This talk is dedicated to my
best friend and colleague Dr. Joseph R. Dwyer
who sparked my scientific interest in understanding of lightning.
Hamid K. Rassoul
May 22, 2019

Genesis of High Energy Radiation from Lightning at Florida Tech

Experimental Investigations of x-ray and gamma ray associated with lightning and thunderclouds from Florida, USA

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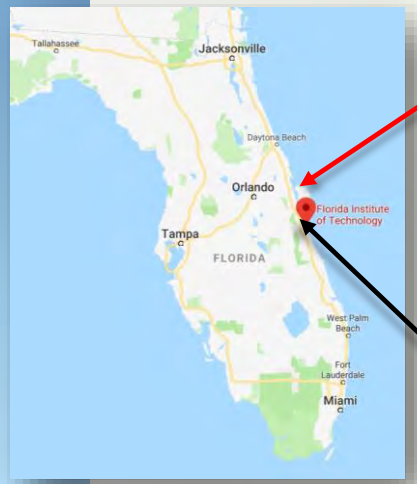
Content (60 slides)

- **Where is Florida Tech (or FIT)?**
- **Mysteries of Lightning**
- **Lightning Research at FIT (1960-2000) & (after 2000)**
  - What changed in 2000?
  - Natural Lightning in Action (video)
  - Building & deploying our first x-ray detector (XLB-1)
  - Moment of Truth – X-ray from lightning
  - Birth of Thunderstorm Energetic Radiation Array (TERA)
  - Triggered Lightning in Action (video)
  - Examples of TERA observations/results
- **Discovery of Terrestrial Electron Beam**
- **Discovery of Positron Clouds**
- **Discovery of X-ray from Laboratory Sparks**
- **Theoretical Advances (List)**
- **Summary & What's Now?**

Where is FIT?

Florida Institute of Technology (FIT) or Florida Tech located in the Central Florida, on southeastern U.S. by the Atlantic coast



Kennedy Space Center NASA

FLORIDA INSTITUTE OF TECHNOLOGY
AD ASTRA PER SCIENTIAM
1958

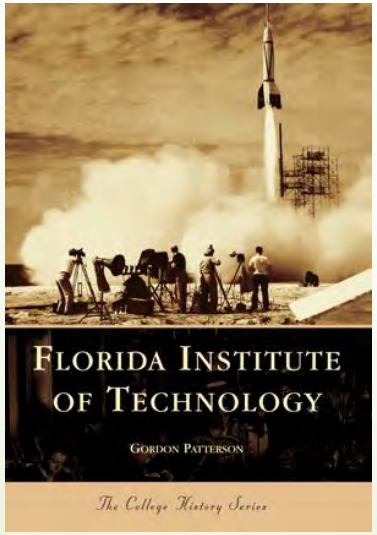
FIT = 28.1° N, -80.6° E
KSC = 28.5° N, -80.7° E

About FIT … We have a *shared history with NASA KSC*

***Young (60 yrs.) ;* premier private technological university *(5000 students); Elite Tie-1 with many NATL & INTL Rankings* and *Accolades* …**

Learn more at https://www.fit.edu/
Learn more at https://www.fit.edu/about/rankings-and-accolades/

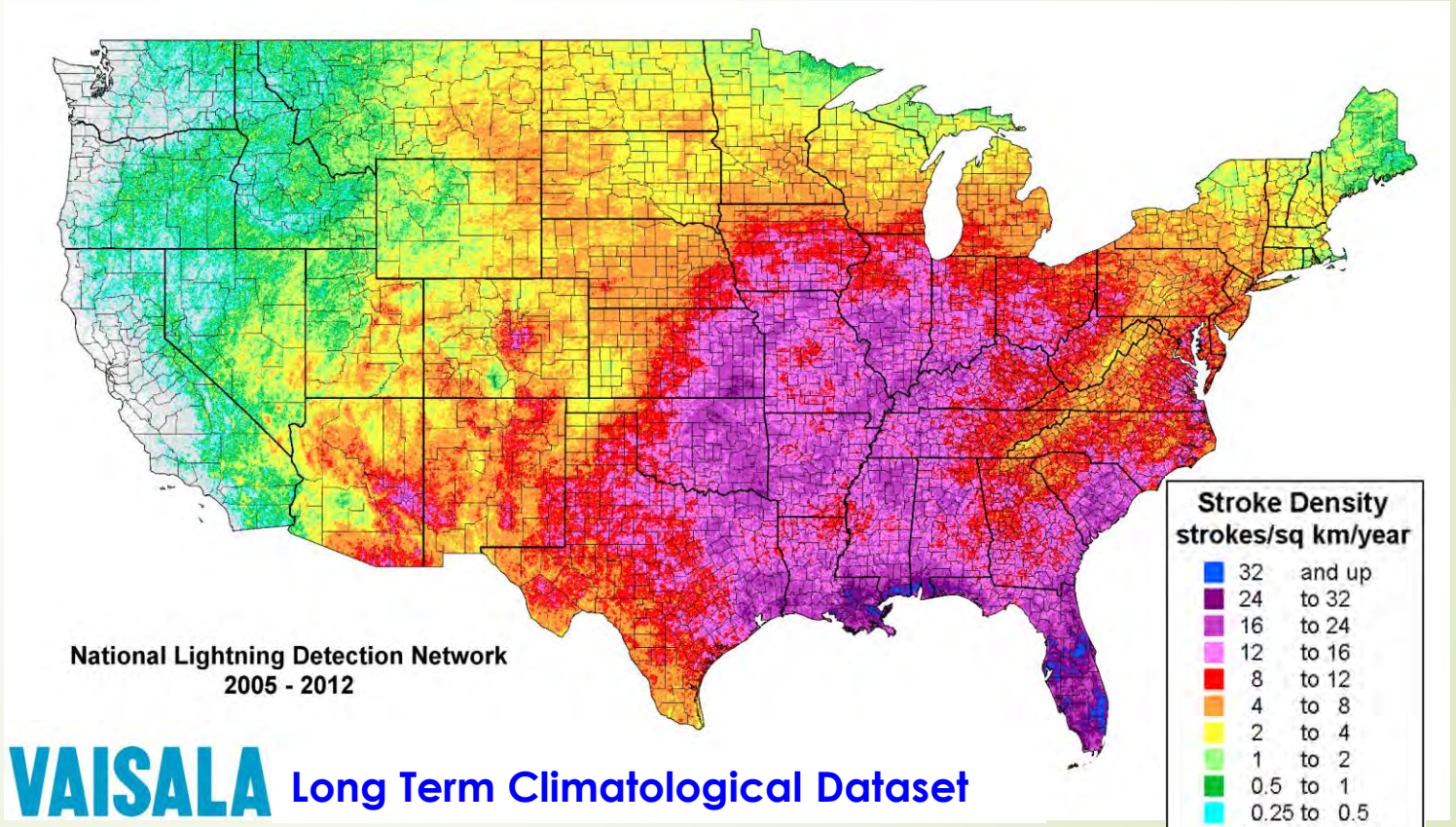
- Ranked among the top 5 percent of 18,000 degree-granting institutions worldwide in the 2018-19 World University Rankings.
- Named one of just 14 U.S.-based Golden Age universities in 2018 by *Times Higher Education*.
- Selected as one of the nation's Best Value Colleges by *Forbes* in 2018.
- Offers bachelor's, master's and doctoral degrees in engineering, science, mathematics, computing and cybersecurity (COES), aeronautics and aviation (COA), business (COB) and psychology and Liberal Arts (COPLA).



About Florida and Central Florida

Florida = "*Lightning Capital*" of the United States.
Central Florida = "*Lightning Alley*" of Florida.

- **Florida** leads nation in lightning fatalities and injuries (the No. 1 cause of weather-related deaths).
- **Central Florida** has ~ 100 major lightning storm days per year.
- **In the U.S.**, the odds of becoming a lightning victim in any one year is 1 in 700,000. The odds of being struck in your lifetime is 1 in 3,000. (Best odds of winning the national lottery in your lifetime is estimated to be 1 in 14 millions).

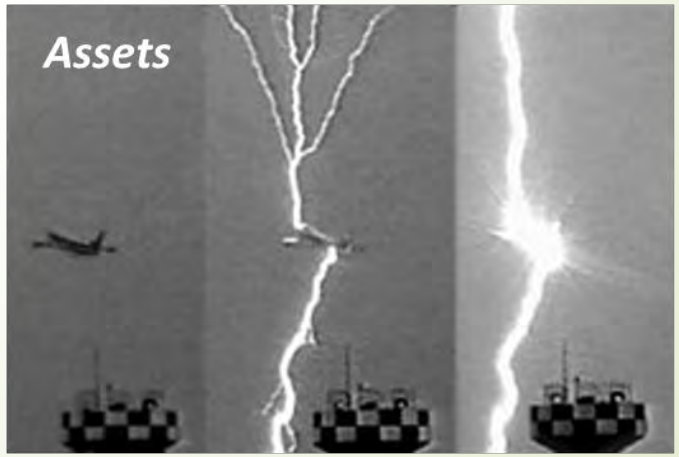


Mysteries of Lightning -- from Basic Science to Applied Science

Basic Science: *Despite its familiarity, lightning remains a mystery 250 years after Franklin's kite experiment:*

Big Question # 1: **Charging:** How does a thunderstorm charge up?
Big Question # 2: **Initiation:** How does lightning get started inside thunderstorms?
Big Question # 3: **Propagation:** How does lightning travel through tens of miles of air?
Big Question #4: **Attachment:** Why does lightning hit one thing rather than another?
Big question # 5-99: **What the heck was that?** Strange events are afoot with lightning (TGF's; CID's ; TLE's; EMPs, Ball Lightning; etc.)

Applied Science: *Protecting* ***Operations***, ***Communications***, ***Assets***, *and* ***Personnel***



FIT Lightning Research (1960-2000)

Assisting KSC with lightning engineering systems in support of launch operations (field sensors, camera, LDAR, etc.)

Lightning strikes Space Shuttle Endeavour's Launch Complex 39A on July 11, 2009 during a thunderstorm event. The complex was struck at least 11 times, delaying the launch for at least 24 hours.

Advanced lightning protection system for KSC pad 39B

TIPP Research: Using KSC VHF sensors, we did some research work on characterization of Trans-Ionospheric Pulse Pairs (TIPPs) that are correlated with intracloud pulses.

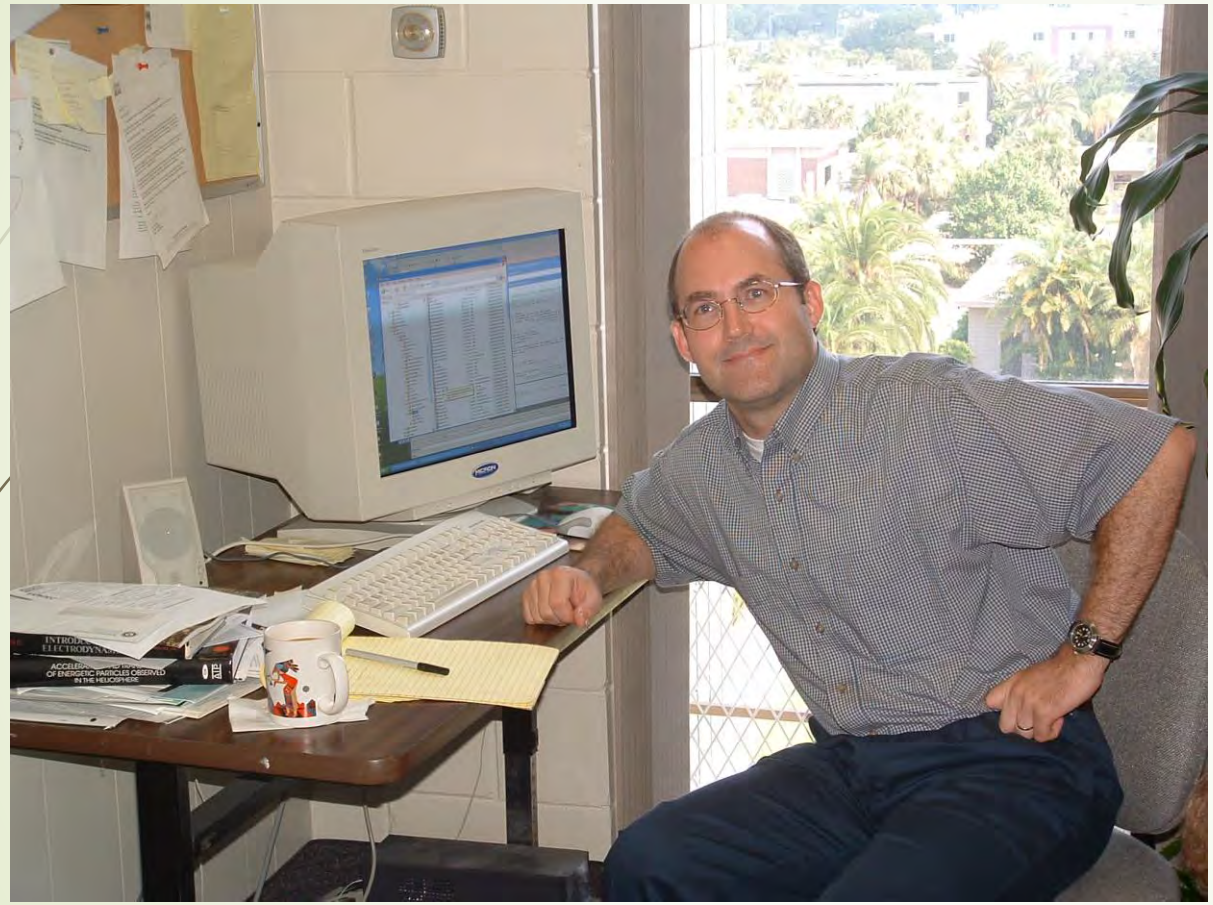
FIT Lightning Research (after 2000): Focus on physics of lightning

Advances in both Theoretical and Experimental for High Energy Radiation from Atmospheric Discharges

A lot of what is known about x-ray emissions from lightning comes from our work at Camp Blanding.

1. Established once and for all that lightning does indeed emit bright bursts of x-rays.
2. In Triggered Lightning, we discovered that dart leaders emit x-rays
3. In Natural Lighting, we demonstrated that x-rays are produced during the step formation of leaders
4. … and many more!

In 2000, What Changed at FIT?



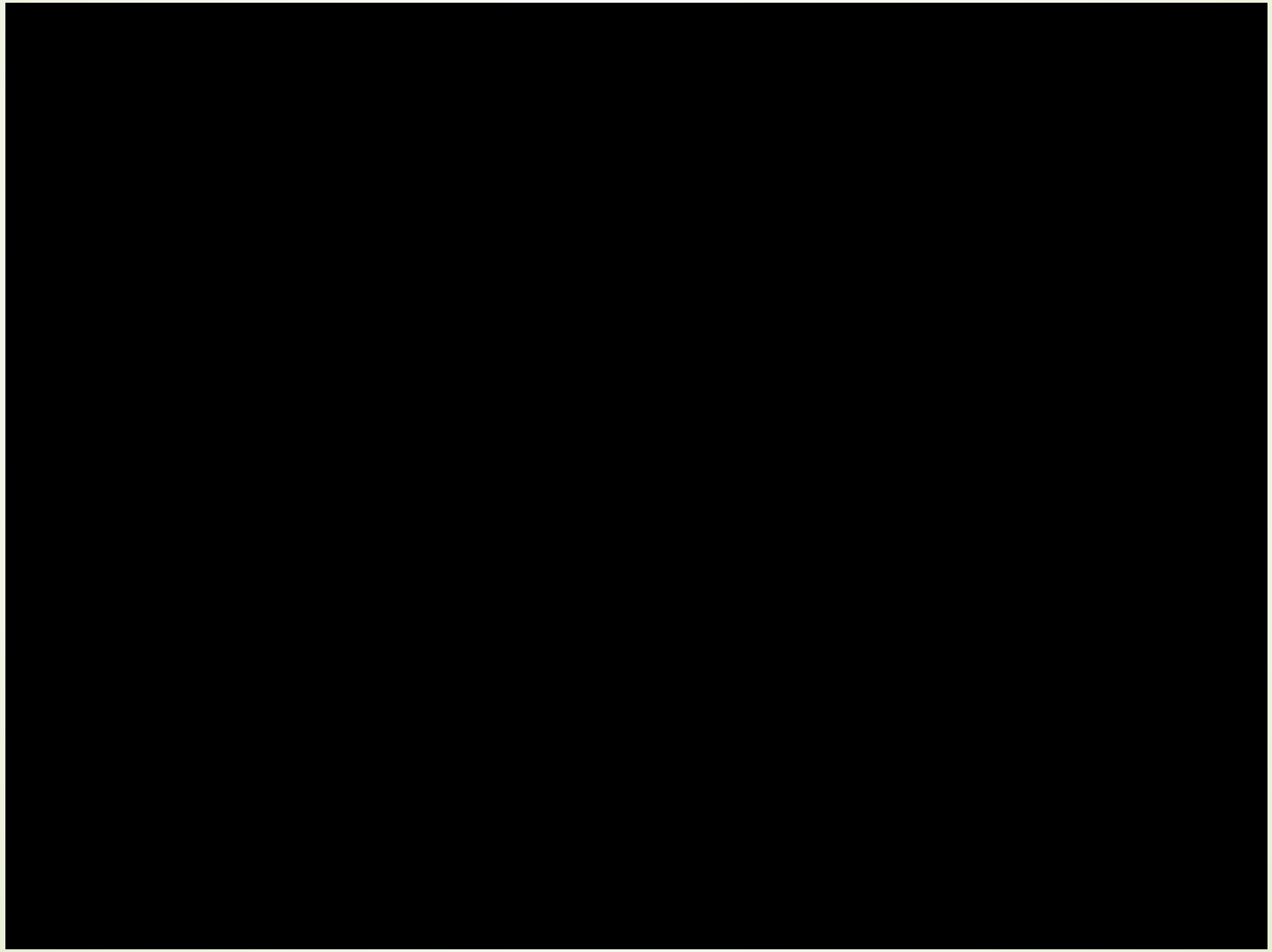
Joseph (Joe) R. Dwyer – Space Physicist, PhD 94, University of Chicago

Florida summer (May-Oct)
Daily shows 2:00-6:00 pm

In addition to acoustic radiation, lightning excites all EMS frequencies. "*Theoretically, they should also produce non-thermal X-ray radiation. …we should go after X-ray in lightning, to see if they are there! Of course, at ground level, we must be close to its source*."

What you can see from your office window?

Florida summers -- Afternoon "Lightning Show"



Reported X-ray in thunderstorms and lightning?

Experiment	Location	X-rays in thunderstorms?	X-rays in lightning?
Appleton & Bowen (1933)	ground	No	No
Macky (1934)	balloon	No	No
Clay et al. (1952)	ground	Yes	No
Hill (1963)	300 m tower	No	No
McCarthy & Parks (1985)	aircraft	Yes	No
Fishman et al. (1994)	space	Yes	No
Moore et al. (2001)	Mountain Top (3.3 km)	No?	Yes
Dwyer, Rassoul et al.	Ground (sea-*level*)	TBD	TBD

Moore et al 2001 reported the detection of energetic radiation during natural CG lightning. It was not clear whether the source of the radiation was the lightning leader or the overhead thundercloud, similar to earlier measurements. Their detector could not determine the nature of radiation (x-rays, gamma-rays or electrons), although MeV gamma-rays were suggested --making it impossible to estimate the distance to the source.

At that time, the general consensus was that thunderstorms may produce x-rays emission but lightning probably did not.

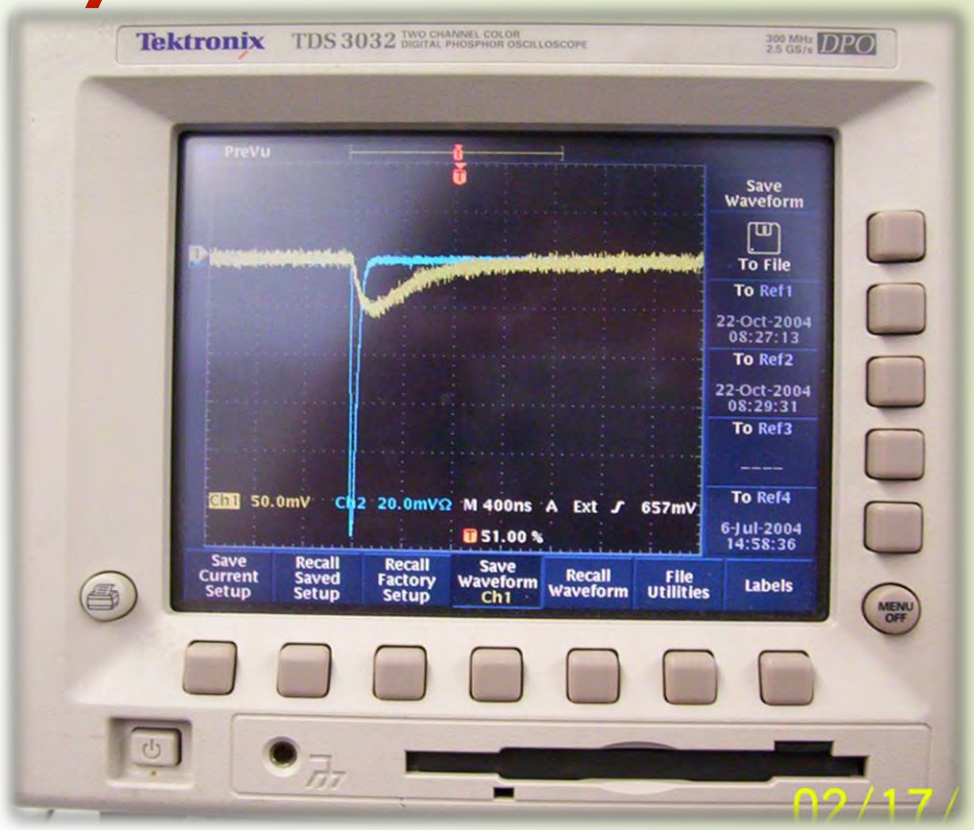
Early results were either ambiguous or contradictory, in part due to the unpredictability of lightning and the challenges of measuring energetic radiation in the electromagnetically noisy environment created by the lightning.

More Details on early attempts of measuring x-rays from thunderstorms and lightning

Experiment	Location	Technique	Time Resolution	Source Distance	Count Increase	
					Lightning	Thunderstrom
Schonland [1930]	South Africa (ground)	Ionizing chamber	10 min	>250 m	…	…
Schonland and Viljoen [1933]	South Africa (ground)	G-M tube	5 ms	20-60 km	X	X
Appleton abd Bowen [1933]	SE England (ground)	G-M tube	1 s	2000-3000 km	X	…
Halliday[1934, 1941]	United Kingdom (ground)	Cloud chamber (expansion)	statistical	overhead to 40 km	X	…
Macky [1934]	United Kingdom (balloons)	photographic plates	days	in active thundercloud	…	…
Clay et al. [1952]	Amsterdam (ground)	ionization tubes, counters	14 s/ 1 hour	a few kilometers	…	X
Hill [1963]	Ilinois (90 m tower)	photographic emulsions	1-2 weeks	tower strikes	…	…
Shaw [1967]	Tucson, Az (2800 m)	NaI scintillation detectors	1 min/1 ms	tower strikes to few kilometers	…	X
Whitmire [1979]	Louisiana (549 m tower)	TLD dosimeters	9 months	tower strikes	…	X
Mccarthy and Parks [1985]	Aircraft	Scintillators	??	in active thundercloud	…	X
D'Angelo [1987]	Ground	Cloud chamber (diffusion)	1s	few 100 m	X	…
Fishman et al [1994]	Space	??		few 100 km	…	X
Moore et al. [2001]	Ground	NaI scintillation detectors	few ms/us	few 100 m	X	…
Dwyer et al. [2003]	CampBlanding, FL (Ground: Natural and Rocket- Triggered lightning)	NaI scintillation detectors	2 s/ 1 us	0-1 km	X	…

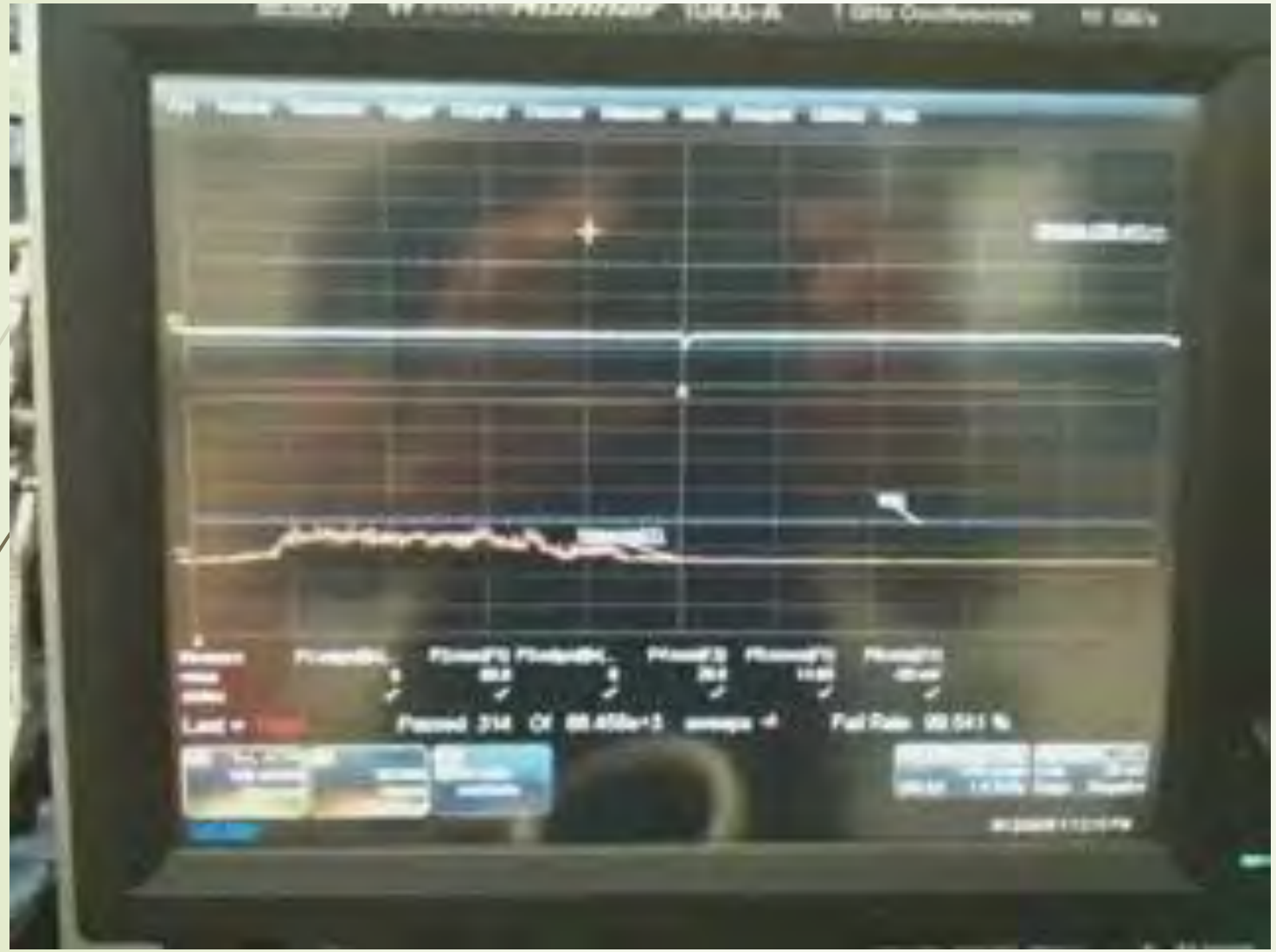
How do we measure X-ray?

Two different types of **scintillator detectors** used for measuring energetic radiation. (NaI or LaBr3), a light pulse is emitted and then get converted into an electrical signal using a photomultiplier tube.



Signal response from Sodium Iodide detector (Yellow) and Lanthanum Bromide detector (Blue). **LaBr has a faster response (16 ns) as compared to NaI (230 ns).**

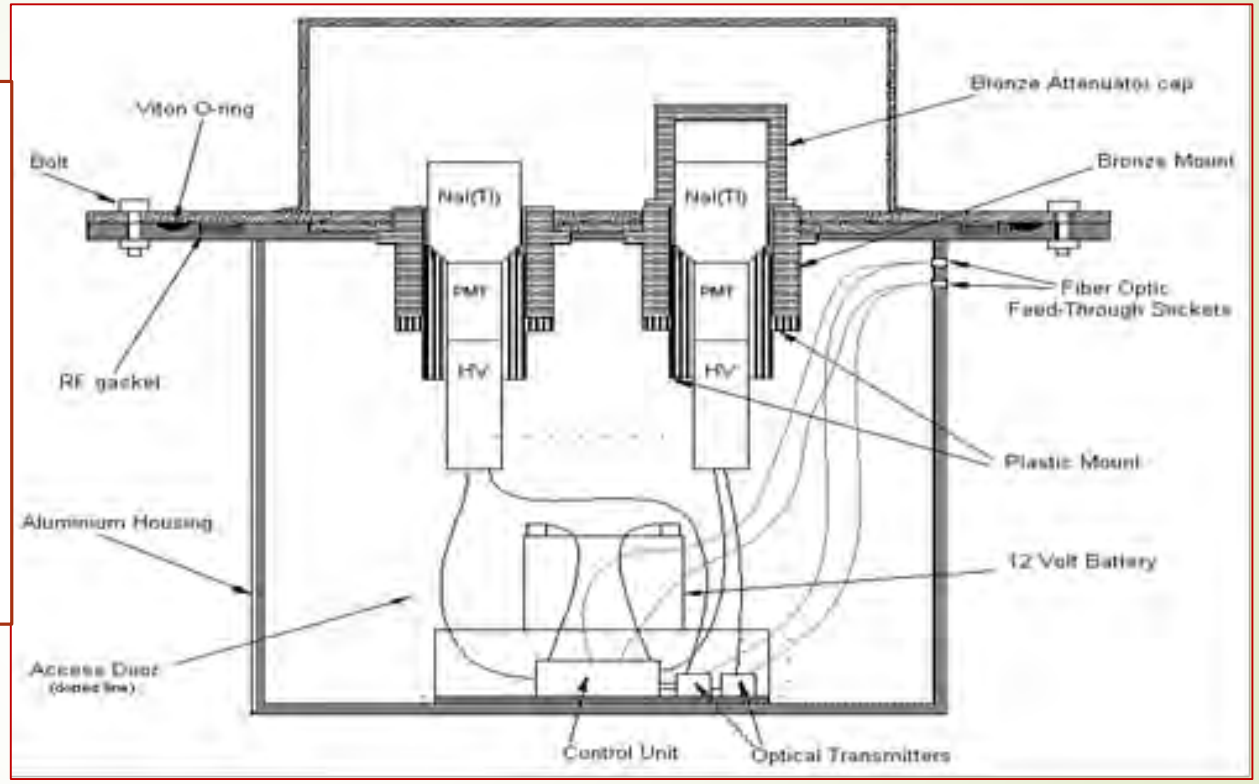
Calibration! Dr. Dwyer injected with Technetium-99m



Technetium-99m is a metastable nuclear isomer of technetium-99. It is used in tens of millions of medical diagnostic procedures annually, making it the most commonly used medical radioisotope. It is used as a radioactive tracer and can be detected in the body by scintillators . Half-life: 6 hours.

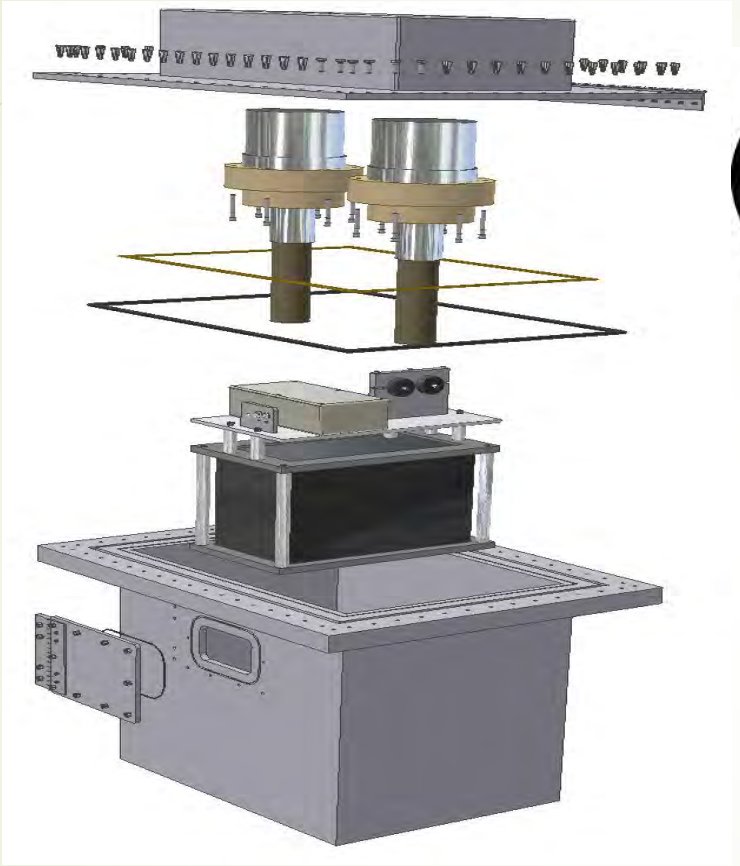
Building our first X-ray Lightning Box (XLB)

Instrument used to measure X-rays from lightning at the International Center for Lightning Research and Testing (*ICLRT*) at Camp Blanding, FL



Cross section view of an XLB showing different parts of the box. It contains *1 or 2 NaI(TI)/photomultiplier tube detector(s)* shielded inside a thick (1.25 cm) aluminum boxes to *eliminate RF noise, light, and moisture*. The detector(s) inside were *battery powered* and the electric signals from the PMT anode were transmitted over via FM *optical transmitter over a fiber optic link* back to a separate shielded room that contains the data acquisition system.

So it all started with One X-ray Lightning Box (XLB-1)



[Left Panel] show a 3D CAD model of XLB1 showing the box and the instruments inside.

[Right Panel] XLB1 fully assembled and deployed in the field.

Rocket Triggered Lightning *(more later)*

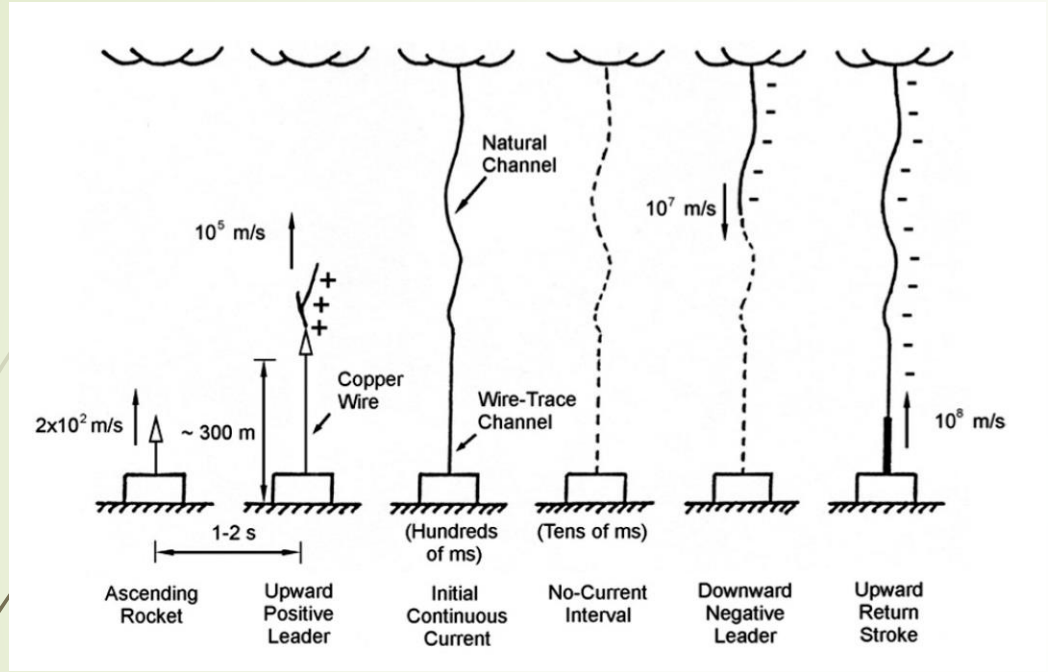


Diagram showing sequence of events in classical triggered lightning. Stages 1 and 2 in the diagram constitute the initial stages [Rakov et al. (1998)]. The figure on the right is a still image of a rocket triggered event with multiple return strokes.

Natural Lightning flash

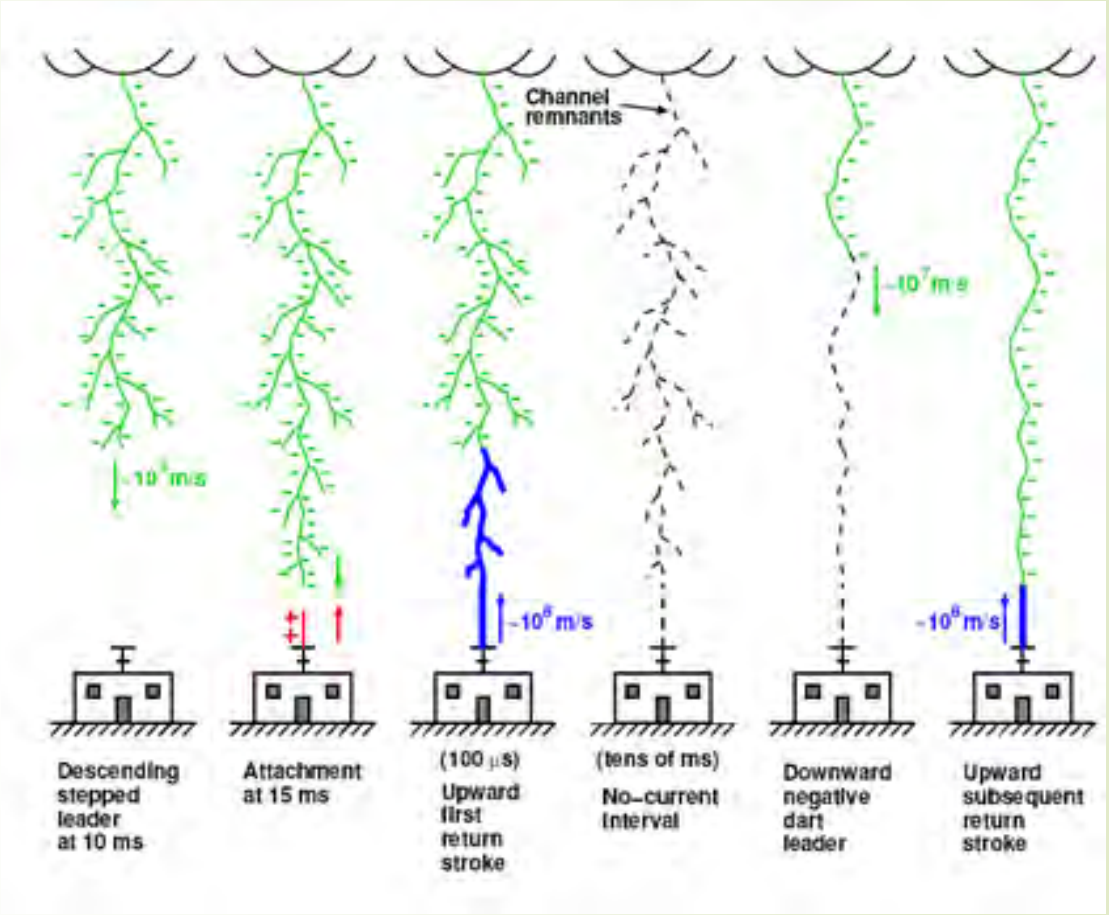
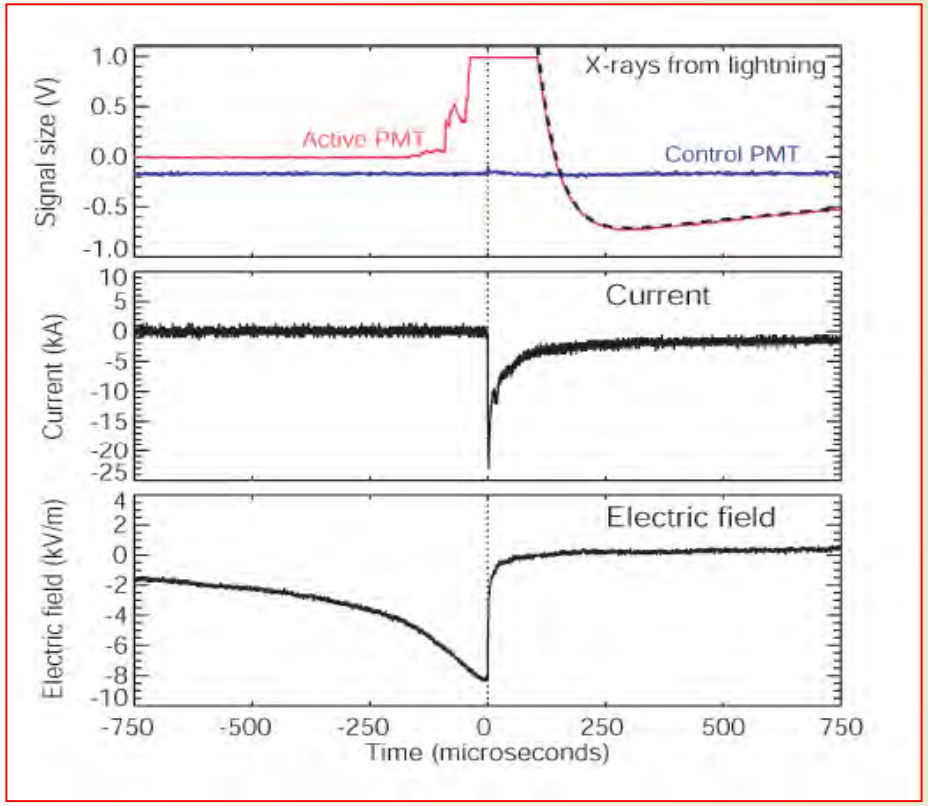


Diagram showing sequence of events in a natural lightning flash. The first stage is a stepped leader then followed by consecutive dart leaders. The figure on the Left is a still image of a natural lightning flash with multiple branches.

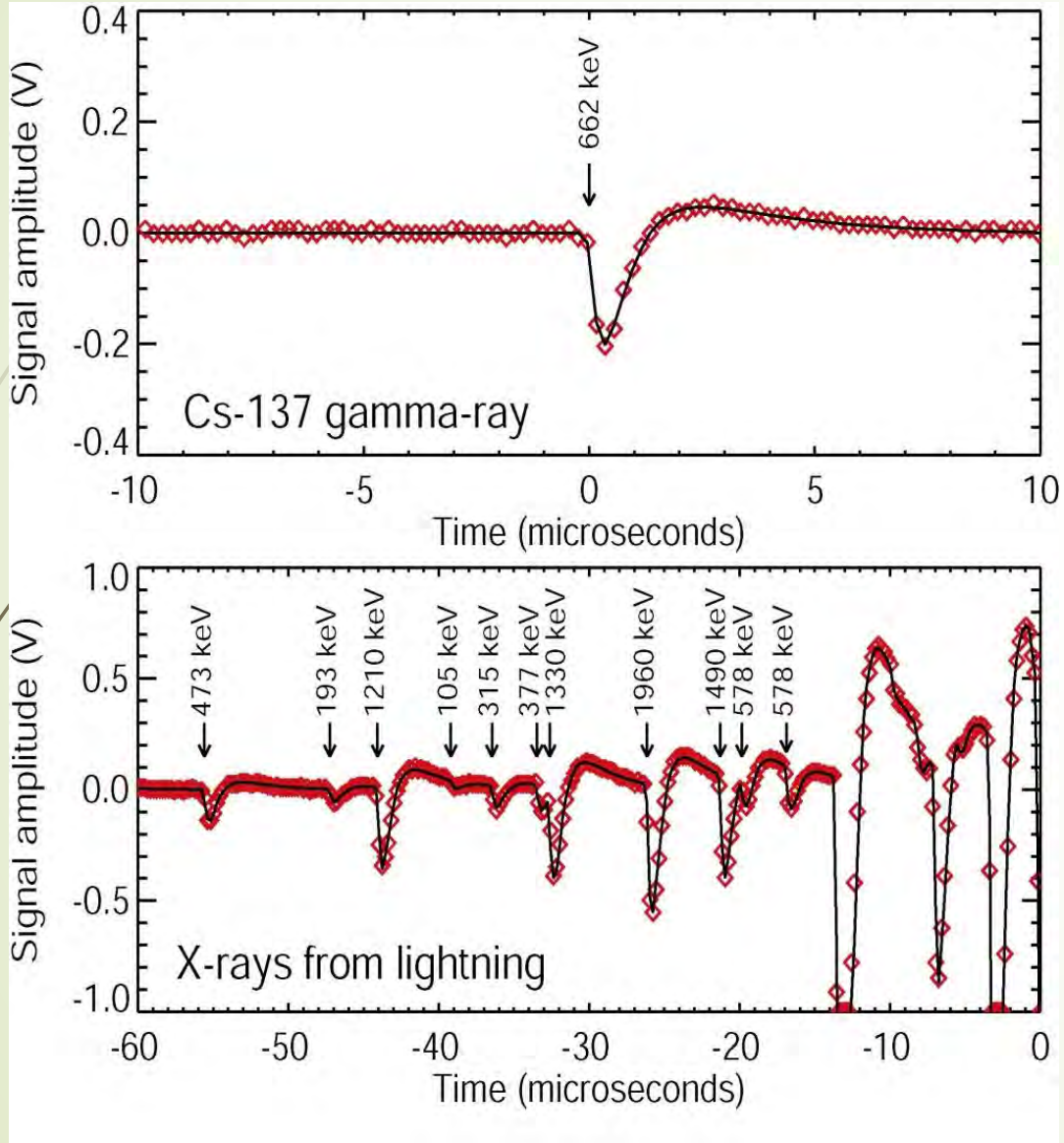
Moment of truth! (Summer 2002)

Large bursts of x-rays were observed !!!



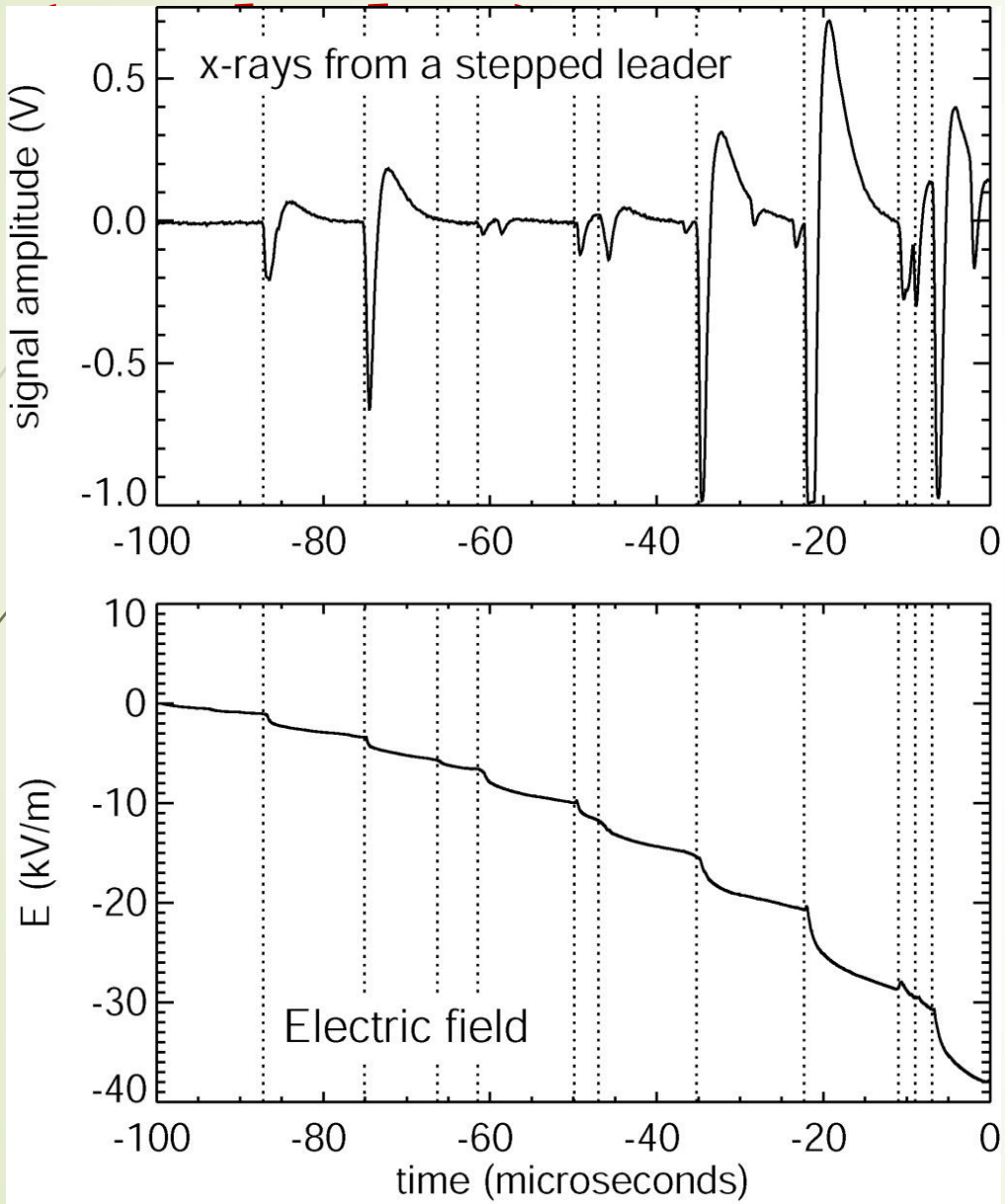
X-ray waveform from a rocket triggered lightning event along with electric current and electric field measurements. Left panel shows the launch tower used in triggered lightning [Dwyer et al. (2003)]

X-rays Observations from trig. lightning dart leaders



- We were able to show that x-ray emission are originating from the dart leader in triggered lightning.
- X-ray observed in the last few hundred meters of a channel, and the source propagated downward with the leader as it approached the ground.

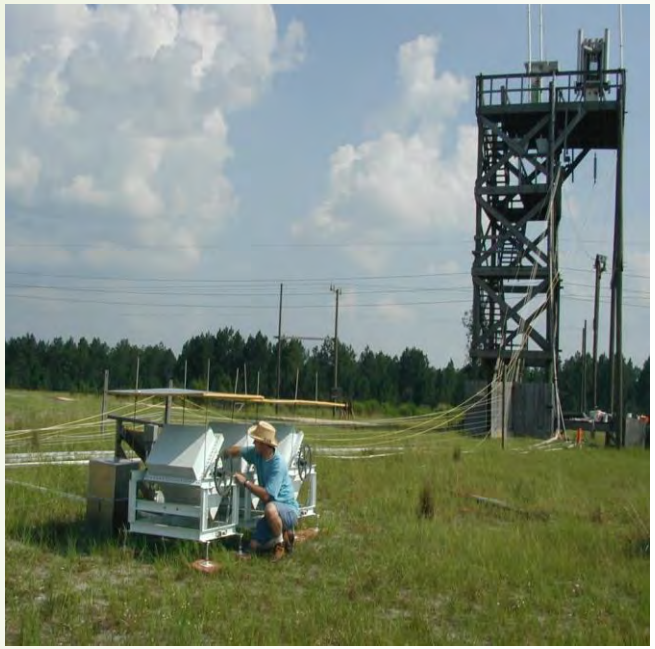
X-rays observation from natural CG lightning

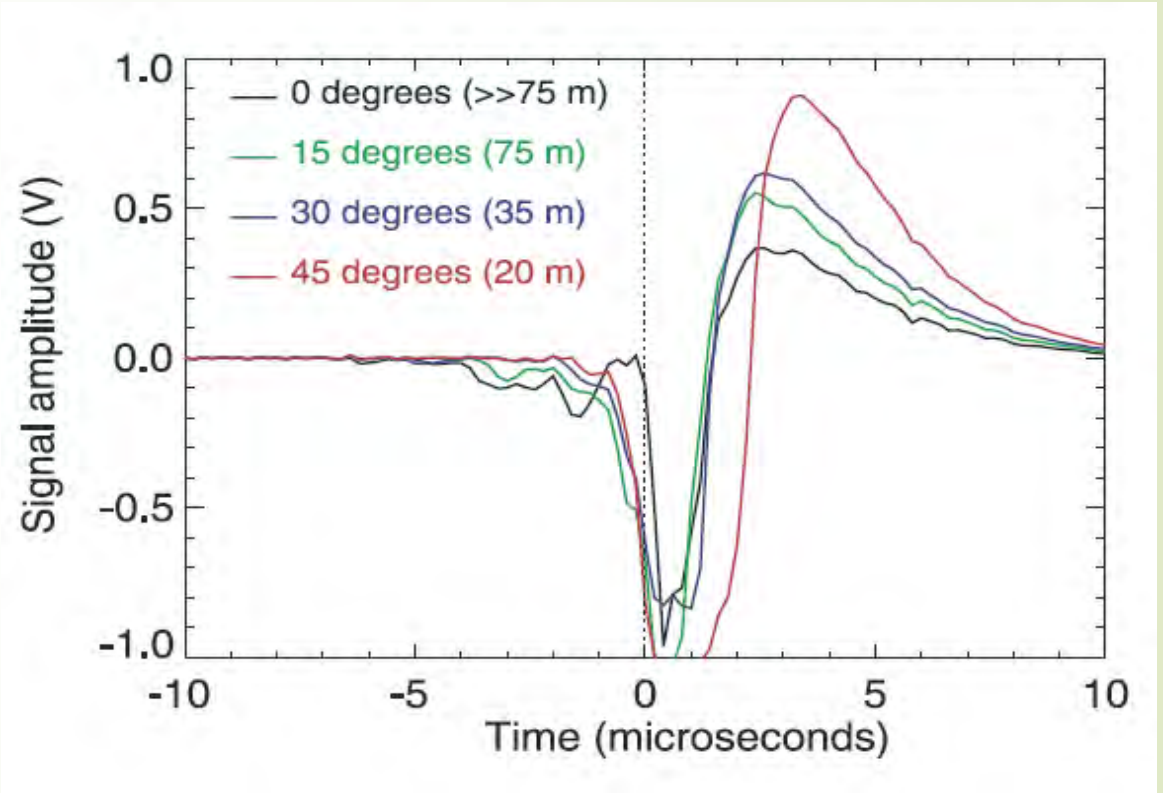


- Found clear correlation between stepped leader steps and x-ray bursts.
- For the larger x-ray bursts the x-rays often arrive up 1 microsecond before the formation of the step.

2003, 2004 --XLB[1+,2,3,4,5] at ICLRT

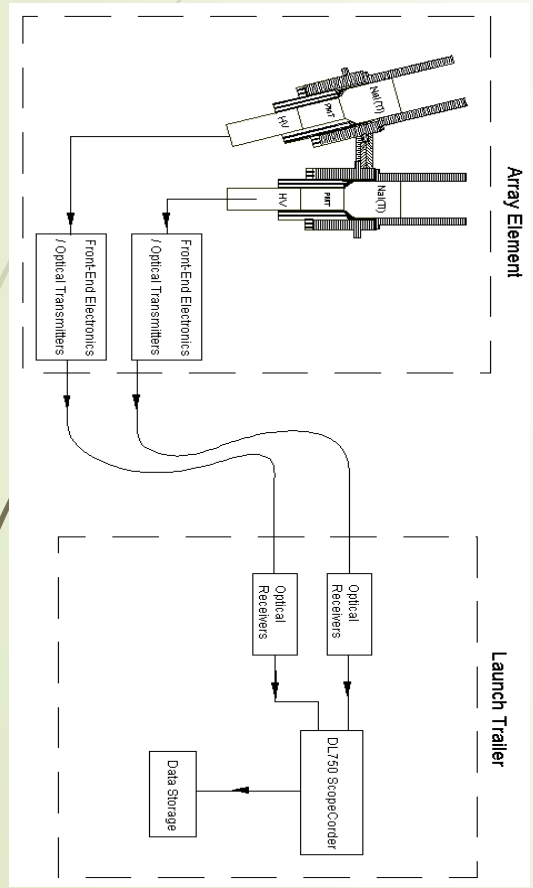
3 XLBs with adjustable tilt platforms in front of rocket launch tower used to trigger lightning at ICLRT

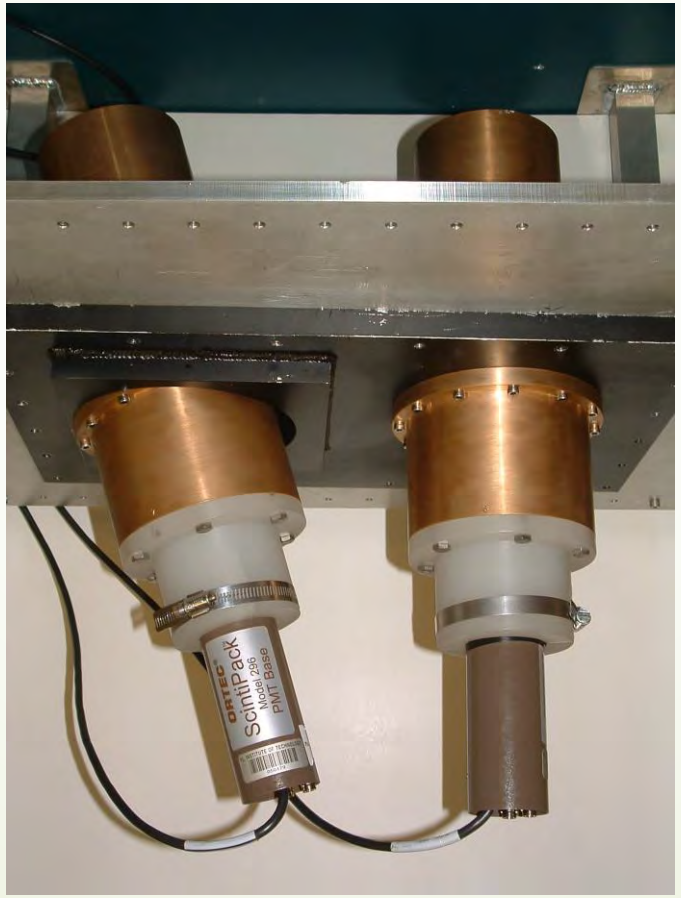




- Experiment with various coulometers and attenuators to characterize of the radiation beam.

Data acquisition is triggered using current measurements for triggered lightning and optical measurements for natural lightning. For e ach trigger, the signals from the PMT anodes are recorded for 2 seconds (0.5 sec pre-trigger data) with 0.1 μsec resolution.





Redesign XLBs

- The XLB design was simply overbuilt, especially when you try to deploy it on a large scale. Based on our know knowledge on the nature and energetic of the radiations , a simpler and more compact design was developed. The new array of instruments, called **TERA** (**T**hunderstorm **E**nergetic **R**adiation **A**rray).

- TERA had a total of 26 x-ray boxes containing 45 NaI/photomultiplier tube (PMT) detectors and 5 fast plastic scintillator detectors.

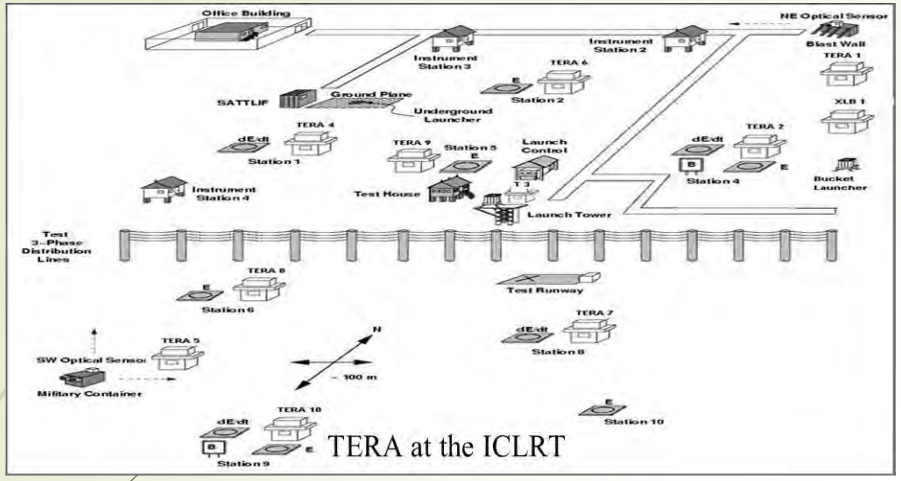
2005
New instrument Design

[Left panel] A 3D isometric view of the TERA instrument. All instruments are equipped with shielded (1/8” lead) NaI detector (SPMT) while the other detector is left unshielded (UPMT).

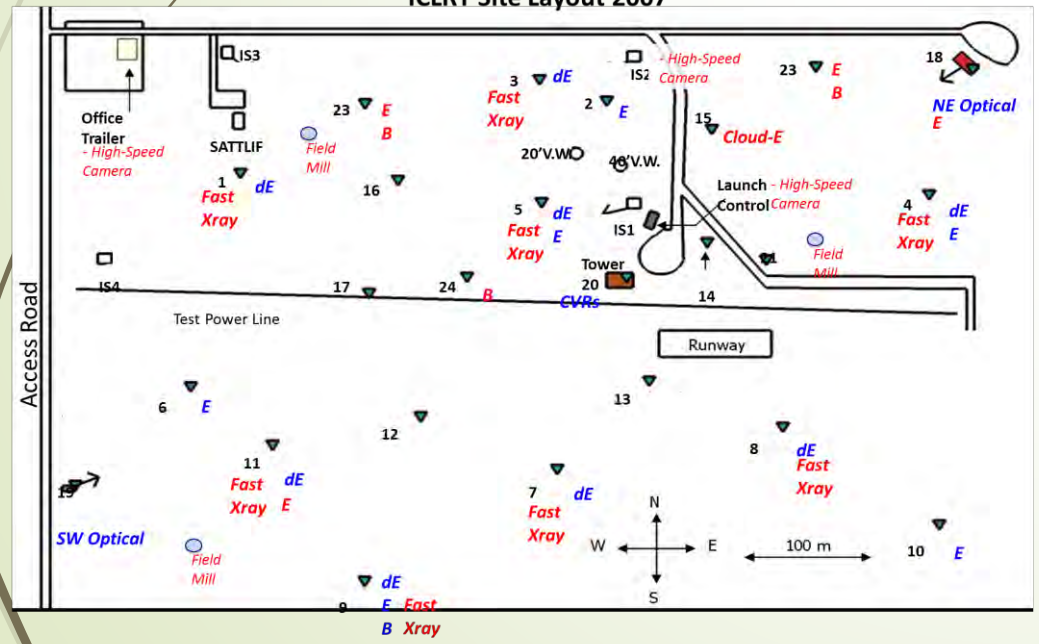
Thunderstorm Energetic Radiation Array (TERA)

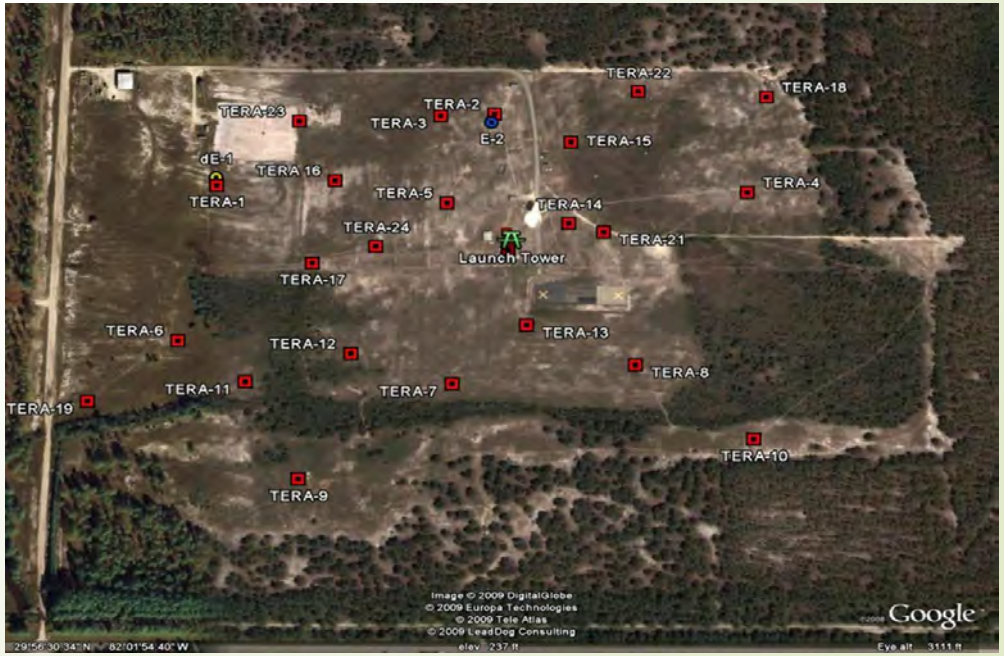
- 32 new x-ray instruments, each containing two 3” NaI(Tl)/PMT detectors, covering 1 square km at the ICLRT.
- At the TERA stations we also made electric and magnetic field, fast *dE/dt* and optical measurements. In addition, we had direct current measurements for all triggered lightning.
- TERA made detailed measurements of x-ray emission from natural and triggered lightning and thunderstorms.

TERA in 2005 (8 TERA boxes)



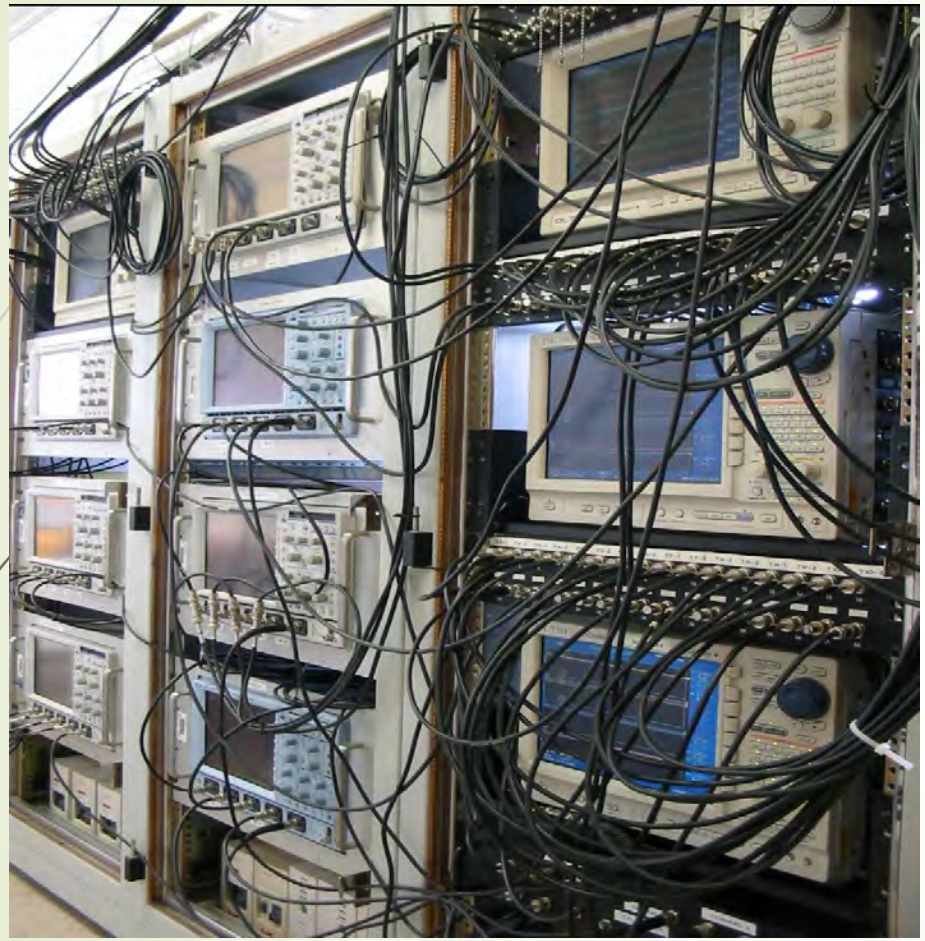
ICLRT Site Layout 2007





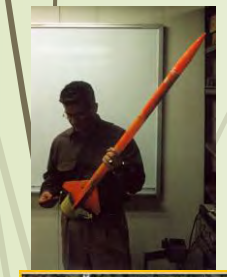
4 – 1080i HD cameras : 4 NTSC cameras : 6 35mm Still Cameras

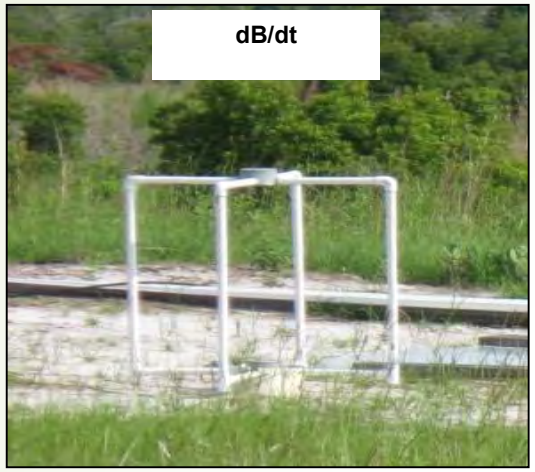
TERA support -1

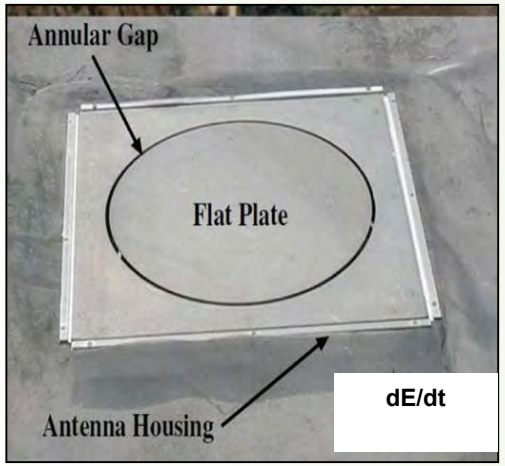


[**Left panel**] shows the Yokogawa and Lecroy digitizers operating at 10 and 200 Ms/s rate consecutively. [**Top right panel**] NASA field mill used to measure the electrostatic field at ground. [**Bottom right panel**] Flat plate antenna for measuring fast dE/dt.

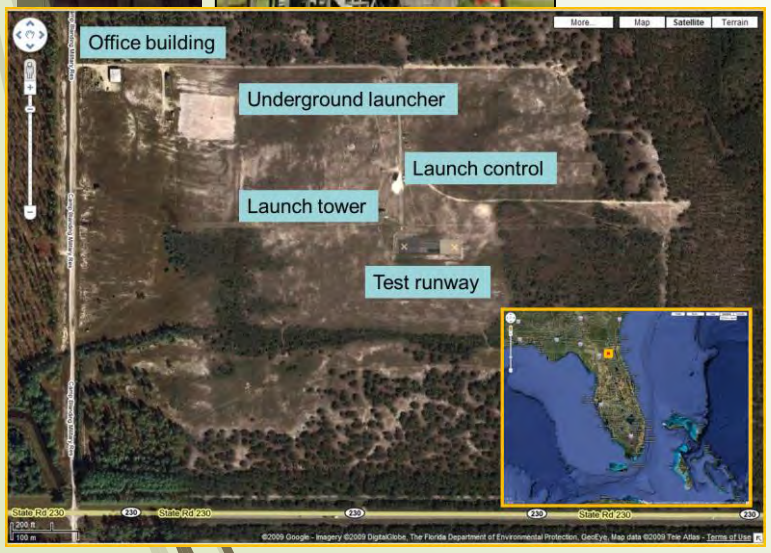
TERA Support – 2

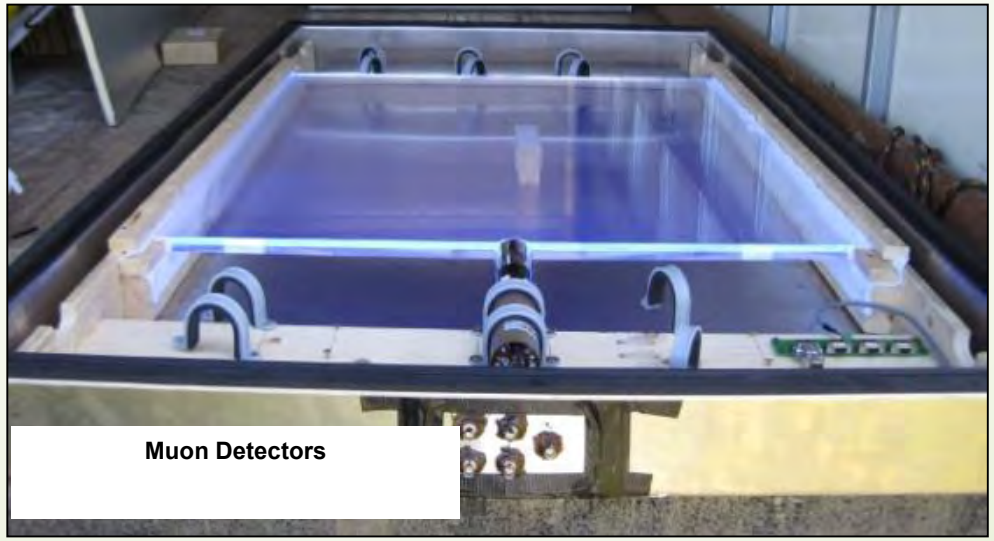


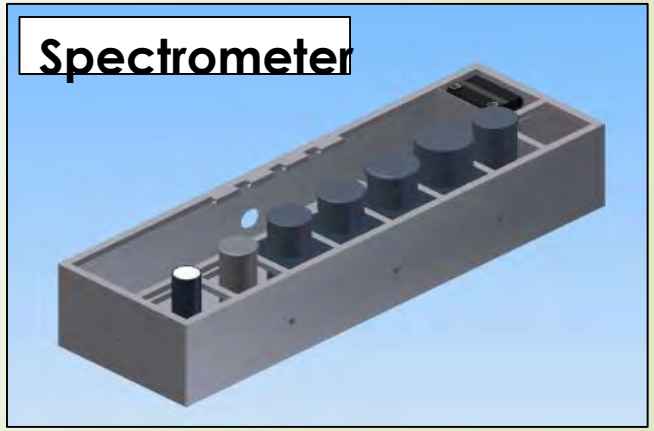




Phantom Vx & megaspeed HHC-X2

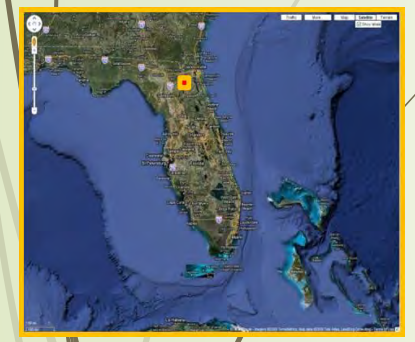






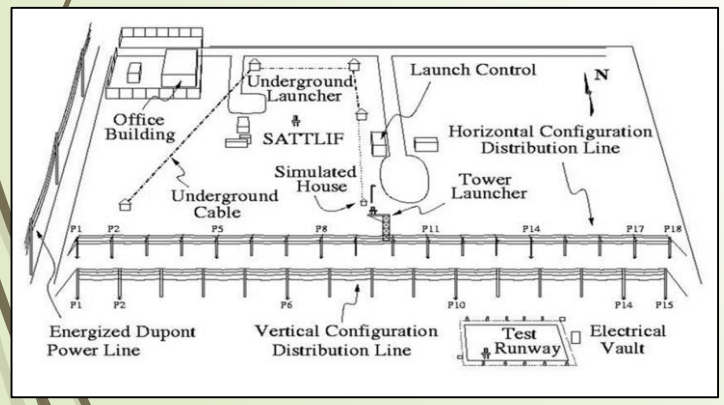
The International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida

(http://www.lightning.ece.ufl.edu)



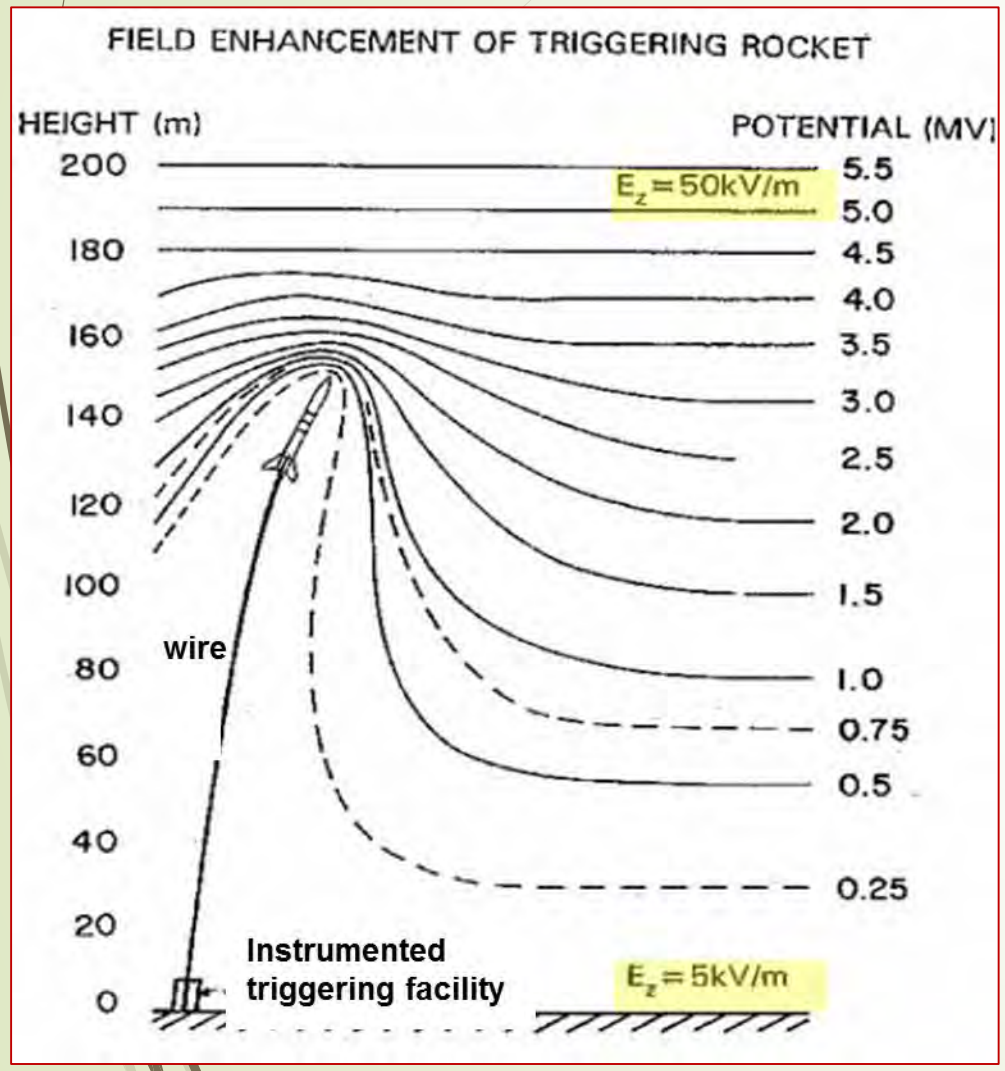
The lightning-triggering facility at Camp Blanding, Florida, was established in 1993 by the Electric Power Research Institute (EPRI) and Power Technologies, Inc. (PTI). Since September 1994, the facility has been operated by the University of Florida (UF). Over 40 researchers (excluding UF faculty, students, and staff) from 15 countries representing 4 continents have performed experiments at Camp Blanding concerned with various aspects of atmospheric electricity, lightning, and lightning protection.

Since 1995, the Camp Blanding facility has been referred to as the International Center for Lightning Research and Testing (ICLRT). Since 2008, it is jointly operated by UF and Florida Institute of Technology (FIT) and additionally includes the Lightning Observatory in Gainesville (LOG) and the Golf Course Station (GCS) in Starke.



Courtesy of Prof. Vladimir Rakov

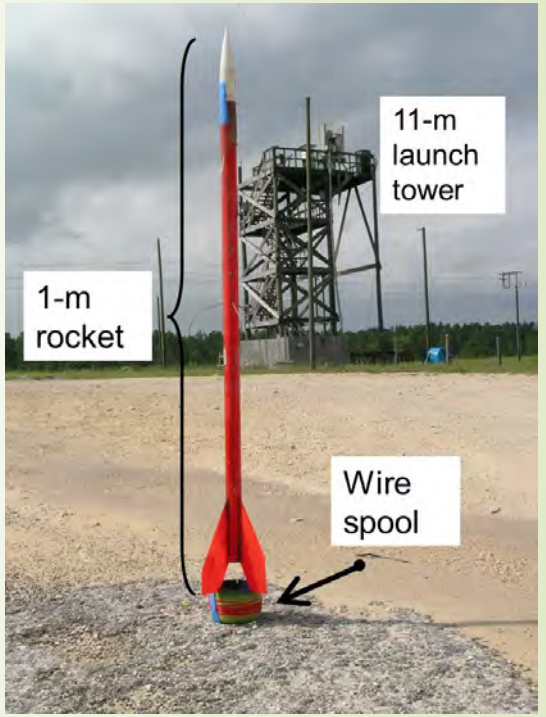
Rocket-and-wire triggered lightning



$$E_z = -\Delta V/\Delta z$$

Schematic illustration of the equipotential surfaces in the lowest 200 m and their interaction with a rocket extending grounded wire in the thundercloud electric field.

The equipotentials are closely spaced aloft where the vertical field is assumed to be 50 kV/m, and near the tip of the rocket, where they are concentrated geometrically. They are further apart near the ground, where the field is greatly reduced by corona space charge.



Fiberglass rocket with a spool of Kevlar-coated 0.2-mm diameter copper wire

Courtesy of Prof. Vladimir Rakov

… *Rocket triggered lightning in action* – *When & Where + Currents*

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Lightning <u>when</u> and <u>where</u> we want it !

Observational Science to Experimental Science

Let's see a LAUNCH !

Not all launches are successful in triggering lightning (chance of success 55-75%)

Example of a failed attempt to trigger lightning (just a wire burn -- not good timing !)

Let's see a successful launch …