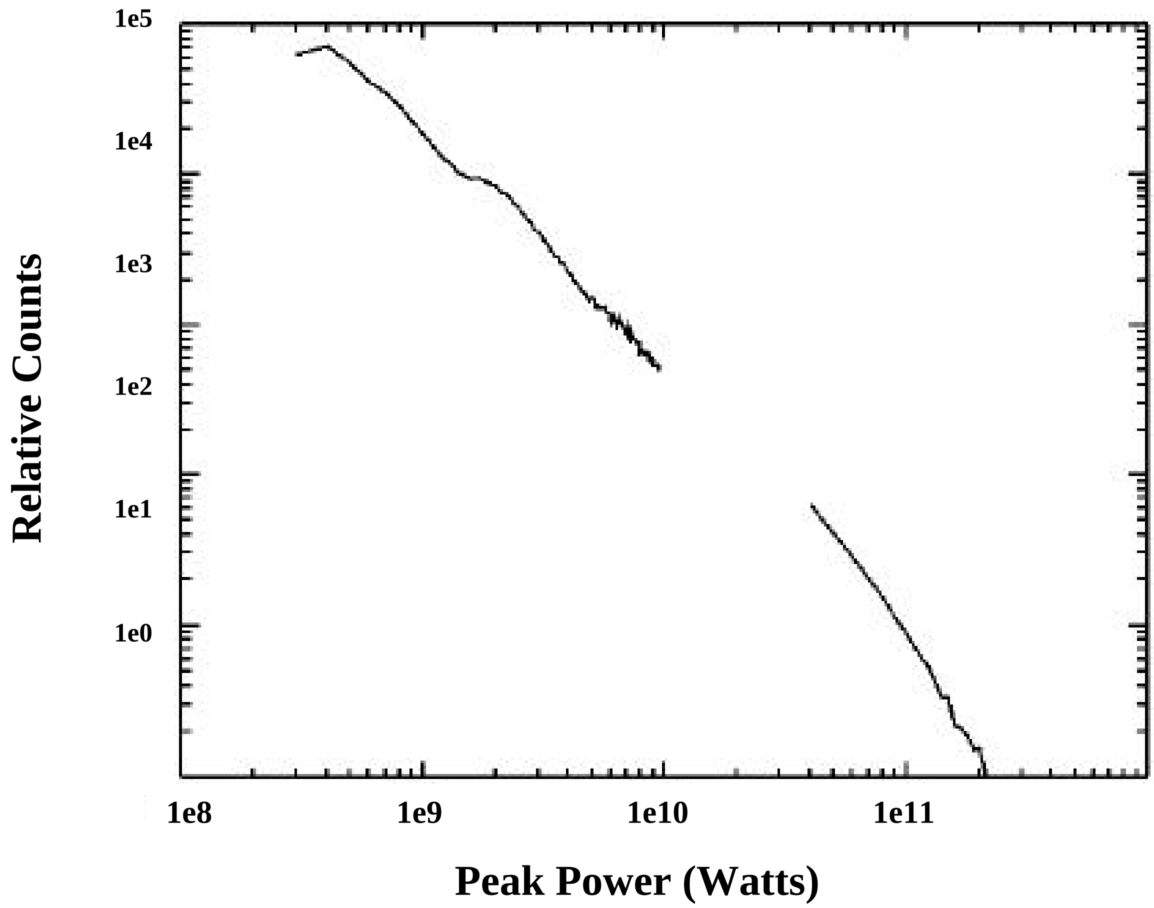
The FORTE/PDD observations

As mentioned above, the PDD has collected over a million events in its first 19 months of operation. For these events we have imposed a limited classification algorithm to identify particle events, events caused by electronic noise in the sensor, and events caused by sunlit spacecraft or ocean surfaces. Those events that survive this classification process are attributed to lightning. This algorithm has been described by *Kirkland et al.* [1998]. We point out that the energetic particle test rejects short duration events having small peak-to-extinction decay times (<45 uS), or total durations < 75 uS. The noise test rejects events having a signal maximum-to-minimum amplitude ratio of less than 15. While this latter constraint is somewhat arbitrary, it does impose a minimum peak amplitude on the surviving events that also corresponds to the effective false alarm (due to noise) floor of the PDD [*Kirkland et al.*, 1998]. In the first 19 months of operation, this algorithm eliminated approximately 40% of the triggered events, leaving approximately 600,000 events attributed to lightning. This down-selected set of events forms the base population of optical lightning data used in this work.

Once an event passes the energetic particle and noise tests, the digitized optical signal is parameterized in a limited manner. The peak amplitude of the signal is stored, as is the sensor's location relative to the Earth. The signal is integrated to yield an estimate of the energy in the recorded signal. We note that in a few percent of the cases the signal duration exceeds the 1.9-millisecond (ms) record length of the PDD, so that we underestimate the signal energy for those long signals. These two parameters of peak power and energy can be used to calculate an effective pulse width, which is the ratio of the energy to the peak power and has units of time.

Figure 1 shows the peak power distribution of PDD events attributed to lightning, assuming that the source radiates isotropically, and is located at nadir, and that the signal is not attenuated by clouds or air. Thus we calculate the lower bound on the peak power at the assumed point source. The gap in the distribution corresponds to a region in which the PDD sensitivity changes. The power law fit to this distribution gives an exponent of –1.64. The median peak power in the distribution is about 0.98 GW. Only 0.4% (or ~2500) of the down-selected events attributed to lightning have peak powers at the source exceeding 100 GW. Throughout the remainder of this paper, we will refer to the subset of PDD events having peak source powers > 100 GW as “bright events.”

Figure 1. Distribution of >650,000 estimated peak optical powers at an isotropic source located at nadir relative to the FORTE/PDD sensor. We assume a satellite altitude of 825-km, with no atmospheric extinction of the signal. The excised region of the distribution is where a change in instrument sensitivity occurs. See text for details.



In Figure 2 the pulse energy distribution is shown for all events attributed to lightning. The energies associated with bright optical events lie in the upper tail of the energy distribution. This finding is consistent with the data reported by *Turman* [1977].

Figure 2. Distribution of >650,000 estimated source energies at an isotropic source located at nadir relative to the FORTE/PDD sensor. We assume a satellite altitude of 825-km, with no atmospheric extinction of the signal.

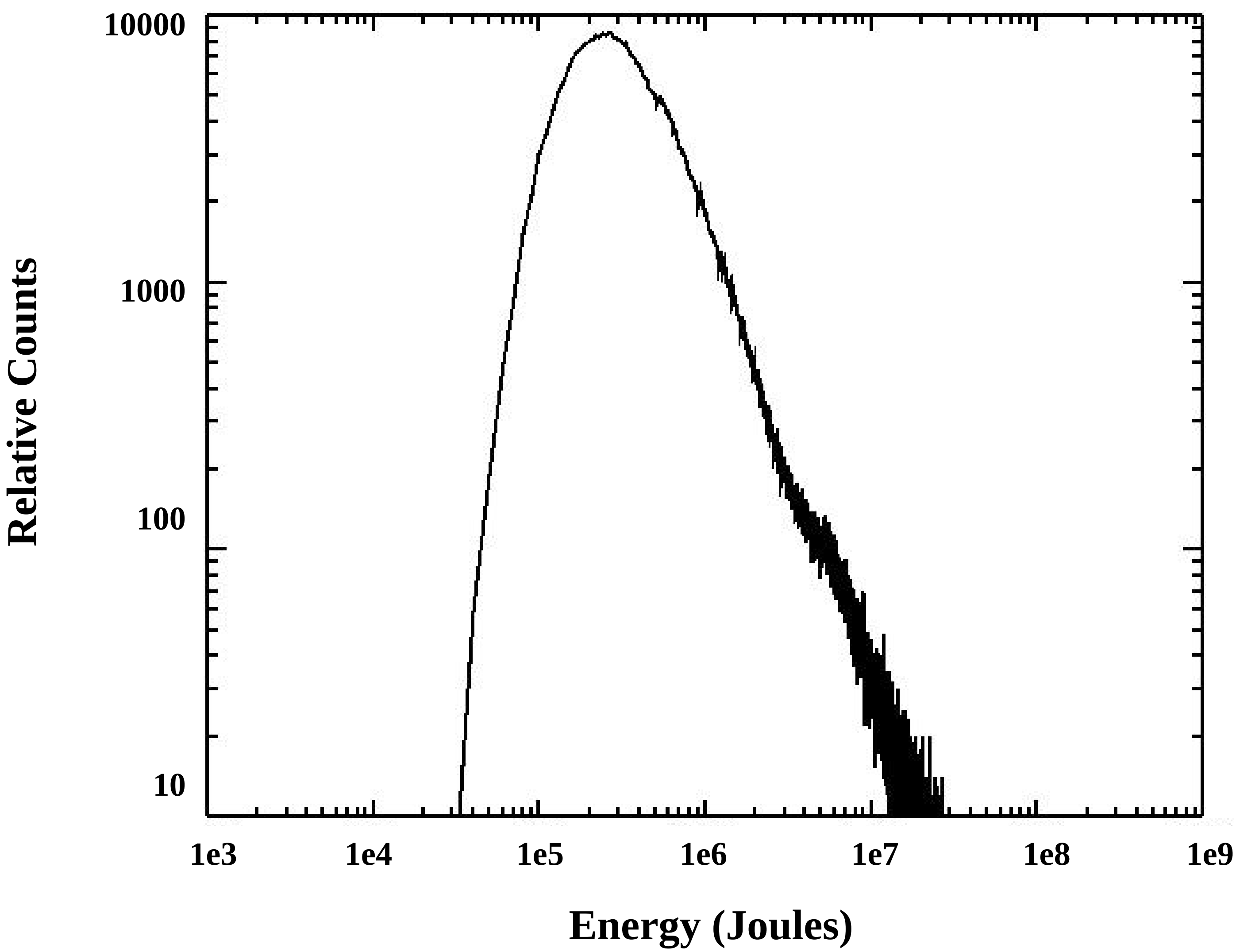
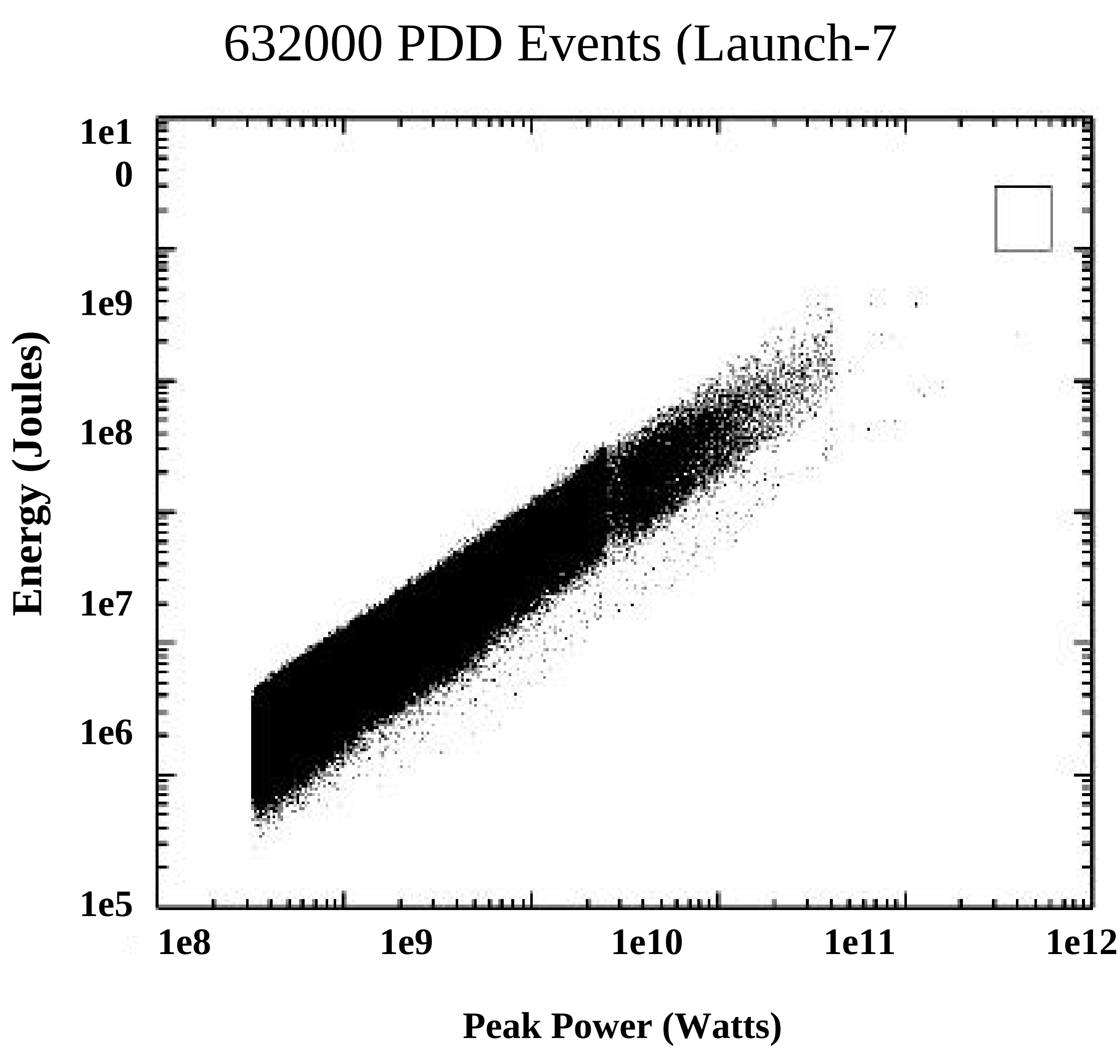


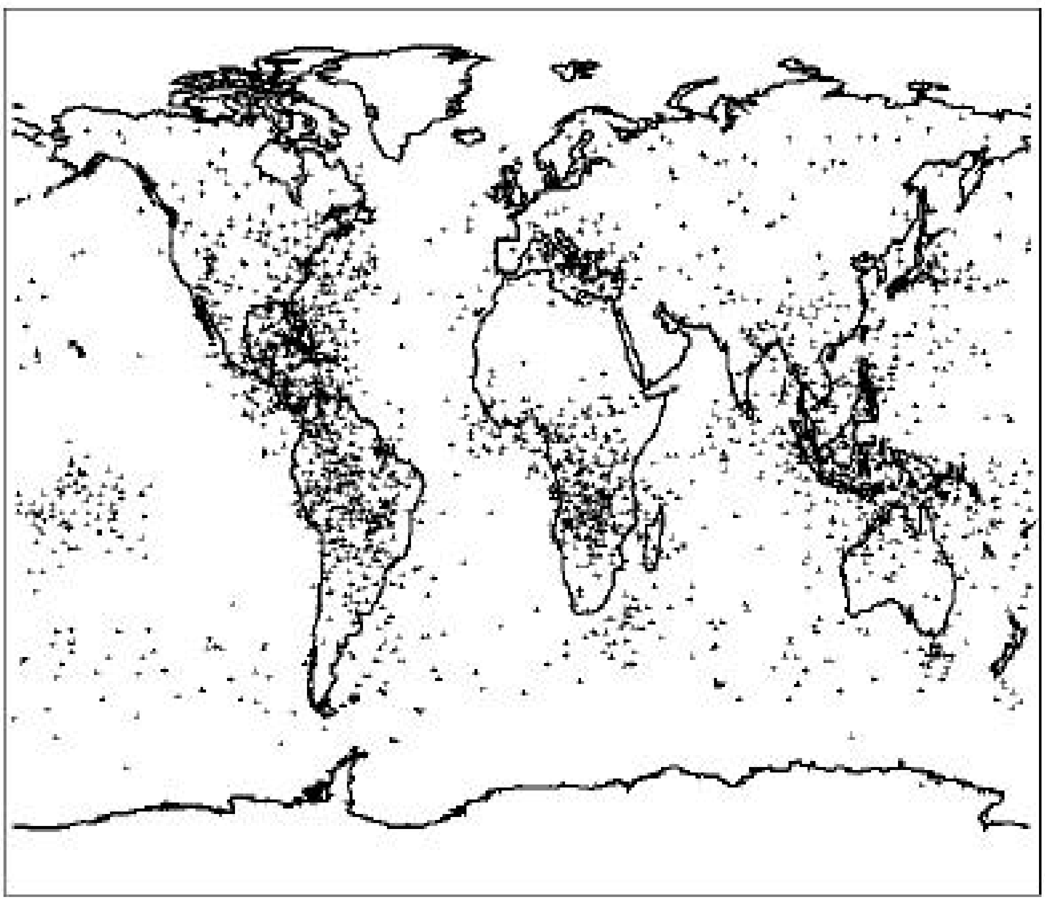
Figure 3 shows a linear relationship between peak source power and source energy. The events having peak source powers >3 TW that were reported in tabular form by *Turman* [1977] all lie within the box in the upper right quadrant of Figure 3. Although none of the contemporary PDD data lie in this peak power-energy regime, the trend in the data suggests that the Turman events simply lie on the upper end of the distribution shown in Figure 3. We infer that although the Turman superbolts are extremely bright and energetic, that they are simply events on the tails of single, generic peak power and energy distributions.

Figure 3. Scatter plot of the peak power versus energy of >650,000 PDD events attributed to lighting. A dependence of energy on peak power is seen. Change in the PDD sensitivity can be seen at approximately the 25 and 400 GW peak power points. The box in the upper right quadrant of the figure defines the region containing the superbolts discussed by Turman [1977]. See text for discussion.



In Figure 4 we show the subsatellite points where bright optical events were detected. The locations tend to cluster over the American, African and Indonesian-maritime continents. This finding is consistent with the occurrence of bright optical lightning events wherever generic lightning tends to occur [c.f. *Turman*, 1978; *Turman and* Edgar, 1982; *Goodman and Christian*, 1993]. We infer that bright optical events are ubiquitous.

Figure 4. Global map showing the locations of 2735 subsatellite points coinciding with the occurrence of bright optical signals having >100 GW at the isotropic, nadir-located source. These powerful events occur over the usual lightning producing regions of the world.

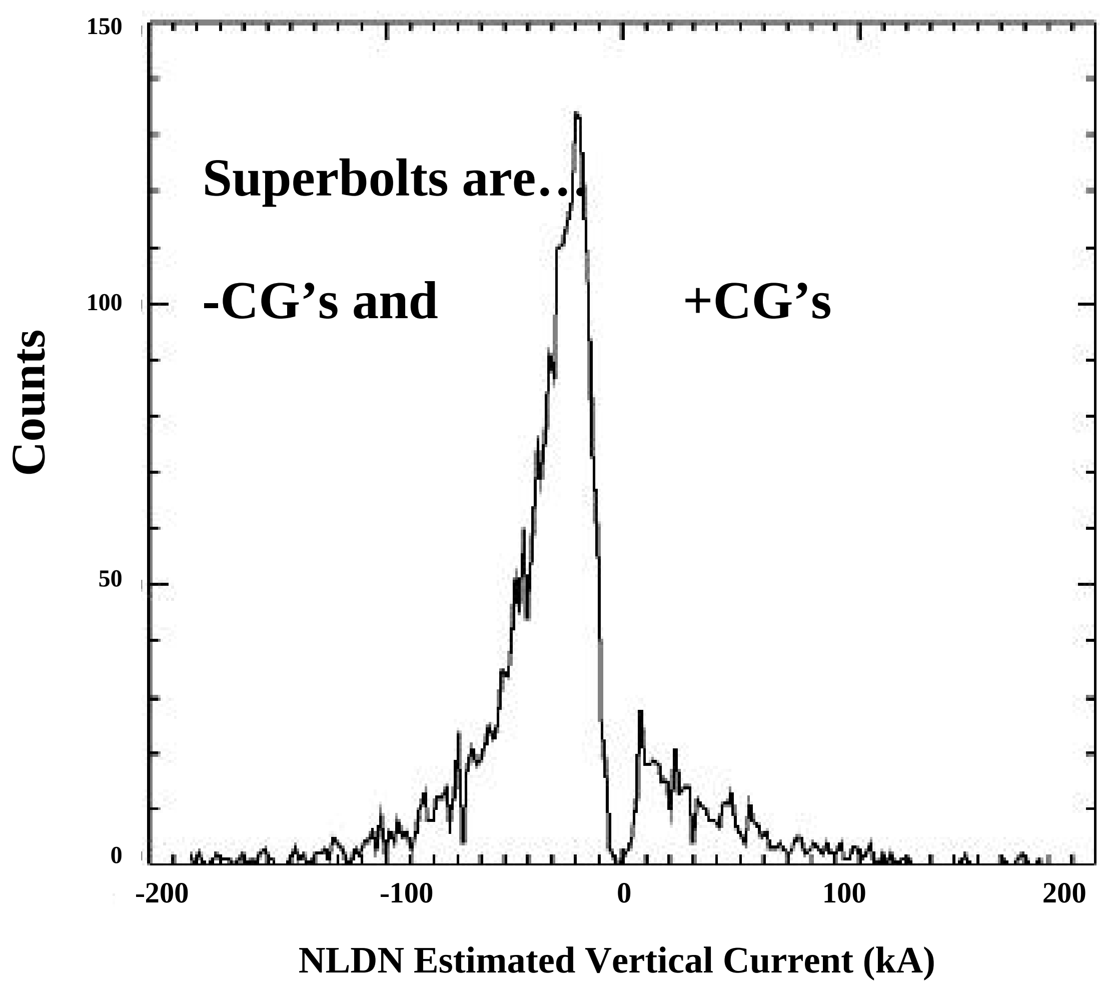


Comparison with correlated NLDN data

We identified 260 bright optical events that occurred over the continental United States (CONUS) during the April-September 1998 season. These events were correlated with data from the National Lightning Detection Network (NLDN) by using a 5-millisecond coincidence window and imposing the requirement that the temporally-associated NLDN event lie within the PDD field of view. The 5-millisecond coincidence window is sufficient to allow the signal to occur (typically < 1-ms) and propagate to the sensor (< 3-ms). These criteria yield 238 NLDN-correlated events, which is 92% of the total bright PDD events observed over the CONUS during the April-September 1997 period. Of these 238 optically bright NLDN-correlated events, 130 were reported to be CG-events by NLDN and 108 were reported as intra-cloud (IC) events. We point out that the fact that the CG/IC ratio is near unity is interesting, since the NLDN array data processing algorithm typically rejects IC events. We conclude that either (1) both IC and CG events can produce bright optical emissions having peak powers >100 GW at the source, or (2) that the NLDN-reported event-type is inaccurate in some of these cases.

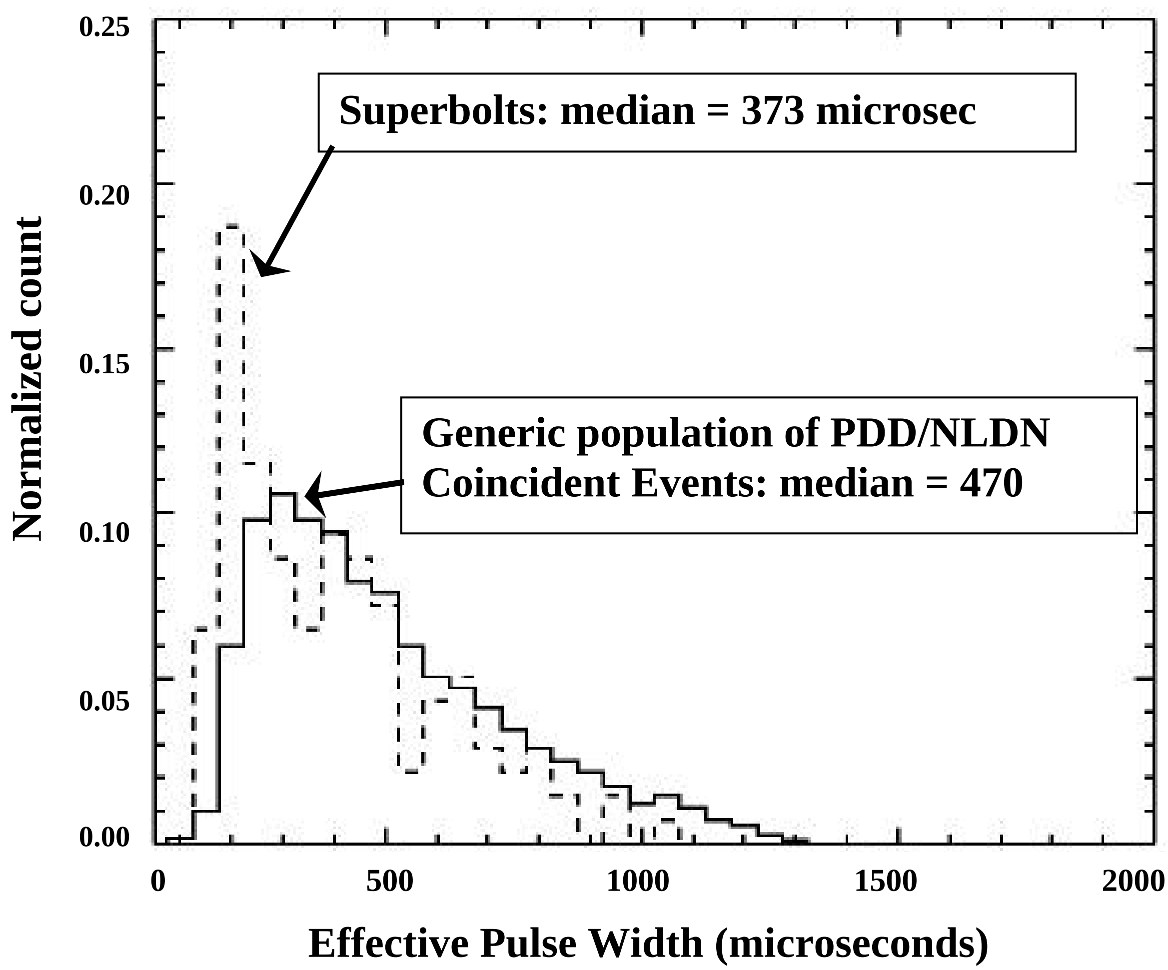
Taking the subset of bright optical events that are correlated with NLDN CG events, we find that the NLDN-reported events have both polarities [Figure 5]. This new result demonstrates that bright optical events originate from cloud-to-ground events of either polarity, rather than having a preference for the positive polarity as suggested by *Turman* [1977, 1979].

Figure 5. Distribution of NLDN-estimated vertical currents for 130 cloud-to-ground events (CG) associated with bright optical signals (>100 GW). Bright optical signals are associated with both positive and negative polarity CG events.



The effective pulse width is defined as the ratio of the pulse energy to the peak power of the pulse. This corresponds to the width of a square-wave pulse having an amplitude equivalent to the peak power. In Figure 6 the distribution of effective pulse widths for all correlated NLDN/PDD events is shown and compared to the median values of effective pulse width for optically bright NLDN/PDD-correlated events. We see that events of all optical brightnesses as a group have ~100 uS broader median pulse width than optically bright events. However, when we consider only bright optical events, the effective pulse widths for CG and IC events are smaller compared to their optically weaker counterparts. One might argue that the bright optical events have smaller effective pulse widths because they occur at the edge of clouds, where line of sight from the satellite to the event is relatively unobscured. A clearer line of sight would reduce the amount of signal extinction that occurs due to clouds and also reduce the amount of Mie scattering experienced by the photons as they propagate to the satellite, thus reducing the observed pulse widths. This lack of obscuration is qualitatively consistent with bright, narrow pulses, as was suggested by *Turman* [1977, 1979].

Figure 6. Histograms of optical pulse effective widths for >1500 PDD/NLDN-correlated events (solid), and for 238 optically bright PDD events associated with NLDN events (dashed). The median effective pulse widths are smaller for the optically bright events compared to the population of less powerful events.



Comparison with correlated FORTE VHF data

Using a coincidence window of 20 ms, we find over 1000 instances of a FORTE-detected VHF emission associated with about 300 bright optical emissions. To place this into the context of the parent data sets, we found over 37500 PDD events associated with a VHF emission in a 20-ms coincidence window. Of these 37500 PDD/VHF events, only ~300 had estimated peak optical powers exceeding 100 GW at the source. One may infer that bright optical events are not generally associated with VHF emissions, Conversely, VHF emissions may not imply an association with bright optical events.

Plate 1 shows two pairs of time-correlated VHF and optical emissions detected by FORTE. These events were selected to illustrate the point that the character of the VHF emissions from bright optical events can differ from event to event. Spectrograms of the detected VHF emission are shown on the left, and the time series of the associated optical signal are shown on the right. In both cases the time of the strong VHF emissions that trigger the RF system approximately coincides with the start time of the optical signal. However, in the top panel we see that the VHF emissions have a defined start time, whereas the bottom panel shows a VHF emission in which a more impulsive, broadband signal is embedded within a longer duration, broadband signal that decays rapidly after the trigger point. One sees that the two VHF emissions do not have the same character. The relative timing of the VHF and optical signals is also important to consider. In Plate 1, the optical trigger in the upper right panel occurs 167 uS after the associated VHF trigger in the upper left panel. In the bottom set of panels, the optical and VHF triggers are nearly simultaneous. We point out that the VHF emission at t=167 uS in the top panel differs in character from the VHF emission at t=0 in the bottom panel.

Plate 1. Four panels containing a spectrogram showing VHF emissions (LHS) and the associated optical signal (RHS) for two separate optically bright events. The spectrograms show time in microseconds on the abscissa and frequency in MHz on the ordinate, with color depicting power in dBm. The optical signal amplitudes are shown in watts per square meter at the sensor, with time also in microseconds. The horizontal line in the RHS plots of PDD signal is the 100 GW threshold for isotropic sources at nadir, assuming no signal extinction. We note that the VHF emissions have different time-frequency-power behaviors, and thus are likely not associated with the same type of breakdown processes.

Plate 1, top

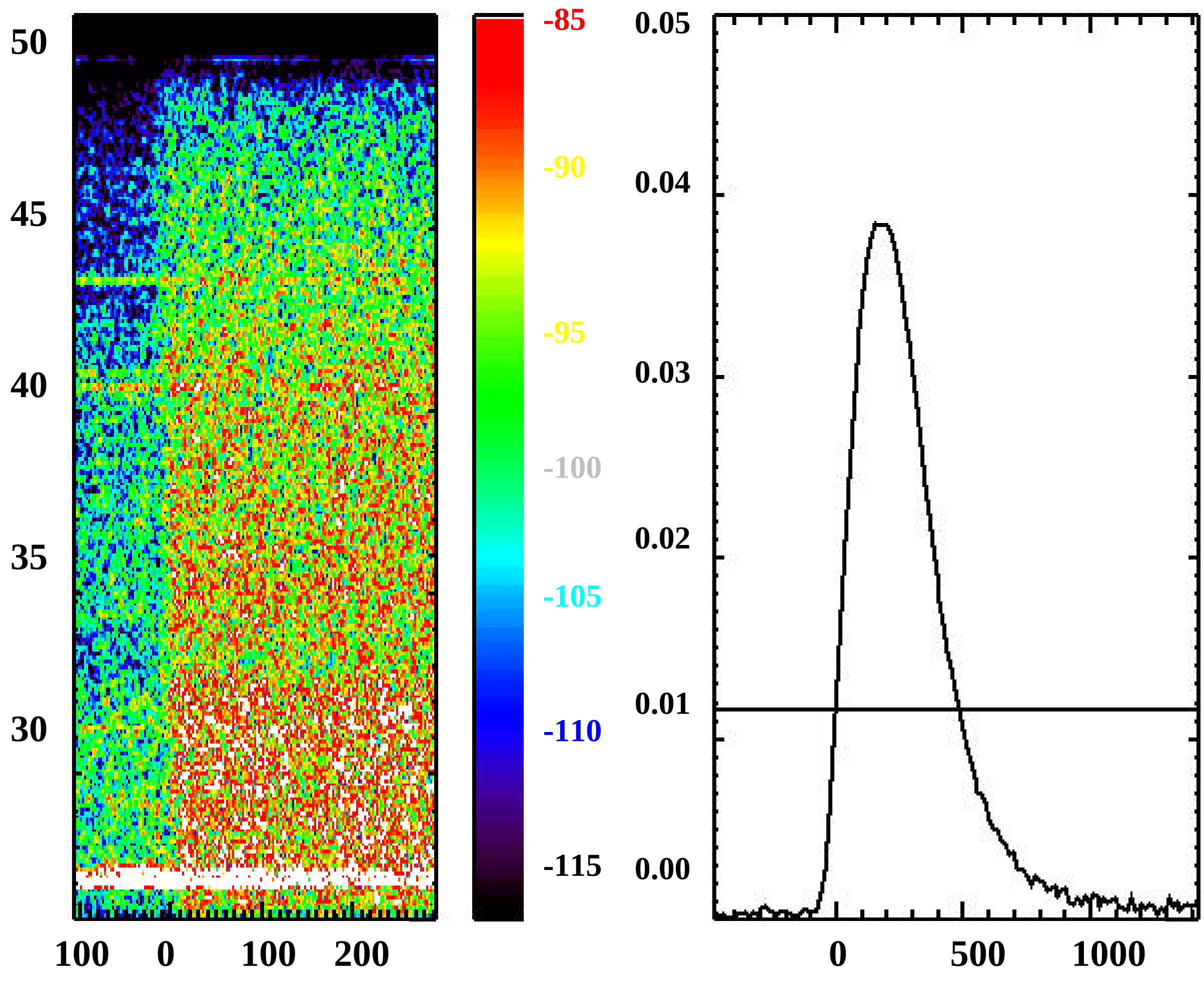
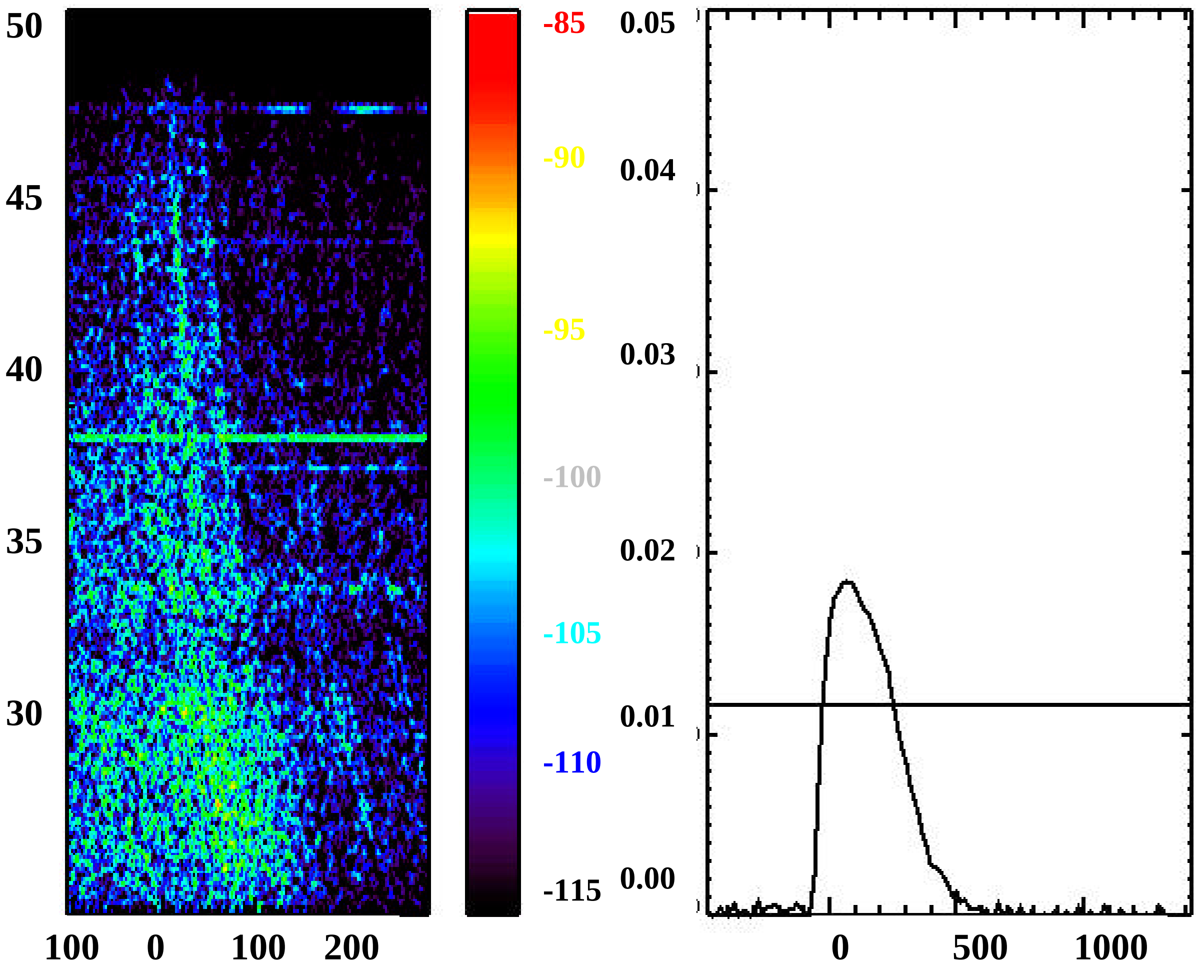


Plate 1, bottom



A review of several correlated VHF/optical events reveals the same basic finding: that bright optical events are associated with VHF emissions having different characteristics. From this finding we infer that the lightning channel breakdown/ionization processes associated with bright optical events can differ, thus producing VHF emissions of different flavors. We conclude that bright optical events are not unique in terms of their associated VHF emissions and are thus not likely to be uniquely associated with a specific type of lightning (CG versus IC versus first return stroke versus subsequent return stroke, etc…).

Discussion and Conclusions

In reviewing data from the PDD instrument on FORTE, we find that optical events tend to cluster in a fairly well defined region of the peak power-energy parameter space. The trend in this clustering is for the optical pulse energy to increase with peak power, for the range of observed peak powers [Figure 1]. The region of peak power-energy parameter space, in which the *Turman* [1977] superbolts reside, lies beyond the upper extreme of the PDD distribution. However, this region is located where the trend in the PDD data suggests that very bright optical events should occur. From this observation we infer that the so-called superbolts are simply the brightest occupants of the peak power and energy distributions of ordinary lightning.

We also examine the geographic distribution of subsatellite points for all optically bright PDD lightning events. We find that the geographic distribution of optically bright events is very similar to the geographic distribution of weaker events, despite the much smaller number of bright events. We conclude that optically bright events are globally ubiquitous.

Taking that subset of optically bright events that correlate with NLDN-reported lightning events, we find that bright optical events are classified by the NLDN as intracloud (IC) almost as often as they are classified as cloud-to-ground (CG). This finding can have one of two implications: (1) bright optical events are associated with both IC and CG events or (2) the NLDN mis-characterizes lightning waveforms that are associated with bright optical events at nearly the 50% level. In any case, those bright optical events that do correlate with NLDN-reported CG-events are also associated with both flavors of CG polarity. We juxtapose this finding with the speculation made by *Turman* [1977, 1979] that superbolts are associated with positive CG-events, and by *Uman* [1978] that positive or negative CGs could be responsible. We also find that optically bright, NLDN-typed IC and CG events seem to have shorter effective pulse widths than their weaker counterparts. We suggest, as did *Turman* [1977, 1979], that this is consistent with less obscuration of the lightning channel by clouds, resulting in less Mie scattering of the optical photons by cloud water, and thus less broadening of the optical pulse. This suggestion is consistent with explanation that less cloud obscuration results in more powerful and narrower events, as detected by FORTE.

Finally, we examine the VHF emissions recorded by FORTE that can be associated with bright optical events. We find that for several cases (two shown in this paper) the VHF emissions from bright optical events vary from event to event. We conclude that bright optical events are not unique in terms of of their associated VHF emissions and are thus not likely associated with specific types of lightning.

The sum of these findings leads us to conclude that superbolts are simply very bright optical events that belong to a single population of global lightning. That we observe powerful events having smaller-than-usual effective pulse widths is consistent with the explanation that the FORTE photodiode detector occasionally has an unobscured line of sight to the lightning channel.

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Figure Captions

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