

The Frequency of Terrestrial Gamma-ray Flash Electron Beam Observations

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Abstract

Terrestrial gamma-ray flashes (TGFs) are brief bursts of gamma-rays detected by satellites. Electrons associated with TGFs are also sometimes observed, though much less frequently as electrons are confined into narrow beams by the geomagnetic field. We present simulations of electron beam production and propagation and estimate the likelihood of satellite detection of electron beams. A Monte Carlo average comparing satellite detection frequencies indicates that electron beams overall account for $\sim 1\%$ of TGF observations though the average likelihood of detection varies strongly with source latitude.

1 Introduction

Terrestrial gamma-ray flashes (TGFs) were first detected in 1994 as millisecond-duration bursts of gamma-rays with a very hard energy spectrum [1]. Radio observations of coincident thunderstorm electrical activity shows that TGFs are associated within ~ 1 ms and within a few hundred kilometers of a detectable lightning discharge [2, 3, 4]. Subsequent observations and spectral analyses indicate TGFs are produced at 15 to 20 km altitudes [5, 6] and contain photons with energies up to 40 MeV [7, 8], perhaps even as high as 100 MeV [9].

These intense, energetic bursts of photons are accompanied by energetic electrons and positrons due to Compton scattering and pair production as the photons escape the atmosphere. Any electrons emitted are confined by the geomagnetic field and reach satellite altitude in a narrow beam displaced from the source along the geomagnetic field instead of spreading to illuminate a wide area as for TGF photons. A visualization of an example electron beam is shown at left in figure 1. These electron beams are detected similarly to TGFs but have longer duration and can be displaced a large distance from the TGF source lightning [10, 11, 12, 13].

Such electron beams provide new information about TGFs as they can be directly traced to the photon source and carry information about the energy and directional distribution of the TGF photons. Unfortunately, electron beam observations are rare. This paper examines how rare and studies the conditions under which electron beams are likely to be detected.

2 Electron Beam Simulations

The results in this paper are derived from simulations of electron beam production and propagation. Electron beam production is simulated with GEANT4 [14], an energetic particle Monte Carlo simulation code. An initial population of energetic photons is started at 20 km altitude directed uniformly in solid angle with zenith angle $< 45^\circ$. The photon energy spectrum is a bremsstrahlung spectrum consistent with TGF observations as in [6]. All simulations are carried out in the IGRF11 model of the geomagnetic field. Electrons that escape the atmosphere are propagated in the geomagnetic field with a guiding center motion simulation. Particles that again hit the atmosphere can be again simulated with GEANT4 but as this paper examines the detectability of electron beams we will focus only on the first, most intense “hop” of electrons from hemisphere to hemisphere.

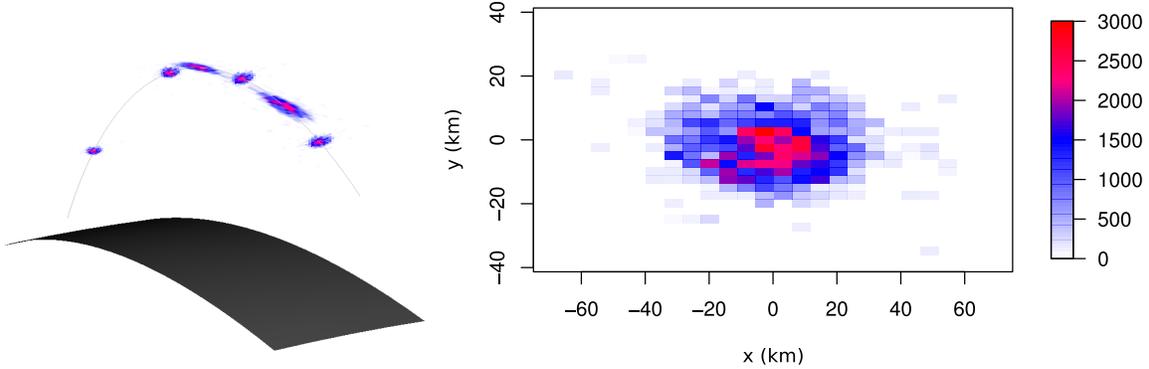


Figure 1: Left: A visualization of an example electron beam. The beam propagates along the geomagnetic field (grey line) above the earth (grey surface) with flux cross sections and the flux at satellite orbit shown by the colored slices. Right: A 2-dimensional histogram of electron flux taken in a slice perpendicular to the geomagnetic field. The x axis is roughly east-west while the y axis is roughly up-down. The intensity scale is arbitrary but comparable to the TGF intensity.

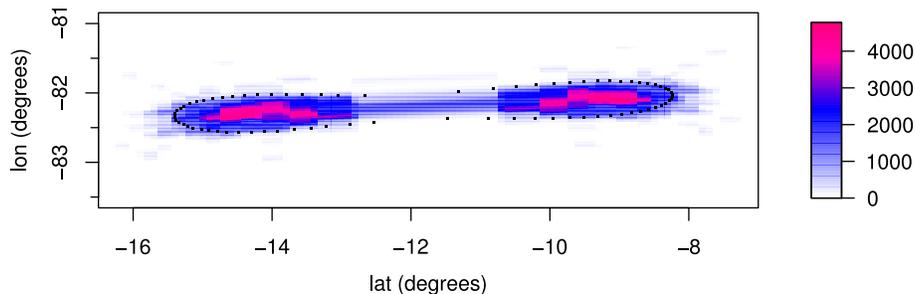


Figure 2: Electron beam shape at satellite altitude. The color indicates flux as in figure 1. The dots indicate the expected boundaries of the beam as measured by tracing along the geomagnetic field from a disk of 25 km radius above the source.

3 Electron Beam Detection

The electron beams have a width of ~ 30 km horizontally and ~ 20 km vertically as seen at right in figure 1 though the exact beam shape depends on the latitude of the source. The shape of the illuminated region in the satellite plane is latitude-dependent but can be well-approximated by tracing along the geomagnetic field from a disk of radius 25 km located above the source as seen in figure 2. This approximate region is hereafter assumed to be the region of the satellite orbit where the electron beam would be detected. This calculation can be easily repeated for many source locations without time-consuming particle Monte Carlo simulations.

Analysis of the photons that reach satellite altitude show that they are detectable for sub-satellite positions displaced from the source by up to 500 km. The area of the electron beam is much smaller but varies with latitude. In order to assess the relative likelihood of detection of an electron beam by a realistic satellite, we have made a Monte Carlo average over the TGF positions observed by RHESSI and the positions of a satellite with orbital inclination 26° and altitude 550 km (such as the Fermi Gamma-ray Space Telescope). For each RHESSI TGF position, the region illuminated by electrons is simulated by tracing along the geomagnetic field as in the dots in figure 2. The region illuminated by photons is calculated by placing a 500 km radius disk above the source at satellite altitude. The probabilities of detection of TGF and electron beam are then measured by drawing random phases from a satellite orbit and counting the fraction of the resulting satellite positions that fall within the electron and photon illumination regions. The probability

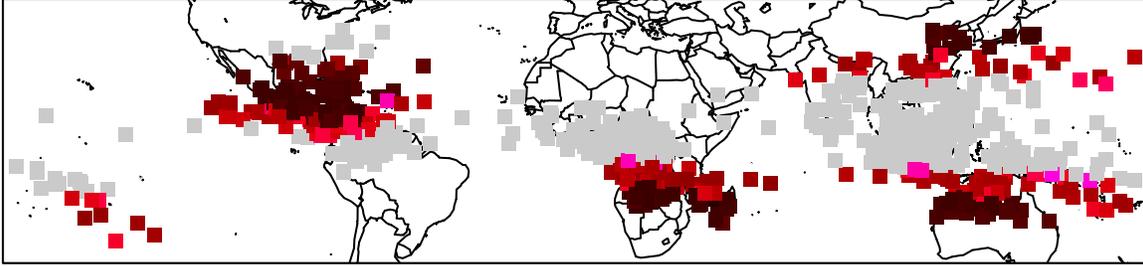


Figure 3: Map of TGF positions seen by RHESSI, colored according to the likelihood of satellite observation of a TGF-associated electron beam. Undetectable events are grey, while low and high detectabilities are black and magenta respectively. The most detectable sources are $\sim 20\times$ more likely to be detected than the least likely.

of detection of TGFs is approximately uniform, but the probability of electron beam detection varies by a factor of 20 with geomagnetic latitude. A map of TGF positions color-coded by likelihood of electron beam detection is shown in figure 3.

The Monte Carlo gives the ratio of electron beam observations to TGF observations as $\sim 1\%$, in line with earlier order of magnitude estimates based on relative beam size. However, as can be seen in figure 3, a large fraction of TGFs cannot emit detectable electron beams as they do not occur near geomagnetic field lines that reach satellite altitude, and some locations are 20 times more likely to produce an observable electron beam than others. As such, simplistic overall frequency estimates are naive and only coincidentally agree with the more rigorous calculation.

4 Discussion

At a fractional rate of $\sim 1\%$, TGF electron beams should be detected a few times per year by satellites. This is in line with the observed rates. The calculations above can be improved by accounting for the intensity distributions of electrons and photons instead of simple position and distance thresholds as used here, though this requires knowledge of the intensity distribution of the TGF source and should not significantly affect the results.

Though TGF electron beam detection is rare, the events are quite common with $\sim 50\%$ of TGFs capable of producing detectable electron beams. Their implications for lightning, TGF production, and the space physics environment are unknown. As such, these interesting events warrant further study.

5 Acknowledgments

This work was supported by the Norwegian Research Council.

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