High spatial resolution correlation of AGILE TGFs and global lightning activity above the equatorial belt.

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The AGILE satellite detects Terrestrial Gamma-ray Flashes (TGFs) in the 0.35-100 MeV energy range using its Mini-Calorimeter (MCAL) instrument with an average detection rate of 10 TGFs/month. Thanks to its Low Earth Orbit with only 2.5 degree of inclination, AGILE guarantees an unprecedented exposure above the equator, where both lightning activity and TGF detection peak. Here we report the comparison between the AGILE TGFs detected between March 2009 and February 2010 and full climatology lightning worldwide distribution based on satellite optical observations from LIS (Lightning Imaging Sensor) and OTD (Optical Transient Detector) instruments. This approach is complementary to the one-to-one TGF/lightning correlations by ground-based sferics measurements. Based on mono and bi-dimensional Kolmogorov-Smirnov tests, we show that the AGILE TGFs and time-averaged global lightning in the equatorial area are not drawn from the same distribution. However, we find significant regional differences in the degree of correlation as well as in the TGF/lightning ratio. In the case of south east Asia we find a 87% probability for the TGF and lightning being samples of the same distribution. This result supports the idea that the physical conditions at play in TGF generation can have strong geographical and climatological modulation. Based on the assumption that the observed range of TGF/flash ratio holds at all latitudes we can estimate a global rate of $\dot{N} \simeq 220 \div 570$

TGFs per day. The observed TGF/flash geographical modulation as well as the TGF global rate estimate are in agreement with previous observations.

1. Introduction

Terrestrial Gamma-ray Flashes (TGFs) are very fast (< 1 ms) high energy transient events (up to 100 MeV) [*Tavani et al.*, 2011] generated in the atmosphere. TGFs were serendipitously discovered in 1994 by the BATSE experiment onboard CGRO satellite [*Fishman et al.*, 1994] and more recently observed by instruments onboard RHESSI [*Smith et al.*, 2005], AGILE [*Marisaldi et al.*, 2010] and Fermi satellites [*Briggs et al.*, 2010]. Up to now TGFs have been associated with positive cloud-to-ground (+CG) discharges [*Fishman et al.*, 1994; *Inan et al.*, 1996; *Cummer et al.*, 2005] but also with intra-cloud (IC) discharges [*Stanley et al.*, 2006; *Williams et al.*, 2006; *Shao et al.*, 2010], so it is not possible to identify a preferential lightning class for TGF production, at the moment. Several indications that TGFs are produced at the top of thunderstorm systems [*Williams et al.*, 2006] are supported by Monte Carlo modeling [*Dwyer and Smith*, 2005; *Østgaard et al.*, 2008], that estimate a typical altitude of 15-20 Km for TGF generation, in good agreement with the average tropopause height. In a recent work, Smith et al. [*Smith et al.*, 2010] correlate RHESSI TGFs and global lightning activity linking the TGF production altitude to tropopause height experimental data, and accounting for the corresponding gamma-ray absorption due to different atmospheric depth. Although this method improves the global correlation between RHESSI TGFs and lightning distribution above a very wide latitude belt, it does not account for all the observed discrepancies, so no strong experimental confirmation of the preferential altitude for TGF generation is possible at the moment.

Although many lightnings can be directly located with few kilometers accuracy, only few TGFs (8 out of 118) were directly localized in gamma-rays by the AGILE gamma-ray imaging detector [*Marisaldi et al.*, 2010b], and none of these TGFs was detected farther than ∼400 Km from the satellite nadir. Without direct gamma-ray localization, TGFs are indirectly associated with lightning geolocated via ground radio waves (sferics) detected in close temporal association with the gamma-ray event, demonstrating that instruments in Low-Earth Orbit (LEO) tipically detect only TGFs laying not farther than 300 km from the satellite footprint [*Cummer et al.*, 2005; *Hazelton et al.*, 2009; *Cohen et al.*, 2010; *Briggs et al.*, 2010; *Connaughton et al.*, 2010]. This result is based only on the ∼10-30% of the TGFs with associated single geolocated lightning because of the limited sensitivity of the localization networks. However, *Connaughton et al.* [2010] showed that the fraction of *Fermi*-GBM TGFs associated with lightning discharges localized by the World Wide Lightning Location Network (WWLLN) is compatible with all TGFs being associated to lightning.

Thanks to its detection capabilities and its very low inclination orbit, AGILE guarantees a very high exposure above a narrow equatorial belt. With 118 TGFs detected in 12 months of observation, the AGILE satellite record the highest TGF rate surface density. This paper proposes another approach to study the TGF phenomenology, based on statistical comparison between TGF and global lightning distribution as derived from LIS and OTD instruments onboard the NASA TRMM and Orbview missions. The geographical features in the TGF distribution around the equator are provided with an unprecedented high spatial resolution for this region and are compared with the average global lightning activity as observed from space.

2. TGF and lightning datasets

AGILE is a small size satellite of the Italian Space Agency devoted to astrophysical observation [*Tavani et al.*, 2009] that detects X and gamma rays in the range from the keV to GeV. Thanks to the onboard trigger logic for transients implemented on very short timescales (down to 293 μsec) [*Fuschino et al.*, 2008], the MCAL instrument [*Labanti et al.*, 2009] is a very sensitive TGF detector, operating in the energy range 0.35-100 MeV. The AGILE TGF sample considered here was obtained during the first twelve months (i.e. March 2009 - February 2010) of stable operations of the fully configured onboard trigger logic. A total of 118 events, with an average rate of 10 TGFs/month, were detected. To build the geographical distribution of AGILE TGFs, since the MCAL detector has no imaging capabilities, the position of the satellite nadir at the TGF start time was used.

The public data of Optical Transient Detector (OTD), onboard the Orbview-1 spacecraft, and Lightning Imaging Sensor (LIS), as part of TRMM NASA mission, (available at http://ghrc.msfc.nasa.gov/), provide detailed lightning worldwide distributions based on satellite optical observations [*Christian et al.*, 2003]. The LIS/OTD average lightning density rate distributions are valid instruments for statistical analysis of global (Intra-Cloud -IC- and Cloud to Ground -CG-) lightning activity or global climatology on different geographic areas. In this work we have considered the distribution map called High Resolution Full Climatology (HRFC) containing the flash rate density per km^2 per year with a spatial resolution of 0.5 degrees for both longitude and latitude. This map (HRFC_COM_FR), comprising about 10 years of observations (1995-2005), is depicted in Figure 1-A for the region of interest.

3. Comparison of TGF and lightning distributions

Due to the different orbit inclination of AGILE and TRMM, the sub-satellite point of the two spacecraft spanned quite different areas. A direct comparison between global distributions, accounting for this effect as well as for the different observing time spent on different Earth regions, requires the MCAL exposure. The MCAL exposure map (shown in Figure 1-B) was evaluated using telemetry data, selecting only the periods in which the MCAL onboard trigger logic was active, during the whole observing period. The lack of exposure over the Brazil-Atlantic Ocean region is due to the MCAL trigger logic switch off as entering the South Atlantic Anomaly (SAA).

The AGILE TGF sensitivity has been considered uniform above the whole orbit for all the observing time. We note that the average background rate of ∼350 events/sec shows a smooth 10% modulation along the orbit, including the areas close (but outside) the SAA, so that quite a small modulation can be seen also in the distribution of all onboard triggers (∼95/day). All events triggered onboard are screened on ground with a reliable selection/validation algorithm [*Marisaldi et al.*, 2010] mainly based on the fluence and on the spectral hardness. This validation method fully removes the small orbital modulation effect on sensitivity, rejecting all triggers due to statistical fluctuations or electronic noise.

Figure 1-C shows the global lightning distribution multiplied by the MCAL exposure, that is directly comparable with AGILE TGF distribution. The bin size of 2.5 deg in longitude and 1 deg in latitude corresponds, on ground, to about 275 km and 110 km respectively. In the same image all AGILE TGF positions are also shown, with white and

black crosses. In Figure 1-D the TGF (red) and the exposure-corrected lightning (black) longitude distributions are shown, summed over all latitudes.

Figure 2 shows details for the three continental zones marked with a red contour in Figure 1-C. The left column reports the lightning spatial distribution after multiplication by the MCAL exposure and TGF positions. The center and right columns show, respectively, the longitude distribution, summed over all latitudes, and latitude distribution, summed over all longitudes, for both TGFs and exposure-corrected lightning map, the latter normalized to the total number of TGFs.

At a qualitative level, the longitudinal distributions for TGF and lightning above the continental areas (Figure 1-D) show quite good agreement. In both profiles it is possible to recognize the main features of the three continental areas, like the sharp cut over the Congo or the double-peaked feature due to Sumatra and Borneo islands. The latitude profiles mainly highlight the AGILE exposure effects, like the excess of events at high latitudes or the lack of detections above the southern Brazil due to the instruments switching off as entering the SAA. However it is possible to note also some discrepancies like an excess of TGFs above central America and a lack of TGFs for positive latitudes in Africa.

To estimate the compatibility between the TGF and lightning distributions, using the fixed bin size maps shown in Figure 1-C, we calculated the 2D cross-correlation coefficient using the function *correl_images* available in the IDL astrolib package (http://idlastro.gsfc.nasa.gov). The largest 2D cross-correlation coefficient is $r = 0.68$, obtained for zero systematic offset between the two distributions. We note that for normalized distributions and zero offset, as is our case, the 2D cross-correlation coefficient corresponds to the Pearson's correlation coefficient. Unfortunately, the Pearson's coefficient does not allow to estimate a probability value for the null hypothesis that TGFs are drawn from the distribution of lightning, but only for the hypothesis that the two distributions are uncorrelated, which is clearly not the case. The chi-square test was not appropriate as well because of its unreliability in the regime of small number of counts per bin. Further rebinning of data would smooth all most significant geographical features.

A relevant statistical test for our case is the Kolmogorov-Smirnov test (KS hereafter), which provides a probability value (P) for the null hypothesis that two unbinned data sets are drawn from the same distribution. Using the KS test we carried out comparisons between TGF and exposure-corrected lightning distributions, both for global longitude distributions and for the relevant continental areas, selected in the longitude ranges -100 ÷ -50 degrees, -30 ÷ 50 degrees and 80 ÷ 150 degrees, for central America, Africa and south east Asia respectively. These regions account for 22, 60 and 28 TGFs, respectively. Since the KS test works with one-dimensional datasets, for the three continental regions of interest we tested separately longitude and latitude distributions. For each test, the model dataset was built extracting 100000 independent random positions from the exposure-corrected lightning distribution (Figure 1-C). In order to exploit the bi-dimensional characteristics of the data, we also used the generalization of the Kolmogorov-Smirnov test to two-dimentional datasets (2DKS hereafter) as described in the work by [*Press et al.*, 2007]. In this case, however, the resulting p-value is distribution dependent, so we evaluated it by means of Monte Carlo simulations, extracting from the model 1000 synthetic datasets, each with the same number of points as the real TGF datasets, and counting what fraction of synthetic results had a distance D from the model distribution exceeding that obtained with the TGF experimental data. This fraction is our probability. We performed this test both for the global distributions and for the different continental areas described above.

4. Results and Discussion

The results of the tests described above are summarized in Table 1. The KS and 2DKS results for the global case show that the AGILE TGF sample for the considered period is not compatible with the averaged global lightning distribution as is, i.e. AGILE TGFs are not a random sub-sample of time-averaged lightning. This is clearly evident by the small p-value obtained, although the Pearson's correlation coefficient suggests an overall agreement between the two distributions. The results above the single continents show a general improvement in the correlation probability, but with significant differences among different areas. America and Africa show quite poor correlation in both tests. In general, we must also consider that the satellite is sensitive to TGFs occurring roughly in a circle of 300 km radius from the footprint, so lightning well out of the AGILE-covered latitude belt can in principle contribute to TGF detections. This effect contributes as a sort of smearing of the parent lightning distribution, and could be particularly significant for Africa, where the Congo basin accounts for the largest lightning density. However, in the case of south east Asia a high degree of correlation is obtained, suggesting that TGFs and lightning are drawn from the same distribution with a probability of 87%. This is a remarkable result, especially considering the much poorer correlation obtained for the global case and the other continental areas. Although the lightning/TGF association is well established, this result suggests that in south east Asia the global lightning activity is by far a better proxy for TGF production than in other equatorial regions. The reason for this could rely on climatic characteristics peculiar to this region and can be a useful hint for climatological studies as those reported in the work by [*Splitt et al.*, 2010].

Comparing the lightning and AGILE TGF distribution in the equatorial south east Asia region, where a high degree of correlation holds between TGFs and lightning activity, we can estimate an average TGF/lightning flash ratio of $R \simeq 7.5 \text{ x } 10^{-5}$. If we extend the same calculation to other regions where the correlation is poorer we obtain $R \simeq 6.0 \text{ x } 10^{-5}$, $1.5 \text{ x } 10^{-4}$ and $7.8 \text{ x } 10^{-5}$ for Africa, central America and the global case, respectively. Assuming this range of values for the TGF/flash ratio holds at all latitudes and geographical regions, and considering a global occurence of 44 ± 5 flashes per second, as pointed out in the work by [*Christian et al.*, 2003], we can estimate a total global occurrence of $\dot{N} \simeq 220 \div 570$ TGFs per day, which is quite in agreement with the results reported in the work by [*Carlson et al.*, 2009]. However, given the evidence for different TGF production rate above different geographical regions, this global rate must be considered only a crude estimate.

The results shown here are an independent confirmation of those reported in the work by [*Smith et al.*, 2010] concerning an excess of TGFs above central America and south east Asia and a corresponding depletion above Africa. At the moment we cannot discriminate whether this discrepancies are due to an intrinsically different production rate or to a dead-time driven observational bias above Africa due to higher TGF brightness, as suggested by [*Smith et al.*, 2010]. We also note that [*Smith et al.*, 2010] reports an eastward shift between TGF and lightning distribution above south east Asia, which is currently not supported by the the very good agreement we found for the two distributions above that region. However, we must note that our result is obtained over a much narrower latitude region than that considered in the work by [*Smith et al.*, 2010]. Moreover we must consider that the TGF dataset considered span very different periods of time. In fact, while AGILE dataset includes 118 TGFs detected in 12 months, the 1^{st} RHESSI TGF catalog [*Grefenstette et al.*, 2009] includes 144 TGFs in the same latitude range, but detected during 102 months of observation. So, while RHESSI TGFs are up to now the most complete sample for climatological studies at a global scale, AGILE exhibits the higher detection rate surface density (TGFs/month per square degree), even though over a smaller geographical region limited by its orbital inclination.

5. Conclusion

We present a correlation study, based on mono and bi-dimensional Kolmogorov-Smirnov test, of AGILE TGFs detected in one year of observation and global lightning activity provided by LIS/OTD observations. The aim is to link TGFs to average properties of lightning geographical distribution. After correction for the AGILE exposure, we find that we cannot consider the global TGF distribution as a random sample of the lightning distribution. However, we find significant regional differences in the degree of correlation. In particular, in the case of south east Asia we find a 87% probability for the TGF distribution being a sub-sample of lightning. Based on the crude assumption that the observed TGF/lightning ratio holds at all latitudes we can estimate a global rate of $\dot{N} \simeq 220 \div 570$ TGFs per day, in agreement with previous estimates. The observed regional differences are partly in agreement with previous observations and point towards a climatological factor for TGF production. We point out that TGF and lightning samples cover different and not superposed time periods. Given the well known annual lightning activity variation, the high AGILE TGF detection rate surface density will allow time resolved lightning/TGF correlation on seasonal/annual basis, which will be the logical follow-up of this work.

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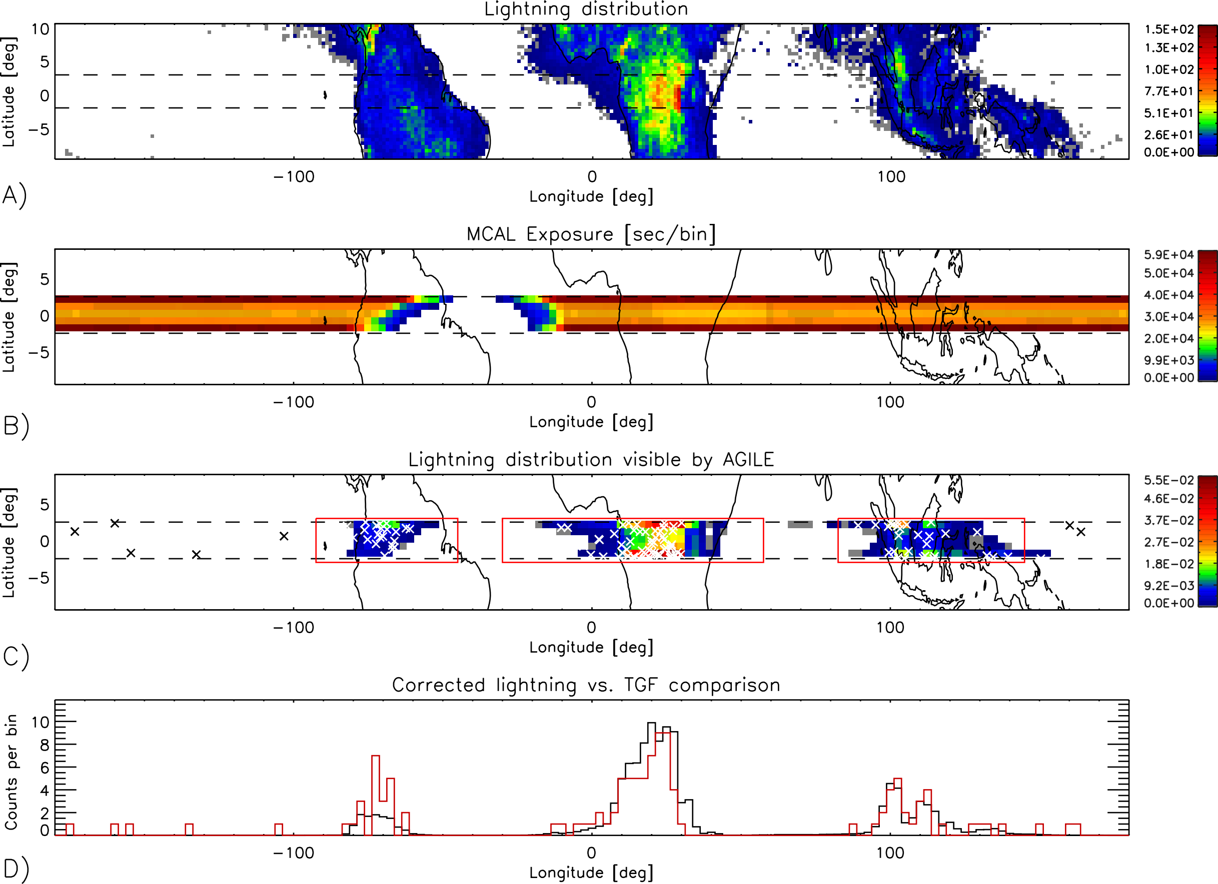
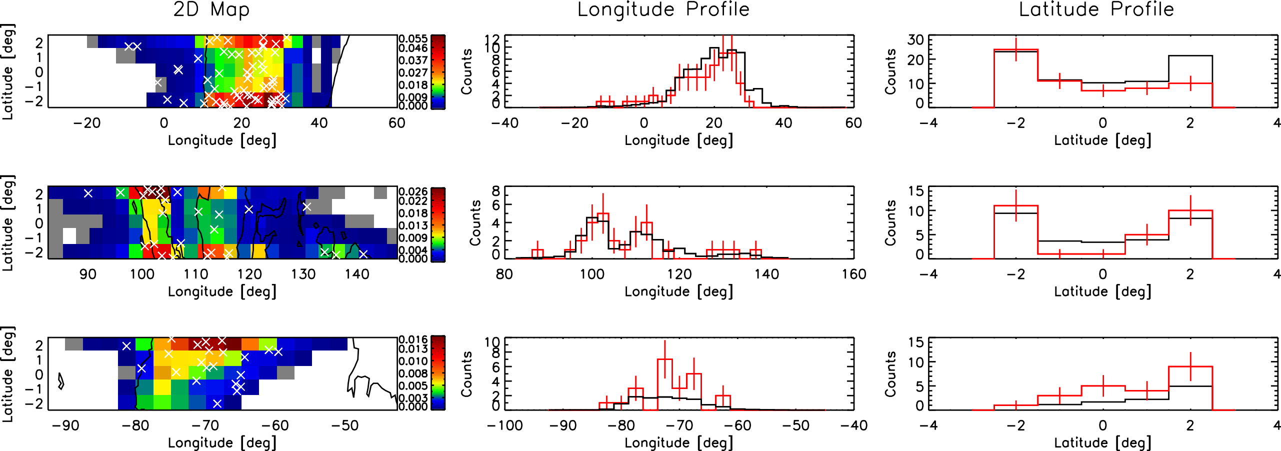
Figure 1. Lightning and TGF maps. A: LIS-OTD high resolution full climatology flashes rate [flashes/km^2/year] (0.5x0.5 deg per bin); B: MCAL exposure map [sec/bin] (2.5x1.0 deg per bin); C: LIS-ODT multiplied by MCAL exposure [flashes/km^2] (2.5x1.0 deg per bin). The crosses indicate the AGILE-TGF locations. The red borders indicate the continental zones showed with more details in Figure 2; D: Longitude distributions, summed over all latitudes, of the AGILE-TGF map (red) and LIS/OTD corrected map (black), corresponding to the maps showed in panel 1-C, normalized to the total number

Figure 2. TGF and lightning distributions comparison. Zoomed views of the continental regions marked with red contours in the Figure 1-C, corresponding respectively to (top to bottom): Africa, South-East Asia and South America. Left column: Exposure-corrected lightning distribution and TGF (white crosses) scatter plot. Center column: longitude distribution, summed over all latitudes, for both lightning (black) and TGF (red). Right column: latitude distribution, summed over all longitudes, for both lightning (black) and TGF (red). Lightning profiles in center and right columns are normalized to the total number of TGFs. Error bars for TGFs are calculated assumin Poisson statistics.

Area	KS p-value		2DKS p-value
of interest	Longitude	Latitude	
Global	0.002	-	0.002
America	0.34	0.45	0.13
Africa	0.17	0.14	0.03
Asia	0.95	0.78	0.87

Table 1. Statistical significance for KS and 2DKS tests


Lightning distribution
Latitude [deg]
10
5
0
−5
−100
0
100
Longitude [deg]
1.5E+02
1.3E+02
1.0E+02
7.7E+01
5.1E+01
2.6E+01
0.0E+00
A)
MCAL Exposure [sec/bin]
5.9E+04
5.0E+04
4.0E+04
3.0E+04
2.0E+04
9.9E+03
0.0E+00
B)
Lightning distribution visible by AGILE
5.5E−02
4.6E−02
3.7E−02
2.7E−02
1.8E−02
9.2E−03
0.0E+00
C)
Corrected lightning vs. TGF comparison
Counts per bin
10
8
6
4
2
0
D)


2D Map
Longitude Profile
Latitude Profile
Latitude [deg]
Longitude [deg]
Counts
Latitude [deg]
0.055
0.046
0.037
0.027
0.018
0.009
0.000
−20
0
20
40
60
−40
12
10
8
6
4
2
0
30
20
10
−4
−2
2
4
1
−1
0.026
0.022
0.018
0.013
0.009
0.004
90
100
110
120
130
140
80
160
15
5
0.016
0.013
0.010
0.008
0.005
0.003
−90
−80
−70
−60
−50
−100