FORTE observations of optical emissions from lightning: Optical properties and discrimination capability

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[1] Lightning type identification of temporally coincident optical-VHF time series event pairs collected by the Fast On-orbit Recording of Transient Events (FORTE) satellite's photodiode detector (PDD) and VHF instrument allows for the investigation of optical properties as a function of lightning type. General trends in the peak optical irradiance and characteristic pulse widths of PDD-VHF coincident events are studied as a function of lightning type, using previously established techniques to identify lightning type based on VHF spectogram-power time series. While lightning type cannot be identified from optical data alone, there are several notable features in the optical record. The distribution of observed characteristic widths of PDD events has a cutoff near 200 μs, which represents a lower limit on the combination of intrinsic optical emission time and pulse broadening due to photon scattering in the intervening clouds. Events with the highest peak optical irradiances observed at FORTE are typically positive initial return strokes. Also, the median value of peak optical irradiance for cloud-to-ground lightning events is more than double that for in-cloud lightning. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* lightning, optical emissions, satellite observations

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1. Introduction

[2] The foundation for a global, space-based, lightning monitoring system has been laid over the last decade by fundamental advances in the science and engineering of space-based remote sensing of lightning. The Optical Transient Detector (OTD) operated in the mid-1990s by the National Aeronautics and Space Administration Marshall Space Flight Center (NASA/MSFC) and the NASA/MSFC Lightning Imaging Sensor (LIS) currently aboard the Tropical Rainfall Monitoring Mission (TRMM) spacecraft have pioneered optical monitoring of lightning from space. The Fast On-orbit Recording of Transient Events (FORTE) satellite, a joint Los Alamos National Laboratory and Sandia National Laboratories satellite experiment launched in 1997, has extended this approach to include a dual phenomenology (optical and radio-frequency) methodology for lightning detection and characterization.

[3] A desirable feature of any global lightning monitoring system is the ability to discriminate lightning flash types (e.g. cloud-to-ground (CG) versus intracloud (IC) flashes). The ratio of IC to CG lightning flashes in storms has been shown to be a sensitive indicator of storm evolution [e.g., *Williams et al.*, 1989], and the IC/CG ratio (and total flash rate) has been correlated to the onset of severe weather conditions including tornadoes [*Buechler et al.*, 2000; *Williams et al.*, 1999].

[4] Previous work by *Suszcynsky et al.* [2000] and *Light et al.* [2001] has established a robust technique for identifying lightning types using FORTE VHF spectograms and power time series. Ground-based and flight-based efforts to produce an optical lightning-type discrimination capability have been less successful [e.g., *Mackerras*, 1973; *Guo and Krider*, 1982; *Goodman et al.*, 1988; *Kirkland et al.*, 2001]. *Kirkland et al.* [2001] have, however, noted certain trends in FORTE optical waveform properties that warrant further investigation. This paper explores these trends by characterizing the optical pulse widths and peak optical irradiances as a function of lightning type for PDD waveforms. The use of VHF spectogram-time series method to identify both CG and IC optical lightning types provides for a more complete and relatively unbiased study as compared to utilizing the CG-based National Lightning Detection Network (NLDN) data set.

[5] The goals of this paper are to (1) characterize the pulse widths and peak irradiances of FORTE Photodiode Detector (PDD) optical waveforms as a function of lightning type and (2) based on these characterizations, further assess the possibility of identifying optical lightning types from space-based platforms using time-resolved optical waveforms.

[6] This paper is organized as follows: Following the introduction in section 1, section 2 provides a brief description of the instruments used for the study. In section 3, the

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analysis techniques and experimental results are presented. Section 4 contains a discussion of the results presented in section 3.

2. Instrumentation

[7] FORTE is located in a nearly circular, 70° inclination orbit of ~825 km altitude with an orbital period of about 100 min. The instrumentation used for this study includes the PDD of the FORTE Optical Lightning System (OLS) and the two narrower-band FORTE VHF receivers (for in-depth instrument descriptions, see *Kirkland et al.* [2001] and *Jacobson et al.* [1999]).

[8] The PDD is a broadband (0.4–1.1 μm) silicon photodiode detector that collects amplitude versus time waveforms of lightning transients occurring within an 80° field-of-view centered on the sub-satellite point. The instrument typically collects 1.92 ms records with 15 μs time resolution and is amplitude-threshold triggered.

[9] The VHF instrumentation consists of two broadband receivers that can each be independently configured to cover a 22-MHz sub-band in the 30–300 MHz frequency range, with a 50 MHz (20 ns) sample rate. The instrument was designed such that the 3-dB attenuation contour of the antenna corresponds to the PDD field-of-view. Triggering occurs when at least 5 of 8 1-MHz wide sub-bands within the bandwidth exceed an amplitude threshold. This study considers only 800 μs records in the 26–48 MHz range in order to optimize the detection and identification of VHF lightning emissions.

3. Data, Analysis, and Results

3.1. Data Selection

[10] During the 2-year span from January 1998 to December 1999, 3,042,236 events were autonomously collected by the FORTE VHF receiver, and 1,637,184 events were autonomously detected by the FORTE PDD. Of these events, 3210 FORTE VHF-PDD coincident events were selected for this study using the selection criteria described below.

[11] A VHF-PDD coincident event is defined as an optical-VHF waveform pair for which the VHF trigger time precedes the optical trigger time by up to 600 μs, or lags it by up to 50 μs (Figure 1). This choice of trigger time differences selects coincident events for which the optical and VHF emissions are associated with the same stroke or pulse within the flash. This time coincidence window excludes both the left- and right-hand shoulders of the distribution in Figure 1, which are primarily attributed to in-cloud events in which the optical and VHF emissions are only generally correlated on flash timescales [*Light et al.*, 2001], as opposed to optical-VHF correlations of CG events that are directly correlated on μs timescales [*Suszcynsky et al.*, 2000].

[12] In addition, we only consider those events that were taken during local nighttime conditions. *Kirkland et al.* [2001] have shown that PDD events taken during daytime are biased toward the most powerful events because of reduced FORTE OLS sensitivity. We also exclude events for which the VHF signal continued past the end of the record, and those in which more than one lightning event was

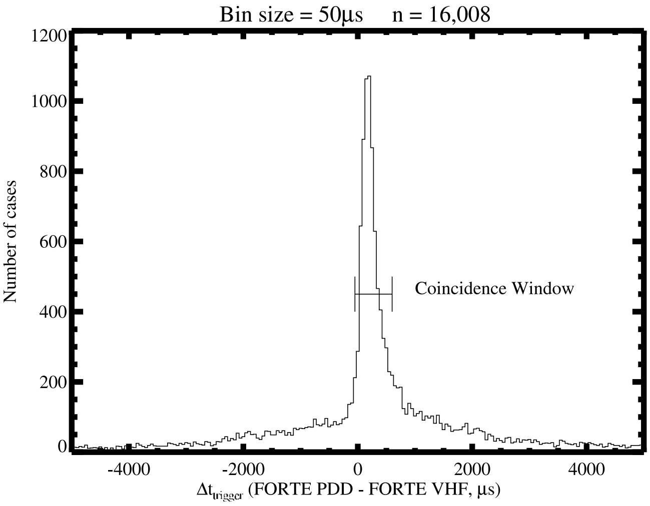

Figure 1. Histogram of the nearest neighbor trigger time differences in seconds between the FORTE PDD and VHF receiver.

observed within the VHF record. The resulting 3210 coincident events were placed into one of the 3 in-cloud and 3 cloud-to-ground categories used by *Light et al.* [2001]: negative initial return stroke, positive initial return stroke, subsequent (negative) return stroke, nonimpulsive in-cloud, impulsive in-cloud, mixed (impulsive/nonimpulsive) in-cloud.

3.2. Data and Results

[13] The peak optical irradiance and effective optical pulse widths are measured for each optical event. Effective pulse width measurements are made by dividing the time-integrated optical waveform by the peak optical irradiance [*Mackerras*, 1973]. For the 3210 events used in this study, a median peak optical irradiance of 155 $\mu W/m^2$ and a median effective pulse width of 558 μs is measured. These values are in agreement with *Kirkland et al.* [2001], who found a median effective pulse width of 592 μs and a median peak optical irradiance of ~130 $\mu W/m^2$ for FORTE PDD-National Lightning Detection Network (NLDN) coincident events.

[14] Figure 2 contains plots of peak optical irradiance measured at FORTE versus effective pulse width. Figure 2a displays all 3210 events with the 347 CG events plotted in red and the 2863 IC events plotted in black. In Figure 2b, the peak power versus effective pulse width is again plotted, but with each of the 6 lightning types (described above) represented by a different color. In addition, for each lightning type, the data is sorted by effective pulse width and plotted such that each point represents the median value for a group of either 5 or 50 events. For IC types, data is grouped into bins of 50. Due to the significantly smaller number of CG events, they are grouped into bins of 5 events.

[15] There are several features of Figure 2 worth noting. First, it is not possible to discriminate between CG and IC lightning types based on the optical characteristics of peak power and effective pulse width. In addition, there is a cutoff of effective pulse widths at ~250 μs. Also, positive return strokes appear to have slightly higher median peak

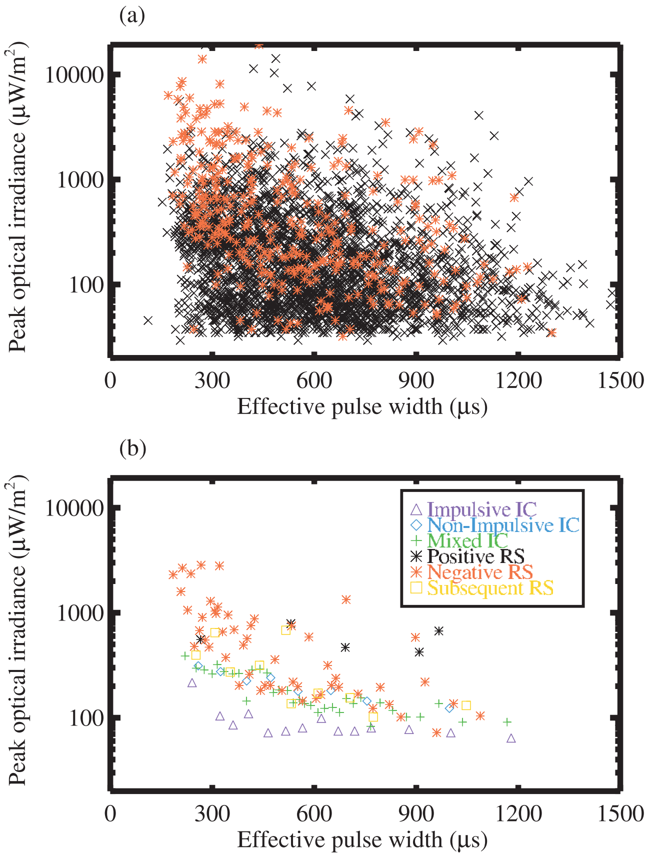

Figure 2. Plots of peak optical irradiance versus effective optical pulse. (a) All 3210 PDD-VHF pairs plotted, with IC events represented as black crosses and CG events as red stars. (b) Binned median values (see text description) for each of the 3 CG and 3 IC categories of events.

powers, for given values of effective pulse width, than their negative counterparts. Lastly, impulsive in-cloud events have distinctly lower peak powers than do other in-cloud events. These trends are discussed in the next section.

4. Discussion

4.1. General Characteristics of IC and CG Events

[16] Figure 2 and Table 1 show that in general, IC events are broader and have smaller peak optical irradiances than CG events. The median peak optical irradiances for CG events are observed to be a factor of 2 to 6 greater than those associated with IC events. This is generally consistent with the aircraft results of *Goodman et al.* [1988] and the satellite-based observations of *Suszcynsky et al.* [2000] and *Light et al.* [2001], each of which links the strongest observed optical signatures with CG events rather than IC activity. Although CG light suffers more scattering and attenuation than IC light as a consequence of more intervening cloud between the CG light source and the satellite (greater optical depth), this effect is more than compensated for by the factor of 10 larger average current (increased optical emission) associated with CGs as opposed to ICs [*MacGorman and Rust*, 1998]. Optical emissions from impulsive IC events are observed to produce the weakest optical lightning observed, over a factor of 4 less than the median emissions from CGs. This is in good agreement with the results of a more detailed study by *Light and Jacobson* [2002].

4.2. Lower Limits to Effective Pulse Width

[17] The lower limit cutoff of the effective pulse width for all lightning types in Figure 2 is significant and does not seem to be an instrumental bias. This cutoff is more clearly illustrated by the histogram of effective pulse widths presented in Figure 3. 95% of the coincident optical events have effective pulse widths above 255 μs, with the smallest width at 111 μs. The smallest "recordable" PDD optical pulse width is a function of the pre-trigger particle filter, which sets a minimum number of samples for which the amplitude must exceed threshold before a trigger-occurs [*Kirkland et al.*, 2001]. This filter was set to 5 samples (75 μs) for this study, which is significantly smaller than the observed 255 μs cutoff.

[18] There is evidence that the source of the lower limit in effective pulse widths is due both to the intrinsic optical width of the lightning events as well as to the broadening of the pulse by the intervening clouds. Although no measurements of intrinsic effective pulse width for IC flashes have been reported, ground-based measurements of cloud-to-ground strokes with unobstructed line-of-sights reveal intrinsic characteristic widths of 150–200 μs [*Mackerras*, 1973; *Guo and Krider*, 1982]. From Table 1, the median effective pulse width for negative initial return strokes is 443 μs. This implies approximately 250 μs pulse-broadening for negative initial CG strokes. We note, however, that a ground-based observer sees the lightning channel below the cloud, whereas we believe FORTE observes the

Table 1. Optical Properties of FORTE PDD-VHF Pairs

Lightning Type	Number of Events	Percentage of Total	Peak Optical Power, μW/m² Median	Peak Optical Power, μW/m² Mean	Effective Pulse Width, μs Median	Effective Pulse Width, μs Mean
All events	3210	100.0	155	376	558	589
IC events	2863	89.2	139	299	565	595
CG events	347	10.8	358	1008	484	534
Negative CG	267	8.3	366	1061	443	507
Positive CG	27	0.8	556	1700	736	712
Subsequent CG	53	1.7	246	387	530	576
Nonimpulsive IC	400	12.5	195	358	509	553
Impulsive IC	720	22.4	80	177	595	630
Mixed IC	1743	54.3	171	336	564	590

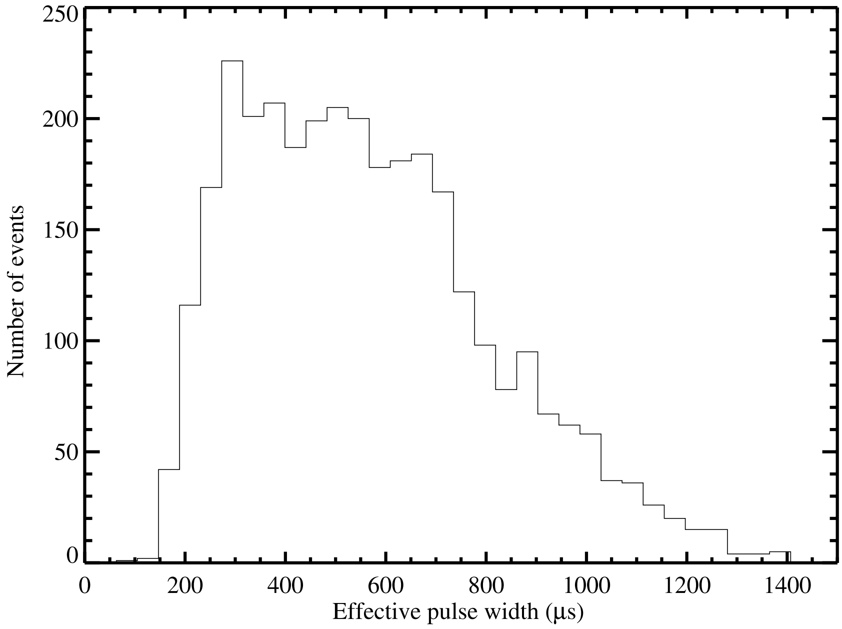

Figure 3. A histogram of effective pulse widths for all 3210 events with a bin size of ~60 μs.

light emitted from within the cloud once the current has propagated up the channel [*Suszcynsky et al.*, 2000; *Light et al.*, 2001], and therefore the signal observed by FORTE may have a greater intrinsic width than this 150–200 μs ground-based value. Thus 250 μs represents an upper limit for the amount of broadening due to scatter within the cloud.

4.3. Positive Versus Negative Initial Return Strokes

[19] As can be seen from Figure 2 and Table 1, positive initial return strokes are more powerful and broader than their negative counterparts. The population of +CGs in Figure 2 appears to have been shifted (up) to higher peak powers relative to the other events in this study. Although a detailed analysis is beyond the scope of this paper, we offer several plausible explanations for the trends of +CGs in the optical record.

[20] The most likely source of the difference between peak optical irradiances of +CGs and −CGs is the prevalence of higher peak current +CGs [*Berger et al.*, 1975]. Although the median values of peak current for + and −CGs are similar, the +CG distribution is skewed towards higher values of peak current. Implicit in this explanation for the discrepancy between peak optical irradiances of + and −CGs is the assumption that peak current is a proxy for peak optical output. This relationship has been observed in laboratory spark experiments [*Gomes and Cooray*, 1998], and has been indirectly observed in previous FORTE studies that have shown a linear relationship between peak optical output and peak VHF power [*Light et al.*, 2001], and between peak VHF power and peak current measured by the National Lightning Detection Network (NLDN) [*Light and Jacobson*, 2002].

[21] Another possible source of the difference in peak power and pulse widths between −CGs and +CGs is the larger horizontal extent of +CGs. The ratio of horizontal- to vertical-distance (D/H) for +CGs has been observed to be >1 to 5, whereas −CGs rarely have D/H values greater than 0.5 [*Fuquay*, 1982]. To get an idea of the amount of optical source duration that could be accounted for by this mechanism, one could assume a positive return stroke speed of 10^8 m/s (similar to that for negative return strokes) and a horizontal extent of 10 km. Although it must be stressed that neither of these values have been measured in this study, these values would yield an additional 100 μs of optical source duration.

5. Summary

[22] We analyzed the peak optical irradiances and effective optical pulse widths as a function of lightning type for several thousand events recorded simultaneously by the FORTE VHF and optical instruments.

[23] Although lightning-type discrimination capability based on the optical parameters of peak irradiance and pulse width is not possible due to the large spread in the data, we note that CG lightning events have higher peak optical irradiances than ICs by more than a factor of two. We also observe a cutoff in effective pulse widths near 250 μs which we interpret as being due to both the intrinsic duration of the optical emission as well as pulse broadening due to photon scattering in the intervening clouds. Also, +CGs have higher peak optical irradiances and larger effective pulse widths than −CGs.

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