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Terrestrial gamma-ray flashes with ADELE, GODOT and THOR

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Over the past 15 years, the high-energy atmospheric physics group at the University of California, Santa Cruz, has developed and deployed instrumentation for the detection of TGFs on the ground and aboard aircraft. While the nature of this observing strategy is that far fewer events are observed than can be seen from spacecraft, with their very large (~600km radius) detection footprint, there are many discoveries that can only be made by observing up close, and our group and other groups internationally have had numerous successes. Using our three generations of detector arrays (ADELE, 2009-2015; GODOT, 2014-present; and THOR, 2021-present) we have observed:

- the downward reverse beam from an upward TGF (Bowers et al. 2018)
- neutrons produced as a byproduct of TGF gamma-rays and electrons (Bowers et al. 2017)
- the absence of TGFs from most lightning, with luminosity limits up to a factor of 10^7 lower than expected TGF luminosities (Smith et al. 2011, 2018)
- downward TGFs associated with unique classes of radio emission that had previously been connected with upward TGFs seen from space (slow pulses and energetic intracloud pulse (EIPs)); (Chaffin et al. 2024)
- downward TGFs detected from unexpectedly large distances, suggesting a much broader beam than has been inferred for upward TGFs (Ortberg et al. 2024)
- evidence for production of bursts of radiation all during downward leader propagation taking place at the top of the growing channel, transitioning gradually to a "full"TGF during the return stroke current (unpublished work).

There are six copies of THOR, our latest generation of detector, deployed worldwide to investigate TGF production in distinct environments: mountaintop and low-elevation, coastal and inland, tropical and temperate, and regions that primarily experience summer or winter lightning. The primary technical advances of THOR over the previous generations of instrument are 1) microsecond absolute timing using GPS, and 2) a dual data mode that returns both a list of individual photon events (time and energy tagged) with 100% coverage, and small bursts of data with the direct digitized output of the photomultiplier tubes at 12.5 nanosecond resolution when a bright event like a TGF occurs.

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