Optical Signatures of Cloud-to-Ground Strokes Observed by High-Speed Video Camera and the GLM

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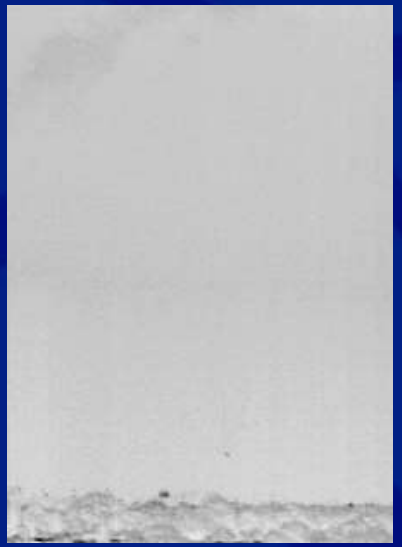
Introduction to Ground-truth Dataset

- **In this study we examine the responses of the Geostationary Lightning Mapper (GLM) for lightning occurring in Florida during 2018-2023.**
- **We used as "ground-truth", GPS-timestamped high-speed video camera records for 71 negative cloud-to-ground (CG) flashes** (including 71 first and 90 subsequent strokes).
  - In addition to video camera records, channel-base current measurements, recorded at the instrumented Kennedy Space Center (KSC) Industrial Area Tower (IAT), were available for 8 flashes (8 first and 12 subsequent strokes).
  - All strokes were matched with the associated event reported by the U.S. National Lightning Detection Network (NLDN).
- The cameras were operated at the Melbourne Lightning Observatory (MLO) and at the KSC IAT.
  - The minimum and maximum interframe intervals were 1.26 μs and 100 μs (~793,650 fps and 10,000 fps, respectively).
  - The strokes occurred at distance range of 0.42-66.9 km from the cameras, with the median distance being 21.6 km.
- **The channel-base current measurements at the KSC IAT were acquired on top of the 91.5-m tall tower using a shunt and Rogowski coil.**

Flash on 07/02/2020

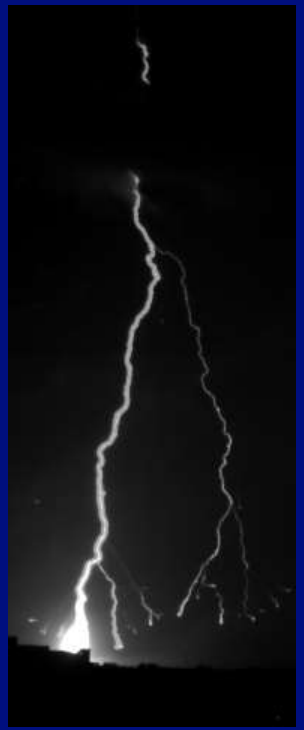


Flash on 07/02/2020
Inverted

Analysis Techniques

Continuing current duration from HS video

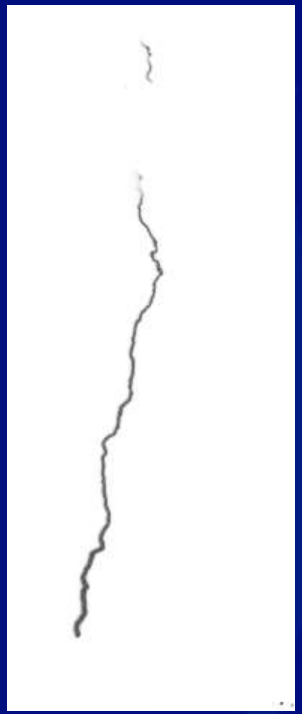
Frame 688



Frame 689

CC Start Frame

...



Frame 808

Inverted Color Image

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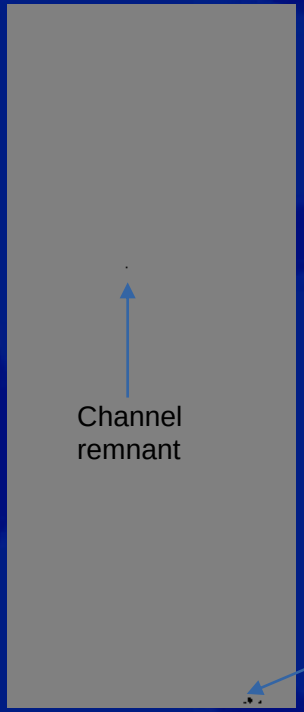


Frame 1196

Frame 1197

CC End Frame

Summary of Stroke Characteristics

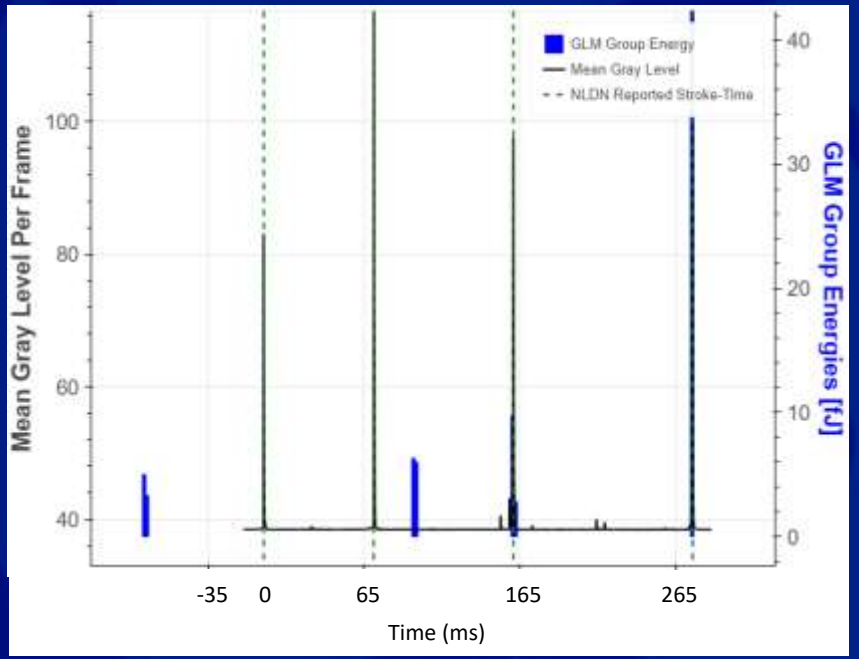
Characteristic		Sample size	Minimum	Maximum	Median
NLDN-reported peak current (kA)	First strokes	71	-4	-228	-24
	Subsequent strokes in new channel	7	-8	-34	-23
	Subsequent strokes in pre-existing channel	83	-4	-64	-20
Continuing current duration (ms)	First strokes	71	0.26	298	3.39
	Subsequent strokes in new channel	7	0.46	15.9	1.82
	Subsequent strokes in pre-existing channel	83	0.58	248	3.08
First-stroke to last-stroke time interval (ms)*		35	26.3	963	189
Interstroke time interval (ms)		89	1.47	546	63

*For multiple-stroke flashes

Matching High-Speed Video and GLM data

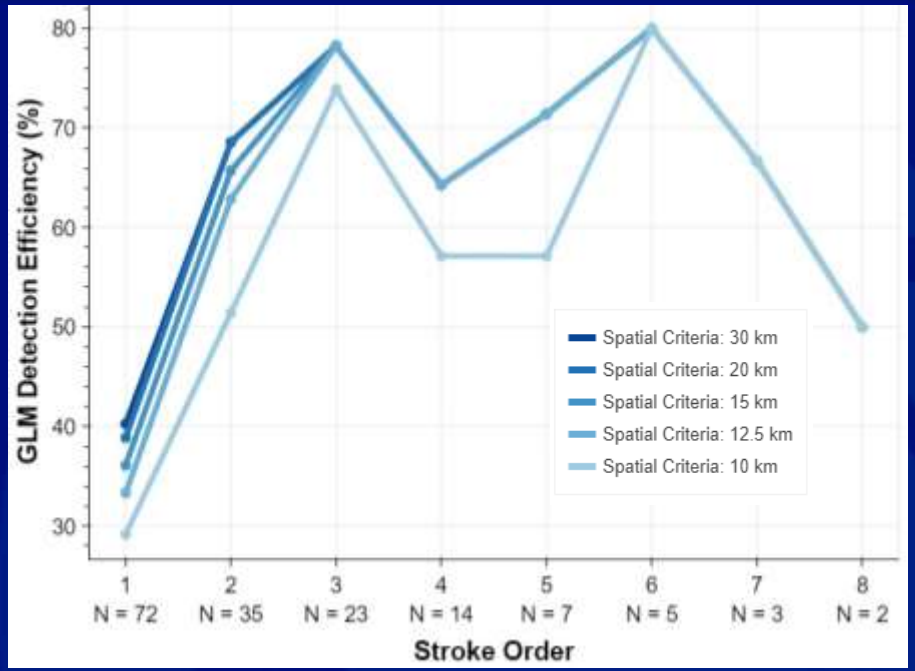
- For **each flash**, we searched for GLM groups that matched the following space-time criteria:
  - Within -1 s and +2 s of NLDN-reported first stroke time
  - Within 30 km of NLDN-reported first stroke location
- For **each stroke**, we searched for GLM groups that matched the following space-time criteria:
  - Within +/-4 ms of the stroke's NLDN-reported time.
  - Within the following distances of the NLDN-reported location:
    30, 20, 15, 12.5, and 10 km.

- Adjoining figure shows an example of a four-stroke flash on 07/02/2020 detected by the GLM.
  - The GLM group energies are plotted along with mean gray level of each video-camera frame as a function of time.
  - The GLM did not report any groups matching the first and second strokes and reported groups matching the third and fourth strokes.



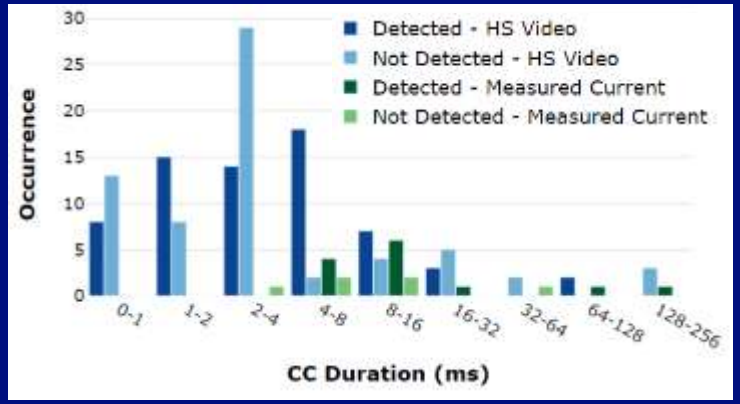
GLM Detection Efficiencies

Event type	Matching criteria for GLM groups relative to NLDN strokes	GLM DE
All flashes	Within -1 and +2 s and 30 km	88.9%
All strokes	Within +/-4 ms and 30 km	57.1%
	Within +/-4 ms and 20 km	56.5%
	Within +/-4 ms and 15 km	54.7%
	Within +/-4 ms and 12.5 km	52.8%
	Within +/-4 ms and 10 km	46.6%
First strokes	Within +/-4 ms and 12.5 km	**33.8%**
Subsequent strokes in new channel		**67.5%**
Subsequent strokes in pre-existing channel		**71.4%**



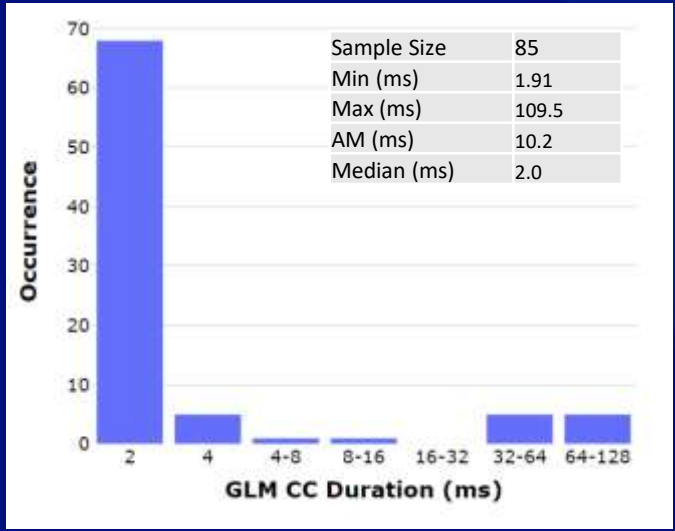
- **GLM flash DE was 89% for all flashes.**
- **GLM stroke detection efficiency appears to be the significantly higher for subsequent strokes (68-71%) than for first strokes (34%).**
- GLM stroke DE is highest for the third (78%) and sixth (80%) strokes in our dataset.

Characterization of GLM Detections

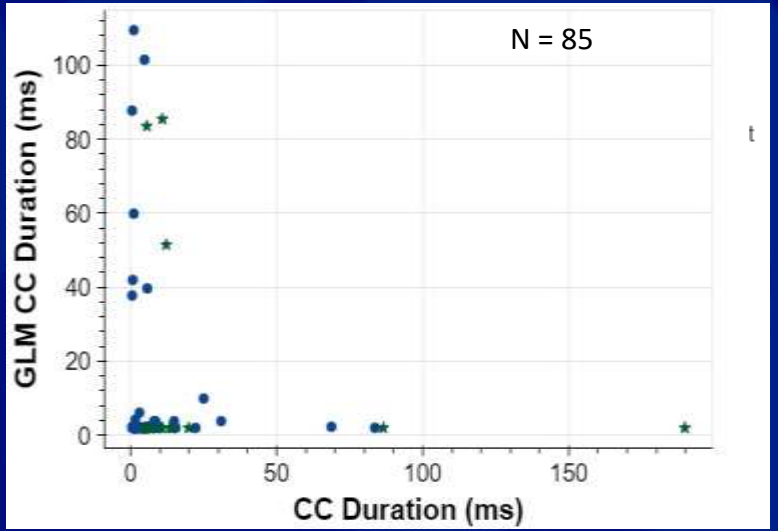


	Measured from HS video camera records		Measured from current waveforms		
	Detected by GLM	Not detected by GLM	Detected by GLM	Not detected by GLM	All Strokes
Sample Size	72	69	13	7	161
Min (ms)	0.58	0.26	4.74	2.87	0.26
Max (ms)	83.7	248	190	272	298
AM (ms)	7.06	14.5	29.9	52.2	14.5
Median (ms)	3.11	2.49	10.9	12.2	3.1

We estimated a continuing current duration from the GLM data for each of the 85 strokes detected (using the 12.5-km, 4-ms space-time criteria) by measuring the time-period during which a GLM group was reported within 4 ms of the previous group.



Sample Size	85
Min (ms)	1.91
Max (ms)	109.5
AM (ms)	10.2
Median (ms)	2.0



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Summary

- We analyzed the GLM responses to 161 first and subsequent strokes in 71 flashes recorded in Florida in 2018-2023.
- 89% of the flashes were reported by the GLM, with matching groups within -1 and +2 s and 30 km.
- With a space-time matching criteria of +/-4 ms and 12.5 km, the GLM stroke DE was 52.8%
  - GLM stroke detection efficiency appears to be the higher for subsequent strokes (68-71%) than for first strokes (34%).
  - GLM stroke DE is highest for the third (78%) and sixth (80%) strokes in our dataset.
  - This is likely due to subsequent stroke channels trying to neutralize more distant pockets of charge by extending inside the thundercloud and perhaps reaching higher altitudes leading to optical emissions from the cloud top that are detectable by the GLM.
- Continuing current durations estimated using GLM groups close to the ground-strike location appeared to be unrelated to those measured from high-speed video camera records or channel-base current waveforms.

Thank you!

Analysis Techniques (Details)
Continuing current duration from HS video and measured currents

- **The start time was defined as when the downward leader attached with the upward leader**, i.e., the time of the first frame showing the leader-channel luminosity near the ground ‘abruptly’ increased compared to the previous frame.

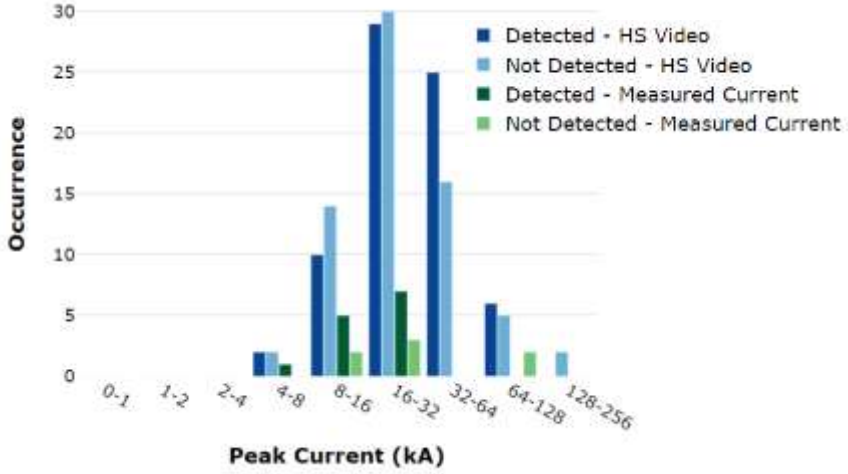
- **The end time was the time of the frame when the channel could not be distinguished from the frame’s background anymore.**

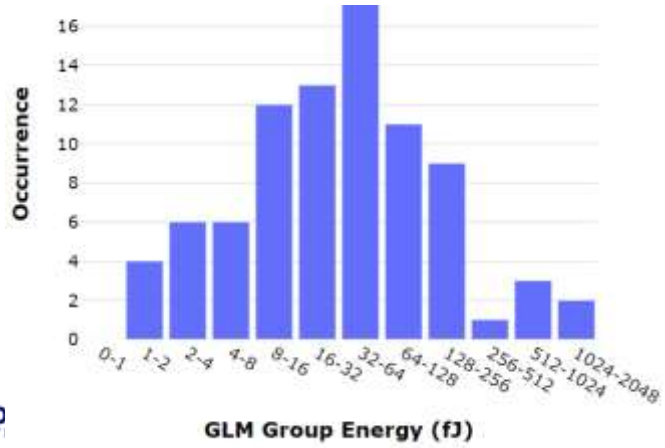
- First strokes and subsequent strokes in new channels were recognized by the significant branching and stepping observed as the downward leader approached ground in conjunction with relatively slow leader speed.

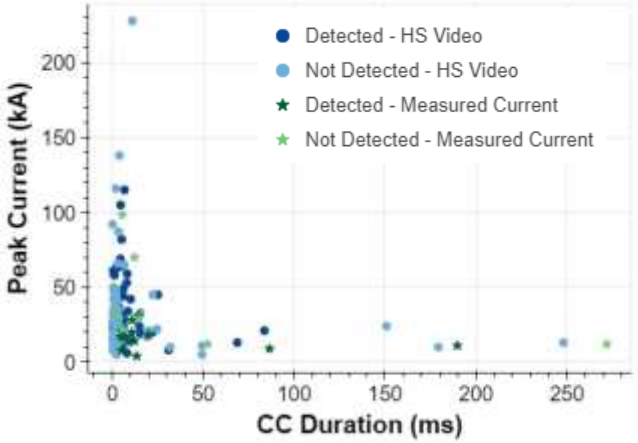
- Subsequent strokes in pre-existing channels were recognized by the lack of the branching characteristics described in the previous bullet along with a significantly faster leader speed.

- For strokes with channel base current measurements, **we defined the continuing current duration as the time-interval between when the return stroke current decayed to 10% of its peak value and when the current decayed to zero in our most sensitive current measurement channel**.

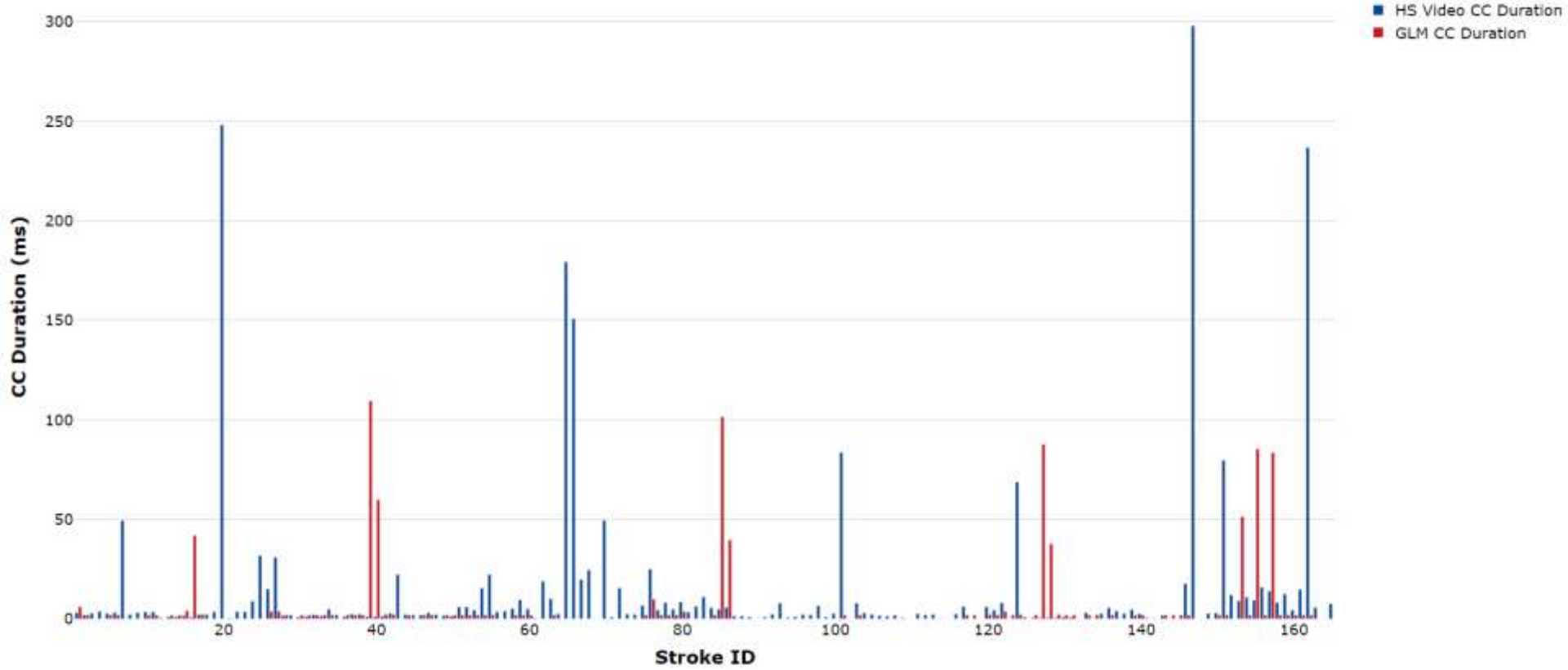
Characterization of GLM Detections



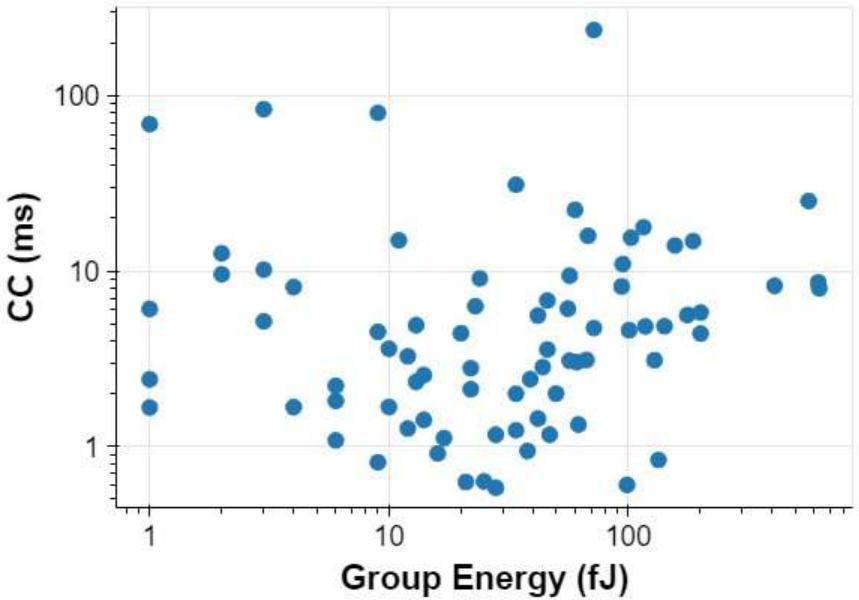


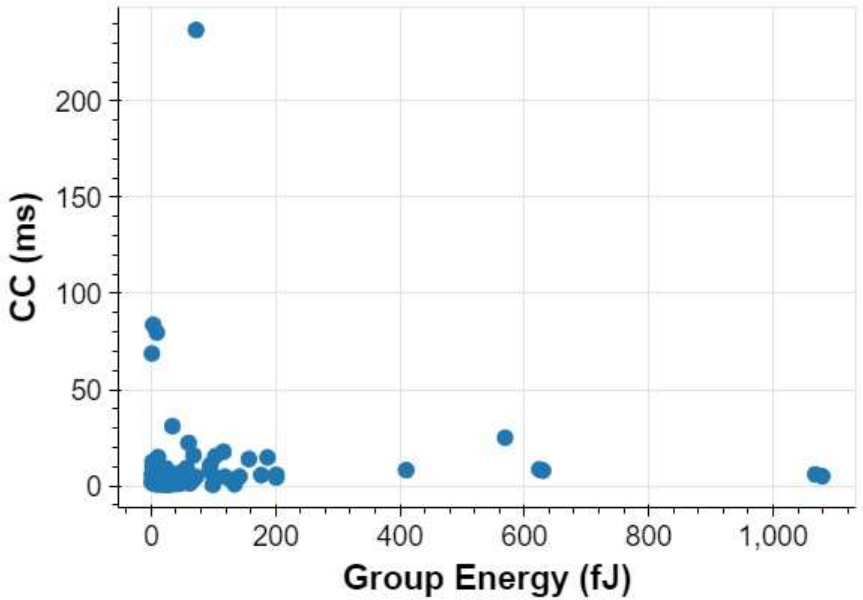


Characterization of GLM Detections

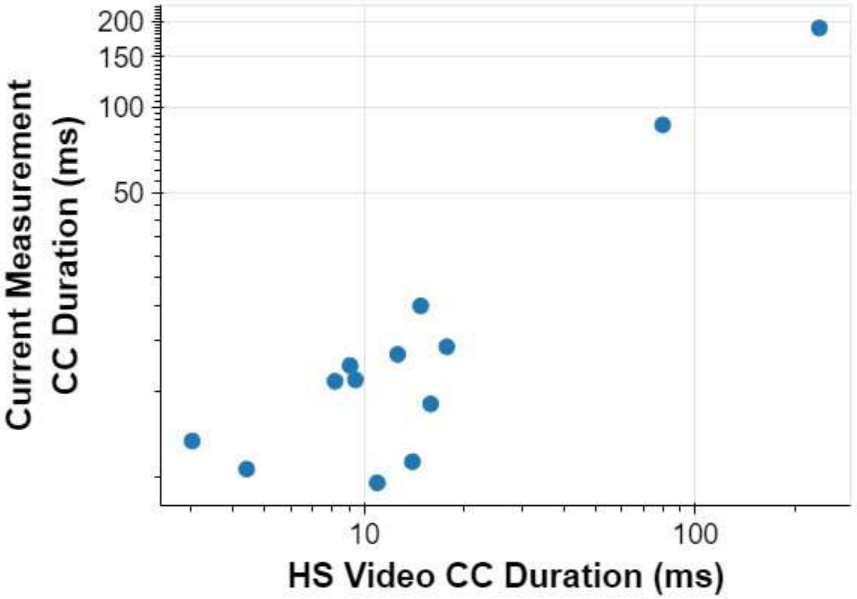


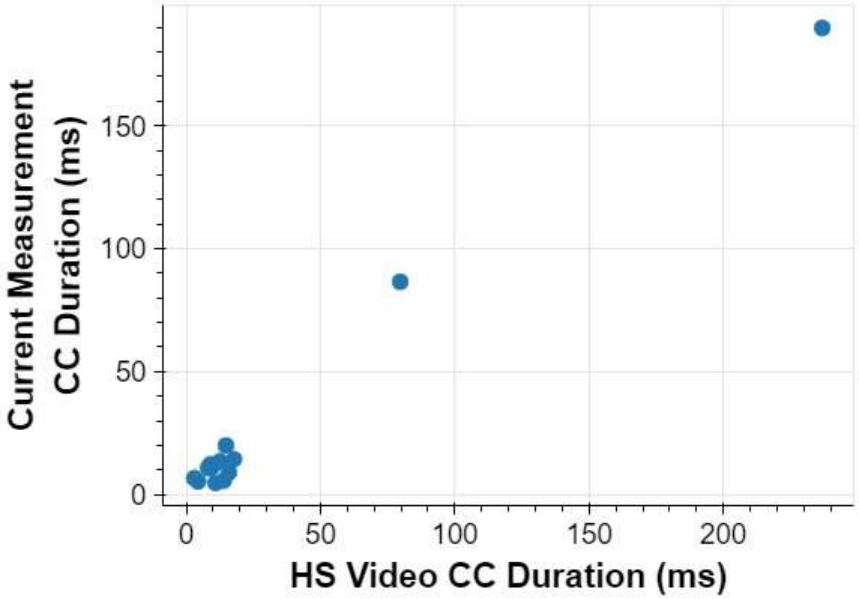
Group Energy vs CC





Ground-truth data characterization





Group Energy vs Peak Current