Combined Optical and Radio-Frequency Measurements of a Lightning Megaflash by the FORTE Satellite

Michael Jay Peterson[1], Tracy Ellen Lavezzi Light[2], and Xuan-Min Shao[2]

[1]ISR-2,Los Alamos National Laboratory
[2]Los Alamos National Laboratory (DOE)

November 24, 2022

Abstract

The optical and VHF instrumentation on the FORTE satellite is used to document the combined phenomenology evolution of a lightning "megaflash" - mesoscale lightning that propagates laterally over exceptional distances. We identify a FORTE flash whose maximum extent was 82 km and inferred length over multiple distinct branches exceeded 100 km. This flash lasted 1.2 s and produced 250 optical and 591 RF events. We find that the channel development mapped by FORTE's pixelated lightning imager (LLS) occurred at a typical speed of 2.6×10^5 m/s and was accompanied by sustained periods VHF emission that could individually exceed 100 ms in duration. The impulsive IC events generated by the flash indicate that this development occurred at altitudes between 3 and 8 km. Four +CG strokes were identified in the VHF waveform data that are responsible for two of the three highly-radiant LLS groups (the third radiant group came from a possible -CG while 2 of the +CGs were not as optically bright as the others). These strokes occurred at different locations throughout the flash footprint with the most distant strokes separated by approximately 50 km. These space-based observations match previous observations of megaflashes from space as well as ground-based measurements of slow negative leader development during "spider" lightning, suggesting that FORTE is sensing the same phenomena.

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of a Lightning Megaflash by the FORTE Satellite

Michael Peterson[1], Tracy E. L. Light[1], Xuan-Min Shao[1]

[1]ISR-2, Los Alamos National Laboratory, Los Alamos, New Mexico

Corresponding author: Michael Peterson (mpeterson@lanl.gov), B241, P.O. Box 1663 Los Alamos, NM, 87545

Key Points:

- Combined FORTE optical / RF instrumentation document the evolution of a mesoscale oceanic lightning "megaflash"

- Optical observations reveal the development of long horizontal lightning channels that extended over 82 km

- RF observations indicate substantial leader activity accompanying channel development as well as 4 distinct +CG strokes spread throughout the flash area

23   **Abstract**

24

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26   combined phenomenology evolution of a lightning "megaflash" – mesoscale lightning that

27   propagates laterally over exceptional distances. We identify a FORTE flash whose maximum

28   extent was 82 km and inferred length over multiple distinct branches exceeded 100 km. This

29   flash lasted 1.2 s and produced 250 optical and 591 RF events. We find that the channel

30   development mapped by FORTE's pixelated lightning imager (LLS) occurred at a typical speed

31   of 2.6×10^5 m s^{-1} and was accompanied by sustained periods VHF emission that could

32   individually exceed 100 ms in duration. The impulsive IC events generated by the flash indicate

33   that this development occurred at altitudes between 3 and 8 km. Four +CG strokes were

34   identified in the VHF waveform data that are responsible for two of the three highly-radiant LLS

35   groups (the third radiant group came from a possible -CG while 2 of the +CGs were not as

36   optically bright as the others). These strokes occurred at different locations throughout the flash

37   footprint with the most distant strokes separated by approximately 50 km. These space-based

38   observations match previous observations of megaflashes from space as well as ground-based

39   measurements of slow negative leader development during "spider" lightning, suggesting that

40   FORTE is sensing the same phenomena.

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42 **Plain Language Summary**

43

44   Pixelated lightning imagers map the lateral development of lightning flashes by recording

45 how the locations of radiant pulses produced by lightning change over time. Most lightning

46 flashes measured by instruments including NASA's Lightning Imaging Sensor (LIS) and

47 NOAA's Geostationary Lightning Mapper (GLM) are small and repeatedly illuminate the same

48 cloud region with little apparent motion between pulses. However, certain thunderstorms are able

49 to produce "megaflashes" that start in one place and then develop up to hundreds of kilometers

50 horizontally from the initiation point. These propagating flashes pose a unique hazard because

51 they can strike the ground in places where lightning is not expected.

52   We use measurements from the FORTE satellite to investigate what radio-frequency

53 signals accompany the optical signatures of a lightning megaflash. RF data provide insights into

54 the physical origin of the optical lightning emissions. A detailed analysis of a megaflash 82 km

55 across reveals that optical flash propagation is accompanied by abundant VHF signatures of

56 leader development as well as multiple distinct +CG strokes at different places across the flash.

57

1 Introduction

Lightning generates optical signals by rapidly heating the air surrounding the lightning channel. Temperatures along the channel may exceed 20,000 K (Prueitt, 1963), causing ionization of the major atmospheric constituent gasses. The ionization, excitation, and recombination of atmospheric constituents results in particularly strong optical emissions in the near-infrared neutral oxygen and neutral nitrogen atomic lines. Optical pulses are produced by Cloud-to-Ground (CG) strokes as well as a myriad of in-cloud processes that illuminate the lightning channel.

Space-based lightning imagers such as NOAA's Geostationary Lightning Mapper (GLM: Goodman et al., 2013) and NASA's Optical Transient Detector (OTD: Christian et al., 2003) and Lightning Imaging Sensor (LIS: Christian et al., 2000; Blakeslee et al., 2014) report the spatial and temporal evolution of individual flashes by measuring transient changes in cloud-top illumination from the lightning discharges that comprise the flash. OTD, LIS and GLM record the optical radiance in a narrow band centered on the neutral Oxygen line triplet at 777.4 nm to take advantage of the emissions peak resulting from these underlying physical processes (Christian et al., 2000; Goodman et al., 2010).

Optically bright lightning processes vary in terms of extent, speed, current, and polarity. Identifying reliable optical signatures for specific processes such as strokes (Koshak, 2010) has proven difficult because optical measurements provide little information on the nature of the source beyond the intense heating along the channel, and also because the optical signals recorded from space have been modified by scattering and absorption in the cloud medium (Thomson and Krider, 1982; Koshak et al., 1994; Light et al., 2001a,b; Thomas et al., 2000; Suszcynsky et al., 2000). Scattering causes the optical signals to be diluted in space and

81   broadened in time. Flashes that occur in particularly inhomogeneous clouds have their footprints

82   sculpted by spatial distribution of hydrometeors in the thundercloud (Peterson et al., 2017a).

83   Flashes that occur near a cloud boundary often take on an irregular shape as the radiance

84   measured from space follows the boundary (Peterson et al., 2017b), while dense convective cells

85   can produce "holes" in otherwise contiguous flash footprints by blocking light from reaching

86   orbit in sufficient quantities to trigger the instrument. Radiance can also reflect off the sides of

87   neighboring clouds or the tops of lower cloud decks to expand the flash footprint far beyond the

88   extent of the parent thunderstorm (i.e., Figure 1 in Peterson and Liu, 2013). Due to these

89   scattering effects, the optical signals recorded by OTD, LIS and GLM may contain as much

90   information about the cloud scene as they do about lightning.

91   Still, there are optical signatures in the lightning imager data that reveal key aspects of

92   the physical evolution of the lightning flash. Lateral propagation in the optical flash structure, for

93   example, indicates horizontal leader development (Peterson et al., 2018). LIS and GLM observe

94   both the flickering at the ends of developing lightning channels and the waves of radiant energy

95   retracing an established channel back to its origin that have been noted in ground-based

96   observations (Mazur et al., 1998; Winn et al., 2011). The optical pulses that map the

97   development of these flashes are small and relatively dim, so the shapes of their footprints (as

98   imaged by a lightning imager with kilometer-scale pixels) are not modified substantially by

99   scattering. Thus, the structure of propagating optical flashes measured by space-based lightning

100   imagers approximates a two-dimensional vertically-integrated view of the three-dimensional

101   flash structure that would be mapped by a Lightning Mapping Array (LMA: Rison et al., 1999).

102   The two key caveats with optical space-based lightning mapping are the large pixel footprints (4-

103   5 km for LIS and 8-14 km for GLM) and the decreasing source detection efficiency as the optical

104 thickness of the intervening cloud layer increases. Leader propagation through deep convection

105 that is routinely observed by LMAs (i.e., Lang et al., 2017) is generally not resolved from space.

106 As a result, the LIS / GLM measurements of flash extent are a minimum estimate for the scale of

107 lightning that mostly captures long horizontal channels in stratiform and anvil clouds (Peterson

108 and Liu, 2011).

109 We have used lightning imager data to measure the horizontal extent of propagating

110 flashes and to calculate their development speeds (Peterson et al., 2018). We have also defined

111 "series" features (Peterson et al., 2017b) to describe distinct periods of sustained optical emission

112 that typically accompany widespread branching and recoil waves, but can also capture lightning

113 emissions related to gigantic jets (Boggs et al., 2019) and return stroke continuing currents

114 (Bitzer, 2017). Peak optical emissions during individual series are also used to define an optical

115 multiplicity that describes how often flashes light up well above the numerous low-radiance

116 pulses associated with cloud discharges (Peterson and Rudlosky, 2019). The optical multiplicity

117 is advanced by strokes as well as K-changes that both produce strong emission along the

118 channel.

119 While these optical-only capabilities are useful for analyzing lightning activity, a

120 comprehensive view of lightning physics is achieved when optical and RF measurements are

121 combined to describe the same flash. We previously used coincident optical and VHF

122 measurements taken by the Fast On-Orbit Recording of Transient Events (FORTE) satellite to

123 identify the physical processes responsible for the optical signals recorded by its pixelated

124 lightning imager during a hybrid CG flash (Peterson et al., 2020a). In this study, we use the same

125 approach to investigate the combined-phenomenology evolution of a horizontally-expansive

126 lightning megaflash observed over the open ocean near the Canary Islands.

127

2 Data and Methodology

129   The FORTE satellite was a unique platform for examining lightning from space because

130 it contained both optical and RF payloads for observing transient lightning pulses, and because

131 its instrumentation was operated in campaign mode. The optical / RF trigger settings, data record

132 lengths, and RF frequency bands were periodically reconfigured on-orbit over the FORTE

133 mission. FORTE thus provinces multiple different types of coincident data that can be used to

134 assess various aspects of lightning discharges. A detailed description of the FORTE RF payloads

135 is provided in Jacobson et al. (1999), while the optical payloads are described in Suszcynsky et

136 al. (2000, 2001). Moreover, the FORTE mission and its key scientific findings are reviewed in

137 Light (2020). The sections below summarize the RF and optical payload configurations that

138 pertain to our megaflash case of interest.

139   2.1 The FORTE Optical Lightning System

140   The optical payload on FORTE was known as the Optical Lightning System (OLS). The

141 OLS consisted of two different optical instruments. A high-speed photodiode detector recorded

142 broadband (0.4 μm – 1.1 μm) lightning pulses in 2 – 6 ms records with a 15 μs sampling interval.

143 The PDD could be triggered by optical lightning pulses anywhere within its 80° field of view. If

144 we think of the PDD as a single-pixel lightning imager, then it would have an effective frame

145 rate of 66,667 FPS. In both Peterson et al. (2020a) and this study, the PDD was configured to

146 trigger autonomously and produce 1.92 ms records of optical lightning activity. The PDD had a

147 dead time between records that was approximately equal to the record length. Thus, we will see

148 ~2 ms gaps between the PDD records from successive triggers during periods of sustained

149   optical emission. We also noted in Peterson et al. (2020a) that the PDD stops reporting after a

150   specific number of triggers on flash time scales. As the megaflash case occurred around the same

151   time as the previous hybrid CG flash case, this 20-trigger maximum will be a limitation in the

152   present study as well.

153   The second OLS instrument was a pixelated lightning imager known as the Lightning

154   Locating System (LLS). The LLS consisted of the same front-end optical assembly and fixed-

155   position CCD focal plane assembly used by LIS that was provided by NASA Marshall Space

156   Flight Center, and an operations and signal processing module designed by Sandia National

157   Laboratories. The LLS was designed to have a lower (405 FPS) frame rate than LIS (500 FPS).

158   The key role of the LLS was to geolocate lightning sources. Coordinated observations with the

159   PDD would then enable light curves to be resolved at orders of magnitude finer time scales than

160   LLS or LIS could measure.

161   Because the LLS signal processing module was designed by Sandia, the artifact filters

162   and cluster feature algorithm developed for LIS (Christian et al., 2000) were not applied to the

163   LLS data during the FORTE mission. LLS observations in its standard operating mode include

164   only pixel-level "event" detections. Events are recorded whenever the measured radiance in a

165   given CCD pixel during a single 2.47-ms integration frame exceeds a noise-riding threshold

166   above the radiance of the background scene. Note that this description of events follows the

167   NASA terminology. The raw LLS events (subsequently termed "super-events" because they are

168   conceptually similar to the proposed concept of "supergroups" in Tillier et al., 2019) can

169   describe the same pixel being illuminated for multiple frames. For consistency with the other

170   sensors such as LIS, we extract the single-frame pixel detections from the raw LLS super-events

171   and use the standard term "events" to describe them. Artifacts are handled by simply ignoring

172   subsequent detections from the same pixel once events are recorded in that pixel during two

173   adjacent integration frames. This filter prevents the LLS from measuring sustained optical

174   emission from a stationary source (i.e., continuing current with a return stroke), but still permits

175   the LLS to record sustained emission from propagating sources (i.e., lateral flash development,

176   K-waves).

177   2.2 The FORTE Radio Frequency (RF) System

178   The Radio Frequency (RF) system was comprised of three broadband receivers

179   connected to the two identical Log-Periodic Antennas (LPAs) mounted along FORTE's 10-m

180   nadir-pointing boom. The three receivers were divided between two RF payloads known as

181   TATR and HUMR. TATR consisted of 2 independent RF receivers (TATR/A and TATR/B) that

182   could each be tuned to measure one of the FORTE antennas over a 22-MHz subband. The record

183   lengths and the ratio of pretrigger to posttrigger data could also be configured. HUMR,

184   meanwhile, sampled a wider (85 MHz) band over longer records that typically lasted 3 ms.

185   This study and Peterson et al. (2020a) both use TATR observations from late 1999 when

186   it was configured to record lowband (26 – 48 MHz) waveforms and set to trigger autonomously.

187   In its autonomous mode, TATR monitored the RF power in eight RF channels that were each 1-

188   MHz wide. Whenever the received power exceeded the noise-riding background value in one of

189   these channels by a certain threshold, the instrument would report an alarm. Triggers require

190   multiple simultaneous alarms in the 8 channels, and the number of alarms required to trigger the

191   instrument and report an event was a commandable parameter. Typically, only RF events that

192   triggered 5 of the 8 channels are examined (i.e., Jacobson et al., 2000), but we instead consider

193   all TATR triggers during a time window encompassing LLS flashes (+/- 330 ms) in order to

194   capture the weakest lightning phenomena detectable from orbit.

195   While optical lightning signals are modified by scattering in the cloud, VHF pulses are

196   modified by the ionospheric plasma between the source and satellite. Ionospheric dispersion

197   causes a frequency-dependent group delay in the recorded VHF pulses. Signals on the low-

198   frequency side of the band arrive after the high-frequency signals, and the waveforms appear

199   "chirped" (Jacobson et al., 2000). The severity of the dispersion depends on the Total Electron

200   Content (TEC) of the ionospheric slant path between the source and sensor. By fitting the

201   dispersion in the received signal to a physics-based mathematical model, we can "dechirp" the

202   data and align the VHF waveforms to their vacuum time of arrival. The dechirping process also

203   yields an estimate for the ionospheric TEC encountered by the signals along their slant path

204   through the ionosphere, which we can further use to identify signals that come from elsewhere in

205   the FORTE field of view (Jacobson et al., 1999.

206   Unlike in the hybrid CG case in Peterson et al. (2020a), we find no evidence that

207   thunderstorms located at different slant angles are contributing TATR triggers during the

208   duration of the megaflash considered here. However, there is one TATR trigger in the flash that

209   resulted from an on-board discharge. This trigger was a single impulsive event that produced the

210   strongest peak RF power over the flash duration, but had no evidence of ionospheric dispersion

211   in the event waveform data. This on-board discharge event is preserved in the RF waveform

212   records to show how these features contaminate natural lightning signals, but it is otherwise

213   ignored in the broader discussion of the flash.

214   2.3 FORTE combined-phenomenology lightning cluster data

215   Though flash cluster data was not created from the LLS events during the FORTE

216   mission, the LIS (Christian et al., 2000) and GLM (Goodman et al., 2010) flash cluster

217   algorithms have been documented in the literature and can be adapted for use with FORTE. We

218   used the GLM algorithm as the basis for constructing a combined-phenomenology lightning

219   cluster feature dataset in Peterson et al. (2020a) that includes both optical and RF features.

220   Design considerations for the full FORTE cluster feature dataset are described at length

221   in Peterson et al. (2020a) and we will discuss only the optimal data structure for FORTE

222   analyses here (shaded boxes in Table 1 from Peterson et al., 2020a). LLS events are used to

223   define "group" features that represent contiguous regions on the LLS CCD array that are lit up

224   during the same 2.47-ms integration frame. Groups are then clustered into LLS "flashes" using

225   the same Weighted Euclidian Distance (WED) model as LIS / GLM. The distance and time

226   thresholds for assigning two groups to the same flash are 16.5 km and 330 ms, respectively. If a

227   new group occurs that could belong to multiple flashes, a "full fit" matching technique is

228   employed that merges the two candidate flashes into a single flash cluster. "Series" features are

229   also constructed that describe sustained optical emission within individual flashes. Series

230   encompass all groups in a given flash that occur either sequentially or following a 1-frame gap.

231   Finally, thunderstorm areas of interest (or "areas") are constructed by applying the WED model

232   to the flash cluster data with the same 16.5 km distance threshold and no time threshold (though

233   all flashes in the same area should occur during the same FORTE orbit).

234   The FORTE PDD and RF data are ingested into the LLS hierarchy at the event level after

235   making a minor change to the "event" definition. In the LIS / GLM literature, an event is defined

236   as a single triggered pixel on the CCD array during an integration frame. We slightly generalize

237   this definition to describe an event as a unique trigger during the millisecond-scale triggering

238   interval associated with the instrument. The PDD and RF system can have only one unique

239   trigger from their FOVs at a given instant, while the LLS would have a unique trigger for each

240   pixel that lights up in a given frame. With this change, we can construct lightning cluster feature

241   data structures (i.e., areas, flashes, groups) for the PDD and RF system that parallel the LLS

242   hierarchy. The high sampling rates of these instruments also allow us to extend the data tree to

243   finer time scales that occur within a single "event." We define "pulses" as features describing

244   periods of sustained emission above a noise-riding background threshold that occur within a

245   single event record. We also define "samples" as single calibrated measurements at the native

246   sampling rate of the instrument. Events are the parents of pulses and the grandparents of

247   samples. We finally integrate the LLS, PDD, and RF features by defining "step-parent"

248   relationships that assign PDD and RF events, pulses, and samples to LLS groups, series, flashes,

249   and areas.

250

3 Results

252   The present study aims to investigate the RF signatures that accompany lateral

253   propagation in the optical lightning imager data. In particular, we will be focusing on the large-

254   scale propagation that we see with megaflashes where the lateral development is widespread and

255   organized along multiple distinct branches. LMA networks have mapped extensive propagating

256   flashes that measure 321 km from one end to the other (Lang et al., 2017), while GLM has

257   recorded cases that exceed 500 km in length (Peterson, 2019c; Lyons et al., 2019). The most

258   exceptional megaflash cases recognized as lightning extremes by the World Meteorological

259   Organization (WMO) are now two different cases of GLM flashes that reached 709 km in extent

260   and 16.73 s in duration, respectively (Peterson et al., 2020b).

261   The common aspect shared by all of these exceptional megaflash cases is that they

262   primarily develop through the electrified stratiform region of a large (mesoscale) mature or

263   dissipating storm system. Stratiform clouds become electrified through a combination of the

264   advection of charged ice particles from the convective core (Carey et al., 2005) and in-situ

265   charging in the radar bright band (Rutledge and MacGorman, 1988) that may be enhanced by

266   local mesoscale updrafts (Ely et al., 2008; Lang and Rutledge, 2008). These processes generate

267   multiple vertically-thin charge layers that can extend laterally over hundreds of kilometers

268   (Marshall and Rust, 1993; Stolzenburg et al., 1994; Lang et al., 2004; Marshall et al., 2009) and

269   act a conduit for lightning propagation.

270   The combined optical and RF phenomenology of complex horizontally-propagating

271   "spider" lightning was studied from the ground in Mazur et al. (1998) using a whole sky

272   intensified camera system co-located with a VHF interferometer. They concluded that spider

273   lightning consists of slow ($2\text{-}4 \times 10^5$ m s^{-1}) negative leaders that produce transient optical pulses

274   at the tips of the branching channels and occasional continuous illumination along the entire

275   channel resulting from sustained current flow that may last tens to hundreds of milliseconds.

276   Because the development speeds, VHF signatures, and flickering at the ends of branches in the

277   optical measurements are all similar to stepped-leaders in negative CG flashes, they suggested

278   that spider lightning results from the same underlying physical processes.

279   The FORTE satellite is equipped to make similar optical and VHF measurements of

280   horizontally-propagating lightning to Mazur et al. (1998) from space. FORTE observations have

281   an expanded horizontal domain compared to the range from a single site to the local horizon, and

282   its orbital measurements are mapped in geographic coordinates rather than spherical coordinates

283   surrounding the site. Thus, we do not have to assume an altitude for the lightning channels to

284   compute lateral distance or propagation speed. However, the key limitation to observing

285   megaflashes with FORTE is the short view times over a given thunderstorm (on the order of

286   minutes) due to its low Earth orbit. The FORTE satellite would have to be in the right place at

287   the right time to see a megaflash – and this is why megaflashes are rarely observed in the OTD /

288   LIS records. The FORTE LLS has detected a small number of megaflashes whose extents are <

289   100 km, but whose total lengths are considerably larger. In the following sections, we will

290   examine the longest of these LLS megaflash cases in detail.

291   3.1 Overview of FORTE measurements during an oceanic megaflash on 12/3/1999

292   Megaflash cases are identified in the FORTE record according to the maximum great

293   circle distance between LLS groups. This is a low estimate of flash scale because megaflashes do

294   not propagate directly from one end to the other, but instead take a meandering path through the

295   electrified cloud. Peterson et al. (2018) attempted to measure total flash length by constructing

296   skeleton images of the two-dimensional flash structure reported by LIS and found that flash

297   length was usually 2-3 times greater than its reported extent.

298   The top LLS flash in terms of extent occurred over the Atlantic Ocean between the

299   Canary Islands and the Azores on 12/3/1999 at 22:30:22 UTC (23:30:22 local time in Santa Cruz

300   de Tenerife). It was 82 km across and produced 69 LLS series, 98 LLS groups, and 230 LLS

301   events over a duration of 1180 ms. In total, it illuminated a cloud-top area of 5203 km^2 with the

302   largest group in the flash illuminating 2386 km^2 of cloud. In addition to these LLS triggers, the

303   PDD contributed 20 optical events and TATR recorded 591 VHF events.

304   The LLS Flash Extent Density (FED: Lojou and Cummins, 2004) plotted in Figure 1a

305   indicates that the flash rate for the storm was low (3 flashes in 15 minutes), and that there were

306   no intense thunderstorms nearby that could have contributed the large number of TATR triggers

307   during the flash duration. The trigger rates in Figure 1b show that there was only 1 isolated

308   optical trigger in the minute leading up to the flash and that subsequent triggers after the flash

309   occurred more than 1 s following the final LLS group. Unlike the hybrid CG case in Peterson et

310   al. (2020a), this case did not contain any RF triggers before first LLS light or after final light.

311   3.2 Evolution of optical signals from the megaflash

312   Figure 2 documents the overall evolution of the LLS flash. The central panel (Figure 2c)

313   shows the plan view of the events and groups in the flash. Normalized event energies from each

314   pixel on the CCD array are summed to produce a color contour plot representing the spatial

315   radiance distribution. The progression of groups is traced in time with line segments that connect

316   each group centroid to its nearest preceding group. The greyscale color palette denotes the

317   sequential group index from dark (first group) to light (final group), and is standardized between

318   all panels in Figure 2. Figure 2a shows the longitudinal extent of all groups in the flash while

319   Figure 2d shows their latitudinal extents. Figure 2b displays a histogram of group energy

320   presented as a sigma level (the number of standard deviations above or below the mean for all

321   groups in the flash). Figure 2e and f, finally, show timeseries of group area and normalized

322   group energy.

323   The flash began along the southwestern flank of its footprint (Figure 2c) and propagated

324   to the northeast. At least 6 primary branches spanning more than 20-km (~2 pixels) can be noted

325   in the group-level structure that contain smaller features propagating laterally off the main

326   channels. The LLS groups associated with this lateral development are typically dim and small

327   (100 – 200 km^2 in Figure 2e) – yet they account for the clear majority of optical triggers from the

328   flash. Only 3 groups reach the +1-sigma level (Figure 2b). We use the 1-sigma group count to

329   define an optical multiplicity parameter that quantifies how often a given flash lights up beyond

330   the baseline radiance from these common dim cloud pulses under the specific viewing conditions

331   of the flash. The optical multiplicity for this flash would thus be 3, with intervals of 43 ms and

332   311 ms separating the series containing these bright groups. The FORTE megaflash considered

333   in this study produced groups that reached an exceptional 8-sigma above the average group

334   energy for the flash.

335   3.3 Combined optical and RF assessment of flash evolution

336   The timeseries in Figure 3 show the combined-phenomenology evolution of the LLS

337   flash. Optical group energies are plotted in Figure 3a for LLS and Figure 3b for PDD and are

338   normalized to the peak received group energy for each instrument on a logarithmic scale. TATR

339   event records are dechirped and "prewhitened" (to remove narrowband carrier waves), and then

340   the band-averaged peak VHF power for each trigger is shown in Figure 3c. Like the optical

341   energy, RF power is normalized relative to the strongest emissions during the flash window. The

342   TATR pulses recorded in each event are categorized as isolated impulses (single pulse), isolated

343   pulse pairs (single pair of pulses representing an IC source with a ground reflection), pulse trains

344   (multiple pulse pairs per TATR record), or diffuse / mixed pulses (broad pulses that may include

345   superimposed impulsive features). TATR records that do not contain any classifiable pulses are

346   designated "sustained featureless emission." We divide the flash duration into 2-ms bins

347   (comparable in scale to PDD records or LIS / GLM groups) and then compute the fractions of

348   each pulse type per bin in Figure 3d.

349   Because we know the geographic position of the flash from the LLS observations, we can

350   compute the altitude of impulsive IC sources using the satellite position and the time delay

351   between pulses in each Trans-Ionospheric Pulse Pair (TIPP: Holden et al., 1995). Estimated

352   altitudes for the isolated impulsive IC events and pulse trains from Figure 3d are shown in Figure

353   3e. Finally, Figure 3f integrates the received optical LLS energy and TATR antenna response (in

354   V^2 m^{-2}) to compare the accumulation of optical / RF signals over the duration of the flash.

355   In our previous -CG case (Peterson et al., 2020a), the TATR triggers were intermittent

356   and dominated by impulsive IC events and K-changes. Leader activity ahead of the return stroke

357   produced sustained featureless emission that strengthened over multiple TATR records as the

358   stepped leader developed towards the surface and then a single strong VHF pulse occurred upon

359   seawater attachment. The TATR records in the current megaflash case, by contrast, are

360   dominated by periods of sustained featureless VHF emission over tens to hundreds of

361   milliseconds (Figure 3d). The longest-lasting TATR series feature started 200 ms into the LLS

362   flash and then persisted for 169 ms. Of the total 591 TATR events, 516 were classified as

363   sustained featureless emission. The remaining 75 TATR records contained 38 TIPPs, 38 diffuse

364   pulses, and 5 isolated single impulses (including one from the on-board discharge mentioned

365   previously). Note that the total number of pulses is greater than the number of events due to

366   certain events containing multiple pulses.

367   As with the energy budget from previous -CG flash in Peterson et al. (2020a), optical

368   energy from the megaflash accumulated rapidly in 1-2 frame increments in Figure 3f, while the

369   RF signals accumulated gradually over longer time intervals. The three high-radiance groups in

370   the LLS flash that exceeded the 1-sigma level contributed 5%, 30%, and 17% of the total energy

371   of the flash (total: 52%). The remaining 95 groups contributed 48% of the total energy.

372   While most TATR waveform records appear to originate from IC sources, four TATR

373   events contained the signatures of positive-polarity CG strokes described in Light et al. (2001b).

374   A spectrogram for the first of these strokes (at 14 ms into the LLS flash) is shown in Figure 4.

375   +CG events have a quick onset typically followed by a broad VHF pulse due to considerable in-

376   cloud activity following attachment. This lingering tail can last for tens of milliseconds, spanning

377   multiple TATR records. Mazur et al. (1998) noted comparable behavior from the ground in their

378   analysis of +CGs in spider lightning.

379   The other +CGs in the FORTE megaflash occur at 282 ms, 335 ms, and 592 ms into the

380   LLS flash with similar TATR records to the spectrogram shown in Figure 4. The key difference

381   with these later +CGs is that they occurred under a stronger RF background from the widespread

382   leader activity in the later stages of the flash. We use these RF signatures to divide the flash into

383   4 phases: initial horizontal development of the lightning channel and first +CG stroke (0 ms to

384   265 ms), peak optical emission during the second +CG stroke followed by weaker emission

385   during the third +CG (265 ms to 400 ms), further branching along the northern flash extent

386   leading up to the fourth +CG stroke (400 ms to 700 ms), and then final optical activity after the

387   continuous VHF emission ceased (700 ms to 1180 ms). The evolution of the flash during these

388   phases is discussed below.

389

4 Discussion

4.1 Initial horizontal development of the lightning channel and first +CG stroke

An evolution plot for the first optical / RF events in the flash is shown in Figure 5. The key difference between the format of Figure 3 and Figure 5 is that the group area timeseries is removed and a TATR RF power timeseries is displayed in its place. PDD sample energies are also plotted in blue alongside the normalized LLS group energies in Figure 5e. The LLS flash began with a single-pixel event at t = 0 ms that has slightly less than 1% of the optical energy of the most radiant group in the flash. The baseline for single-pixel detections is ~0.7% to 1% of peak emission. These optical emissions from individual LLS pixels were too faint / localized for the PDD to trigger.

The first 2 TATR events were recorded 4 ms and 14 ms into the LLS flash. The first TATR event consisted of an impulsive IC TIPP with additional IC pulse pairs embedded in the VHF background. Unlike Peterson et al. (2020a), this flash did not start with a powerful TIPP waveform from a Narrow Bipolar Event (NBE). Any IC events that could have occurred before first LLS light were too weak to trigger TATR.

The first +CG stroke occurred 14 ms after the first LLS event and 10 ms after the first TATR event. The first long period of continuous RF triggering occurred following this stroke (Figure 5f). During this time, two impulsive IC events were noted at ~5 km altitude as well as an isolated single impulse. This single-peak event at 22 ms was caused by the on-board discharge noted previously. The remaining TATR triggers from 14 ms to 41 ms were all diffuse featureless

410   emission associated with leader activity. The PDD triggered continuously over this period,

411   demonstrating that there was sustained optical emission accompanying the continuous VHF

412   activity. The LLS only triggered twice, however, with a 5-pixel group at 14 ms and a single-pixel

413   group at 24 ms. The optical energies in all lit-up pixels were near the minimum for the flash

414   (Figure 5c), suggesting that the emissions that triggered the PDD were spread over a large area

415   with energy densities only occasionally exceeding the LLS detection threshold in its individual

416   pixels.

417   The continuous TATR triggering stops at 41 ms and then there is a lull with only 2 TATR

418   triggers (one IC pulse train at 4.2 km altitude and one sustained featureless emission) until 112

419   ms into the LLS flash. The time period from 112 ms until 215 ms depicted in Figure 6 describes

420   the incremental development of the flash to the north and east through small / dim groups

421   illuminating the tips of the extending branches. RF activity is intermittent before 200 ms and

422   evenly distributed between IC pulse pairs / trains from sources at 6 km altitude and sustained

423   featureless emission. The LLS and PDD trigger simultaneously at 157 – 160 ms following a

424   pulse train with a relatively weak peak RF power, and the PDD continues to trigger until its 20

425   triggers are exhausted by 210 ms.

426   TATR began its longest period of continuous triggering at 200 ms. Unlike the previous

427   continuous period, it did not begin with a stroke. The PDD recorded sustained emissions starting

428   at 160 ms. The remainder of the initial IC lateral development phase from 230 ms until 265 ms is

429   shown in Figure 7. The first LLS groups at 235 ms resulted from the tips of all existing channels

430   being simultaneously illuminated. Then the first 1-sigma bright group is detected during the next

431   integration frame (starting at 238 ms) where nearly the entire extent of the main channel lit up at

432   once. VHF waveform analysis of what caused this behavior is inconclusive, as the high VHF

433   background obscures portions of the waveforms that are important for pulse characterization.

434   Figure 3d shows that sustained featureless VHF emission accompanied the first 1-sigma LLS

435   group. However, a detailed analysis of the TATR waveforms found a single narrow peak in the

436   TATR trigger at 235 ms consistent with a -CG. This peak is so poorly resolved that the

437   automated dechirp algorithm fails to find it - causing no TEC estimate to be retuned and the

438   event to be labeled as sustained featureless emission.

439   We do not see the increasing VHF emission leading up to attachment that typically

440   accompanies -CGs in the event recorded at 235 ms, as it would be buried in the high VHF

441   background. Furthermore, the peak occurred at the end of the TATR record due to the

442   continuous TATR triggering. Thus, we cannot be certain that this was a single solitary peak from

443   a -CG. An alternate explanation could be that it was an impulsive IC event where the second

444   peak in the TIPP occurred during the dead time between TATR records. Of these two

445   possibilities, the strong optical emission accompanying the event suggests that the -CG

446   explanation is more likely - but this is not assured.

447   The subsequent groups over the next 20 ms were all located along the main channel and

448   constituted one of the longest-lasting LLS series features in the flash (15 ms in duration). These

449   factors seem to indicate a sustained flow of current down the channel that is only partially

450   resolved in the pixelated LLS data. PDD data would be required to confirm continuous optical

451   emission (as with the first +CG). The maximum group separation by 260 ms was 68 km, and this

452   lateral development allows us to infer an average propagation speed 2.6×10^5 m s^{-1}.

453   The development of this FORTE flash is consistent with the ground-based observations

454   of spider lightning from Mazur et al. (1998). We find pulses illuminating the tips of branched

455   channels in the flash and luminosity along the channel that may have been sustained for many

456   milliseconds in agreement with their video observations. The lateral development speed of our

457   flash also fits within their 2-4x10^5 m s^{-1} range for the slow negative leaders that occur in spider

458   lightning events, while the sustained RF emission recorded by TATR also agrees with their RF

459   records of strong continuous VHF radiation from the slow leader (Figure 12 and 13 in Mazur et

460   al., 1998). Unlike the previous ground-based results, the FORTE LLS did not map lightning

461   activity that was distinct from the propagating spider event. If additional fast negative leaders or

462   positive leaders occurred in other parts of the lightning "tree" as described in Mazur et al. (1998),

463   they were either too weak to be resolved from space or co-located with the geographic extent of

464   the developing spider flash.

465   4.2 Optical emission during second and third +CG strokes

466   The most radiant group in the flash (8-sigma) occurred at 282 ms in the evolution plot in

467   Figure 8. This was the second bright group (> 1-sigma) in the flash, with the first describing the

468   illumination of the long horizontal channel during a possible -CG. The RF power coincident with

469   this second bright group increased rapidly by 10 dB and then fell back to the average sustained

470   RF power level over a period of 12 ms – conforming to the +CG signature that we saw with the

471   first stroke in Figures 4 and 5. The long-duration VHF activity following the stroke (also seen in

472   the +CG strokes in Mazur et al., 2008) is interesting because it was not noted in the TATR

473   waveforms from Light et al. (2001b), where the "normal" (i.e., non-megaflash) +CG pulses were

474   shown to last between ~150 μs and 500 μs.

475   This behavior may be a unique feature of VHF emission from megaflashes that can

476   access charge from throughout their vast networks of ionized lightning channels during strokes

477   and funnel it to the surface. We see evidence for this in the LLS data from this second +CG. This

478   second +CG stroke was located along the northeastern flank of the flash. If we assume that the

479   strokes are co-located with the centroid of the brightest simultaneous LLS groups, then the first

480   and second +CG strokes were separated by approximately 50 km. However, the 8-sigma bright

481   group is not the only LLS activity during the second +CG. Two single-pixel groups occurred

482   during the VHF tail that appear to extend the existing channel: one at the flash origin, and one on

483   the eastern flank of the flash south of the second +CG (though, still within the cloud-region that

484   the stroke illuminated two frames prior). This indicates that the whole 60-km channel was active

485   during this stroke, with these new breakdowns contributing to the VHF tail. It is likely that the

486   channel was continuously illuminated (as we saw with the PDD waveforms during the first

487   stroke), but that LLS only triggered intermittently in the pixels corresponding to emissions with

488   high energy densities. However, this is only speculation as the PDD triggers that could confirm

489   sustained optical emission had been exhausted by this point in the flash.

490   The second of the single groups in Figure 8 would become important because it marked

491   the initial development of a new branch in the flash that would go on to produce the third +CG

492   stroke at 337 ms. Flash evolution at the time of the third stroke is shown in Figure 9. While this

493   stroke was not accompanied by strong VHF emission (only 5 dB above the baseline RF power

494   during the flash), it was optically bright – producing a LLS group with more than 10% of the

495   energy of the 8-sigma stroke. It likewise has a long VHF tail (12-15 ms following the primary

496   pulse) within which LLS activity could be noted back at the flash origin – again, suggesting that

497   the whole channel was active during this period. The single-event group at 362 ms marks the last

498   time when LLS detected activity near the flash origin until the final phase of the flash.

499   4.3 Channel extension and branching leading up to the fourth +CG stroke

500   The period following the third +CG strokes is marked by continued incremental lateral

501   development of the existing branches along the lightning channel and the later establishment of a

502   new northwestern major branch. The first portion of this period from 450 ms to 550 ms is plotted

503   in Figure 10, and it lacked the sustained VHF emission that we noted previously with the initial

504   development of the flash. The impulsive IC events during this period originated from a broad

505   range of altitudes between 4 km and 7 km. TATR events included isolated IC pulse pairs,

506   sustained featureless emission, and diffuse RF pulses as the northeastern and eastern branches

507   were extended by 1-2 pixel LLS groups illuminating their tips. Small features can also be noted

508   on the order of 1 pixel or less departing from the main channel (light grey features in Figure

509   10c). These smaller features may be short branches or they might be caused by uncertainties in

510   the source locations due to the pixelated LLS grid.

511   The final group during this period established the beginning of a new northern branch

512   that would continue to develop to the northwest over the next few groups and go on to produce

513   the fourth +CG stroke. The initial development of the northwestern branch from 540 ms to 590

514   ms is shown in Figure 11. There are a few RF-only triggers from 540 ms to 550 ms in Figure

515   11e,f followed by sustained RF activity that resembles the initial TATR triggers in the flash.

516   However, the strong RF pulse at the beginning of the sustained RF triggering appears to be a K-

517   change rather than a stroke in this case due to its relatively-slow rise time. This sustained VHF

518   emission lasted ~70 ms and appears to describe leader activity along only the northern branches

519   of the flash (Figure 11c).

520   The time period from 585 ms to 700 ms is shown in Figure 12 and includes the fourth

521   +CG stroke at 593 ms. The VHF pulse reached 12 dB above the RF background and generated

522   the second-most radiant optical group in the LLS flash at 4-sigma. The LLS group had an oblong

523 footprint with the most radiant pixels following the linear path of the northwestern branch

524 (Figure 12c). As with the previous +CG events, a VHF tail can be noted lasting for 20 ms

525 following the stroke. Subsequent groups in Figure 12 describe re-illumination along the

526 northeastern branch of the flash and further extension of some of the smaller branches away from

527 the main channel.

528 4.4 Final development after continuous RF emission ceased

529 The last 480 ms of the flash is shown in the evolution plot in Figure 13. The sustained

530 featureless VHF emission that accompanied the slow leader ceased by 670 ms, and this final

531 period was marked by intermittent impulsive IC events and diffuse K-changes. All but one of the

532 LLS groups occurred along the northeastern branches in the flash. The group at 722 ms is the

533 exception, as it illuminated part of the initial southwestern branch. The group at 752 ms extends

534 the flash to its maximum lateral extent of 82 km across. The final impulsive IC event near 8 km

535 altitude occurred at 820 ms, while the four last impulsive IC events in the flash were located at or

536 below 6 km altitude. The final RF event was a diffuse pulse that had optical coincidence at 1120

537 ms, while the final LLS group was a single-event trigger that occurred 60 ms later along the

538 northernmost extent of the flash structure.

539

540 **5 Conclusion**

541 We use coincident optical and RF instrumentation aboard the FORTE satellite to examine

542 the combined-phenomenology evolution of an oceanic megaflash that was 82 km across and

543 lasted nearly 1.2 s. There are a number of distinct features in the optical / RF signatures that

544 stand out in this flash, which may be unique to this distinct class of lightning.

545   No RF triggers occurred before the first optical event, while the initial RF / optical

546   signals were some of the weakest recorded from the flash. The 591 TATR events produced by

547   this megaflash were dominated by sustained featureless VHF emission that constantly triggered

548   TATR over periods lasting tens to hundreds of milliseconds. Impulsive IC events occurred at

549   altitudes between 3 and 8 km. The LLS groups describe the incremental lateral development of

550   the lightning channel at a typical development speed of 2.6×10^5 m s^{-1}. Three of these groups

551   were particularly radiant and accounted for 5%, 38%, and 17% of the total optical energy from

552   the flash (52% from all three, combined). The top two most radiant groups come from +CG

553   strokes, while the third appears to have resulted from a -CG stroke, though RF waveform

554   analysis was inconclusive. Two additional +CG strokes were also identified whose optical

555   energies did not reach the 1-sigma level for the flash.

556   These observations are consistent with previous ground-based studies that show "spider

557   lightning" in horizontally-propagating flashes occurring as slow negative leaders ($2\text{-}4 \times 10^5$ m s^{-1})

558   that develop at low levels (~4 km) in mature / dissipating stratiform clouds via the same apparent

559   mechanism as the stepped leaders that precede negative return strokes. Similarities in the general

560   optical / RF phenomenologies and the signatures that are present suggest that we are sensing the

561   same processes from orbit that they recorded at ground level. The sustained RF emission during

562   extensive flash propagation in the optical data confirm that this behavior is related to leader

563   activity in the cloud and provides additional context for our previous assessment of the speed and

564   scale of optical flash development (Peterson et al., 2018).

565

566 **Acknowledgments**

569

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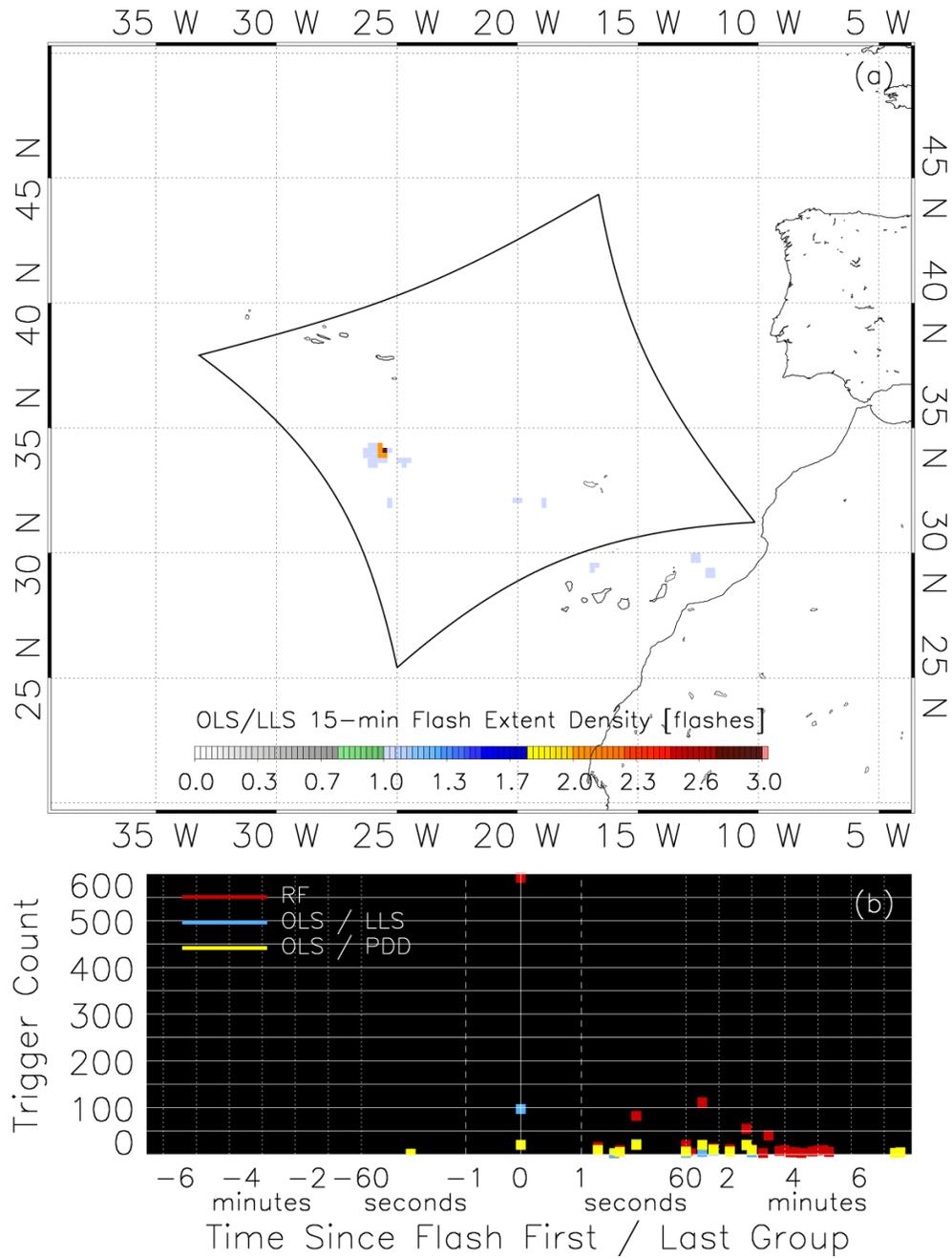
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684   **Figure 1.** FORTE LLS lightning activity near the flash of interest. (a) FED across the LLS FOV and (b) optical and
685   RF trigger rates during the 15-minute window surrounding the flash. Because lightning was infrequent across the
686   FORTE FOV during the flash window, triggers from other flashes are unlikely.
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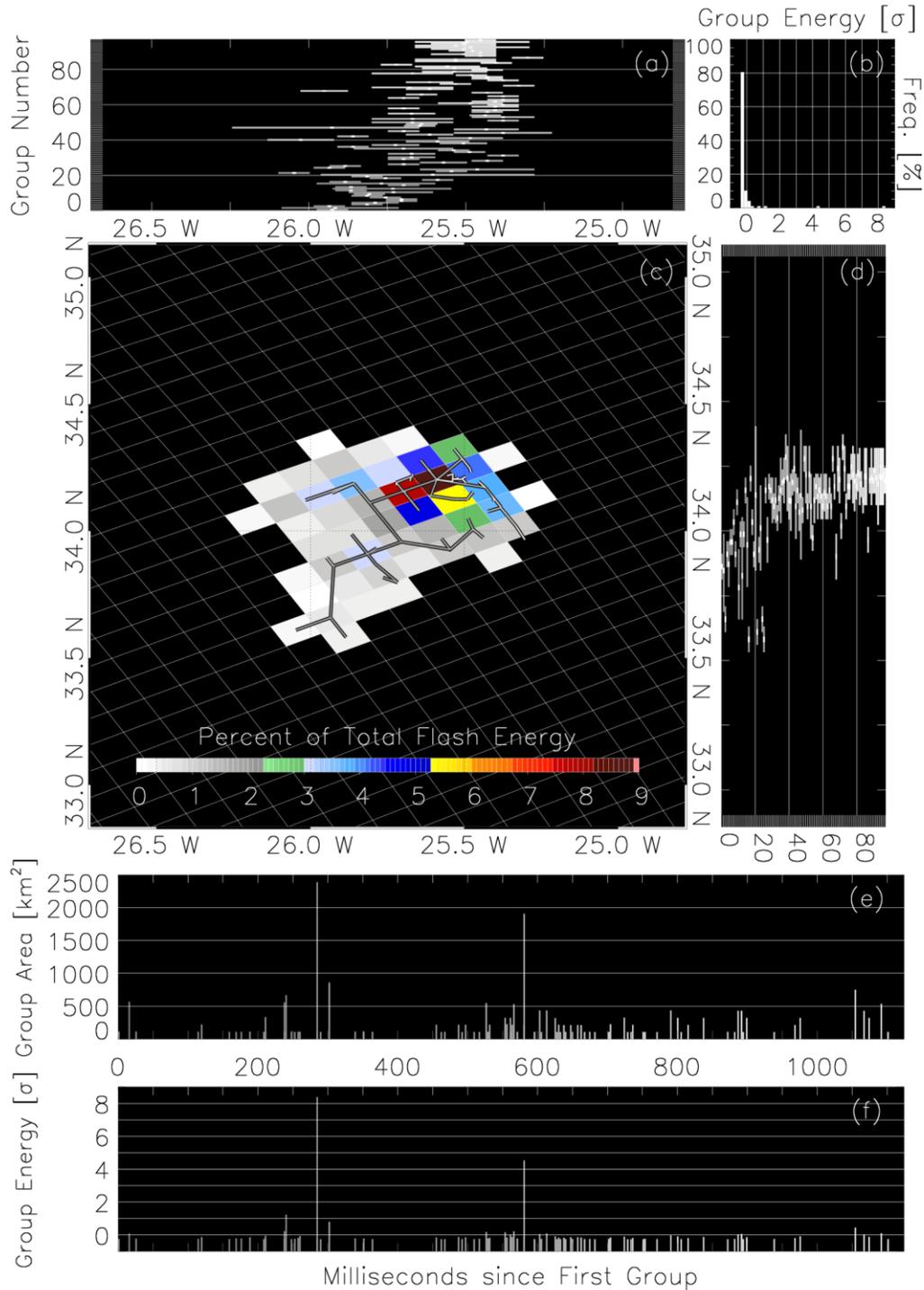
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689 **Figure 2.** Evolution plot for the LLS flash. (a) group extent by longitude, (b) group energy distribution, (c) plan
690 view of flash energy (color contour) and group extent (line segments), (d) group extent by latitude, (e) timeseries of
691 group area, and (f) timeseries of group energy. Group energies are expressed as a sigma level relative to the average
692 group energy in the flash. The greyscale in all plots represents the group number.
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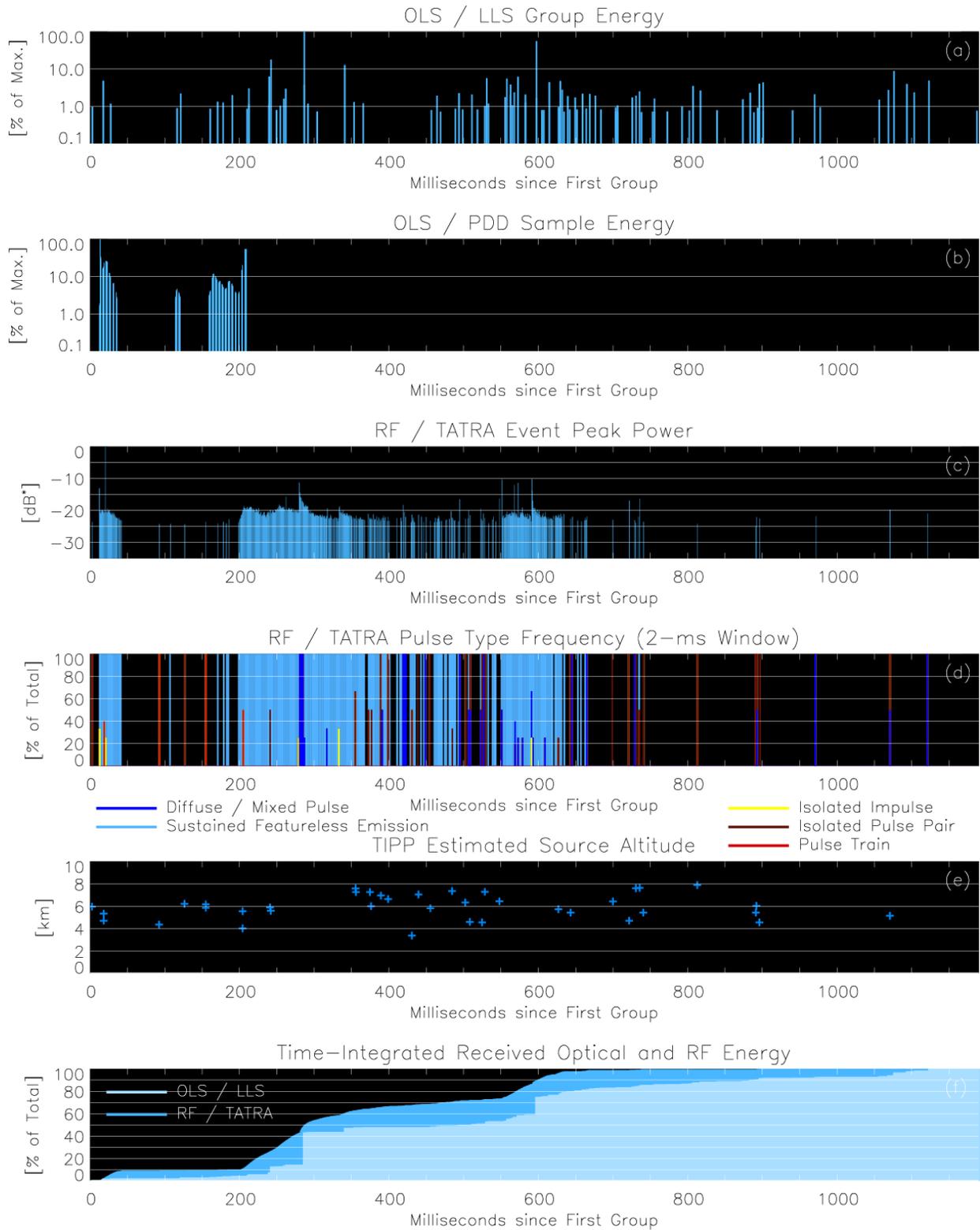
Figure 3. Timeseries showing the combined optical / RF evolution of the flash. (a) LLS and (b) optical energies. (c) TATR event peak RF power. (d) TATR pulse classification shown as the frequency of each pulse type in a 2-ms window. (e) estimated altitude of in-cloud (TIPP) sources. (f) time-integrated optical and RF energies over the flash duration
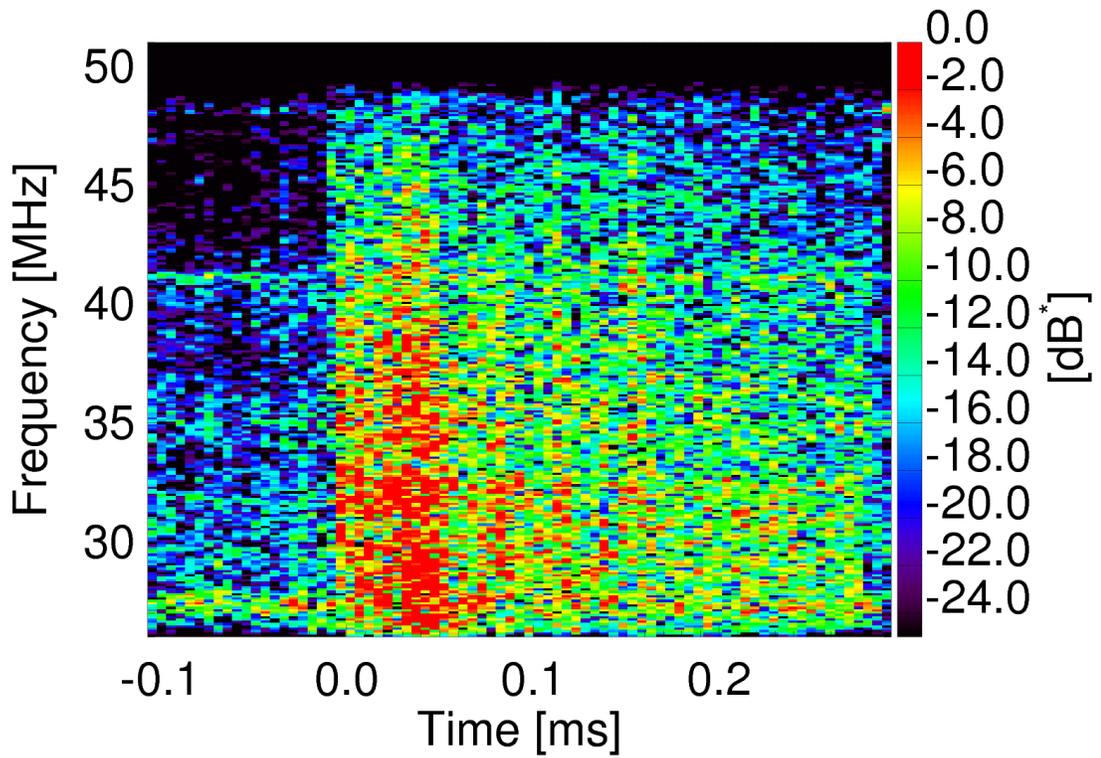
700
701 **Figure 4.** Spectrogram showing normalized RF power over the lowband frequency range as a function of time
702 sensed by TATR during the first +CG event at 14 ms into the LLS flash. The sharp onset and long-duration pulse are
703 common VHF features associated with +CGs.
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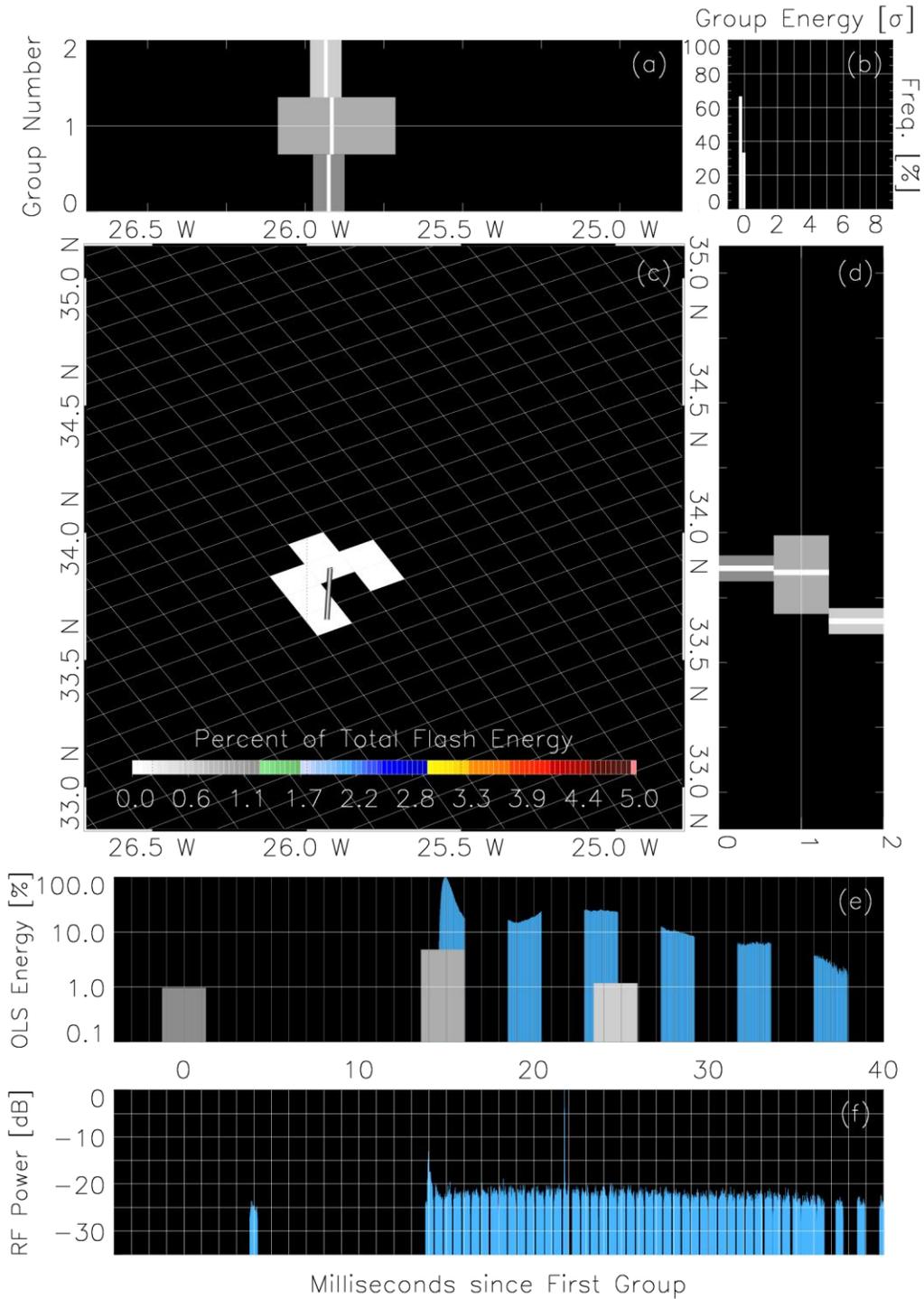
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708 **Figure 5.** Evolution plot for the first 40 ms of optical triggers in the flash. Identical to Figure 3, but with LLS group
709 area replaced by TATR RF power (f) and PDD data plotted blue in (e)
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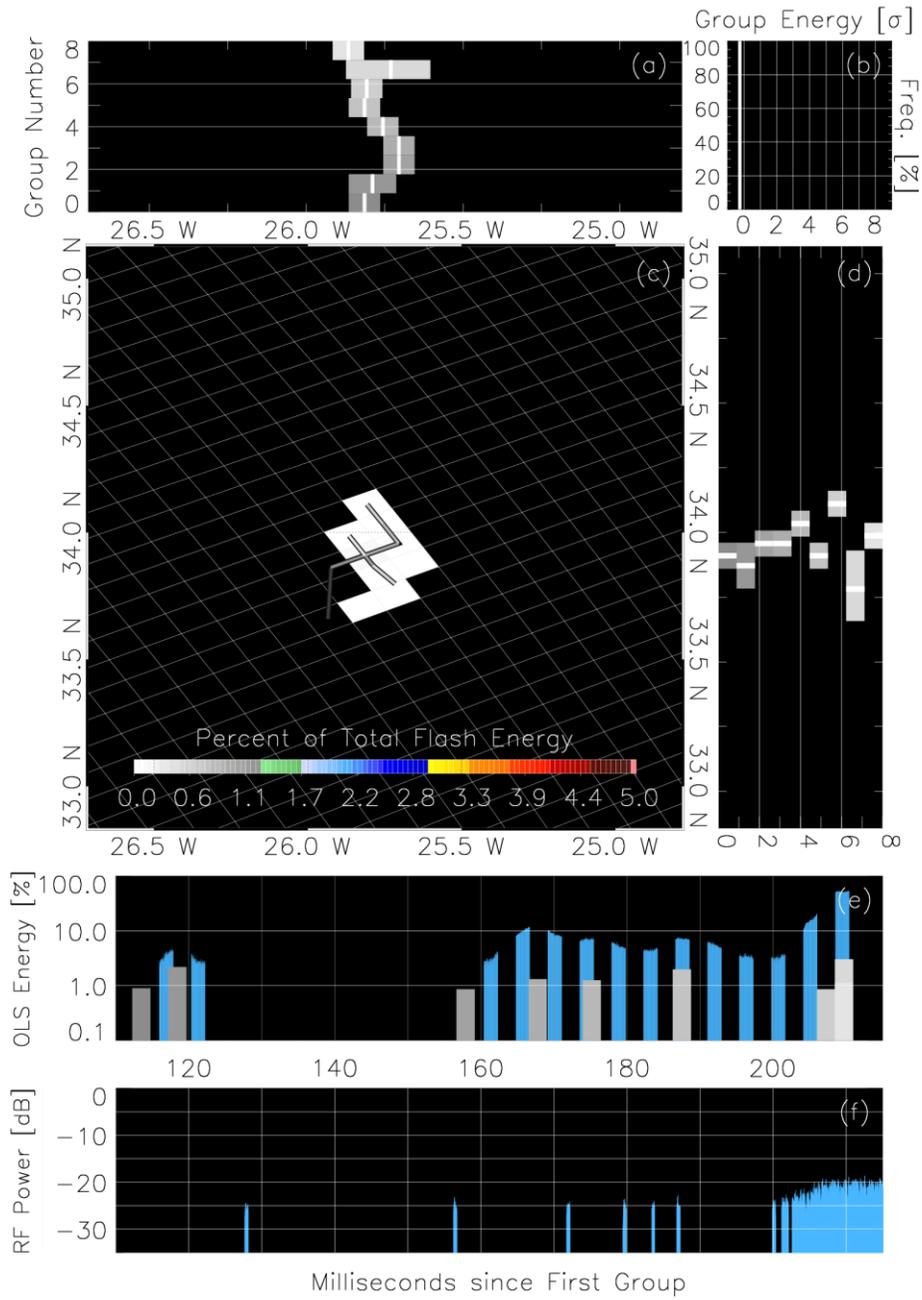
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714 **Figure 6.** Same as Figure 5, but for the period 110 ms – 215 ms that begins the longest period of sustained PDD /
715 TATR triggering
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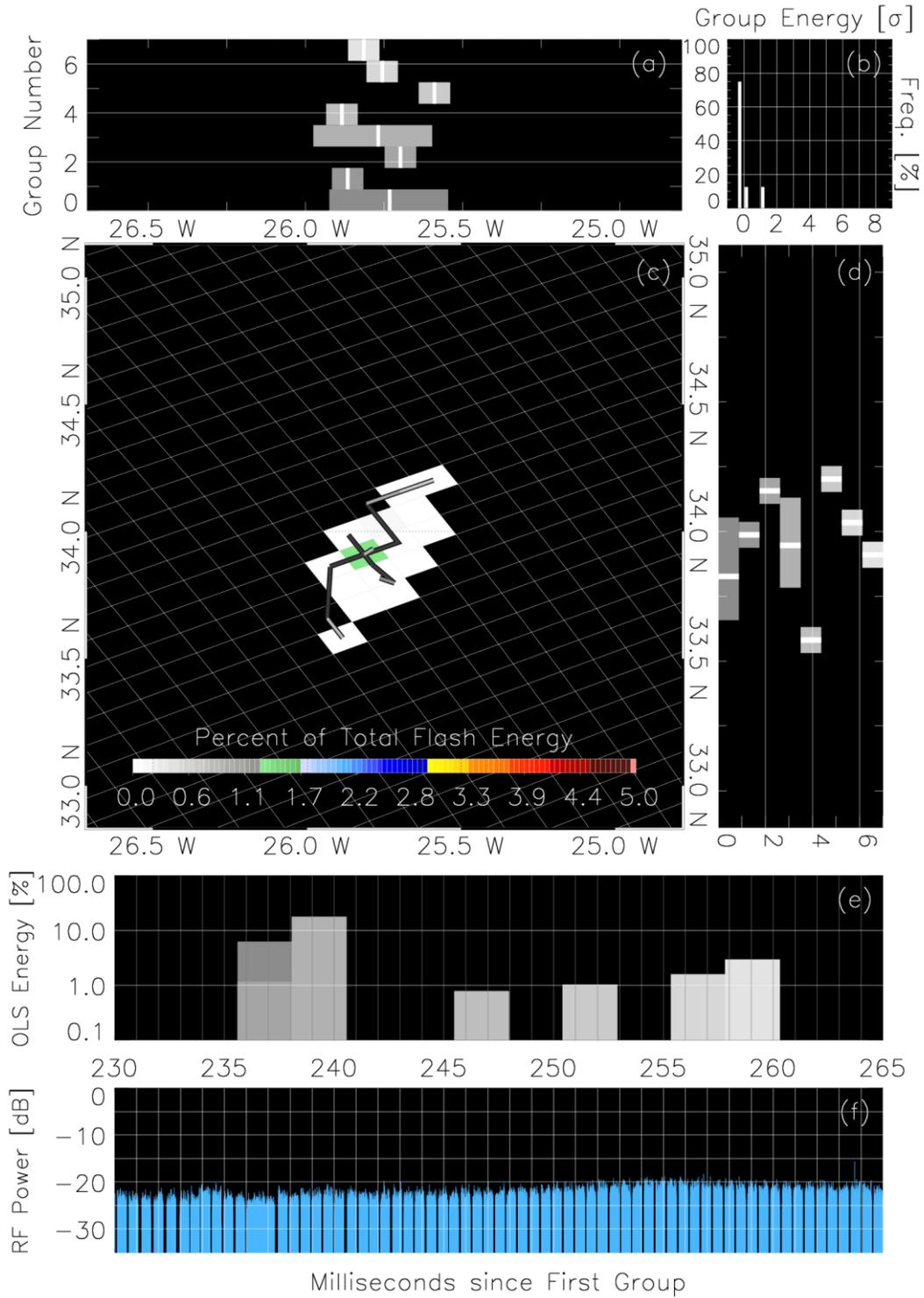
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718   **Figure 7.** Same as Figure 5, but for the period 230 ms – 265 ms during the initial development phase of the spider
719   flash
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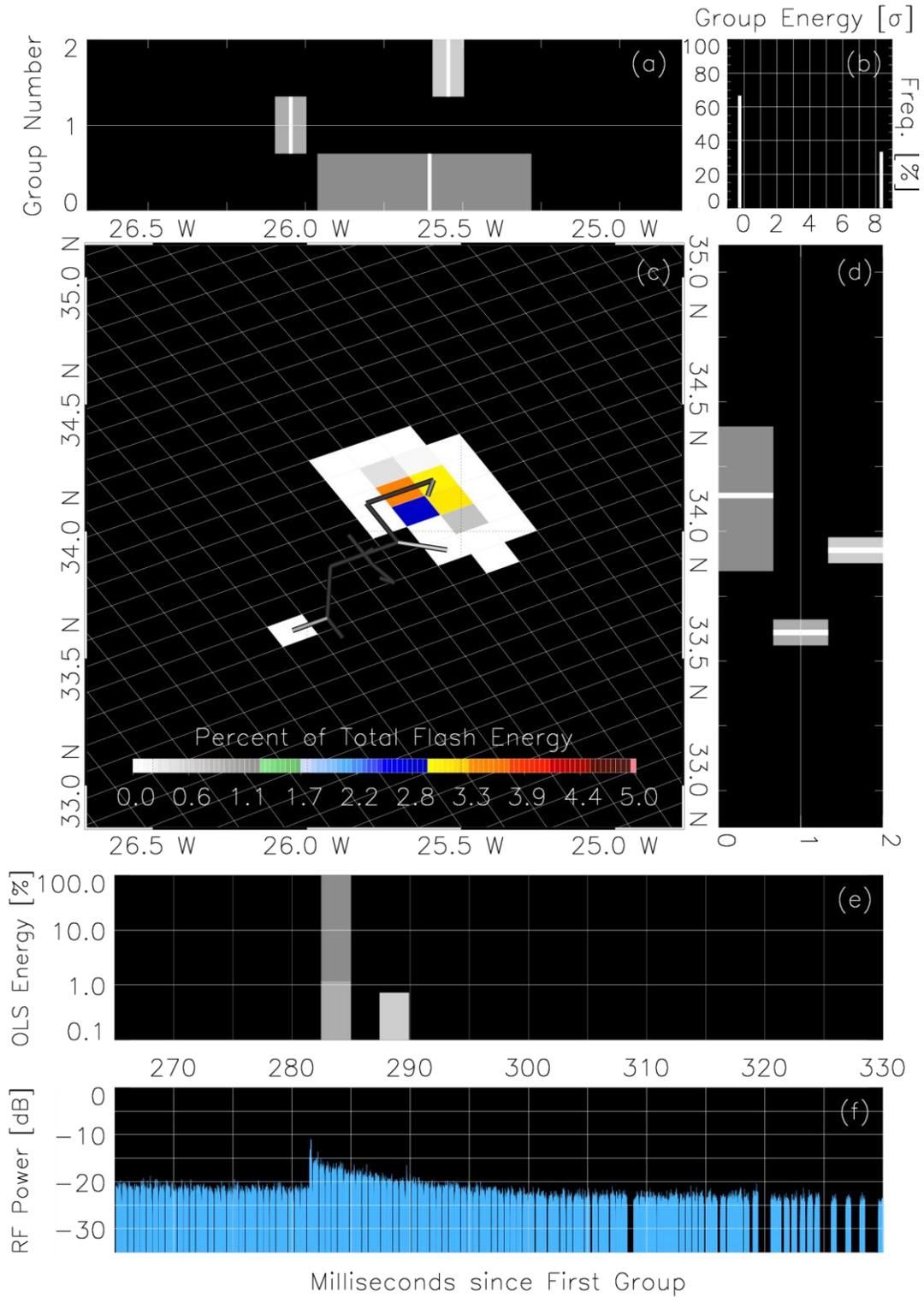
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722   **Figure 8.** Same as Figure 5, but for the period 265 ms – 330 ms that includes the first possible +CG stroke
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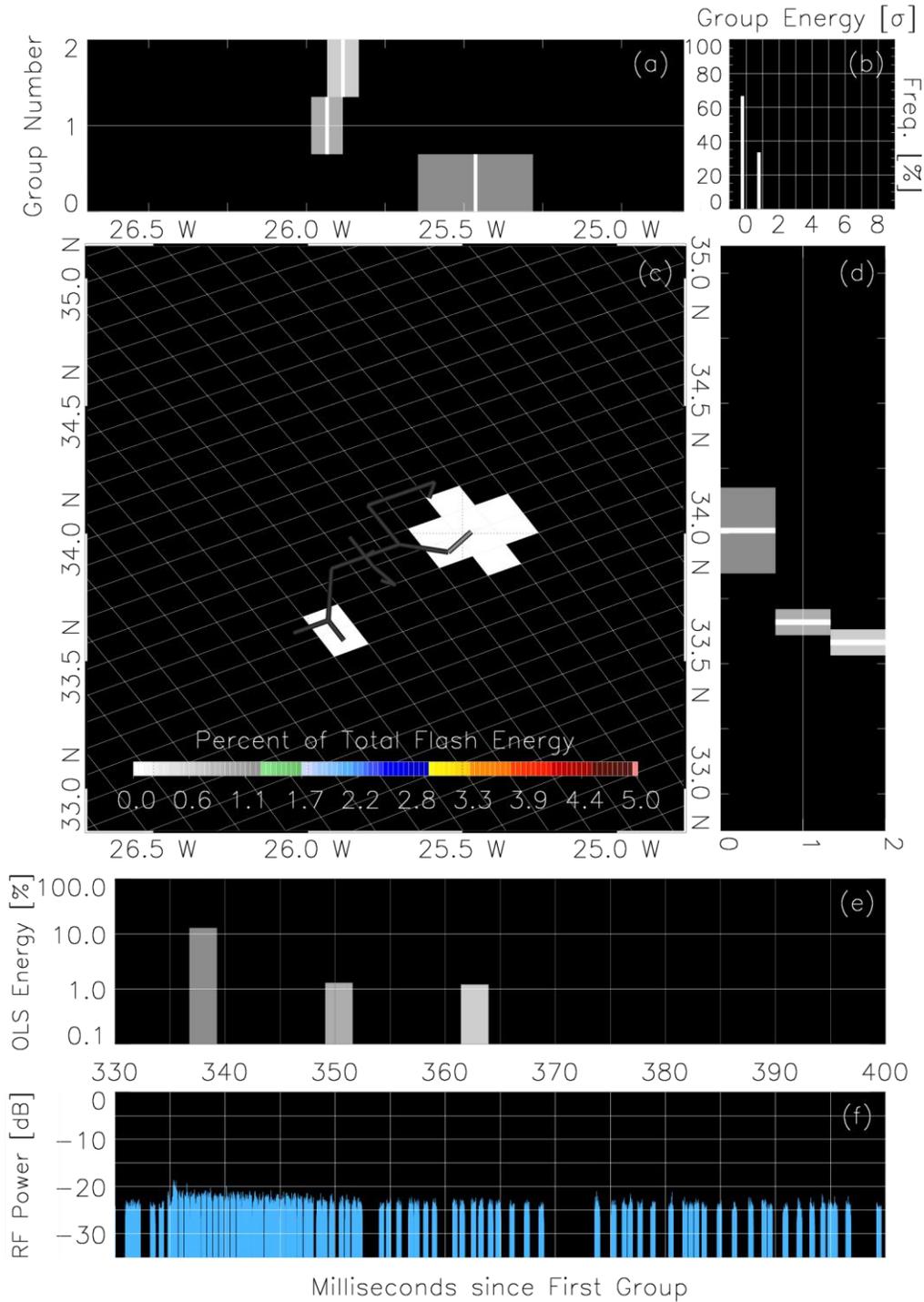
725
726 **Figure 9.** Same as Figure 5, but for the period 330 ms – 400 ms that shows a possible (questionable) second +CG
727 stroke in a different location than Figure 8
728
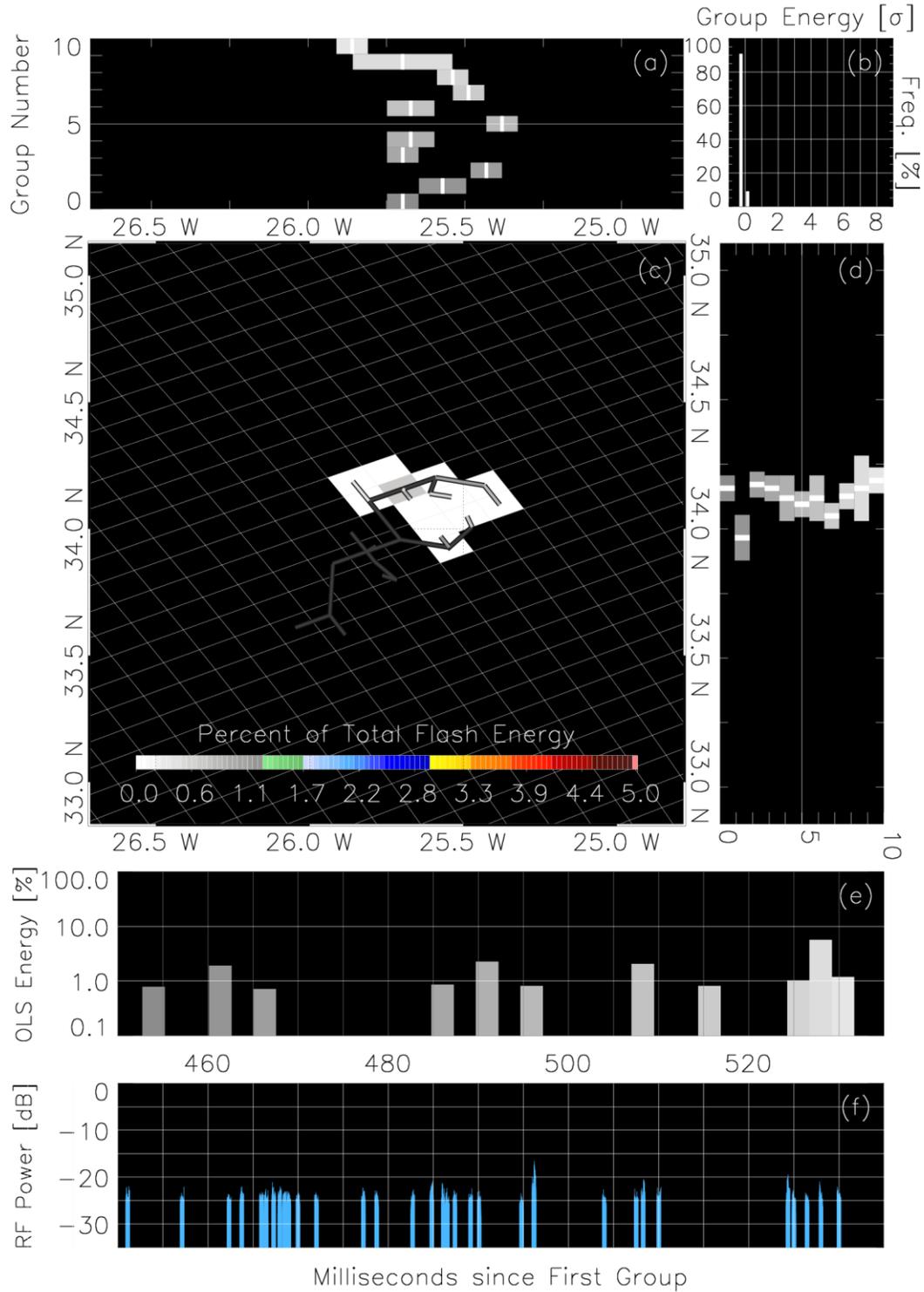
730 **Figure 10.** Same as Figure 5, but for the period 450 ms – 535 ms showing additional lateral development ending
731 with the start of a new main branch to the northwest
732
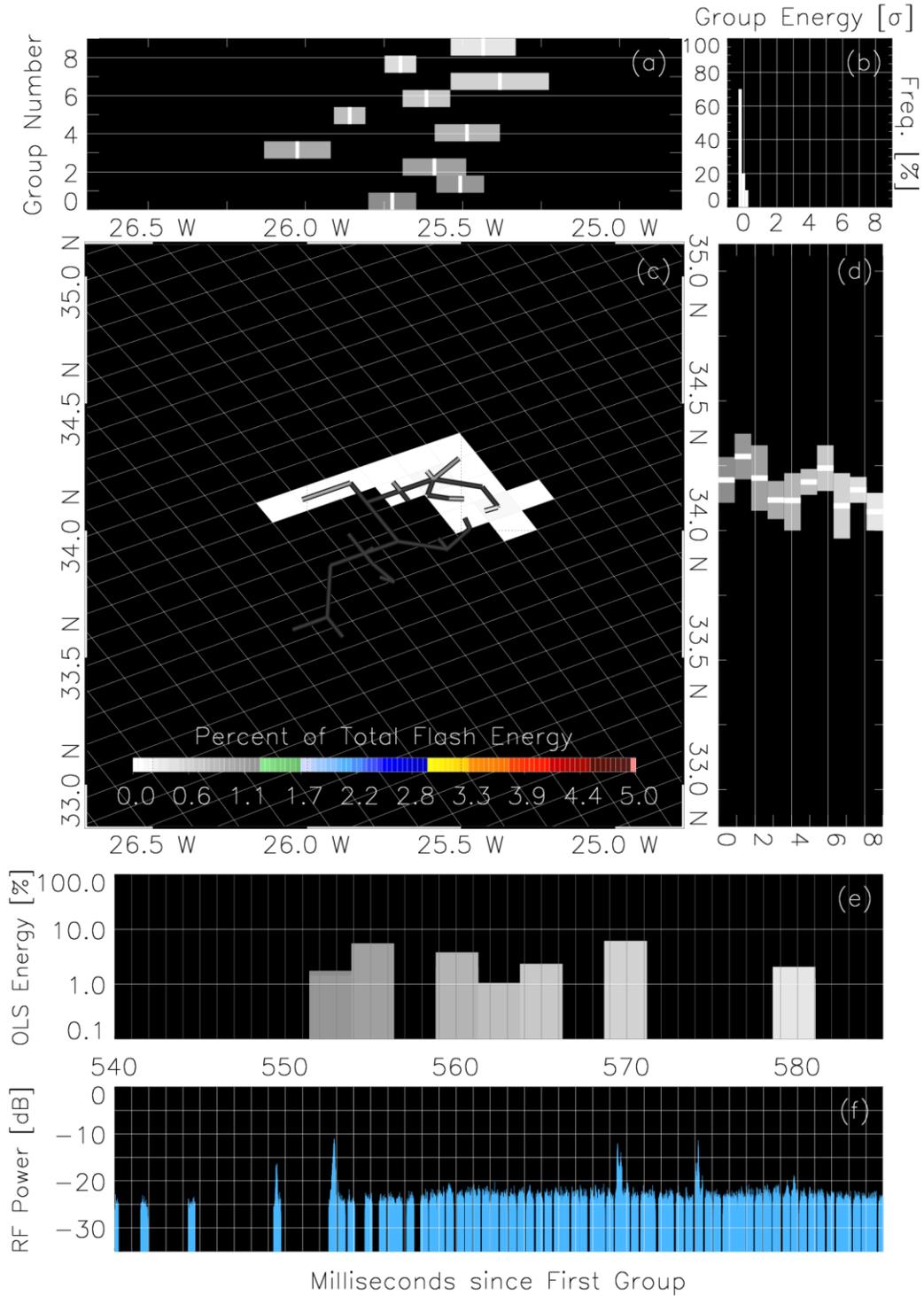
733
734   **Figure 11.** Same as Figure 5, but for the period 540 ms – 585 ms where sustained TATR triggering resumes after a
735   diffuse VHF pulse
736
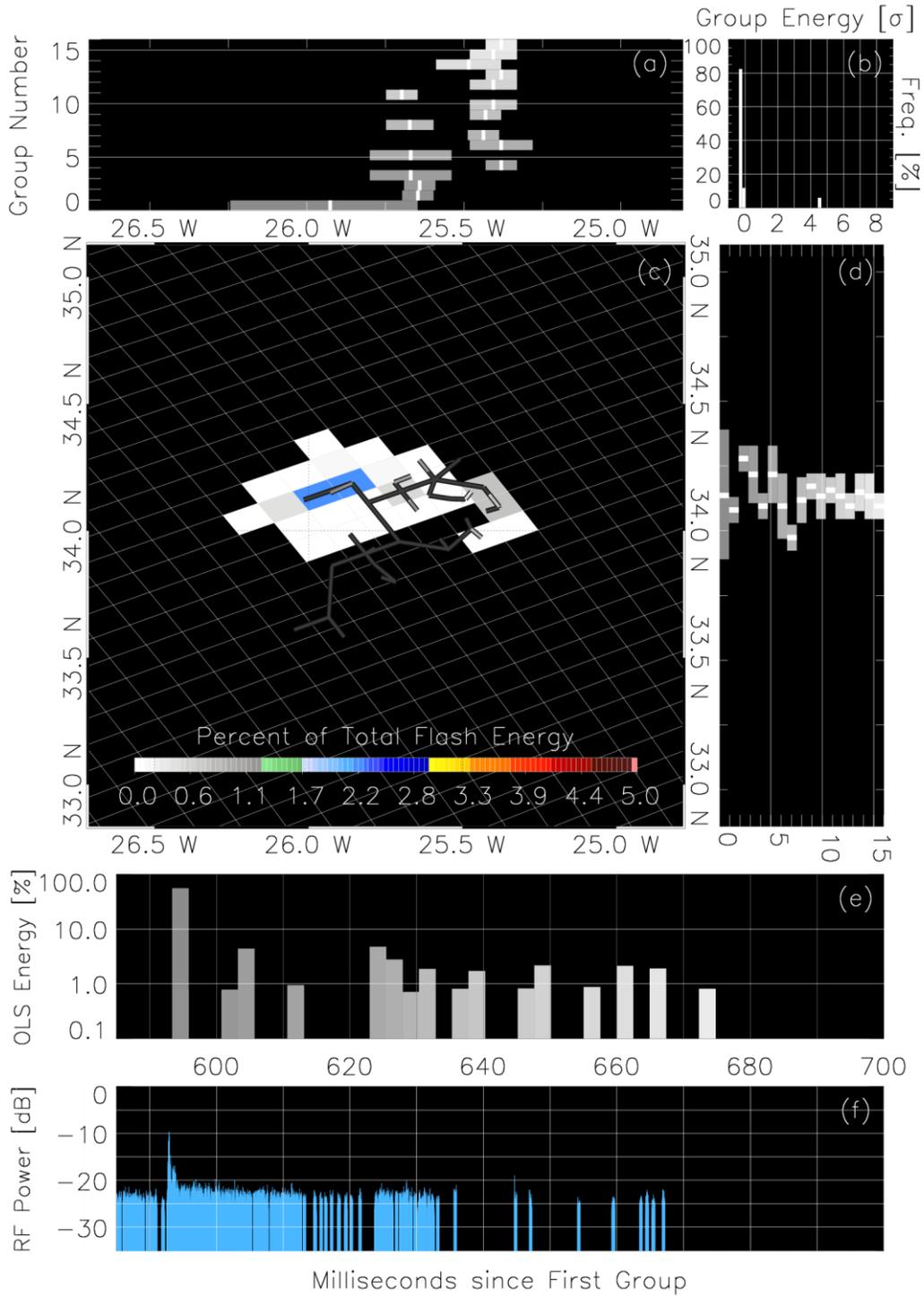
Figure 12. Same as Figure 5, but for the period 585 ms – 700 ms showing a possible (questionable) third +CG
stroke along the new northwest branch

740
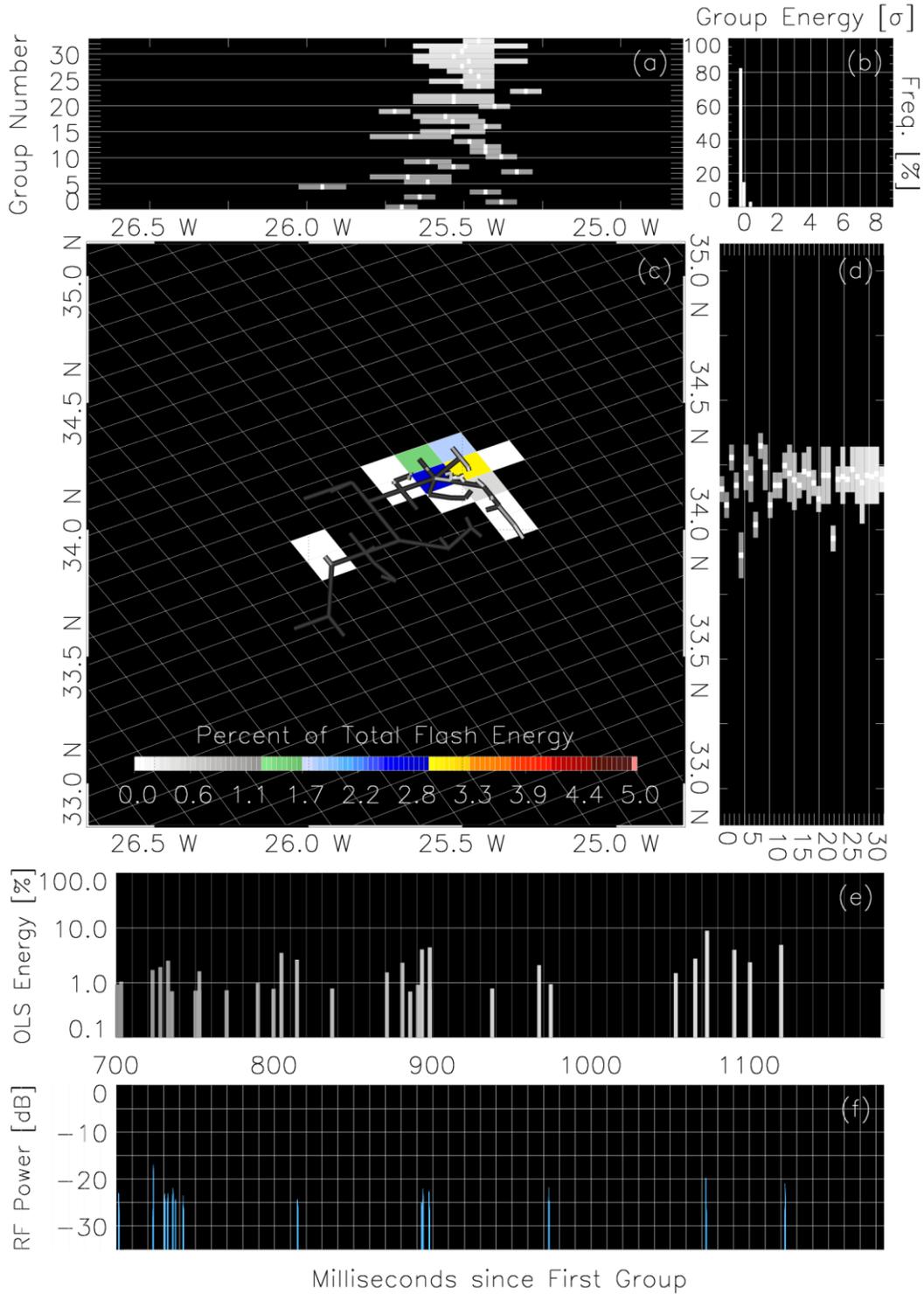
742 **Figure 13.** Same as Figure 5, but for the period 700 ms – 1180 ms that documents the final LLS / TATR pulses after
743 the sustained VHF emission has ceased
744

Figure 1.

(a) OLS/LLS 15-min Flash Extent Density [flashes]

0.0   0.3   0.7   1.0   1.3   1.7   2.0   2.3   2.6   3.0

(b)

Trigger Count

RF
OLS / LLS
OLS / PDD

600
500
400
300
200
100
0

−6 −4 −2 −60   −1   0   1   60   2   4   6
minutes   seconds   seconds   minutes

Time Since Flash First / Last Group

Figure 2.

(a)

Group Energy [σ]

(b)

Freq. [%]

(c)

Percent of Total Flash Energy

0   1   2   3   4   5   6   7   8   9

(d)

Group Area [km²]

(e)

Group Energy [σ]

(f)

Milliseconds since First Group

Figure 3.

OLS / LLS Group Energy

(a)

[% of Max.]

Milliseconds since First Group

OLS / PDD Sample Energy

(b)

[% of Max.]

Milliseconds since First Group

RF / TATRA Event Peak Power

(c)

[dB*]

Milliseconds since First Group

RF / TATRA Pulse Type Frequency (2-ms Window)

(d)

[% of Total]

Milliseconds since First Group

Diffuse / Mixed Pulse
Sustained Featureless Emission
Isolated Impulse
Isolated Pulse Pair
Pulse Train

TIPP Estimated Source Altitude

(e)

[km]

Milliseconds since First Group

Time-Integrated Received Optical and RF Energy

(f)

[% of Total]

OLS / LLS
RF / TATRA

Milliseconds since First Group

Figure 4.

Figure 5.

(a)

Group Energy [σ]

(b)

Freq. [%]

(c)

Percent of Total Flash Energy

0.0 0.6 1.1 1.7 2.2 2.8 3.3 3.9 4.4 5.0

(d)

OLS Energy [%]

(e)

RF Power [dB]

(f)

Milliseconds since First Group

Figure 6.

(a)

Group Energy [σ]

(b)

Freq. [%]

(c)

Percent of Total Flash Energy

0.0 0.6 1.1 1.7 2.2 2.8 3.3 3.9 4.4 5.0

(d)

(e)

(f)

Milliseconds since First Group

Figure 7.

Group Energy [σ]

(a)

(b)

Group Number

Freq. [%]

Percent of Total Flash Energy

0.0   0.6   1.1   1.7   2.2   2.8   3.3   3.9   4.4   5.0

(c)

(d)

OLS Energy [%]

(e)

RF Power [dB]

(f)

Milliseconds since First Group

Figure 8.

(a)

Group Number
2
1
0

26.5 W   26.0 W   25.5 W   25.0 W

Group Energy [σ]

(b)

Freq. [%]

100
80
60
40
20
0

0   2   4   6   8

(c)

Percent of Total Flash Energy

0.0 0.6 1.1 1.7 2.2 2.8 3.3 3.9 4.4 5.0

35.0 N
34.5 N
34.0 N
33.5 N
33.0 N

26.5 W   26.0 W   25.5 W   25.0 W

(d)

35.0 N
34.5 N
34.0 N
33.5 N
33.0 N

0   1   2

(e)

OLS Energy [%]

100.0
10.0
1.0
0.1

270 280 290 300 310 320 330

(f)

RF Power [dB]

0
-10
-20
-30

Milliseconds since First Group

Figure 9.

Percent of Total Flash Energy

Group Energy [σ]

Figure 10.

Group Energy [σ]

(a)

(b)

Freq. [%]

(c)

(d)

Percent of Total Flash Energy

0.0 0.6 1.1 1.7 2.2 2.8 3.3 3.9 4.4 5.0

(e)

OLS Energy [%]

(f)

RF Power [dB]

Milliseconds since First Group

Figure 11.

Group Energy [σ]

Group Number

8

6

4

2

0

(a)

(b)

Freq. [%]

100
80
60
40
20
0

26.5 W   26.0 W   25.5 W   25.0 W

0   2   4   6   8

35.0 N

34.5 N

34.0 N

33.5 N

33.0 N

(c)

35.0 N

34.5 N

34.0 N

33.5 N

33.0 N

(d)

Percent of Total Flash Energy

0.0   0.6   1.1   1.7   2.2   2.8   3.3   3.9   4.4   5.0

26.5 W   26.0 W   25.5 W   25.0 W

0   2   4   6   8

OLS Energy [%]

100.0

10.0

1.0

0.1

(e)

540   550   560   570   580

RF Power [dB]

0

−10

−20

−30

(f)

Milliseconds since First Group

Figure 12.

(a)

Group Number

Group Energy [σ]

(b)

Freq. [%]

(c)

Percent of Total Flash Energy

0.0 0.6 1.1 1.7 2.2 2.8 3.3 3.9 4.4 5.0

(d)

(e)

OLS Energy [%]

(f)

RF Power [dB]

Milliseconds since First Group

Figure 13.

Percent of Total Flash Energy