

Revisiting the Detection of Lightning Superbolts

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Abstract

This study uses Fast On-Orbit Detection of Transient Events (FORTE) satellite observations to identify superbolt-class optical lightning events and evaluate their origins. Superbolts have been defined by Turman (1977) as lightning pulses whose peak optical power exceeds 1011 W. However, it has been unclear whether superbolts resulted from particular types of high-energy lightning process or whether they were the result of measurement bias. In the latter case, any decently-bright lightning process could be recorded as a superbolt if the sensor had a particularly clear sight line to the hot channel without thick clouds diluting the optical signals. Our 12-year analysis of FORTE superbolt detections indicates that the lower optical superbolt energy range (~ 100 GW) is dominated by normal lightning, but brighter cases are predominantly strong +CG strokes that originate from specific types of storms. Oceanic storm systems, particularly during the winter, and especially those located around Japan are shown to produce these intense superbolts. We suggest that some optical superbolts result from favorable viewing conditions and would not be identified as such by another instrument located elsewhere, and that others are associated with a unique set of physics that may merit the “superbolt” distinction.

1 **Revisiting the Detection of Optical Lightning Superbolts**

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16 **Key Points:**

- 17 • Optical superbolts are identified based on peak optical power. Short-duration superbolts
18 may be missed if defined by total energy
- 19 • Normal lightning produces optical superbolts worldwide, but these superbolts are
20 relatively weak - near the 100 GW threshold
- 21 • Powerful (>350 GW) optical superbolts result preferentially from +CGs and are often
22 found in oceanic wintertime storms

25 **Abstract**

26 This study uses Fast On-Orbit Detection of Transient Events (FORTE) satellite
27 observations to identify superbolt-class optical lightning events and evaluate their origins.
28 Superbolts have been defined by Turman (1977) as lightning pulses whose peak optical power
29 exceeds 10^{11} W. However, it has been unclear whether superbolts resulted from particular types
30 of high-energy lightning process or whether they were the result of measurement bias. In the
31 latter case, any decently-bright lightning process could be recorded as a superbolt if the sensor
32 had a particularly clear sight line to the hot channel without thick clouds diluting the optical
33 signals.

34 Our 12-year analysis of FORTE superbolt detections indicates that the lower optical
35 superbolt energy range (~ 100 GW) is dominated by normal lightning, but brighter cases are
36 predominantly strong +CG strokes that originate from specific types of storms. Oceanic storm
37 systems, particularly during the winter, and especially those located around Japan are shown to
38 produce these intense superbolts. We suggest that some optical superbolts result from favorable
39 viewing conditions and would not be identified as such by another instrument located elsewhere,
40 and that others are associated with a unique set of physics that may merit the “superbolt”
41 distinction.

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44 **Plain Language Summary**

45 In 1977, Turman identified lightning that was 100 times brighter than normal in the Vela
46 satellite data. These pulses radiated between 100 GW and multiple terawatts of optical power at
47 the source. This observation sparked a debate as to whether these “superbolts” were caused by a
48 certain type of powerful lightning, or were merely the result of measurement biases. Clouds
49 dilute the optical signals generated by lightning, and reduce the optical powers recorded by
50 satellites. If lightning occurs at the edge of the storm, then the light can travel to the space-based
51 sensor at full intensity. Thus, any lightning event could produce a superbolt if the satellite
52 happened to be in a favorable position to see it, and sensors elsewhere might not classify it as a
53 superbolt.

54 This study analyzes FORTE satellite data to garner a better understanding of optical
55 superbolts. We find that weaker superbolts (100 GW) result from both scenarios: some come
56 from normal lightning, while others are caused by strong +CG strokes that tend to occur in
57 oceanic regions, in the winter, and often near the coast of Japan. The most powerful superbolts
58 (>350 GW), however, predominantly come from strong +CGs and may still merit the “superbolt”
59 distinction.
60

61 **1 Introduction**

62 The most energetic lightning emissions have been termed “superbolts,” outshining
63 normal lightning by a factor of 100 or greater. The first measurement of a superbolt was made by
64 the optical payload on the Vela satellite constellation, which was designed to detect nuclear
65 explosions from space. Turman (1977) defined superbolts as having an estimated source optical
66 power of at least 10^{11} W.

67 This designation of a certain class of optical lightning emissions as superbolts initiated a
68 debate in the lightning research community as to whether these highly-radiance events resulted
69 from some undiscovered exotic lightning process (new physics), whether they were produced by
70 a particular type of lightning event enabled by favorable conditions in the electrified cloud
71 (unique physics), or whether superbolts were just normal lightning in ordinary storms that
72 happen to have been observed by an on-orbit sensor with an unobstructed view of the hot
73 lightning channel (normal lightning). If these events represented a new or unique set of physics,
74 then the “superbolt” designation may be appropriate. If superbolts are simply the result of
75 measurement bias from particularly favorable viewing conditions (rather than lightning physics),
76 then it is not warranted. Over the past four decades, evidence has accumulated that supports both
77 concepts.

78 1.1 Superbolts as a unique type of lightning

79 The case for superbolts representing a unique set of physics is built on similarities
80 between Turman’s superbolt Vela waveforms and ground-based optical measurements of
81 positive-polarity cloud-to-ground (CG) strokes taken by Berger and Vogelsanger (1969), as well
82 as a geographic and seasonal preference for superbolt activity over Japan and the northern

83 Pacific Ocean during the winter months. This wintertime oceanic preference for superbolts
84 differs from the behavior of normal lightning that primarily occurs over land during the warm
85 season (Cecil et al., 2014) and usually produces negative-polarity CG strokes (Rakov, 2003).

86 While land-based storms produce frequent lightning and neutralize charge imbalances
87 with each flash, oceanic storms have low flash rates and thus continue to build charge separation
88 over long periods of time. Above-cloud aircraft electric field measurements have shown that
89 oceanic thunderstorms generate steady-state conduction currents (Wilson currents) that are 1.7x
90 stronger than their land-based counterparts (Mach et al., 2010) despite producing less lightning.
91 This discrepancy in the Direct Current (DC) supplied by land and ocean storms to the Global
92 Electric Circuit (GEC) helps to explain why the diurnal cycle of lightning disagrees with the
93 daily change in the fair-weather electric field (the Carnegie curve) (Mach et al., 2011).
94 Thunderstorm dynamics and the resulting precipitation structure of electrified weather differs
95 between land and ocean. Accounting for these structural differences using space-based radar and
96 passive microwave observations leads to the closest reconstruction of the Carnegie curve from
97 supply-side GEC measurements to date (Peterson et al., 2017a). This approach additionally
98 confirms the aircraft-based finding that Wilson currents from oceanic thunderstorms are 1.7x
99 greater than land-based storms (Peterson et al., 2018).

100 With oceanic storms accumulating large amounts of charge before initiating lightning, it
101 is not surprising that oceanic flashes can be particularly powerful when they do occur. Peterson
102 and Liu (2013) used optical Lightning Imaging Sensor (LIS: Christian et al., 2000)
103 measurements to show that oceanic regions produced particularly bright optical lightning flashes
104 that illuminated large areas of the surrounding storm, and that the strength and cloud-top extent
105 of the optical emissions correlated with the lightning peak current reported by matched National

106 Lightning Detection Network (NLDN: Cummins et al., 1998) CG strokes. Peterson et al. (2017b)
107 later refined these results to demonstrate that oceanic flashes were still larger and more radiant
108 than their land-based counterparts when they illuminated similar clouds under the same
109 background illumination. The oceanic preference for optically bright lightning thus arises from
110 physical differences in the flashes produced by oceanic storms, not from viewing conditions
111 affecting the measurements.

112 The wintertime lightning off the coast of Japan that is tied to superbolt activity is a
113 special case of oceanic lightning due to the influence of nearby Siberia on thunderstorm
114 organization and structure. The Sea of Japan and the Pacific Ocean are prone to cold air outbreak
115 events that generate notably shallow storms with cloud-top heights near 4 km, radar echoes
116 extending up to 3 km, and freezing levels near or below the surface. Frontal systems further east
117 over the Pacific may reach 8 km in height with a melting layer extending below 4 km
118 (Yamamoto et al., 2006). Turman (1978) attributed the superbolts detected by Vela in the region
119 to this specific type of weather pattern. In one case, the superbolt originated near the frontal
120 occlusion in a thunderstorm with cloud-top heights of 5.5 km.

121 These vertically-compressed wintertime thunderstorms are known to produce large
122 fractions of anomalous positive-polarity lightning flashes (Miyake et al., 1992). Positive-polarity
123 CG lightning is fundamentally different from its -CG counterpart. For net positive charge to be
124 transferred to the ground, the lightning channel must access a positive charge reservoir within the
125 cloud. This often occurs in bolts from the blue (Rust et al., 1981), while the storm is dissipating
126 (Mazur et al., 1998), or when lightning accesses an electrified stratiform region in a Mesoscale
127 Convective System (MCS) (Lang et al., 2004, 2017). In stratiform cases, the lightning channels
128 can extend horizontally over hundreds of kilometers with their dendritic structures encompassing

129 a charge region that is up to a hundred thousand square kilometers in area (Peterson, 2019a). The
130 largest of these stratiform flashes that has been observed was 709 km in horizontal extent, while
131 the longest-lasting flash was 16.73 s in duration (Peterson et al., 2020a). Enormous amounts of
132 charge from across vast regions can then be funneled down the vertical channels once they attach
133 to ground. +CGs are usually comprised of a single stroke with continuing current that produces
134 broad optical and Radio Frequency (RF) pulses that are hundreds of microseconds in duration
135 (Rakov, 2003). +CGs are thought to generate strong secondary electric fields above the cloud
136 that also lead to the generation of sprites (Pasko et al., 1995,1997). Sprites have been observed in
137 the wintertime oceanic storms near Japan associated with superbolts, even when these storms are
138 smaller than the minimum size threshold required for sprite activity in the continental United
139 States (Hayakawa et al., 2004). Blanc et al. (2007) additionally linked superbolt activity with the
140 production of such transient luminous events (TLEs). If superbolts primarily arise from these
141 intense +CG strokes, then their distinction may well be justified.

142 1.2 Superbolts as normal lightning

143 The case for ordinary lightning generating superbolts is based on the cloud layer between
144 the emissions source and the observing satellite diluting the optical signals via scattering and
145 absorption (Light et al., 2001a). If the lightning flash occurs under a thick layer of cloud, very
146 little light will transmit through the cloud top to reach the satellite (Peterson, 2019b). This causes
147 some lightning activity to be missed by optical space-based lightning imagers (Thomas et al.,
148 2000). However, if a high-current lightning process like a stroke or K-change occurs near the
149 edge of a cloud, the optical emissions can transmit to the satellite at full intensity. In this way,
150 any optically bright CG or IC process could generate a superbolt if the viewing conditions
151 happen to be particularly favorable.

152 One situation where this might arise is when the space-based lightning imager is located
153 near the horizon. If the elevation angle of the satellite is low enough, then the instrument may be
154 able to see below the anvil shield and directly record the undiluted emissions from the exposed
155 lightning channels in CG strokes. For satellites at higher elevation angles, optical emissions from
156 sources near the sides of the storm can still reflect off of neighboring clouds to reach the satellite
157 without transmitting through the full cloud depth. In either case, the signals recorded by the
158 space-based lightning imager will be particularly bright and may reach the superbolt threshold. If
159 superbolts are merely the result of viewing conditions and the geometry of the measurements
160 rather than the underlying physics of the discharge, then the superbolt designation would not be
161 merited. A second sensor at a different location would likely not classify the same optical pulse
162 as a superbolt.

163 Turman (1977) noted this possibility and observed that only 20% of his superbolts were
164 detected by multiple Vela satellites, which were positioned at different azimuth and elevation
165 angles around the source. This fraction of reporting satellites was consistent with Lund's (1973)
166 previous estimates for the probability that a flash would have a clear line-of-sight to a given
167 satellite. Kirkland's (1999) study of superbolt-class detections by the photodiode detector (PDD:
168 Kirkland et al., 2001) on the Fast On-Orbit Detection of Transient Events (FORTE) satellite
169 added additional evidence that superbolt-class detections might not describe extraordinary
170 lightning. Lightning pulses are broadened temporally by scattering in the cloud, yet the widths of
171 Kirkland's superbolt pulses were considerably narrow compared to normal lightning. This
172 suggests that the emissions took a relatively clear path to the satellite. Coincident NLDN
173 measurements during FORTE PDD superbolts over the United States between April and
174 September 1998 further showed that these highly-energetic optical pulses were generated by both

175 positive- and negative-polarity CGs whose peak currents were as low as 10 kA. Superbolt cases
176 were ubiquitous across the lightning-producing regions of the world (i.e., not concentrated in an
177 anomalous region or season) including the tropical lightning hotspots (Albrecht et al., 2016).
178 Finally, the FORTE very high frequency (VHF) waveforms that accompanied the optical
179 superbolt detections had signatures of multiple types of CG and IC processes (Light et al.,
180 2001b).

181 1.3 Anvil and stratiform superbolts

182 Kirkland's (1999) results do not eliminate the possibility that superbolts originate from a
183 unique type of lightning, but they show that unique flashes and thunderstorms do not hold a
184 monopoly on extremely bright optical pulses. Peterson et al. (2020b) also demonstrated this by
185 quantifying superbolt frequency in LIS measurements from the Tropical Rainfall Measuring
186 Mission (TRMM: Kummerow et al., 1998) satellite according to the Precipitation Radar (PR)
187 reported cloud type in the region illuminated by the flash. The most energetic optical pulses
188 recorded by LIS typically occurred in one of two scenarios: "anvil superbolts" where most of the
189 illuminated pixels were located near cloud boundaries outside of the raining area of the storm,
190 and "stratiform superbolts" that almost exclusively illuminated raining stratiform clouds.

191 Peterson et al. (2020b) also used continuous Geostationary Lightning Mapper (GLM:
192 Goodman et al., 2013; Rudlosky et al., 2019) observations to examine how lightning
193 characteristics changed over time within a single storm system. These analyses showed that early
194 convection was favorable for large flashes that lacked apparent lateral motion. Such flashes
195 could illuminate large portions of the convective anvil as well as neighboring clouds due to their
196 brightness combined with proximity to the storm edge – occasionally leading to anvil superbolts.

197 Upscale growth and organization into an MCS eroded this proximity to the storm edge, causing
198 large-stationary flashes to become overshadowed by the horizontally-propagating stratiform
199 lightning flashes that are associated with stratiform superbolts.

200 The TRMM and GLM data in Peterson et al. (2020b) supported both interpretations of
201 superbolt origins. There exists a class of superbolts where favorable viewing conditions allow
202 normal lightning to be particularly radiant. However, there is also a class of superbolts associated
203 with a particular type of lightning (strong peak current +CGs) that results from a unique set of
204 physics. Unfortunately, LIS is an integrating instrument that lacks the necessary time resolution
205 to resolve superbolts based on peak optical power, and this made drawing parallels with
206 Turman's (1977) sample of superbolts difficult.

207 The present study uses high-speed PDD detections over the complete FORTE dataset
208 (1997-2010) to identify superbolt-class optical lightning events around the world, and coincident
209 RF data to investigate their origins. We hypothesize that the brightest optical emissions from
210 lightning (> 350 GW at the source) come from +CGs, while weaker superbolts (100 GW – 350
211 GW) result from both normal lightning with favorable viewing conditions and +CGs. While
212 there is certainly a subset of superbolt-class detections that does not warrant distinction due to
213 their dependence on how the signals are measured, we propose that the term is justified for the
214 +CG cases.

215 **2 Data and Methodology**

216 A combination of optical and RF measurements is used to examine optical lightning
217 superbolts. These measurements were provided primarily by the FORTE satellite (Light et al.,
218 2001b; Kirkland et al., 2001). NLDN measurements from across North America during the

219 FORTE mission are also leveraged to add peak current and polarity information to the optical
220 events recorded by FORTE. We do not show waveforms from FORTE's RF payload because the
221 superbolts at the 10^{12} W peak optical power level either had NLDN coincidence or occurred
222 when the RF payload was inoperable (starting in 2003). Section 2.1 describes the FORTE optical
223 sensor package while Section 2.2 outlines our methodology for distinguishing lightning
224 superbolts in the space-based optical measurements.

225 *2.1 The FORTE Sensor Package*

226 The FORTE satellite carried multiple detectors that provided a wealth of information
227 about its recorded lightning events. FORTE’s Optical Lightning System (OLS) consisted of two
228 instruments: the Lightning Locating System (LLS), and the Photodiode Detector (PDD). These
229 instruments recorded the steady-state background radiance of the cloud scene and then triggered
230 on transient optical pulses caused by lightning illuminating the clouds or other phenomena that
231 resemble lightning.

232 The LLS was based on the LIS design with hardware provided by NASA Marshall Space
233 Flight Center. It had a lower frame rate than LIS (a nominal 405 FPS compared to 500 FPS), and
234 the relatively high 800-km orbit of FORTE resulted in a pixel size of 10 km projected to ground.
235 The key difference between LLS and LIS lies in how the stream of event detections was
236 processed. The LLS did not use LIS signal processing techniques, but instead employed a
237 module designed by Sandia National Laboratories. Single-pixel, single integration-frame triggers
238 known as “events” in the LIS community were not clustered into more complex lightning
239 features representing lightning flashes during the FORTE mission.

240 The second instrument in FORTE’s optical payload was the PDD. The PDD was a high-
241 speed (66,667 FPS) broadband (0.4–1.1 μm) photodiode detector that recorded 2–6 ms records
242 that integrate all lightning activity across its 80° FOV. FORTE’s PDD may be the closest analog
243 to the original Vela instrumentation that reported the first superbolts. However, the FORTE PDD
244 had two key limitations that could prevent detection in certain scenarios: (1) there was a dead
245 time after each trigger that was approximately equal to the record length, and (2) only a specific
246 number of successive triggers could be recorded over a short time. The exact number depends on
247 the instrument configuration, but limits of 10 or 20 are common. This record limit is the more
248 restrictive caveat of the two because +CGs are often preceded by extensive cloud activity that

249 can trigger the PDD. In these cases, the PDD might exhaust its record limit before the return
250 stroke that would produce the superbolt.

251 In addition to recording lightning, the PDD was also known to trigger on energetic
252 particle impacts and other non-lightning events that produced waveforms that are inconsistent
253 with lightning behavior. Kirkland et al. (2001) documented a collection of filters that remove
254 non-lightning triggers from the PDD dataset. We apply these methods to the full PDD data
255 record used in this study to screen for artifacts.

256

257 *2.2 Identifying Optical Superbolts*

258 Superbolts have generally been identified by choosing a somewhat arbitrary energy
259 threshold in the top 1% of lightning emissions, and then classifying anything above that
260 threshold as a superbolt. For the FORTE PDD, we leverage the methodology used by Turman
261 (1977) and Kirkland (1999) to identify superbolts. The optical waveforms recorded at the
262 satellite are used to compute peak optical powers and total radiated energies at a source that is
263 assumed to be directly below the satellite. PDD events with peak optical powers at the source
264 that exceed 10^{11} W are classified as superbolts.

265 Lightning imagers (LIS, LLS) lack the high frame rates required to measure the peak
266 optical power of the lightning pulse. Entire waveforms recorded by the PDD are captured in a
267 single LLS frame. LIS / LLS capture photons throughout the frame duration and then report the
268 total received radiance over this time at readout. “Superbolts” that are identified based on pulse
269 total energy measurements (Peterson et al., 2017c, Holzworth et al., 2019) may not be the same
270 as Turman’s (1977) superbolts identified based on peak optical power.

271 Fortunately, the FORTE PDD waveforms allow us to test whether superbolt thresholds
272 based on energy and power describe the same flashes. Figure 1 shows two-dimensional
273 distributions of PDD peak power against total integrated energy for the most radiant PDD events.
274 Both parameters are normalized to estimate the emission at the source rather than the radiance
275 received at the satellite. The thatched regions in the plot signify superbolts determined by peak
276 optical power (>100 GW) or total integrated energy (10^8 J). Events in the double-thatched region
277 to the top right of the plot meet both criteria.

278 There were 20,283 PDD superbolt-class events across the globe based on peak optical
279 power (>100 GW) of acceptable quality, representing the top 0.21% of the 9.3 million PDD

280 lightning detections. This fraction matches Turman's (1977) proportion of superbolts at the 100
281 GW level. Increasing the threshold drastically reduces the sample size. By 350 GW, only 1086
282 PDD events remain comprising 0.011% of all lighting. The proportion of 3-TW events in the
283 Vela data documented by Turman (1977) suggests that the FORTE PDD should have detected ~4
284 of these events over its mission. The PDD actually detected two such events, but waveform
285 analyses suggest that one of them is a Hyper-velocity Microgram Particle Impact (HMPI) at the
286 satellite rather than a terrestrial lightning source.

287 Figure 1 shows how the superbolts identified based on total optical energy differ from
288 those identified by peak optical power. For each peak optical power level (for example, 10^{10} W),
289 there is a range of approximately 1-2 orders of magnitude in the associated total optical energy
290 due to varying pulse widths and the limited millisecond-scale record lengths. Defining an energy
291 threshold (say, 10^8 J) will still capture the 100-GW peak power superbolts with the broadest
292 peaks, but the majority of the peak-power superbolts will be missed.

293 The brightest events in terms of total optical energy are still superbolts, but they do not
294 represent *all* of the superbolts. Particularly quick events, -CGs for example, will be missed
295 because they do not radiate for a long enough period to reach this total energy threshold. Thus,
296 instruments like LIS (Peterson et al., 2017c) and GLM (Peterson, 2019a) will excel at finding
297 +CG superbolts with their broader pulses, but may have difficulty identifying other types.

298 **3 Results**

299 The FORTE PDD provides similar representations of optical lightning pulses to the Vela
300 optical system. For this reason, the high-energy events reported by FORTE will be a more
301 appropriate analog to Turman's (1977) superbolt observations compared to superbolts identified

302 by other types of measurement types. In the following sections, we document where and when
303 these energetic optical pulses occur, and what types of lightning produce them.

304 *3.1 NLDN measurements of superbolt flashes*

305 We first examine the polarities and peak currents of the NLDN strokes that accompany
306 superbolt-class PDD events. Kirkland's (1999) NLDN analysis of PDD events over North
307 America between April and September 1998 showed that both +CGs and -CGs could generate
308 >100 GW events. The NLDN data suggested that even relatively weak strokes with peak currents
309 < 20 kA could produce superbolts. This view is not supported by Holzworth et al. (2019) whose
310 Earth Networks Global Lightning Network (ENGLN) peak current distribution lacks superbolt
311 cases below 100 kA.

312 The most likely reason for this discrepancy is because the WWLLN superbolts identified
313 by Holzworth et al. (2019) are measured by RF instruments rather than optically. It is thus not
314 guaranteed (and probably unlikely) that they capture the same sample of lightning events as
315 Turman (1977). Kirkland's PDD (1999) analysis supports the idea that particularly favorable
316 sight lines can cause many types of lightning to produce superbolts, but RF measurements such
317 as those provided by WWLLN and ENGLN are not modified by the clouds in this way. For
318 WWLLN to record a high-energy stroke, it must be a strong CG. Since the ENGLN peak current
319 threshold for matched WWLLN superbolts is identical for +CGs and -CGs, both parameters
320 (ENGLN peak current and WWLLN energy) should be highly correlated. Peak current is
321 calculated from the Range-Normalized Signal Strength (RNSS) of a geolocated source, and is a
322 measure of the peak E-field in the RF waveform. In this way, it is similar to the PDD peak
323 optical power of the source calculated from the maximum in the PDD waveform. WWLLN
324 energies, meanwhile, are calculated by integrating the E-field through the spheric, and are thus

325 similar to the PDD total optical energy. Holzworth's (2019) comparisons between peak current
326 and WWLLN energy are then, essentially, an RF analog to our Figure 1 for the FORTE PDD,
327 and it is not surprising to see that RF-detected superbolts generate powerful emissions recorded
328 by both RF networks.

329 However, the other issue that both studies share is their limited sample size of superbolt-
330 class event coincidence with the ground networks that report peak current. Kirkland (1999)
331 identified just 130 superbolt cases coincident with NLDN, while Holzworth et al. (2019) found
332 just 18 matches with ENGLN. It is unclear whether either analysis is truly representative.
333 To generate more robust statistics, we repeat Kirkland's (1999) approach for identifying NLDN
334 matches to PDD events and extend it to the whole FORTE record (1997 – 2010). NLDN
335 observations are limited to a domain surrounding the United States. These matches are only
336 representative of the global PDD dataset under the assumption of [identical physics across all](#)
337 [terrestrial strokes](#). Figure 2a shows the population density of all of our 3.1×10^4 NLDN-matched
338 PDD events. Figure 2b shows the average peak current for the PDD / NLDN matches. PDD peak
339 optical power generally correlates with NLDN peak current, and the strokes associated with
340 superbolts exceed 80 kA, on average. For a given peak optical power, however, the NLDN peak
341 current tends to decrease as the total energy increases. In other words, lower peak currents are
342 required to generate bright optical pulses (in terms of peak optical power) that have longer-
343 duration pulses and higher total energies than quicker events. Finally, we compute the fraction of
344 all NLDN matches that are +CGs in Figure 2c. For non-superbolt cases, the +CG fractions at a
345 given peak-power increase from < 10% of all lightning in the lowest-energy (quickest) events to
346 50-100% of all lightning in the highest energy (longest-lasting) events. This supports the idea
347 that LIS / GLM superbolts identified based on total optical energy are more likely to be +CGs

348 than those identified by peak optical power.

349 Since the low sample sizes at each gridpoint in the superbolt domain of Figure 2 obscure
350 the peak current and polarity trends, Figure 3 accumulates all PDD / NLDN matched events
351 above certain PDD optical power levels and constructs histograms (bar plots) and Cumulative
352 Density Functions (lines) for each level. The histograms are normalized according to the total
353 number of PDD / NLDN matches: positive-polarity (yellow) plus negative-polarity (blue). Figure
354 3a shows the distributions for all PDD matches from Figure 2. These matches are most
355 frequently 10 - 30 kA NLDN strokes (median: -21 kA, +14 kA), primarily -CGs. Figure 3b
356 subsets the sample to only include PDD / NLDN matches where the peak optical power at the
357 source exceeds 100 GW. The inclusion of both positive and negative strokes as well as the
358 overall -CG dominance agrees with Kirkland's (1999) and Holzworth's (2019) findings.
359 However, the peak currents for these 100 GW optical superbolts are notably higher than
360 Kirkland's (1999) assessment with mean values of -73 kA and +103 kA, though still weaker than
361 the superbolt peak current range in Holzworth et al. (2019).

362 If we continue increasing the PDD peak power threshold to only capture stronger events,
363 we start to see the -CG peak erode until it is overtaken by the +CG peak. By 350 GW (Figure
364 3c), the histogram is dominated by +CGs that exceed 100 kA (mean: +133 kA). This change
365 shows that the superbolts at 100 GW are generated by a different set of lightning processes than
366 those at higher peak powers. It is thus possible that Kirkland's (1999) assessment from NLDN
367 events and FORTE VHF waveforms that positive and negative CG and IC pulses may generate
368 superbolts is correct at the 100 GW level, while terawatt-scale superbolts only occur in certain
369 circumstances enabled by the dynamics and charge structure of the parent thunderstorm.

370

371 *3.2 Global and seasonal distributions of FORTE PDD superbolts*

372 To gauge where superbolts at different source peak power levels come from, we construct
373 global distributions for the FORTE satellite subpoint locations during these radiant PDD events.
374 These maps do not capture accurate source locations because the emitter could be located
375 anywhere across PDD's FOV that is ~1200 km across. In cases where we have LLS coincidence
376 with the PDD, we can geolocate the source to within 10 km, but many of our superbolt cases
377 occurred while the LLS was not reporting. Thus, only 9.3% of the 100 GW superbolts occur
378 alongside an LLS event.

379 Figure 4 shows the distribution of FORTE positions during PDD superbolts whose peak
380 optical powers exceeded 100 GW at the source. As in Kirkland's (1999) analysis, these sources
381 are distributed broadly across the globe with high concentrations of events near the tropical
382 chimney regions in South America, central Africa, and the Maritime Continent in Asia. Weaker
383 local maxima can also be noted leeward of the major continents, and in the Mediterranean Sea.
384 Many of these regions were identified by Holzworth et al. (2019) as hotspots for WWLLN
385 superbolt activity, though clear maxima over the Andes and in the North Sea are not evident in
386 the optical PDD data.

387 As with the NLDN peak current histograms in Figure 3, increasing the peak power
388 threshold changes the global distribution of superbolt cases. Figure 5 maps the global distribution
389 of all cases whose peak powers at the source exceeds 350 GW (as in Figure 3c). The maxima
390 near the tropical chimneys disappear entirely, leaving a few scattered (primarily oceanic) cases
391 across the tropics. The previously-secondary peaks along the Gulf Stream, in the Mediterranean,
392 and surrounding Japan become the most prominent features in the distribution – with the Sea of
393 Japan / North Pacific Ocean further east producing more superbolts than any other region across

394 the globe.

395 The seasonal cycles for these superbolt flashes also change based on the peak optical
396 power threshold. Figure 6 plots the frequency of superbolts ranging from 100 GW to 500 GW for
397 each month of the year in the northern mid-latitudes (Figure 6a), the tropics (Figure 6b) and the
398 southern mid-latitudes (Figure 6c). There are two distinct maxima in the seasonal cycle for 100
399 GW superbolts in the northern mid-latitudes (Figure 6a): one in July, and another in December.
400 The tropical curves (Figure 6b) are mostly flat over the year with three peaks at lower energies
401 (March, July, and October). The southern hemisphere curves (Figure 6c) all have a single
402 pronounced wintertime peak. The northern hemisphere summer peak declines as we move up in
403 power, however. It is no longer the annual maximum by 150 GW, and is indistinguishable in the
404 300 GW and 500 GW curves. At these higher peak optical powers, subtropical superbolts are
405 dominated by winter lightning in both hemispheres, in agreement with the WWLLN statistics
406 shown in Holzworth et al., (2019).

407 The fact that maxima in the lightning distributions flip from the tropics to the subtropics
408 and from summer to winter between 100 GW and 350 GW provides further support that the
409 composition of the lightning sample is highly sensitive to the selected peak optical power
410 threshold. The relatively weak cases at 100 GW appear to comprise a diverse sample of “normal”
411 lightning, but the 350+ GW superbolts predominantly occur in wintertime oceanic storms that
412 are known for strong +CGs.

413 3.3 *The most radiant superbolts observed by the FORTE PDD*

414 Our previous analyses have stopped at 350 GW due to the limited number of cases above
415 this peak power level. The FORTE PDD did measure superbolts that were more radiant,
416 however. There were a total of 38 PDD events that reached the terawatt scale, and these are

417 listed in Table 1. Because peak optical power and total integrated optical energy are correlated
418 (i.e., Figure 1), all of these cases generated at least 10^8 J of energy with effective pulse widths
419 ranging from 155 μ s to 542 μ s. Nine of the 38 events were detected exclusively by the PDD with
420 no other FORTE sensor reporting. This was particularly commonplace after the RF payload
421 became inoperable in 2003. There were 4 events that occurred over North America and all four
422 had NLDN coincidence. NLDN reported peak currents ranged from 94 kA to 167 kA and were
423 all cases of positive-polarity return strokes.

424 The overall brightest superbolt recorded by the PDD had a peak optical power at the
425 source of 3.14×10^{12} W, a total integrated source energy of 7.99×10^8 J, and an effective pulse
426 width of 255 μ s. The PDD waveform for this event is shown in Figure 7. The light curve builds
427 quickly to its initial peak, and then optical emission persists for at least 1.3 ms afterwards. The
428 PDD record ends before the radiance reached the background value. The slowly-varying weak
429 emissions appear to be continuing current from the CG.

430

431 **4 Summary**

432 We use the full FORTE PDD record (1997-2010) to identify optical superbolts and
433 examine the types of lightning that produce them. We find that the weaker superbolts (10^{11} W)
434 analyzed by Turman (1977) in the Vela data and Kirkland (1999) in the FORTE PDD data result
435 from a variety of lightning types. Many of these are not exceptional cases of lightning, but
436 instead normal lightning that happens to have a clear sight line to the sensor. However, the
437 brighter events that have coincidence with ground-based measurements - including some
438 terawatt-scale detections – are predominantly intense +CG strokes. These brightest events result
439 from unique thunderstorm dynamics that are often found in oceanic storms, particularly during

440 the winter, and especially surrounding the Japanese archipelago and Mediterranean Sea.

441 The frequency and intensity of FORTE PDD superbolts is found to be consistent with
442 Turman’s (1977) results from the Vela constellation, though our results are limited by the fact
443 that FORTE was a single satellite in low Earth orbit. Terawatt-class superbolts are exceptionally
444 rare phenomena. In 12 years of on-orbit operations, the FORTE PDD only detected one valid
445 lightning case that exceeded Turman’s (1977) 3-TW threshold. Staring coverage from a high-
446 speed optical instrument in a geosynchronous orbit would allow these events to be readily
447 detected. The upcoming LANL/SNL/NNSA SENSER payload will feature instrumentation
448 similar to the FORTE sensor package in a western hemisphere geosynchronous orbital slot that
449 should allow these exceptionally-bright cases to be detected and compared with space-based
450 lightning imagers (GLM, LIS), long-range ground-based networks (NLDN, WWLLN, ENTLN),
451 and regional Lightning Mapping Arrays (LMAs) across the Americas. While only some of the
452 Earth’s superbolt hotspots will be observed by all of these instruments, this wealth of data will
453 enable unprecedented examinations of the physics behind these interesting lightning events – and
454 perhaps finally settle the debate as to whether certain flashes merit the distinction of
455 “superbolts.”

456

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459 contract number 89233218CNA000001. The FORTE PDD superbolt detections presented in this
460 study are available in Peterson (2020). The NLDN data used in this study were provided by
461 Vaisala, Inc. (<https://www.vaisala.com>), and may be ordered from them.

462

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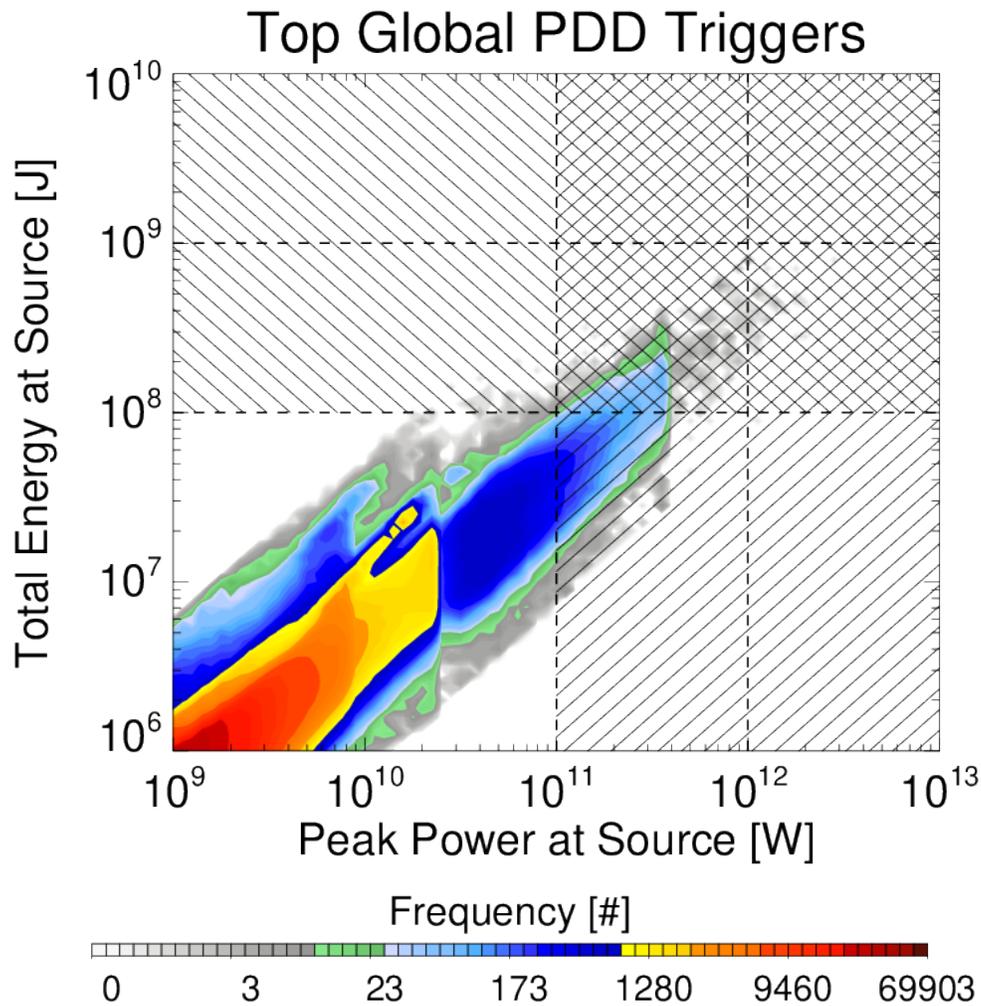
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577 **Table 1.** Terawatt-class lightning superbolt cases detected by the FORTE PDD between 1997
 578 and 2010. Only one case reached the 3-TW level, like the cases listed by Turman [1977]. All
 579 four cases around CONUS (shaded yellow) had NLDN coincidence and resulted from +CG
 580 return strokes. Reported peak currents (from top-down) were +168 kA, +95 kA, +175 kA, and
 581 +161 kA, respectively.
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DATE	UTC TIME	PDD LON	PDD LAT	PEAK POWER [W]	TOTAL ENERGY [J]	PULSE WIDTH [μ s]	LLS OR RF MATCH?	NLDN MATCH?
07/31/99	10:10:38.73	30.5	-33.1	1.03E+12	4.71E+08	458	YES	N/A
02/05/00	18:14:16.43	-170.0	45.6	1.03E+12	3.51E+08	341	NO	N/A
01/28/03	10:07:10.34	49.4	29.6	1.03E+12	3.69E+08	359	YES	N/A
05/23/03	22:43:53.52	27.8	-28.9	1.03E+12	3.98E+08	387	NO	N/A
12/23/05	00:49:36.80	-150.3	33.7	1.03E+12	3.40E+08	331	YES	N/A
12/30/97	09:32:19.48	-74.7	29.6	1.08E+12	3.62E+08	336	YES	YES
08/14/04	06:10:02.81	-73.3	21.4	1.08E+12	2.73E+08	253	YES	N/A
07/26/07	05:05:37.88	74.0	41.1	1.08E+12	3.15E+08	292	YES	N/A
06/13/99	21:10:16.49	-128.9	-42.1	1.13E+12	2.39E+08	212	NO	N/A
10/21/07	14:13:54.31	11.8	37.1	1.13E+12	5.77E+08	512	YES	N/A
12/18/98	12:13:01.42	-138.4	-47.5	1.18E+12	4.06E+08	346	YES	N/A
02/22/99	07:03:25.27	40.2	47.5	1.18E+12	3.87E+08	329	NO	N/A
03/25/01	09:02:37.16	-68.0	37.8	1.18E+12	5.56E+08	473	YES	YES
11/28/01	21:02:43.02	170.8	45.4	1.18E+12	2.99E+08	255	YES	N/A
01/31/03	12:11:48.02	1.2	41.8	1.18E+12	5.53E+08	470	YES	N/A
09/13/05	23:57:15.65	157.8	-34.4	1.18E+12	4.07E+08	346	YES	N/A
07/09/07	23:09:15.89	36.8	-43.9	1.18E+12	2.59E+08	220	NO	N/A
01/08/08	13:03:13.36	118.1	0.0	1.18E+12	3.06E+08	261	YES	N/A
07/05/07	15:07:10.85	-48.3	-43.4	1.23E+12	5.17E+08	422	NO	N/A
04/18/01	13:33:10.66	-68.0	39.2	1.27E+12	3.91E+08	307	YES	YES
12/13/04	00:31:46.46	148.2	10.5	1.27E+12	4.59E+08	361	YES	N/A
01/28/05	12:54:30.66	18.9	46.2	1.27E+12	5.26E+08	413	YES	N/A
01/18/09	04:14:01.16	131.0	36.2	1.27E+12	3.55E+08	278	YES	N/A
05/17/02	16:13:10.15	-87.8	35.8	1.32E+12	7.18E+08	542	YES	YES
06/12/99	09:14:11.62	3.2	55.9	1.42E+12	4.68E+08	329	NO	N/A
02/06/05	09:06:45.70	39.3	34.3	1.42E+12	4.59E+08	323	YES	N/A
04/03/05	14:30:30.49	136.1	33.5	1.42E+12	5.78E+08	407	YES	N/A
01/30/00	13:21:59.83	142.0	37.8	1.47E+12	4.00E+08	272	NO	N/A
11/24/05	06:38:18.99	5.1	36.6	1.47E+12	4.92E+08	335	NO	N/A
03/16/07	19:20:31.20	-111.1	-40.2	1.62E+12	4.01E+08	248	YES	N/A
05/07/02	19:02:58.14	48.0	40.1	1.86E+12	7.76E+08	417	YES	N/A
09/20/01	16:57:23.66	151.8	-57.6	1.91E+12	5.13E+08	268	YES	N/A
12/23/05	04:12:00.30	159.0	34.5	1.91E+12	4.68E+08	245	YES	N/A
05/15/02	16:13:17.67	101.9	-42.2	1.96E+12	3.07E+08	157	YES	N/A
12/07/05	02:52:24.32	14.6	44.8	2.01E+12	3.11E+08	155	YES	N/A
12/23/05	21:31:23.58	45.3	37.8	2.01E+12	4.89E+08	243	YES	N/A
06/10/01	14:26:40.10	75.5	64.2	2.16E+12	1.02E+09	475	YES	N/A
08/16/02	15:44:32.64	-111.5	-70.1	3.14E+12	7.99E+08	255	YES	N/A

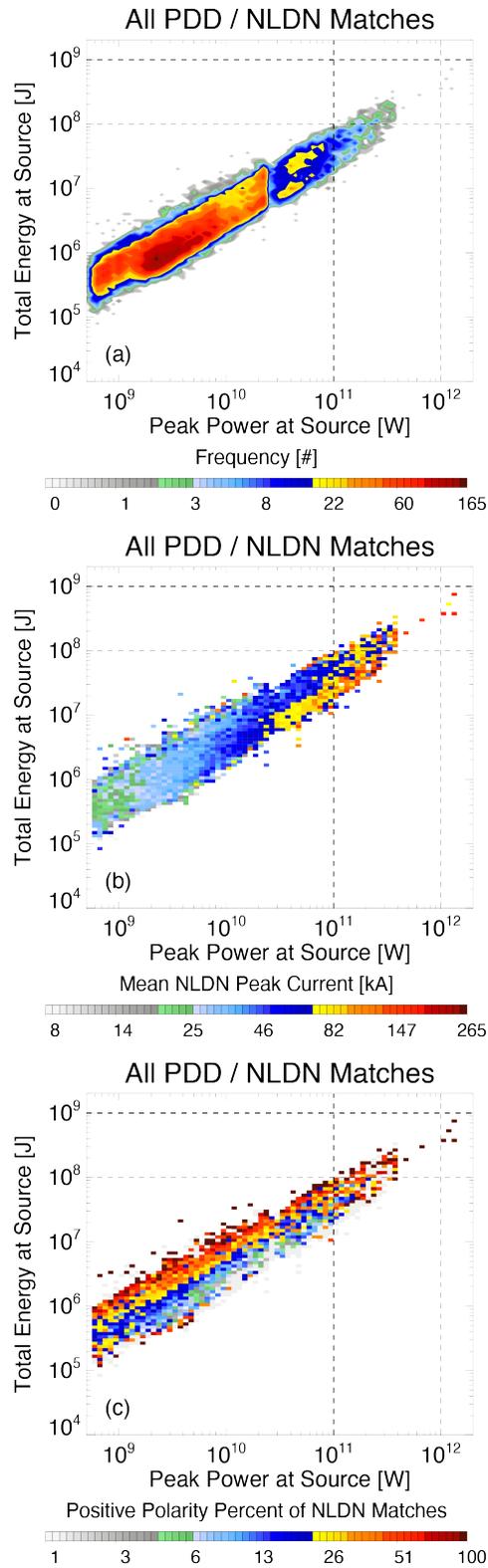
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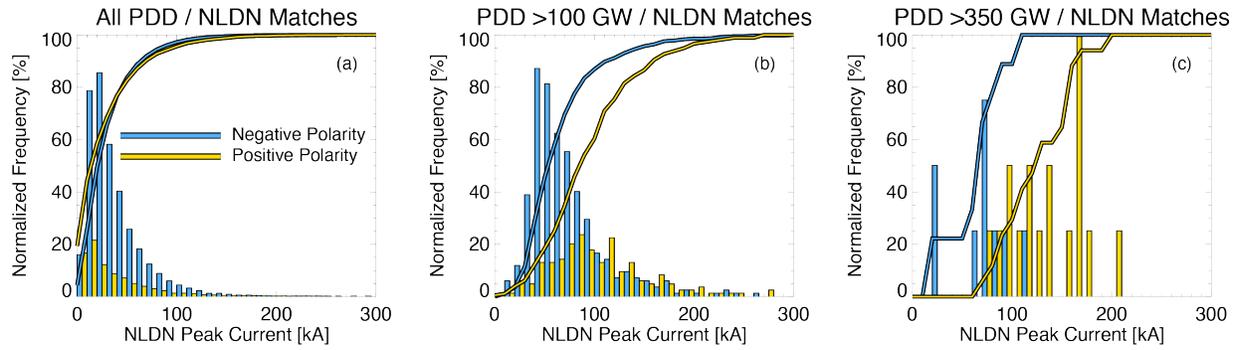


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Figure 1. Two-dimensional histogram of peak optical power (abscissa) and the total integrated energy at the source (ordinate) for the brightest PDD events. Superbolts defined by peak optical power (> 100 GW) and total energy ($> 10^8$ J) are thatched. Only events in the double-thatched top-right region are identified as superbolts by both power and energy criteria. Note that the steps in frequency at 20 GW and 300 GW are due to the piecewise linear dynamic range of the PDD discussed in Kirkland et al. (2001).

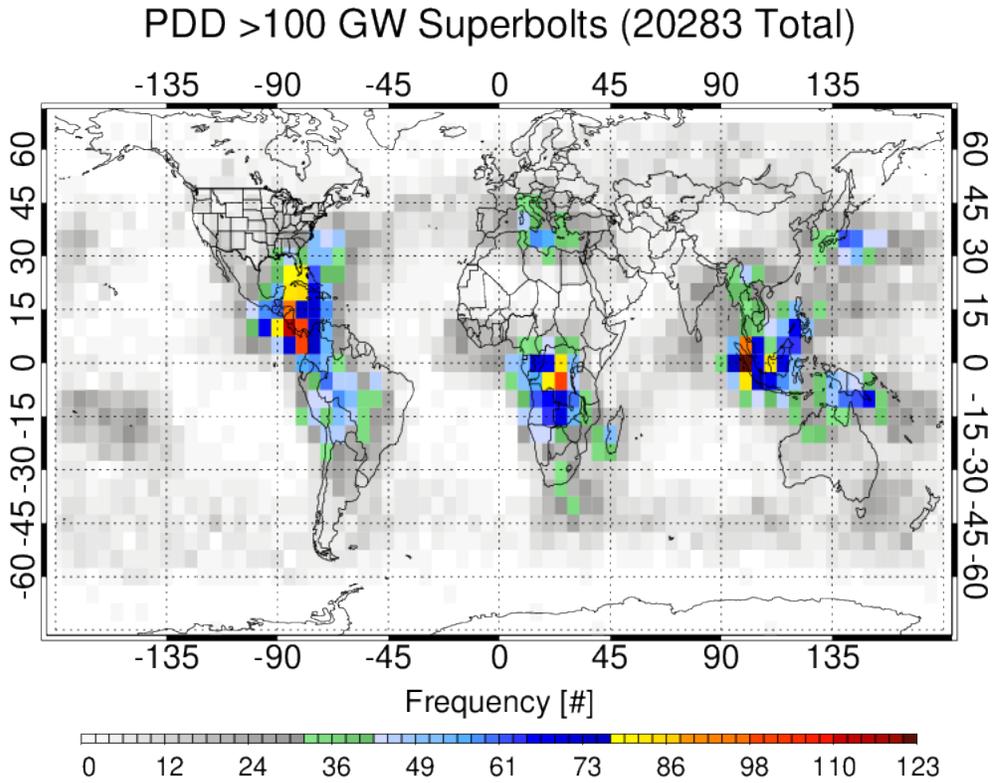


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 607 **Figure 2.** Two-dimensional histograms of peak optical power and the total integrated energy for
 608 PDD events with NLDN matches. Frequency (a), mean NLDN peak current (b), and the percent
 609 of NLDN matches that are positive-polarity (c) are shown.



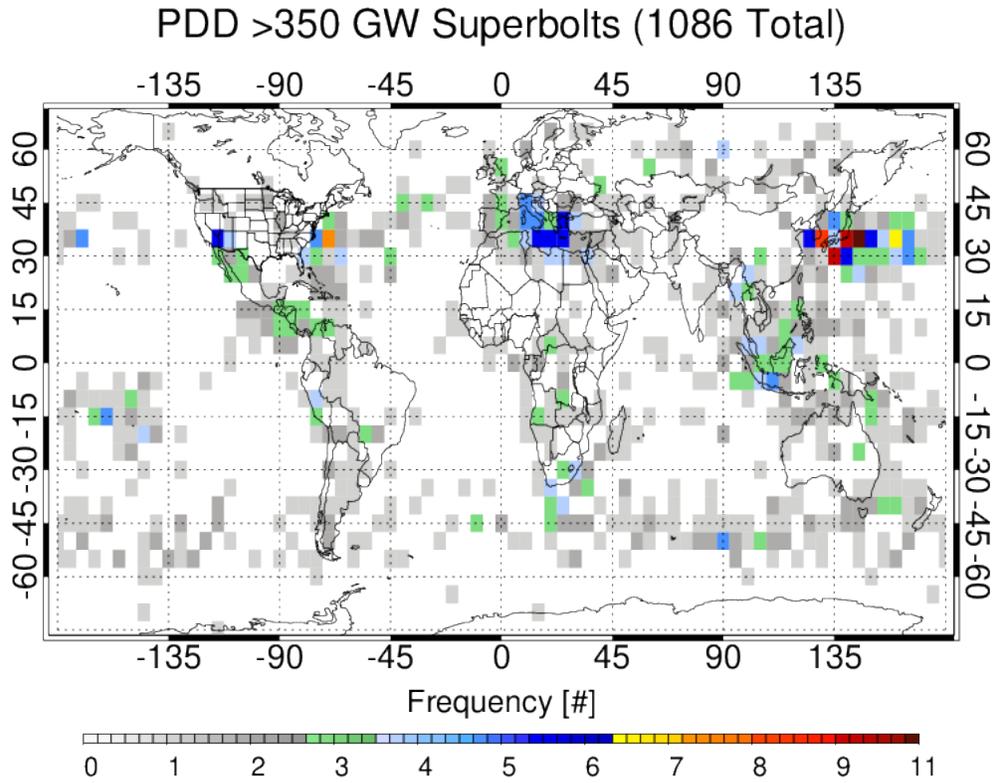
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Figure 3. Histograms (bar graphs) and Cumulative Density Functions (lines) for the NLDN peak current associated with (a) all PDD / NLDN matches, (b) >100 GW PDD / NLDN matches, and (c) >350 GW PDD / NLDN matches. Most PDD matches occur with negative-polarity (blue) NLDN strokes, but high-energy superbolts (>350 GW) are disproportionately positive-polarity (yellow) NLDN strokes.



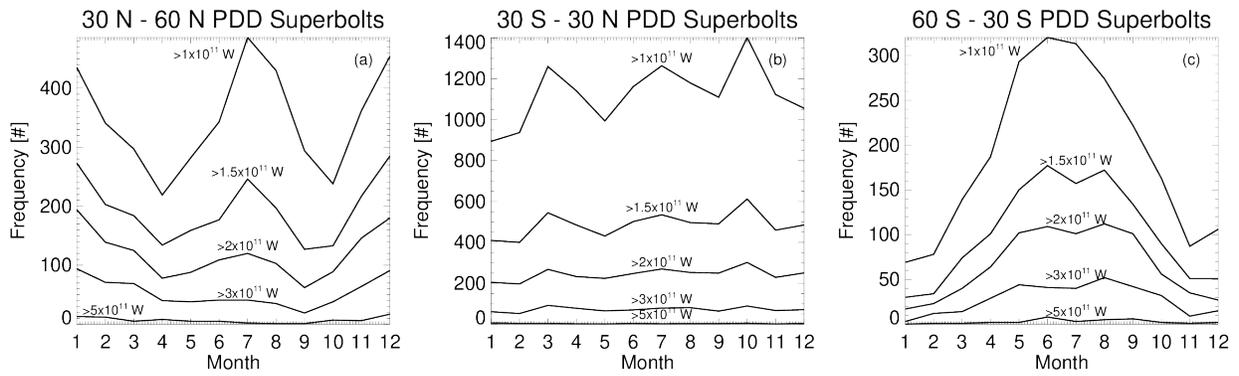
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Figure 4. Global distribution of all PDD events whose peak powers at the source exceeds 100 GW. The highest concentration of superbolts are concentrated in the tropical chimney regions around Colombia / Venezuela in the Americas, the Congo Basin in Africa, and the Maritime Continent in Asia.

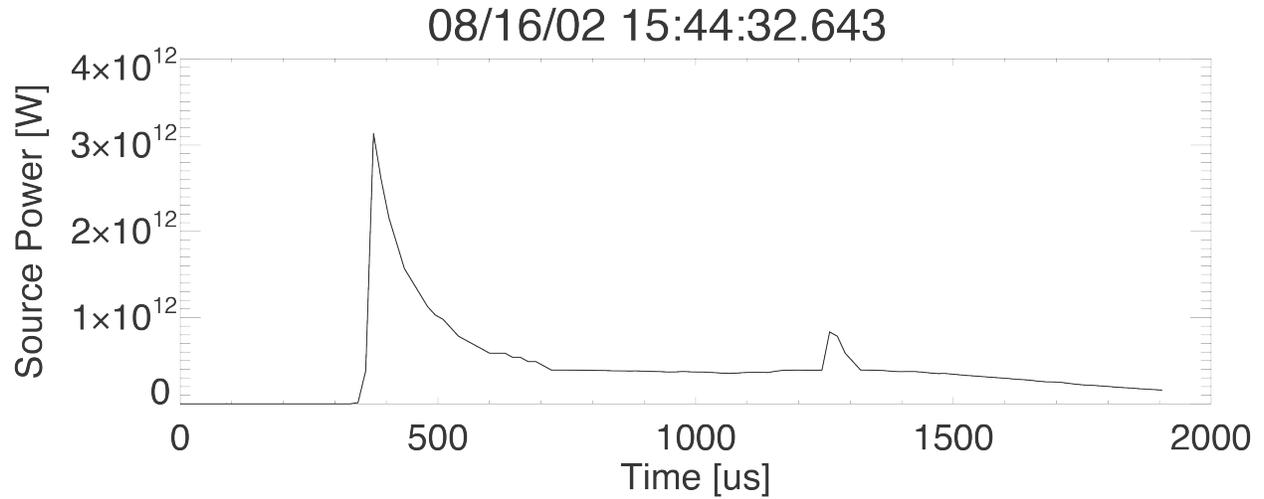


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Figure 5. Global distribution of all PDD events whose peak powers at the source exceeds 350 GW. The highest concentrations of superbolt activity at this power level are found in the mid-latitudes, particularly in the Mediterranean Sea, the Sea of Japan, and the northern Pacific Ocean. Note that the contour levels are lower than in Figure 4 due to the decreased sample size.



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 633 **Figure 6.** Annual cycles of superbolts activity over the (a) northern mid-latitudes, (b) the tropics,
 634 and (c) the southern mid-latitudes. Individual curves are drawn for various source peak power
 635 levels from 100 GW to 500 GW. Mid-latitude superbolt activity peaks in the winter months, but
 636 the northern hemisphere has a second summertime peak that erodes at higher power levels.
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Figure 7. PDD optical waveforms from the most radiant superbolt case observed by FORTE. The intense peak was followed by 1.3 ms of continuous emission including a second weaker peak 1-ms after the first.