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A new method reveals more TGFs in the RHESSI data

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[1] This letter presents a new search algorithm for identifying Terrestrial Gamma ray Flashes (TGFs) in the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) data. The algorithm has been applied to data from the period 2004–2006 and we have found more than twice as many TGFs as previously reported. The new TGFs follow the same geographical and seasonal variations as the previously reported TGFs. The match percentage between the new TGFs and World Wide Lightning Location Network (WWLLN) data is comparable to the RHESSI catalog TGFs. Our results shows that previous searches only identified the most intense events, and that there might be a large population of faint TGFs. **Citation:** Gjesteland, T., N. Østgaard, A. B. Collier, B. E. Carlson, C. Eyles, and D. M. Smith (2012), A new method reveals more TGFs in the RHESSI data, *Geophys. Res. Lett.*, *39*, L05102, doi:10.1029/2012GL050899.

1. Introduction

[2] TGFs were discovered by *Fishman et al.* [1994] and since then a few satellites have made TGF observations [*Smith et al.*, 2005; *Marisaldi et al.*, 2010a; *Briggs et al.*, 2011]. The majority of TGFs have been observed by RHESSI. By September 2010 the RHESSI catalog contained 975 TGFs, and the instrument is still operating [*Grefenstette et al.*, 2009]. Observations by other spacecraft add up to a few hundreds of TGFs. The Burst And Transient Source Experiment (BATSE) observed 78 TGFs (http://gammaray.msfc.nasa.gov/batse/misc/triggers.html) during its eight year mission. Fermi observed 50 TGFs during their first 21 months of operation [*Fishman et al.*, 2011]. Astrorivelatore Gamma a Immagini Leggero (AGILE) has observed 130 events satisfying stringent TGF selection criteria during the period June 2008 to January 2010 [*Tavani et al.*, 2011]. In addition one TGF has been observed from an airplane by the Airborne Detector for Energetic Lightning Emissions (ADELE) [*Smith et al.*, 2011]. The limited number of events is partially due to the high trigger threshold imposed on the data in order to eliminate spurious events. Relaxing the trigger criteria leads to increasing TGF detection rates [*Fishman et al.*, 2011]. The population of fainter TGFs is currently unknown.

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[3] TGFs have a typical duration of less than 1 ms. The average duration of the RHESSI catalog TGFs is $\sim 0.6 - 0.7$ ms [*Smith et al.*, 2010]. By correcting for deadtime in the BATSE instrument, *Gjesteland et al.* [2010] determined the TGF duration of five TGFs to be between 0.2 ms and 0.3 ms. New results from Fermi have shown that TGFs can be as short as 50 μs [*Fishman et al.*, 2011]. Despite the different methods used to determine TGF duration, the consensus is that typical TGFs are significantly shorter than 1 ms.

[4] Observed TGFs have an energy spectrum $\propto 1/E$ with an exponential cutoff [*Dwyer and Smith*, 2005] where the energy of single photons may be up to several tens of MeV's [*Smith et al.*, 2005; *Marisaldi et al.*, 2010b].

[5] The RHESSI TGF catalog is presented by *Grefenstette et al.* [2009] and can be found at http://scipp.ucsc.edu/~dsmith/tgflib_public. In the following we will refer to these TGFs as the catalog TGFs. *Grefenstette et al.* [2009] also present results from an alternative search algorithm. The numbers and quality of these new events were not quantified, but clearly indicate that there are more TGFs than presented in the catalog.

[6] In this letter we present a new and optimized search algorithm which has been applied to the RHESSI data and show that there are many more RHESSI TGFs than previously reported.

2. Search Algorithm

[7] RHESSI consists of nine segmented germanium detectors for X- and γ- ray detection in the energy range from 3 keV to 17 MeV, where the rear detectors measures counts with energy > 25 keV. For more description of the RHESSI instrument refer to *Smith et al.* [2002] and *Grefenstette et al.* [2009]. The raw RHESSI data are available at: http://hesperia.gsfc.nasa.gov/hessidata.

[8] We use data from the rear RHESSI detectors, considering only counts with energy > 30 keV. Detector G2 was operating poorly, in an unsegmented mode at low voltage, during 2004–2006. As in the work by *Grefenstette et al.* [2009] G2 is not included in our search. Since a high energy photon may deposit energy in more than one detector we combine counts that are detected within ± 1 binary microsecond (2^{-20}s) and regard these counts as one photon. This was also done by *Grefenstette et al.* [2009].

[9] Our search algorithm is in two steps, first a coarse search and then a fine search. The following definitions will be used. The result from the coarse search is called an *event*. If the event passes the fine search we call it a *trigger* and if it also passes a final set of selection criteria which is described below, we call it a TGF.

[10] In the coarse search we use a 1 ms search window. Since TGFs typically last < 1 ms the entire TGF will be within the 1 ms search window. However, there is a

possibility that a given TGF is divided between two consecutive search windows. To avoid this we move the 1 ms search window in steps of 0.5 ms.

[11] For each window we calculate the expected number of background counts for that window. The number of expected background counts is calculated using the average background count rate over times range $t \in [-220, -20]$ ms and $t \in [20, 220]$ ms, where $t = 0$ is the time at the beginning of the search window. The reason for not including the 40 ms around the search window is to exclude the counts from the event itself. While RHESSI TGFs are typically < 1 ms, electron beams produced by TGFs may be up to 25 ms [*Dwyer et al.*, 2008; *Carlson et al.*, 2009, 2011; *Briggs et al.*, 2011]. The average RHESSI background rate is two counts per ms [*Grefenstette et al.*, 2009].

[12] For each window we calculate the probability of getting a false event assuming the background follows a Poisson process:

$$p(x \geq X|N) = 1 - e^{-N} \sum_{i=0}^{X-1} \frac{N^i}{i!}, \qquad (1)$$

where N is the number of expected background counts in the search window and X is the number of counts in the search window. Windows where $p(x \geq X|N) < 10^{-6}$ are called an event. The events are then moved to the fine search. With $p < 10^{-6}$ we would expect $\sim 3 \cdot 10^4$ events per year. However, we found $\sim 10^5$ events per year which we believe is a result of cosmic rays creating several counts in the detectors.

[13] In the fine search we use three sliding search windows; 0.3 ms, 1 ms and 3 ms. As in the coarse search we calculate the probability to measure the number of counts in the search window, X, or greater given an expected background of N, but with a more stringent requirement. If $p(x \geq X|N) < p_{\max}$, where $p_{\max}$ is a chosen threshold, we call the event a trigger. In one year there are $\sim 3 \cdot 10^{10}$ intervals of length 1 ms and since our smallest search window is 0.3 ms there are $\sim 10^{11}$ independent search windows per year. Choosing $p_{\max} = 10^{-11}$, means that we expect to have one false trigger per year due to statistical fluctuations.

[14] To be identified as a TGF a trigger from the fine search must fulfill five selection criteria:

1. Triggers where the background before and after the trigger varies by more than 15% are rejected. This removes triggers artificially caused by event data being turned back on as the satellite leaves the South Atlantic Magnetic Anomaly (SAMA), as well as other false triggers due to a sudden change in background count rate.

2. The duration of a trigger should be more than 0.1 ms and less than 3 ms. The lower duration criterion remove possible cosmic rays which last $\ll 0.01$ ms, but may last up to 0.05 ms in the electronics [*Grefenstette et al.*, 2009]. The longer duration criterion removes possible TGF electron beams which typically last 5–25 ms [*Dwyer et al.*, 2008; *Carlson et al.*, 2009, 2011]. It also removes soft gamma ray repeaters and solar flares which both have longer durations. The duration is determined as $\pm 2\sigma$ of a Gaussian fit to the light curve with bin size of 0.25 ms. Since TGFs may be shorter than the bin size, we have used the same method as *Grefenstette et al.* [2009] to calculate the lower end of the duration, that is, we require that the time between the first and the last photon in the 0.3 ms trigger window should be more than 0.1 ms.

3. To avoid false triggers caused by high voltage arcing in any one of the RHESSI detectors [*Grefenstette et al.*, 2009] only allowed at most 25% of the counts in one detector. We have relaxed this criterion slightly: For the distribution of counts in the eight detectors we require that the value of $\sigma/\sqrt{n} < 1.5$, where σ and n are the standard deviation and the mean of the distribution. A Monte Carlo test of this criterion has shown that this method falsely rejects $\sim 0.2\%$.

4. The hardness ratio H_r of the trigger is determined as the number of counts with energy $E > 1$ MeV divided by the number of counts with energy $E \leq 1$ MeV. Triggers where $H_r \leq 0.025$ are rejected. For TGFs with < 40 counts this criterion implies at least one count with energy > 1 MeV.

5. Triggers where the number of overflow counts (counts with energy > 17 MeV) is larger than 30% are rejected. This criterion removes triggers which we believe comes from high energy deposit by cosmic rays that are not removed by the other criteria.

3. Results

[15] Figure 1 shows three example TGFs from our search. Figures 1a–1c show the light curve and a scatter plot of energy versus time for the counts in the TGFs. The TGF in Figure 1a with $p = 3.07 \cdot 10^{-12}$ is the one found over the Sahara desert, which is a place we do not expect to observe TGFs. However, it could be a part of a TGF electron beam as reported by *Dwyer et al.* [2008] and *Briggs et al.* [2011]. Figure 1b shows one of the weakest TGFs found in the new search ($p = 8.16 \cdot 10^{-12}$) and contains only 11 counts. The TGF in Figure 1c with $p < 10^{-16}$ is a typical TGF. This one is also in the RHESSI catalog.

[16] In the data from 2004, 2005 and 2006 we found a total of 1012 TGFs, of which 958 passed our criteria with a 0.3 ms search window, 648 with 1 ms search window and 272 with 3 ms search window. Figure 1d shows the new TGFs as red circles and the catalog TGFs as green dots. For the period 2004–2006 the RHESSI catalog contains 474 TGFs of which our search algorithm found 458. Hence, there are 16 catalog TGFs which are not found in this new search. Seven of these had $p > 10^{-11}$ and so the rest were rejected due to the criteria we applied.

[17] We have searched for matches between the new RHESSI TGFs and WWLLN events as described by *Collier et al.* [2011]. A match is defined when a WWLLN event occurs closer than 2400 km from the RHESSI sub satellite point within ± 10 ms of the TGF. The result is shown in Table 1. We found that the number of matches is slightly higher than reported by *Collier et al.* [2011]. They found that the catalog TGFs that matched with the WWLLN events were from the weaker part of the TGF intensity distribution. Thus the comparable match percentage we found for the new search, which contains fainter TGFs than in the catalog, is consistent with the result of *Collier et al.* [2011]. Also *Connaughton et al.* [2010] found a comparable match percentage between WWLLN and FERMI when the search criteria were relaxed.

[18] By choosing $p_{\max} = 10^{-10}$ we find 1283 events. Some of these appear in regions where one does not expect to find TGFs. Also the match percentage with WWLLN starts to

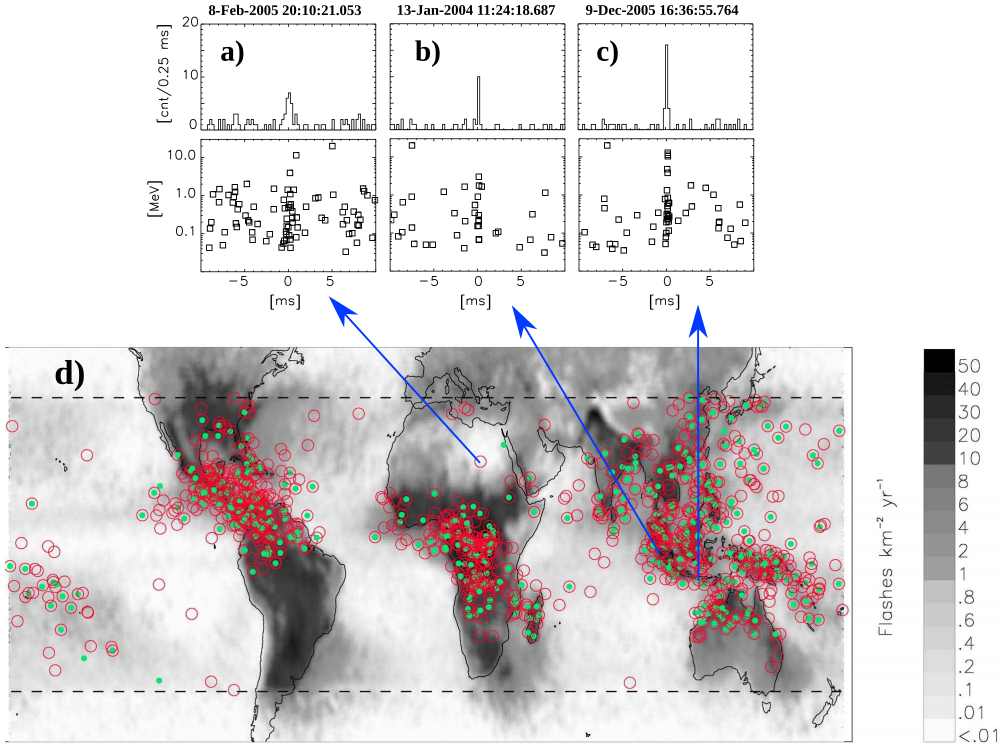

Figure 1. (a–c) (top) The light curve and (bottom) each photon with energy versus time. Figures 1a and 1b are new TGFs. Figure 1c is also presented in the RHESSI catalog. (d) RHESSI TGFs for the years 2004, 2005 and 2006. The red circles are TGFs found with the new search algorithm (1012 TGFs) and green dots are TGFs from the RHESSI TGF catalog (474 TGFs). There are no TGFs in most of South America since RHESSI does not provide data for this region (SAMA). The grey scale indicates lightning activity measured by LIS/OTD. The dashed lines are the limits of the RHESSI 38° inclination orbit.

drop at $p_{\max} = 10^{-10}$. Even if many of the events where $p_{\max} = 10^{-10}$ are assumed to be real TGFs we choose to use $p_{\max} = 10^{-11}$ to keep our search results clean.

[19] An animation showing the lighting activity from the Lightning Imaging Sensor (LIS) gridded time series data [*Christian et al.*, 2003] and the occurrence of TGFs is uploaded in the auxiliary material.[1] Animation S1 shows that the TGFs we have found follow the seasonal variation in lighting activity. For example during the northern hemisphere winter we have found only one TGF over the Caribbean while the vast majority of TGF observations in the Caribbean occur during northern hemisphere summer and fall. A similar variation is also found in the lightning activity [*Christian et al.*, 2003]. This seasonal variation of TGFs is well established. *Splitt et al.* [2010] have shown that RHESSI catalog TGFs follow the diurnal, seasonal, and geographic patterns of lightning activity.

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2012gl050899. Other auxiliary materials files are in the HTML. doi:10.1029/2012GL050899.

[20] The intensities of the new RHESSI TGFs and the catalog TGFs are shown in Figure 2a, with black and red curves respectively. As expected most of the new TGFs are weaker than the catalog TGFs. Assuming that the TGF fluence distribution follows a power law we would expect to find more TGFs when the lower threshold for detection are reduced [*Collier et al.*, 2011; *Østgaard et al.*, 2012].

[21] Due to radiation damage in the RHESSI instrument, events occurring before 1 January 2005 are the most reliable for energy analysis [*Grefenstette et al.*, 2009]. Figure 2b

Table 1. Number of TGFs/Year From the RHESSI Catalog N_c and From the New Search N_n[a]

	RHESSI Catalog		New Search TGFs	
Year	N_c	Match (%)	N_n	Match (%)
2004	156	7.7	362	7.2
2005	181	6.1	344	7.8
2006	135	7.4	306	12.4

[a]The percentage match between TGFs and WWLLN for the RHESSI catalog, N_c [*Collier et al.*, 2011], and the new search N_n is also shown.

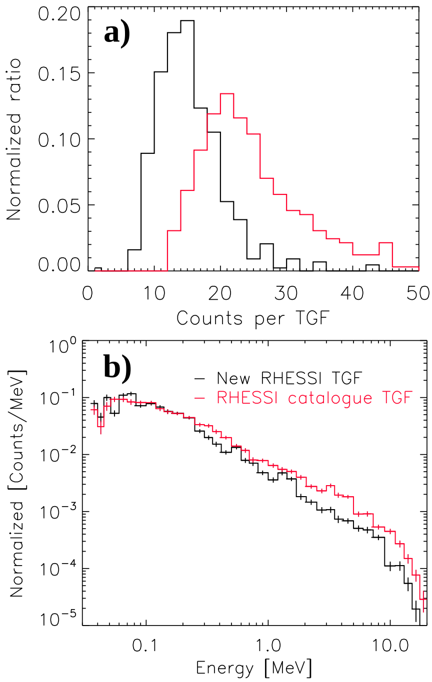

Figure 2. (a) Distribution of TGF intensity for year 2004, 2005 and 2006. Black is from 554 new TGFs and red is from 474 catalog TGFs. (b) The energy spectrum from 156 catalog TGFs in 2004 in red. The black spectrum is 210 TGFs only found in the new search. Notice that the new energy spectrum is softer than the catalog energy spectrum.

shows superposed energy spectra for TGFs occurring during 2004. The red curve is TGFs from the RHESSI catalog. The black curve contains only new TGFs for the same period. The energy spectrum from the new TGFs is softer than the energy spectrum from the catalog. If we assume an upper limit on the TGF intensity we expect that reducing the detection threshold leads to an increase in the satellite's field of view since attenuation and distance effects reduce the TGFs fluence at increasing distances. Simulations by *Østgaard et al.* [2008] have shown that Compton scattering will soften the energy spectrum for TGFs observed at large distances. It is also found that RHESSI TGFs measured at large distances have a softer energy spectrum than TGFs measured closer to the sub-satellite point [*Hazelton et al.*, 2009; *Gjesteland et al.*, 2011].

[22] The main difference between the algorithm presented here and the one presented by *Grefenstette et al.* [2009] are: 1) Relaxing the signal to noise threshold. *Grefenstette et al.* [2009] required at least $12 \cdot \sqrt{N+1} + N$ counts in a 1 ms window where N is the background. This will give a threshold of $p < 10^{-16}$ when $N = 2$ counts per ms which is the average RHESSI count rate . The new algorithm require $p < 10^{-11}$.2) We have used a shorter search window (0.3 ms in addition to 1 ms and 3 ms). 3) We have included a criterion on the hardness ratio similar to the one used in AGILE search [*Marisaldi et al.*, 2010a].

[23] The search presented here is developed to lower the threshold for detection to find new TGFs with $p < 10^{-11}$. The p-value is chosen such that we expect to find one false TGF per year based on statistical fluctuations. However, since the background spectrum is softer than the TGF spectrum, our criteria may reduce this value. We cannot be sure that our search does not include false TGFs. However, since the new TGFs are found in regions known to produce TGFs, and since the match with WWLLN events is improved in the new search we feel confident that the vast majority of the TGFs found in this study are real TGFs.

[24] In the auxiliary material we provide the time to the nearest ms and location for the 1012 TGFs found by our search. It has been suggested that the RHESSI clock is approximately 1.8 ms slower than UTC [*Grefenstette et al.*, 2009] and therefore 1.8 ms should be added to the times we present.

4. Summary

[25] We have developed a new search algorithm which has been applied to the RHESSI data for the years 2004, 2005 and 2006. Our findings are:

1. We have more than doubled the population of detected RHESSI TGFs in this period.
2. The RHESSI TGFs follow the seasonal variation of lightning activity.
3. The match percentage with WWLLN events is comparable for the new TGFs, indicating that WWLLN is just as sensitive to the source lightning for new TGFs as the catalog TGFs.
4. The superposed energy spectrum of the new RHESSI TGFs is softer than the superposed spectrum of the RHESSI catalog, which indicates that RHESSI field of view is increased.

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