Detecting the charge transported by lightning

Richard Sonnenfeld

Physics Department &
Langmuir Laboratory for Atmospheric Physics
New Mexico Institute of Mining and Technology

Support:
National Science Foundation
Langmuir Endowment - NMT
New Mexico Space Grant – NMSU

U. S. Forest Service; U. S. Navy; Federal Aviation Administration

(Photo courtesy of Harald Edens)

Collaborators

William Winn, Graydon Aulich, Steven Hunyady, Kenneth Eack, John Battles,
Paul Krehbiel, Ron Thomas, Bill Rison,
Will Walden-Newman, Victor Alvidrez, Gaopeng Lu, Harald Edens

Langmuir Laboratory, New Mexico Tech, Socorro, NM

William W. Hager, Beyza Aslan

Mathematics Department, University of Florida, Gainesville, FL

Outline

- Introduction
  - Costs to society from Lightning
  - Lightning Climatology
  - Parameterizing a lightning flash
- Questions on Charge and Charge Transport

Lightning's costs to society

- Lightning kills approximately 100 people/year in US
  - (1959-1996: NM 85 deaths and 181 injured).
- Causes fires in homes, mines and ammunition depots.
- Costs $4-5 Billion/yr in disrupted power lines, destroyed electronics.

Broader benefits of lightning research

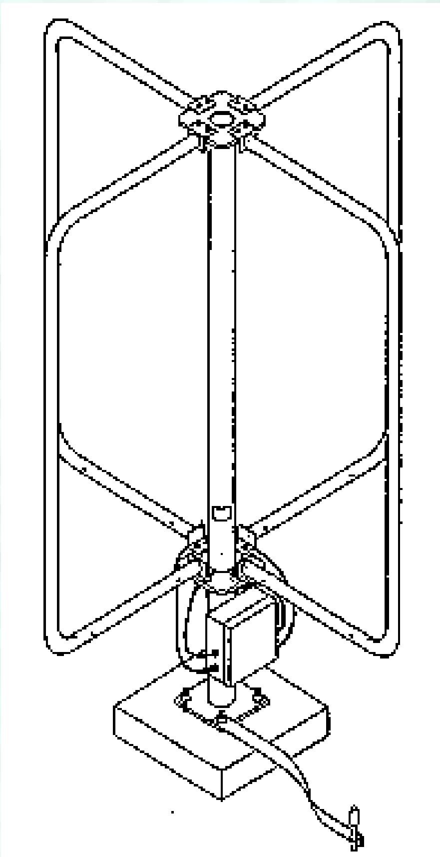
- Understanding of lightning effects on climate change (N2O production)
- Improved lightning rods
- Lightning resistant aircraft
- Lightning warning systems / tornado warnings?
- Global lightning location networks

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

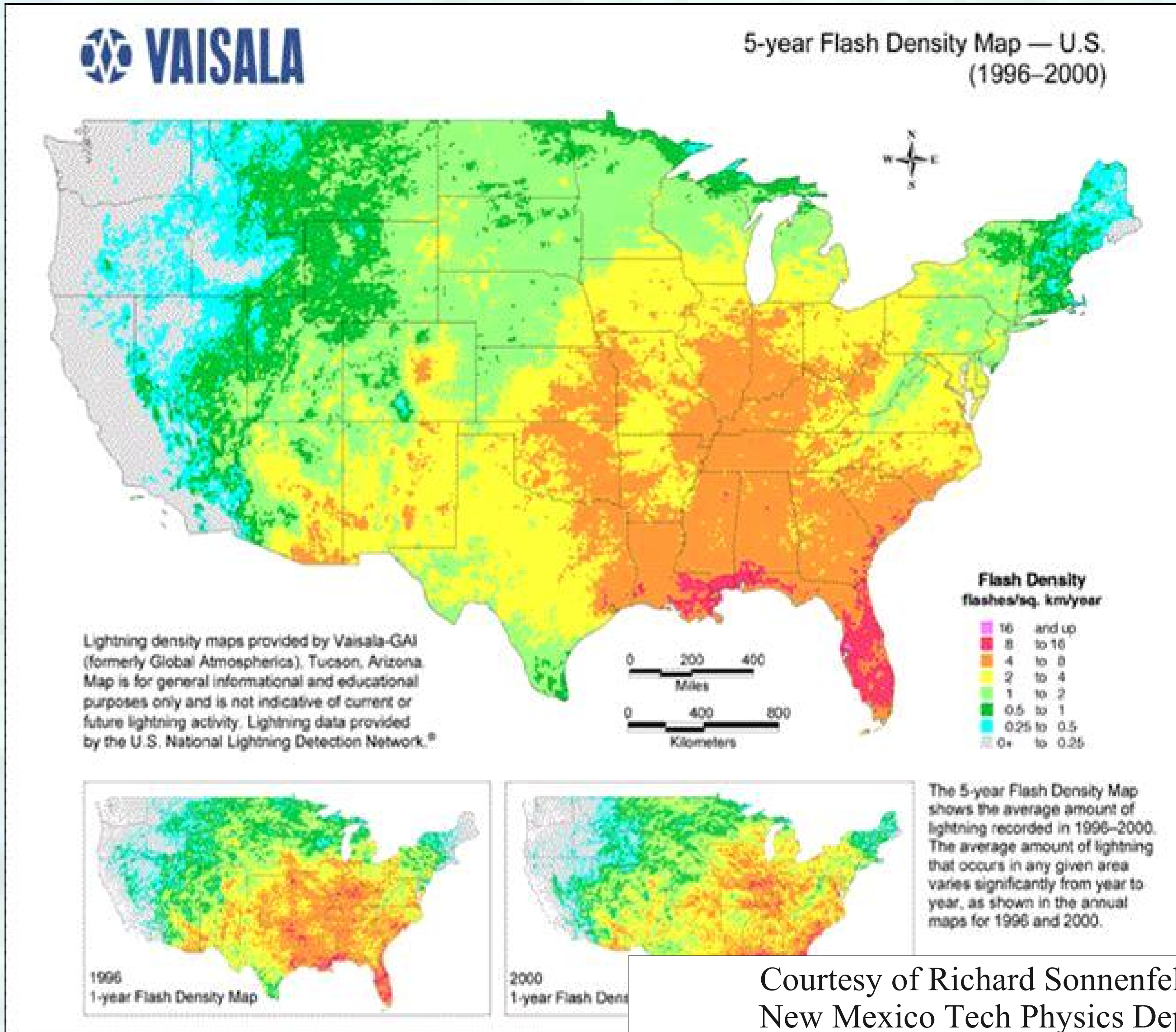
Climatology: The National Lightning Detection Network (NLDN)

Full-time, real-time coverage of the continental US.

NLDN_Movie



Magnetic Loop Antenna



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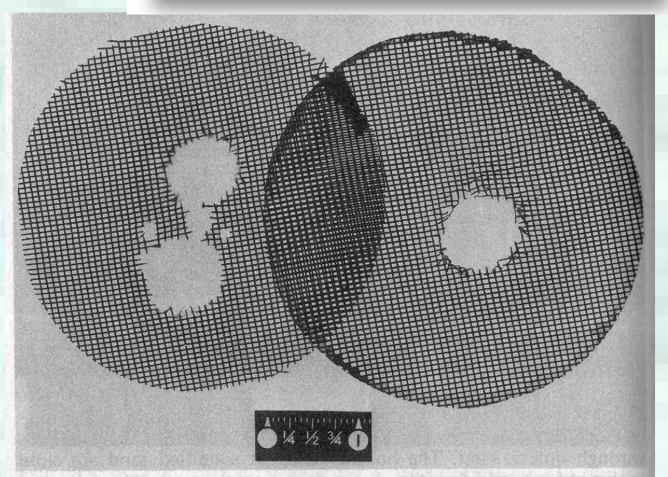
Lightning statistical parameters

- 40 flashes/second on Earth.
- I_peak=100,000 amps
- V_cloud=100 Megavolts
- Charge transfer Q=20 coulombs
- E= 1 Giga joules
- Current rise-time 1 microsec
- P_peak = many Terawatts
- Channel radius r=1 cm
- Stepped Leader velocity <0.001c
- Dart Leader velocity 0.1c
- Return Stroke velocity 0.5c

(NASA Photo)



(From Uman, “All About Lightning “)

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

Questions on Charge & Charge Transport

- Charging
  - How are charges distributed in storms?
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- Discharging
  - How does the plasma channel propagate to ground and inside clouds?
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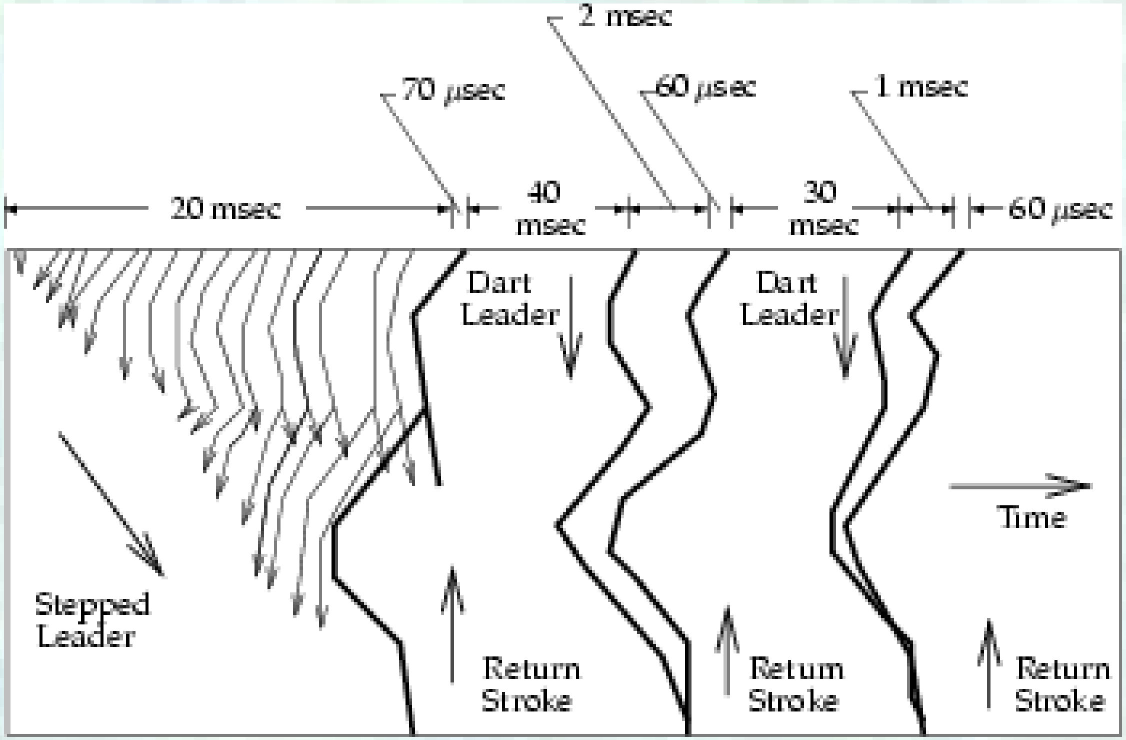
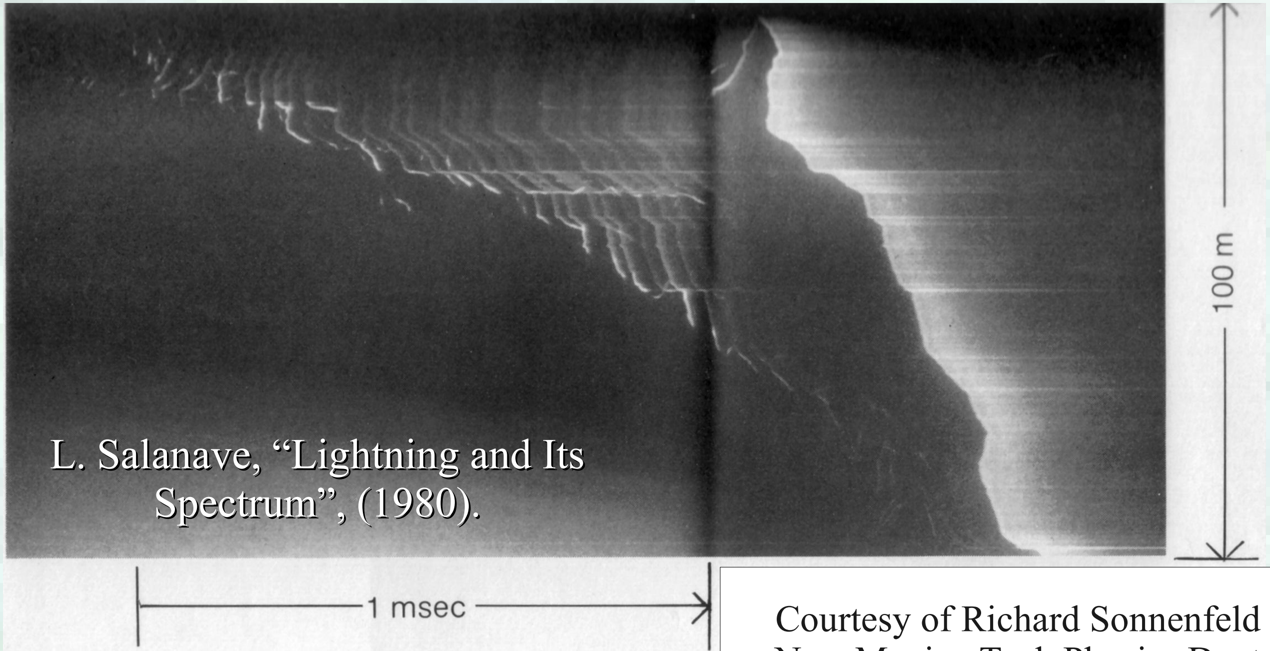
Progress of the plasma channel:

The stepped leader process





L. Salanave, "Lightning and Its Spectrum", (1980).

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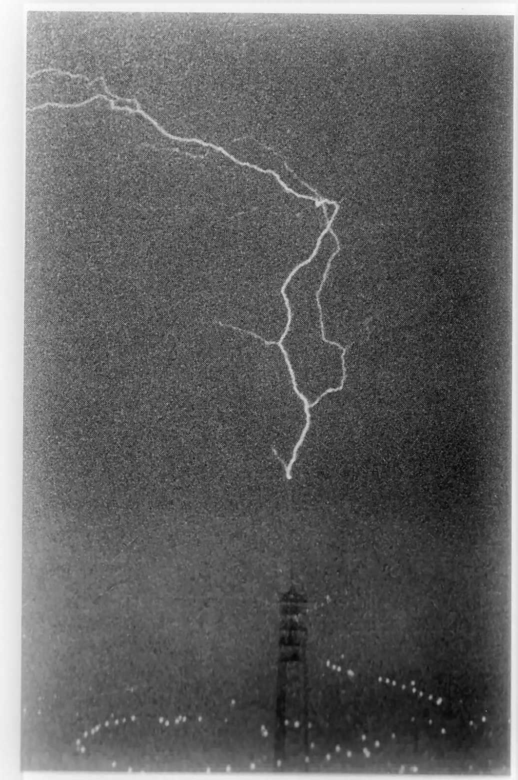
Lightning Launched Upward from Structures



From: L. Salanave, “Lightning and Its Spectrum”, Univ. of Arizona Press, (1980).

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Lightning Launched Upward from Structures

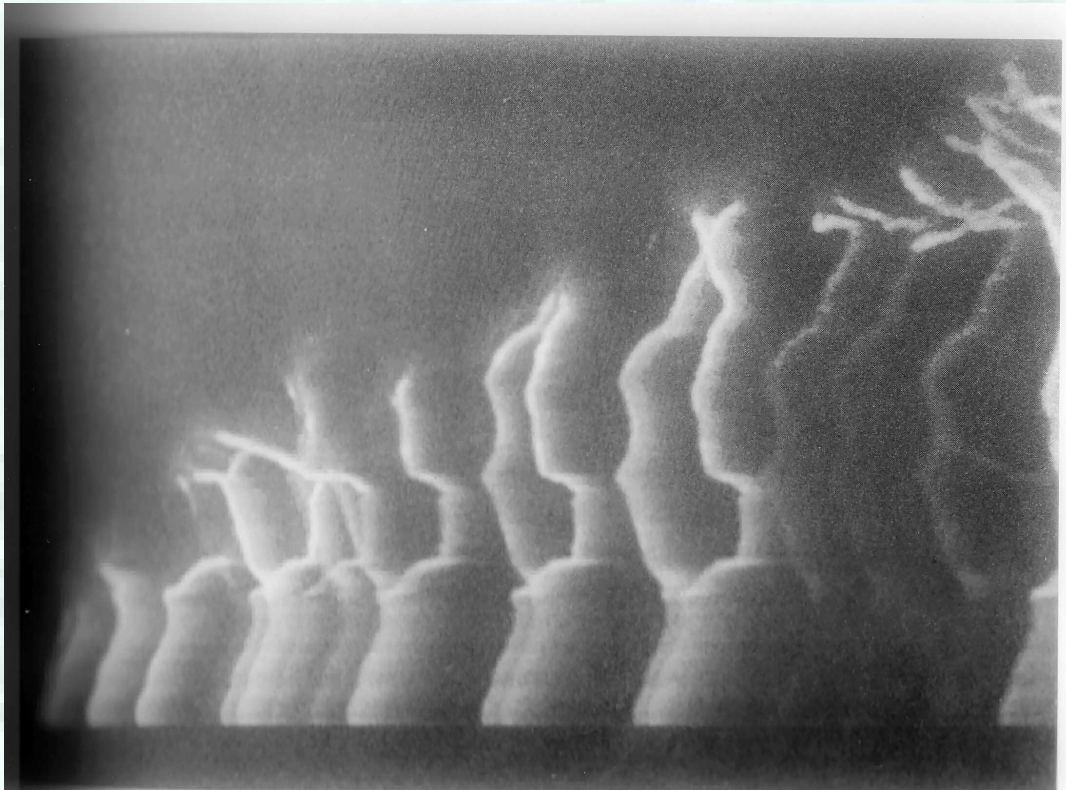
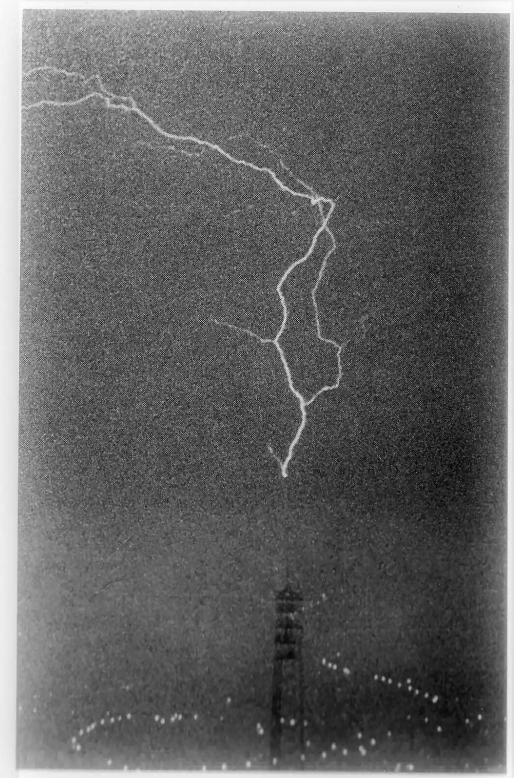


Figure 4.14 Early phases in development of upward propagating negative leader



From: L. Salanave, "Lightning and Its Spectrum", Univ. of Arizona Press, (1980).

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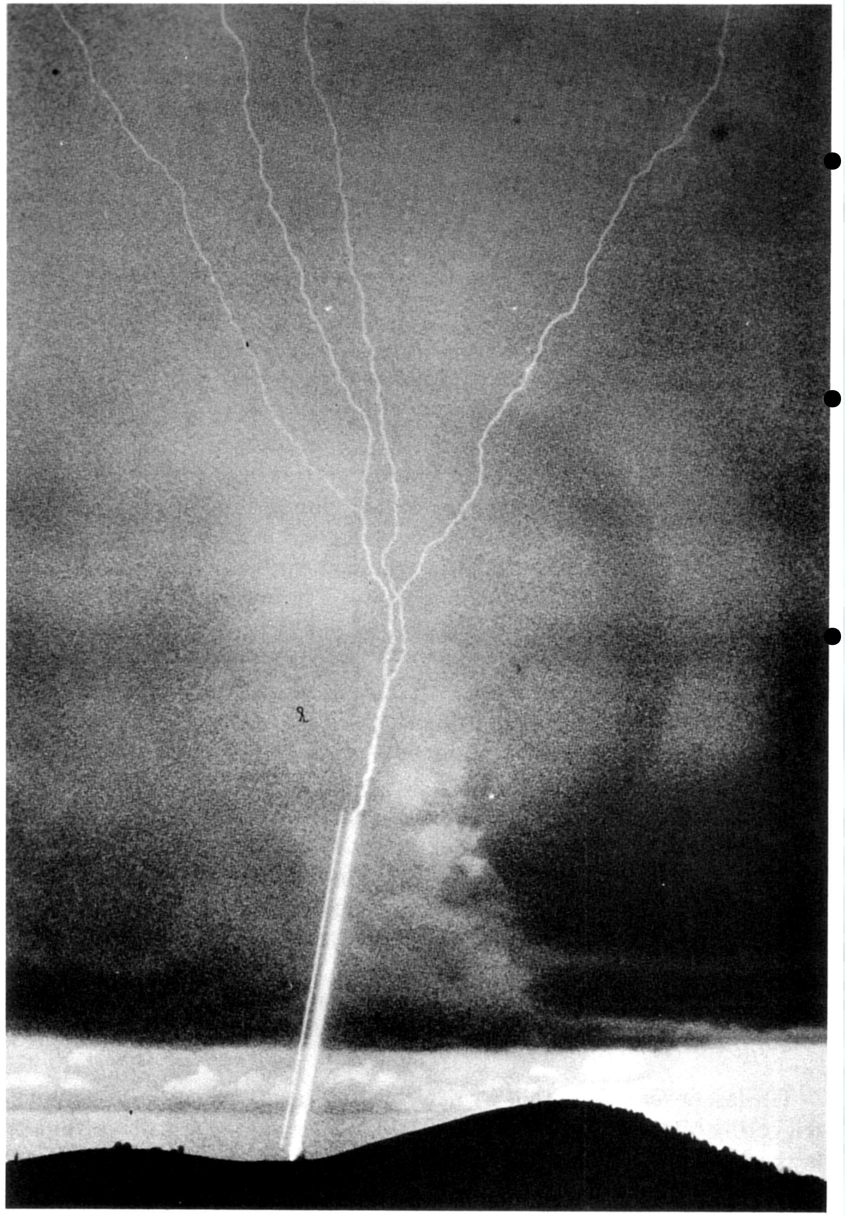
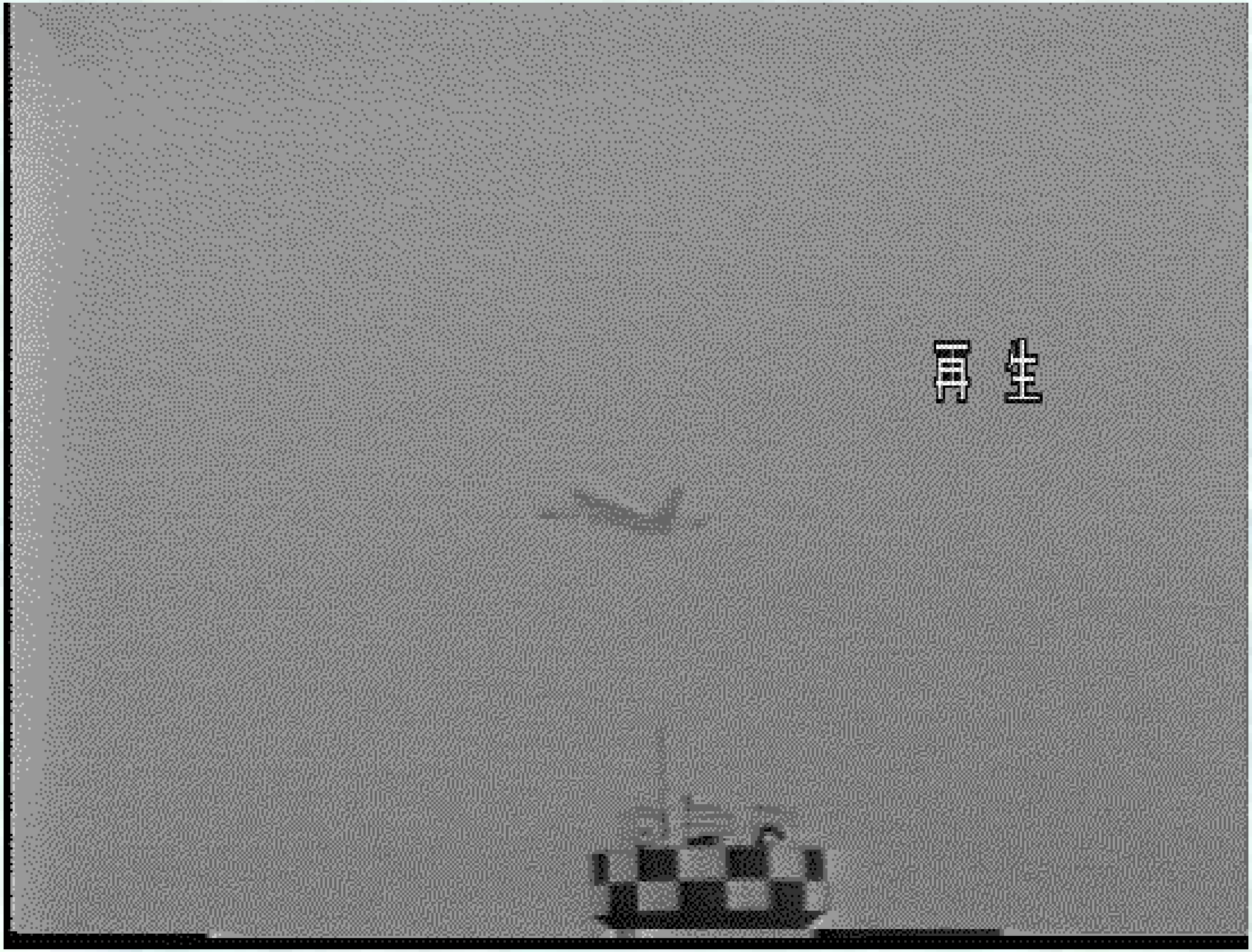
Triggered Lightning



- Extend a wire into a storm at about 300 m/s
- Can be used to study lightning effects
- Bring the lightning to your home /airplane / computer / power plant.

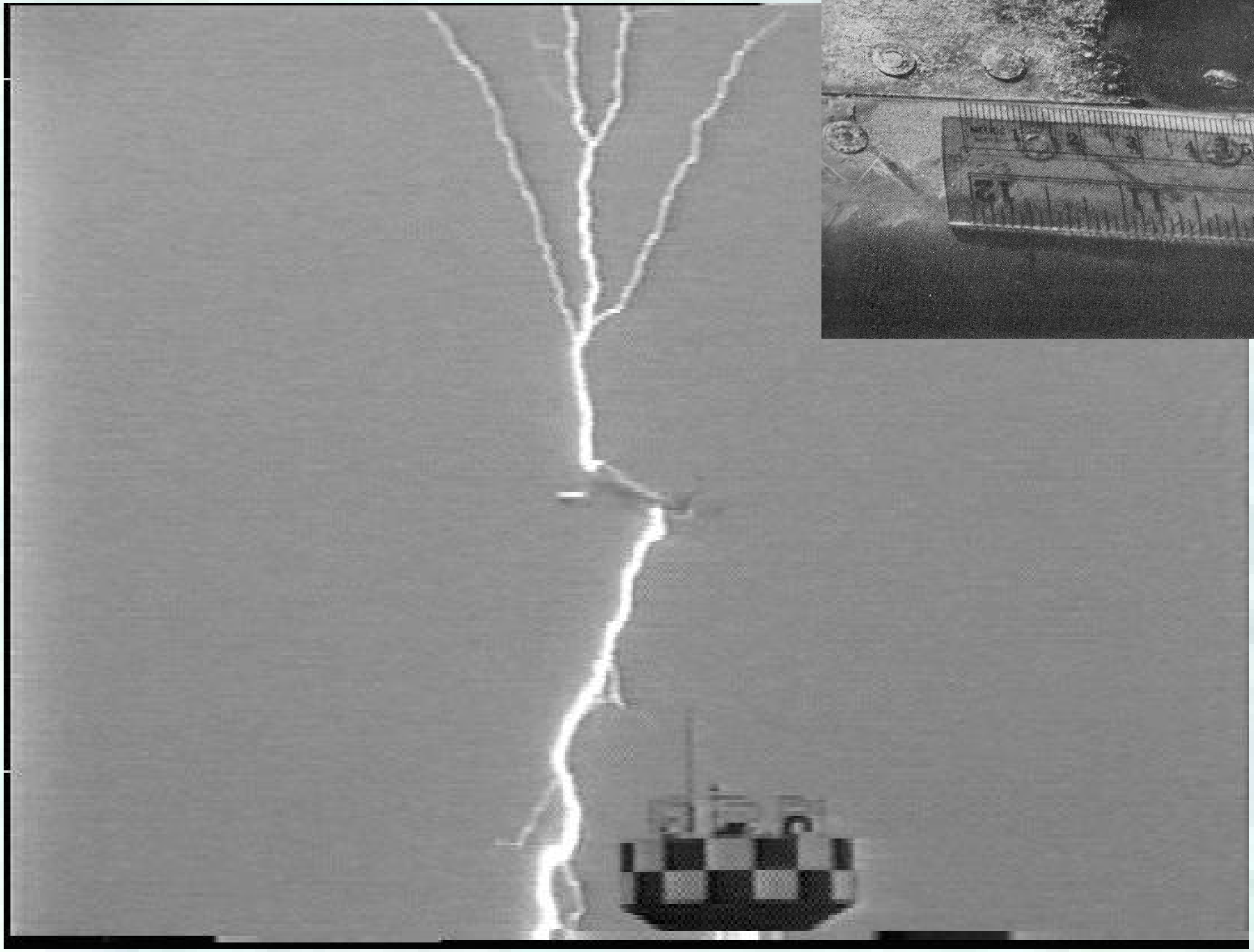
Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

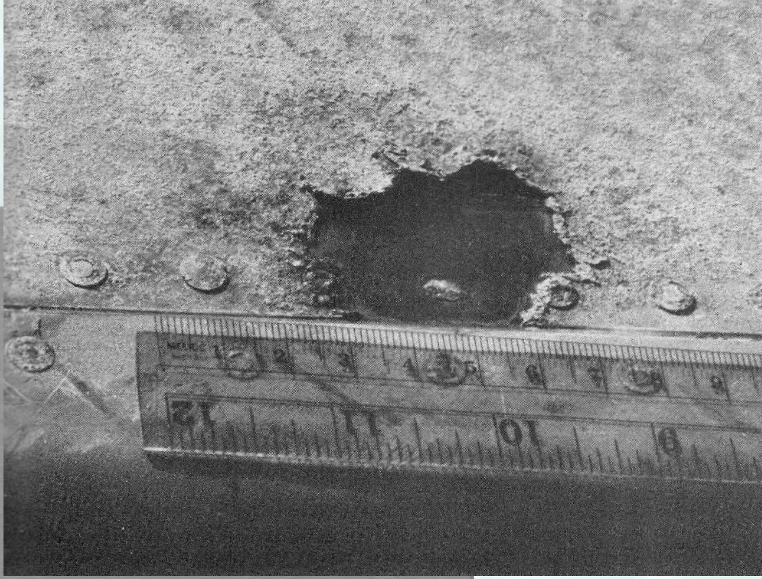
Triggered Lightning (Unintentional)



Aircraft at Kamatsu Air Force Base (Courtesy of Prof. Zen Kawasaki).

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept





Commercial aircraft at Kamatsu Air Force Base (Courtesy of Prof. Zen Kawasaki).

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New Mexico Tech Physics Dept

Lightning Connection Process – Upward Leaders

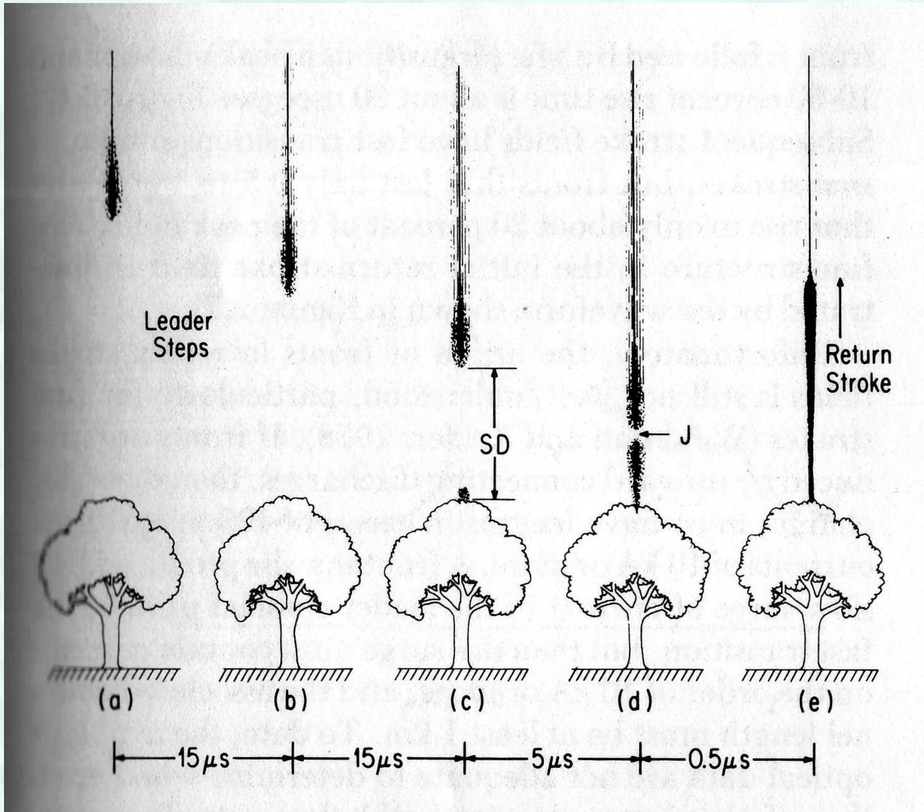

FIGURE 2.3 Sketch of the luminous processes that occur during attachment of a lightning stepped-leader to an object on the ground.

From: P. Krider, "Physics of Lightning", National Academy Press, (1986).

From: Rakov and Uman, "Lightning: Physics and Effects", Cambridge U. Presse, (2003).

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

High-speed video of stepped-leader

(from Dr. Mathew McHarg

USAFA)

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

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Courtesy of Richard Sonnenfeld
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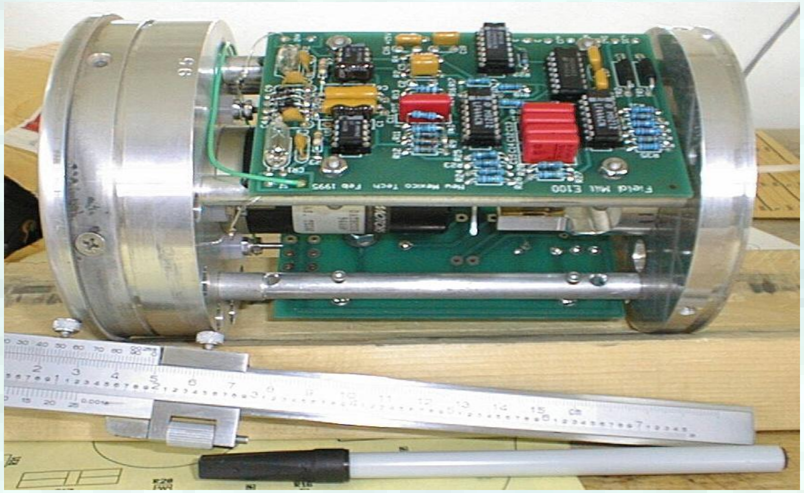
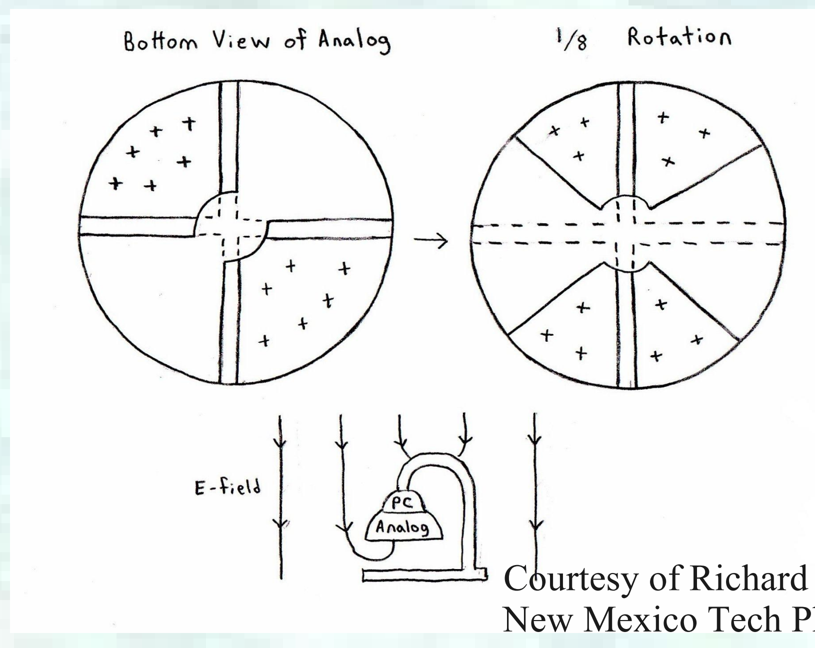
Electric field detection (ground based)



“E100” Field meter
Prof. W. Winn,
New Mexico Tech



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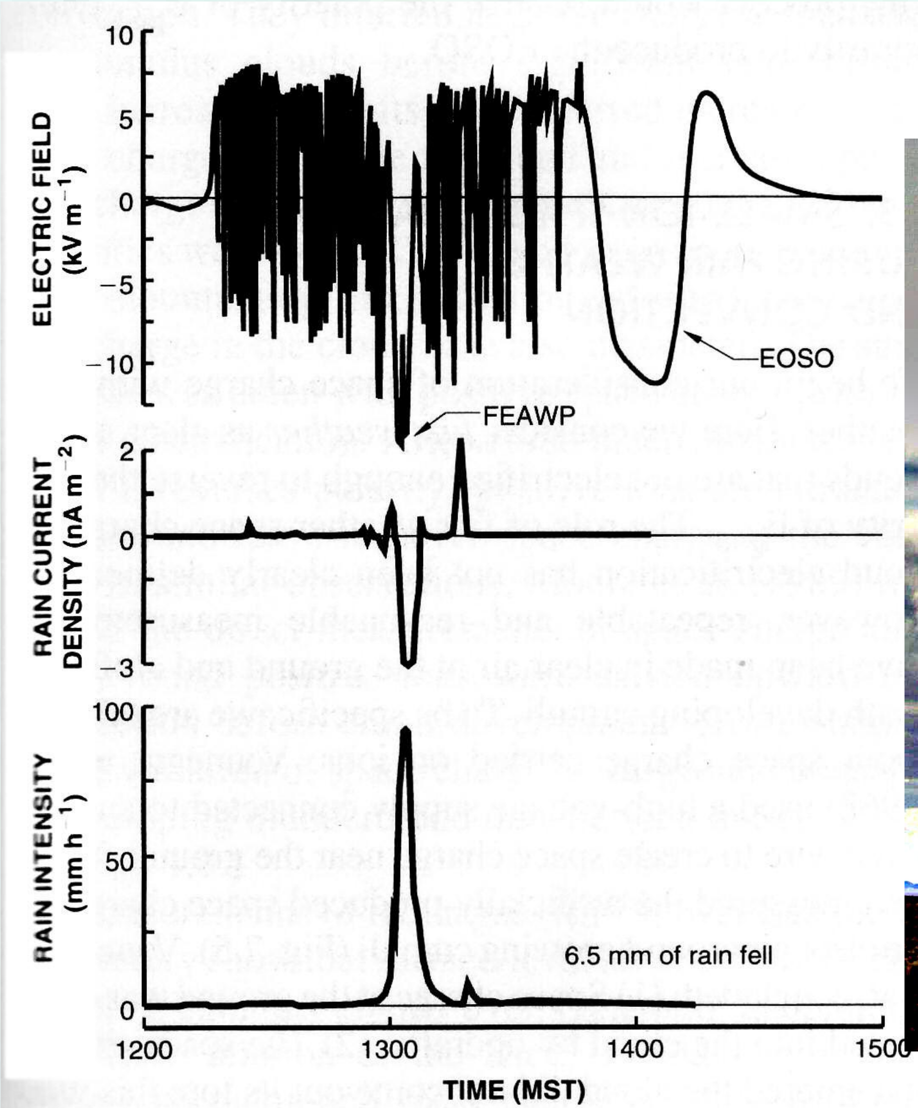
Electrical Activity of a Small Mountain Storm



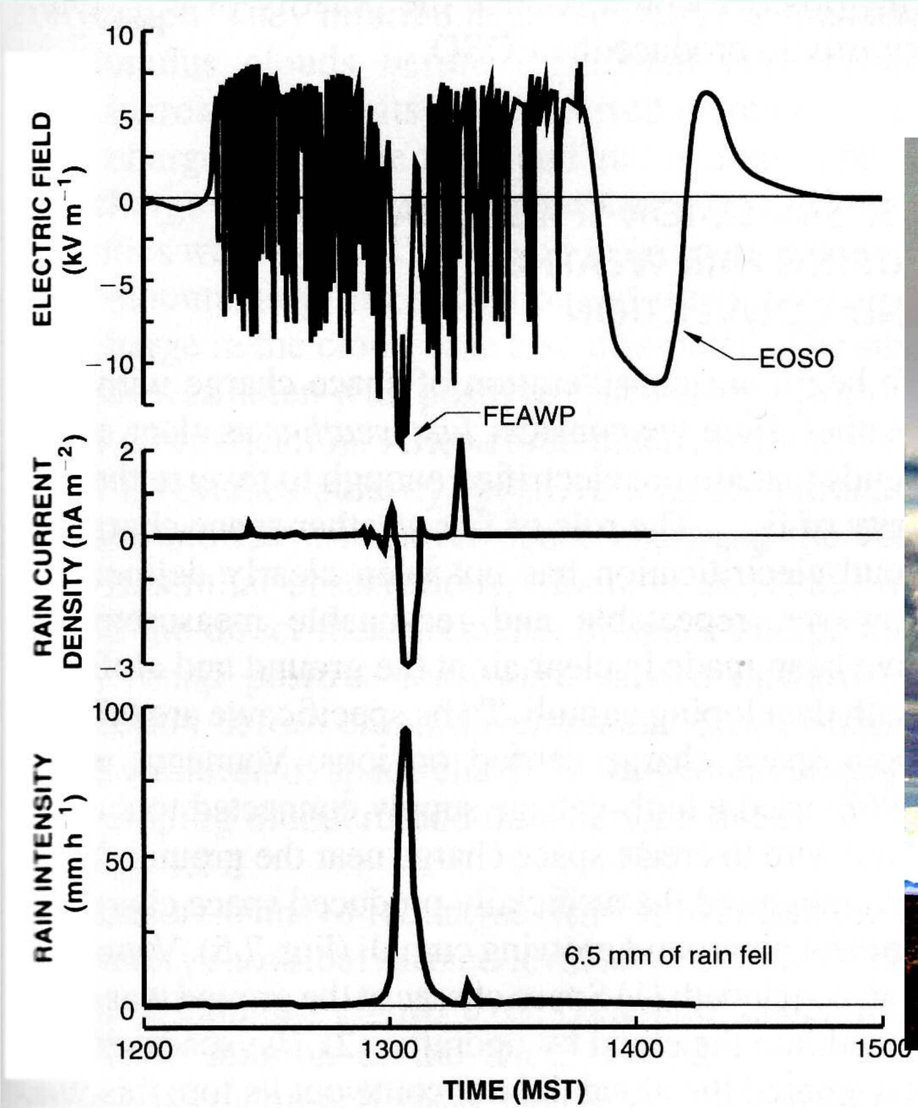
From Moore and Vonnegut, “The Thundercloud”
(in Lightning V.1 -- R.H. Golde, editor)

$$E_{fair} = -200\frac{V}{m}$$

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

Electrical Activity of a Small Mountain Storm

$$E_{foul} \geq +2\,\frac{kV}{m}$$



From Moore and Vonnegut, "The Thundercloud"
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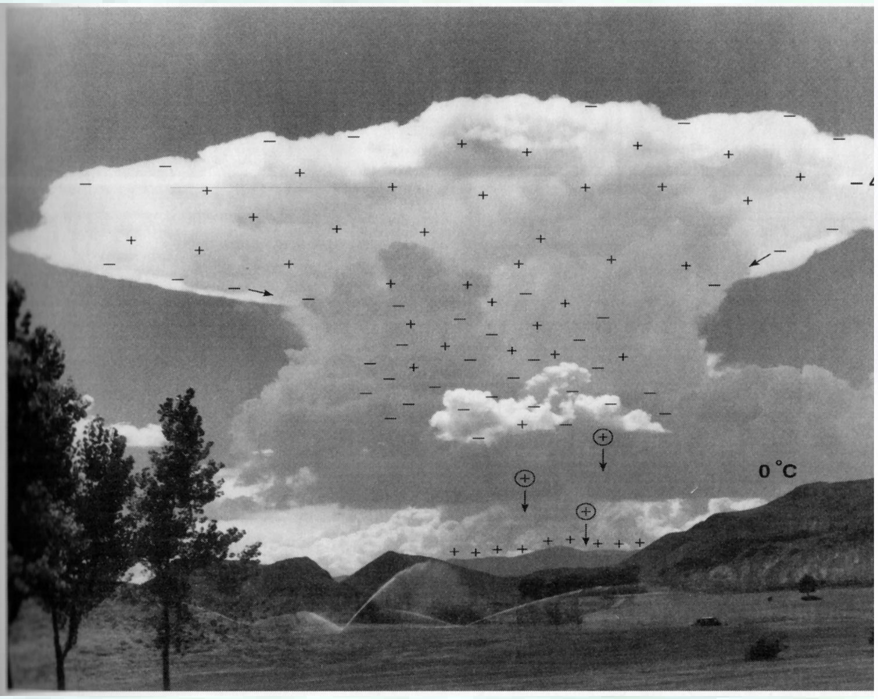
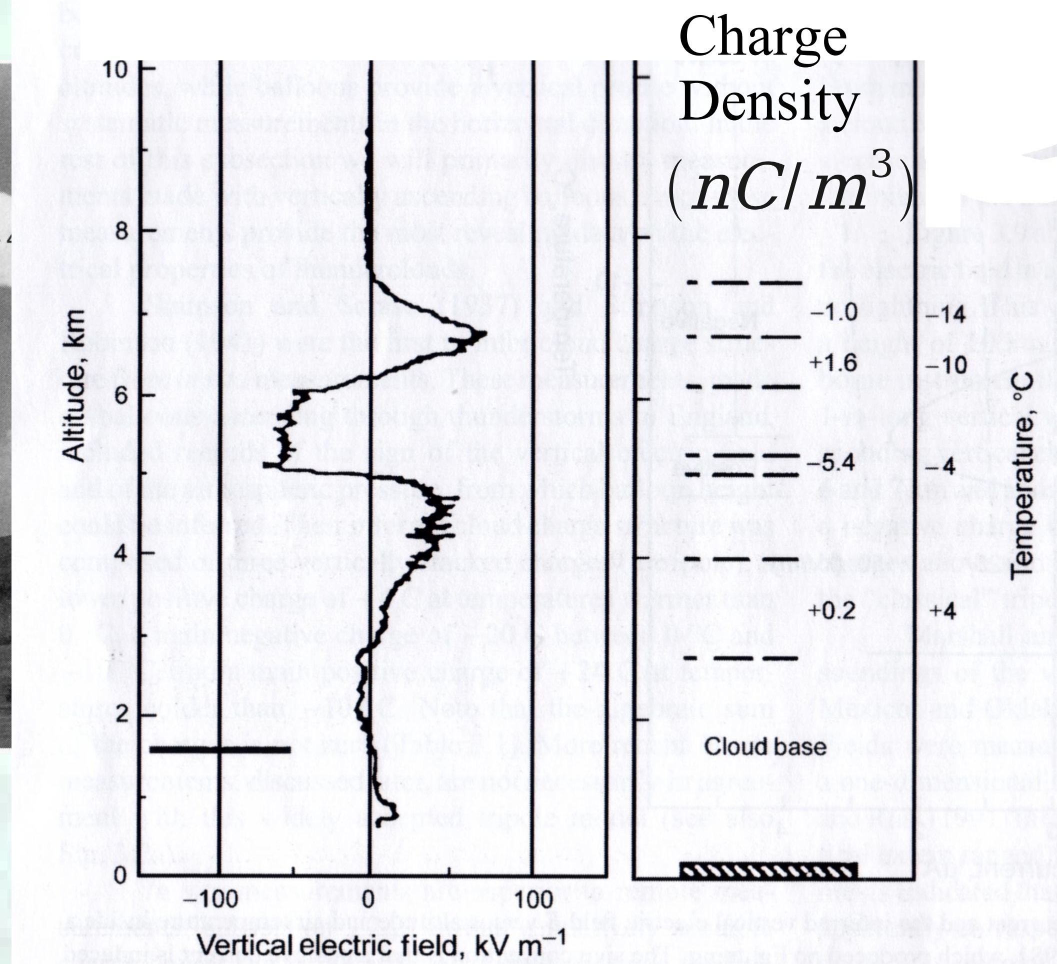
Electrical structure of storms





$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\rho = \epsilon_0 \frac{\Delta E}{\Delta z}$$

$$8.86 \times 10^{-12} \frac{C}{V \cdot m} \frac{130\,kV}{700\,m} = 1.6 \times 10^{-9}\, C/m^3$$

From Marshall and Rust, "Electric Field soundings through thunderstorms", Journal of Geophysical Research, (1991)

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

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Collisional Inductive Charging (Elster-Geitel charging)

- High electric fields polarize water drops
- Cloud droplets scatter off of raindrops or graupel
- Mechanism can occur in warm clouds or cold (sub-freezing) clouds

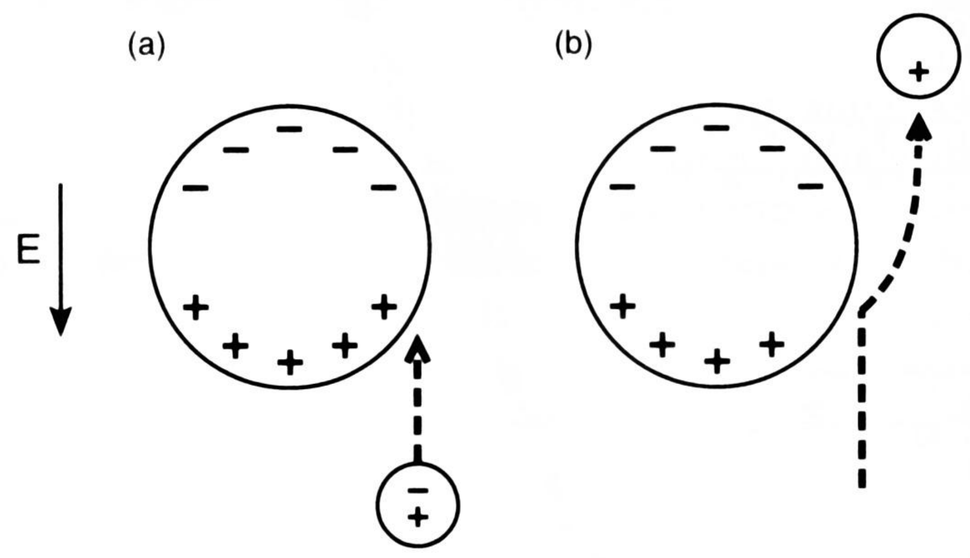
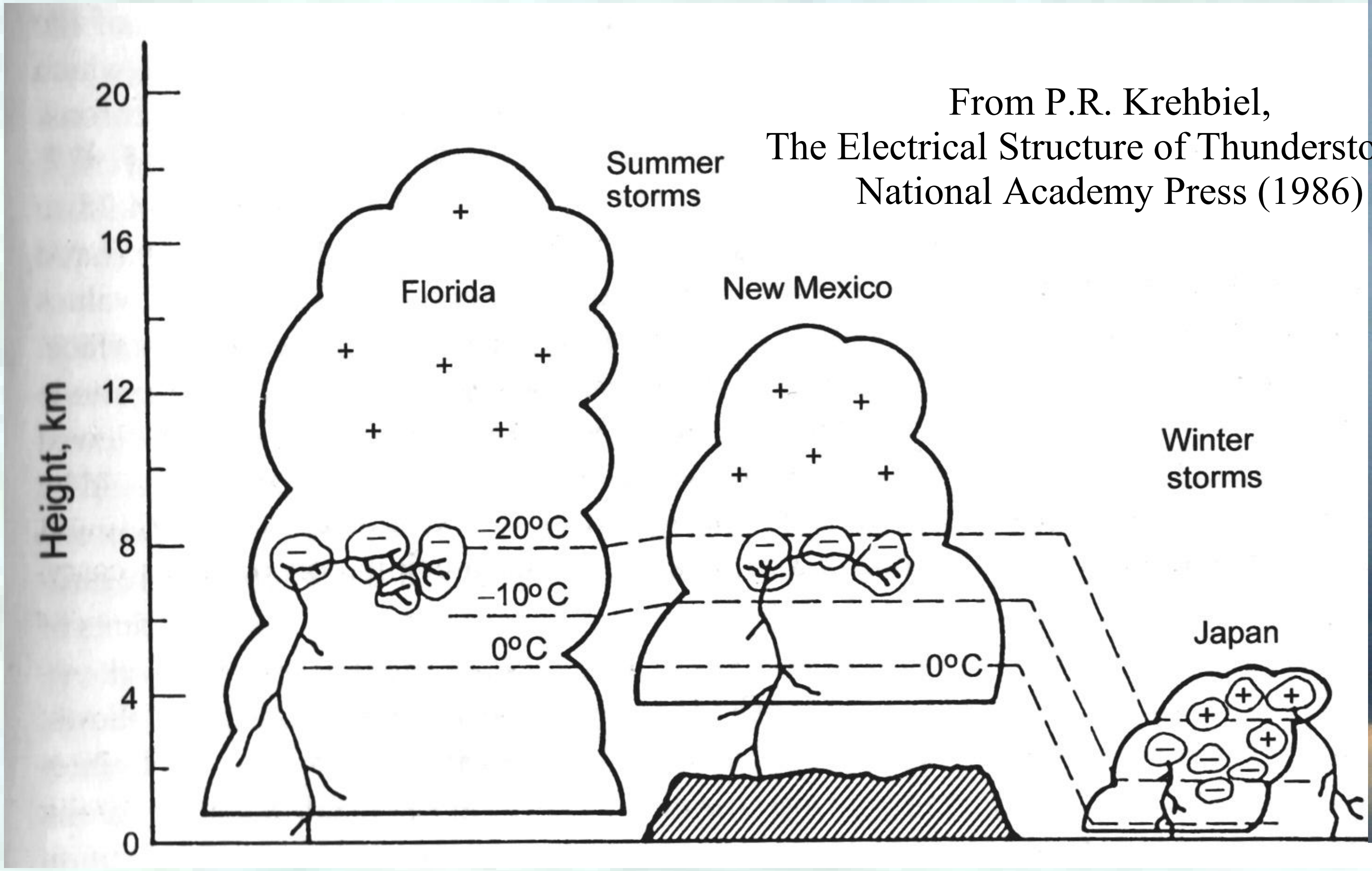


Fig. 3.11. Inductive charging of rebounding particles.

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

- The negative charge center in storms is always found around the –10C Isotherm.
- This is taken to mean that charging is somehow associated with the freezing of ingested water.



From P.R. Krehbiel,
The Electrical Structure of Thunderstorms”
National Academy Press (1986)

Courtesy of Richard Sonnenfeld
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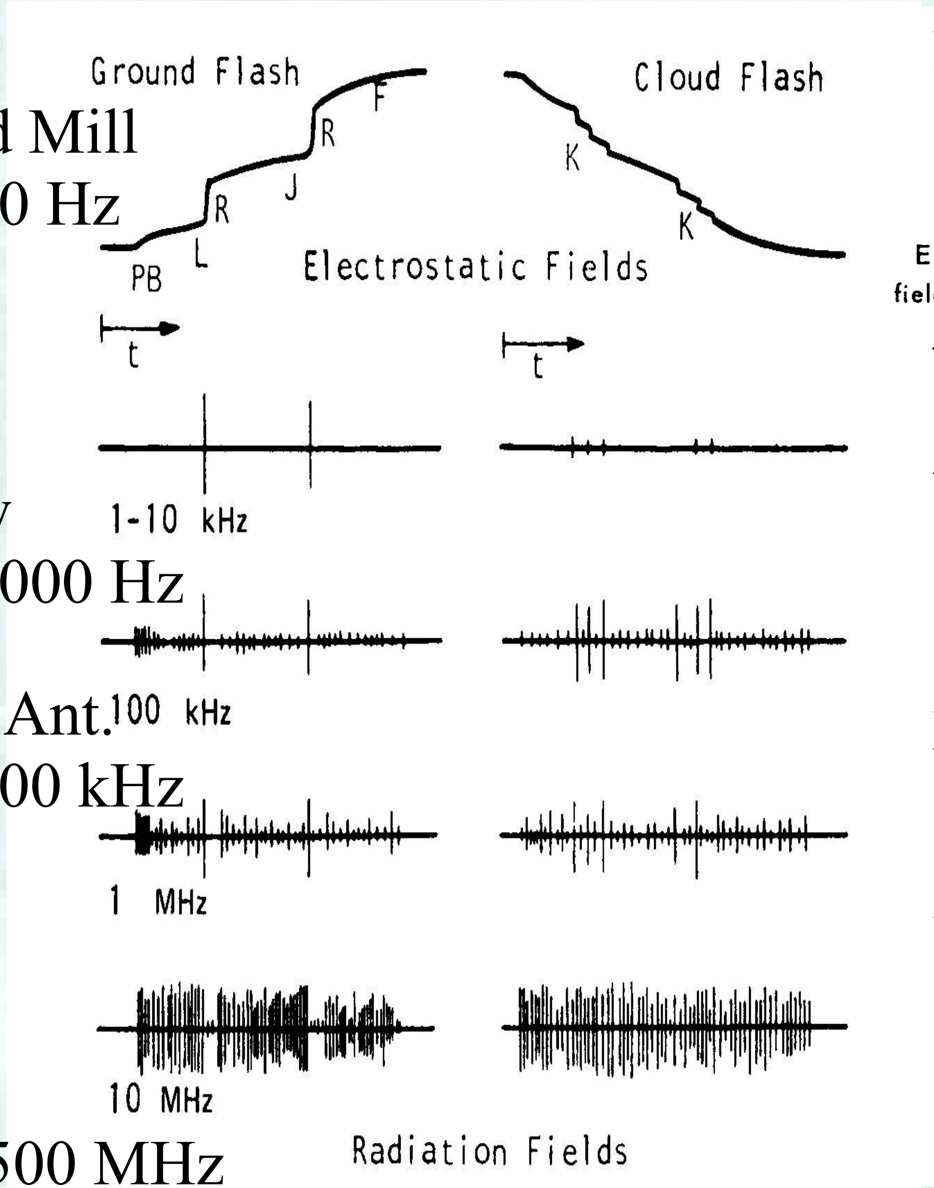
Electric field spectrum

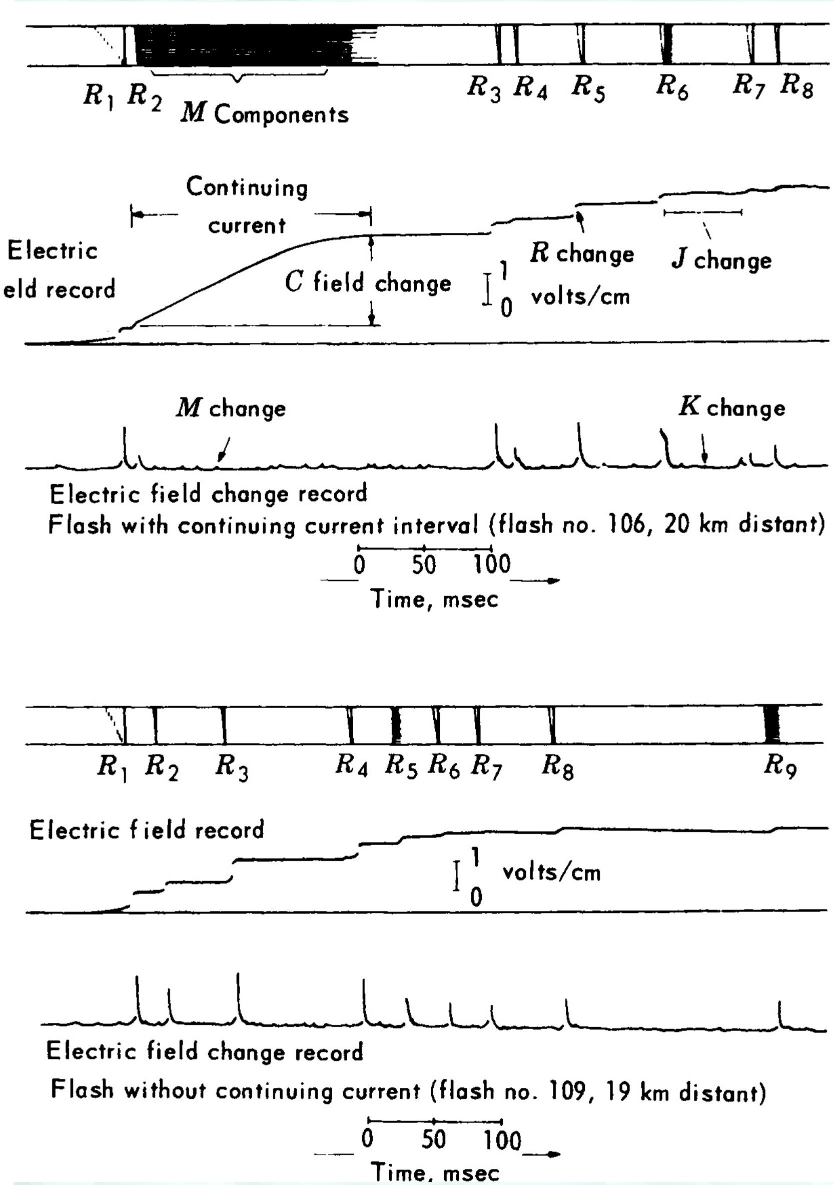
Field Mill
0-20 Hz

Slow
1-20000 Hz

Fast Ant.
1-1000 kHz

RF
10-500 MHz





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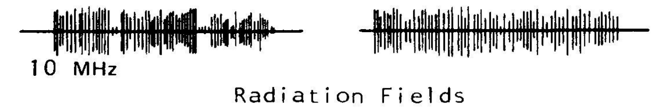
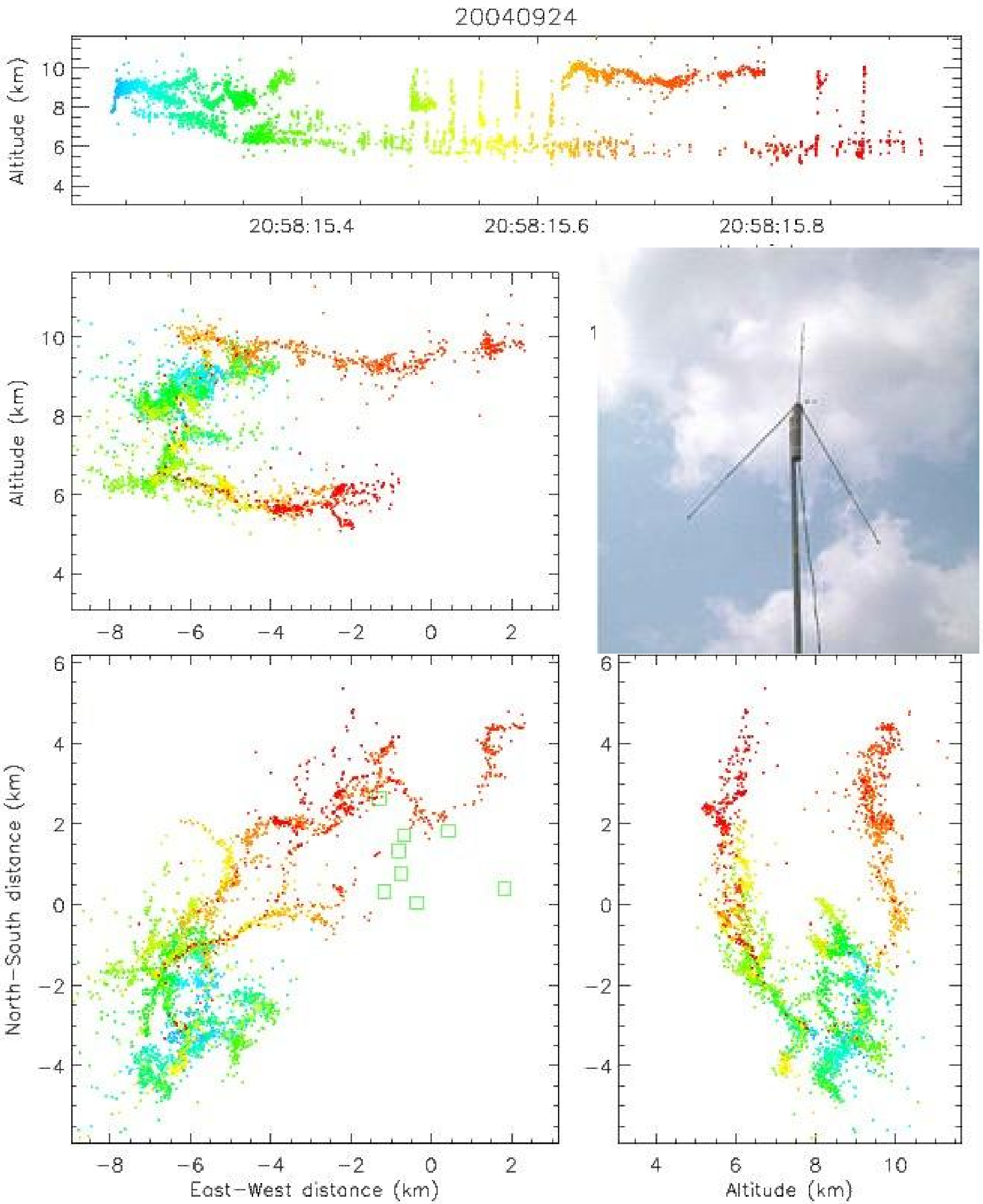
The inverse problem

- E-field measurements on the ground show a rich spectrum from 0.001 Hz – 500 MHz
- E-field features are understood in general terms, and the lower frequency features are understood as "charge transport".
- Knowledge of charge allows precise prediction of fields. The inverse is not true.
- How to solve the inverse problem?
  - Cheat – use other info.
  - Get full vector information (needs a balloon)
  - Get multi-station charge measurements

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

New Mexico Tech
Lightning Mapping Array (LMA)





- Uses a network of 12 television receivers tuned to 66 MHz.
- Lightning radio pulses are correlated in time between stations.
- Location in sky and emission time are fit and plotted.
- Images intra-cloud (IC) flashes

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

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Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

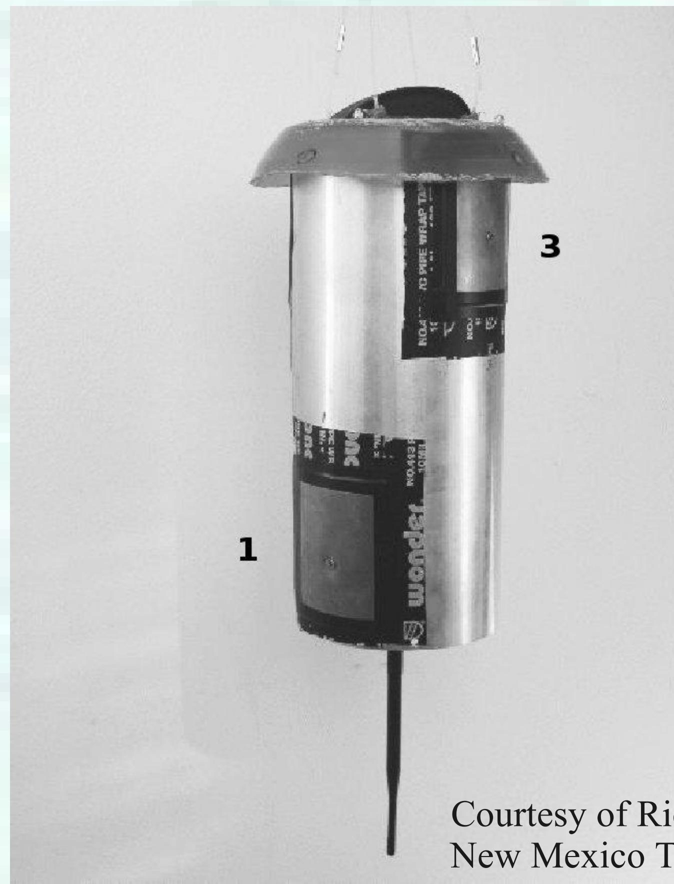
Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

August 2004 Launch
of delta-E Sonde

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

A vector field-change sonde

- 10,000 Samples/s
- 16-bits/Sample,
- Measure 8 channels
  - E-field (Channels 0-3)
  - Timing (Channel 4)
  - B-field (Channels 5-7)



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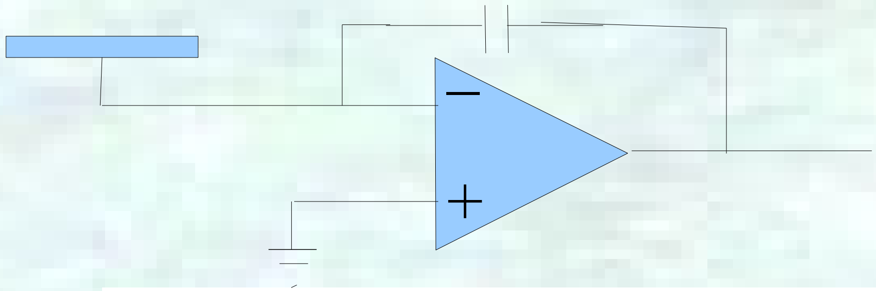
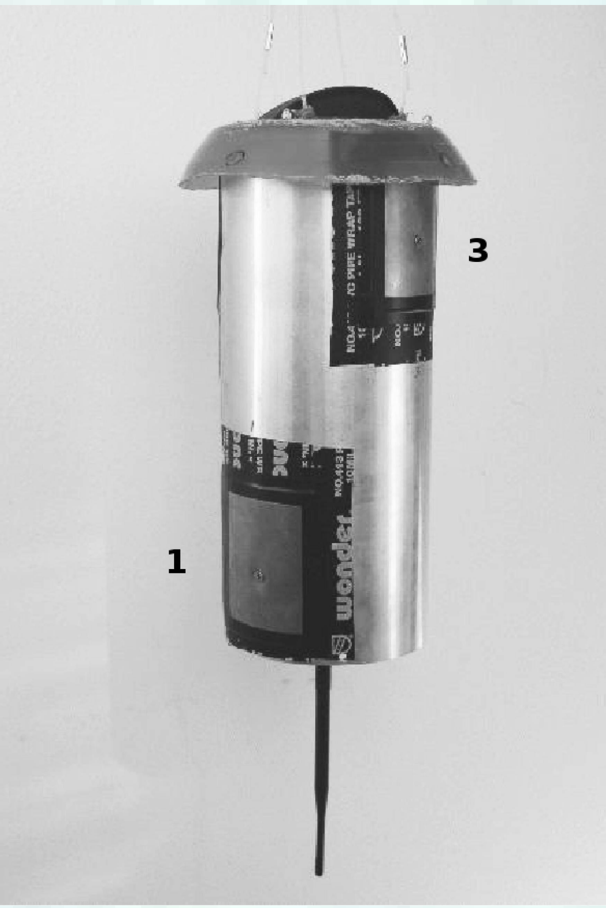
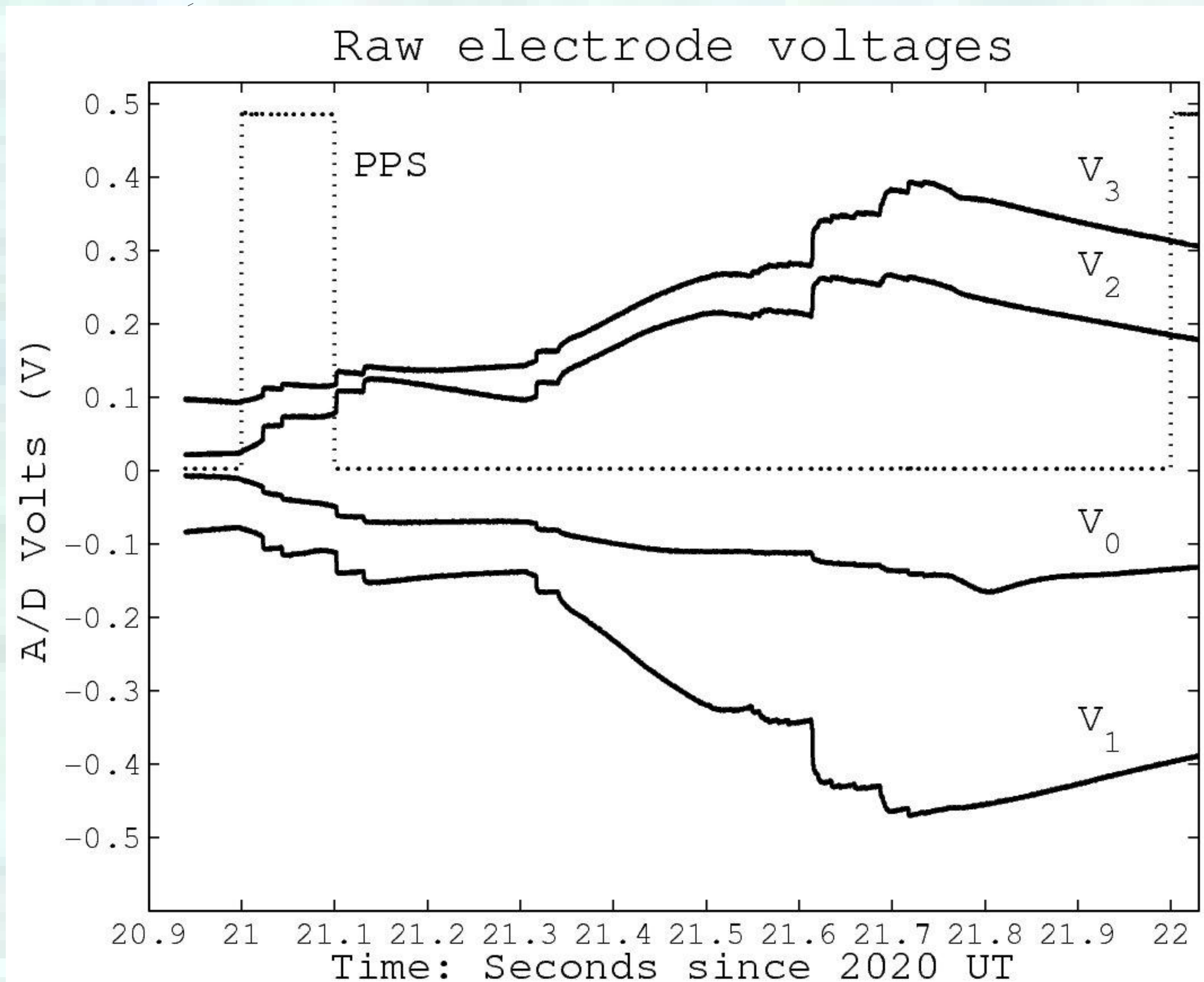
$$V_1 = \epsilon_0 E_1 \frac{A}{C}$$







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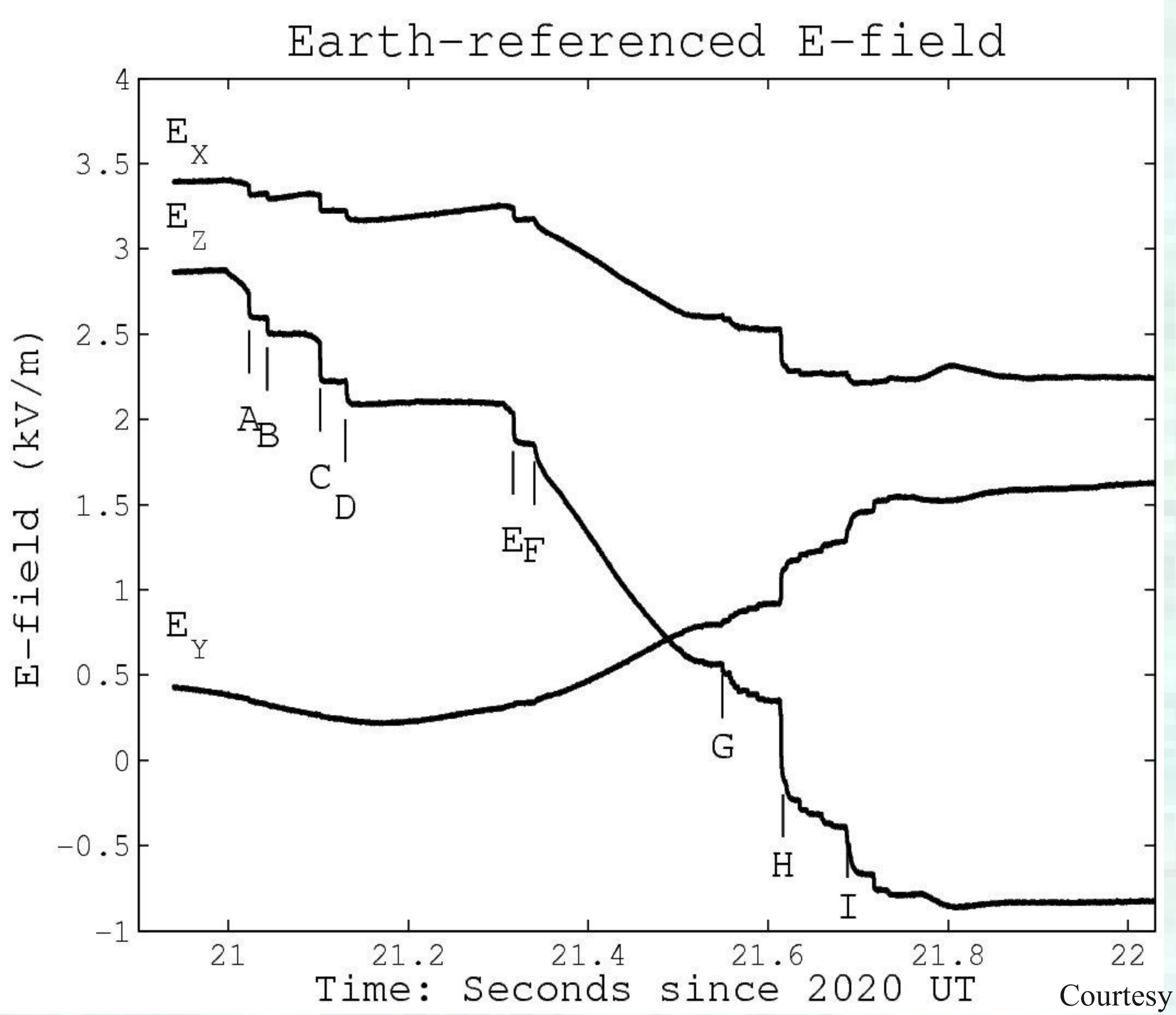
CG Flash with multiplicity of 10 – Balloon observation, Aug 18, 2004



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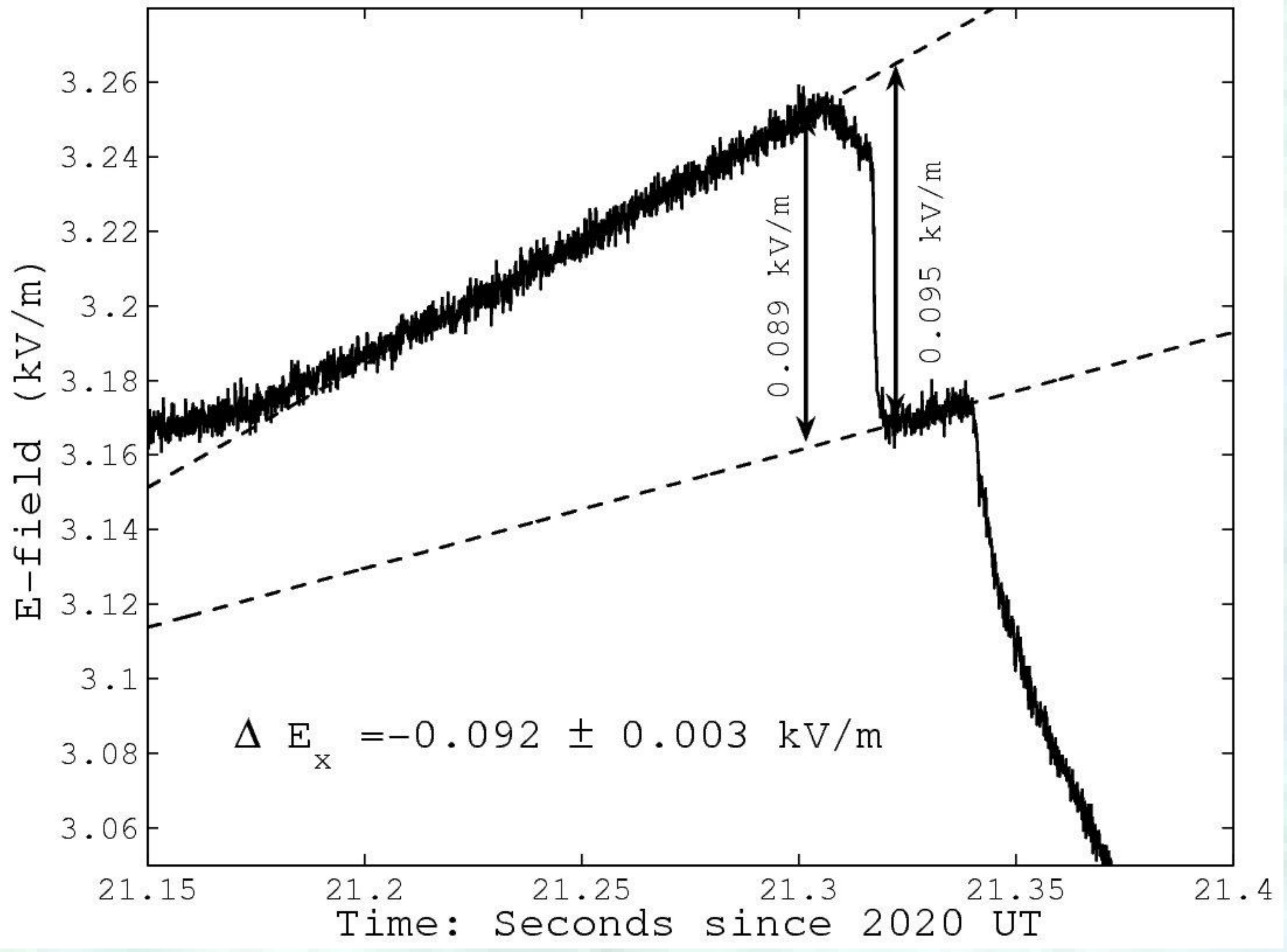
Measuring field change for each return stroke.



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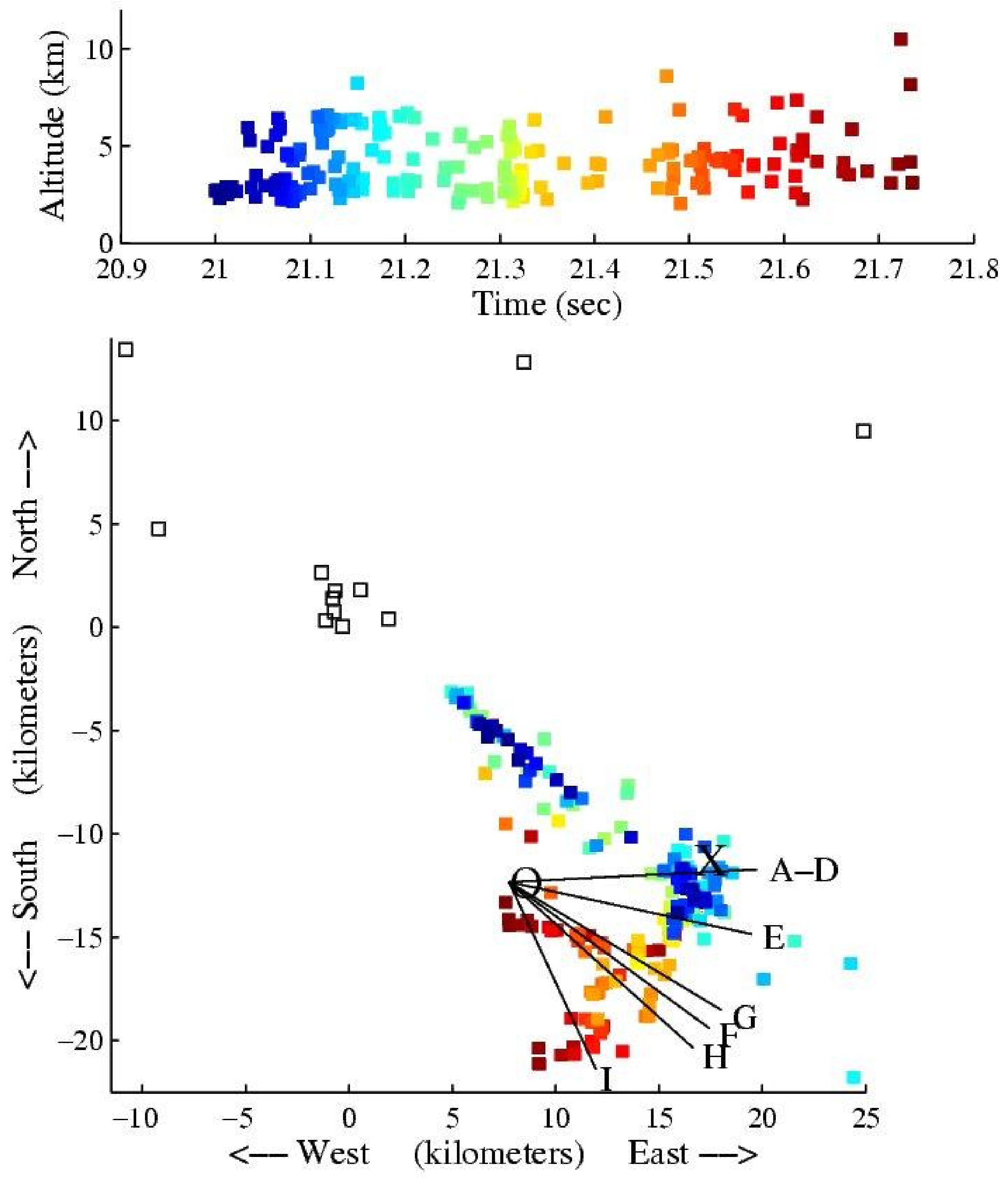
Calculating vector to Charge centers

Note steady progression away from Ground-strike point



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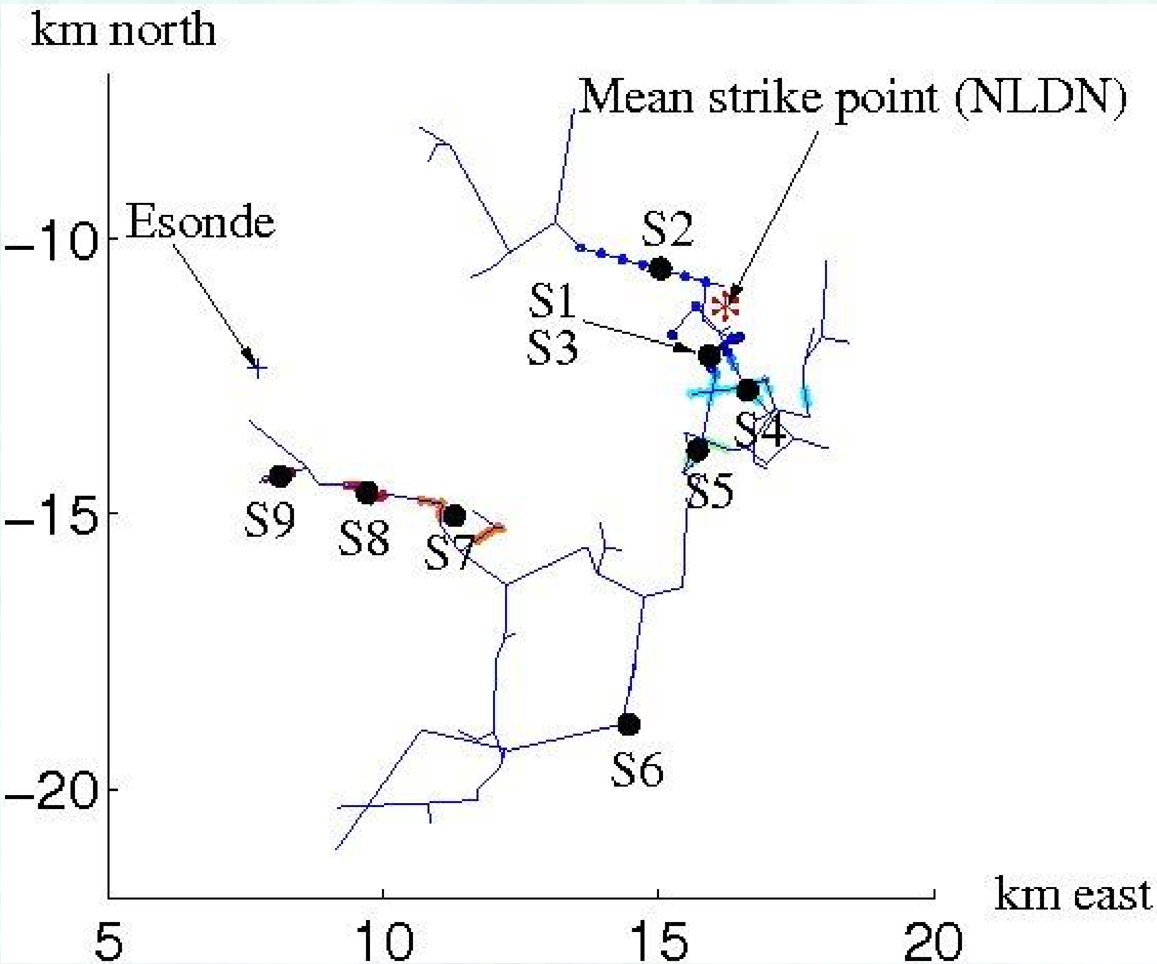

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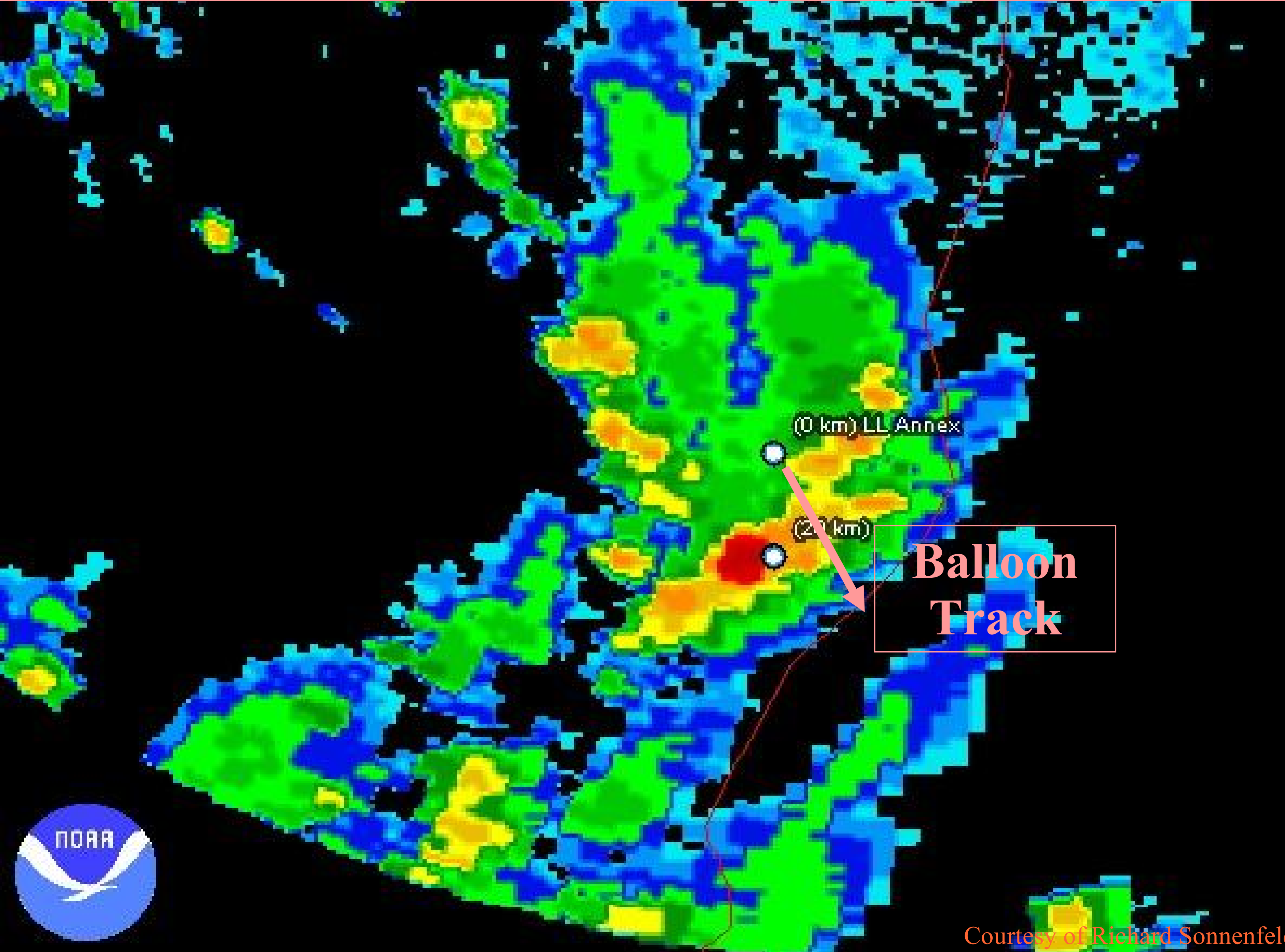

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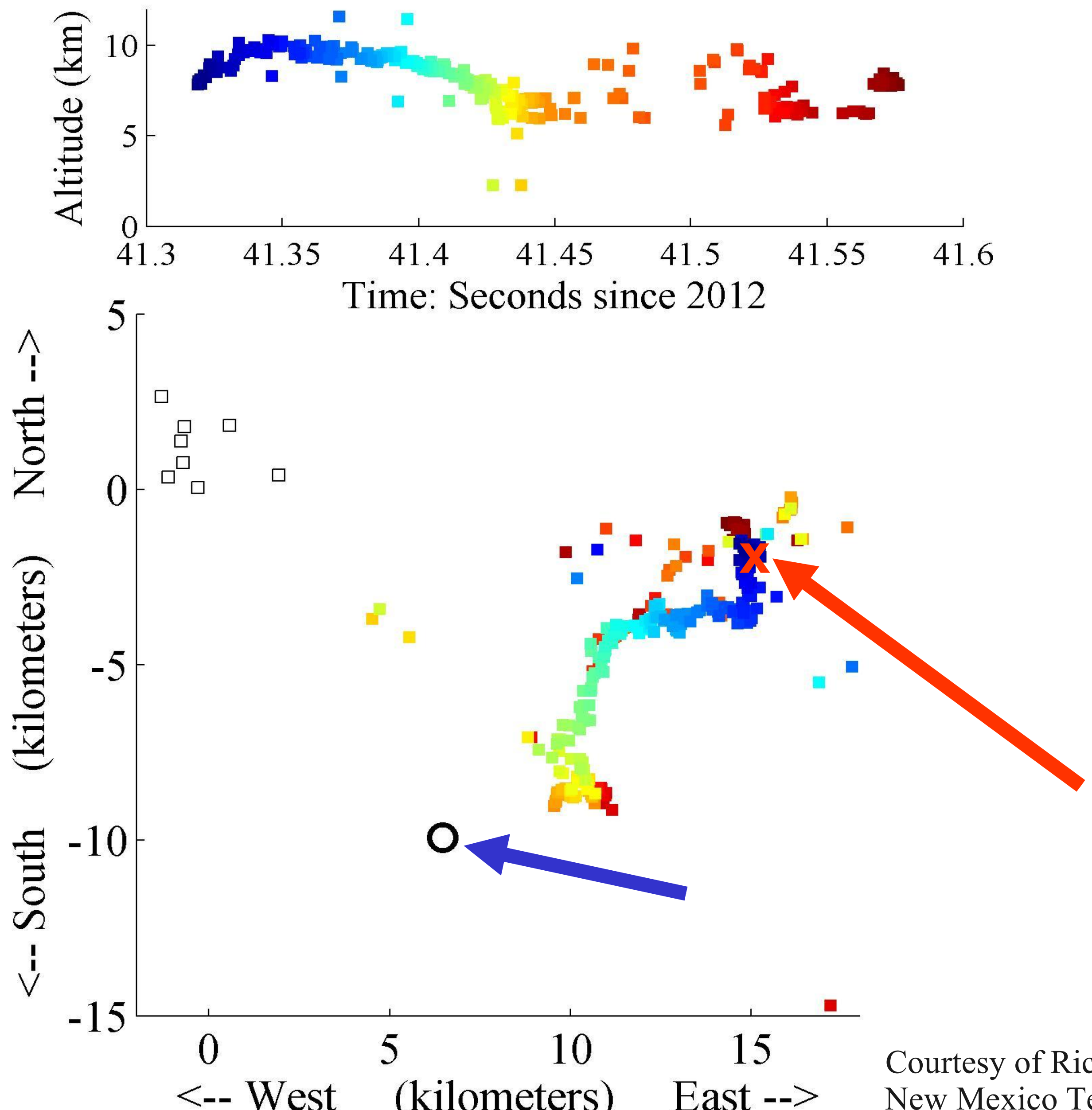
LMA Plot for IC flash "C"

Altitude vs. time

Planview



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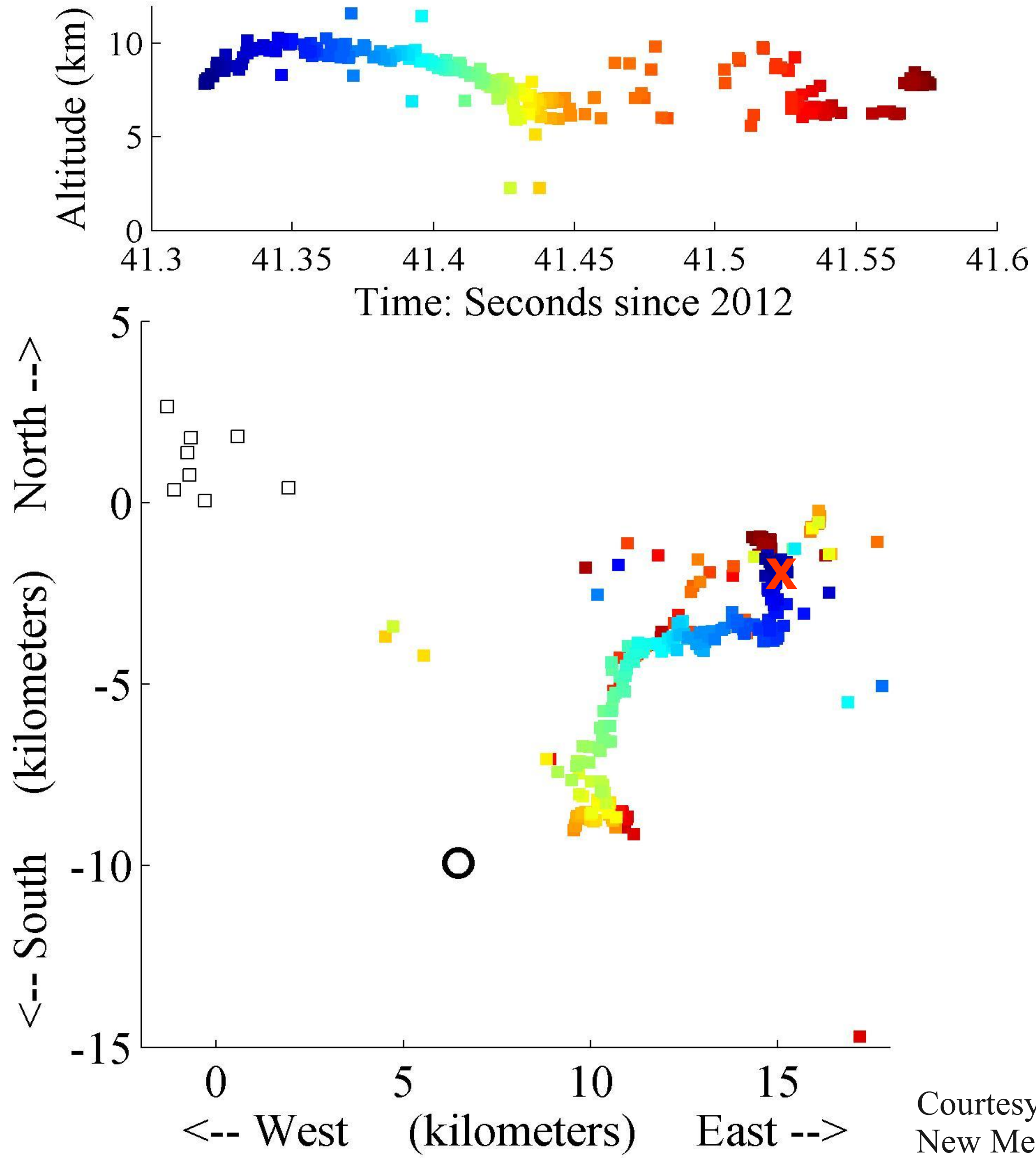

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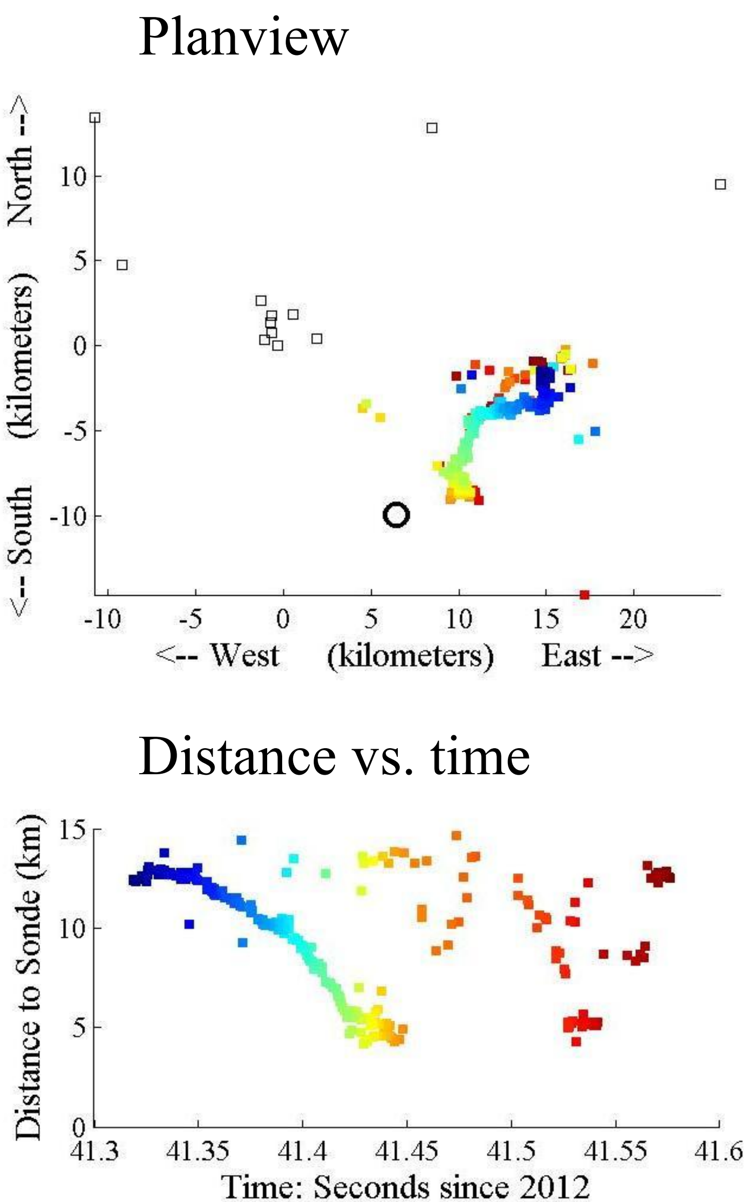
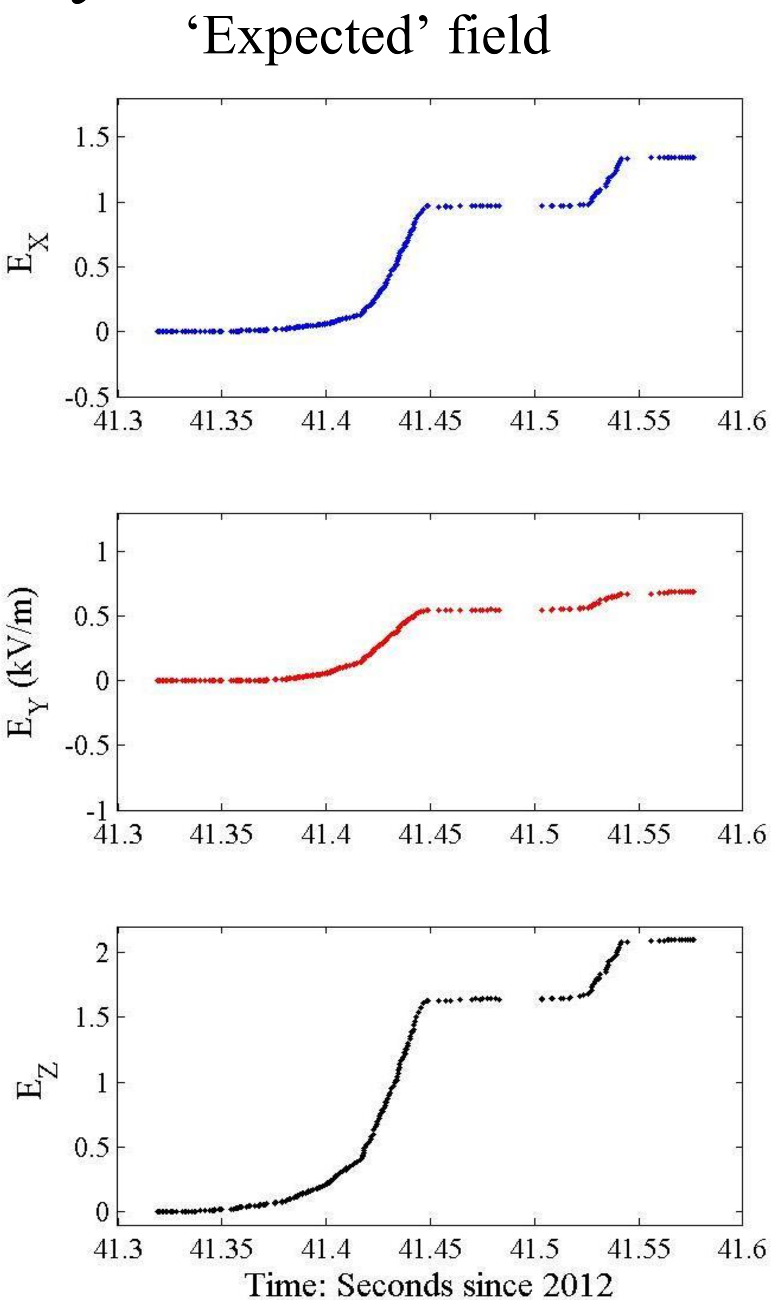
Distributed Charge Analysis for IC flash "C"

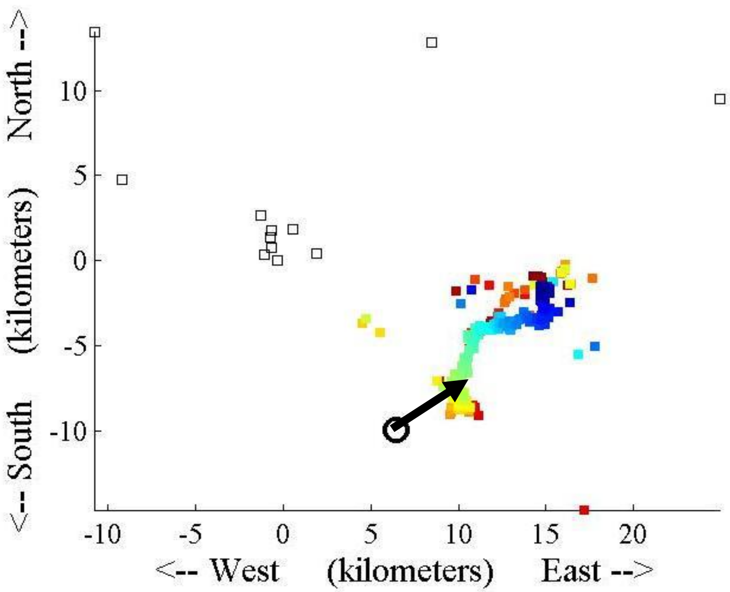


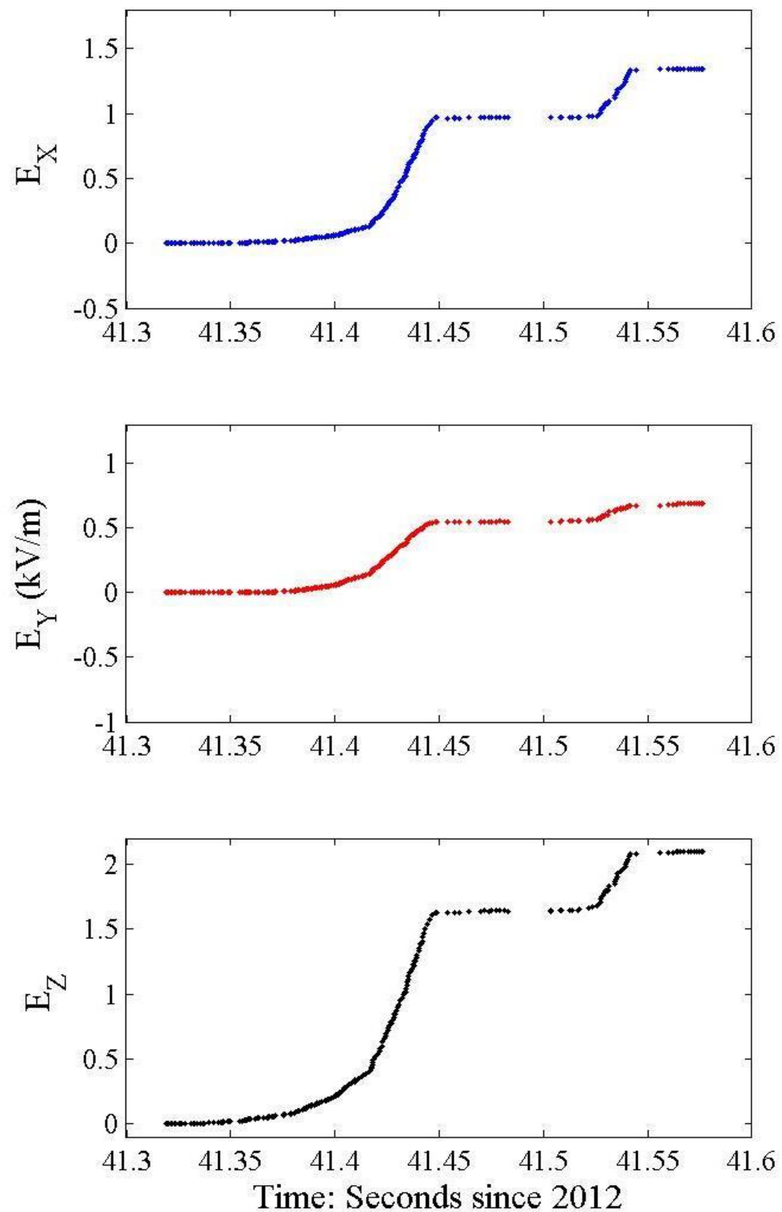


Distributed Charge Analysis for IC flash “C”

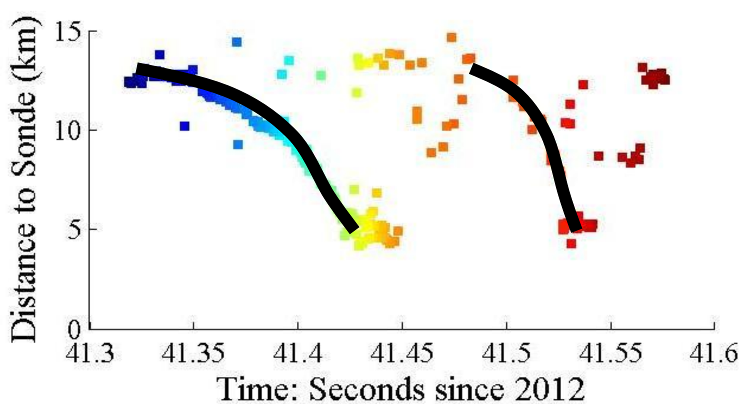
‘Expected’ field

Planview

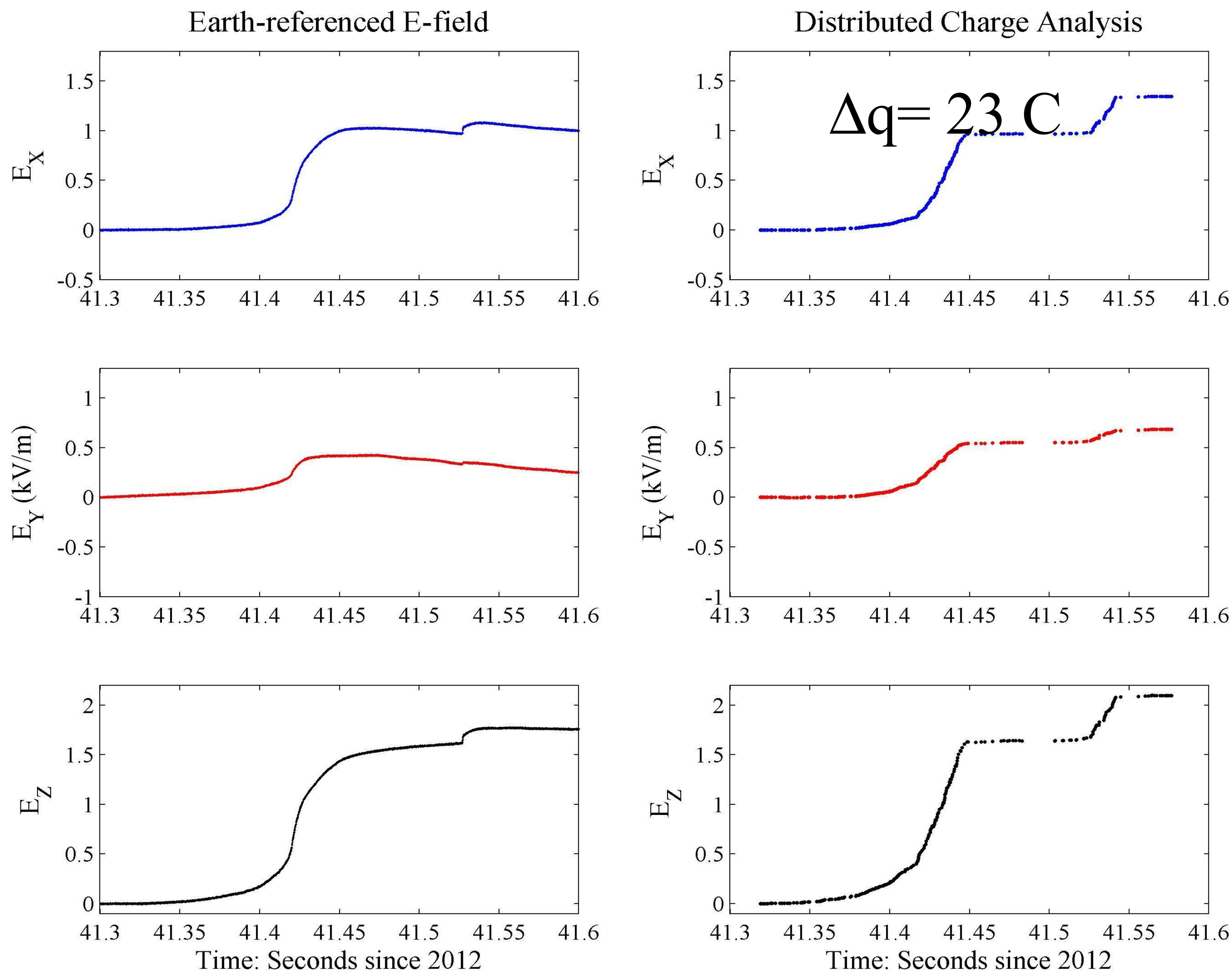




Distance vs. time



Comparing Expectation and Experiment for flash “C”



Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

1) Coulomb’s Law
2) Method of images to handle ground “plane”
3) Charge conservation
4) LMA indicates location of channel

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

Lumped charge analysis –

A large charge -Δq is placed on new LMA RF sources.

-Δq moves with the sources

-Δq is constant

An opposite charge Δq remains behind

Distributed charge analysis –

A small charge -δq is placed on new LMA RF sources.

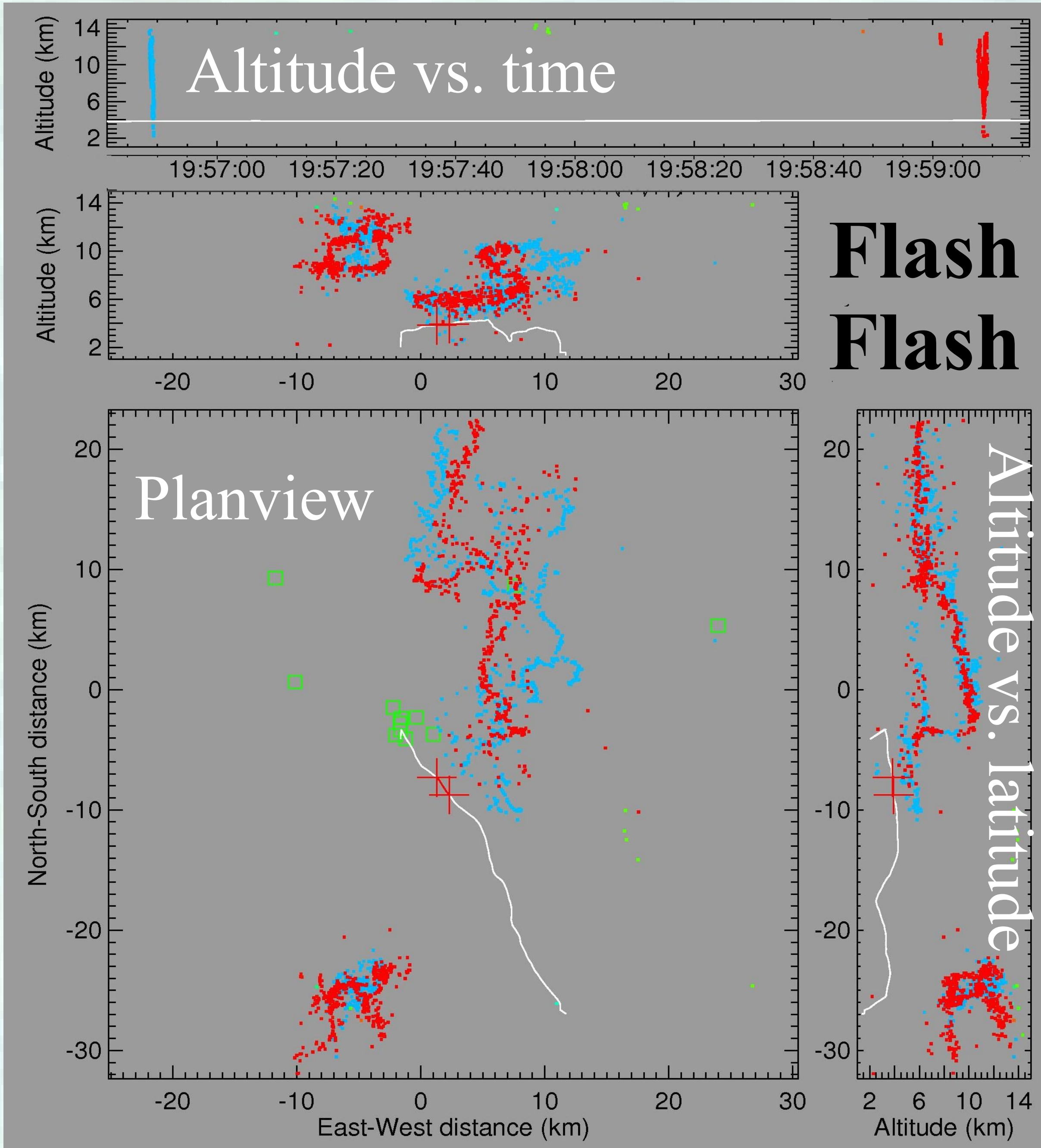
-δq is added to each new source, but never removed from the previous source.

A growing opposite charge -δq remains at the initial LMA source.

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

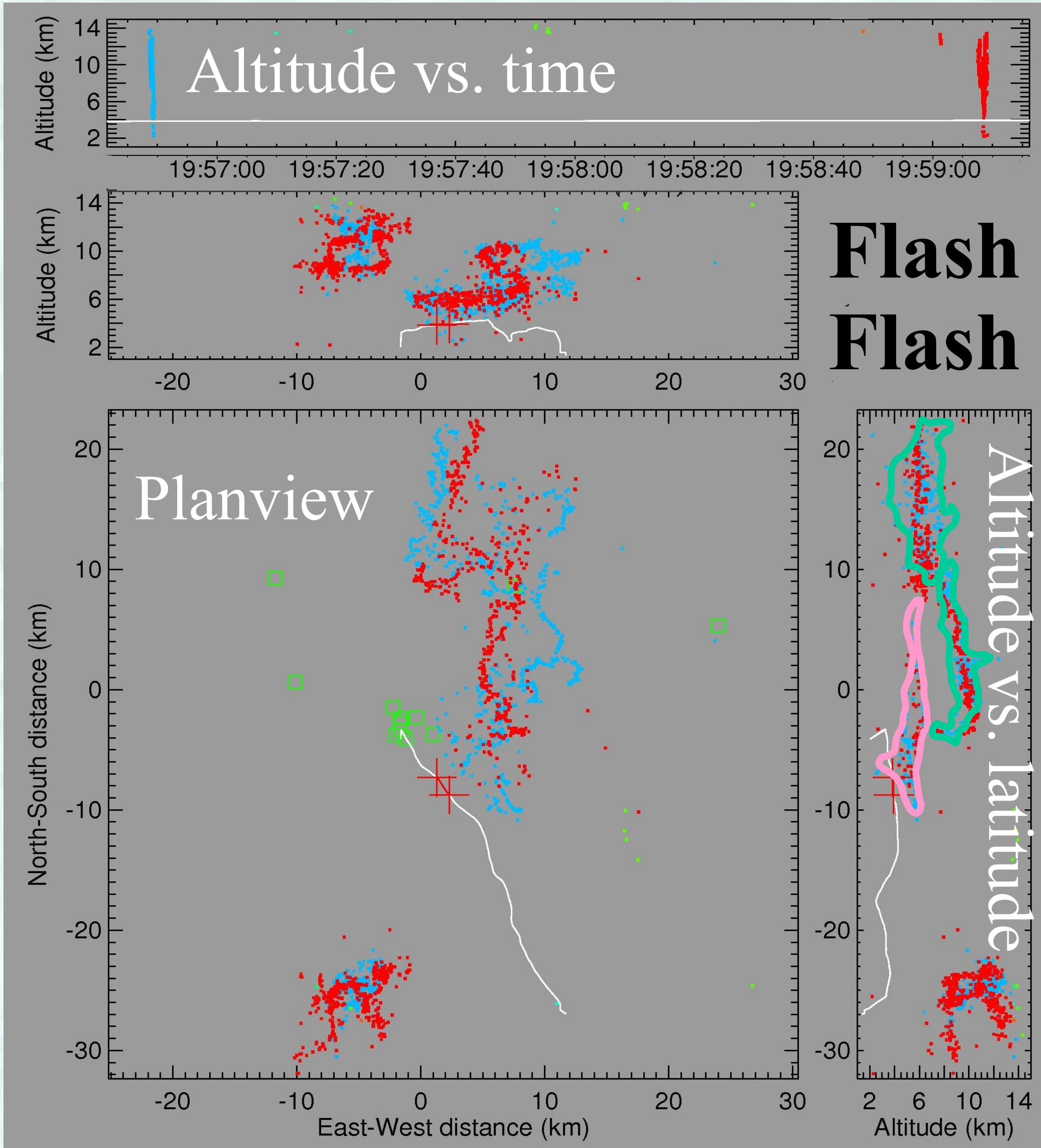
For certain flashes, the greatest field changes occur at times one would not predict by looking at the LMA data alone.

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept



Flash A: 19:56:49
Flash B: 19:59:08 UT

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept



Flash A: 19:56:49

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Flash B: 19:59:08 UT

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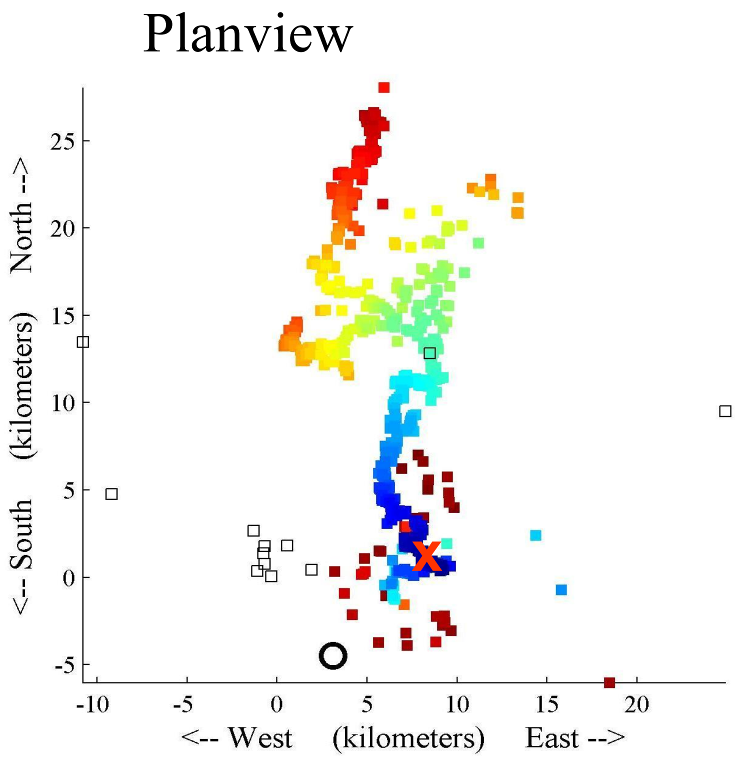
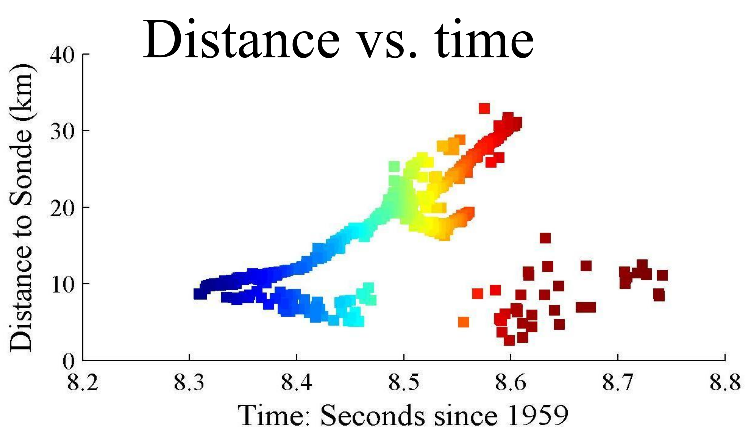
Flash B



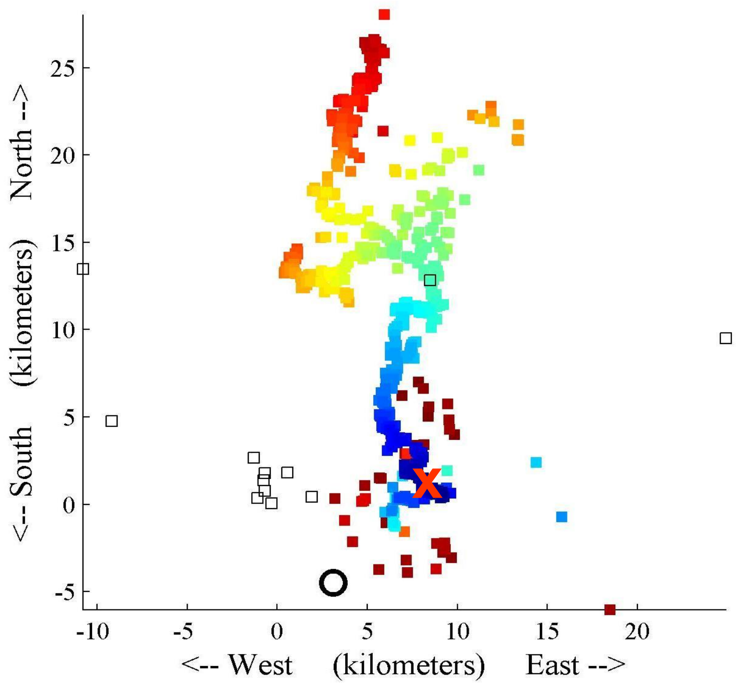


LMASim_20040818_20061212

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept
As of: 13-Dec-2006

Flash B

Planview



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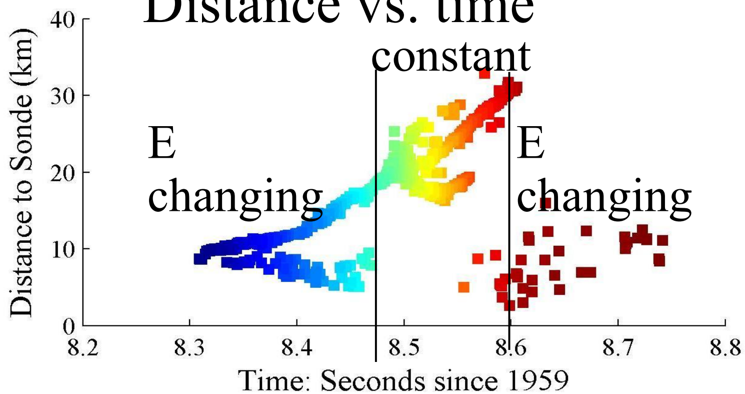

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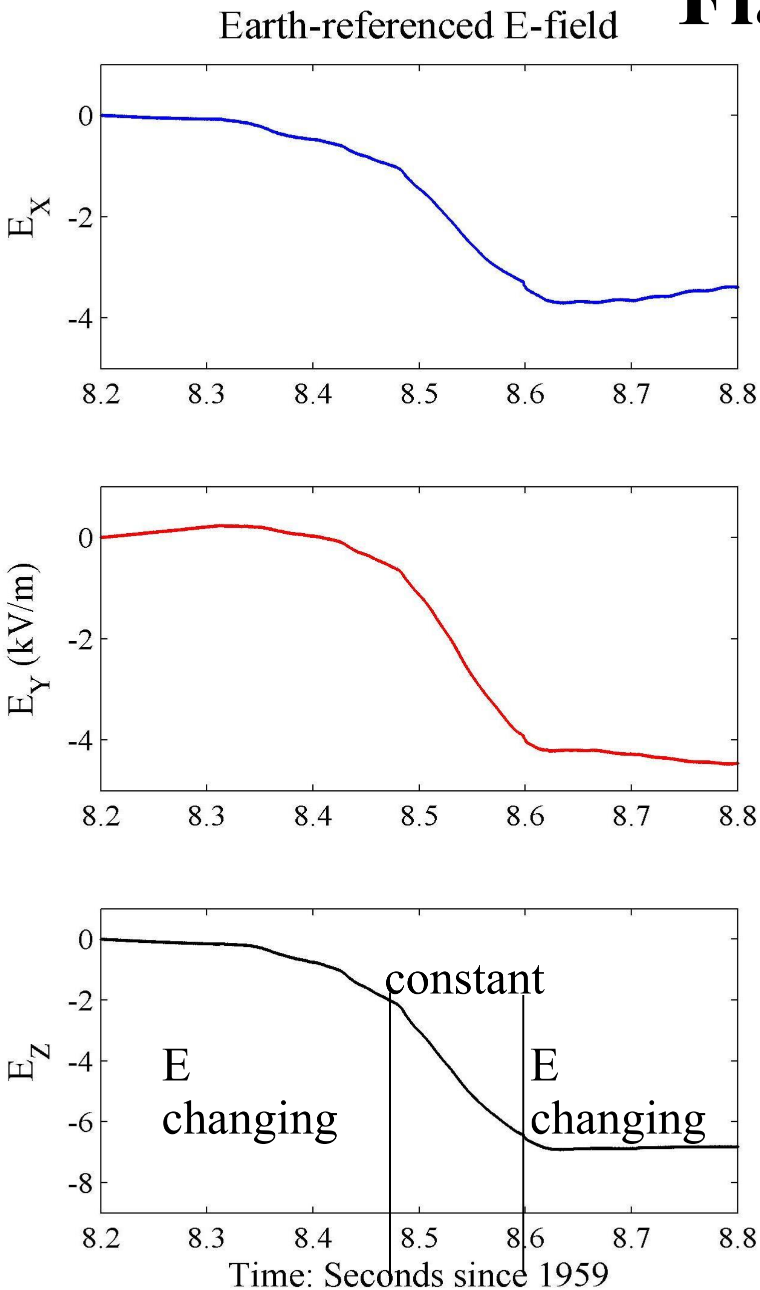
Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept
As of: 13-Dec-2006

Flash B



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How to fix this?

There must be a nearby positive charge that the LMA is not seeing

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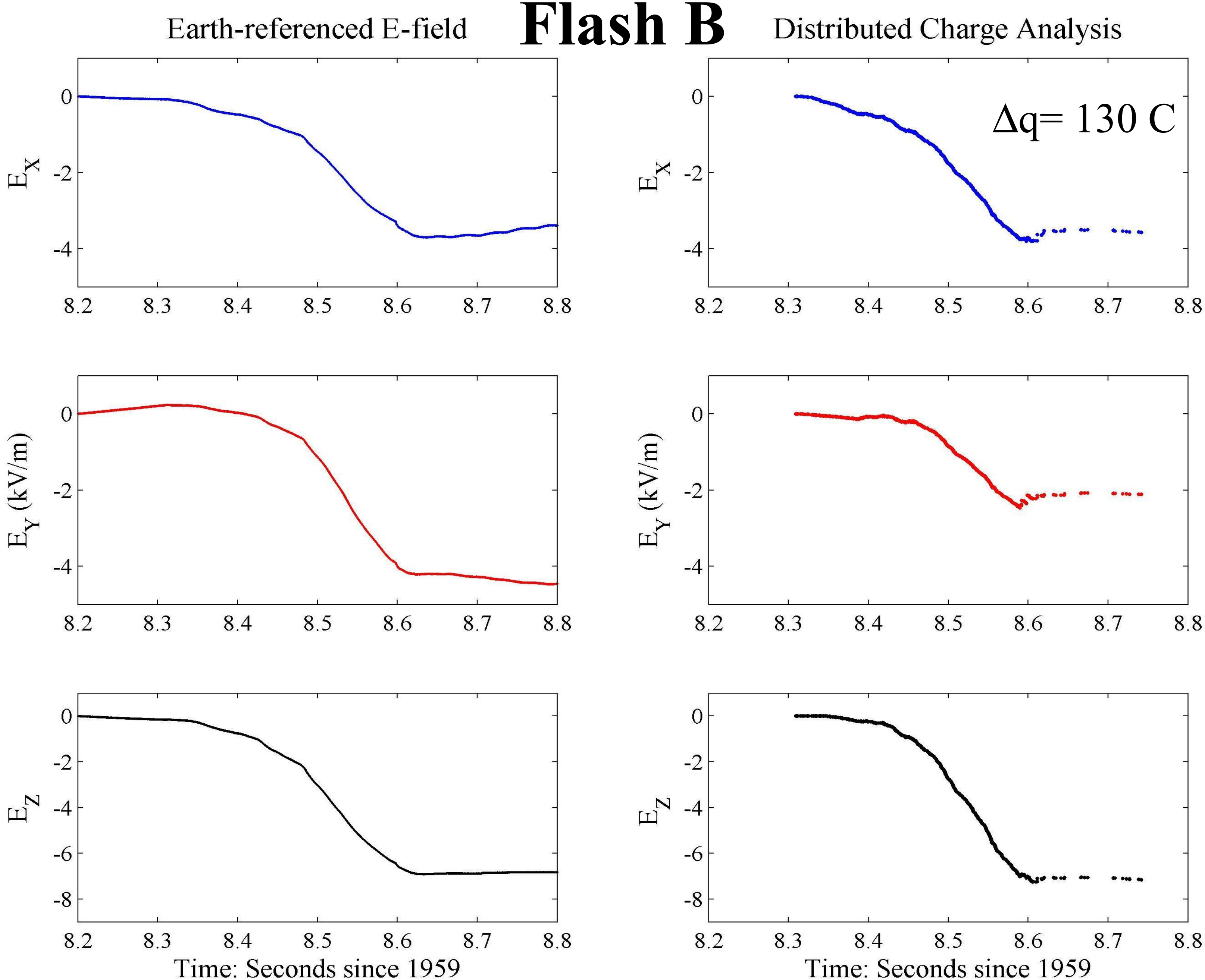
Flash B



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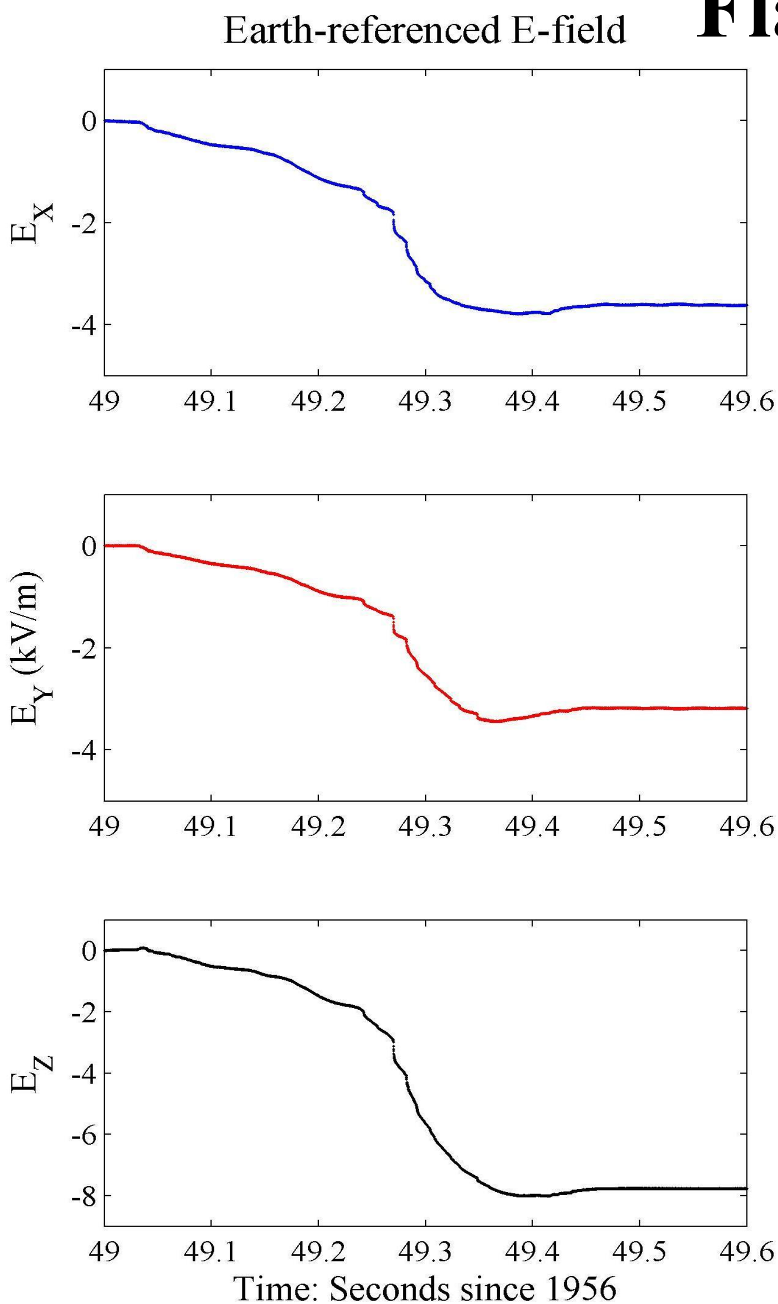

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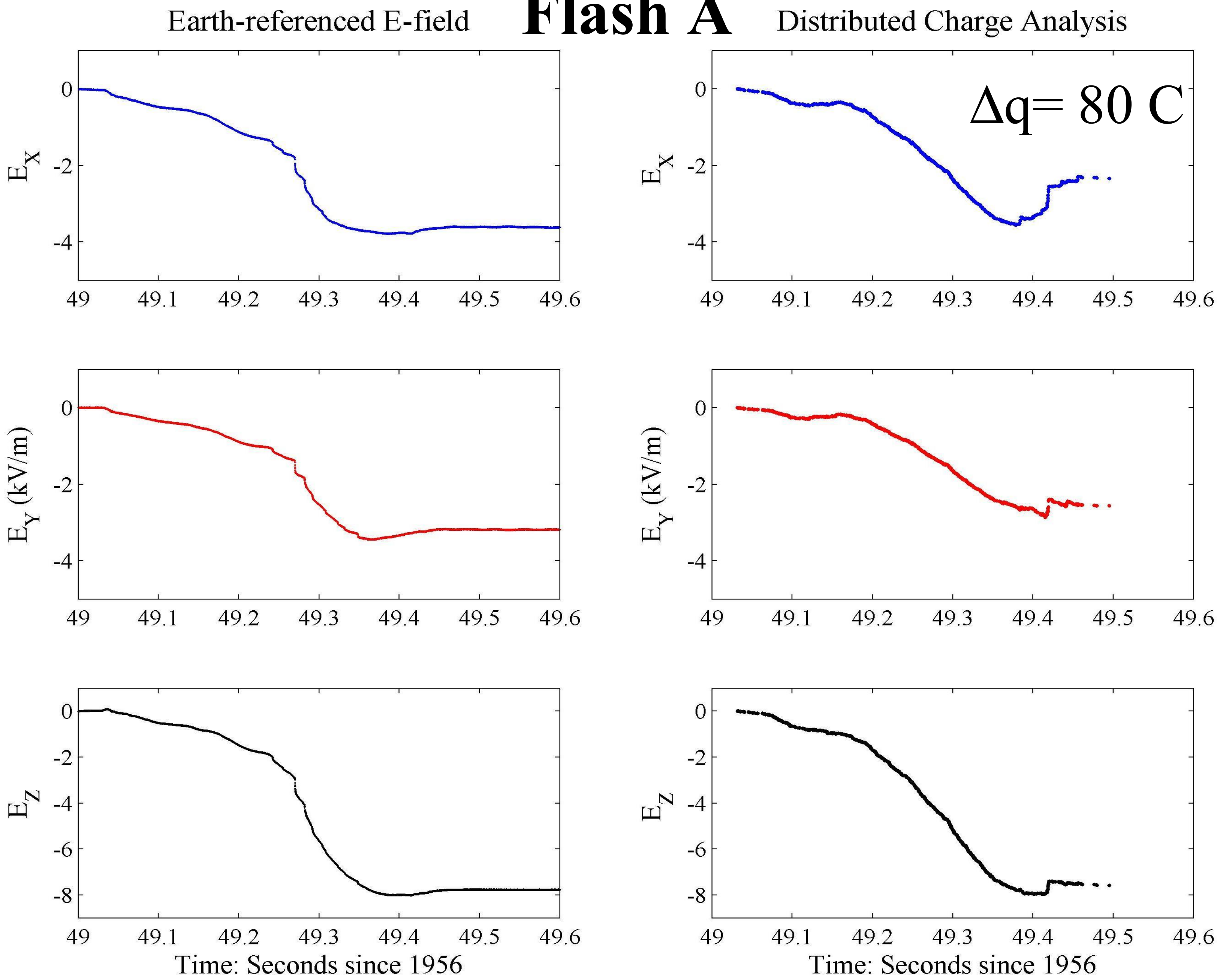
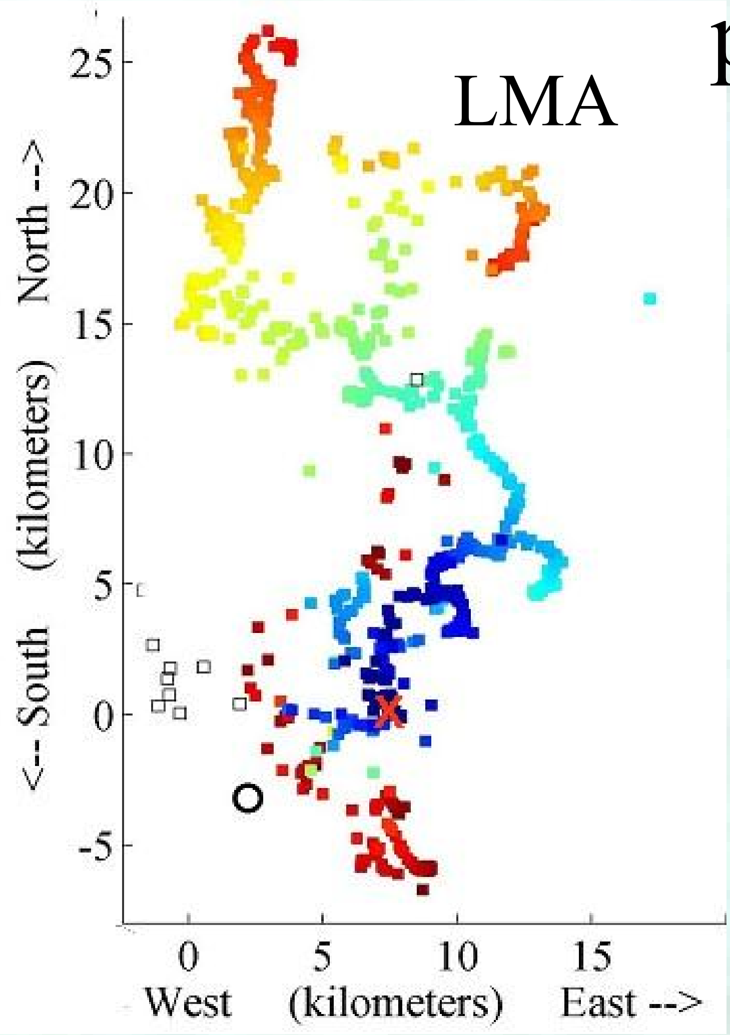
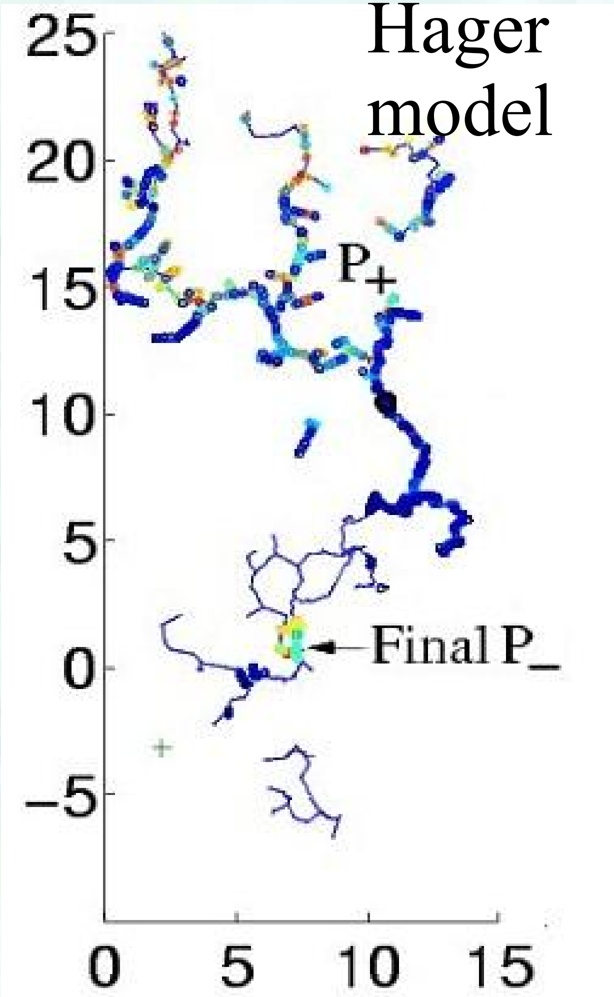
Flash A



Earth-referenced E-field
Distributed Charge Analysis
Δq= 80 C
E_X
E_Y (kV/m)
E_Z
0
-2
-4
-6
-8
49
49.1
49.2
49.3
49.4
49.5
49.6
Time: Seconds since 1956
Time: Seconds since 1956

Large E-field changes can occur during "RF quiet" periods. They are consistent with growing + charges near the flash initiation point.





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The inverse problem

- E-field measurements on the ground show a rich spectrum from 0.001 Hz – 500 MHz
- E-field features are understood in general terms, and the lower frequency features are understood as “charge transport”.
- Knowledge of charge allows precise prediction of fields. The inverse is not true.
- How to solve the inverse problem?
  - Cheat – use other info.
  - Get full vector information (needs a balloon)
  - Get multi-station charge measurements

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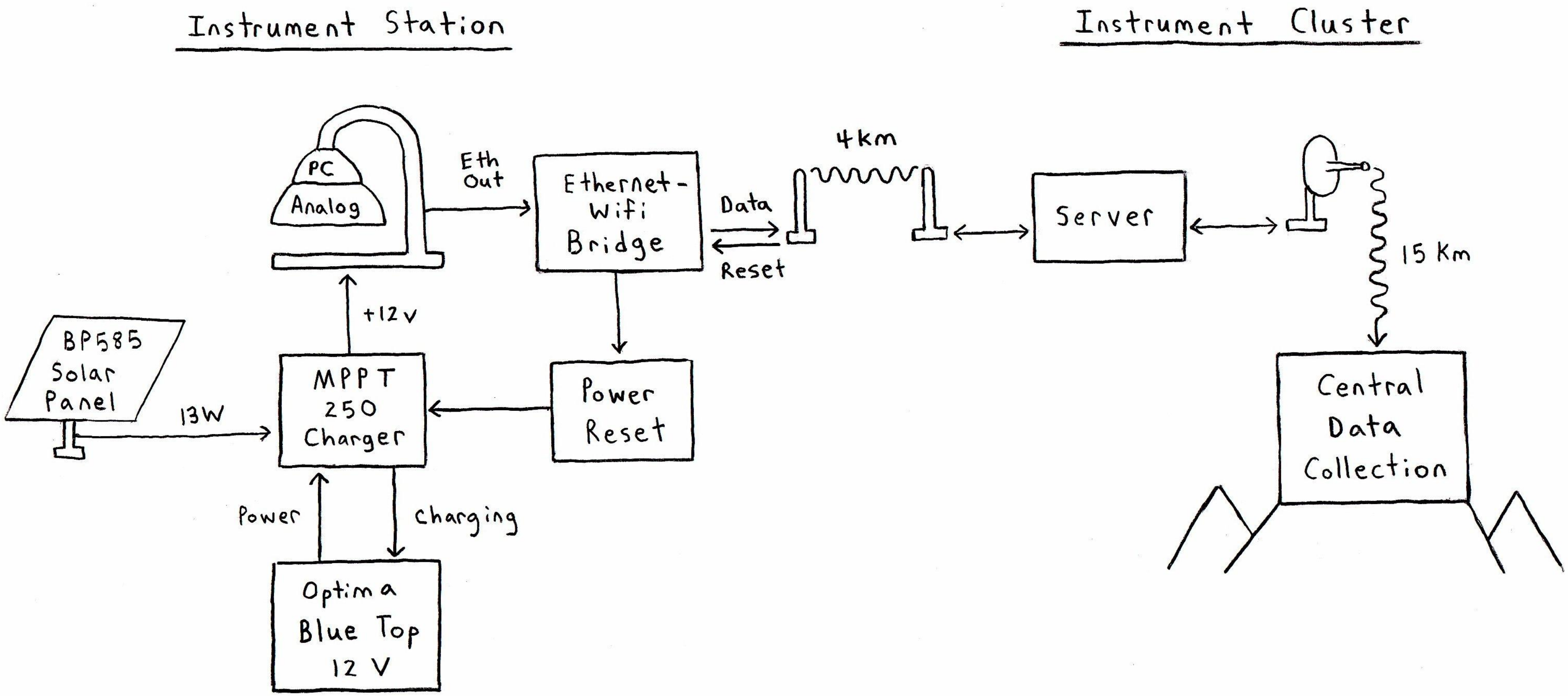
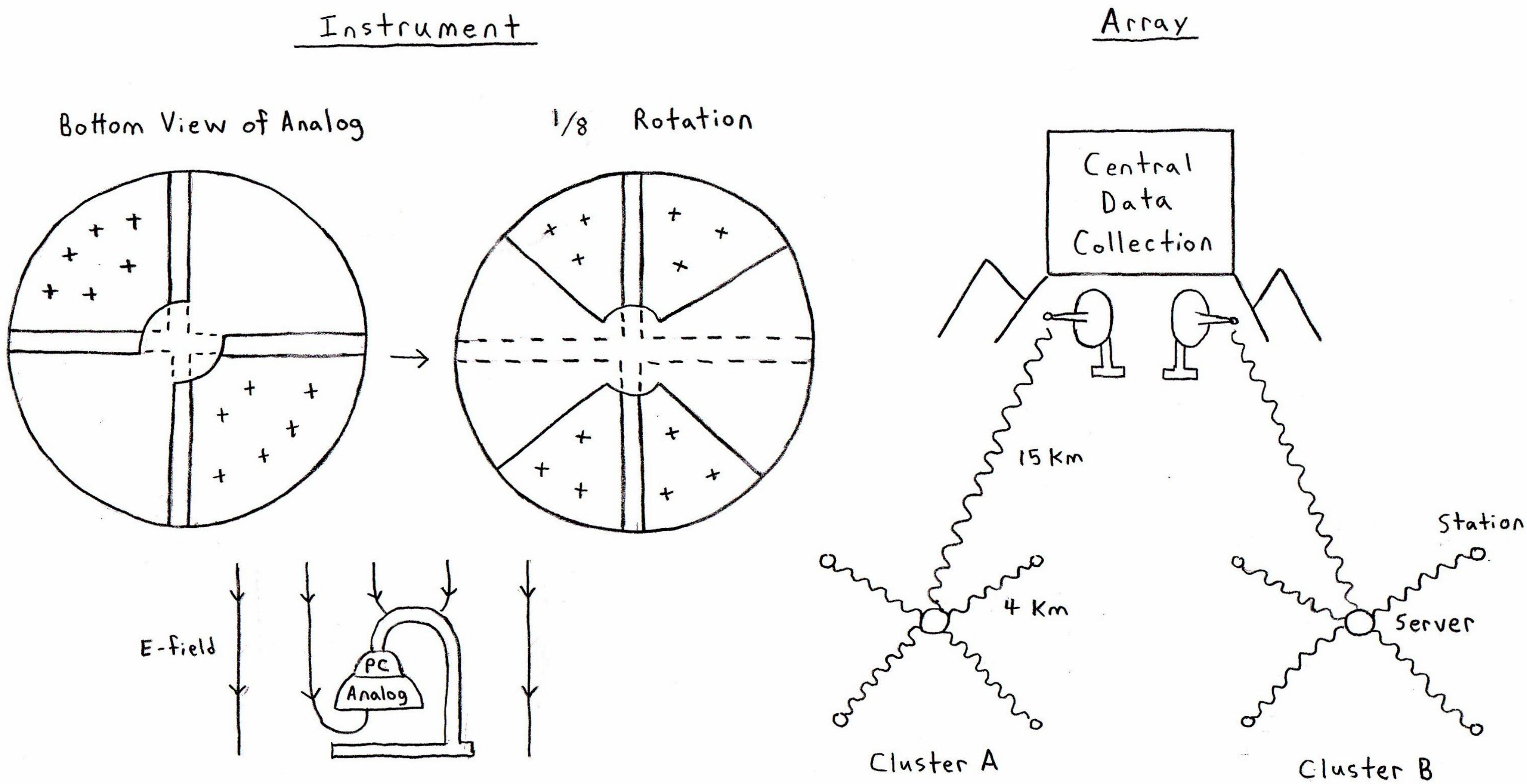
A dozen simultaneous measurements greatly constrain the problem



Sketches by Will Walden-Newman

Courtesy of Richard Sonnenfeld
New Mexico Tech Physics Dept

The "Fairly Large Array"



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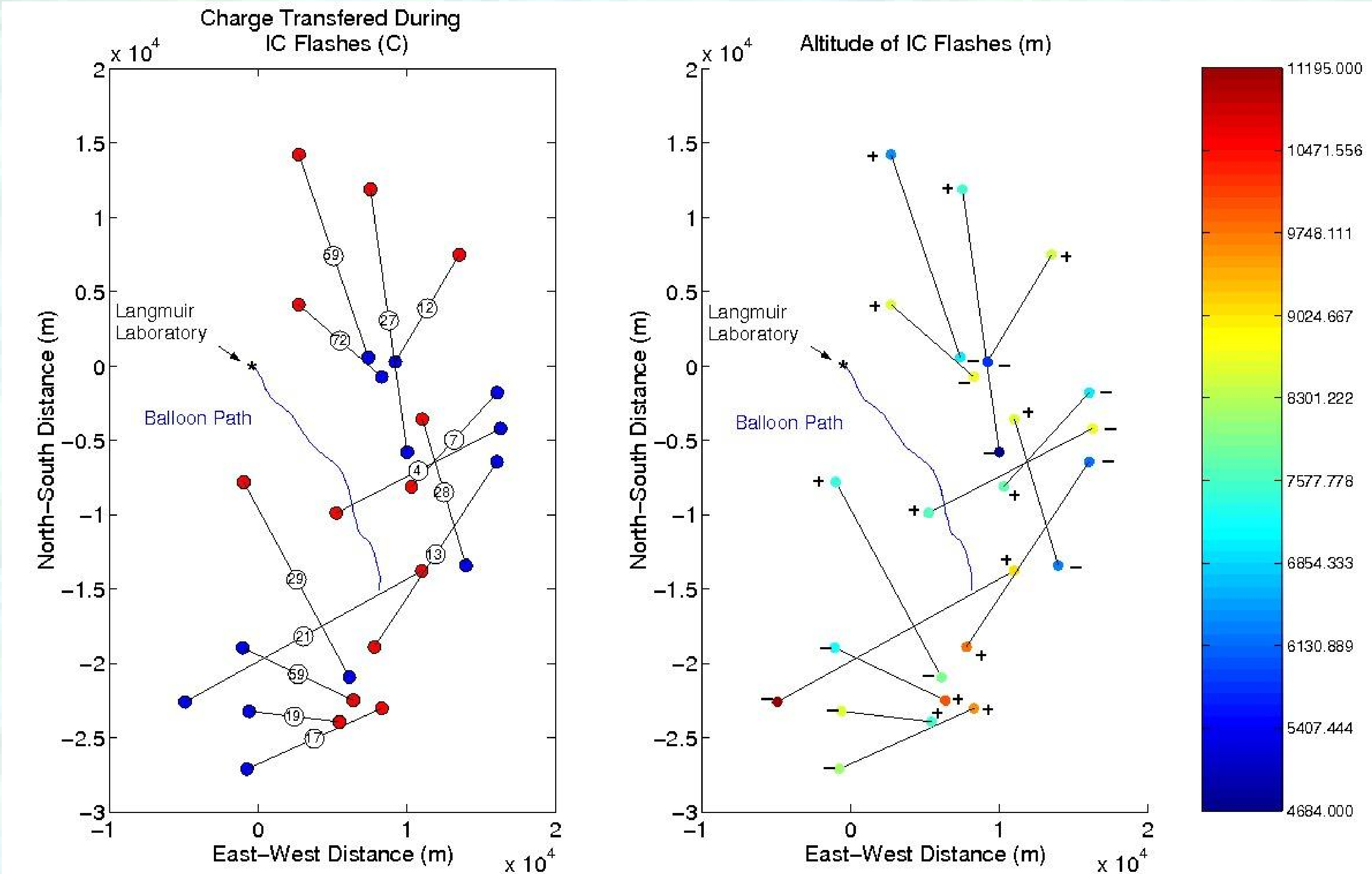

Models from Aslan and Hager
AGU Fall Meeting 2007

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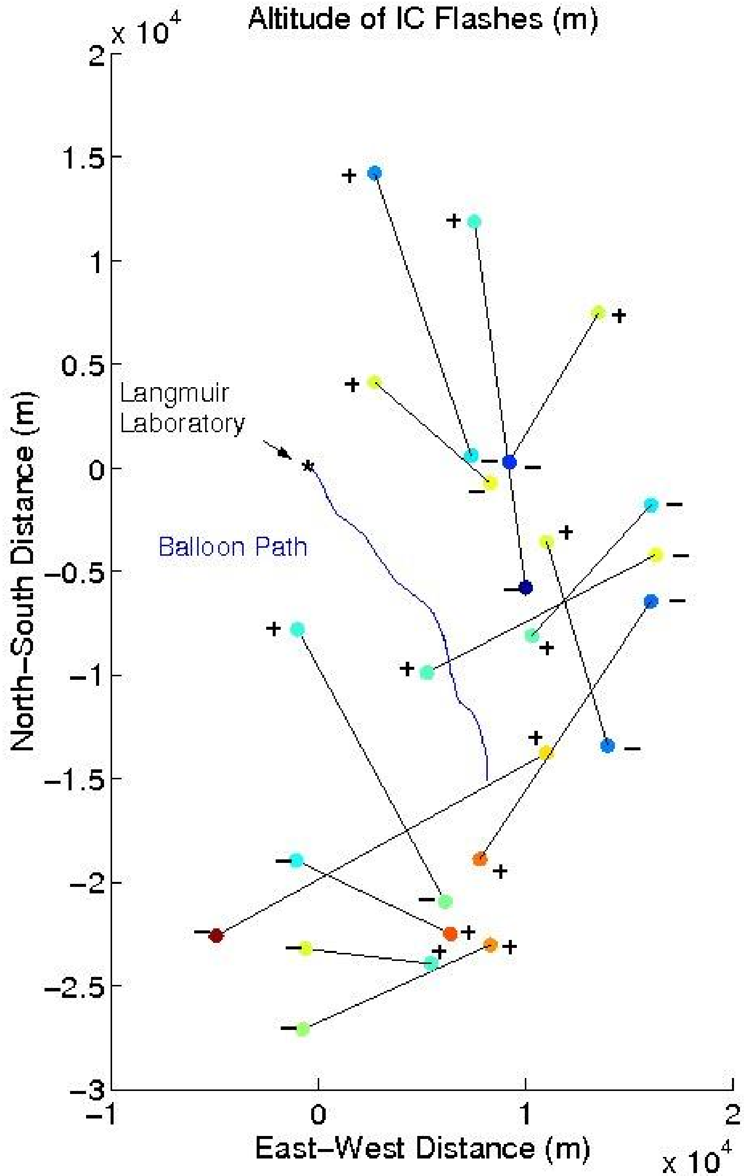

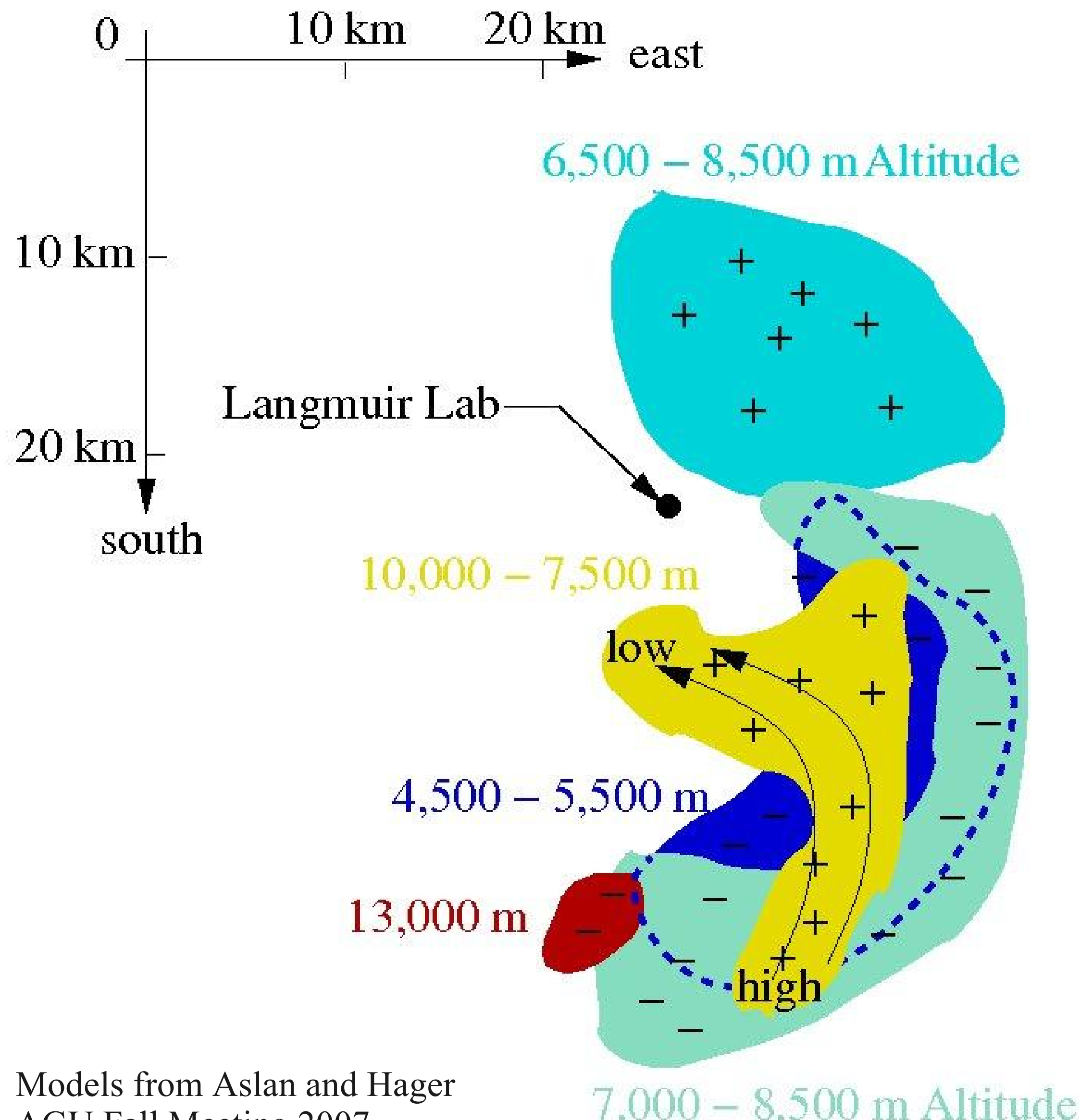

Models from Aslan and Hager
AGU Fall Meeting 2007

Courtesy of Richard Sonnenfeld
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Summary

- Electric field measurements have historically contributed much to the understanding of lightning.
- We are developing multiple instruments aimed at overcoming the electrostatic “inverse problem” and watching the charge transport in a lightning flash
- Our initial results are consistent with a model in which each lightning flash leaves a constant amount of charge / unit length of channel
- Close-by measurements might allow us to see a charge concentration at the channel tip which one would expect to see.

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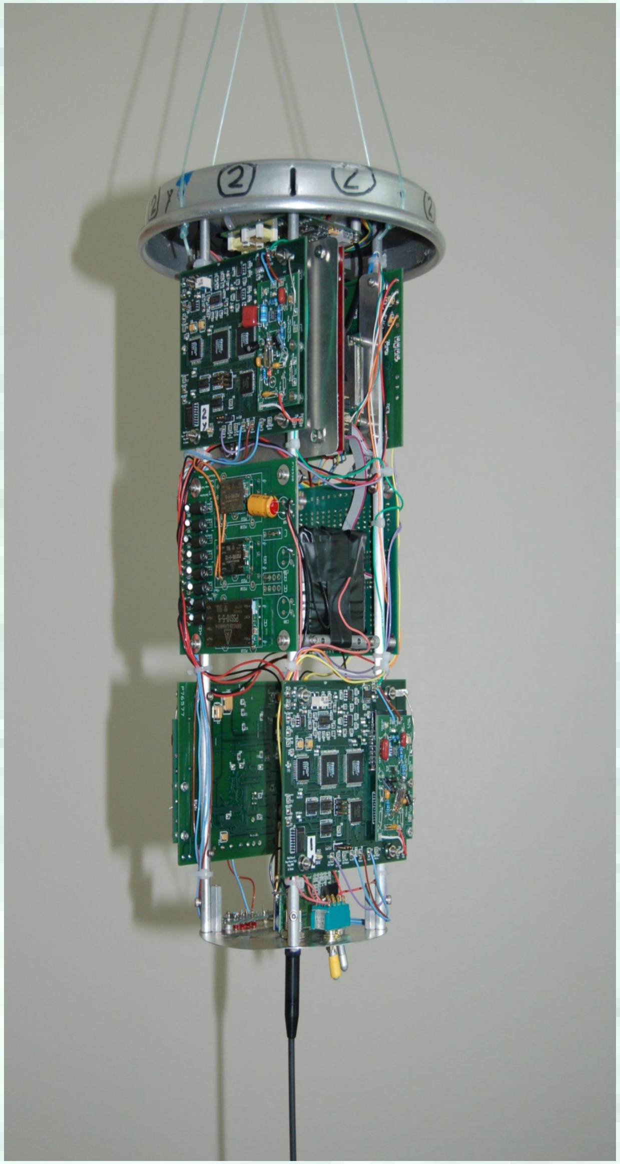

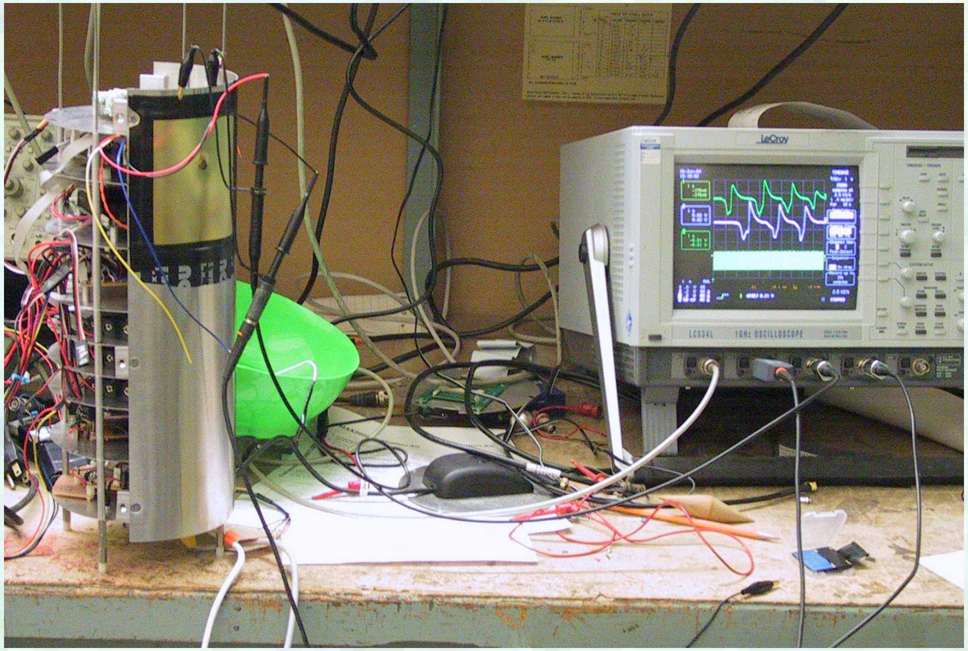

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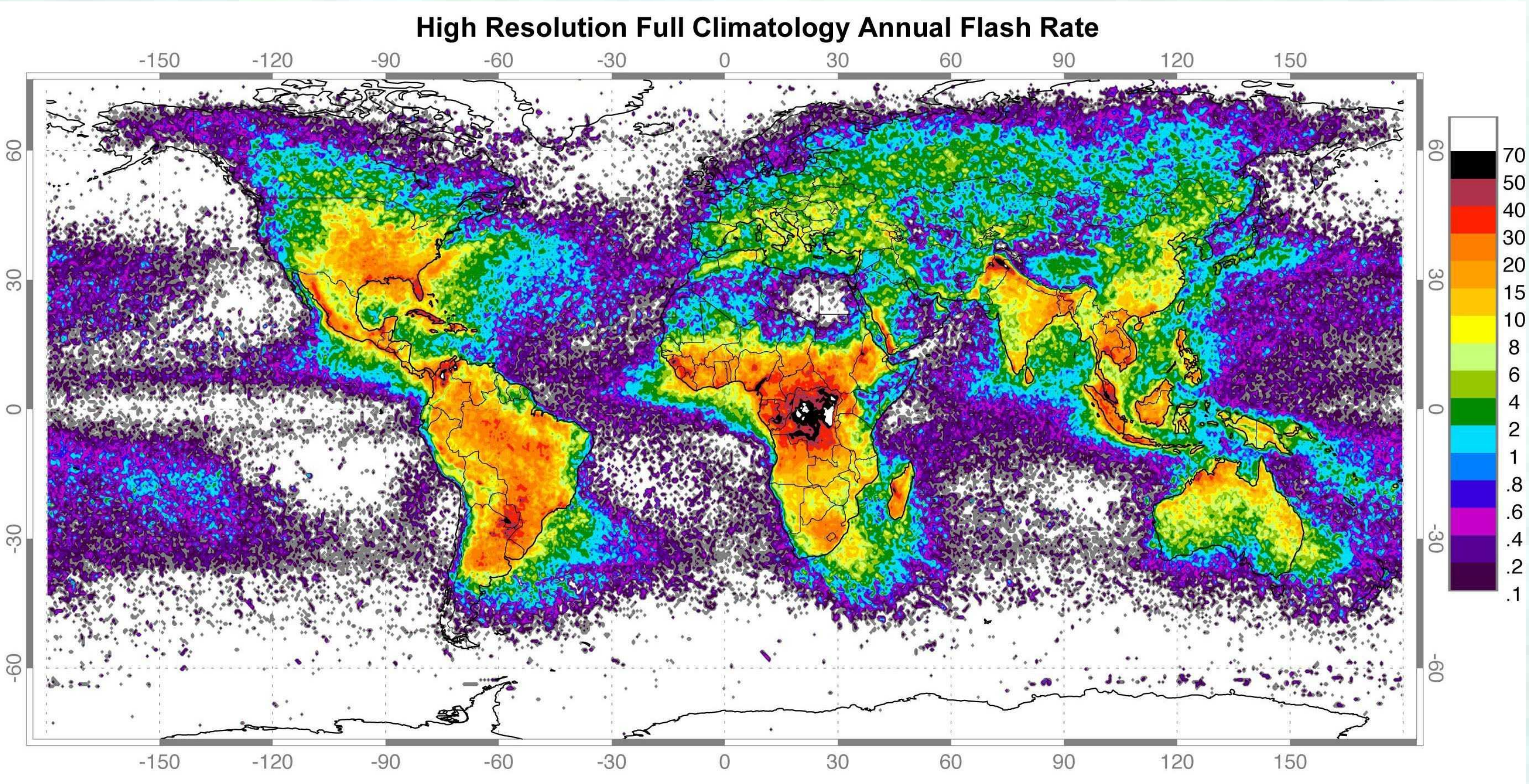

LIS and OTD data
published by
From Hugh Christian et al
NASA GHCC

Courtesy of Richard Sonnenfeld
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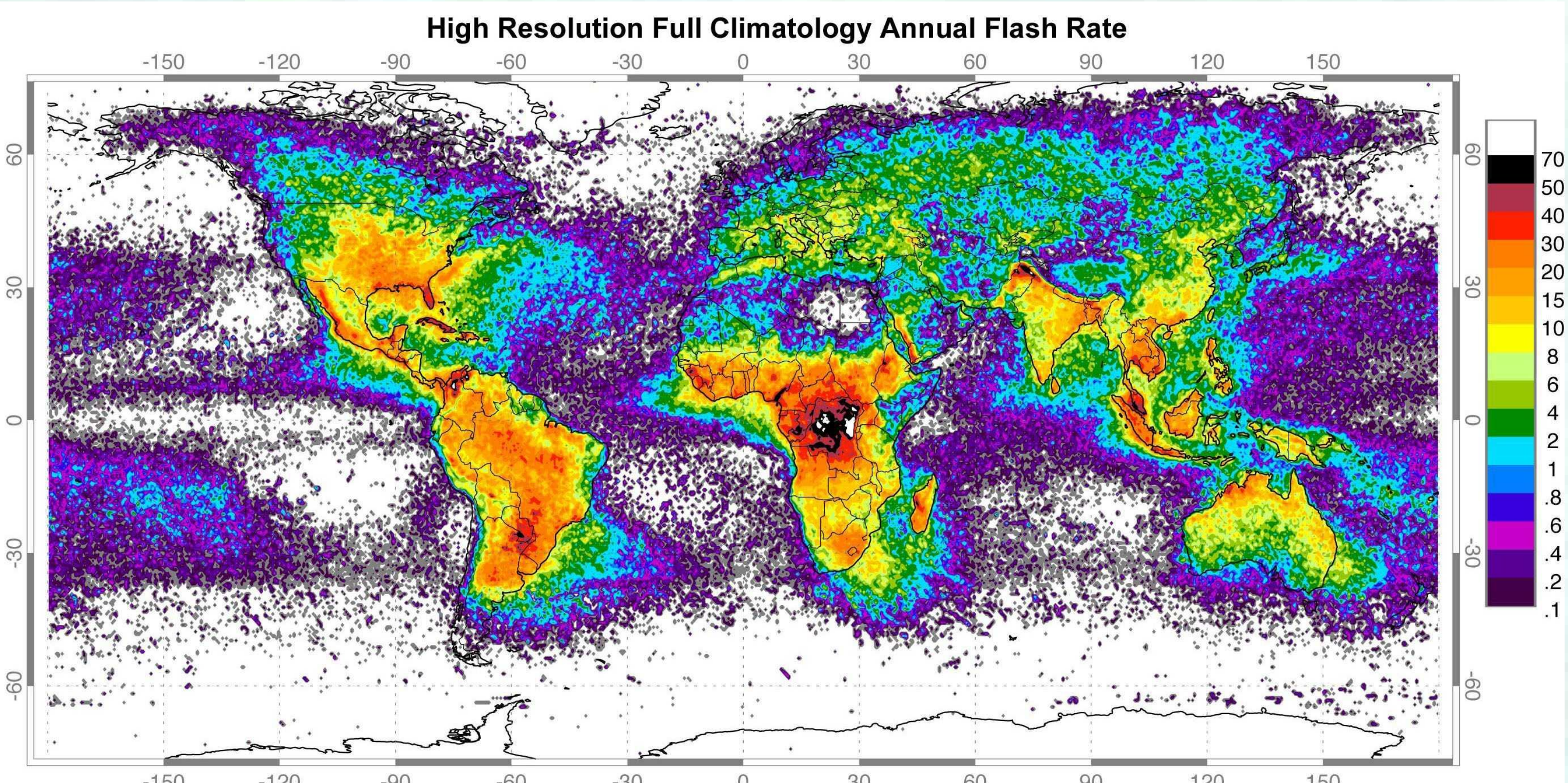

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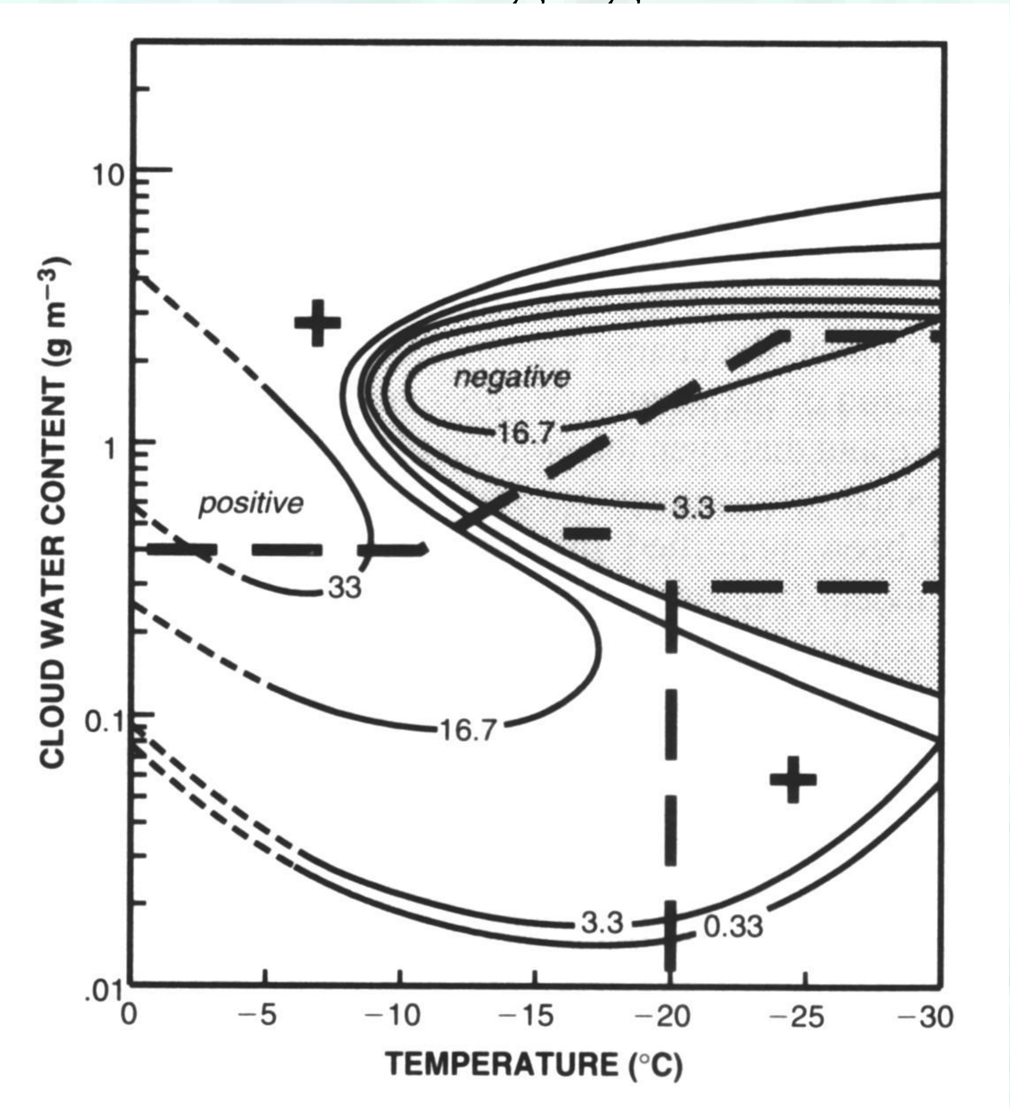
Collisional Non-Inductive Charging

- Contact potential difference of ~100 mV observed between wet ice and dry ice.
- Ice crystals scatter off of 'riming graupel' (hail with a freezing surface layer) and acquire charge
- Mechanism requires cold (sub-freezing) clouds



Adapted from Takahashi, (1978)

Courtesy of Richard Sonnenfeld
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