Triggered Lightning (Normal Speed Video)

Today's
"Prometheus"

Or

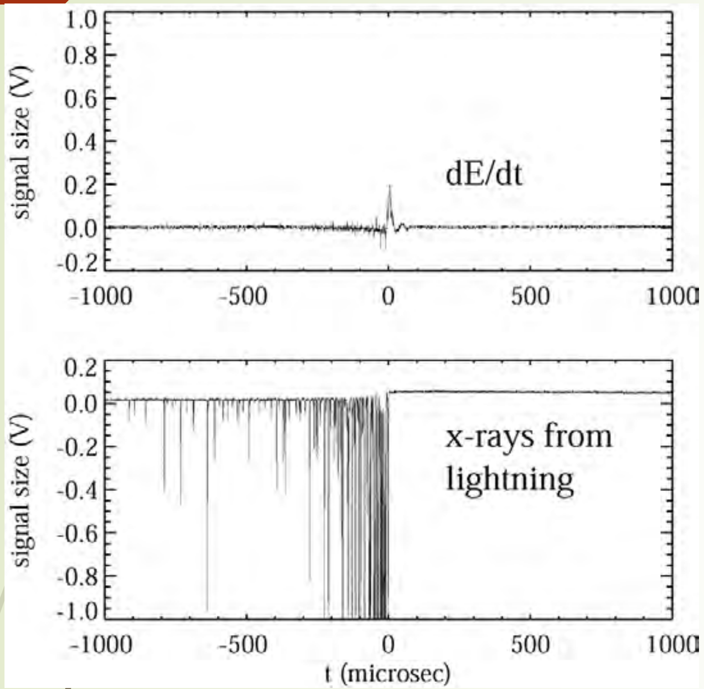
Modern Day
"Franklin"

Note: More examples of UF's successful triggered Lightning can be found on YouTube.

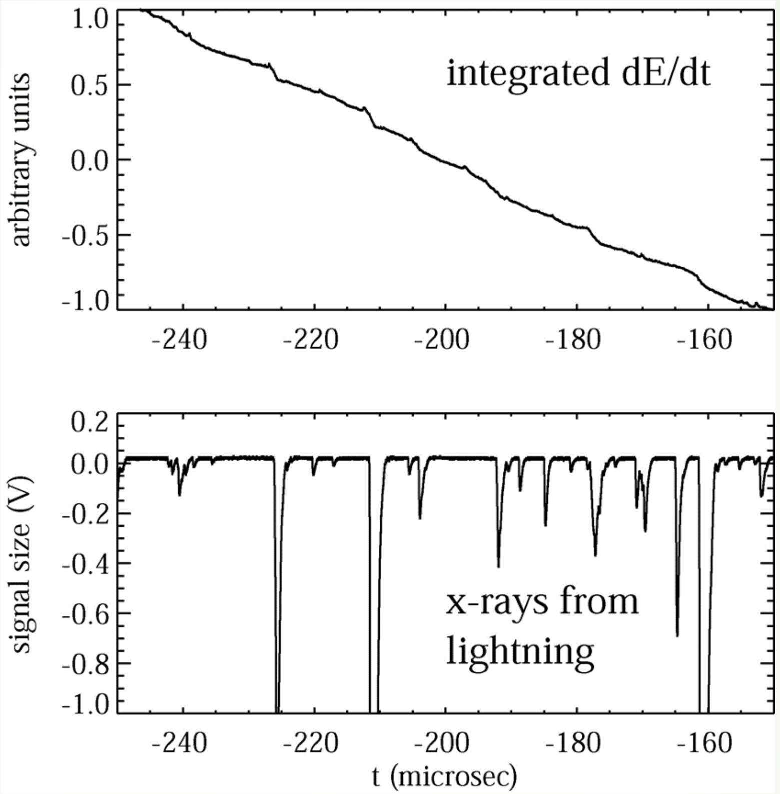
Triggered Lightning (Slow Motion Video)

Exciting discoveries are the currency of scholarships. Scholarships can be the currency of research funding to do more pioneering work.

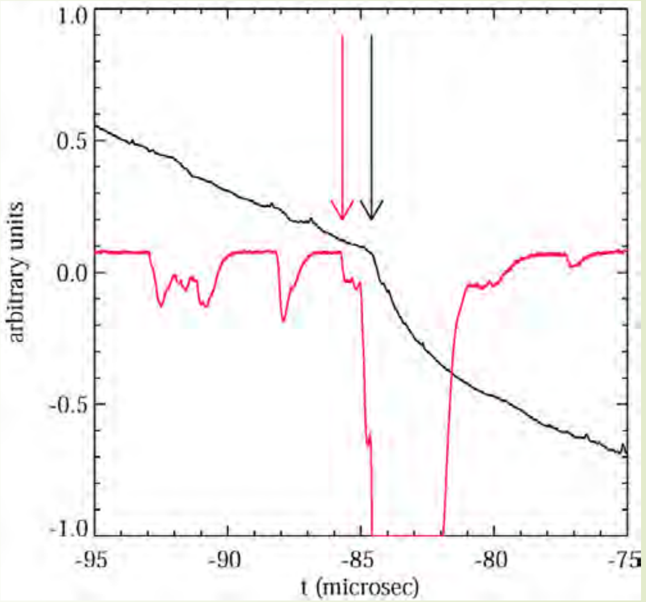
Example of TERA observation



Natural lightning strike as measured by a TERA station 600 m away from strike point.



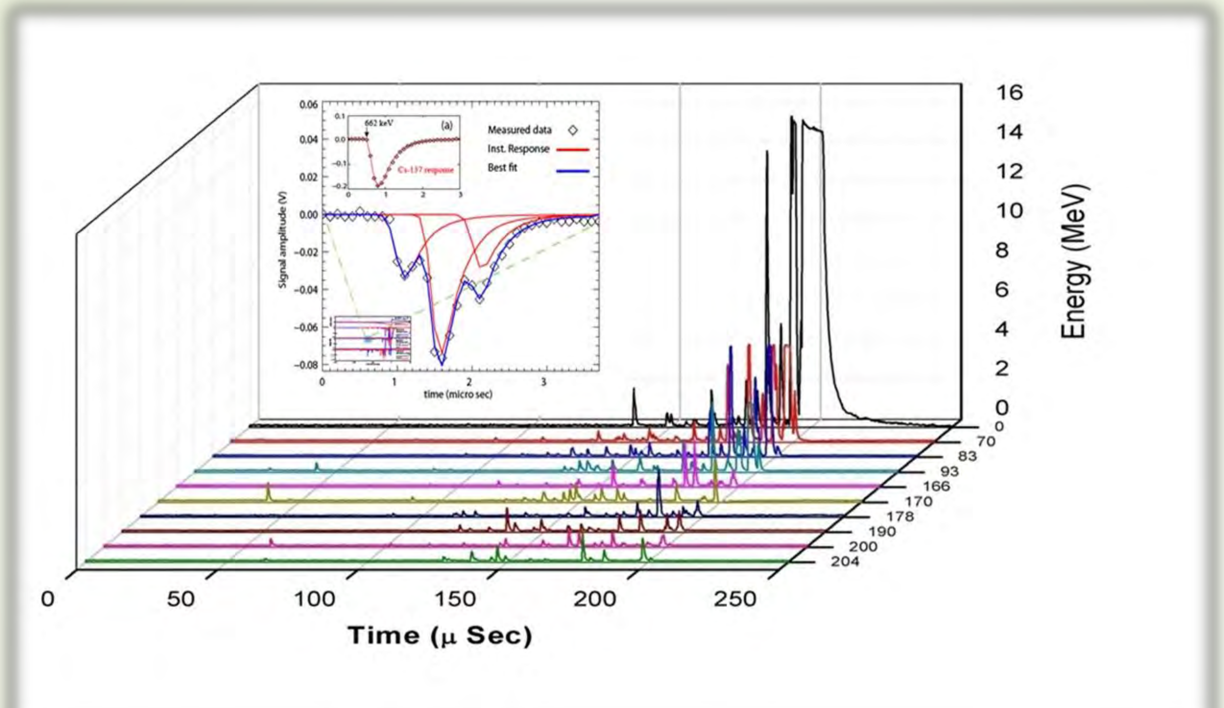
Close up of the same TERA station data



High resolution comparison of x-ray (red) pulses and electric field (black) data for a stepped-leader step.

Correlation between stepped leader steps and x-ray bursts

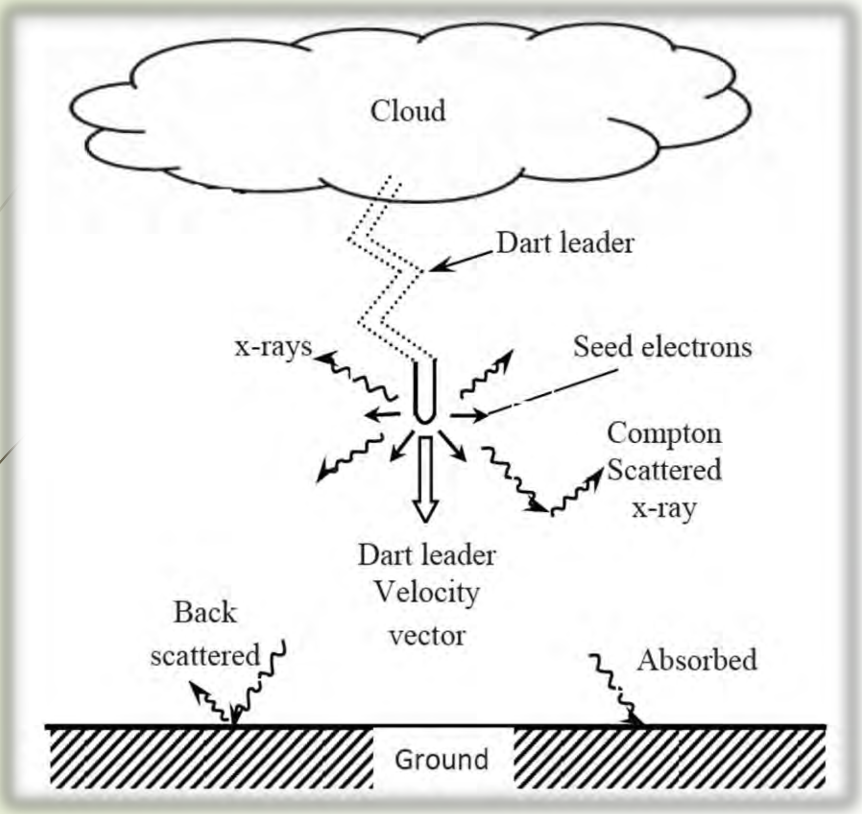
Rocket triggered event July 14, 2007

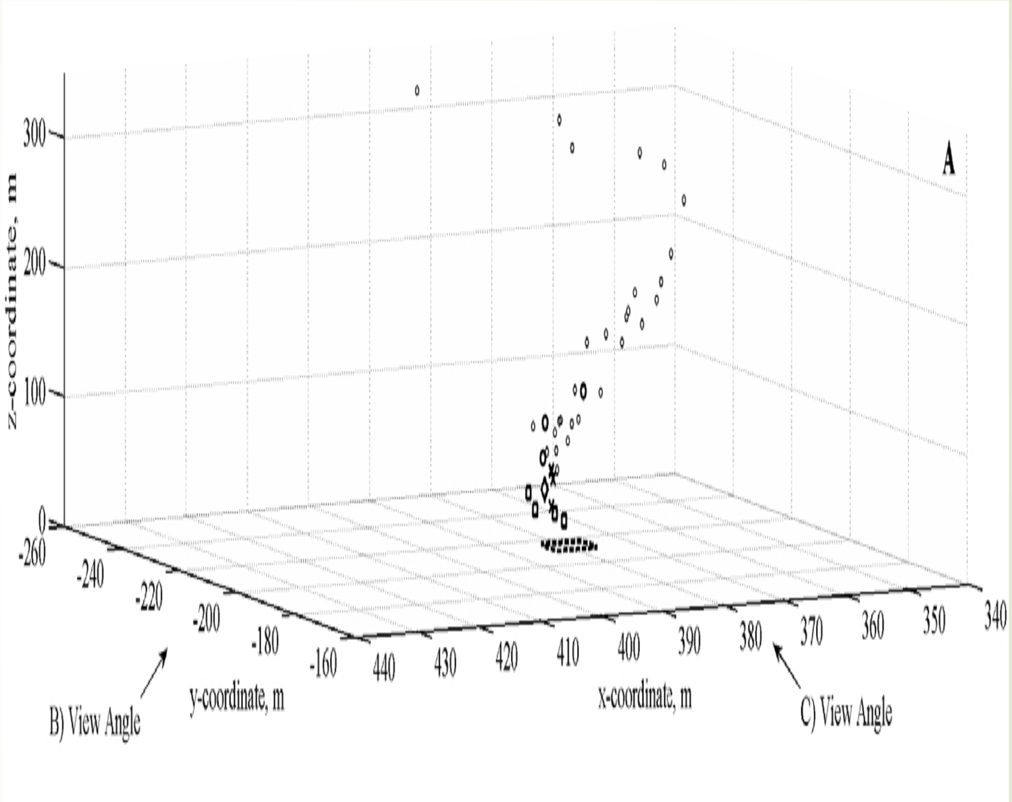


Data representation for the rocket triggered event. The plot shows the **signal waveforms on different x-ray detectors** arranged from the inside out based on the boxes locations from the lightning channel. The inset shows the instrument response function.

Our X-ray observations are consistent with the production of runaway electrons in lightning from CRE (Cold (thermal) Runaway Electrons) mechanism. CRE (not RREA -- Relativistic Runaway Electron Avalanche) is responsible for producing X-rays from lightning leaders.

What else to do with reported observations?
Do physics ! Modeling of a Dart/Stepped leader





[Left panel] Schematic diagram which depicts the emission from a dart/stepped leader. The energetic electrons are produced near the leader and emitted in all directions as the dart leader propagates downward .

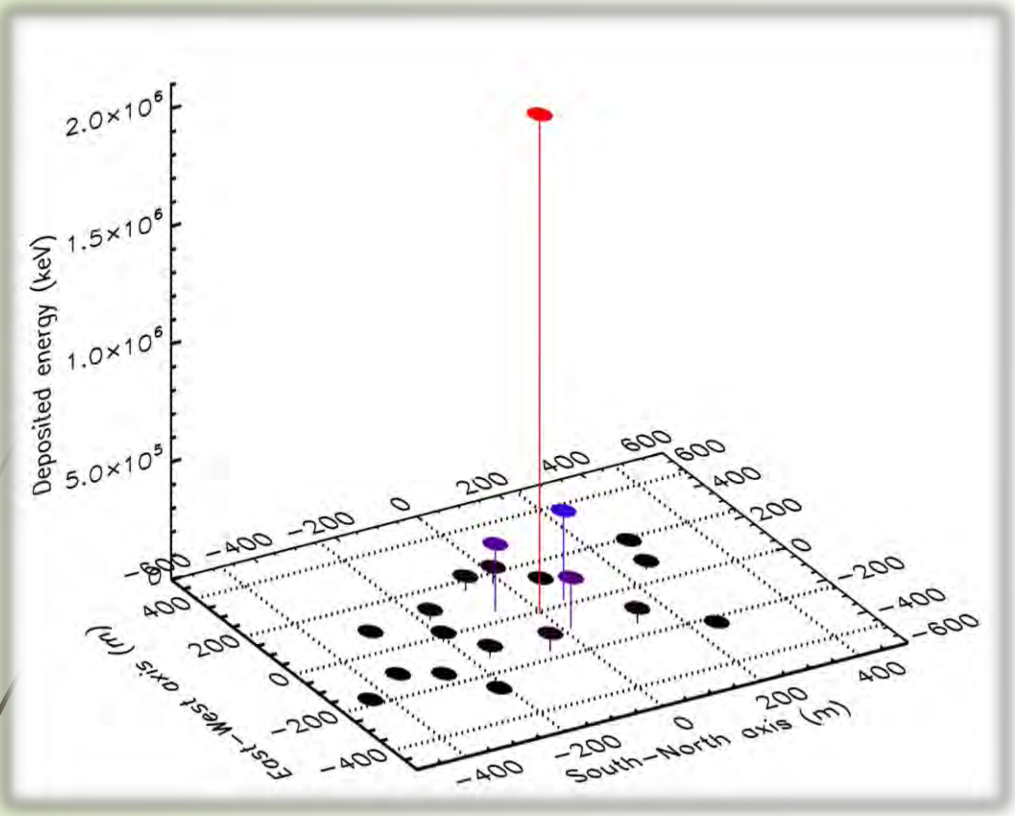
[Right panel] 3D map of the dE/dt pulses as determined by the x-ray TOA technique [Howard et al .(2008)].

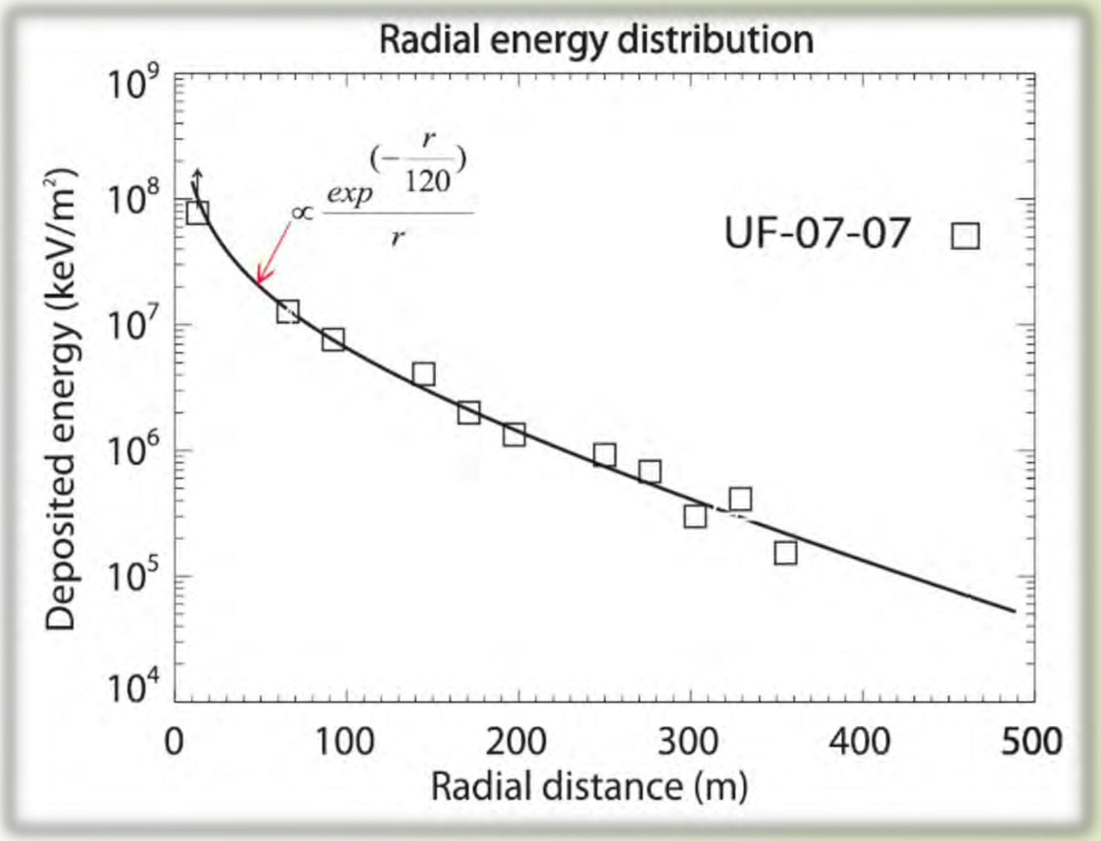
Examples of other work using TERA observations
(upcoming -- one slide per published paper)

1. Found empirical relations for <u>radial</u> x-ray emission distribution
2. Found X-ray energy spectra (using a spectrometer)
3. Investigated the structure of X-ray emission (using XCAM)
4. Studied the Angular Distribution of X-ray bursts ("lighthouse" effect in the x-ray emission)
5. Discovered the first ground-level TGF

Found empirical relations for radial x-ray emission distribution

Radial energy distribution for triggered lightning

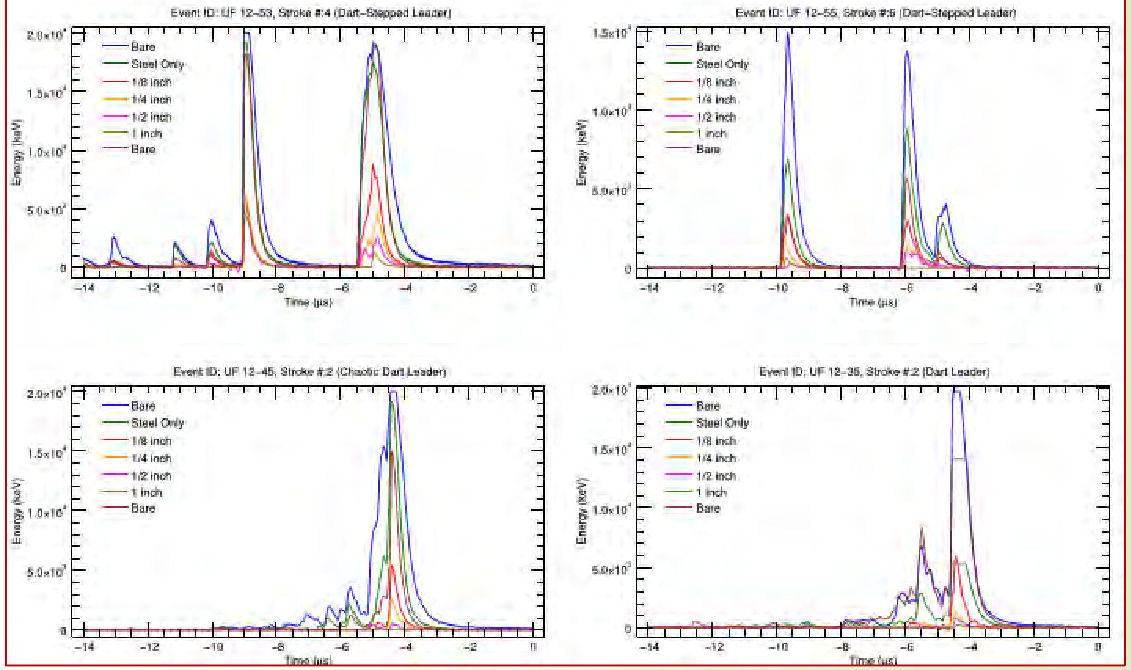




Energy deposited on the unshielded detectors versus their radial distance from the lightning channel for three rocket triggered events. The intensity peaks at the center and falls off approximately exponentially with a 120 m length scale as shown with solid line. [Saleh et al. 2009]

Found X-ray energy spectra (using a spectrometer) [2015]

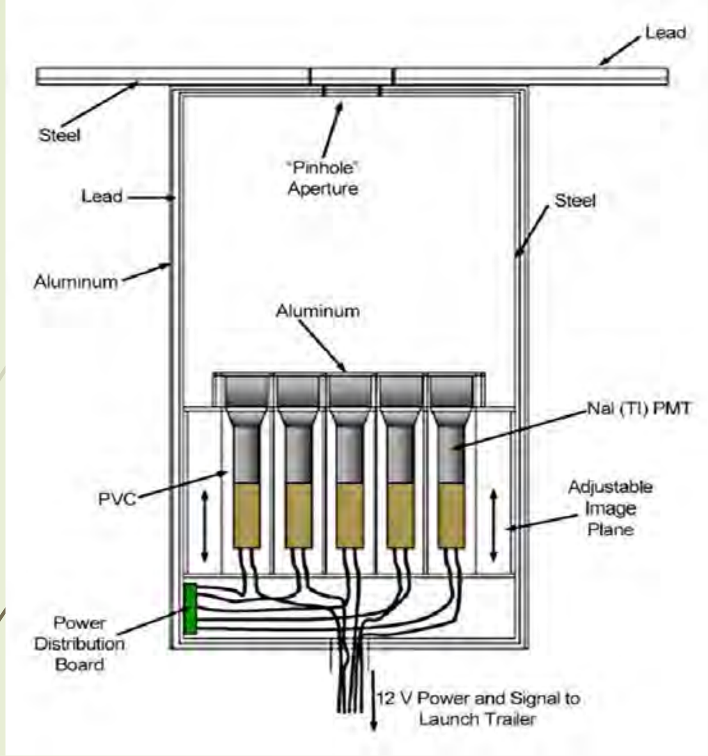
Tube	Shielding
1	*No Shielding (Bare)*
2	0.2385″ *Steel*
3	0.035″ *Pb* (*No Shielding prior to Aug* 10, 2012)
4	0.2385″ *Steel* + 0.125″ *Pb*
5	0.238″ *Steel* + 0.25″ *Pb*
6	0.2385″ *Steel* + 0.5″ *Pb*
7	0.2385″ *Steel* + 1″ *Pb*



- no characteristic energy for leader X-rays (power-law for energy spectra); we never observed leader X-ray photons with energies above 1.5 MeV

- Observations are consistent with the production of runaway electrons from CRE mechanism. In CRE, due to the short scale avalanche regions [Babich, 2003, Bakhov et al., 2000], the runaway electrons barely gain energies of more than a few MeV from the background electric field.

X-ray Camera (XCAM) -- Investigated the structure of X-ray emission [2011]



[Left] Schematic diagram of the X-ray lightning camera. The camera is 0.64 m wide and 1.25 m long, with 1.27 cm thick lead sheets completely surrounding the camera on all sides, except for a 7.62 cm diameter circular "pinhole" aperture at the front of the camera. The lead sheets, which together weigh 550 kg, are mounted on a 0.64 cm thick welded steel box (with the pinhole aperture open). The camera uses 30 7.62 cm diameter NaI/Photomultiplier to record the X-rays passing through the pinhole aperture.
[Right] XCAM in action at ICLRT

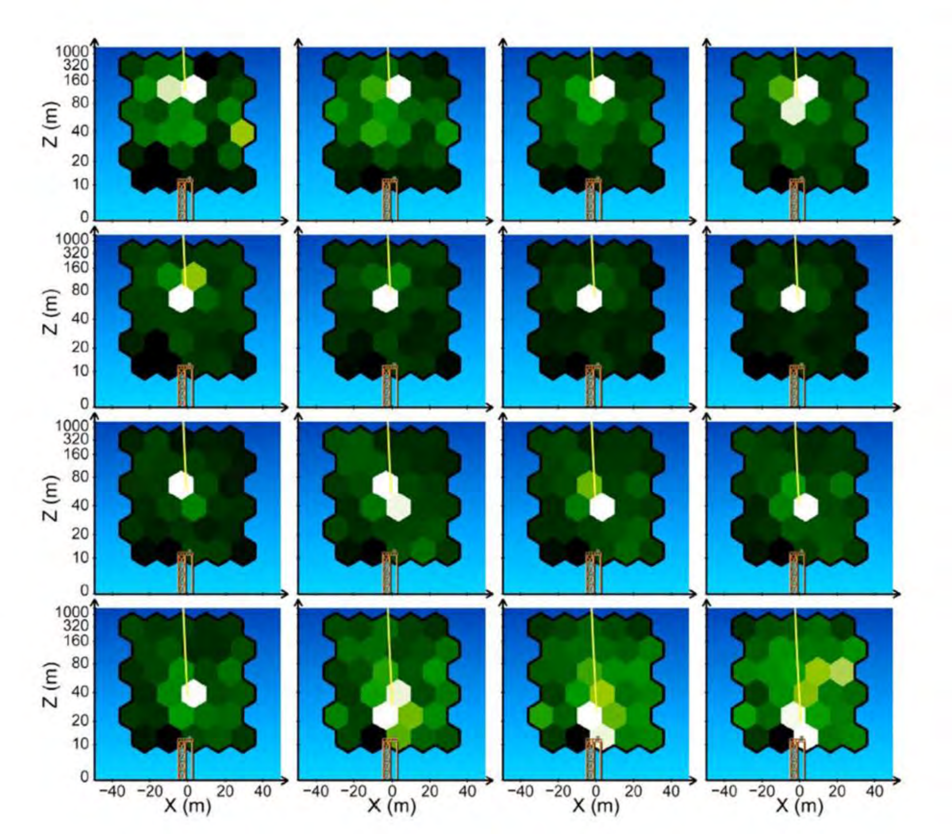
X-ray Camera (XCAM) – ten million images per second

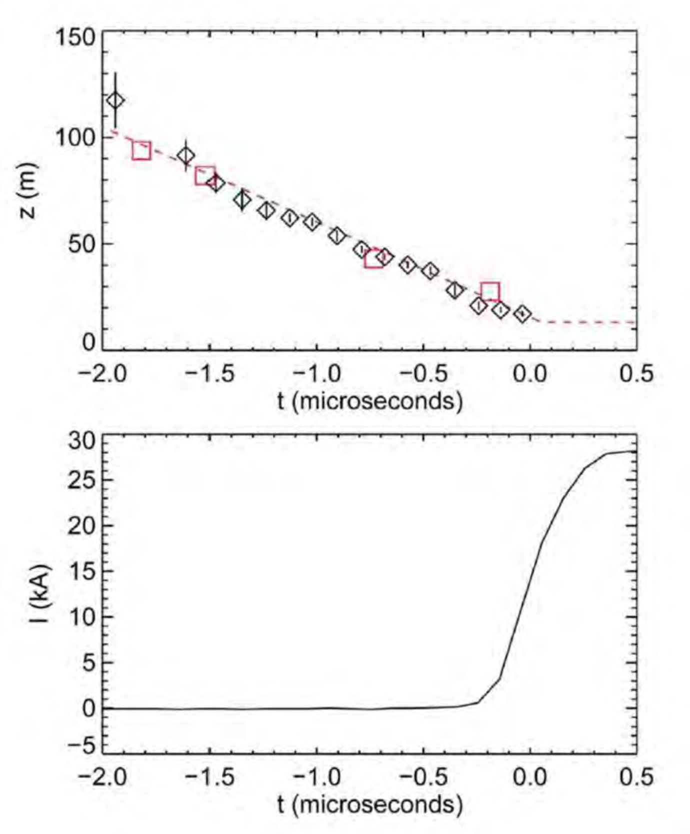
Data Acquisition and Electronics Located in Launch Control

Data Acquisition and Electronics Located to the right of the XCAM

Make first x-ray images (movies) of lightning

- x-ray source descending with the lightning at up to 1/6 c.
- The tip of channel produced the brightest of x-rays with a diffuse glow surround the channel.
- Diffuse component arrived simultaneously with the attachment component





- [LEFT] Successive 0.1 ms images of the X-ray emission from lightning.
- [RIGHT] (top) Average vertical position of the X-ray emission versus emission time, showing that the X-ray source propagated down with the dart leader. (bottom) Electrical current measured at the launch tower.

First x-ray movie of lightning

The camera stops the action at one-sixth the speed of light.

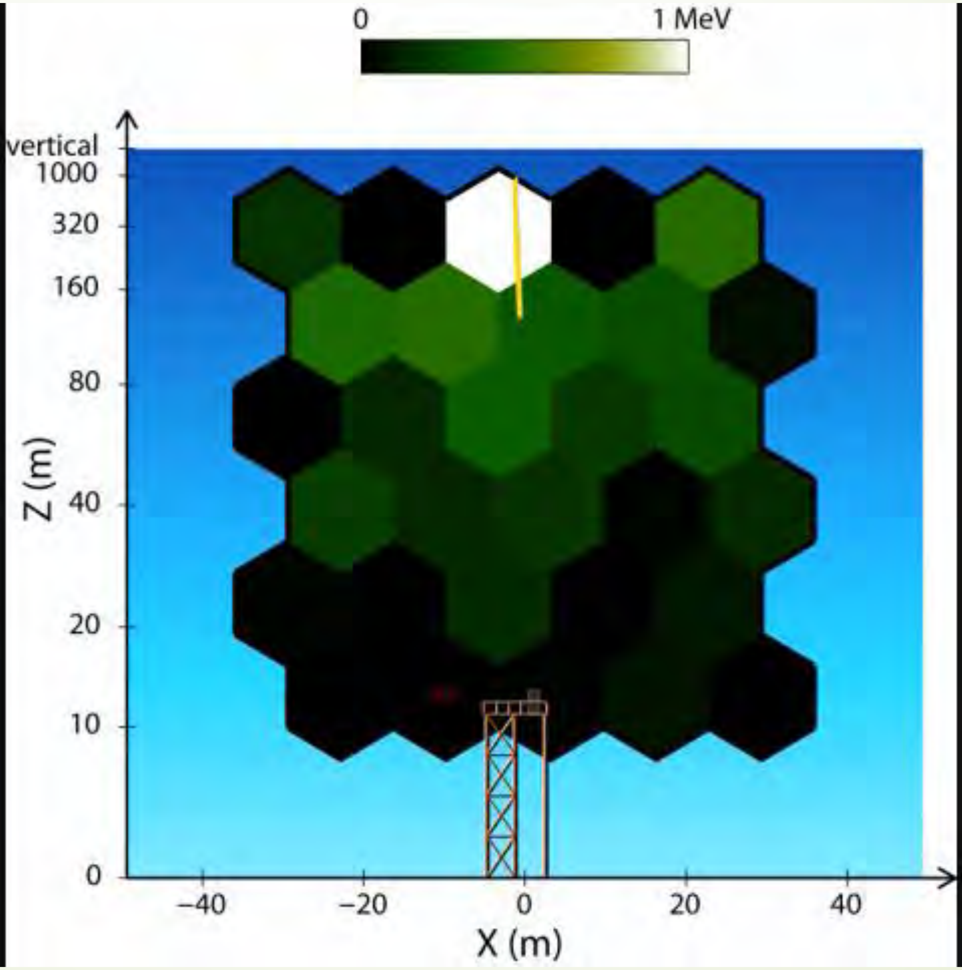
(… something moving this fast would go from the Earth to the moon in ~ 8 seconds!)

Speedy Trade-Off: Less Data Space

10^6 images per second for **30** pixels per image (relatively low resolution)

Watch the tip of channel.

It produced the brightest of x-rays with a diffuse glow surround the channel.



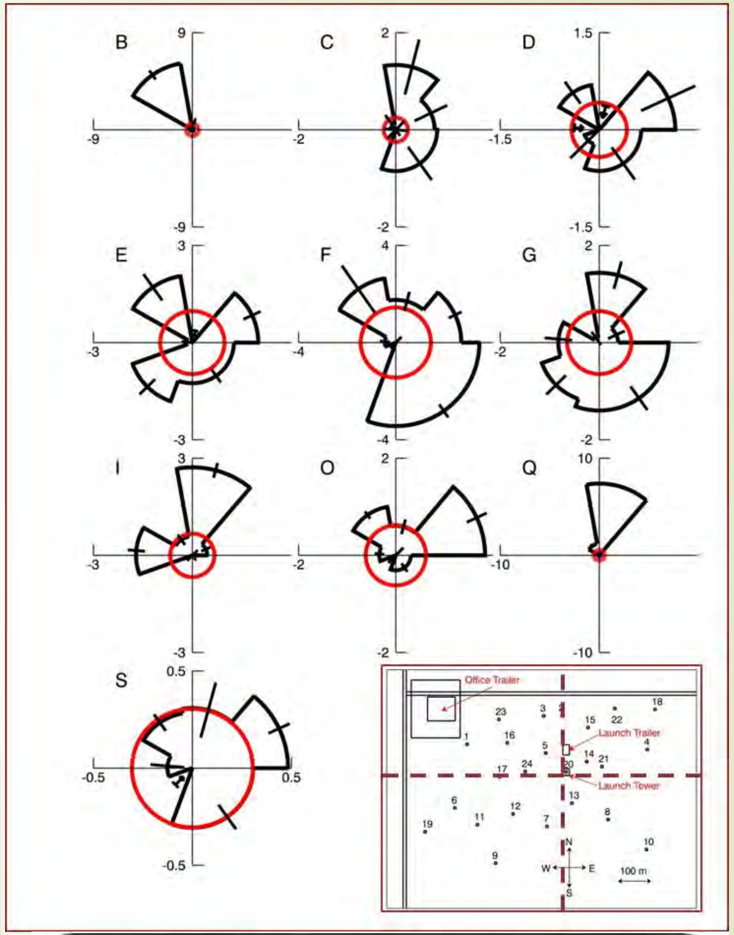
Studied the Angular Distribution of X-ray bursts [2014]

“lighthouse” effect for x-ray emission

Isotropic emission for an integrated burst … How about in higher time resolution?

We observed Anisotropy for dart leaders (stepped and chaotic leaders).

The observed anisotropy moved in a spiraling motion in the clockwise direction around the vertical channel. This would suggest a sort-of “lighthouse” effect in the x-ray emission. Rotational rate of the x-ray emission = 1 million rotations per second or = 1 rotation completed in 55 μs.



Anisotropy implies that the electron population in the source region is not uniform on all field lines, **OR**, the leader channels were not vertical (even though the electric field may be symmetrical around then non-vertical channel) causing an anisotropy in the direction that the leader channel was tilted.

Compare deposited energy versus radial distance to modeled radial distribution to account for radial fall-off of detected energy for each angular region. A maximum likelihood technique is used to determine the x-ray intensity in each azimuthal direction.

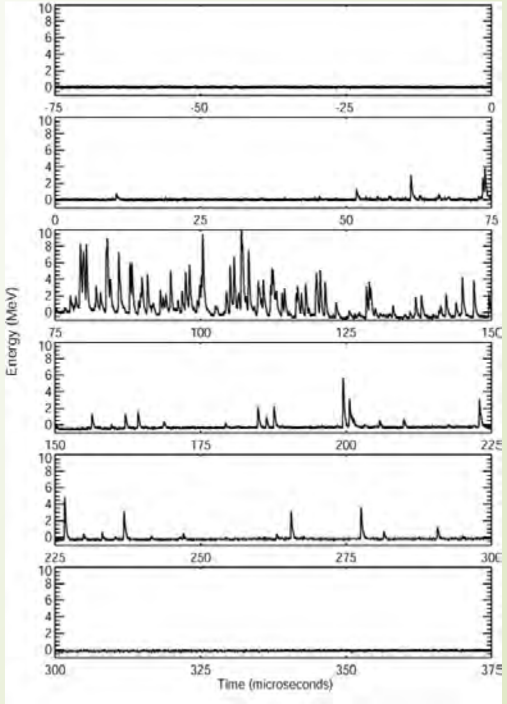
Discovered the first ground-level TGF (First reported 2004)

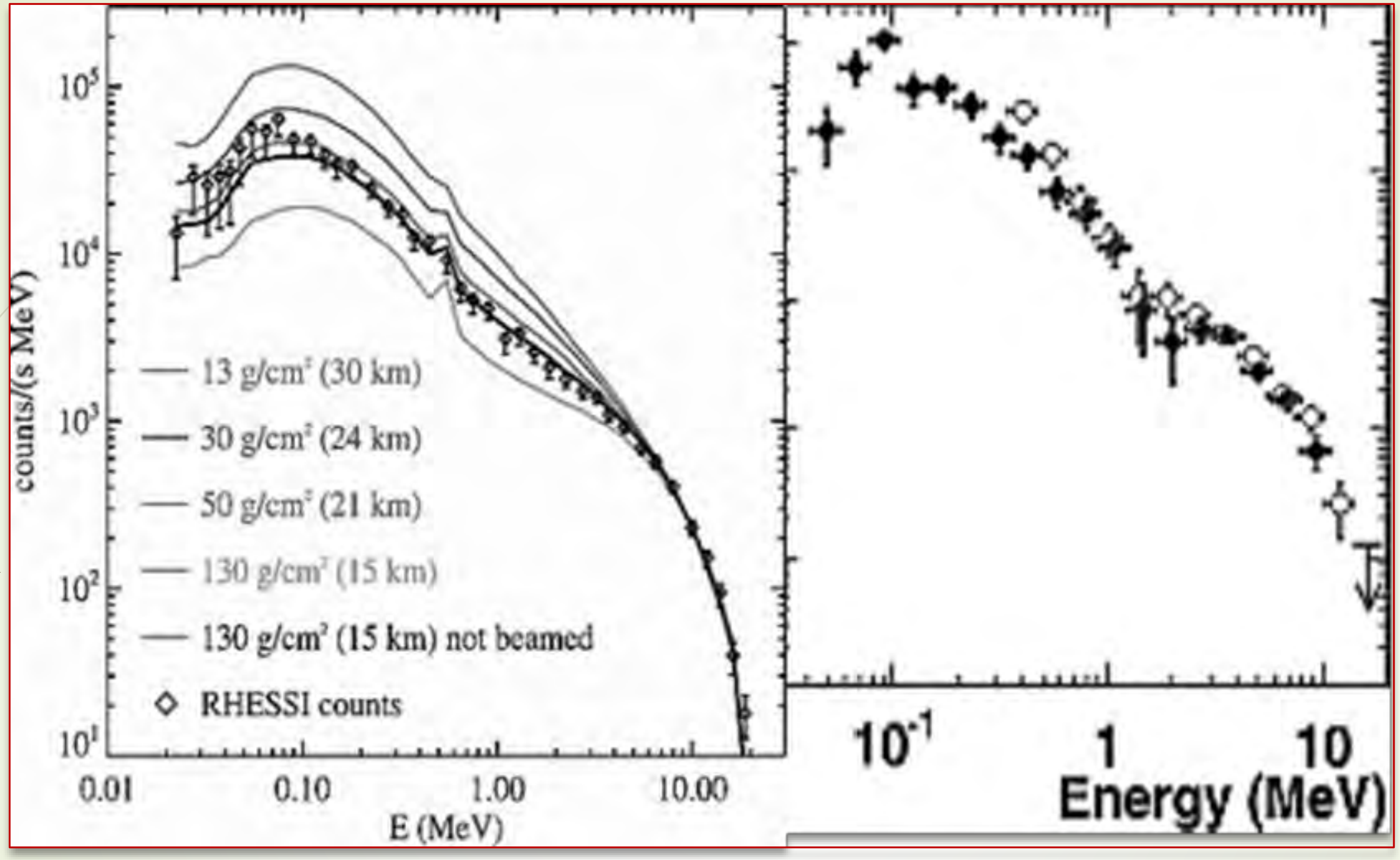
TGF: Bursts of gamma radiation with durations from 10s-100s microseconds (certainly shorter than < 2 ms, and certainly not a classical *thunderstorm ground enhancement*!) .

Our discovery of the 1st ground-based TGF (in 2003) and follow up studies of space-based TGF helped us to determine that TGFs come from thunderstorms (and not sprites).

Ground-based observations of TGFs are very rare. Reported events: so far 5 (2003 TGF-trg (FL), 2009TGF-ntr (FL), 2014TGF-trg (FL), and 2015-ntr (FL), 2019-ntr (JPN)

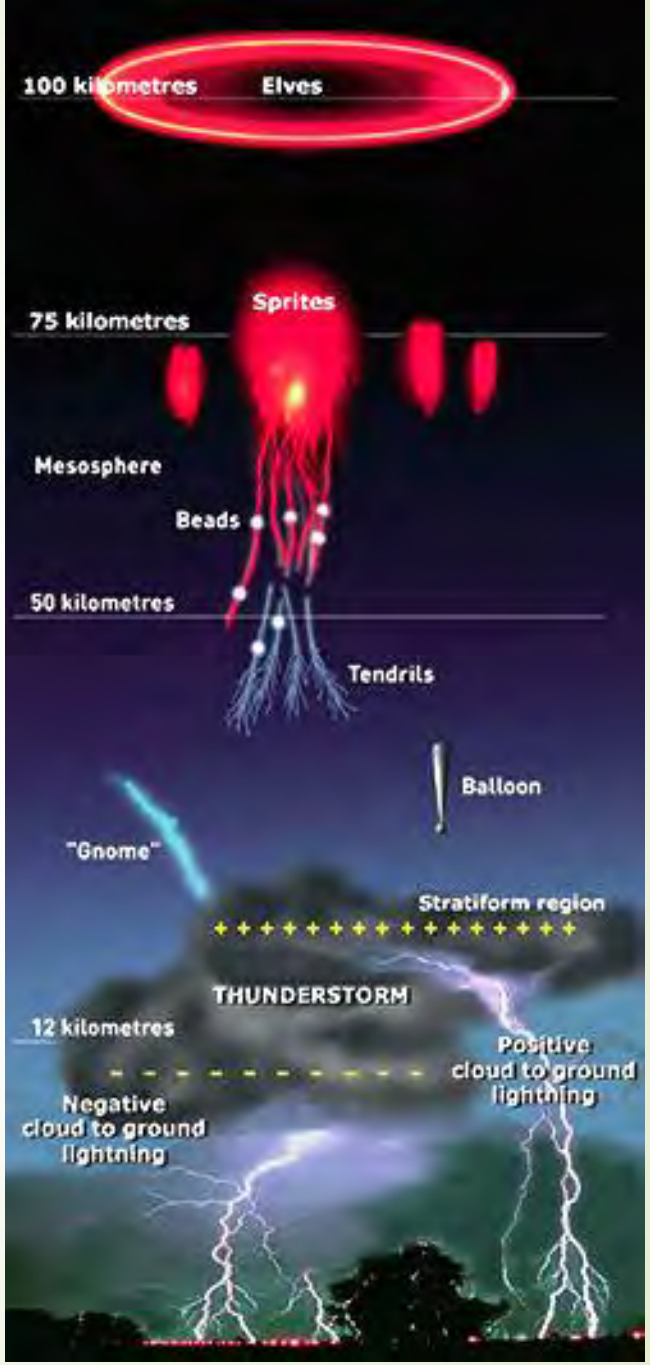
The first ground level gamma-ray flash observed during the initial stage (IS) of a classically triggered lightning.
[*Dwyer et al.*,2004a]





[Left]: Spectrum of many combined TGFs from the *RHESSI* satellite (data points) along with the modeled response to the expected RREA spectrum originating from various depths in the atmosphere. **[Right]:** Spectrum of a glow seen from the ground in Japan, showing the same RREA spectral shape. [Courtesy of David Smith, UCSC, CA]

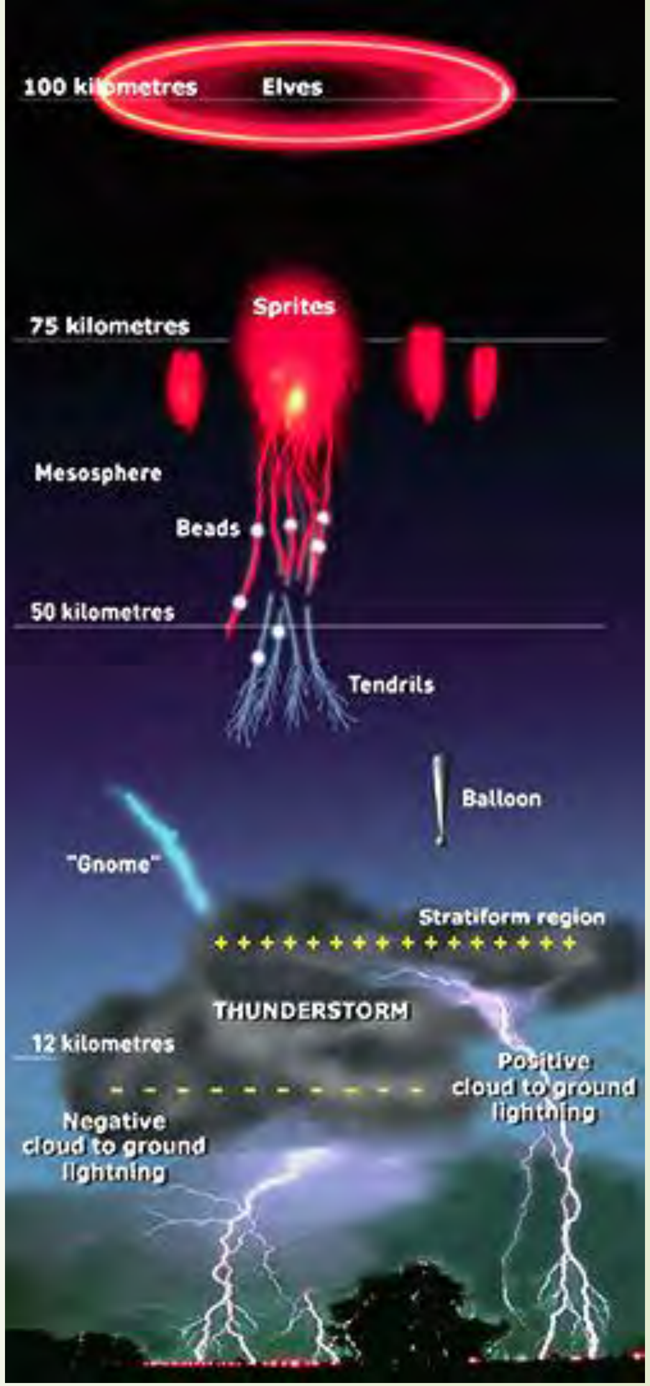
Where do they come from?



http://www.holoscience.com/news/balloon.html

Where do they come from?

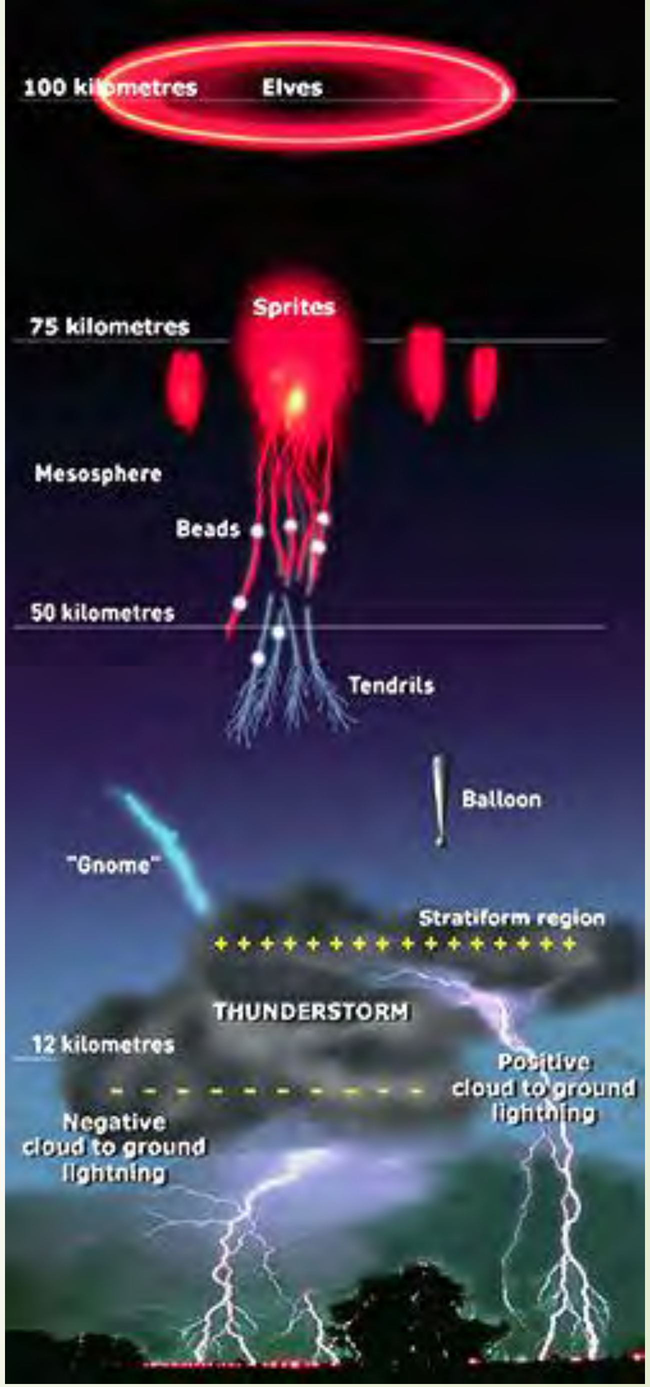
1994 – 2005: Here



Where do they come from?

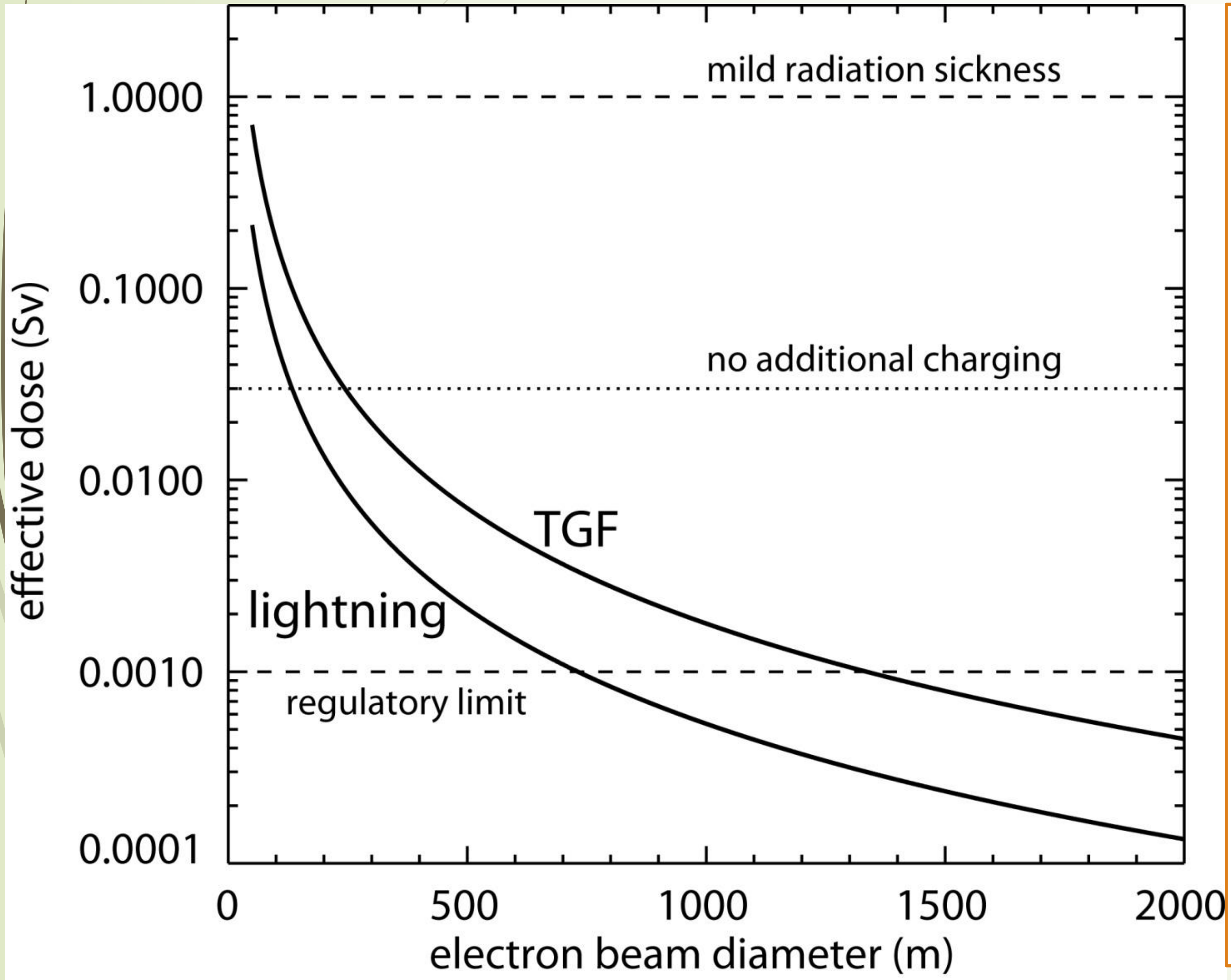
1994 – 2005: Here

After 2005: Here



Lots of energetic radiation …
How dangerous they can be?
Dose?

Calculated radiation doses received by individuals inside an “unlucky” aircraft (2009)!



In the part of a thundercloud where TGFs are generated, they might produce a radiation dose of up to 1 Sv or more if they are created over a small area. This is sufficient to produce immediate radiation sickness and a high risk of later cancers in humans.

The secondary neutrons created by gamma-ray interactions in air and aircraft could pose a risk of single-event upsets in avionics components.

The critical open questions for evaluating whether TGFs pose a significant hazard in some contexts include

(1) whether TGFs are common or rare,

(2) how large the region of their generation is (the smaller it is, the more concentrated the radiation dose),

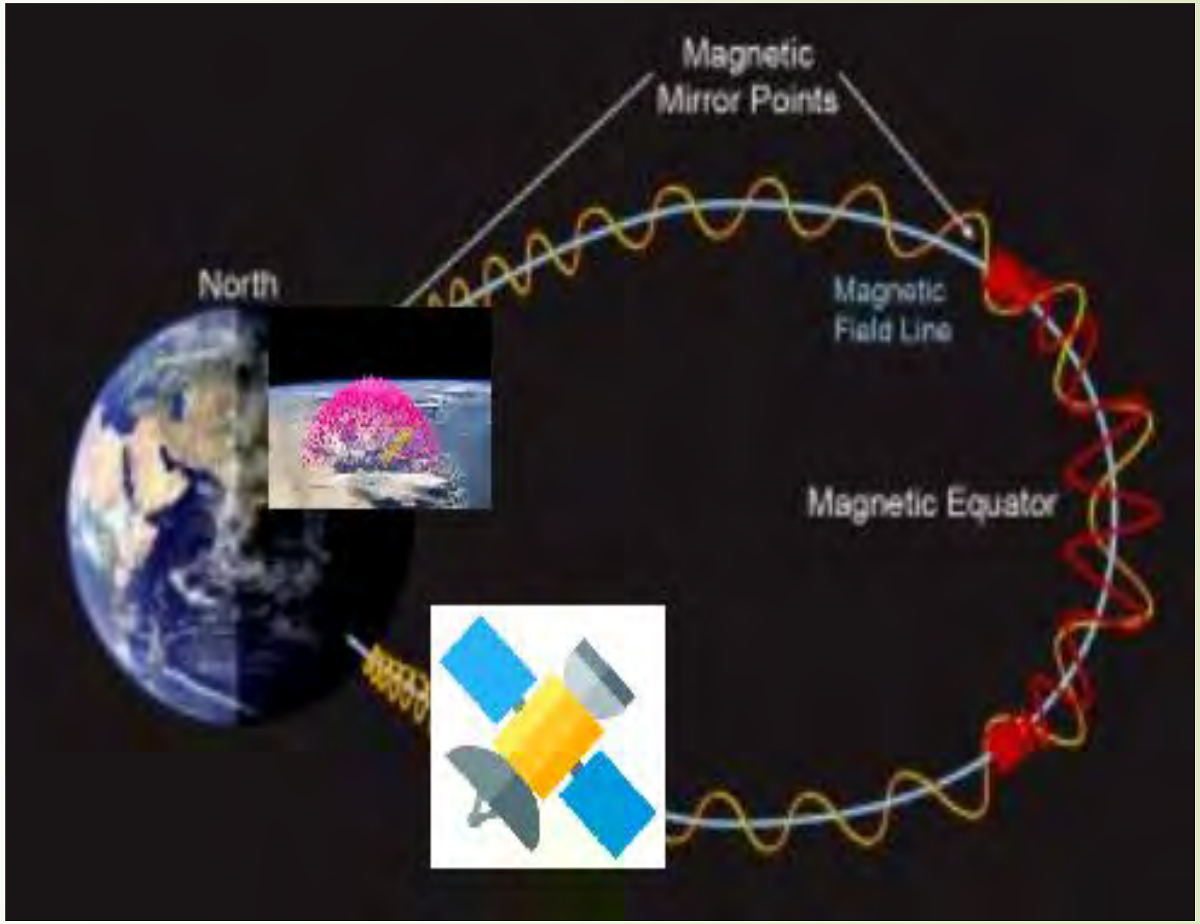
(3)whether downward TGFs ever occur close enough to the ground to present a high dose to people, and

(4)whether TGFs are more or less likely to occur in the sort of lightning that strikes aircraft.

Discovered Terrestrial Electron Beams (TEBs) [2008]

Beams of highly relativistic electrons [and/or positron] which escape to space from underlying TGFs or TGFs occurring in vicinity of the magnetic conjugate of observation points. This was first suggested using intense "gamma ray" observations (indeed MeV electrons) in space (over Sahara Desert) where no nearby lightening were present.

Later on, a few more cases of TBEs were inferred from BATSE, RHESSI, Fermi-GBM. The most recent one from ASIM detailed observations (EGU 2019).



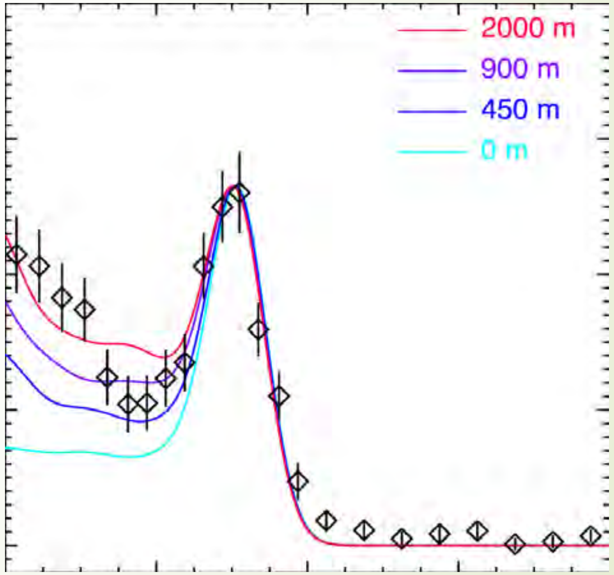
TEBs = A new source of high energy electrons for the ionosphere and inner magnetosphere!!!

[Dwyer et al, 2015]

Discovered positron clouds inside thunderstorms

- We flew our instruments aboard a research plane (NCR/NSF Gulfstream V) over Florida thunderstorms. We inadvertently flew into the extremely violent thunderstorm — and, it turned out, through **2 isolated clouds of positrons (lots of 511 keV emission), without other associated physical phenomena such as energetic gamma-ray emissions**!

- One possible explanation for the sudden appearance of positrons is that our aircraft itself dramatically influenced the electrical environment of the thunderstorm, but how?! Is it possible that we detected a kind of exotic electrical discharge inside the thunderstorm that involves a lot of positrons (**Are these fingerprints of Dark Lightning?**)
- **No explanations were/are totally satisfying. In the room, are some authors of a promising UiB modeling work on TEBs. Any comment?**

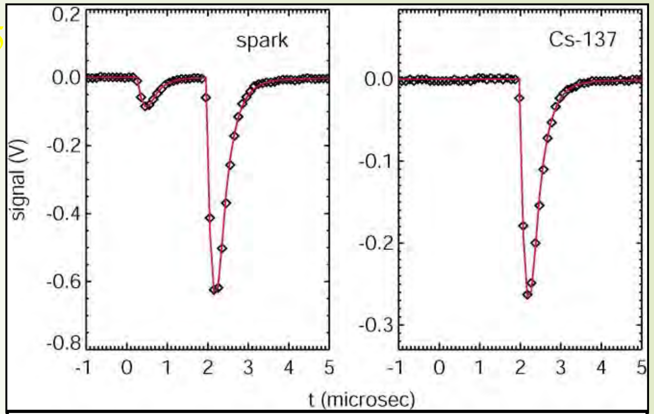


Airborne Detector for Energetic Lightning Emissions

Energy spectrum showing the 511 keV enhancement. The data are the combined energy spectra of the two events, from both top and bottom NaI detectors,. The colored curves are the model results with the positrons filling a volume of air out to the specified radius in the figure.

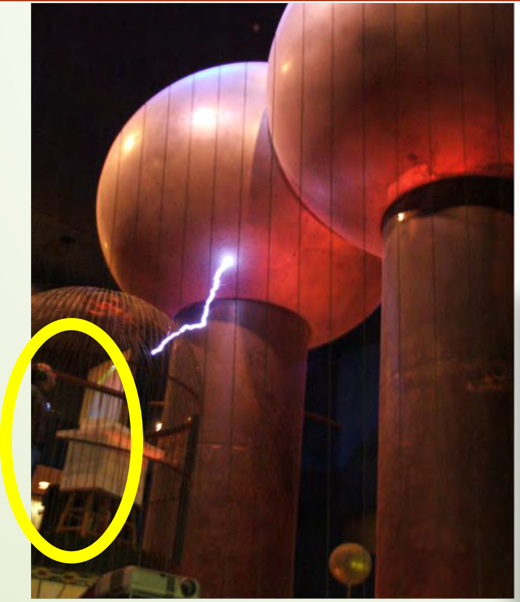
Discovered that laboratory sparks make X-rays (Discovered first in 2005, and later confirmed and expanded in 2008).

- X-ray bursts (30 -300 keV; 0.5 ms duration, gaps 10-140 cm) observed from sparks generated from 1.5 & 1.0 MV Marx generators. (*High Voltage Labs in Pittsfield 2005 & Uppsala 2008*)
- Bursts arrived when gap's voltage was the largest **or** in the process of collapsing.
- Both polarities and wide range of electrode geometries.



X-ray pulses for the spark on left. Marx fired at $t = 0$. The black dots are from our XLB, and the red curve is the detector response function. Right panel shows 662 keV from a Cs-137 source, placed temporarily on top of the box.

Footnote> No x-rays were observed from large sparks from the Van de Graaff machine at the Boston Museum of Science.



What does it mean? (1) The results implied that runaway breakdown is occurring in relatively small high-voltage sparks, and that (2) physics of such sparks involves more than just a conventional breakdown. It opened up research area using laboratory sparks to study the poorly understood phenomenon of runaway breakdown.

… and here are a few advances in theories by our team …

- Developed REAM Monte Carlo code, which has helped establish many key features of runaway electron avalanches and TGFs. It includes the vital relativistic feedback mechanism, specially for higher electric fields.

- Estimated of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft

- Developed a theoretical foundation for remote sensing of electric field inside thundercloud

- Developed theory of radio emissions from TGFs

Summary

1. **Discovered that leaders emit x-rays and established once and for all that lightning does indeed emit bright bursts of x-rays.**
2. A lot of what is known about x-ray emissions from lightning and cold runaway electron production comes from our work at Camp Blanding.
3. **Discovered the first ground-level TGF in 2003**
4. Discovered that laboratory sparks make x-rays
5. **Discovered and investigated the relativistic feedback mechanism, which is a leading candidate for explaining TGFs. Developed REAM Monte Carlo code, which has helped establish many key features of runaway electron avalanches and TGFs.**
6. Helped demonstrate that TGFs come from thunderstorms and not sprites
7. **Discovered Terrestrial Electron Beams (TEBs)**
8. Developed theory of radio emissions from TGFs
9. **Make first x-ray images (movies) of lightning**
10. Discovered positron clouds inside thunderstorms

Summary: Major discoveries

15 years ago – lightning emits bright bursts of X-rays.
12 years ago – laboratory sparks emit X-rays similar to those from lightning.
11 years ago – thunderstorms emit bright bursts of gamma-rays.
9 years ago – thunderstorms eject beams of high energy electrons / positrons into the space.
5 years ago – "Dark lightning" is a new form of atmospheric electrical discharge.
2 years ago – single thunderstorm is capable of making multiple forms of upward discharges.
2017-2018– confirmation that lightning more powerful over ocean than land.

>100 refereed publications, including 2 in Science & 3 in Nature, 8 Book Chapters, and numerous conference presentations /invited talks.
Patents: 6 (for lightning geolocation technology)
Outreach: Discovery Channel; National Geographic; Scientific American Magazine; etc.
Trained: >17 PhDs; 12 MS; 50's UG; 11 postdocs

Promote Science; Do Science; and prepare the next generation of scientists.

What's Now?

- The discovery of x-rays from lightning allowed us to make significant progress in understanding of some basic questions on mysteries of atmospheric discharges.
- There remain many great challenges surrounding thunderstorms and lightning, including giant flashes of gamma-ray seen from space, powerful radio bursts from thunderclouds, and high amplitude EMPs. So, what we are our focus at FIT now?

Ongoing Campaigns at FIT includes

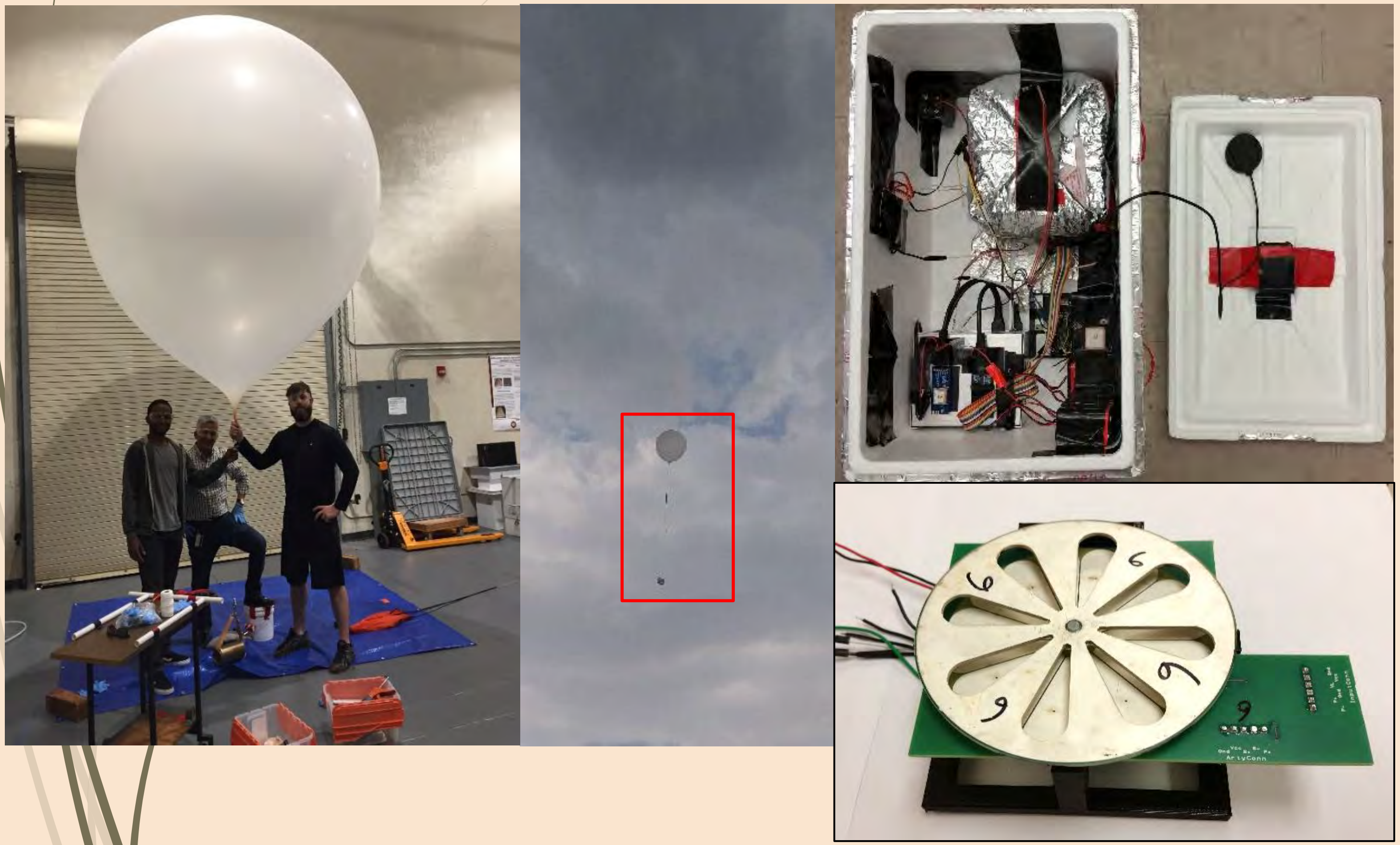
- **Balloon observations of gamma-ray glows within thunderstorms**
- **High Speed Spectrograph observation of TLEs**
- **Ocean vs Land lightning**
- **Attachment processes for grounded Tall Towers**
- **Effects of large-amplitude EMPs on ionosphere**


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
MEHRBANI
GRAZIE
BOLZÏN
MERCI
BÏYAN
SHUKRIA
TINGKI
GOZAIMASHITA
EFCHARISTO
JUSPAXAR
KOMAPSUMNIDA
MAAKE
PALDIES

Q & A / Comments?

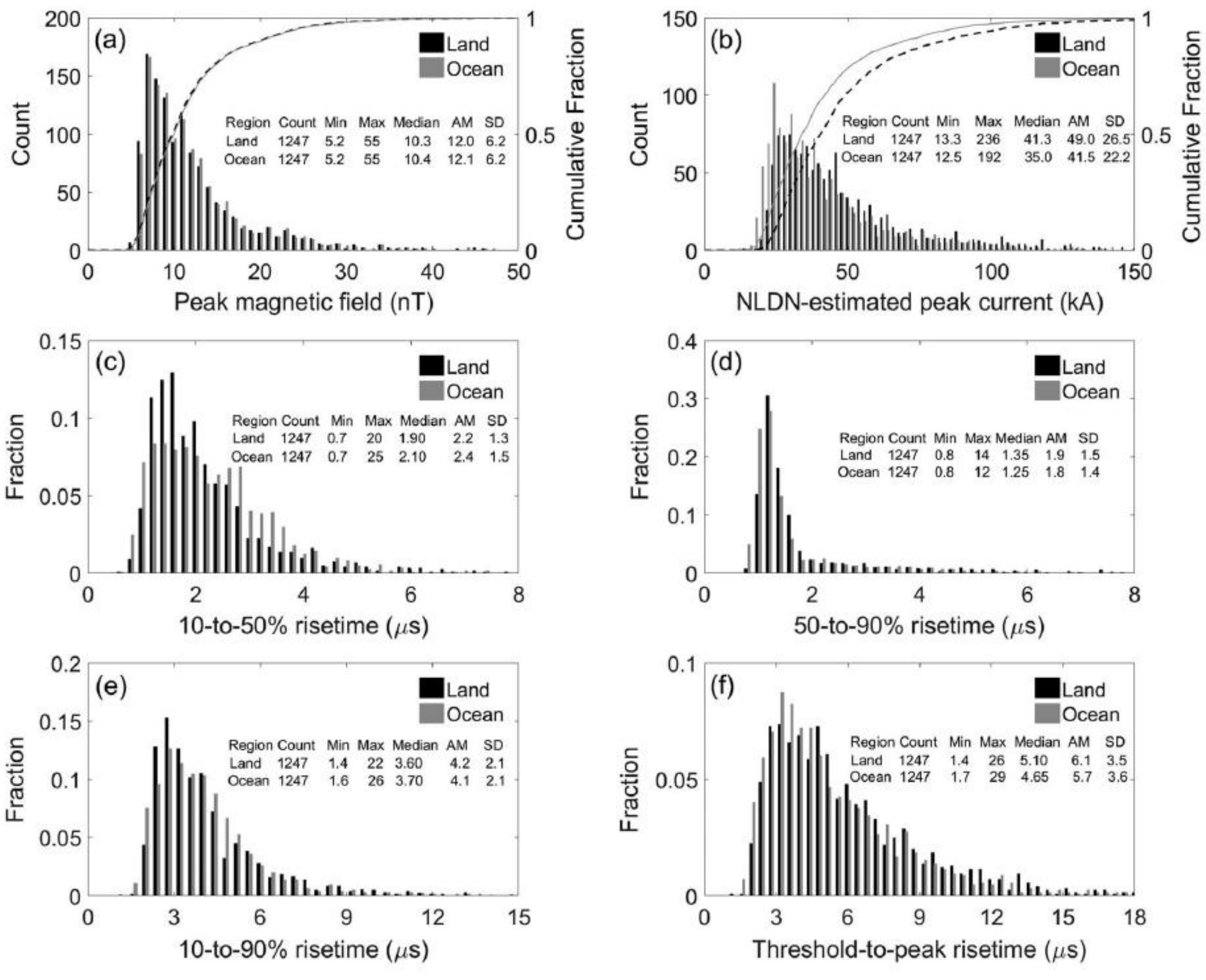
Extra Slides (if time permits)

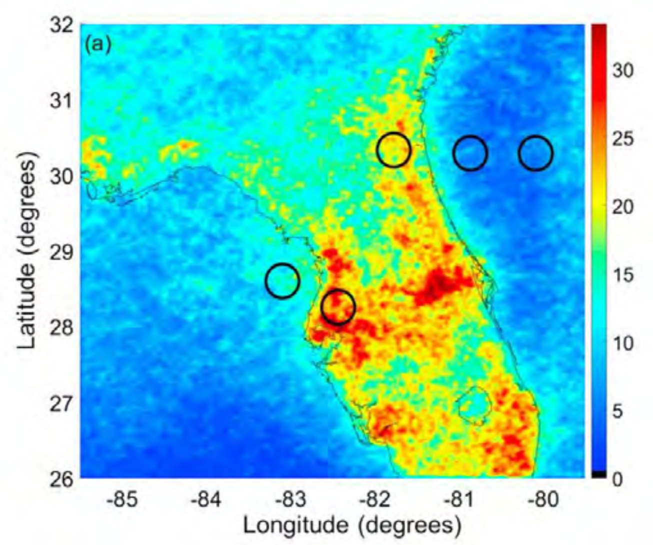
CURRENT-1: Balloon observations of gamma-ray glows within thunderstorms



- Florida Tech and UNH have designed balloon-based instrumentation for flying into thunderstorms with the aim of detecting high-field regions of thunderstorms.
- The instrumentation includes one BGO scintillator coupled to a Silicon Photomultiplier (SiPM), two Geiger-Muller tubes, and a low-power lightweight electric Field Mill sensor, designed and calibrated to measure both the polarity and amplitude of the vertical electric field inside the thunderstorm region.
  - **The current configuration is capable of measuring gamma rays and charged particles with energies from 100 keV up to 6 MeV.**
  - Additionally, with polarity information from the Field Mill sensor, runaway electrons can be differentiated from positrons.

CURRENT-2: Ocean vs Land lightning See Nag et al. (2017, 2018)

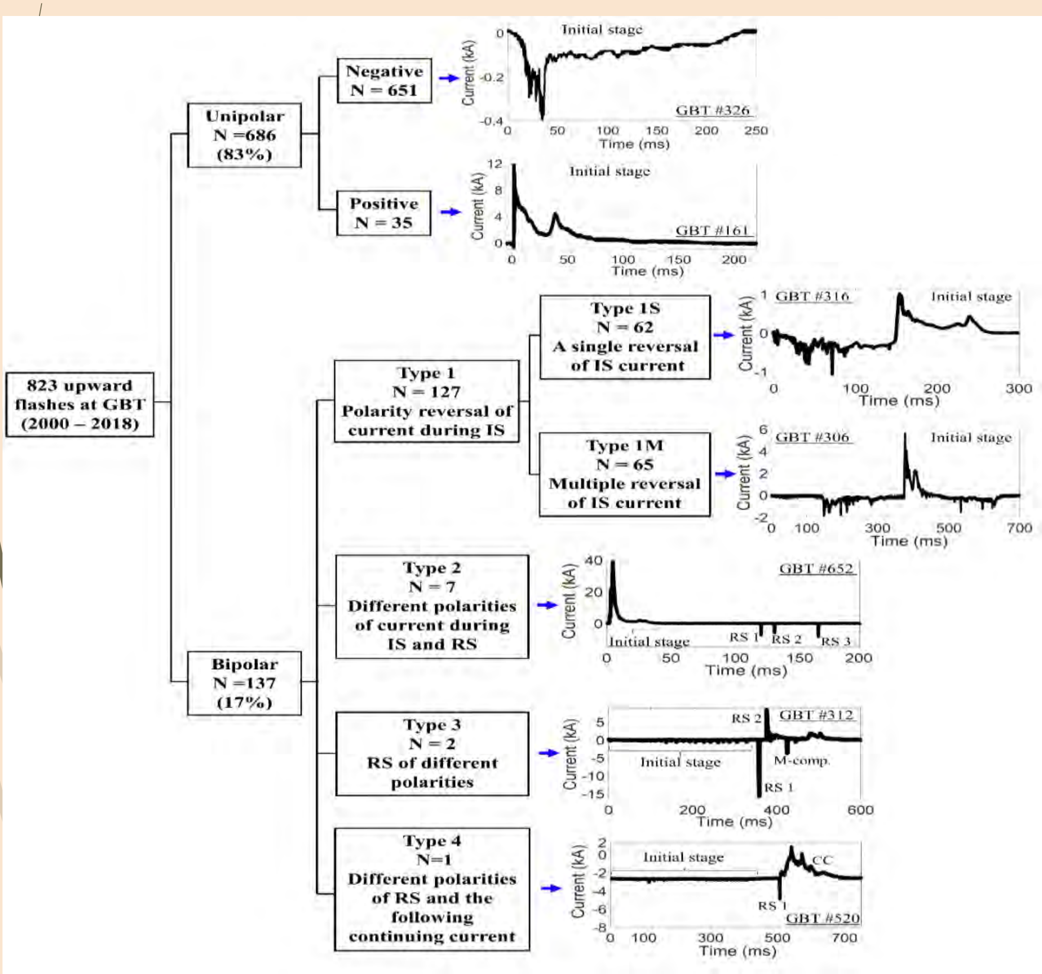


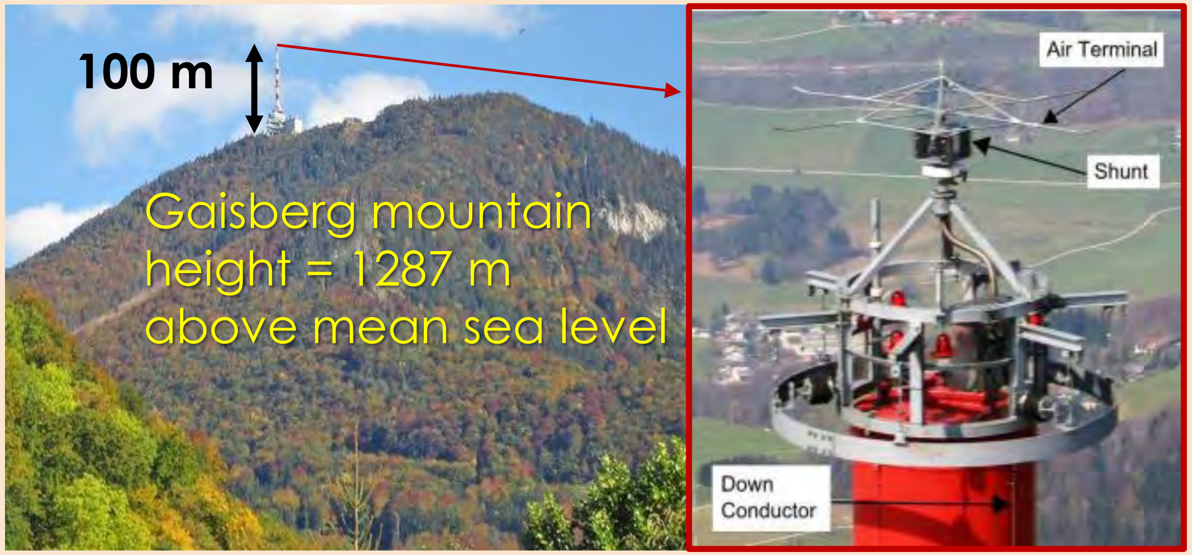


Thunderstorms are electrified differently over ocean than land.

- We examine downward leader characteristics for negative first return strokes, along with estimated first stroke peak currents, for lightning occurring over land and ocean reported by the NLDN.
- We found **higher first stroke peak currents for lightning occurring over ocean than land.**
- We found **longer median (up to 50%) risetime of negative first RS over ocean.**
- We suggested that the upward leader-initiation differences over land versus over ocean affect the slow-front portion of first RS field waveforms.

CURRENT-3A: Attachment processes for grounded Tall Towers See Watanabe et al. 2019

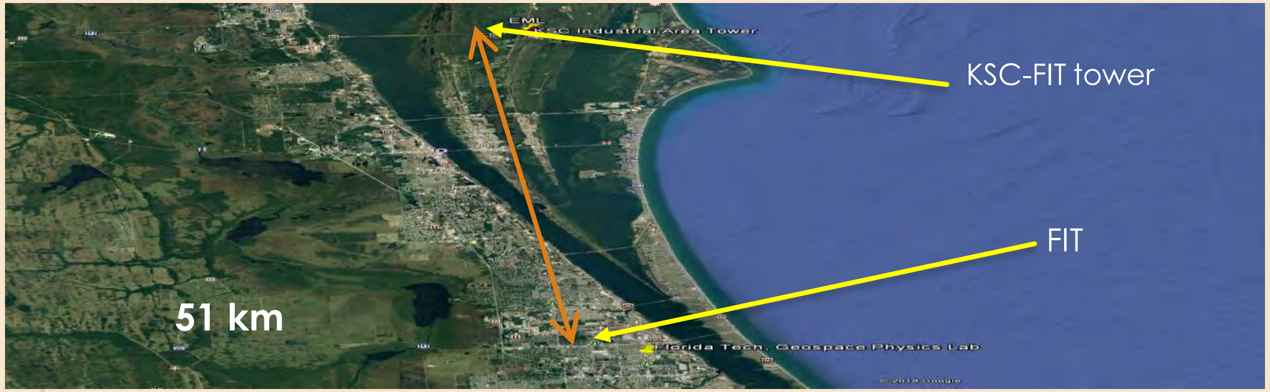


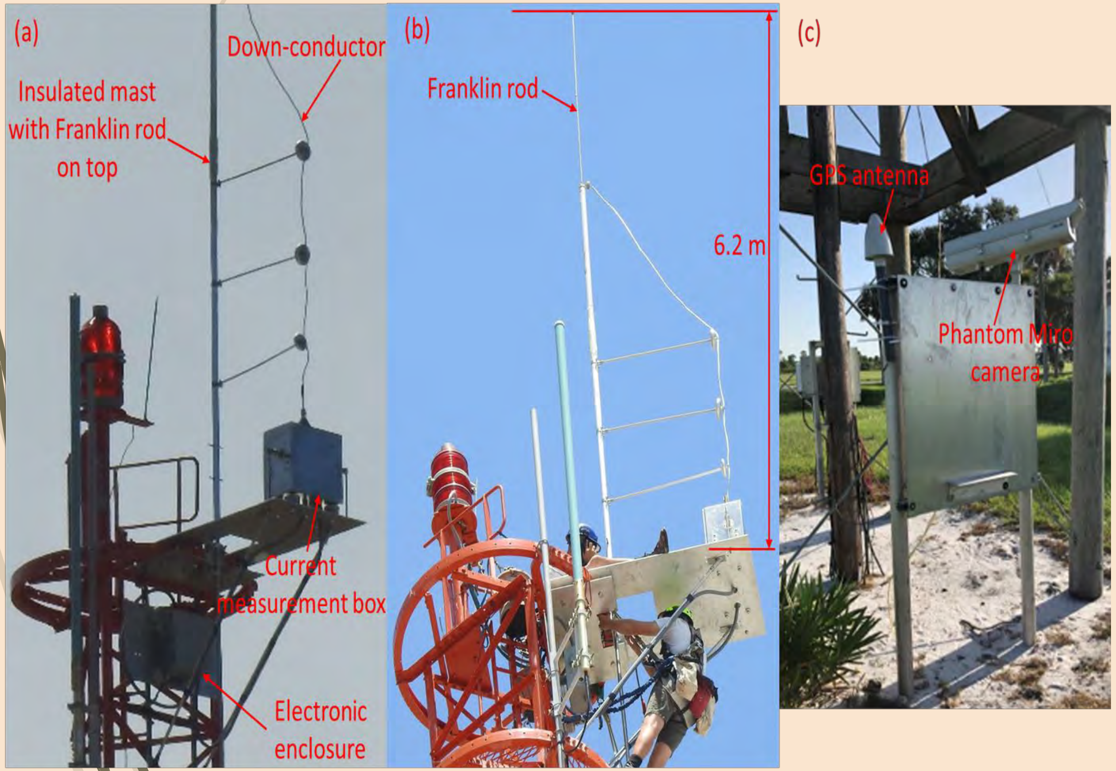


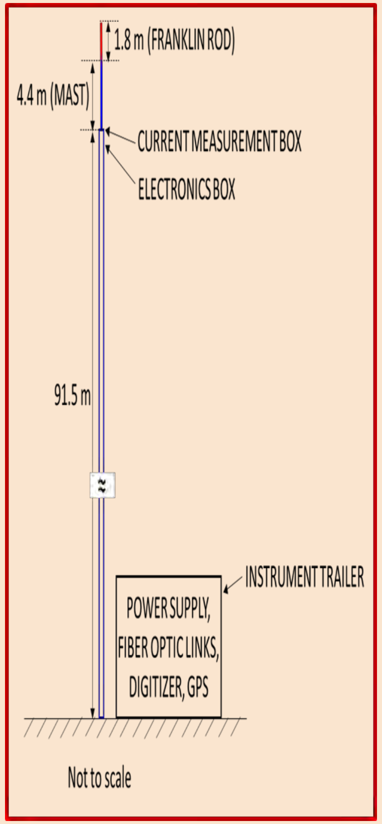
- We analyzed current waveforms (measured using a 0.25-mΩ shunt) of **823 upward flashes** initiated from the **Gaisberg tower.**
- We expanded the traditional classification of bipolar flashes to include **five categories.**
- Of the 137 bipolar flashes,
  - ✓ 45% were of Type 1S (single current polarity reversal during IS),
  - ✓ 47% of Type 1M (multiple reversals of current polarity during IS),
  - ✓ 5.1% of Type 2 (different polarities of current during IS and return stroke),
  - ✓ 1.5% of Type 3 (return strokes of different polarities), and
  - ✓ 0.73% (one flash) of Type 4 (different polarities of return stroke and the following continuing current).

Upward lightning can transfer charges of different polarities at different times.

CURRENT-3B: Attachment processes for grounded Tall Towers

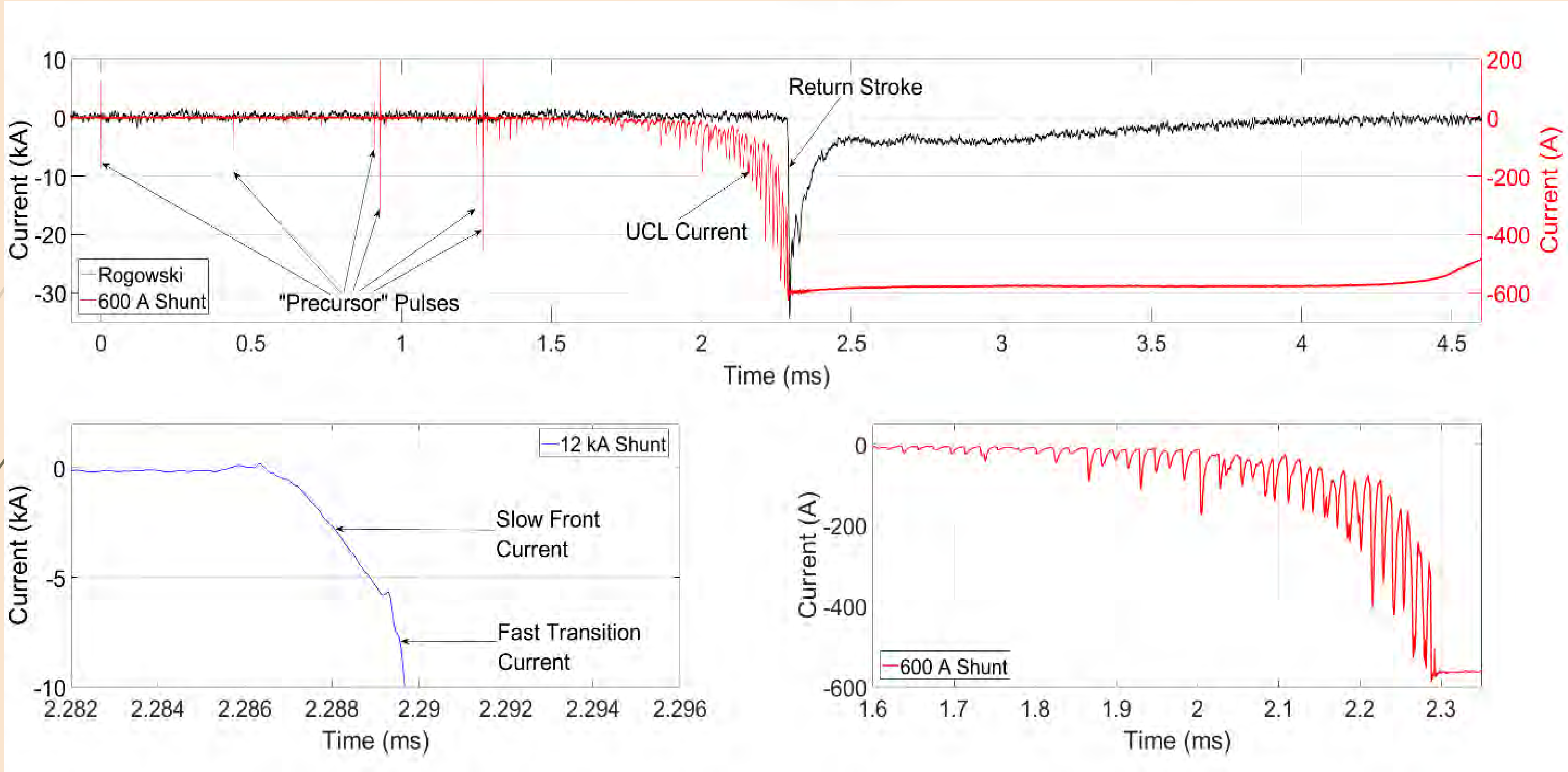






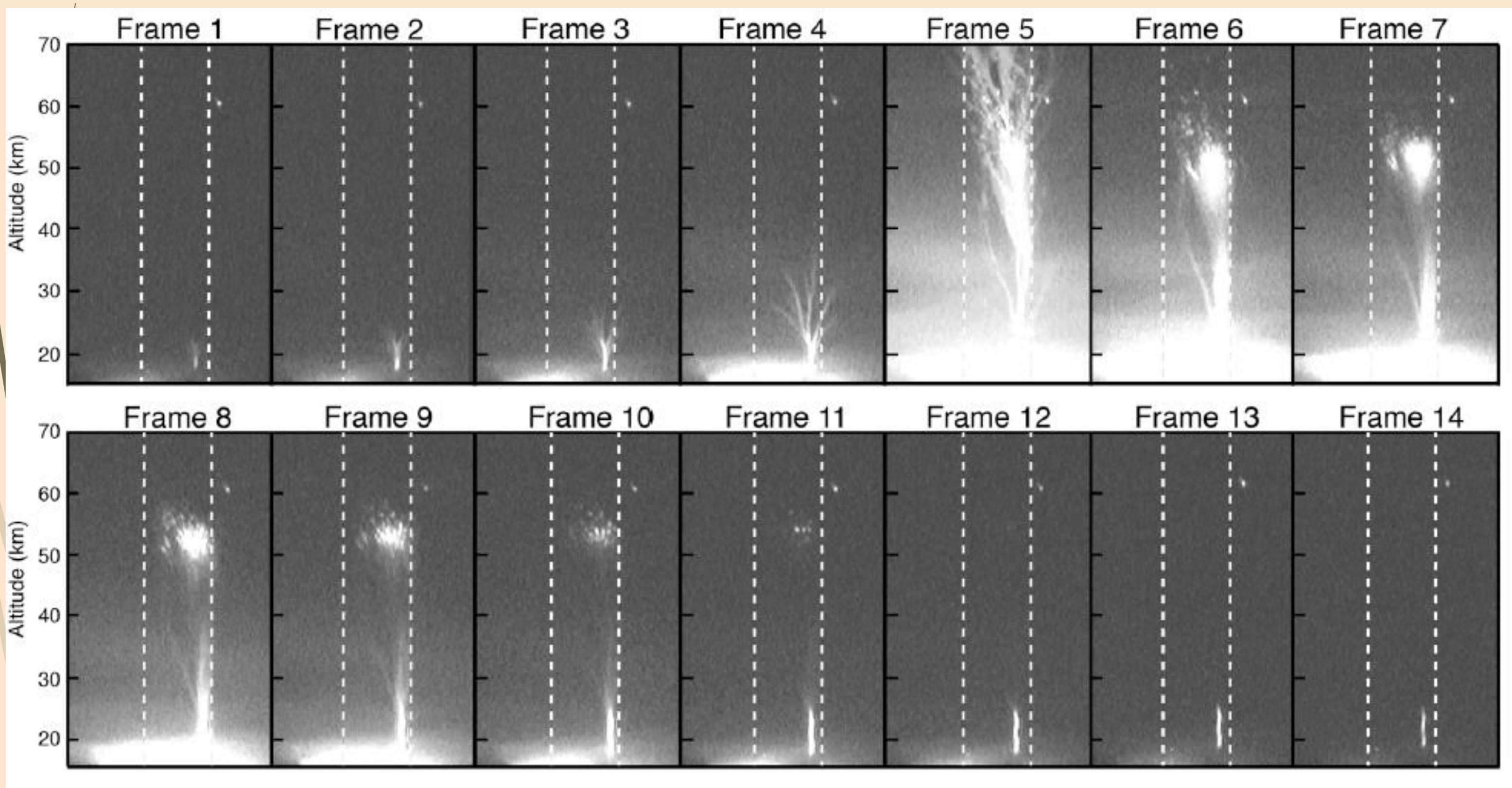
- We operate the ONLY **natural-lightning electric current measurement facility** operating in the United States.
- Located in a region of **high lightning flash density** (5 - 6 flashes are expected at the tower per year).
- **Located in a unique region** with a large number of lightning and meteorological measurement systems: VHF lightning mapping array, VHF interferometric network, electric field mill network, weather radars, high-speed video camera.
- We have **a suite of electromagnetic field measurements** near the tower to further augment the scientific/research value this facility.

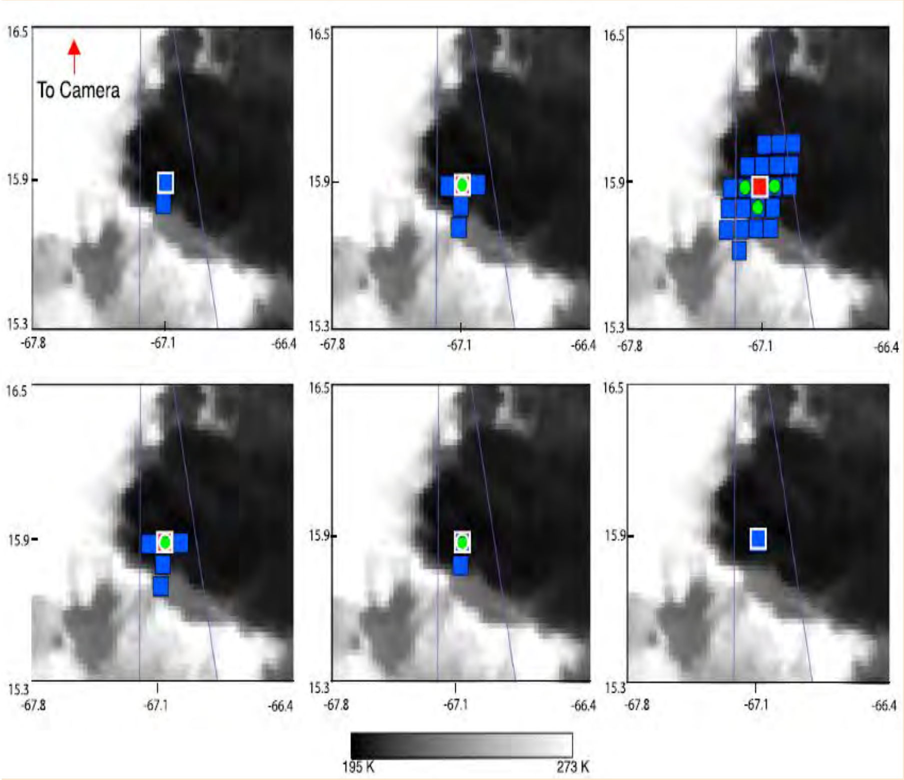
Example of our KSC Tower Observation



CURRENT-4: Observations of TLEs, incl. Gigantic Jets from geostationary orbit.

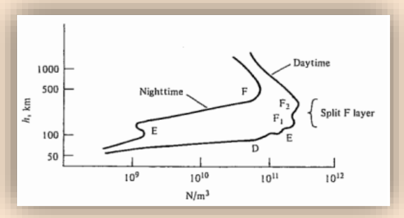
See Boggs et al. (2019)





- **Gigantic jets** (GJs) are a type of transient luminous event (TLE) above thunderstorms.
- These electrical discharges **exit the tops of thunderstorms and reach 70 to 90 km altitudes**, capable of **transferring tens to hundreds of coulombs of charge between the thundercloud and the ionosphere**.

CURRENT-5: Ionospheric disturbances associated with large amplitude Electromagnetic Pulses (EMPs)



- The Earth's ionosphere is an example of a naturally occurring, **weakly-ionized plasma**

$$f_{Crt}\,[Hz] \cong 9\sqrt{n_{max}[m^{-3}]}$$

- **Ionospheric [natural] perturbations** that can result in transit modifications of its parameters and dynamics (***hence its EM communication capabilities***) *are:*
  - (a) perturbations by lightning (transient luminous events or TLEs including ELVES (h ~ 100 km; lifetime ~ 1 millisecond), lightning-induced electron precipitation),
  - (b) perturbations driven by solar activity (X-ray flares),
  - (c) perturbations related to intergalactic radiation (γ rays),
  - (d) perturbations due to radiation belt dynamics (via lightning-induced electron precipitation), and
  - (e) perturbations by atmospheric gravity waves.
  - (f) Large Amplitude (>100kA) EMPs events **(Ongoing Project)**

Large localized ionospheric disturbances result in scattering of VLF communication systems.