Radiation Risk Assessment Associated With Terrestrial Gamma Ray Flashes for Commercial Flights

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Key Points:

- The probability for a commercial flight to be hit by a terrestrial gamma ray flash (TGF) is estimated by two methods
- Estimation of an upper bound of the probability: one flight hit by a TGF every 2 years over the total air traffic
- Estimation of one flight hit by a TGF every 390 years over the whole Air France fleet

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Radiation Risk Assessment Associated With Terrestrial Gamma Ray Flashes for Commercial Flights

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Abstract Terrestrial gamma ray flashes (TGFs) are bursts of high-energy photons produced in thunderstorms. Photons are produced by bremsstrahlung from high-energy electrons, gaining energy through the electric field in the thunderstorm. Both electrons and photons are ionizing radiation and could have an impact on the radiation exposure of commercial aircrews and passengers. Previous works from Dwyer et al. (2010) and Pallu et al. (2021) have quantified doses possibly delivered by TGFs. They showed that the photon doses are sufficiently low so as not to be taken into account in the calculation of the radiation doses received during flights. However, electrons could deliver high doses up to 1 Sv, though in a compact area around the TGF source. In this work, we estimate an upper bound of the probability for a commercial flight to find itself in the electron beam of a TGF. Using the first Fermi-Gamma ray Burst Monitor TGF catalog and both simulated routes between airports as a first step and real flight routes from Air France airline for 2.5 years as a second step, we show that the probability is lower than one aircraft hit every 2 years for the total air traffic. Knowing that we did not take into account altitudes and the fact that pilots usually avoid thunderstorms, it is likely that no aircraft would have been hit by the source of a TGF since the beginning of the commercial aviation.

Plain Language Summary Terrestrial gamma ray flashes (TGFs) are bursts of high-energy photons produced in common thunderstorms. Generated by bremsstrahlung from relativistic electrons, they have been estimated to be able to deliver high radiation doses, though in very compact areas (<200-m radius around the source). This work presents a statistical study to estimate the probability for a commercial flight to be hit by a TGF. We show that this probability is low, estimated to be less than one aircraft hit by a TGF every 2 years for the total air traffic.

1. Introduction

Terrestrial gamma ray flashes (TGFs) are bursts of high-energy photons produced in thunderstorms. They are associated with lightning leaders and intracloud discharges (Lu et al., 2010; Stanley et al., 2006). Most models are based on relativistic runaway electron avalanche processes (e.g., Dwyer et al., 2012), which allow the production of a great number of high-energy electrons to comply with satellite observations of gamma rays, that is, $\sim 10^{18}$ photons through bremsstrahlung (e.g., Gjesteland et al., 2015; Mailyan et al., 2016, 2019).

Considering this high number of gamma rays and electrons in an altitude range overlapping that of commercial flights, Dwyer et al. (2010) predicted that high doses could be delivered by the electrons depending on the electron beam radius. We then previously estimated the doses delivered by gamma rays and electrons through numerical modeling, clarifying the dependency on the beam radius (Pallu et al., 2021). This work established that doses delivered by TGF photons should not exceed safety limits used for exposed workers, but doses delivered by electrons may exceed these limits, yet in very compact regions corresponding to the TGF source region. This region is estimated to have a ~200 meter radius. That result could lead to a significant exposure of aircrews and passengers in commercial aircraft flying in thunderstorms, in addition of exposure to cosmic radiation. In fact, passengers are usually not considered at risk because they fly so much less than aircrews, which only makes sense because continuously acquired doses are considered rather than acute exposures that would equally affect everyone on the plane, such as TGFs. In countries having regulation regarding exposure of aircrew (as in the European Union), only cosmic radiation has to be taken into account in exposure assessment (Euratom, 1996). The legal radiation dose assessment of flight crews is made by software, taking into account only galactic cosmic radiation and solar energetic proton events (e.g., Clairand et al., 2009). Annual aircrew exposures remain below

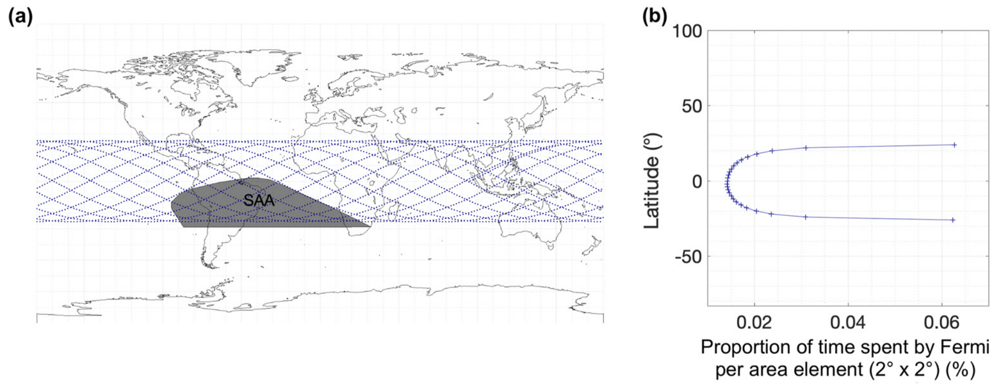

Figure 1. (a) Simulated Fermi trajectory for 1 day. The shaded area depicts the region of the South Atlantic Anomaly (SAA), over which Fermi-Gamma ray Burst Monitor (GBM) is turned off. (b) Proportion of time spent by Fermi over each surface element as a function of latitude (averaged over the longitudes).

the annual legal limit for exposed worker of 20 mSv and never exceed 6 mSv per year for European company for example (IRSN, 1996). Dose measurements with individual dosimeters has never been in widespread use since the development of dose monitoring software, software being more accurate and reliable, and providing directly the effective dose, which quantifies the impact of ionizing radiation on body tissues, but that is not measurable (ICRP, 2007). Therefore, due to the considered approach for dose monitoring, even if presently not mandatory by regulations, any other sources of exposure (such as TGFs or gamma ray glows) that could contribute to aircrew exposure are not currently taken into account nor assessed. Determining the level of exposure from atmospheric electricity events such as TGF is therefore of importance because possibly calling for a change in the paradigm of aircrew dose assessment and associated regulation if those exposures would be considered as not negligible. After the previous study evaluating dose values delivered by TGFs (Pallu et al., 2021), the need of an evaluation of the probability for an aircraft to find itself in the high dose region of a TGF clearly arises. Moreover, the fact that a commercial aircraft is struck by lightning one to two times a year on average (Fisher et al., 1999) indicates that aircraft are not excluded from being hit by high-energy events produced in thunderstorms, even though pilots usually try to avoid thunderstorms.

In the following of this study, we will use the term “hit by a TGF” for an aircraft that was closer than 200 m of a TGF source. Here, we present a statistical study to estimate the probability for a commercial flight to be hit by a TGF. Fermi-Gamma ray Burst Monitor (GBM)-detected TGFs are used to make a TGF density map, and two different methods are used for flight routes estimation: first an estimation of the world traffic from a list of airports; then the use of real flight data for a single major airline, namely Air France, for which we had access to actual routes. With both methods we show that the probability for a commercial flight to be hit by a TGF is low, estimating an upper limit to be one aircraft hit every 2 years by a TGF in the total air traffic.

2. Method

2.1. Data Used

Four thousand one hundred thirty-five TGFs have been detected between July 11, 2008 and July 31, 2016 by the GBM on board Fermi (Roberts et al., 2018), a NASA satellite launched on June 11, 2008. The GBM is an instrument whose aim is to detect sudden flares of gamma-rays produced by gamma ray bursts and solar flares. Composed of 12 NaI and 2 Bismuth Germanate (BGO) scintillators, GBM detects photons between 5 keV and 25 MeV with an absolute timing resolution of ∼2 μs, hence its ability to detect TGFs. Fermi trajectory goes up to 26° in latitude. Fermi's instruments are turned off over the South Atlantic Anomaly (SAA) to reduce their exposure to radiation belts particles. Consequently no TGF has been detected above this surface. The SAA boundaries as defined for Fermi-GBM are represented in Figure 1a.

As GBM was not initially developed to detect TGFs, the triggering system has been modified several times during the mission (Briggs et al., 2013). In fact, since July 9, 2010, the triggering system can be done on the ground thanks to the possibility to recover the whole data in predetermined areas that are assumed to produce TGFs.

First, an area above the Americas has been defined, then the spatial areas have been extended progressively on January 27, 2011, on May 26, 2011, and on August 31, 2011. On November 26, 2012, this process has been extended to the entire orbit outside the SAA. In order to use a consistent set of data, only TGFs that have been detected between November 26, 2012 and July 31, 2016 have been used in our study, corresponding to 2,807 TGFs. In this work, TGF locations are assumed to be the location of the satellite at the time of the detection. It is worth mentioning that the distance between TGF sources and the satellite footprint can be up to several hundreds of kilometers, but given the randomness of the process, we do not expect significant changes in the results of this study if real TGF positions were to be used. The precision of TGF locations could be improved by using World Wide Lightning Location Network (WWLLN)-associated TGFs, but this would imply a lower number of TGFs used, thus lower statistics.

Fermi goes over all latitudes below 26°. We use a grid made of surface elements based on latitude and longitude coordinates with a resolution of 2°, for longitudes in [−180°; +180°] range for latitudes in [−26°; +26°] range. The area in km^2 of each surface element can be approximated as:

$$dS_{jk} = R^2 \times \left(\frac{\pi}{180}\right)^2 \times \cos\left(y_j \times \frac{\pi}{180}\right) \times (x_k - x_{k+1}) \times (y_j - y_{j+1}) \quad (1)$$

with x and y the longitude and the latitude in degrees, j and k are longitude and latitude indices for the surface elements, and $R = 6{,}371$ km is the Earth radius. The density map is calculated in TGF/km^2/day.

2.2. Lower-Fluence TGFs

The TGFs addressed in this work are Fermi-detectable TGFs that are TGFs intense enough to be detectable by the limited sensitivity of spaceborne instruments from low orbit altitudes. Using Fermi and RHESSI TGF data, Østgaard et al. (2012) estimated the ratio of IC lightning discharges that produce such detectable TGFs to be 2%, and added that we cannot exclude the fact that all lightning could produce TGFs however too dim to be detectable from satellite. Therefore dim TGF research have been undertaken. For instance, Smith et al. (2014), McTague et al. (2015), Østgaard et al. (2015), Smith et al. (2016), and Albrechtsen et al. (2019) have searched for photon counts detected by spaceborne instruments statistically correlated to ground-based IC lightning detection. These studies do not conclude decisively on the proportion of weak TGFs as it depends on the satellite and the ground-based lightning detection network used.

In case of a large proportion of weak TGFs, the results of our present study would not be impacted as we address only satellite detectable TGFs that are estimated to produce a high number of photons (10^{18}) and thus a sufficiently high number of runaway electrons to deliver the harmful radiation doses estimated by Pallu et al. (2021). In fact, Østgaard et al. (2012) estimated that the weaker TGFs could produce 10^{12} runaway electrons, that is from 2 to 3 orders of magnitude below the initial number of thermal runaway electrons estimated by Pallu et al. (2021).

2.3. Fermi Trajectory

In addition to a factor that compensates the number of detected TGFs above each surface element as a function of the surface element area, a correction has to be applied on Fermi TGF data in order to take into account the time spent by Fermi above each surface element.

We use Fermi's orbit parameters (heavens-above.com, 2021) to simulate its trajectory over 10 days to have a good statistics (represented over 1 day in Figure 1a). We calculated the time spent above each surface element. This time is only dependent on the latitudes and can be seen in Figure 1b.

2.4. TGF Density Map

We introduce the following variables:

- $S = \sum_{j,k} dS_{jk}$ is the total surface observed by Fermi (km^2) that is about 224 millions of km^2
- $dt_{jk} = \frac{\text{time above the element } dS_{jk} \text{ over 10 days}}{\text{10 days}}$ are the proportion of time spent by Fermi above each surface element (no units)—can be seen in Figure 1b
- T is the duration between November 26, 2012 and July 31, 2016 (in years) over which the TGFs were detected (~3.6 years)

- FoV is the field of view of Fermi-GBM, chosen to correspond to a disk with a radius r around Fermi's nadir (km^2)
- n_{jk} is the number of TGFs detected in each surface element during T

N_{jk} is the number of TGFs that would have been detected in each surface element if Fermi was able to detect TGFs everywhere over S at anytime during the 3.6 years observation period. It is calculated by:

$$N_{jk} = n_{jk} \times \frac{dS_{jk}}{\text{FoV}} \times \frac{1}{dt_{jk}} \tag{2}$$

The TGF density d_{jk} for each surface element can then be calculated by:

$$d_{jk} = \frac{N_{jk}}{dS_{jk} \times T} \tag{3}$$

To calculate the radius r of Fermi-GBM field of view, we used Figure A1 of Briggs et al. (2022), describing Fermi-GBM TGF detection rate R as a function of the radial distance r. FoV is calculated to have a radius r of 416 km, and this value is used in this work. The density map is expressed in TGF/km^2/year.

2.5. Flight Route Data Simulation

In order to estimate the probability to be hit by a TGF on a commercial flight, we use a list of the 606 biggest airports in the world (ourairports.com, 2021). The route between two airports is calculated as a geodesic, and the aircraft velocity is supposed to be constant and equal to 250 m/s. To simulate the whole commercial flight network, 5,000 routes are drawn randomly by choosing randomly the departure airport and the arrival airport. The proportion between short-haul, medium-haul, and long-haul flights is taken into account afterward, knowing that Wilkerson et al. (2010) estimated the proportion of short-haul flights to be 86%, of medium-haul flights to be 10%, and of long-haul flights to be 4%. The number of flights per year is assumed to be 38.9 millions in 2019 (statista.com, 2021). We emphasize that this approach contains significant biases. However, it provides an interesting order of magnitude estimate.

2.6. Real Flight Route Data

Real flight routes data have been used to complete this study. We use all the flights performed by the Air France fleet between January 1, 2014 and July 31, 2016. Every flight have been recorded as follows: departure airport and the corresponding date, arrival airport and the corresponding date, as well as waypoints on the trajectories, in order to use the actual route flown by the pilots. The number of waypoints can reach up to 20 for the longer flights. The advantage is that these flight data describe the actual routes flown by the pilots. The disadvantage of this approach is that it is limited to one airline that is not likely to be representative of the global air traffic. In addition to a probability calculation on each route performed by Air France, a linear interpolation between the waypoints makes possible the real time and space comparison between Fermi-detected TGF locations and in-flight aircraft.

2.7. Probability Calculations

From Pallu et al. (2021), a harmful radius around the TGF source is deduced to be 200 m. Therefore, we need to estimate the number of TGFs occurring in a 200 m radius per unit time. In that sense, the term "hit by a TGF" in this paper means that the aircraft is closer than 200 m from a TGF source. For each flight, the probability for an aircraft to find itself in the beam of a TGF will be calculated as follows:

- Linearly interpolate the trajectory with one position per second
- Calculate the time Δt_{jk} spent above each surface element (in seconds, with a resolution of 1 s)
- Get the probability for the aircraft to be hit above each surface element by:

$$p_{jk} = \Delta t_{jk} \times d_{jk} \times k_{200\text{m}} \tag{4}$$

The TGF density d_{jk} is expressed in TGF/year/km^2. To calculate the probability for an aircraft to be within the 200-m harmful radius of a TGF, per second, we use the scaling factor $k_{200\text{m}} = \pi \times (0.2)^2/(365 \times 24 \times 60 \times 60) =$

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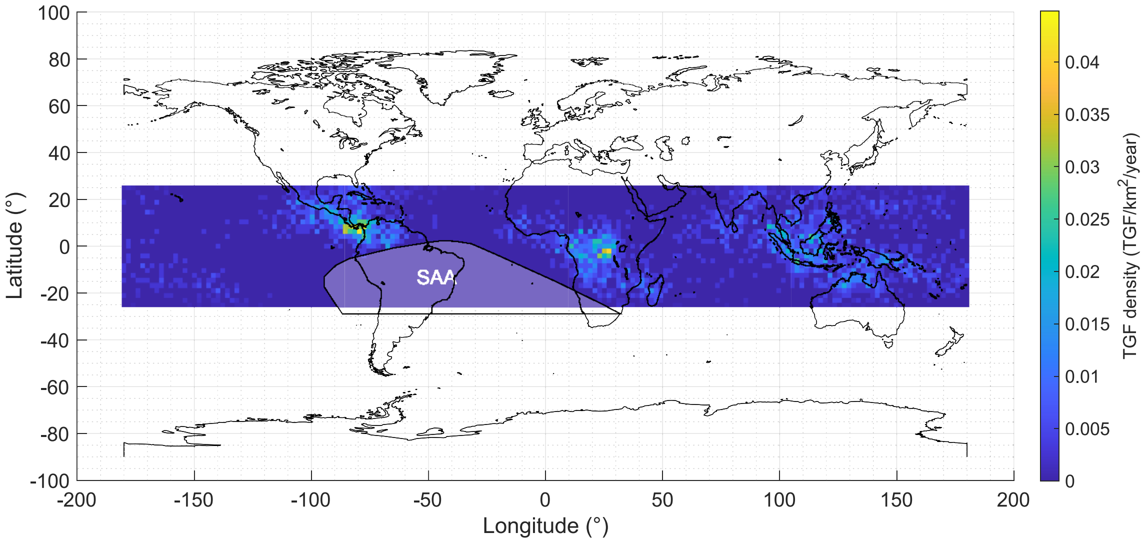

Figure 2. Terrestrial gamma ray flash (TGF) density as a function of the location in number of TGFs per km^2 per year.

3.99×10^{-9}. Thereby, $d_{jk} \times k_{200\mathrm{m}}$ is expressed in TGF/s/(200 m)^2, corresponding to the number of TGF per second within a 200 m-radius area.

- Get the total probability for the aircraft to be hit by a TGF on the whole route by:

$$P_{\mathrm{flight}} = \sum_{j,k \in \Omega} p_{jk} \tag{5}$$

where Ω is the set of indices indexing surface elements crossed by the considered route. One notes that P_{flight} is more rigorously a frequency, implying that, in principle, it could be greater than 1. It corresponds to the number of TGFs hitting the aircraft during a given flight. However, as it is always much lower than one in practice, we use it as a probability in the frequentist sense.

Since P_{flight} is a small number ($\sim 10^{-8}$), to get a more meaningful number, we express this likelihood as the number of flights between two TGF hits on this route. When the frequency of flights on this route is known, the time between two TGF hits on this route will be calculated.

3. Results

3.1. TGF Density Map

The TGF density map has been calculated from Fermi-GBM data and is shown in Figure 2. It represents the TGF density for Fermi-GBM-detectable TGFs, that is to say fluent enough to be detectable at 500 km altitude. We can expect less fluent TGFs to be produced but not detectable by Fermi (discussed in Section 2.2).

The highest TGF density from this map is located above Panama and is equal to ∼5 TGFs/(10 km)^2/year. Using this density map, we can estimate the number of TGFs (i.e., Fermi detectable TGFs) produced per year on the whole surface *S*. We find this value to be 388,000 TGFs/year. This value is consistent with the estimation made by Briggs et al. (2013), who estimated 400,000 TGFs/year using TGF data from the same instrument but not over the same period, neither the same TGF triggering process.

We propose to make a comparison of these results with real measurements from ADELE campaign (Smith et al., 2011b). Researchers of the ADELE project have performed a measurement campaign with an array of six gamma ray detectors aboard an aircraft. Smith et al. (2011b) have detected one TGF and 1,213 lightning flashes (Smith et al., 2011a), within 37 hr of flight near a thunderstorm, hence a really exposed place, in Florida. According to Christian et al. (2003), in Florida the lightning density is 35 lightning/km^2/year. Smith et al. (2011a) observed a factor of 26 above this value, which is not unreasonable since they were flying in the vicinity of thunderstorms. The ADELE project was able to detect a TGF within a ∼10 km radius around the aircraft. Reshaping

Table 1
Table of Probability for an Aircraft to Be Hit by a TGF According to Flight Type

Flight type	Flight duration (hr)	Proportion of the flight type in the world (Wilkerson et al., 2010) (%)	Probability to be hit by a TGF (TGF/flight)
Short-haul	<3	86	8.3×10^{-9}
Medium-haul	3–6	10	4.9×10^{-8}
Long-haul	>6	4	7.8×10^{-8}

our TGF density map for a 10 km disk around the detector, we get the TGF density in Florida: 8.5×10^{-8} TGF/s/10 km-radius. Multiplying this density by the 37 hr of flight and the factor of 26, we get: 1 over 3 campaigns like ADELE could be hit by a TGF. Therefore, this density map seems to be consistent with the results from the ADELE campaign.

3.2. Probability to Be Hit by a TGF on an Especially Exposed Route

In this part, probabilities are calculated from theoretical routes between airports chosen randomly, as explained in Section 2.5.

In order to estimate an upper limit on the probability for an aircraft to be hit by a TGF, we looked for a particularly used route that is especially exposed. For that, the probability on all the routes from Atlanta (Georgia, USA) airport (airport code: ATL), that is the airport with the busiest traffic in the world, to the 605 other airports has been calculated. The most exposed route is then found to be between Atlanta (Georgia, USA) and Santiago (Chile, airport code: SCL). The probability for an aircraft to be hit by a TGF on this route is 6.7×10^{-7} TGF/flight. This corresponds to one flight over 1.5 million of flights that is hit by a TGF on this route. Assuming that the number of flights per week on this route is 16 (flights.com, 2021), it means that on this route, one flight would be hit every ~1,800 years by a TGF.

3.3. Probability to Be Hit by a TGF on a Commercial Flight for the Global Air Traffic

3.3.1. Evaluation of an Upper Limit

We use the results of the probability found for the ATL-SCL route to estimate an upper limit for the probability to be hit by a TGF in a random commercial flight in the world. Assuming the duration of the ATL-SCL flight to be 504 min (with constant aircraft velocity), the probability of hit per second on this route is then 2.2×10^{-11} TGF/s. With 38.9 millions flights per year (statista.com, 2021), the proportion of short, medium, and long-haul flights stated before in Section 2.5 and a mean duration for short-haul flights of 1.5 hr, for medium-haul flights of 4.5 hr, and for long-haul flights of 11 hr, we obtain a mean of 6.7 flights hit by a TGF per year in the world for the upper limit.

We emphasize that this is an estimation of an upper limit, therefore an overestimation, of the probability that an aircraft would be hit by a TGF in the world.

3.3.2. Random Routes

In this part, probabilities are calculated from theoretical routes between airports chosen randomly, as explained in Section 2.5. Five thousand random flights (respectively 885, 648, 3,467 short, medium, and long-haul flights) is sufficient to obtain an accurate estimation of the mean probability. The results can be seen in Table 1.

Taking into account the proportion of each flight type, the probability for an aircraft to be hit by a TGF on a flight is 1.5×10^{-8} TGF/flight. With 38.9 millions flights per year, it means one flight every ~1.7 years would be hit (within 200 m) by a TGF in the total air traffic.

We emphasize that for routes crossing latitudes above or below 26° in latitude, the probability corresponding to the part of the route above or below 26° is set to zero because we do not have TGF data to estimate it. There is a similar issue above the SAA where no data is available. For these particular routes, the result is slightly underestimated by this procedure. As we do not take into account the altitude of the TGFs nor the altitude of the flights (see later discussion in Section 3.5) and since the fact that pilots usually try to avoid thunderstorms is not considered, on the contrary, probabilities are overestimated by these assumptions. We nevertheless evaluated the overestimation caused by ignoring the altitude variability of TGF sources, in Appendix A.

3.4. Air France Flight Data

We use a list of all actual Air France flight routes that have been performed between January 2014 and July 2016; 700,587 flights have been performed by Air France over this period, representing less than 1% of the totality of the flights in the world. We will use only the 97,868 flights that have routes that go below 26° latitude, which

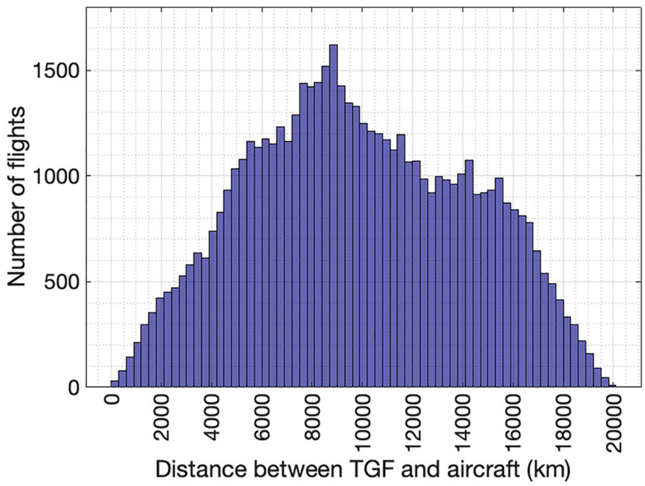

Figure 3. Histogram of distances between a terrestrial gamma ray flash (TGF) and aircraft in flight at the time of the TGF.

represents 14% of the Air France flights over this period. Over this period, 1,942 TGFs have been detected by Fermi and 55,795 of the 97,868 flights that go below 26° latitude were in flight when a TGF has been detected by Fermi.

3.4.1. Real Time Analysis

For each TGF detected between January 2014 and July 2016, we calculate the location of each in-flight aircraft at the time of the TGF and calculate its distance to the TGF. TGF locations are approximated to be the satellite footprint at the time of the detection, but given the randomness of the process, we do not expect significant changes in the results of this study using real TGF positions. The shortest distance that has been reached between a TGF and an aircraft in 2.6 years is 36 km. A histogram of the distances between in-flight aircraft and TGFs is shown in Figure 3. The mean distance is 9,900 km, which is close to the mean distance between two random points on the Earth surface. Only 0.5% of the Air France flights have been at distances below 1,000 km from a TGF.

We performed different linear fits using data for distances up to 10,000 km, in order to have an estimation of the probability of hit. This study leads to different estimated values for the number of years between two TGF hits, depending on the range of data used for fitting. The *R*-squared coefficient associated with the linear fits show higher values (>0.79) for ranges ∼0–9,000 km, corresponding to an estimation of one TGF hit every ∼130 years. Air France flights corresponding to ∼1% of the total air traffic, we found that in the total air traffic there would be one TGF hit every 1.3 years, in agreement with the other methods used in this study. Again, altitudes have not been taken into account for TGFs and aircraft.

3.4.2. Probabilities on Real Flights

We also estimated the probability for each real flight to be hit by a TGF, as done in Section 3.3 for randomized flights. The probabilities go from 6.3×10^{-12} to 1.0×10^{-6}, with a mean probability of 9.5×10^{-9} TGF/flight. The route having the higher probability is MEX (Mexico city, Mexico)–BOG (Bogota, Colombia), for which only two flights have flown in 2.6 years in the Air France fleet, corresponding to one Air France aircraft hit on this route every 1,300,000 years. However, an estimated number of 6 flights/day on this route (flightconnections.com, 2021) involves that there is one hit per flight every 467 years on this route for all the airlines. Figure 4 represents the time between two hits on each route, taking into account the probability and the frequency of flight during the 2.6 years studied. Then, CDG (Paris, France)–JNB (Johannesburg, South Africa) is the most exposed route, representing one flight hit by a TGF every 3,400 years (one hit every 2,400,000 flights and 700 flights/year).

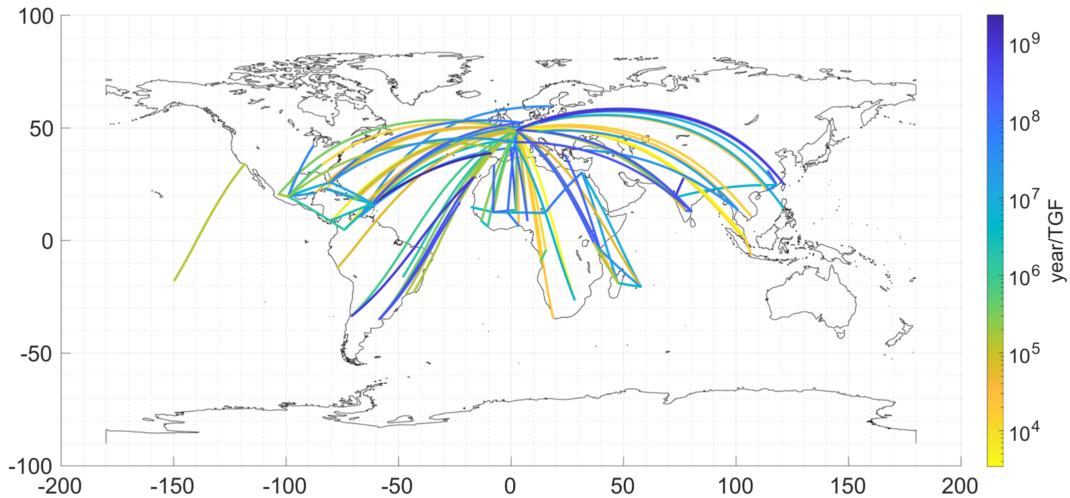

Figure 4. Time (in years) separating two hits of aircraft by a terrestrial gamma ray flash (TGF) on Air France routes.

The total probability on the whole Air France fleet is 0.0026 TGF/year, corresponding to one hit every 390 years on the whole fleet.

3.5. Estimation of the Overestimation in Not Taking Altitude Into Account

It is possible to evaluate the overestimation introduced by ignoring the TGF altitude dependency into account in the probability calculations. We assume that TGFs are produced between 10 and 15 km (e.g., Cummer et al., 2011, 2014, 2015), and commercial aircraft to fly between 9 and 12 km. Considering a uniform distribution of TGFs and flights over their respective altitude ranges, and a vertical hazardous region equal to the size of the runaway electron acceleration region (~1 km) (see Pallu et al., 2021), one finds that the probability for an aircraft to be hit by a TGF calculated above is overestimated by a factor of 10. The detailed calculations are shown in Appendix A.

4. Conclusions

In this work, we have carried out a statistical study to estimate the probability of a commercial aircraft to be hit by a TGF. We used the data of more than 2,800 TGFs reported in the first Fermi-GBM TGF catalog (Roberts et al., 2018). Concerning aircraft flight data, we used two different methods. First, randomized routes between airports have been simulated whereas on the second hand we used real flight data from the airline Air France over 2.6 years.

In the first part of the study, we show that the probability for a commercial aircraft to be hit by a TGF is estimated to be once every ~2 years in the world. Some assumptions and lack of data introduce uncertainties in the evaluation of this probability. For instance, the probability is underestimated by the unavailability of data above the SAA and above 26° latitude. The fact that we did not take into account the altitude distribution of TGFs, and the fact that the pilots usually try to choose routes avoiding thunderstorms when possible overestimate the probability calculated here by likely a larger factor than the underestimation factor of both previous cited assumptions. Concerning the TGF altitude distribution, we estimated in Section 3.5 that the overestimation could be of a factor of ~10, changing the high rates estimated in Sections 3.3.1 and 3.3.2 to be lowered from 7 hits/year to 1 every 1.4 years for the upper limit and from 1 every 1.7 years to 1 every 17 years for the total probability with random routes.

The second part of the present work uses real data to represent better the routes actually flown by the pilots for the real time analysis, in addition to removing the biases associated with randomly picking airports. With these data from Air France company over 2.6 years, we found that one aircraft would be hit every 390 years on the whole fleet. The probability is therefore considered as low, especially as we still do not take the TGF and aircraft altitude into account. The latter would decrease this probability by a factor of ~10. Knowing that the Air France fleet corresponds to ~1% of the total air traffic, this result agrees with the estimation on the total air traffic.

Appendix A: Overestimation in Not Taking Altitude Into Account

We assume that TGFs are produced between 10 and 15 km (e.g., Cummer et al., 2011, 2014, 2015), and commercial aircraft to fly between 9 and 12 km. We consider a uniform distribution of upward TGFs and flights over their respective altitude ranges, and a vertical hazardous region equal to the size of the runaway electron acceleration region (~1 km) (see Pallu et al., 2021). We make the following definitions: TGF_{10-12} is the event "TGF altitude is between 10 and 12 km", A_{10-12} is the event "the aircraft altitude is between 10 and 12 km", h_A is the aircraft altitude, and h_{TGF} is the TGF altitude. The difficulty arises from the fact that the events to consider are not all independent. The probability for an aircraft to find itself within 1 km above a TGF is the following:

$$\mathcal{P} = P(TGF_{10-12} \;\cap\; A_{10-12} \;\cap\; h_A > h_{TGF} \;\cap\; |h_{TGF} - h_A| < 1 \text{ km}) \tag{A1}$$

Conditional probabilities give:

$$\mathcal{P} = P(h_A > h_{TGF} \;\cap\; |h_{TGF} - h_A| < 1 \text{ km} \;|\; TGF_{10-12} \;\cap\; A_{10-12}) \times P(TGF_{10-12} \;\cap\; A_{10-12}) \tag{A2}$$

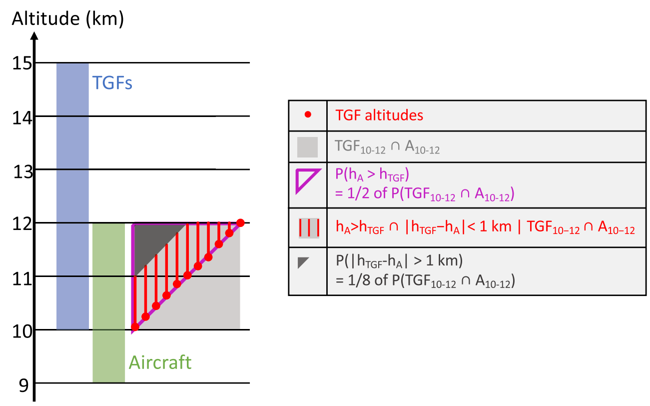

Figure A1. Illustration of the events configuration. The proportion of the red hatched area of the light gray square corresponds to the probability that an aircraft is hit by a TGF, given that they are both in the range 10–12 km. The magenta area corresponds to the area where the aircraft is constrained to be above the TGF. The dark gray area corresponds to the area where the aircraft is above but too far (>1 km) from the aircraft.

Since these can be considered as independent events, the probability that the aircraft and the TGF happen both between 10 and 12 km is:

$$P(TGF_{10-12} \ \cap \ A_{10-12}) = \frac{2}{5} \times \frac{2}{3} = \frac{4}{15} \tag{A3}$$

As illustrated in Figure A1, given that the aircraft and the TGF are in the range 10–12 km, the probability that the aircraft is above the TGF and less than 1 km above it, can be calculated as:

$$\begin{aligned} P(h_A > h_{TGF} \ \cap \ |h_{TGF} - h_A| < 1 \text{ km} \ | \ TGF_{10-12} \ \cap \ A_{10-12}) \\ = P(h_A > h_{TGF} \ | \ TGF_{10-12} \ \cap \ A_{10-12}) \\ -P(|h_{TGF} - h_A| > 1\text{km} \ | \ h_A > h_{TGF} \cap \ TGF_{10-12} \ \cap \ A_{10-12}) \\ = \frac{1}{2} - \frac{1}{8} = \frac{3}{8} \end{aligned} \tag{A4}$$

Finally, the probability for an aircraft to find itself within 1 km above a TGF, according to Equation A2, is:

$$\mathcal{P} = \frac{3}{8} \times \frac{4}{15} = 0.1 \tag{A5}$$

We have verified numerically this method using various altitudes and dangerous range extents for aircraft and TGF locations drawn randomly. One finds that the probability for an aircraft to be hit by a TGF as reported in the present study is overestimated by a factor 10.

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Data Availability Statement

All GBM data used in this paper are available online (at https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/). The Fermi-GBM catalog is available online (at https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/tgf/). The list of airports used in this study can be found on the following link: ourairports.com (2021).

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