PROCEEDINGS OF SCIENCE

Investigating the electron acceleration location in winter thunderclouds by on-ground gamma-ray and radio observations

Kazuhiro Nakazawa,[a,b,*] **Manari Oguchi,**[b] **Ting Wu,**[c] **Yuuki Wada,**[d] **Keigo Okuma,**[b] **Mii Ando,**[b] **Atsuya Tanaka,**[b] **Teruaki Enoto,**[e,f] **Daohong Wang,**[c] **Gabriel Diniz,**[f] **Taro Shinoda**[g] **and Yuko Ikkatai**[h]

[a] *Nagoya University, KMI*
Furo-cho, Chikusa-ku, Nagoya City, Aichi 464-8602, Japan
[b] *Nagoya University, School of Science*
Furo-cho, Chikusa-ku, Nagoya City, Aichi 464-8602, Japan
[c] *Gifu University, Faculty of Engineering*
1-1 Yanagido, Gifu City, Gifu 501-1193, Japan
[d] *Osaka University, Department of Engineering*
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
[e] *Kyoto University, Faculty of Science*
Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
[f] *RIKEN, Extreme Natural Phenomena RIKEN Hakubi Research Team*
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[b] *Nagoya University, ISEE*
Furo-cho, Chikusa-ku, Nagoya City, Aichi 464-8601, Japan
[h] *Kanazawa University, Institute of Human and Social Sciences*
Kakuma-cho, Kanazawa City, Ishikawa 920-1192, Japan

E-mail: nakazawa@u.phys.nagoya-u.ac.jp

Gamma rays from thunderclouds are direct evidence of ~ 30 MeV electron acceleration by static electric field in the sky. On 2021/12/30, five consecutive Terrestrial Gamma-ray Flashes (TGFs) were detected by our gamma-ray detectors placed on Kanazawa City, Japan. Although analog signals of our gamma-ray detectors were severely saturated, timing of the five TGFs were well constrained and compared with radio observations. We detected four slow radio pulses associated with the first four TGFs, which were located ~ 3 km south from the on-going upward negative lightning discharge. Our results suggests that the TGF's acceleration location can be a few km apart from the leader development of the main discharge activity.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)274

1. Introduction

Thunderstorm activity is known to produce gamma rays with energies exceeding 30 MeV, which are direct evidence of electron acceleration in the dense atmosphere (e.g. [1]). Basic mechanism of the acceleration is widely understood to be so called "Relativistic Runaway Electron Avalanche (RREA)", in which seed high-energy electrons are accelerated and amplified by avalanche [2]. However, the actual physical parameters of the acceleration region is far from clear. There are two types of thunderstorm gamma-ray emission known. The first one is a gamma-ray glow, which lasts for minutes. By observations on ground and on air, thundercloud itself is understood to host a quasi-static electron acceleration region(s) (e.g. [3–6]). Another one is the Terrestrial Gamma-ray Flashe (TGF) which is a short duration (< 1 ms) phenomenon. TGFs, when observed by gamma-ray satellites in 400–800 km altitude orbits, typically have a duration of 50–10 μs and a fluence of 0.1–1 photons cm^{-2} s^{-1} (e.g. [7–10]). TGFs are also observed in the sky from airplanes (e.g. [11]) and on ground (sometimes called downward-TGFs; e.g. [4, 12–14]). In both phenomena, origin of the seed high-energy electrons, size and geometry of the acceleration region, and the highest possible radiation doses are not known.

Winter thunderstorms along the Sea of Japan is famous for their low-altitude cloud bases (typically 0.2–0.8 km), which enables ground detection of thunderstorm gamma rays. We have been performing the Gamma-Ray Observation of Winter Thunderclouds (GROWTH) experiment in this region since 2006. We have reported glows (e.g., [4, 6, 16]) and TGFs, or short bursts (e.g., [15, 17]). In all cases, a TGF is associated with lightening discharges, which can be observed by radio antenna arrays [20]. In some cases, termination of glow are associated with TGF(s) (e.g., [18, 19]). On-ground observed TGF is as strong as 1–10 μGy [17] and therefore can be detected in larger distance than a glow, and there are many TGFs observed without a glow.

Combining low-frequency (LF) radio observations with gamma-ray ones is a promising approach. It is reported that some of the satellite-observed TGFs are associated with a specific slow radio signal called (positive) Energetic In-cloud Pulse (+EIP) (e.g. [21]) or (positive) Narrow Bi-polar Events (+NBE) (e.g. [22]). Radio observations showed that TGFs took place at the timing when a negative leader is ascending (e.g. [23]). However, the altitude of the +EIP/NBE is not resolved because the pulse is slow and observed from distance and hence does not have enough resolution to determine its altitude. Similarly, on-ground measurements of TGFs also showed coincidence with slow radio pulses of small-bipolar type with modest peak currents, and the energetic-bipolar type with high peak currents [20].

In this work, we report gamma-ray signals detected from a lightning discharge event observed in Kanazawa city on 30 December 2021 (JST). The timing of the lightning discharge was 04:08:34.8 JST (GMT+9 hr). Five TGFs are detected by five independent gamma-ray detectors, and the signals were compared with the radio signals.

2. Observations and data analyses

2.1 Gamma-ray signals

Gamma-ray glow from the thundercloud was detected in detectors located around Kanazawa station, starting around 04:07:00. See Tsurumi et al. (2023) [25]. XRAIN rain radar detected a

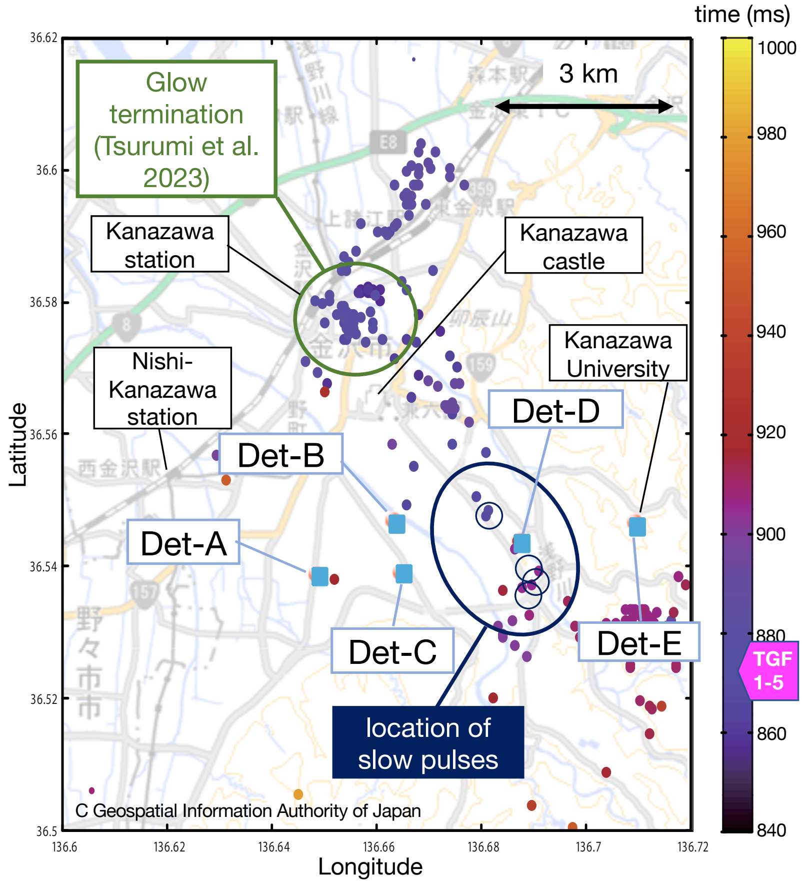

Figure 1: Map of Kanazawa area. Det-A to E denotes the locations of our five detectors. Discharge location time distribution map obtained from FALMA was also shown. Filled circles are from automatic location procedure. In addition, locations of the four apparently slow radio signals coincident with TGF1-4 are shown as open circles. Northern green circle is the region where the gamma-ray glow was reported by [25].

thundercloud with two ∼ 2 km wide high-intensity raining regions (or cores) separated by 3–6 km along northwest to southeast, moving towards east. The glow position matches the northern core, and the lightning discharge was initiated there. By using several compact gamma-ray detectors distributed in the city region, the glow was estimated to have a size of ∼ 2 km in diameter. The glow terminated in coincidence with the lightning discharge.

We were operating another five gamma-ray detectors, located 3–4 km south from the northern core, as shown in Fig 1. They are distributed in an area with a size of ∼ 5 km east-west and ∼ 1 km north-south. Two types of detectors were used in this work, as shown in Fig.2. Det-A, C and E were packaged in water-tight box with ∼ 40 cm size and placed on the roof of Kanazawa Izumigaoka High School (Det-A), Kanazawa University High School (Det-C) and Kanazawa University Kakuma Campus (Det-E). Each detector has a $Bi_4Ge_3O_{12}$ (BGO) scintillation crystal with a size of $25 \times 8 \times 2.5$ cm^3 (hereafter large-BGO). It is coupled with two photo-multiplier tubes (PMTs), and their summed output pulse signals with typically ∼ 2 μs shaping time were fed into a 50 MHz sampling analogue-to-digital converter (ADC). Signal information of the waveform, such as trigger timing and the maximum and minimum value of the ADC (ADC_{max} and ADC_{min}, respectively), were recorded by the data acquisition (DAQ) system (see e.g. [16] for the DAQ sysetem). In addition, Det-D has a $2.1 \times 2.1 \times 0.5$ cm^3 small Gd_2SiO_5 (GSO) crystal. In total, they have four (1 + 1 + 2) signal lines. Det-B and D were individually enclosed in a ~ 1.3 m wide plastic hats. Det-B is located in Ishikawa children's activity center and Det-D in Ishikawa police school. Each system had four large-BGO crystals; three with 2.5 cm thick lead collimator inclined to the west, vertical and to the east. The fourth BGO (called norm-BGO) has no collimator, and its geometry is virtually the same to those of Det-A, C and E, although it has a plastic scintillator to distinguish high-energy electrons. In total, the two detectors have ten (5 + 5) signal lines.

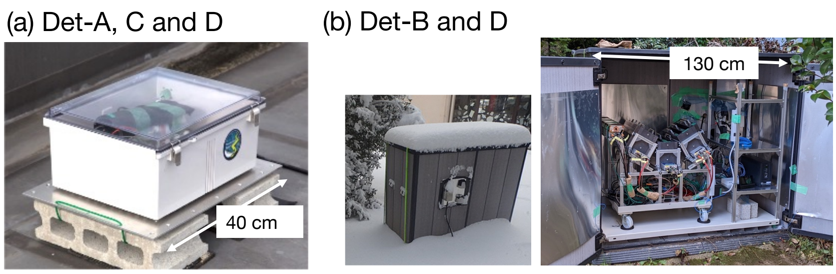

Figure 2: (a) External view of the Gamma-ray detectors, Det-A, C, and D. (b) External view of Det-B. See text for detail.

A spike of signal was detected at 04:08:34.8 (JST) in a 1 s-binned count-rate time profile of all the 14 signal lines. Using the enlarged view of the time profiles, we identified five independent groups in timing, in many all lines excluding the GSO which missed the fifth one. We named them as TGF-1 to 5. Examples and summed profile are shown in Fig.3. TGFs are sometimes known to be associated with ~ 50 ms exponentially decaying component, originating from fast neutron generated via photo-nuclear reaction (e.g. [15]). In this event, such emission was not significant.

In the middle of the five TGFs, the signal intensity is too large and the analog signals of the detectors were severely saturated, with large undershoot observed, i.e. ADC_{min} gets significantly lower than 0 V. Thanks to our DAQ design, gamma-ray signals even within this undershoot period can be triggered and recorded, because we utilized a digital high-pass filter before triggering the signal (see [17] for example). As a result, gamma-ray events hitting the detector right at the peak of each TGF is not fully recorded, but those hitting at the start and end of the TGF are recorded with good efficiency.

Our DAQ systems are time-tagged using GPS, with an accuracy of ~ 1 μs [17]. This fact can give a location accuracy of (1 μs) $\times$ (3×10^8 m s^{-1}) = 300 m using "time of arrival (ToA)" difference, on paper. However, the observed TGF rising edge was not fast enough, and we could not find any statistically significant timing shift among the five detectors. We therefore added all the signals observed in the 14 signal lines, to improve the statistics of our gamma-ray data (see Fig.3 (c)). Statistic has improved significantly, but as many of the photons around the peak intensity is not recorded (because of saturation of individual signal lines), we could not use the "average" timing as the "timing" of each TGF. Thus, to time-tag each TGF, we defined its time region as between "the 11th event from start of the group" and "the 11th from the last", as shown in the Fig.3 (c). The middle of the two timing is indicated as a yellow line, and we used this value as a representative timing of the TGF. TGF-1 started at around 04:08:34.8685 (JST) and TGF-5 lasted until 34.874 (JST). In other words, the gamma-ray event lasted for about 5.5 ms.

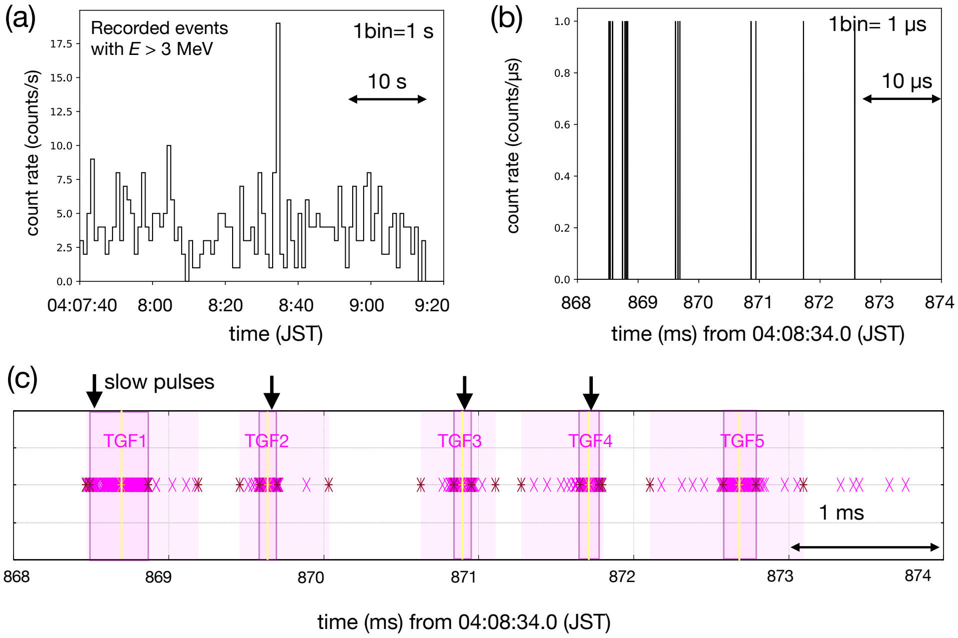

Figure 3: (a) Time profile of the gamma-ray signals recorded by norm-BGO of Det-D. A TGF is recorded at 04:08:34.8 (JST). (b) Enlarged view of the TGF time profile. For ease of discussion, time regions of the five TGFs as we defined is shown with magenta shadows. See text for detail.

2.2 Low-frequency radio signals

We were operating Fast Antenna Lightning Mapping Array (FALMA)[24] in the Hokuriku region, covering Kanazawa city, to obtain a time-tagged-map of lightning discharge channels using ToA of 10 radio antenna in different locations (see e.g. [25]). The system works in the low-frequency band (0.5–500 kHz). As shown in [25], another system called DALMA [26] recorded 3D mapping in higher frequency. For simplicity, we concentrate on FALMA 2D map data in this work. Comprehensive results will be summarized in another paper (Nakazawa et al. 2023, in prep.). The localization accuracy of FALMA is estimated to be about 200 m when observing winter thunder storms[27]. The 2D discharge map was shown in Fig.1.

From the radio array data, Tsurumi et al. (2023) showed that the initiation of the discharge started at the middle of the gamma-ray glow observed around Kanazawa station (4 km north-west of our detectors) at 04:08:34.8565 (JST). The timing was 12 ms before the start of TGF-1. The discharges in this region largely located within the northern core of the cloud (hereafter, the northern discharge), continued for ∼ 30 ms, until 10–15 ms after the end of TGF-5.

The automatic location definition system of FALMA uses faster radio pulses, so that their location can be clearly defined by the ToA method, and therefore slow pulses cannot be identified. By visual inspection of the radio signals, we found four “small-bipolar type” signals associated with

TGF 1–4, individually. The pulses have a typical width of 10–50 μs (hereafter, "slow pulses"). By comparing the ToA of these slow pulses, we determined their location with $\sim$ 500 m accuracy. TGF-5 was also associated with similar signal, but with lower significance, and hence the location could not be determined. Looking at Fig.1, we can see that locations of the four slow pulses are $\sim$ 4 km separated from the northern discharge, and located within our gamma-ray detector region. At the timing of TGFs, there was only a single automatically detected discharge point around our gamma-ray detectors, and the lightning discharge development in this region was not significant at this moment.

3. Discussion and conclusion

Existing combined TGF, 3D radio and low-frequency radio observation in Mexican Bay region has shown that (upward) TGFs took place at the timing when a negative stepped-leader is ascending up the sky. The TGFs were frequently associated in timing with "slow pulses" (i.e. EIP and NBE, e.g. [23]). These relations were understood to be suggesting that the location of TGF is at the middle of the lightning discharge. Notably, our combined gamma-ray and radio observations are literally "consistent" with these reports. However, localization of the four slow pulses were not within the subsequent faster radio pulses, presumably the ascending negative stepped leader in the northern discharge, but located 3–4 km south of it.

Because gamma-ray observations at this moment cannot determine the location of TGFs by their own (mainly because their signals are too strong), it is in principle not clear that the electron acceleration region of a TGF is associated in position with the slow pulse or EIP or NBE associated in timing. However, all seven TGFs detected in four winter seasons in this region are associated either with a specific radio signals called energetic-bipolar and small-bipolar types [20], and therefore association of TGF and slow radio pulses are highly likely. In this case, our results shows that the electron acceleration region of TGF is not necessarily associated within the developing stepped leader. On the other hand, the region of the slow pulses are located within the southern high-intensity raining regions, and still located within the cloud core. Detailed analyses of the radio waveform of FALMA, comparison of the 3D mapping data of DALMA, compared with the XRAIN rain radar 3D reflection map is on-going (Nakazawa et al. in prep.).

Our results showed that the electron acceleration site of a TGF can emerge in a region 3–4 km apart from the ascending stepped leader. The results strongly suggest a need to develop new TGF observing detectors with angular resolution as well as high timing resolution. By locating a few of such detectors, we can determine the location of the electron accelerator in 3D. Comparing this 3D map with that of radio 3D map will make a breakthrough in the TGF science.

Acknowledgement

This work is supported by MEXT/JSPS KAKENHI Grant Number 21H00166, 20H00157, 21K03681 and XXXX. It is also supported by research grant from Foundation of public interest of TATEMATSU, and inter-University research grant of Tokai National Higher Education and Research System.

References

[1] Dwyer, J. R. (2012). The relativistic feedback discharge model of terrestrial gamma ray flashes. Journal of Geophysical Research: Space Physics, 117(A2).

[2] Gurevich, A., Milikh, G., & Roussel-Dupre, R. (1992). Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. Physics Let- ters A, 165(5), 463 - 468.

[3] Torii, T., Sugita, T., Tanabe, et al. (2009). Gradual increase of energetic radiation associated with thunderstorm activity at the top of Mt. Fuji. Geophysical Research Letters, 36(13), L13804.

[4] Tsuchiya, H., Enoto, T., et al. (2007). Detection of high-energy gamma-rays from winter thunderclouds. Physical Review Letters, 99, 165002

[5] Chilingarian, A., Hovsepyan, G., & Hovhannisyan, A. (2011). Particle bursts from thunderclouds: Natural particle accelerators above our heads. Physical Review D, 83, 062001. https://doi.org/10.1103/PhysRevD.83.062001

[6] Wada, Y., Matsumoto, T., et al. Catalog of gamma-ray glows during four winter seasons in Japan, Phys. Rev. Research 3, 043117 (2021)

[7] Fishman, G. J., Bhat et al. (1994). Discovery of intense gamma-ray flashes of atmospheric origin. Science, (5163), 1313–1316.

[8] Smith, D. M., Lopez, L. I., Lin, R. P., & Barrington-Leigh, C. P. (2005, February). Terrestrial Gamma-Ray Flashes Observed up to 20 MeV. Science , 307 (5712), 1085-1088.

[9] Marisaldi, M., Fuschino, F., Labanti, C., Galli, M., Longo, F., Del Monte, E., . . . Salotti, L. (2010). Detection of terrestrial gamma ray flashes up to 40 mev by the agile satellite. Journal of Geophysical Research: Space Physics, 115(A3).

[10] Briggs, M. S., Xiong, et al. Terrestrial gamma-ray flashes in the fermi era: Improved observations and analysis methods. Journal of Geophysical Research: Space Physics , 118 (6), 3805-3830.

[11] McCarthy, M., & Parks, G. K. (1985). Further observations of x-rays inside thunderstorms. Geophysical Research Letters, 12(6), 393-396.

[12] Torii, T., Takeishi, M., & Hosono, T. (2002). Observation of gamma-ray dose increase associated with winter thunderstorm and lightning activity. Journal of Geophysical Research: Atmospheres, 107(D17), ACL 2-1-ACL 2-13.

[13] Chilingarian, A., Daryan, et al. (2010, Aug). Ground-based observations of Signal of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons. Phys. Rev. D, 82, 043009.

[14] Dwyer, J. R., Schaal, et al. (2012). Observation of a gamma-ray flash at ground level in association with a cloud-to-ground lightning return stroke. Journal of Geophysical Research: Space Physics , 117 (A10).

[15] Enoto, T., Wada, Y., et al. (2017, November). Photonuclear reactions triggered by lightning discharge. Nature, 551(7681), 481-484.

[16] Yuasa, T., Wada, et al. (2020, October). Thundercloud Project: Exploring high-energy phenomena in thundercloud and lightning. Progress of Theoretical and Experimental Physics, 2020(10), 103H01.

[17] Wada, Y., Enoto, T., etal. (2019). Downward terrestrial gamma-ray flash ob- served in a winter thunderstorm. Physical Review Letters, 123, 061103.

[18] Wada, Y., Enoto, T., et al. (2019). Gamma-ray glow preceding downward terrestrial gamma-ray flash. Communications on Physics, 2(1), 67.

[19] Hisadomi, S., Nakazawa, K., et al. (2021). Multiple gamma-ray glows and a downward tgf observed from nearby thunderclouds. Journal of Geophysical Re- search: Atmospheres , 126 (18), e2021JD034543.

[20] Wada, Y., Morimoto, T., et al. (2022) Characteristics of low-frequency pulses associated with downward terrestrial gamma-ray flashes., Geophysical Research Letters, Volume 49, Issue 5, article id. e2021GL097348

[21] Lyu, F., Cummer, S. A., et al. (2016). Ground detection of terrestrial gamma ray flashes from distant radio signals. Geophysical Research Letters, 43(16), 8728-8734.

[22] Zhang, H., Lu, G., et al. (2021). On the terrestrial gamma-ray flashes preceding narrow bipolar events. Geo- physical Research Letters, 48(8), e2020GL092160.

[23] Cummer, S. A., Lyu, F., et al. (2015). Lightning leader altitude progression in terrestrial gamma- ray flashes. Geophysical Research Letters, 42(18), 7792-7798.

[24] Wu, T., Wang, D. and Takagi N. (2018) Lightning Mapping With an Array of Fast Antennas, Geophysical Research Letters, 45(8), 3698–3705.

[25] Tsurumi, M., Enoto, T., et al. (2023) Citizen Science Observation of a Gamma-Ray Glow Associated With the Initiation of a Lightning Flash, Geophysical Research LettersVolume 50, e2023GL103612

[26] Wang, D., Wu, T., et al. (2022), 3D Mapping of Winter Lightning in Japan with an Array of Discone Antennas, 17, 1606-1612

[27] Wu, T., Wang, D. and Takagi N. (2020), Multiple-Stroke Positive Cloud-to-Ground Lightning Observed by the FALMA in Winter Thunderstorms in Japan, Journal of Geophysical Research: Atmosphere, 125(20), e2020JD033039