FORTE Observations of Simultaneous VHF and Optical Emissions from Lightning: Optical Source Properties and Discrimination Capability

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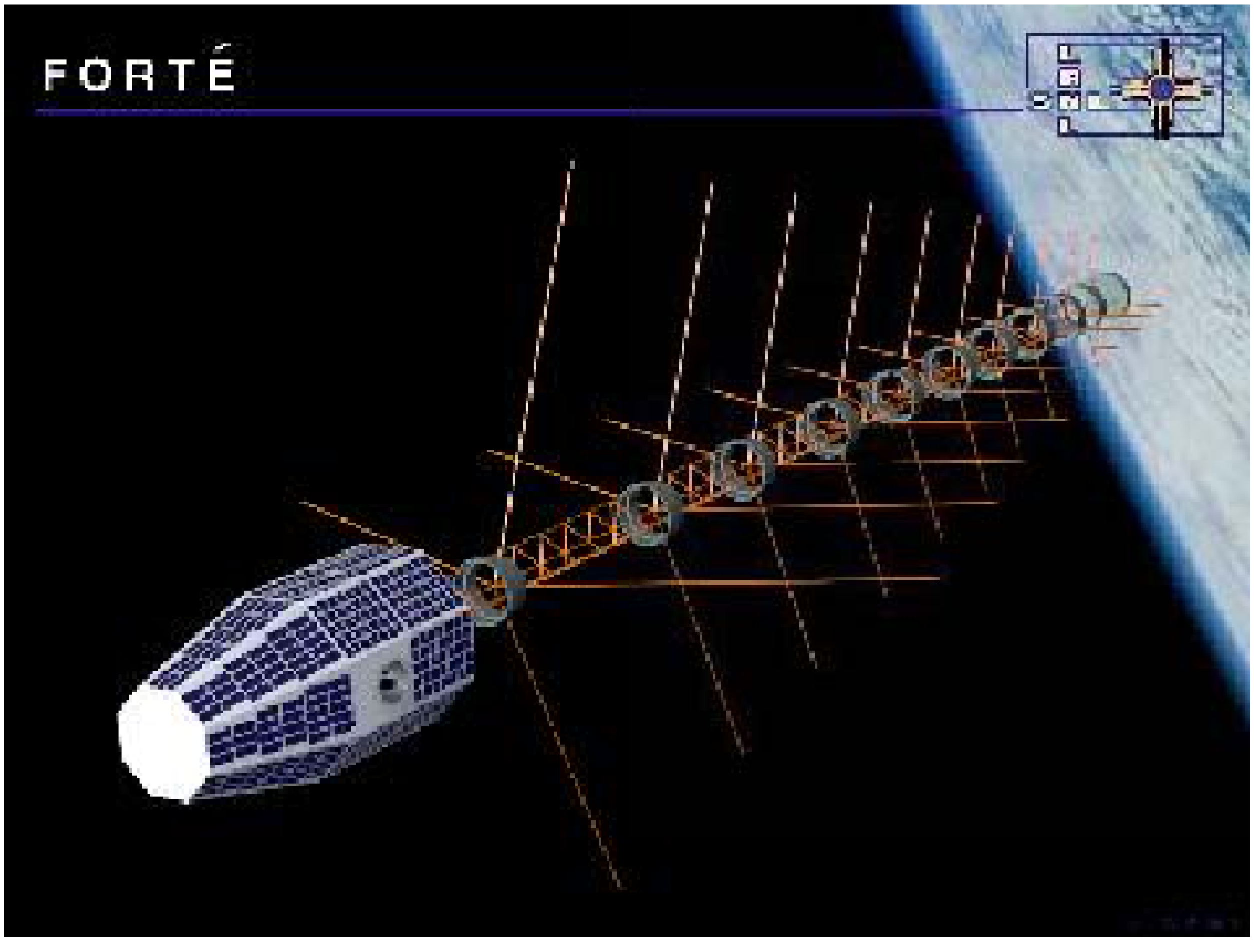
ABSTRACT

The Fast On-Orbit Recording of Transient Events (FORTE) satellite is a joint Los Alamos National Laboratory and Sandia National Laboratories experiment that was launched into a nearly circular low-earth orbit on Aug. 29, 1997. The payload consists of broadband VHF receivers and a two-sensor Optical Lightning System (OLS). The OLS is comprised of a broadband (400 - 1100 nm) silicon photodiode detector (PDD) that collects 1.92 ms records of lightning transients with a 15 us time resolution, and a narrow-band (777.6 nm ± 0.5nm) 128 x 128 pixel CCD array called the Lightning Location System (LLS) that provides imaging and geolocation of these events to within a pixel size of 10 km x 10 km.

This paper presents an overview of the phenomenology of the optical component of temporally-coincident FORTE VHF / FORTE PDD events. In this study, FORTE VHF data provides lightning type information. We discuss the broad correlation between lightning type, effective optical pulse width, and peak optical power. We find that in general, negative cloud-to-ground lightning produces higher peak powers and lower pulse widths at the detector, and that in-cloud lightning typically has lower peak powers spanning a broader range of pulse widths.

In addition, a low-end cutoff of effective pulse widths near 150 us has been observed. The role that lightning source height, scattering, and temporal source duration play in this cutoff is discussed.

FORTE: Fast On-orbit Recording of Transient Events



MISSION

- Testbed for Next Generation Nuclear EMP Sensor Technology.
- Space-based Lightning Detection.

PLATFORM

Altitude: ~ 825 km
Inclination: 70 degrees
Launched: August 29, 1997

SENSORS

Type: Broadband VHF receivers
- (26 – 300 MHz)
- 1 µs or better resolution

Photodiode (PDD)
-15 µS resolution

CCD Imager (LLS)
-10 km location accuracy

Data: Optical/VHF Waveforms
Event times
Event location

FORTE PDD/VHF Instruments

FORTE Photodiode Detector (PDD)

- Broadband (0.4 - 1.1um) Silicon Photodiode Detector
- Records 2 ms optical waveforms with 15us resolution
- Threshold triggered
- 80 degree field of view (~1200 km diameter footprint)

FORTE VHF

- 26 - 300 MHz broadband receiver with 22 MHz bandwidth
- Records 400 - 800 us waveforms with 20 ns resolution
- Noise riding threshold
- 3 dB attenuation at field of view of PDD

Motivations/Purpose of Study

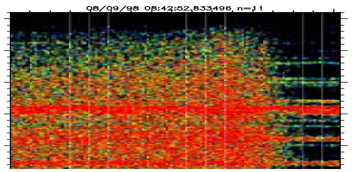
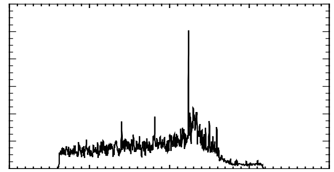
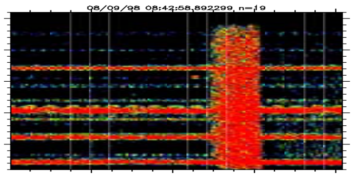
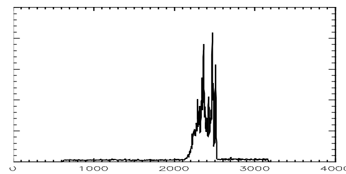
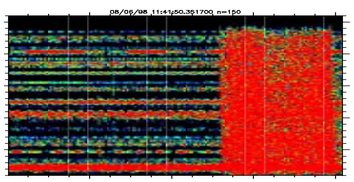
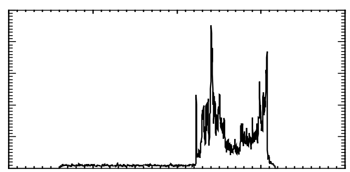
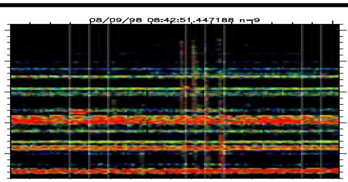
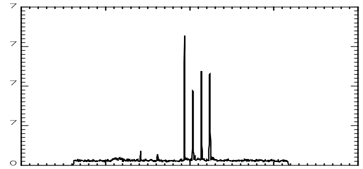
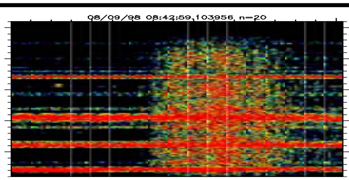
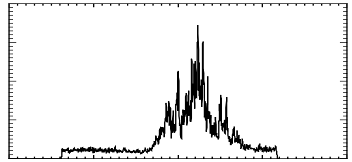
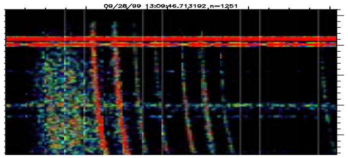
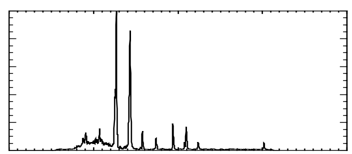
Remote Sensing of Lightning

- To what extent can space-based lightning detectors identify lightning type?

Lightning Physics

- What can we learn of lightning source properties from optical measurements taken from space?

VHF Lightning Type Discrimination

Spectrogram	Power profile	Taxonomy	Features
		1st -RS w/ stepped leader	width > 400 µS, steady increase, impulse at attachment
		Subseq. -RS w/ dart leader	10µS < wid. < 500 µS sharp fall, impulse at attachment
		1st +RS	10µS < wid. < 500 µS sharp rise, impulse at attachment
		Impulsive in-cloud events, including TIPPS	1 µS < width < 10 µS strong
		Non-impulsive in-cloud events including K-events	10 µS < wid. < 500 µS slow rise/fall
		Mixed impulsive and non-impulsive in-cloud events	Mixed of impulsive and non-impulsive features

Background: Lightning Optical Properties

- Ground-based measurements of effective pulse widths for negative initial return strokes indicate a value of 200 μs (Mackerras)
- Guo and Krider report mean width of 158 μs for subsequent return strokes (ground-based)
- Kirkland et al. report median pulse width of 607 μs for negative initial return strokes (space-based)
- Light et al. and Goodman et al. report pulse widths that vary by lightning type, as seen above clouds.

Optical Pulse Widths

- Effective Pulse Width (EPW):

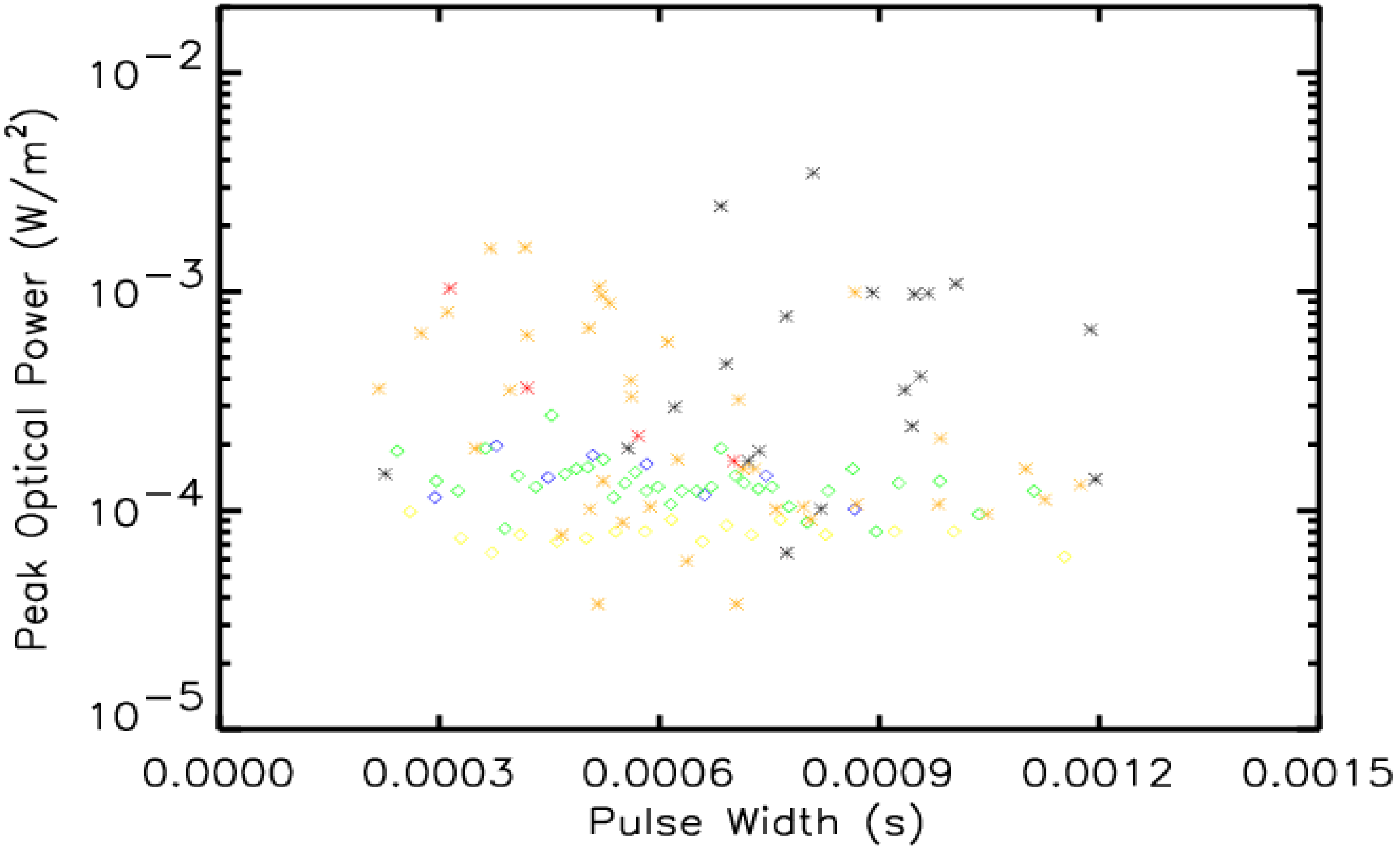
EPW = Total Integrated Energy / Peak Optical Power

- EPW is the width of an arbitrary waveform “shaped” to a box with the height of the original waveform

Data Selection Criteria

- Instruments must be in autonomous triggering mode
- -50 μs < Optical-RF Time < 500 μs
- 800 μs VHF record length
- Data must be taken at night to avoid selecting only the brightest optical events

Plot of Peak Power vs. EPW



Captions and key on next page

Figure 1. This plot shows binned-median values for all 2769 type-identified VHF/PDD pairs. Each point represents the median values of ~40 events, except for the black and orange points, which each represent one event.

Color Key:

Red = Negative Initial Return Stroke

Black = Positive Return Stroke

Orange = Subsequent Return Stroke

Blue = Non-impulsive In-cloud

Yellow = Impulsive In-cloud

Green = Mixed Impulsive/Non-Impulsive

Cloud-to-Ground Lightning

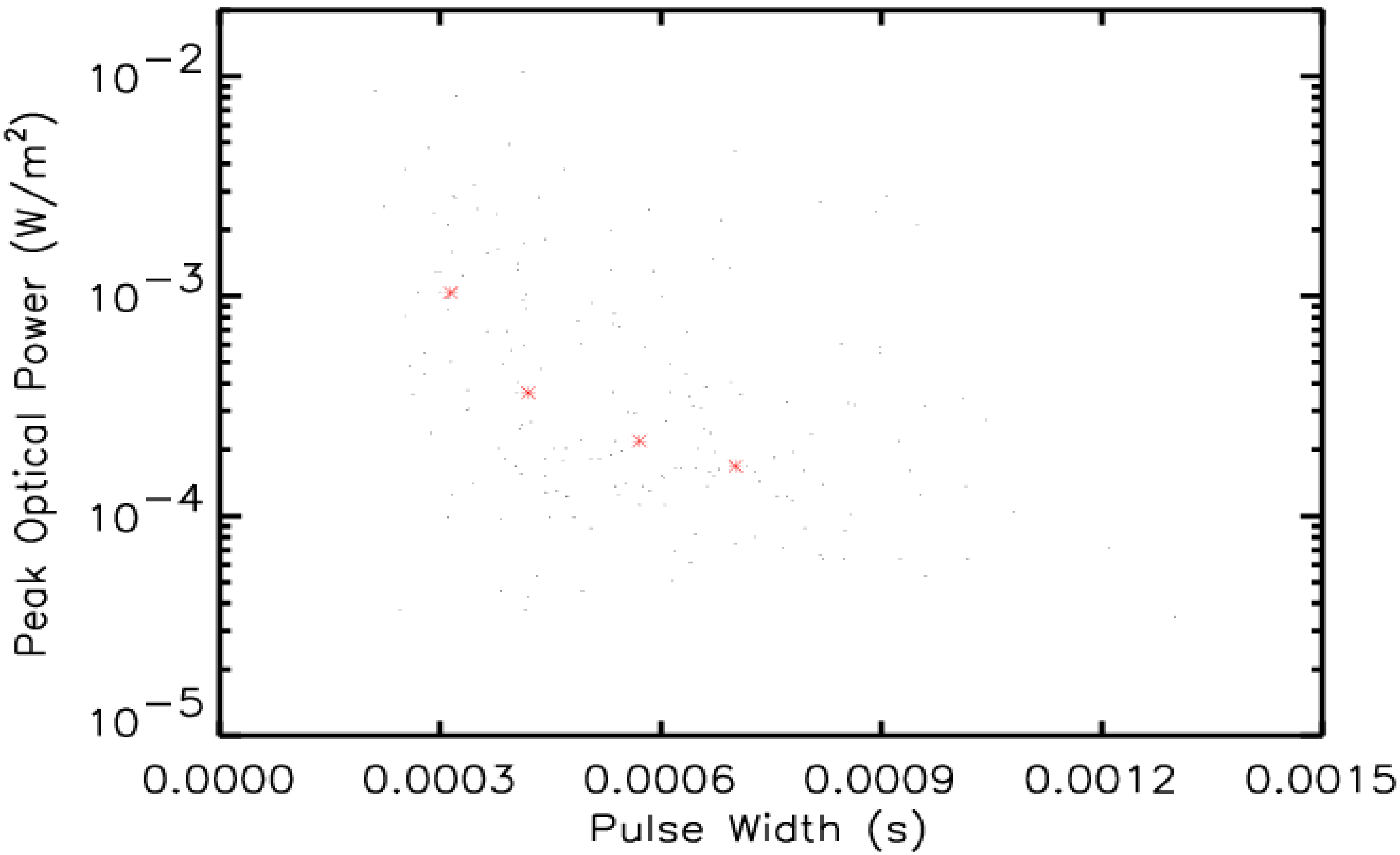


Figure 2. Plotted in black are all 184 negative initial return strokes. Binned median values are shown in red.

In-Cloud Lightning

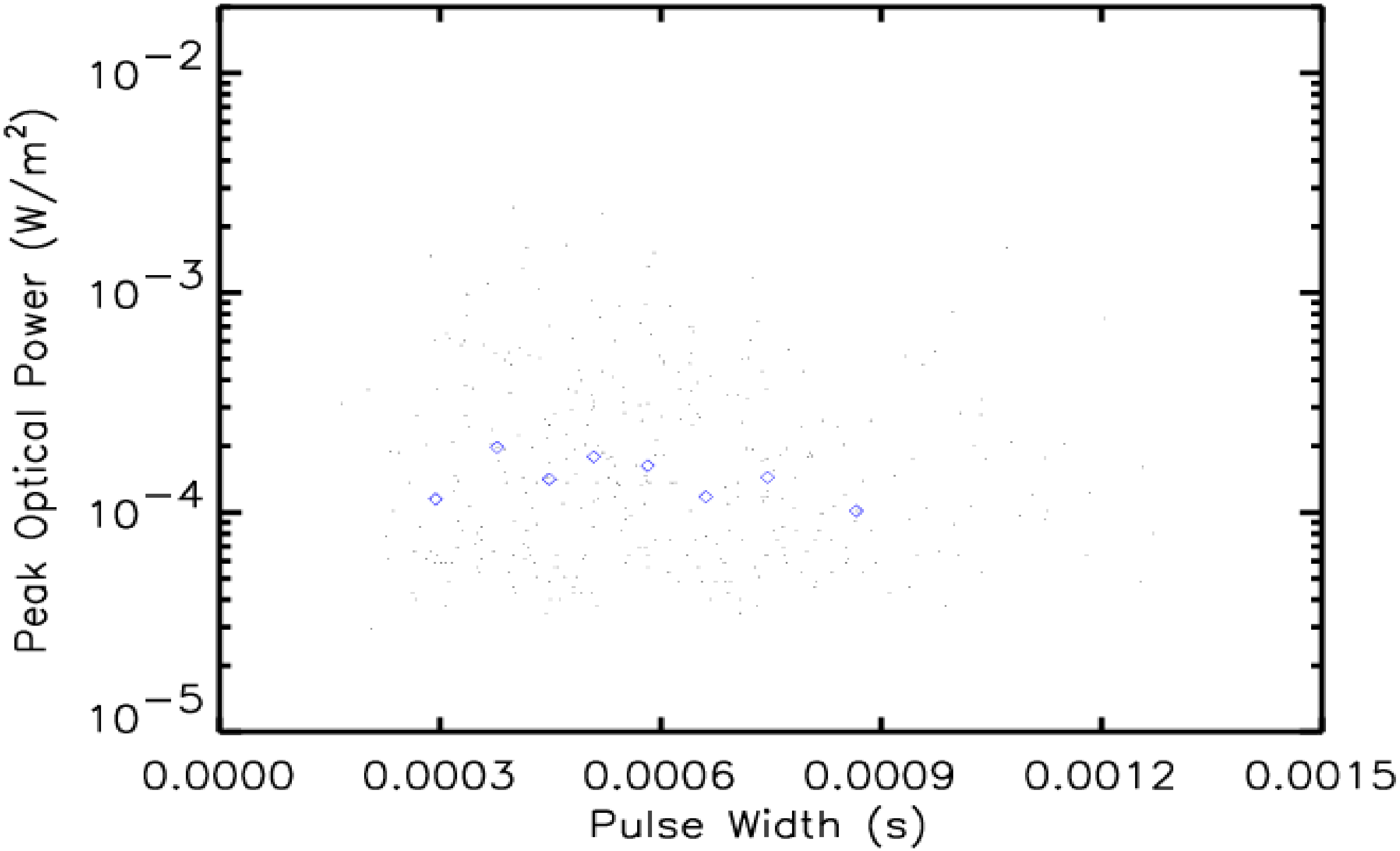


Figure3. Plotted in black are 343 non-impulsive in-cloud events. Binned median values are in blue.

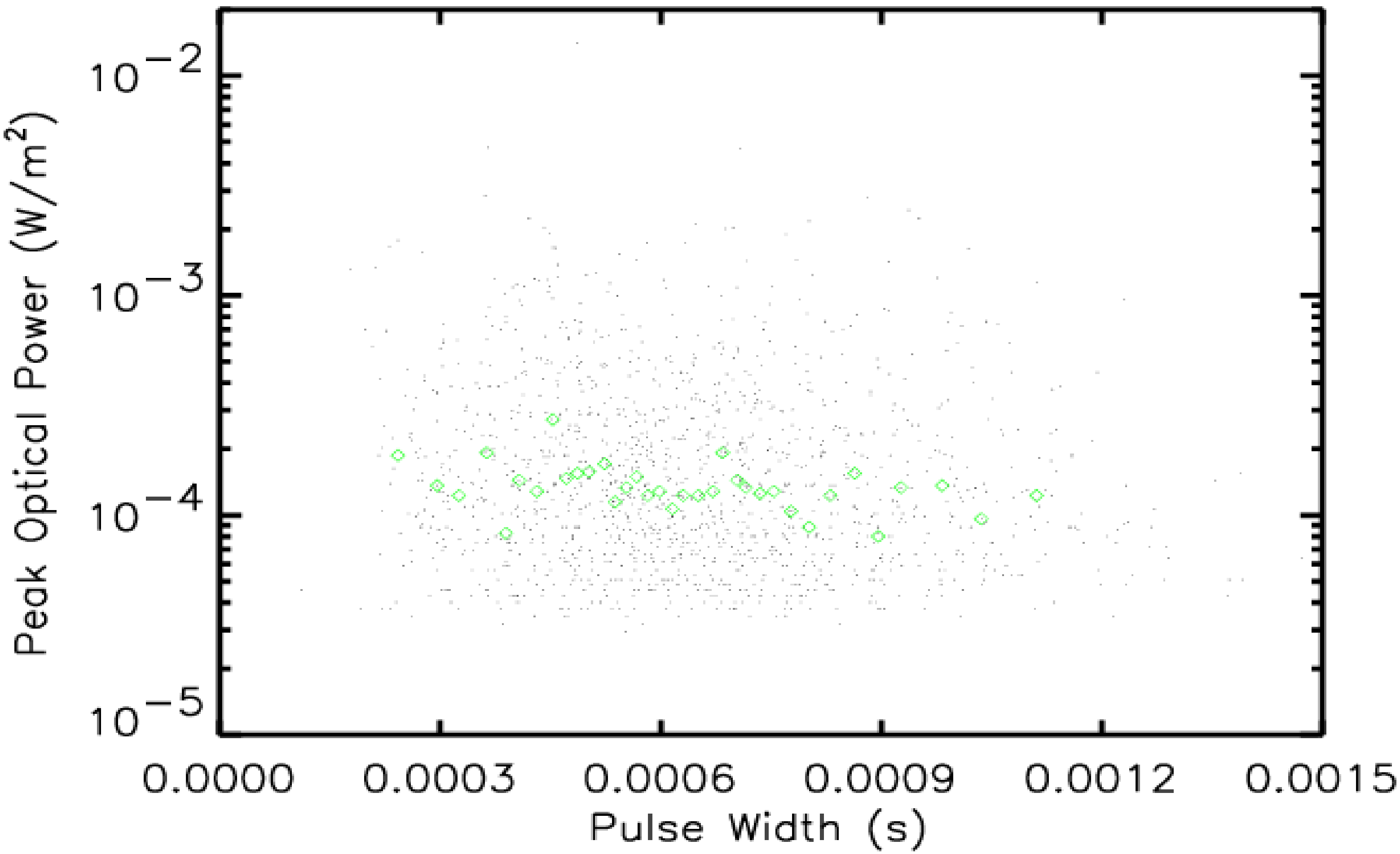


Figure 4. Plotted in black are 1429 Mixed Impulsive / Non-Impulsive events, with binned median values in green

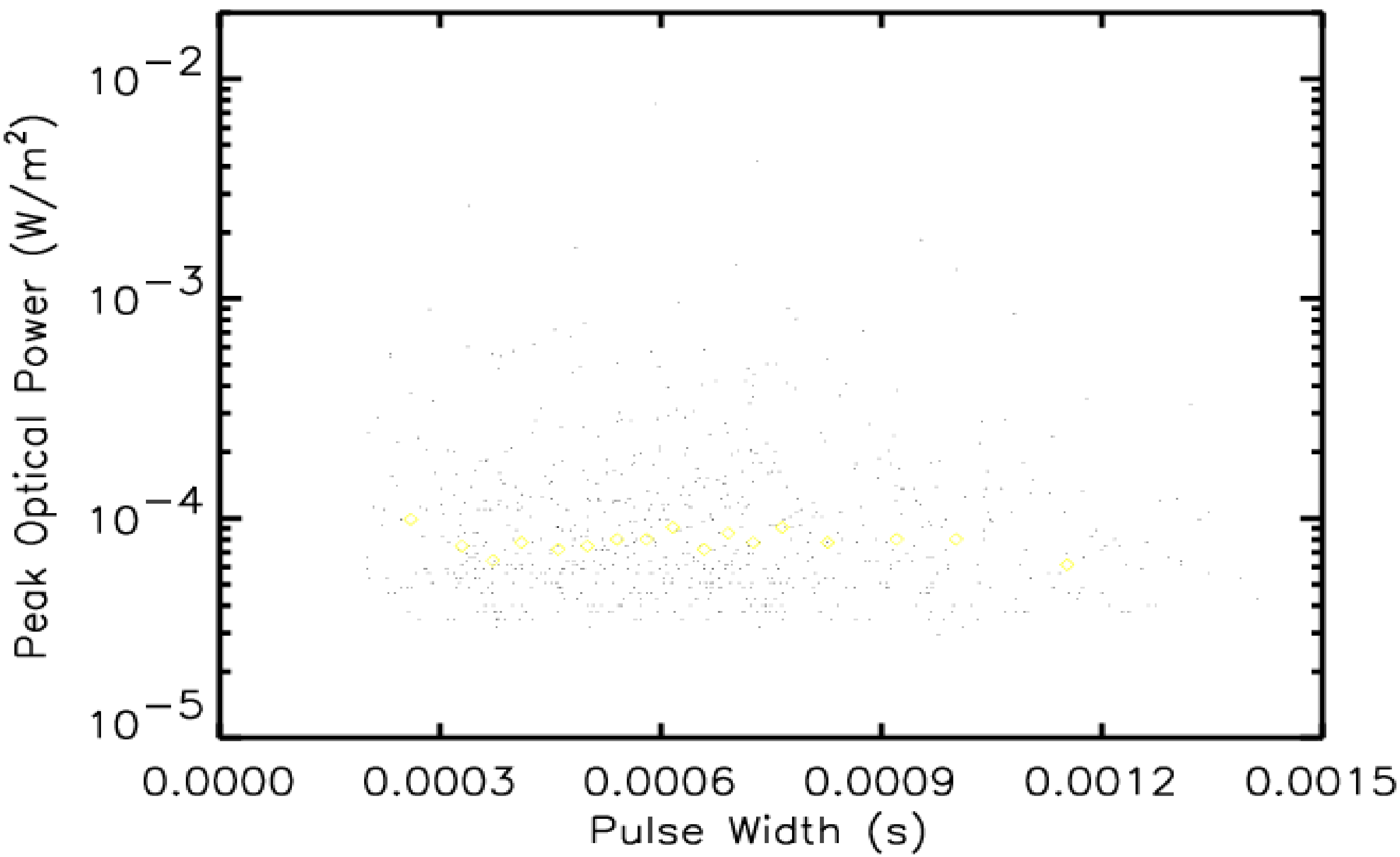


Figure 5. Plotted in black are all 696 impulsive in-cloud events. Binned median values are shown in yellow.

Table of Optical Properties by Type

Lightning Type	Median Pulse Width (ms)	Median Peak Optical Power (W/m2)
- Initial Return Stroke	0.537	2.73E-04
Subsequent Return Stroke	0.588	1.71E-04
+ Return Stroke	0.821	4.11E-04
Non-Impulsive In-Cloud	0.572	1.36E-04
Impulsive In-Cloud	0.625	7.48E-05
Mixed Events	0.621	1.28E-04

Histogram of Effective Pulse Width

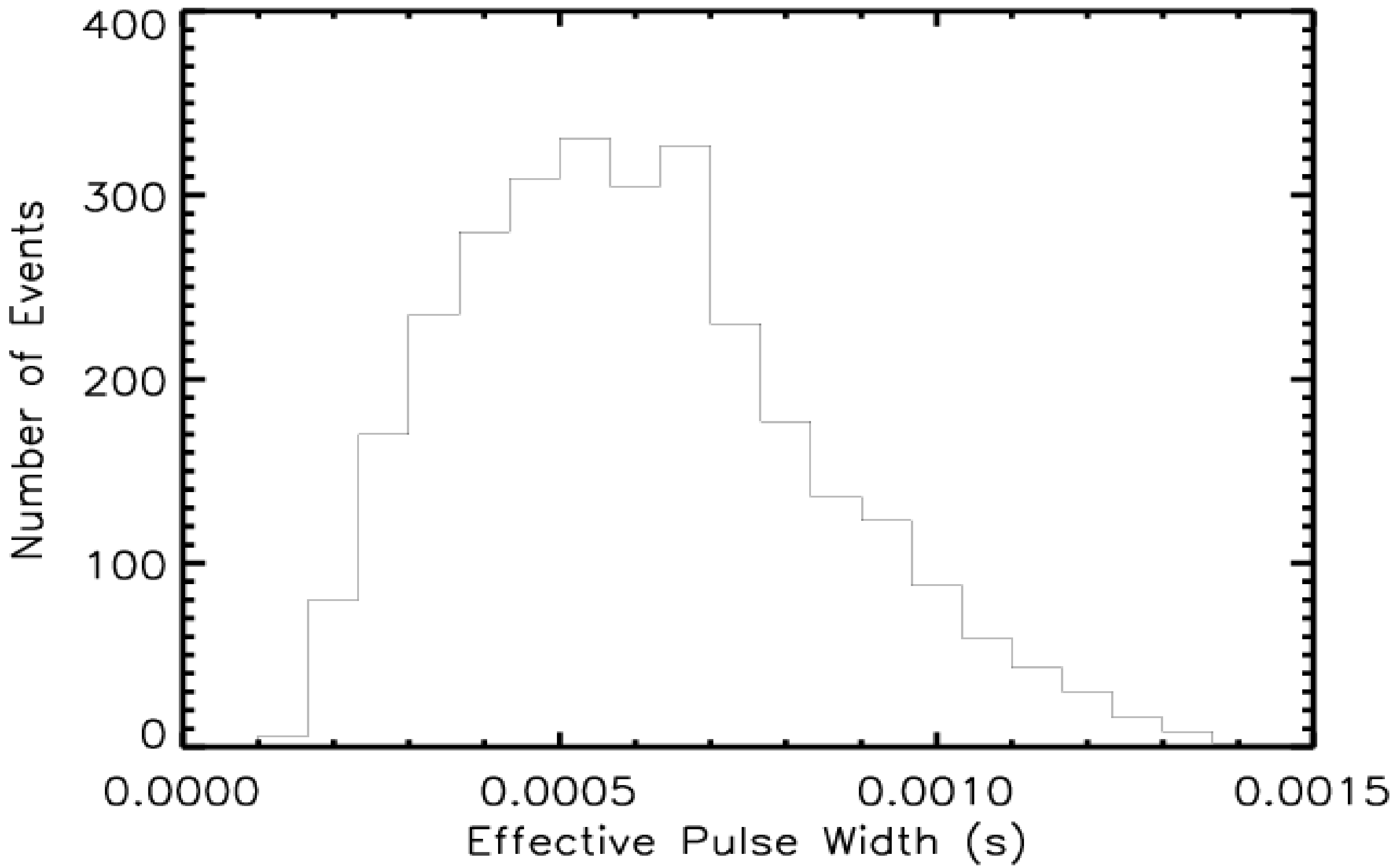


Figure 6. Shown above is a histogram of the effective pulse widths of all 2769 VHF/PDD pairs. The minimum optical pulse width (95 % level) is 294 μs

Explaining the Cutoff

1. Few intrinsic optical pulse width measurements have been made, but Guo and Krider measure ~ 150 μs for ground strokes.
2. Scattering accounts for at least 120μs of broadening
3. The particle filter allows us to see widths > 75μs

Conclusions

- Cutoff is not an instrumental effect but rather is due to both the intrinsic lightning duration coupled with scattering.
- Optical pulses vary to some extent with lightning type:
  - 1^{st} - Return Stroke: strong, narrow
  - Positive Return Stroke: strong, broad
  - In-cloud: weak, broad
- Impulsive events are optically weak:
  - Light et al. 2001b shows optical peak power $\propto$ RF peak power
  - Light and Jacobson show impulsive events strong in RF to be optically dark
  - ⇧ It was expected that the optical components of impulsive events would be weak.
- + RS significantly broader and more powerful than - RS
- It does not appear possible to identify lightning type based only on optical parameters

Future Work

- We are investigating the role that viewing angle plays in optical pulse widths.
- Storm level studies may allow for measurement of intrinsic pulse width via the de-coupling of cloud effects.
- Investigation of -RS / +RS optical property differences, perhaps involving radar data of cloud micro-physical data.

References

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