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# First ten months of TGF observations by ASIM

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## Key Points:

- Simultaneous measurements of TGF by two spacecraft are presented
- Simultaneous measurements of TGF and Elve are not rare coincidence
- The sequence of TGF and main optical lightning pulse is resolved

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## Abstract

The Atmosphere-Space Interactions Monitor (ASIM) was launched to the International Space Station (ISS) on April 2, 2018. The ASIM payload consists of two main instruments, the Modular X- and Gamma-ray Sensor (MXGS) for imaging and spectral analysis of Terrestrial Gamma-ray Flashes (TGFs) and the Modular Multi-spectral Imaging Array (MMIA) for detection, imaging and spectral analysis of Transient Luminous Events (TLEs) and lightning. ASIM is the first space mission designed for simultaneous observations of TLEs, TGFs and optical lightning. During the first ten months of operation (June 2, 2018 to April 1, 2019) the MXGS has observed 217 TGFs. In this paper we report several unprecedented measurements and new scientific results obtained by ASIM during this period: 1) simultaneous TGF observations by Fermi Gamma-ray Burst Monitor (GBM) and ASIM MXGS revealing the very good detection capability of ASIM MXGS and showing substructures in the TGF, 2) TGFs and Elves produced during the same lightning flash and even simultaneously have been observed, 3) first imaging of TGFs giving a unique source location, 4) strong statistical support for TGFs being produced during the upward propagation of a leader just before a large current pulse heats up the channel and emits a strong optical pulse, and 5) the  $t_{50}$  duration of TGFs observed from space is shorter than previously reported.

## 1 Introduction

Terrestrial Gamma-ray Flashes (TGF) discovered by *Fishman et al.* [1994] are flashes of gamma-rays with energies up to 30-40 MeV [*Marisaldi et al.*, 2010, 2019; *Briggs et al.*, 2010] originating from thunderclouds and their durations are from tens to more typically a few hundreds of microseconds [*Gjesteland et al.*, 2010; *Connaughton et al.*, 2013; *Marisaldi et al.*, 2014]. From spectral characteristics of TGFs observed from space [*Dwyer and Smith*, 2005] and associated radio measurements [*Cummer et al.*, 2015] their production altitude has been found to be at 10-15 km produced in positive Intra Cloud (IC+) lightning bringing negative charge upward [*Cummer et al.*, 2005; *Stanley et al.*, 2006].

Combined with radio measurements it has been found that TGFs occur during the initial phase of lightning [*Shao et al.*, 2010; *Lu et al.*, 2010]. This was also reported by [*Østgaard et al.*, 2013] based on the fortuitous coincidence of having two satellites passing less than 300 km apart, one detecting the optical signal from lightning and the other

47 detecting the TGF. Simultaneous radio measurements from ground suggested the initia-  
48 tion of a leader about 4 ms before the TGF, and that the main optical pulse was after the  
49 TGF. These results were revisited by *Gjesteland et al.* [2017] who also reported one more  
50 coincident observation of optical lightning and TGF and concluded that, with the tempo-  
51 ral resolution of the optical data, they could not determine unambiguously the sequence of  
52 events, but only that the two signals were simultaneous to within  $\pm 1.6$  ms.

53 Several studies have reported that TGFs are associated with very large current pulses  
54 ( $>200$  kA) which have been termed Energetic Intra-cloud Pulses [*Cummer et al.*, 2014;  
55 *Lyu et al.*, 2015]. For a few cases it has been shown that a current pulse was observed  
56 simultaneously with the TGF and could well be from the TGF itself [*Cummer et al.*, 2011;  
57 *Pu et al.*, 2019]. Whether this is true for all TGFs is an open question.

58 It has been suggested from theoretical considerations [*Cummer et al.*, 2014; *Lyu*  
59 *et al.*, 2015] and modeling [*Liu et al.*, 2017] that a large current pulse observed by radio  
60 measurements simultaneously with TGFs should also produce Elves, but this has not been  
61 observed before now. ASIM is the first payload that has the ability to address this, and  
62 indeed, *Neubert et al.* [2019a], as the very first results from ASIM, reported the simulta-  
63 neous detection of a TGF and an Elve, and that they were powered by the same lightning  
64 stroke. The TGF was observed at the end of a weak brightening interpreted as the propa-  
65 gation of an ascending leader in an IC+ lightning and had its onset  $10 \mu\text{s}$  ( $\pm 5 \mu\text{s}$ ) before  
66 the onset of a larger optical pulse. The TGF lasted for  $80 \mu\text{s}$ . The optical pulse that fol-  
67 lowed peaked after  $150 \mu\text{s}$  and lasted for  $\sim 1$  ms. The pulse was interpreted as the optical  
68 signature of the current pulse that also produced the Elve.

69 It is now commonly accepted that TGFs are the results of relativistic electrons that  
70 produce X- and gamma-rays through the bremsstrahlung process. Furthermore, these elec-  
71 trons have been accelerated in a very high electric field by the so-called run-away (RA)  
72 process [*Wilson*, 1925], and multiplied by orders of magnitude through a Relativistic Run-  
73 away Electron Avalanche (RREA) process [*Gurevich et al.*, 1992]. However, there are two  
74 main ideas to explain how the large number of gamma-rays ( $10^{17} - 10^{19}$ ) are produced.  
75 One [*Moss et al.*, 2006; *Chanrion and Neubert*, 2010; *Celestin and Pasko*, 2011; *Babich*  
76 *et al.*, 2014, 2015; *Skeltved et al.*, 2017] considers the high electric field at the tip of a  
77 long conductive leader where the streamers in the streamer zone can produce  $10^{12}$  elec-  
78 trons accelerated up to tens of keV and that these seed-electrons are further accelerated

79 and multiplied by RREA in the extended leader field to reach the necessary number of  
80 gamma photons. The other idea considers a feedback mechanism [Dwyer, 2008] where the  
81 gamma photons can backscatter or interact with neutrals to create pairs of electrons and  
82 positrons, and that the gamma photons and positrons go back in the direction of the elec-  
83 tric to produce new seeds for avalanches (RREA). This mechanism does not need a  
84 lot of seed-electrons, as the feedback can account for all the multiplication. The feedback  
85 mechanism could work both in a large uniform field and in the electric field ahead of a  
86 leader.

87 In this paper we present the first observations of TGFs by Atmosphere-Space In-  
88 teractions Monitor (ASIM) that was launched on April 2, 2018. Just during the first ten  
89 months of observations, ASIM has provided several unprecedented measurements. In this  
90 paper we will report examples of these extraordinary findings, many of which will be an-  
91 alyzed in more detail in separate papers. However, already now we can draw conclusions  
92 from these observations that have important implications for TGF research.

## 93 **2 Instruments and Data**

94 The ASIM payload consists of two main instruments, the Modular X- and Gamma-  
95 ray Sensor (MXGS) and the Modular Multi-spectral Imaging Array (MMIA). The ASIM  
96 mission and the two instruments are documented in detail in the three papers by *Neubert*  
97 *et al.* [2019b], *Østgaard et al.* [2019] and *Chanrion et al.* [2019]. Here we give a brief de-  
98 scription of the mission and the instruments. As ASIM is mounted on the International  
99 Space Station (ISS), which is orbiting at about 400 km altitude with a  $51.6^\circ$  inclination, it  
100 will reach the latitudes where particles from the radiation belt and auroral particles precip-  
101 itate in the upper atmosphere. While auroral observations and Lightning-induced Electron  
102 Precipitation (LEP) are among the secondary objectives of ASIM, its main mission is to  
103 measure lightning, TLEs and TGFs.

104 The MXGS has two detector layers for detecting X- and gamma-rays. The MXGS  
105 Low-Energy Detector (LED) consists of pixelated (16384 pixels) Cadmium-Zinc-Telluride  
106 (CZT) detector crystals that detect photons with energies from 20 to 400 keV. Due to  
107 noise, the operational lower energy threshold is about 50 keV. The geometric area of the  
108 LED is  $1024 \text{ cm}^2$  and the effective detection area at 100 keV is  $\sim 400 \text{ cm}^2$ . A hopper-  
109 shaped collimator defines the  $80^\circ \times 80^\circ$  fully coded field-of-view (FOV), while the total

110 partially coded FOV is  $138^\circ \times 138^\circ$  which covers the full Earth size from the ISS. A coded  
111 mask provides the imaging capability of the MXGS LED. The mask pattern is an 8x8 Per-  
112 fect Binary Array of square-formed pixels, 54% open holes and 46% closed by 46.2 mm  
113  $\times$  46.2 mm  $\times$  1 mm Tungsten plates. For more details about the coded mask structure we  
114 refer to *Østgaard et al.* [2019]. The mask assembly is mounted over the aperture at the top  
115 of the hopper. The hopper walls are made of Aluminum (3 mm) and Tungsten (0.1 mm)  
116 and provides a good shielding up to 60 keV photons, which is the peak of Cosmic Diffuse  
117 X-ray Background. The mask is covered with a Kapton foil that stops electrons with en-  
118 ergies up to 200 keV but allows photons down to 15 keV to enter the detector. From the  
119 penumbra pattern created by the flux of photons from a distant point source, their direc-  
120 tion of arrival can be determined. The mask structure supports a weak radioactive source  
121 ( $^{109}\text{Cd}$ ), which is used for the in-flight calibration of the LED. Temporal resolution of  
122 the LED is about 1  $\mu\text{s}$  with a dead-time of about 1.4  $\mu\text{s}$ . The LED only operates during  
123 night-time.

124 The MXGS High Energy Detector (HED) comprises 12 Bismuth-Germanium-Oxide  
125 (BGO) detector bars each coupled to a photomultiplier tube (PMT). The geometric de-  
126 tector area of HED is 900  $\text{cm}^2$  and is sensitive to photons with energies from 300 keV  
127 to  $>30$  MeV. The effective detection area for HED is  $\sim 650 \text{ cm}^2$  at 1 MeV. The HED is  
128 mounted behind the LED and effectively shields the LED against radiation coming through  
129 the rear of the assembly. Three weak  $^{22}\text{Na}$  radioactive sources are mounted in between  
130 the CZT detector plane and the BGO array. These sources are used to perform in-flight  
131 calibration of the BGO detectors. The FOV of the HED is  $4\pi$  and it is sensitive to bright  
132 TGFs up to at least 800 km from sub-satellite point. Temporal resolution of the HED is  
133 28.7 ns with a dead-time of about 550 ns for detection by the same PMT/BGO detector  
134 module. There is no effective dead time for detection by a different detector module. The  
135 HED operates during day and night, but is switched off during passage through the South  
136 Atlantic Anomaly, in order to protect the PMTs from aging and degradation due to high  
137 particle fluxes.

138 The Modular Multispectral Imaging Array (MMIA) includes two cameras imaging  
139 in 337.0 nm and 777.4 nm, at up to 12 frames per second, and three high-speed photome-  
140 ters at 337.0 nm (bandwidth 5 nm), 180-240 nm and 777.4 nm (bandwidth 4 nm) with  
141 a 100 kHz sampling rate. The 777.4 nm emissions are from atomic oxygen and used for  
142 detecting lightning. As emissions in the Lyman-Birge-Hofmann (LBH) UV band (180-

143 240 nm) will be absorbed by molecular oxygen this band will be most sensitive to high  
144 altitude phenomena such as TLEs. The 337.0 nm (N<sub>2</sub>P) will be most sensitive to lightning  
145 but will also see weak signals from TLEs. The FOV of the cameras and the two photome-  
146 ters are square with 80° diagonal, while the UV photometer FOV is circular with 80° full  
147 cone angle. The MMIA only operates during night time.

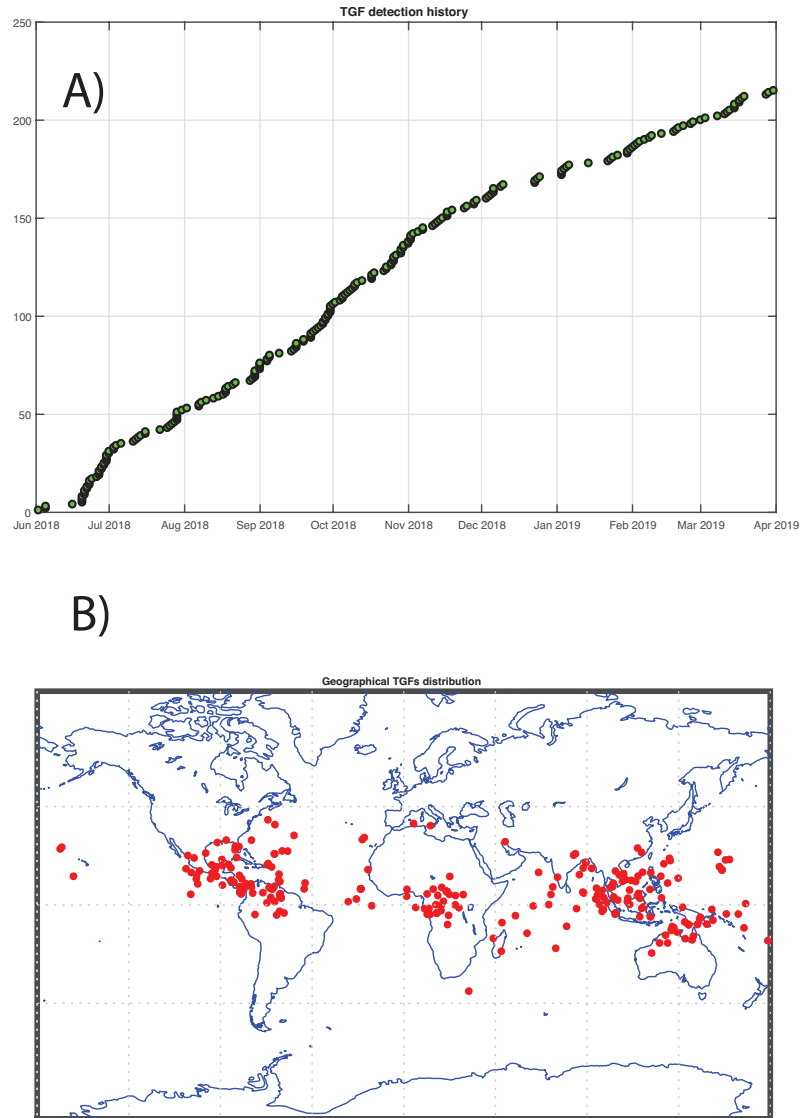
148 The two instruments, MMIA and MXGS, constitute a triggered system. The MXGS  
149 has four (adjustable) trigger windows with default settings of 300  $\mu$ s, 1 ms, 3 ms and  
150 25 ms. When the count rate in one of these trigger windows is above a certain level of  
151 background variations a 2-second string of data is captured and telemetered to ground.  
152 The trigger levels are set such that we receive about 100 false triggers per day. The MXGS  
153 sends a cross trigger signal to MMIA that will also capture 2 seconds of data. The MMIA  
154 also triggers on a certain (adjustable) level for the digital signal of the photometers and  
155 sends a cross-trigger to MXGS. This cross-trigger system allows us to capture optical sig-  
156 nals for each TGF (observed during night-time) and also capture MXGS measurements  
157 during all lightning and TLE events.

158 From launch to April 1, 2019 the two instruments have  $\pm 80 \mu$ s relative timing ac-  
159 curacy and not  $\pm 5 \mu$ s as intended. This is due to a drift term in the relative timing that  
160 varies from 0  $\mu$ s to 160  $\mu$ s and is different for every trigger. It arises due to an uncer-  
161 tainty in the time-stamping of the MMIA photometer samples in the science data relative  
162 to the Time Correlation Pulses (TCPs), which go to both instruments to ensure the rela-  
163 tive timing accuracy, unlike MXGS where each photon is time-stamped with an accuracy  
164 of  $\sim 1 \mu$ s relative to the TCPs. Fortunately, there is a register in the MMIA Data Process-  
165 ing Unit (DPU) firmware which can be read by the software and put into the science data  
166 to resolve the uncertainty. This required an upgrade of the onboard software and was im-  
167 plemented in March 2019, and after this time the relative timing accuracy is  $\pm 5 \mu$ s for all  
168 triggered events. Before March 2019, we were able to identify the drift term for only a  
169 few events.

### 170 **3 Results and Discussion**

171 Figure 1 gives an overview of the 217 TGFs detected by ASIM during the first ten  
172 months in operation (June 2, 2018 to April 1, 2019). The detection rate (Figure 1A) is  
173 about 0.7 TGF per day. This is lower than reported by other missions (RHESSI, AG-

174 ILE and Fermi) and is due to the high inclination ( $51.6^\circ$ ) of the ISS, which means that  
175 it spends more time over areas with low or no lightning activity. Figure 1B shows the ge-  
176 ographic locations of the TGFs, which are in good agreement with earlier observations  
177 [Smith *et al.*, 2005; Briggs *et al.*, 2013; Marisaldi *et al.*, 2014].



178 **Figure 1.** A) The cumulative distribution of the observed number of TGFs versus time B) Geographic  
179 location of the TGFs.



### 3.1 Fluence and duration

With the verification algorithm developed for MXGS HED we can identify TGFs with less than 10 counts (Figure 2A) and duration less than 20  $\mu\text{s}$  (Figure 2B). Although the fluence distribution has a maximum around 30-60 counts, there are more than 60 TGFs observed during the first ten months with more than 100 counts in HED. As will be shown, ASIM has >10 times better detection capability than other missions that currently observe TGFs. This is due to two factors: 1) ASIM has a larger effective detection area and 2) ISS flies at an altitude ( $\sim 400$  km) significantly lower than the other missions.

In order to compare TGF duration with other missions, we have chosen to present the duration as  $t_{50}$  (the time from 25% to 75% of the counts) and  $t_{90}$  (the time from 5% to 95% of the counts). From Figure 2B it can be seen that  $t_{90}$  distribution has a maximum between 60  $\mu\text{s}$  and 120  $\mu\text{s}$ . The value of the  $t_{50}$  distribution has a maximum in the 20-40  $\mu\text{s}$  bin and about 50% have  $t_{50}$  between 20-60  $\mu\text{s}$ , whilst the  $t_{50}$  median is 45.5  $\mu\text{s}$ . This is shorter than the  $t_{50}$ -maximum between 50  $\mu\text{s}$  and 100  $\mu\text{s}$  reported by Fermi when observing photons >300 keV [Connaughton *et al.*, 2013], which is the same energy range we have used. It should be mentioned that they reported a subset of TGFs with World Wide Lightning Location Network (WWLLN) matches, that were found to be among the shorter part of the distribution. For a larger distribution of TGF (423) (not only WWLLN matches) Briggs *et al.* [2013] reported  $t_{50}$  and  $t_{90}$  maxima at 100-150  $\mu\text{s}$  and 150-300  $\mu\text{s}$ , respectively. Due to the better detection capability of ASIM we are able to present a more complete distribution of TGF duration, and the result indicates that TGFs are in general shorter than previously reported from space observations. For very strong and short TGFs, the MXGS HED will be saturated, which means that we miss counts in the middle of the TGF and the  $t_{50}$  will be overestimated. Consequently, the  $t_{50}$  distribution could have a maximum even shorter than shown here. Our  $t_{50}$  distribution is consistent with the  $t_{50}$  maximum in the 0-50  $\mu\text{s}$  bin reported by Marisaldi *et al.* [2015], but our median value of 45.5  $\mu\text{s}$  is significantly shorter than their value of 86  $\mu\text{s}$ . Both Marisaldi *et al.* [2014] and Briggs *et al.* [2013] recognized that their measurements were limited by instrumental dead time, and that the TGF duration distribution most likely should extend to shorter timescales. From ground-based observations of high energy photons associated with lightning strokes it has been reported durations from  $\sim 300$   $\mu\text{s}$  [Dwyer *et al.*, 2004; Hare *et al.*, 2016] down to six <2  $\mu\text{s}$  pulses over 16  $\mu\text{s}$  [Tran *et al.*, 2015] and <10  $\mu\text{s}$  pulses for hun-

212 dreds of microseconds [Abbasi *et al.*, 2018]. We emphasize that our comparison with other  
213 TGF duration distributions only applies to observations from space.

### 216 **3.2 The first unique observations by ASIM**

217 During its first ten months in operation ASIM has already provided what can be  
218 termed "ASIM firsts". This is partly due to the better detection capability of MXGS and  
219 its imaging capability, but more importantly the simultaneous measurements of gamma-  
220 rays from TGF and optical signals from lightning and TLEs.

#### 221 **3.2.1 Simultaneous TGF observation from two platforms**

222 Already after 20 days in operation, on June 21, 2018, ASIM MXGS HED and Fermi  
223 Gamma-ray Burst Monitor (GBM) detected the same TGF over central Africa. Simulta-  
224 neous measurements of the same TGFs have previously been reported [Gjesteland *et al.*,  
225 2016] but never published due to the very low counting statistics. The event we report  
226 here has good counting statistics in both Fermi GBM BGO and ASIM MXGS HED and  
227 is shown in Figure 3. As can be seen in the Fermi GBM BGO measurements (Figure 3C  
228 and 3D) only the last pulse with 13 counts passed their verification algorithm and could  
229 be classified as TGF. A lightning stroke detected by the World Wide Lightning Location  
230 Network (WWLLN) was observed 13  $\mu$ s before this TGF was detected by Fermi. How-  
231 ever, when lined up with the ASIM data (Figure 3A and 3B) the 6 counts in the Fermi  
232 GBM BGO detectors  $\sim$ 2 ms earlier were also part of a pulsed TGF. For these two pulses  
233 ASIM detected 138 and 130 counts, respectively, and also revealed at least 3 smaller pulses  
234 in between. The last "double" pulse detected by ASIM MXGS HED at  $t = 0$  is only  
235 one pulse. The count rate is too high for HED to detect all the photons and it is miss-  
236 ing counts in the middle of the pulse. For the entire TGF event ASIM detected 393 counts  
237 compared with the  $\sim$ 20 detected by Fermi, a factor of 20 better detection capability. It  
238 should be mentioned that the nadir angle and distance to WWLLN location were  $8^\circ$  and  
239 407 km for ASIM and  $38^\circ$  and 685 km for Fermi. These observations reveals that there  
240 are indeed more structures in a TGF than one would conclude from the Fermi measure-  
241 ments alone. The two main pulses were 2 ms apart and the three small pulses in between  
242 were separated by 400-600  $\mu$ s. This time separation could be consistent with leader steps,  
243 but it definitely indicates that there is a series of pulses. We also want to point out that  
244  
245  
246  
247  
248

249 the WWLLN detection was simultaneous with the last pulse, in agreement with the ten-  
 250 dency that was reported by *Mezentsev et al.* [2016].

251 Two more simultaneous observations of TGFs from the two platforms have been  
 252 identified since then (not shown), which also show large differences in detection capabil-  
 253 ity. Part of this difference can be explained by ASIM MXGS BGO larger effective de-  
 254 tection area of 650 cm<sup>2</sup> compared to 320 cm<sup>2</sup> of Fermi GBM BGO and that ISS is fly-  
 255 ing at ~400 km altitude while Fermi is at ~550 km. Other factors, like beaming direction  
 256 and size of the cone angle, that can explain the differences in detected counts for these 3  
 257 events will be analyzed in detail in a separate paper, using all available supporting data.

### 258 **3.2.2 Imaging of a TGF by ASIM**

259 The pixelated detector layer of LED combined with the coded mask provides the  
 260 imaging capability of MXGS. Figure 4 shows the imaging results for a bright TGF ob-  
 261 served on November 2, 2018 with 316 counts in HED and 171 counts in LED (Figure  
 262 4A). We ran the imaging software with the 96 useful LED counts above channel 171 and  
 263 below channel 618 (62-237 keV) in order to maximize the Tungsten pixel opacity. Figure  
 264 4B shows the imaging map of the TGF, with X- and Y axes displaying the offsets with  
 265 respect to the MXGS FOV centre in degrees. Color scale shows Poisson Maximum Likeli-  
 266 hood Function (MLF) defined as

$$\log \left[ \frac{P(S > 0)}{P(S = 0)} \right] \quad (1)$$

267 where S is signal and indicates the location probability (P) on a logarithmic scale. P(S =  
 268 0) is the Poisson probability for the counts "not compatible" with a given position. P(S>0)  
 269 is the Poisson probability for counts compatible with a given position. In this case a unique  
 270 solution was found with a MLF = 9.2. The secondary imaging artifacts have a MLF <  
 271 4.5 which is a factor of 10 000 times less probable location with respect to the solution  
 272 adopted. The TGF footprint position is displayed in Figure 4C (green dot) in southern  
 273 Venezuela. Lightning events from the WWLLN are indicated by the small blue and red  
 274 dots. The continuous black line is the ISS position and flight direction from the centre to  
 275 the northeast. Figure 4D shows a more detailed map of the TGF position and lightning  
 276 data restricted to 100 km × 100 km square. With a distance to source of 418.6 km and  
 277 a source location error of 1.58° the one sigma error is 11.5 km, which is marked as the  
 278 inner ellipse surrounding the TGF position. The external ellipse is the two sigma surface

279 error radius. Blue dot is the lightning cluster centre and the orange dot is the location of  
280 the lightning from the MMIA 777.4 nm camera surrounded by the error surfaces at one  
281 and two sigma. It can be seen that the two images intercept at each ones one-sigma circle.  
282 During the first ten months of operation, we have 29 TGF observations where the count  
283 rate in LED is large enough to determine a unique TGF location, independent of other  
284 measurements of lightning activity. A dedicated paper with the first ASIM Imaging Cata-  
285 logue will follow this publication.

### 293 **3.2.3 TGF and Elve produced by the same lightning flash**

294 As reported by *Neubert et al.* [2019a], ASIM detected for the first time that a TGF  
295 and an Elve were powered by the same lightning stroke. Here we show another clear ex-  
296 ample observed on February 8, 2019 of a TGF and an Elve produced by the same light-  
297 ning stroke (Figure 5). This was a short ( $\sim 40 \mu\text{s}$ ) but fairly bright TGF (69 and 78 counts  
298 in HED and LED, respectively (Figure 5A), where also data from the three photometers  
299 of MMIA were available. This is an event that also illustrates that, for TGFs with very  
300 high flux, the HED was missing counts in the middle of the TGF. The counts marked  
301 with yellow dots in Figure 5B are all detected on the tail of previous signals and the de-  
302 tector is saturated. In Figure 5C one can see an abrupt increase in all the optical channels  
303 simultaneously with the onset of the TGF (Figure 5D). While the 337 nm (blue line) and  
304 777 nm (red line) channels show optical pulses from the lightning, the UV emissions (ma-  
305 genta line) are from the Elve [*Neubert et al.*, 2019a]. These emissions are excited in the  
306 ionosphere by the electromagnetic waves generated at the onset of the lightning current.  
307 It should be noted that the light curves of the lightning in the 337.0 nm and 777.4 nm  
308 (Figure 5C) are affected by scattering in the cloud implying that the rise time is not ex-  
309 actly the rise time of the current pulse. However, the UV emissions from the Elve should  
310 not be affected by scattering, but will be slightly broadened due to the fast expansion of  
311 the rings in the Elve. Even though the rise times of the optical signal from the current  
312 and UV emissions excited by the electromagnetic wave can be steeper than seen by the  
313 photometers, we believe that the onsets of the signals can be determined within a few  
314 tens of microseconds. The rise time, from onset to peak, of the UV pulse is about  $100 \mu\text{s}$   
315 while the optical pulse has a rise time of  $250 \mu\text{s}$ . The relative timing uncertainty between  
316 MXGS and MMIA is, in this case,  $\pm 80 \mu\text{s}$ . This indicates that the current pulse that gen-  
317 erates the optical pulse has its onset simultaneous with the TGF (within the relative timing

318 uncertainty) but develops and reaches its peak intensity after the TGF. For the case re-  
319 ported by *Neubert et al.* [2019a] it was concluded that the onset of the TGF was before the  
320 onset of the current pulse, because, in that case, the relative timing uncertainty was only  
321  $\pm 5 \mu\text{s}$  and the TGF preceded the onset of the Elve by  $10 \mu\text{s}$ . Our observations are the  
322 first that support the theoretical considerations [*Cummer et al.*, 2014; *Lyu et al.*, 2015] and  
323 modeling predictions [*Liu et al.*, 2017] that the lightning stroke that produces a TGF can  
324 also produce an Elve. During the first ten months we have two simultaneous observations  
325 of TGFs and Elves to within  $\pm 80 \mu\text{s}$  and  $\pm 5 \mu\text{s}$ , respectively, and two events where the  
326 Elve and the TGF are from the same lightning flash. We also want to point out that there  
327 is a weak increase  $\sim 0.5\text{-}1 \text{ ms}$ , before the TGF is produced, in the two MMIA lightning  
328 channels, which is indicative of lightning leader activity.

### 335 **3.2.4 The sequence of TGF and main optical lightning pulse**

336 Although we can observe TGF both day and night, the photometers can only be op-  
337 erated during night time. Consequently, out of the 217 TGF we have observed during the  
338 first ten months, there are optical data for 94 of them. A consistent feature in a majority  
339 of these observations is that the TGF is observed during or at the end of a weak increase  
340 in the 337.0 nm and 777.4 nm channels, and before or at the onset of the main optical  
341 pulse. Figure 6A and 6B show the measurements from June 30, 2018 and October 29,  
342 2018, where the onsets of TGFs are simultaneous with the onsets of the current pulses as  
343 seen by the two lightning channels. In both cases there is a weak increase in the lightning  
344 channels about 1-2 ms before the TGF. This is most pronounced in the 337.0 nm chan-  
345 nel. We interpret this as a signature of an increased current in the leader channel prob-  
346 ably related to the propagation of the ascending leader. However, supportive data from  
347 radio (Low Frequency (LF) and/or Very High Frequency (VHF)) are needed to address  
348 this more accurately. The short TGFs ( $\sim 150 \mu\text{s}$  and  $\sim 70 \mu\text{s}$ ) are produced just before the  
349 main 2-3 ms long optical pulses are seen. This optical pulse indicates that a large current  
350 pulse flows through the leader channel. Figure 6C shows the event on November 2, 2018,  
351 where we also see the weaker increase in the lightning channels, indicative of the propa-  
352 gating leader before the larger signal of a current pulse. However, in this case the TGF is  
353 produced during the leader propagation about  $500 \mu\text{s}$  before the onset of a current pulse.  
354 This TGF has a longer duration than the first two. For all these examples the relative tim-  
355 ing uncertainty between MXGS and MMIA is  $\pm 80 \mu\text{s}$ .

362 Of the 94 TGF events where also the MMIA photometers were operated we can  
363 identify an optical pulse associated with the TGF for 58 of them with a relative timing ac-  
364 curacy of  $\pm 80 \mu\text{s}$ . For 17 events no optical pulse could be identified, most likely because  
365 the lightning stroke was outside the FOV of the photometers. There are 19 events with  
366 more than one optical pulse and more analysis and supporting data are needed to identify  
367 if any of these pulses are related to the TGF. In Figure 7 we present the distribution of  
368 the  $\Delta t$  between the onset of the TGF and the onset of the optical pulse for the 58 events.  
369 The onset of the TGF can be determined with a precision of about  $10 \mu\text{s}$ , while the on-  
370 set of the main optical pulse is typically determined with a few tens of  $\mu\text{s}$  precision. The  
371 uncertainty of the relative timing between the two onsets is therefore dominated by the  
372 relative timing uncertainty between the two instruments of  $\pm 80 \mu\text{s}$ . It can be seen that 49  
373 of these 58 events (84%) cluster in a very narrow  $\Delta t$  distribution showing that the TGFs  
374 are produced  $0\text{-}320 \mu\text{s}$  (center of bin)  $\pm 80 \mu\text{s}$  before (23 events) or at (26 events) the on-  
375 set of a large current pulse that flows through the leader channel. Another 6 TGFs (10%)  
376 have their onset up to 1 ms before the onset of the optical pulse. This is a fairly strong  
377 statistical result revealing that TGFs in general are produced just at or before the onset of  
378 a large current pulse. As shown in the three examples in Figure 6 the current pulses last  
379 for milliseconds, while the TGFs last for only a few hundred microseconds.

380 Like the three examples shown in Figure 6 all the 49 TGFs are seen during or at the  
381 end of a weak increase in the MMIA lightning channels starting a few milliseconds before  
382 the main current pulse. We interpret this as a signature of a propagating leader and it im-  
383 plies that the leader plays an essential role in producing TGFs. As the leader propagates,  
384 the electric field ahead of the leader increases and reaches a level where it can acceler-  
385 ate and multiply free electrons [Moss *et al.*, 2006; Celestin and Pasko, 2011; Babich *et al.*,  
386 2014, 2015] and even further by the RREA process [Gurevich *et al.*, 1992] or in avalanche  
387 of RREAs as proposed in the feedback mechanism [Dwyer, 2008]. Supportive data are  
388 needed to determine the exact production mechanism. Of these 49 TGFs, 23 are produced  
389 more than  $80 \mu\text{s}$  before the current pulse, which indicates that these are produced during  
390 the leader propagation and that the leader could still propagate after the TGF is produced,  
391 consistent with the three events reported by Cummer *et al.* [2015].

392 The large optical pulse after the TGF indicates that a large current pulse comes af-  
393 ter the TGF, and in many cases there is only one such pulse. The optical pulse can only  
394 be the result of a large current through the leader channel. This means that the leader

395 that produced the TGF has to connect to some conductive channels in order to make a  
396 large current pulse. Here, we will suggest two possible scenarios for this to occur. In both  
397 cases we consider that some other conductive channels have to form, either inside or out  
398 of the lower negative charge region or, inside or out of the upper positive charge region.  
399 In the first case the positive lower end of the leader will connect to the negative end of  
400 conductive channels that have formed in the lower negative charge region. In the other  
401 case the upper negative end of the leader will connect to the positive end of a conductive  
402 channel that comes down from or develops inside the upper positive charge region. To  
403 explore whether any of these scenarios really occur, one would need radio measurements  
404 (LF and/or VHF), and since ASIM is just in the beginning of its mission, we foresee that  
405 we will obtain such measurements in the near future.

406 A few papers have reported that there is a current pulse from the TGF itself [*Cum-*  
407 *mer et al.*, 2011; *Pu et al.*, 2019]. The current carriers in this scenario are supposed to be  
408 the secondaries produced by the relativistic electrons [*Dwyer and Cummer*, 2013], which  
409 means that there is no heated conductive channel involved, and we would not expect to  
410 see an optical signal from the TGF produced current. Contrary to what is seen in the ma-  
411 jority of our events, the observations presented by *Cummer et al.* [2011], *Lyu et al.* [2015]  
412 and *Pu et al.* [2019] do not indicate any large current pulse after the TGF. Further inves-  
413 tigation are needed to explore whether both a current signal from the TGF itself and a  
414 large current through the leader which makes a strong optical pulse after the TGF are  
415 common when a TGF is produced. At this point we can only state that a large current  
416 pulse that makes a strong optical pulse is seen in the majority of the TGFs observed by  
417 ASIM and that the TGFs are produced  $0\text{-}320 \mu\text{s} \pm 80 \mu\text{s}$  before the onset of the current  
418 pulse we observe.

### 423 3.3 Other events

426 In addition to the observations presented in this paper, ASIM has detected a few Ter-  
427 restrial Electron Beams with duration of several milliseconds (the first event is presented  
428 in [*Sarria et al.*, 2019]) and a couple of X-ray-observations from Lightning-induced Elec-  
429 tron Precipitation. We have also detected many multi-pulse TGFs, typically separated by  
430 2 ms. In Figure 8 we show one example which is almost identical to the one reported in  
431 the discovery paper by *Fishman et al.* [1994] (number 1457 in their Figure 4).

## 4 Summary

In this paper we have presented some unprecedented observations obtained by ASIM during its first ten months in operation. These are:

- 1) Simultaneous TGFs observations by ASIM MXGS and Fermi GBM.
- 2) TGFs and Elves are seen from the same lightning flash.
- 3) The first imaging of TGFs.
- 4) The sequence of TGFs and optical signals.

From these findings we can summarize the following:

- 1) The distribution of duration, as determined by  $t_{50}$ , has a maximum in the 20-40  $\mu\text{s}$  range and a median of 45.5  $\mu\text{s}$ , which is significantly shorter than previously reported from space observations.
- 2) Due to the very good detection capability of ASIM, we have identified fine structures in TGFs that cannot be seen by other missions that currently observe TGFs.
- 3) From 94 events where both gamma-ray and optical measurements were available and with a relative timing accuracy of  $\pm 80 \mu\text{s}$  it is found that a majority of TGFs are produced during the upward propagation of a leader just before a large current pulse heats up the channel and emits a strong optical pulse. The onset of the TGFs precede the onset of the optical pulse by 0-320  $\mu\text{s}$  ( $\pm 80 \mu\text{s}$ ). More observations are needed to understand the system of conductive channels that are involved in order to make such a strong current pulse.

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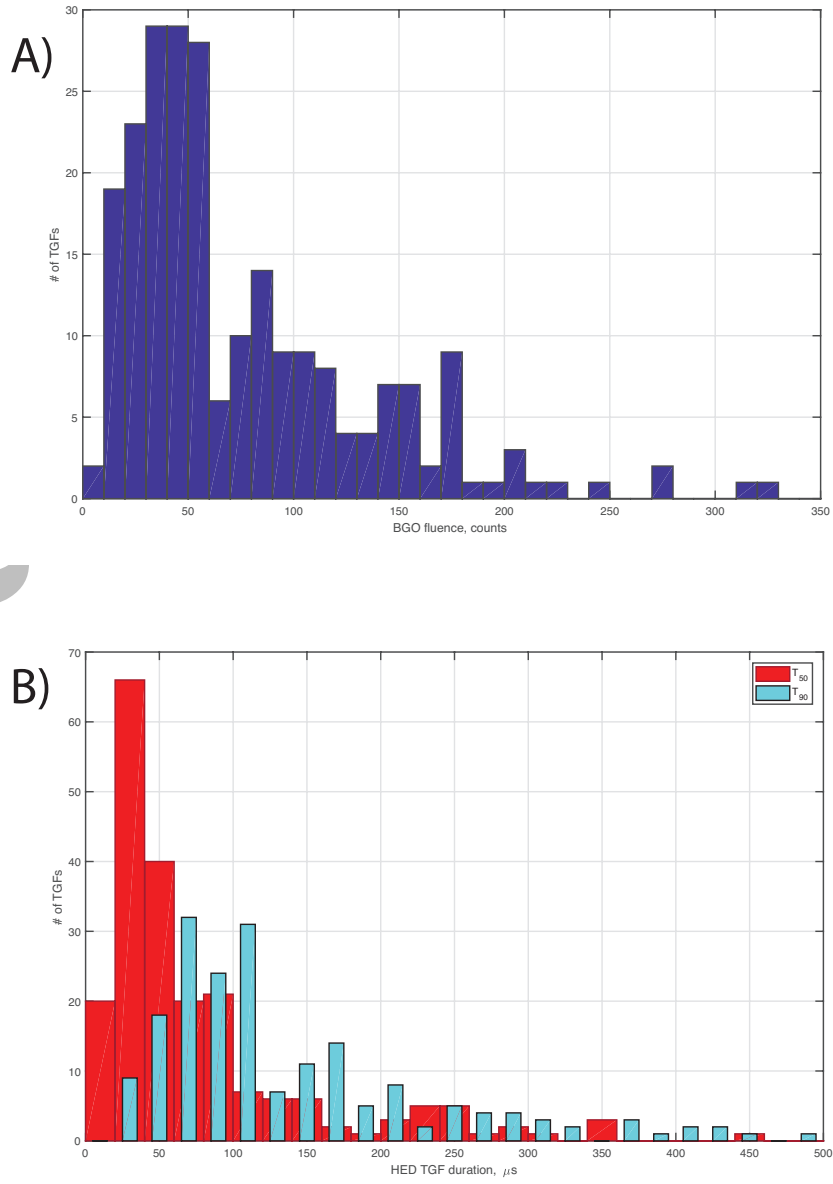
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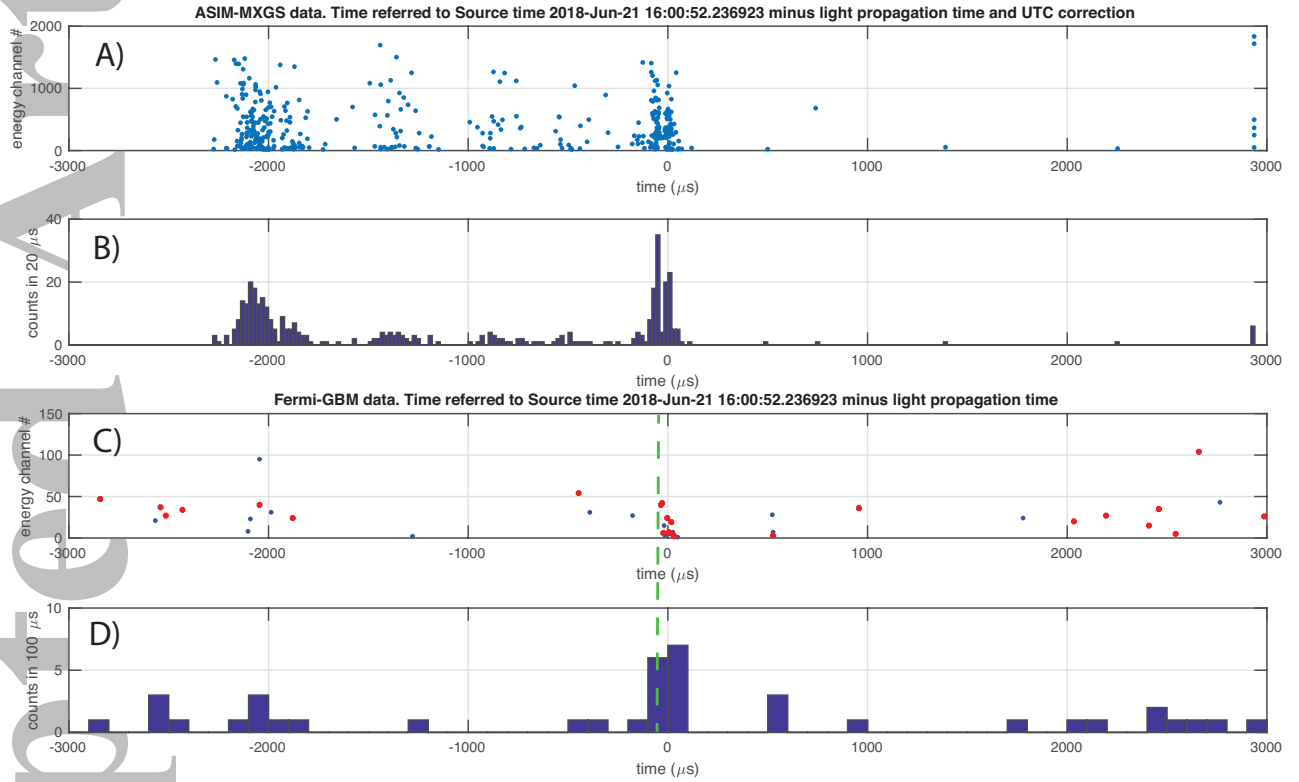
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**Figure 2.** A) Fluence distribution of TGF (in bins of 10 counts). B) Duration of TGFs from the HED data

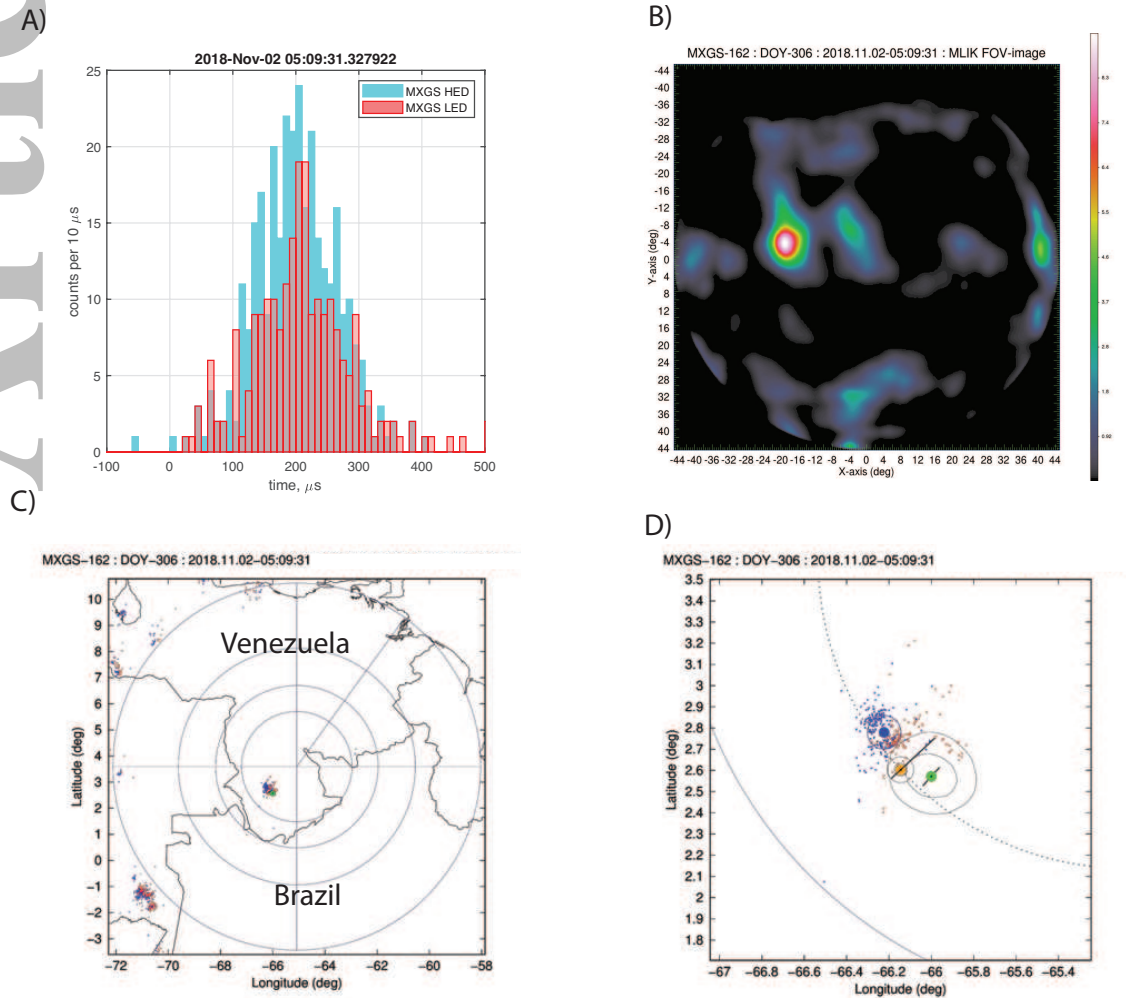
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defined as  $t_{50}$  and  $t_{90}$  in  $20 \mu\text{s}$  bins.

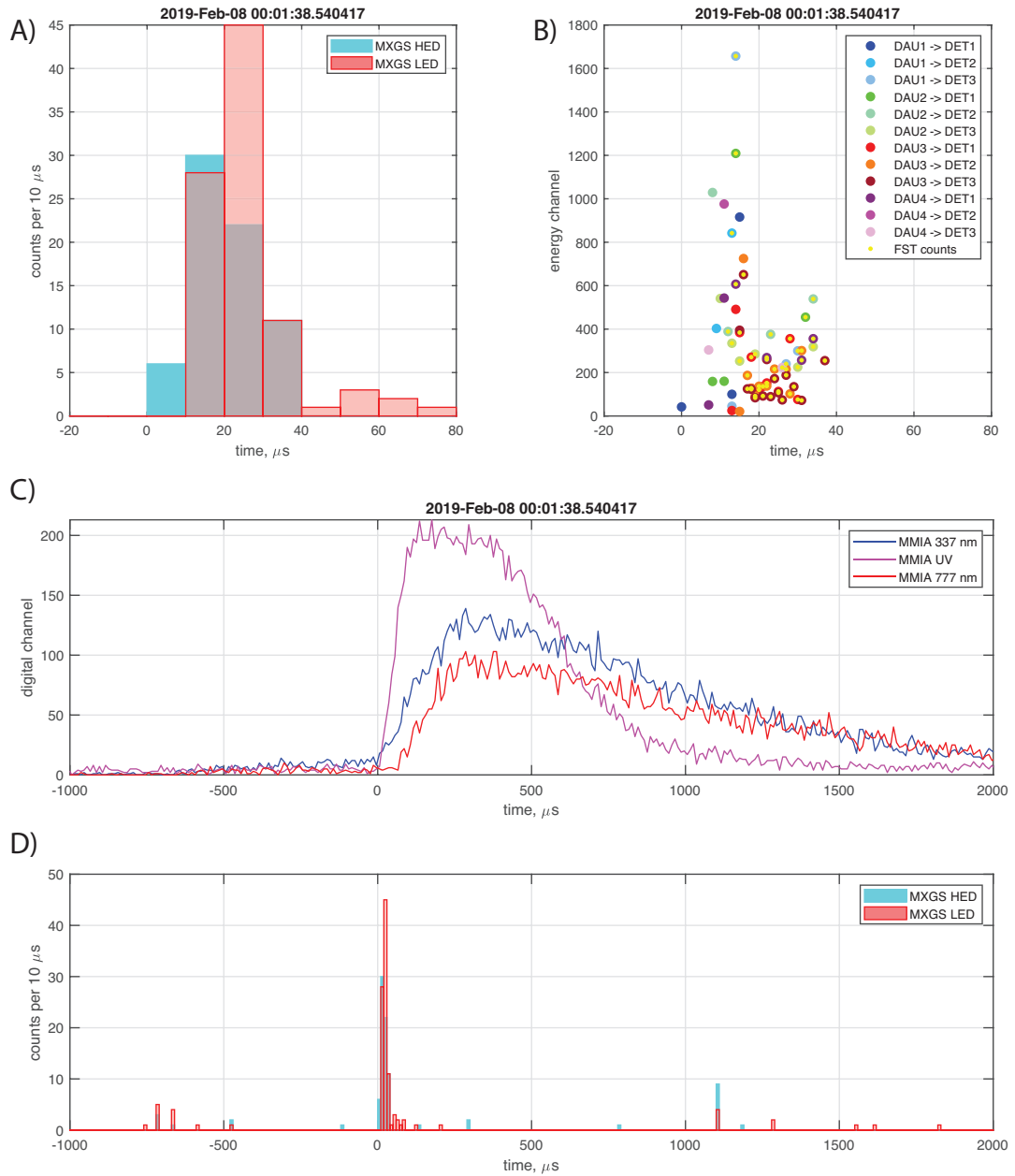




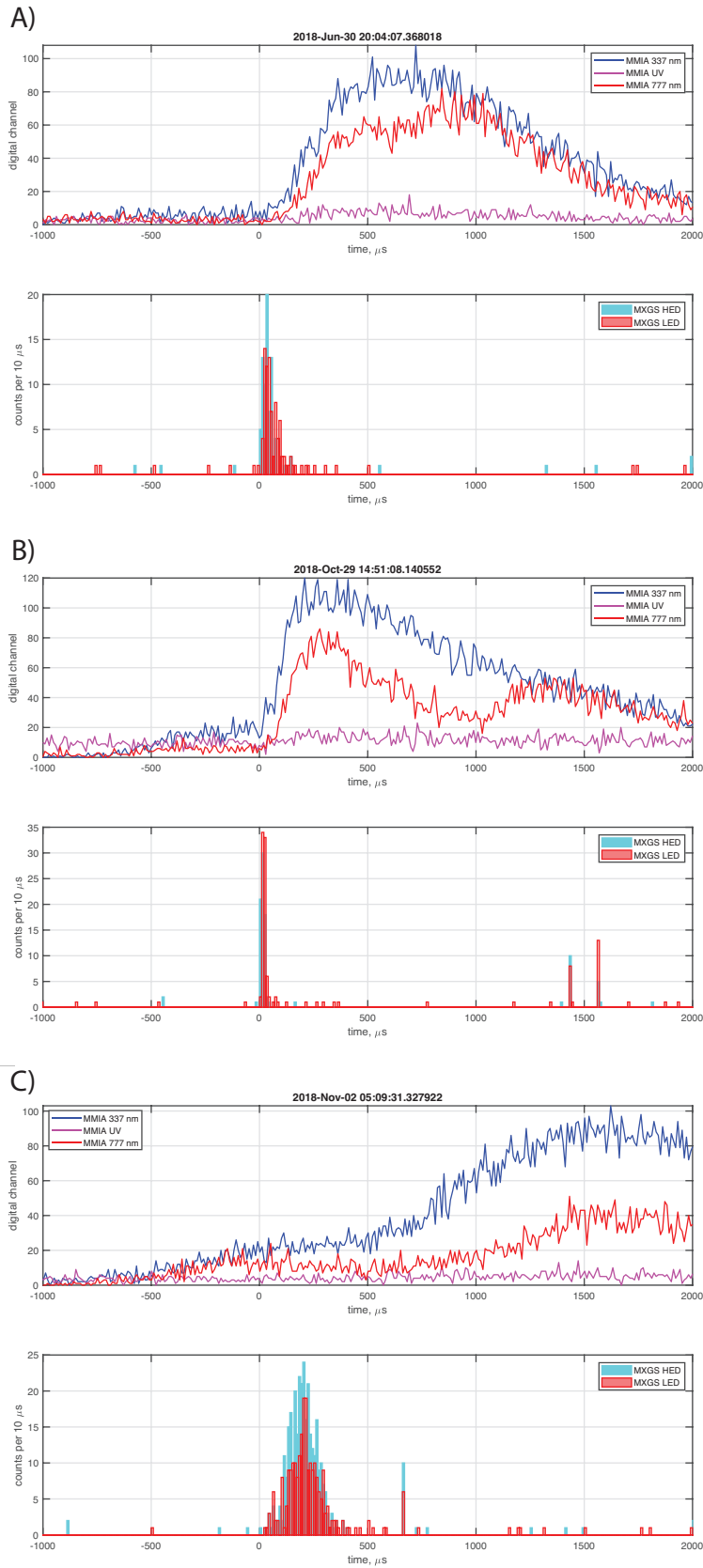
222 **Figure 3.** Simultaneous observations of a TGF over central Africa by ASIM and Fermi. A) ADC channel  
 223 versus time for MXGS HED. B) MXGS HED counts in 20  $\mu$ s bins. C) ADC channel versus time for Fermi  
 224 BGOs. Red is BGO 1 and blue BGO 2. D) Fermi GBM BGOs counts in 100  $\mu$ s bins. The green dashed line  
 225 in panel C and D is the time of a lightning stroke detected by the WWLLN and was found to be simultaneous  
 226 to within 13  $\mu$ s of the Fermi measurements, when propagation time is accounted for.



286 **Figure 4.** Imaging of a TGF observed November 2, 2018 at 05:09:31.327922 UT over Venezuela. A) The  
 287 light curve of the TGF in HED and LED. B) Imaging position in the FOV of the LED. C). The position of  
 288 TGF image on the map. D) A zoomed in view, where the green dot is the MXGS imaging position, the orange  
 289 dot is the MMIA imaging position and the small red and blue dots are the locations of the WWLLN detected  
 290 lightning activity within  $\pm 30$  minutes of the TGF. Red and blue dots are before and after the TGF, respec-  
 291 tively. The large blue dot is the centre of lightning activity. The small black circles indicate the one and two  
 292 sigma uncertainties of the location determined by the MXGS and MMIA data, respectively.



329 **Figure 5.** Simultaneous observation of a TGF and an Elve on February 8, 2019. A) MXGS HED (light  
 330 blue) and LED (red) counts in 10  $\mu\text{s}$  bins. B) ADC channel versus time for MXGS HED. Different colors  
 331 indicate different BGO bars and yellow dots are signals detected at the tail of previous signal. C) The MMIA  
 332 data, where 337.0 nm is in blue, UV (180-240 nm) is in magenta and 777.4 nm is in red. D) Same as panel A,  
 333 but on the same time line as MMIA. The relative timing uncertainty between MXGS and MMIA, in this case,  
 334 is  $\pm 80 \mu\text{s}$ .



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**Figure 6.** Three examples showing the sequence of a TGF and the optical pulses. A) Measurements from

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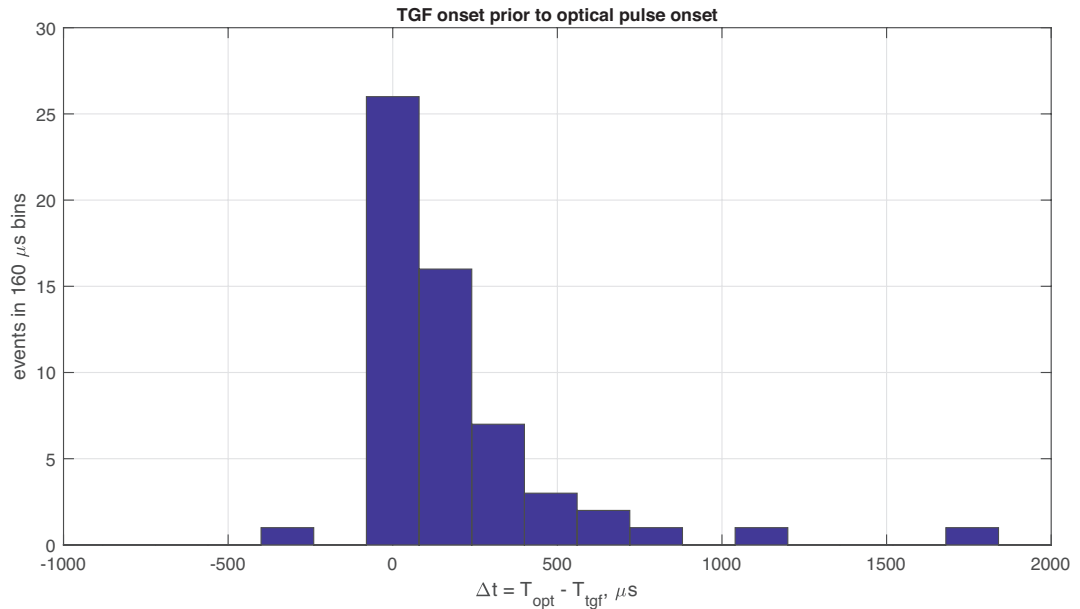
June 30, 2018: Upper panel: The MMIA data with 10  $\mu\text{s}$  resolution: 337.0 nm is in blue, UV (180-240 nm)

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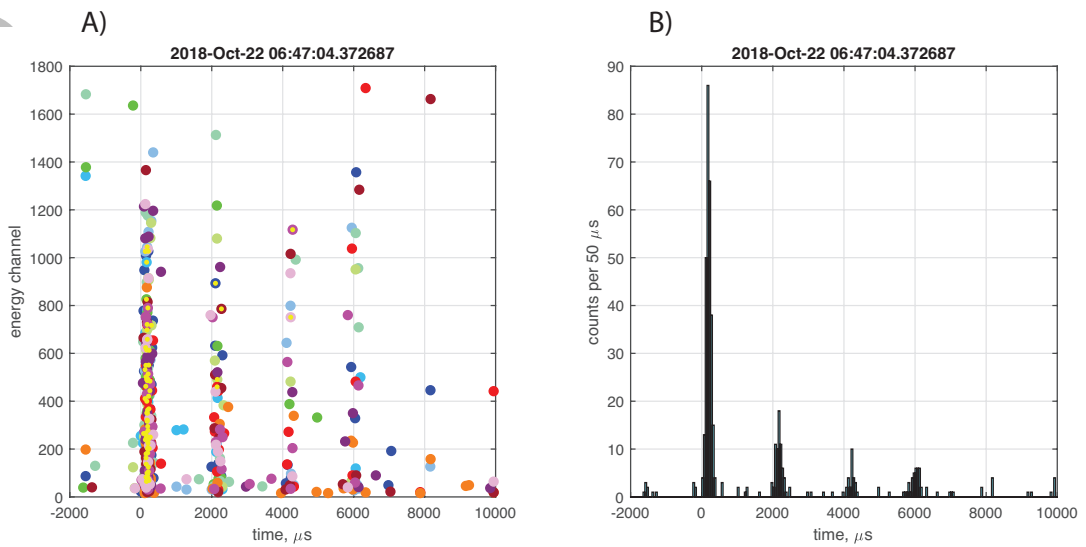
is in magenta and 777.4 nm is in red. Lower panel: The MXGS data in 10  $\mu\text{s}$  bins. HED in blue and LED in

359

red. B) Measurements from October 29, 2018, same format as panel A. C) Measurements from November 2,



419 **Figure 7.** Distribution of  $\Delta t$  between the onset of the TGF and the onset of the optical pulse for 58 TGF  
 420 events where the optical pulse could be identified. Bin size is 160  $\mu s$  consistent with the  $\pm 80 \mu s$  relative tim-  
 421 ing uncertainty between the two observations. Positive  $\Delta t$  means that the onset of the TGF is before the onset  
 422 of the optical pulse.



424 **Figure 8.** A multi-pulse TGF observed in HED on October 22 outside the West African Coast. A) ADC  
 425 channel versus time. B) counts in 50  $\mu s$  bins versus time.