Modeling and Mapping Terrestrial Gamma Ray Flashes

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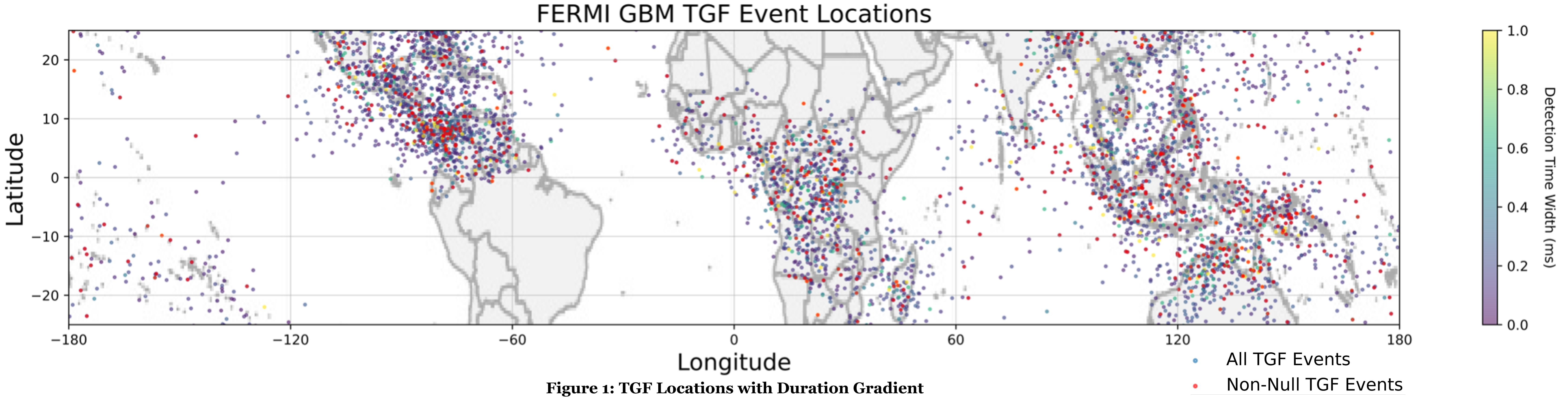

Figure 1: TGF Locations with Duration Gradient
The map presented above plots all TGF locations detected by Fermi's GBM since 2008. A color gradient is used to visually represent TGF event durations. The red locations are TGF events without a 'Null' designation.

Abstract

Given the lack of consensus about the processes governing the locations of Terrestrial Gamma Ray Flashes, we decided to find a way to predict global TGF locations. The goal of our project was to first create a map of TGF occurrences around the world from Fermi Gamma-Ray Monitor, and then to create a Monte Carlo simulation that could serve as a model to predict TGF locations based on observations from the Fermi Gamma-Ray Burst Monitor. We could then test the validity of our TGF map from the Monte Carlo simulation by comparing it to the real observations. However, we would need to create a set of conditions that must be satisfied in order to consider the Monte Carlo simulation and the TGF map. We also plan to use observations from the World Wide Lightning Location Network, as they would help fill in the gaps that the limitations of the Fermi satellite could not.

Brief Introduction to Terrestrial Gamma Ray Flashes (TGFs)

A Terrestrial Gamma-Ray Flash (TGF) is a burst of gamma rays produced in Earth's atmosphere. These gamma rays are thought to be generated by the relativistic runaway electron avalanche process (RREA) when a group of electrons in the atmosphere are driven to relativistic speed in the air by strong electromagnetic fields, leading to bremsstrahlung (braking) radiation. This occurs when a particle exceeds the speed of light in the medium it is traveling in. There is also another source of TGFs via a pathway sourced from cosmic rays hitting the upper atmosphere, colliding with electrons and accelerating them to relativistic speeds. This leads to an exponential growth as each accelerated electron leads to more accelerated electron. Following this acceleration, radiation is released in the form of gamma ray bursts, as the electrons exceed the speed of light in the atmosphere. Because lightning produces extremely strong electromagnetic fields, we can see that there is significant overlap in the location of TGFs and the frequency of lightning strikes in that area. However, the specific conditions which are more or less conducive to the TGF phenomenon are not entirely known. TGFs can also release positrons and neutrinos, but because the specific process has yet to be understood we can only rely on observation.

We can detect TGFs via Fermi Gamma-Ray Burst Monitor (FGBM), which uses a series of detectors to detect longitude, latitude, and duration of TGF events. However, there have only been limited observations in recent years, and there is quite a bit of work to be done in detecting and understanding TGFs.

Locating TGF Event Methodology

Our research project consisted of two elements: the first was to map Terrestrial Gamma-Ray Flashes (TGF) occurrences around the world and the second was to create a Monte Carlo simulation that would serve as a model to predict potential TGF locations based on contemporary knowledge related to TGFs.

Element One: To better understand TGF occurrences a map was created using Python and data offered by the National Aerospace and Space Administration (NASA). This map would function as a control to compare the results of the Monte Carlo simulation. This map places all of the recorded TGF occurrences, also known as trigger time events, over the past 13 years by their latitude and longitude. The data used to create the map was pulled from numerous open-source csv data tables provided by NASA's Gamma-ray Burst Monitor (GBM) aboard the Fermi Gamma-ray Space satellite. Of those data tables, the 'Offline Search' data table was used to create the primary map presented, as this data table presented 4135 trigger time events, the largest quantity offered. Along with this, the 'WWLLN Associations' data table was used to create the secondary map presented.

Element Two: Once a map was made, parameters were decided upon based on knowledge pertaining to TGF characteristics. Numerous research papers focussing on TGF findings were used as the foundation of our knowledge about TGF characteristics. These parameters serve as tests to constrain the results of the Monte Carlo simulations, producing a more accurate model of potential TGF event locations. Using results from the Monte Carlo simulations, a map would then be made using Python to reflect potential TGF event locations around the world.

Finally, the resulting parameter based map would be compared to the Fermi data based map and conclusions can be made about their similarities and dissimilarities.

Mapping and Analysis of FERMI TGF Data

FERMI GBM TGF Event Locations

Our TGF event map has a latitude range of ± 25 degrees centered at the equator along with the entire circumferential Earth longitude range. The data used to create this map, seen in Figure 1, was pulled exclusively from the NASA provided Offline Search Catalog[4]. The latitude, longitude, and altitude values were collected using the WGS84, or World Geodetic System, navigational standard. This data set consists of 4135 GBM-classified TGF events and include but are limited to the following parameters: longitude, latitude, altitude, the width of the discovery bin (i.e. duration), and trigger identification designation, among other parameters.

A color gradient corresponding with TGF event width is used to accentuate the short duration of TGF events. The colors range from purple, which is between 0 ms and 0.2 ms, turquoise, green, and yellow, which is between 0.8 ms and 1 ms. Data points with greater than a 1 ms width are present in the Offline Search Catalog, as GBM has a minimum integration time of 16 ms, but since the typical duration of a TGF is about 0.1 ms the presented gradient range was chosen[5]. This is supported by referencing Figure 1 where purple locations are among the most prevalent and Figure 2 where the vast majority of TGF events have low width values. Data points with a width greater than 1 ms are assigned yellow and are not omitted from the map.

The locations presented in red are 684 TGF events that are not designated with a 'Null' trigger identification, resulting in 83.45% of the TGF events recorded by GBM as such. A TGF event is given this designation if there are any missing or incomplete parameters associated with that event[4]. This designation does not discredit the validity of the reassociated TGF event but should be documented nonetheless.

TGF and Lightning Event Map Visual

A map of 1544 TGF and lightning association events is used to highlight the relationship between TGF occurrences detected by Fermi's GBM and potential lightning strike occurrences detected by the World Wide Lightning Network (WWLLN)[1]. The data used to create the map in Figure 3 was pulled from the NASA provided WWLLN Associations Table with the following parameters used: WWLLN Longitude, WWLLN Latitude, Fermi Longitude, and Fermi Latitude. Data from the WWLLN Associations Table present an average separation offset of 329.2 km between a TGF event and an associated lightning event along with an average time separation of 0.02 ms. This further supports the strong relationship between TGF and lightning events. GBM and Fermi remove background interference such as cosmic rays but there may still be about 1% contamination in the provided data[4].

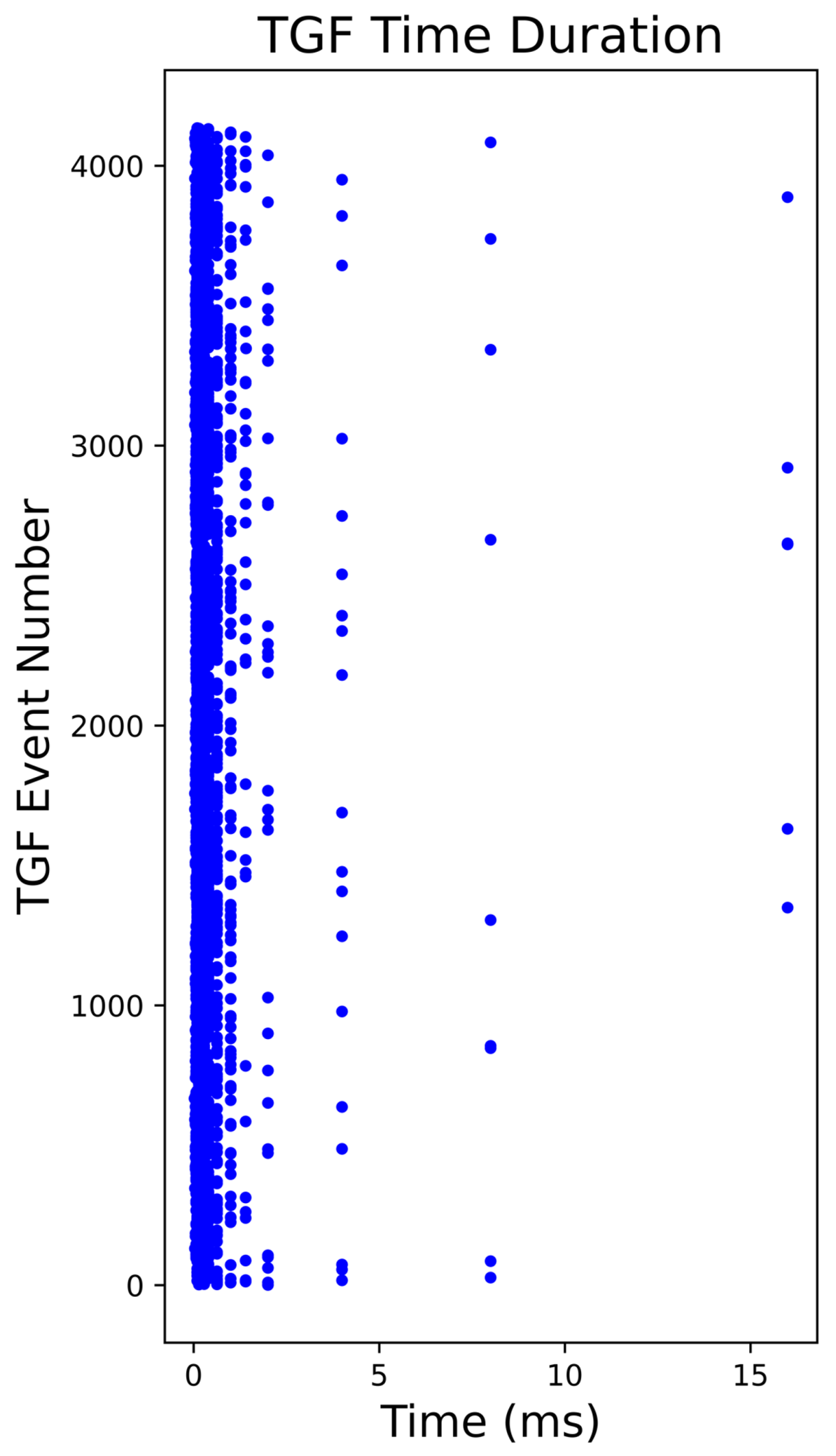

Figure 2: TGF Event Duration
The above scatter plot highlights the typical 0.1 ms duration of the TGF events recorded by GBM. Outlying data points can be attributed to background data collected during GBM's 16 ms detection window.

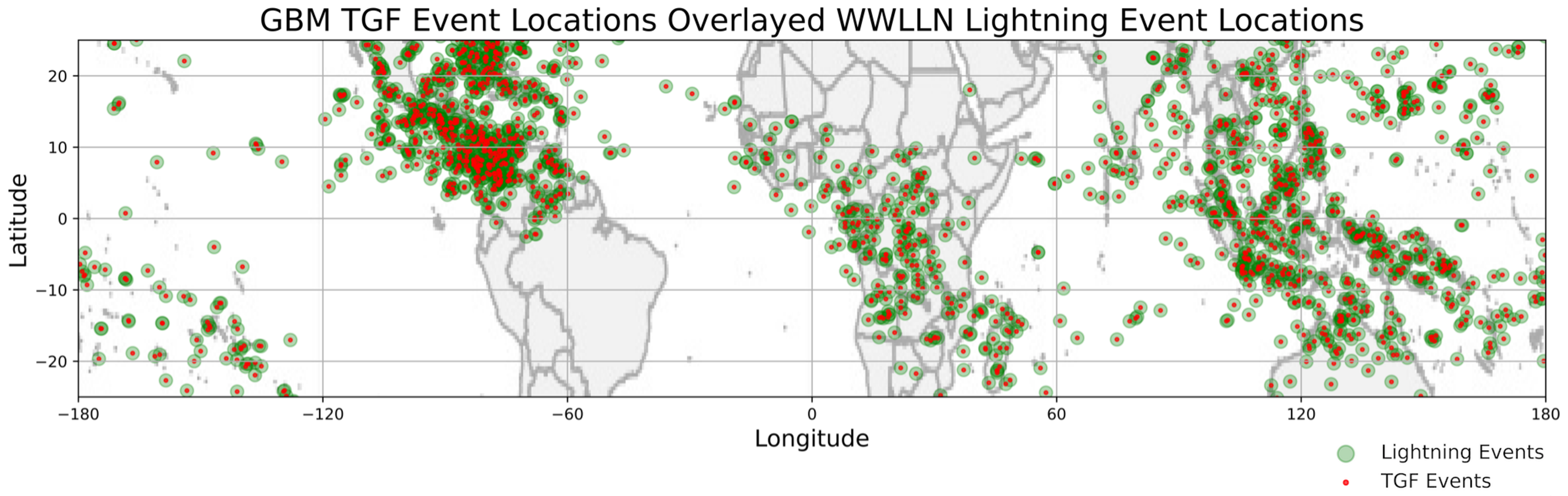

Figure 3: TGF - Lighting Event Locations
This map plots locations of TGF events and associated lightning events. On average, the distance between the two events is about ~329 km.

Modeling TGF Map

In order to model our Monte Carlo simulation for our TGF map, we had to consider some starting assumptions as well as some constraints to pass our randomized data through. A true model of TGF mapping could not be completed due to unforeseen complications in the energy constraints, that require a thorough understanding of bremsstrahlung radiation in the upper atmosphere. Research on this was carried out but without enough time to fully implement it in a meaningful way. This is discussed in the further research section.

Assumptions

- All TGFs are "detected" at sea level – to ensure consistent altitude data
- All TGF's are perpendicular to the ground/all detectors are pointing directly up – to remove inconsistency in TGF angle variance in detection
- All TGF's are detected on the ground and none in the ocean – to simplify our map data towards Fermi's detection methods
- All TGFs occur within 1 ms – as evidenced by data
- All TGFs occur during lightning storms
- Dead time, the time between a detector turning on and detecting, is negligible

Constraints

Altitude

- putting a limit on the potential altitudes using the researched theoretical altitudes that characterize a TGF. Problems in determination of this altitude limit were due to variance in data, rather than a theoretical limit.
    - Stanley et al. suggests an altitude range of 13.6km to 11.5km
    - Shao et al. suggests 10.5-14.1km
- This would be used as an additional parameter to add detail through a map axis. One problem is that there is no exact consensus as to whether TGF production is altitude or storm-event dependent (or both), so we had trouble figuring out our zero-point altitude and function that would evolve the TGF to the end-altitude. The lack of consensus is related to the complicated evolution of TGFs due to bremsstrahlung radiation, which is discussed in the further research section. The following constraint is a potential solution to this problem.

Lightning Frequency – TGFs occur primarily during lightning storms

- Simulated data would be constrained to areas that experience lightning consistently throughout the year. This is done by superimposing all lightning regions on the planet in one year on a map and labeling those areas as potential TGF regions
    - Allows us to add weights to areas with more or less gradient, effectively allowing us to find TGF probability in a given coordinate

Energy

- TGFs occur within a wide range of energies, between 200keV and 40MeV
    - This is difficult to predict because Bremsstrahlung radiation in TGFs at such an altitude are largely unknown – we would need the zero point energies in the lightning storm to be well defined as well as the function that evolves these through to end up at TGF-similar energies
    - Unfortunately, this is the main characteristic of a TGF that puts them in the gamma-range of frequencies. Our inability to fully implement this into our model meant that the data we get from our Monte Carlo simulation would not be sufficiently predictive. More time would be needed to decide on a working function that allows us to define a TGF. The previous two constraints concern mapping, while this one concerns the physics of a TGF itself.

Further Necessary Research - Determination of TGF Energy Function

To develop a meaningful model of a TGF map, we would need to know how Bremsstrahlung evolves the electrons, positrons in the atmosphere that lead to the production of a TGF. Bremsstrahlung is the 'braking' or 'accelerating' radiation that is emitted by a charged particle in the form of photons due to an electric field, usually created by another particle or nucleus. The angle and intensity of this radiation can be used to determine characteristics, such as the energy of the particle. Further research is needed to determine how to evolve a given TGF starting energy.

Known Possible Approximations

The energy range of a lightning storm is known as between 100 million to 1 billion volts, equivalent to 16peV to 160peV per strike. Knowing the average length of a lightning storm and the average number of strikes can give us a sufficiently accurate number of the average potential energy of a lightning storm.

A Lack of Consensus – Bremsstrahlung in the Atmosphere

The more difficult part is determining how this starting energy evolves to that of a TGF. A paper by Berger and Seltzer tells us that for a given energy, we can determine the Bremsstrahlung production spectrum if we know the probability that an electron emits a Bremsstrahlung photon, the temperature of the atmosphere in this location, the electron, positron and photon mean free paths, and our known end energy range. The paper conducted a Monte Carlo simulation to determine if their assumptions were sufficient but concluded in saying that neglecting the multiple Compton scattering of photons result in a significant change between predicted and measured Bremsstrahlung flux spectra. Factors such as incident electron beam angle, an inability to arrive at a particular decision for electron energies, and other limitations in electro-particle physics knowledge led them to conclude that given their analysis, they cannot develop with current physical knowledge, an accurate function for Bremsstrahlung radiation. Still, their tested energy ranges were not completely within those that yielded bremsstrahlung radiation that yielded TGF-like energies, but this was one of few papers we could find and understand on the topic. There is yet to be scientific consensus on this topic.

We would need a deeper and more fundamental background in particle physics, particularly the operations of Bremsstrahlung radiation in the atmosphere concerning electrons and positrons (the latter not outlined in the examined paper), in order to come to an educated decision about how to evolve TGF energies. What was initially an atmospheric physics model must be adapted to account for particle physics phenomena, requiring more time, education and research on the topic. This would then allow us to develop an accurate model and therefore a map about where TGFs should land on earth.

Conclusion

In conclusion, we were able to develop a map of TGF data as provided by NASA's Fermi GBM, completing the first part of our project. We successfully created a map of detected TGF locations, mapping event duration, lightning events and differentiating between TGFs with null trigger IDs. Through this, we were able to draw correlations between TGF occurrences and variables such as altitude, time and weather patterns. Given our assumptions about detectors being primarily on land, we were able to see that TGFs occurred primarily during lightning storms and that a majority of TGFs occurred before the theoretical 1ms. However, in the research phase of our second part, we ran into problems in deciding our third and last constraint on our monte carlo simulation that proved difficult to overcome within the allotted time.

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