Lightning Studies at Pierre Auger Observatory

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Pierre Auger Lightning Study (LASS)

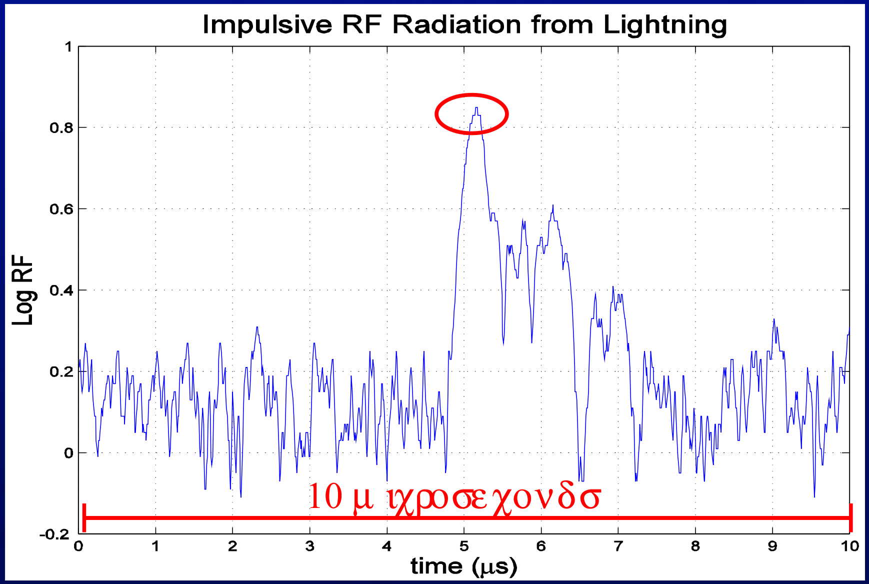
- LASS: Lightning Air Shower Study
- Cooperative project – just getting started
- Collaborators:
  * Langmuir Laboratory group, New Mexico Tech
  * William Brown, Colorado State Univ., Pueblo
  * Andreas Haungs, Karlsruhe Inst. Technology
  * Joseph Dwyer, Florida Inst. Technology
- Two lighting mapping stations currently deployed at Pierre Auger
- Follow-up to preliminary study at Kascade Grande, FZK, Karlsruhe

Goals

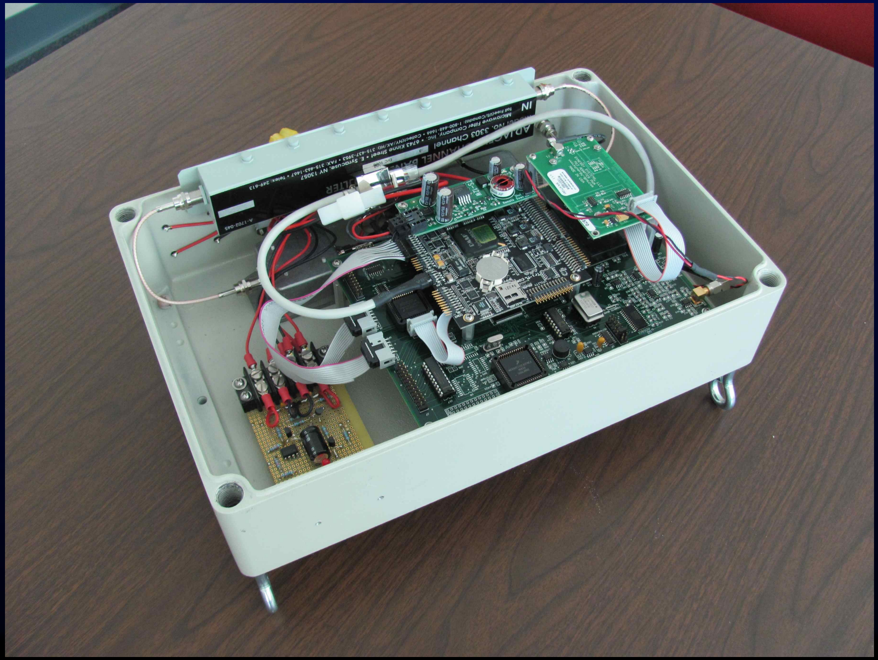
- Determine possible role of cosmic rays in initiating lightning (or producing other electrical effects in storms).
- Study effect of strong electric fields on air showers; e.g., Low frequency VHF studies (LOFAR/LOPES/AERA).
- Provide real-time data on storm and lightning activity over and around Pierre Auger for operational purposes.

Lightning Mapping Array

RF receiver output



Electronics package

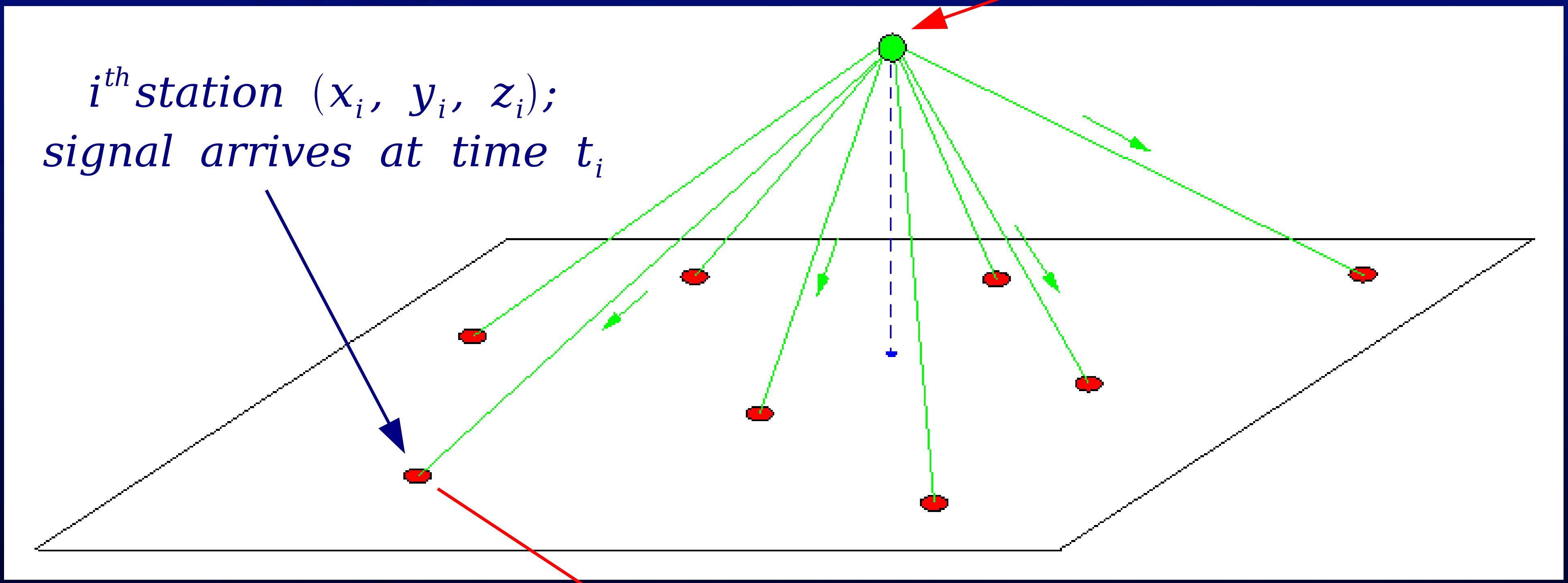


- Locates sources of impulsive VHF radiation events from time-of-arrival (TOA) measured at multiple ground locations.
- Listens on locally unused TV channel (e.g., U.S. Channel 3, 60-66 MHz).
- Measures arrival time of peak radiation with 40 ns timing accuracy
- Typically locates ~100 up to ~1000 radiation events per lightning flash.
- Location accuracy: ~ tens to few hundred meters over or near the network.
- Real time processing and display of observations.

New Mexico Tech

Time-of-Arrival (TOA) Technique

Impulsive lightning event at (x, y, z; t)

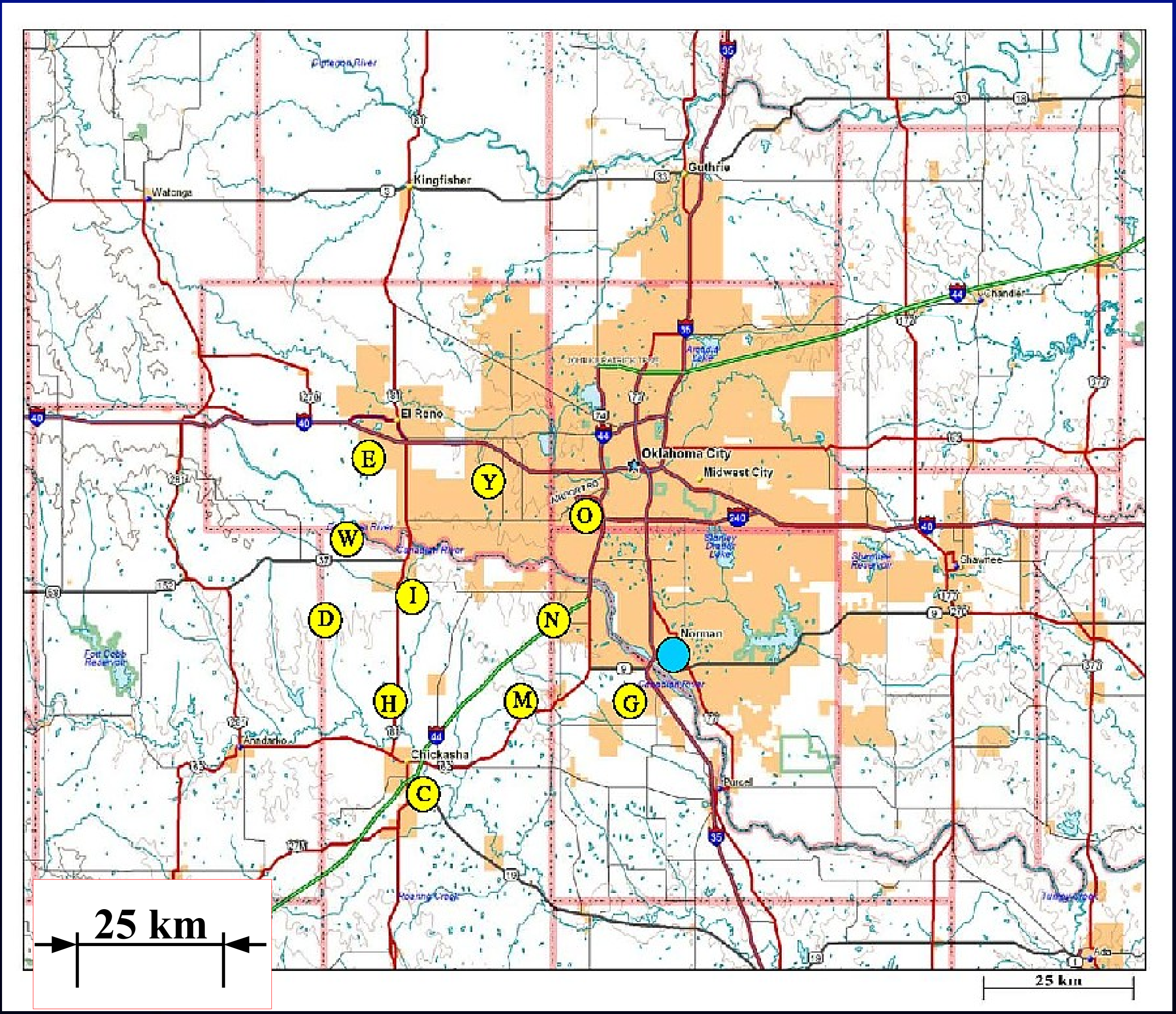


$$t_i = t + \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}}{c}$$

– *Measure t_i at $N \geq 4$ (50 ns accuracy)*

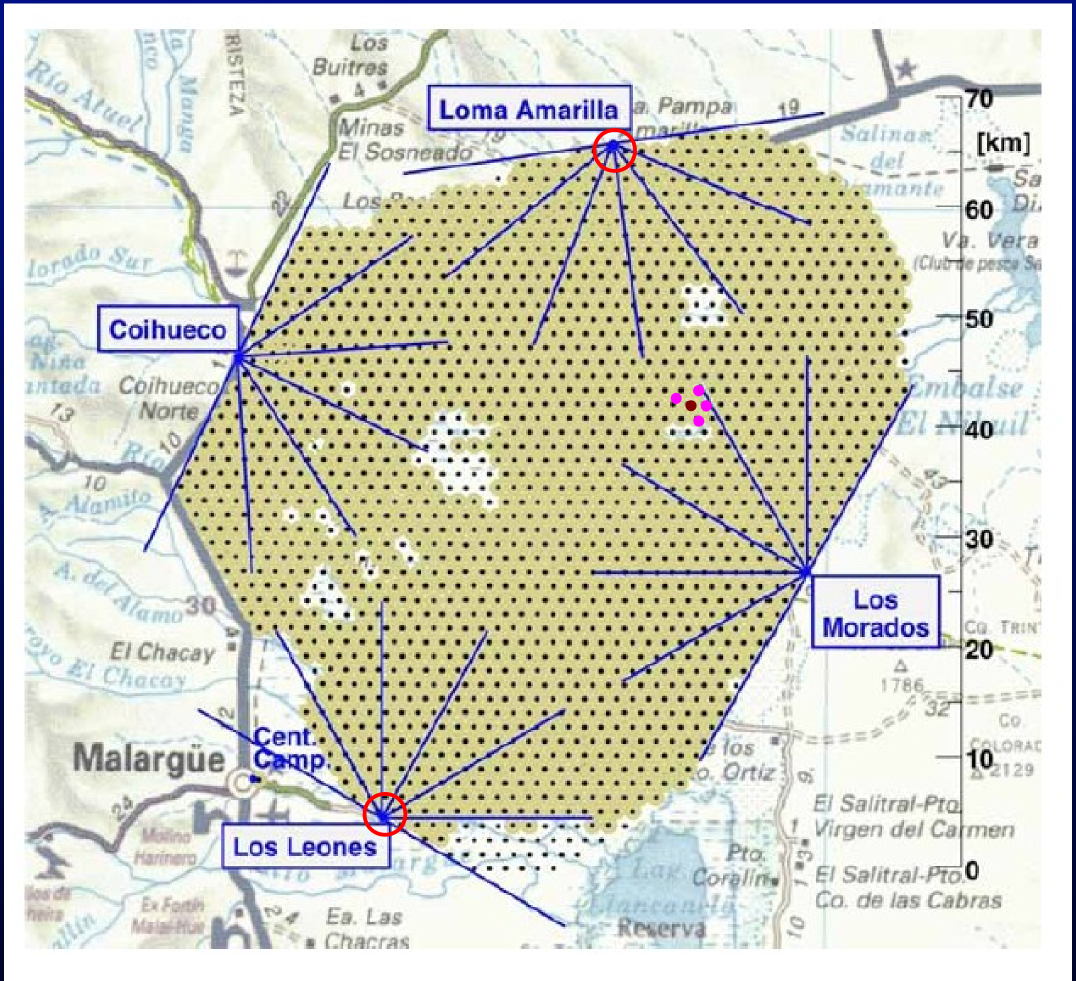
– *Solve for $(x, y, z; t)$ (4 unknowns)*

Oklahoma LMA Station Locations



11 stations over a 50-60 km diameter area, southwest of Oklahoma City

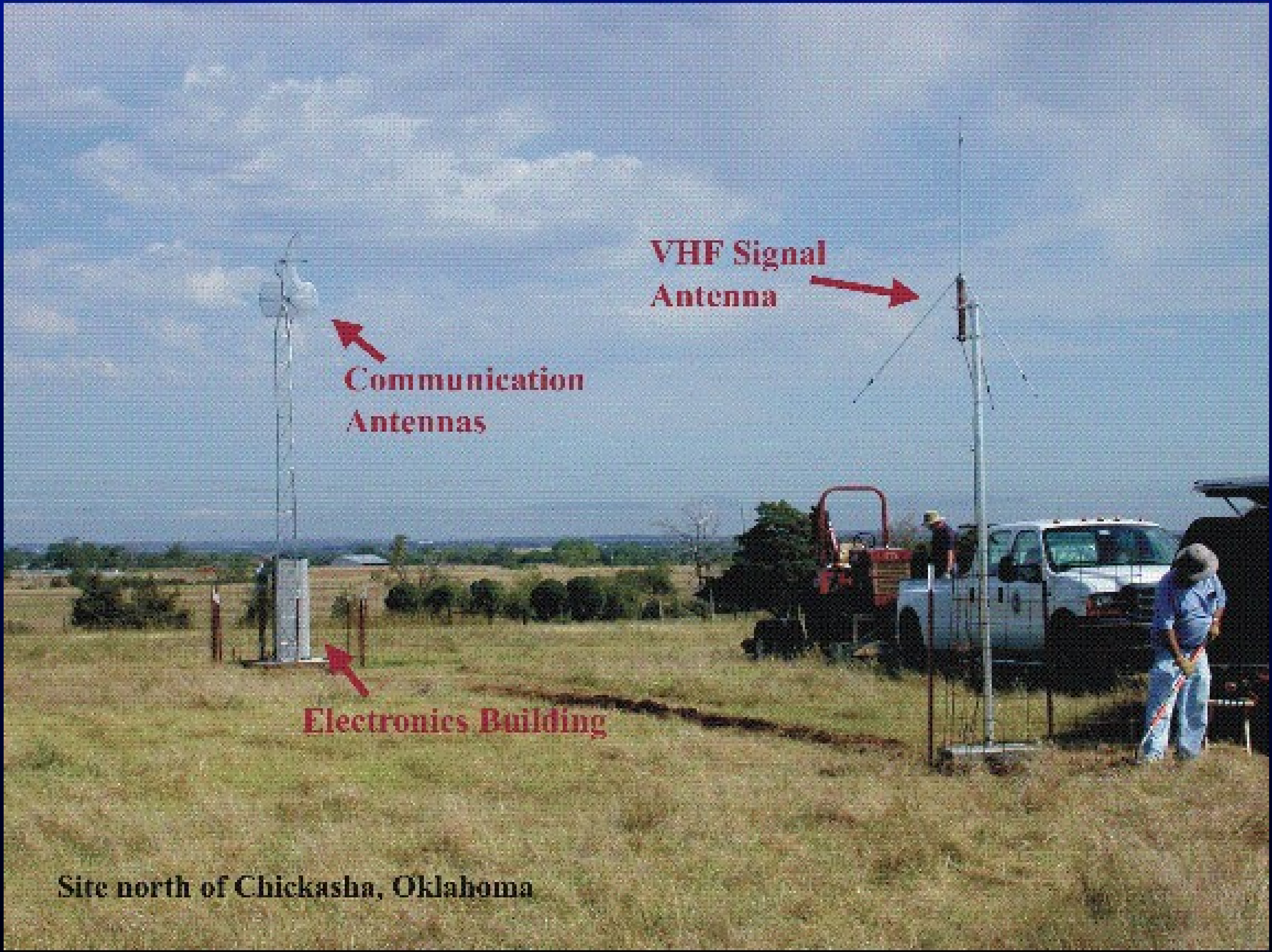
Pierre Auger Surface Detector (SD) Array



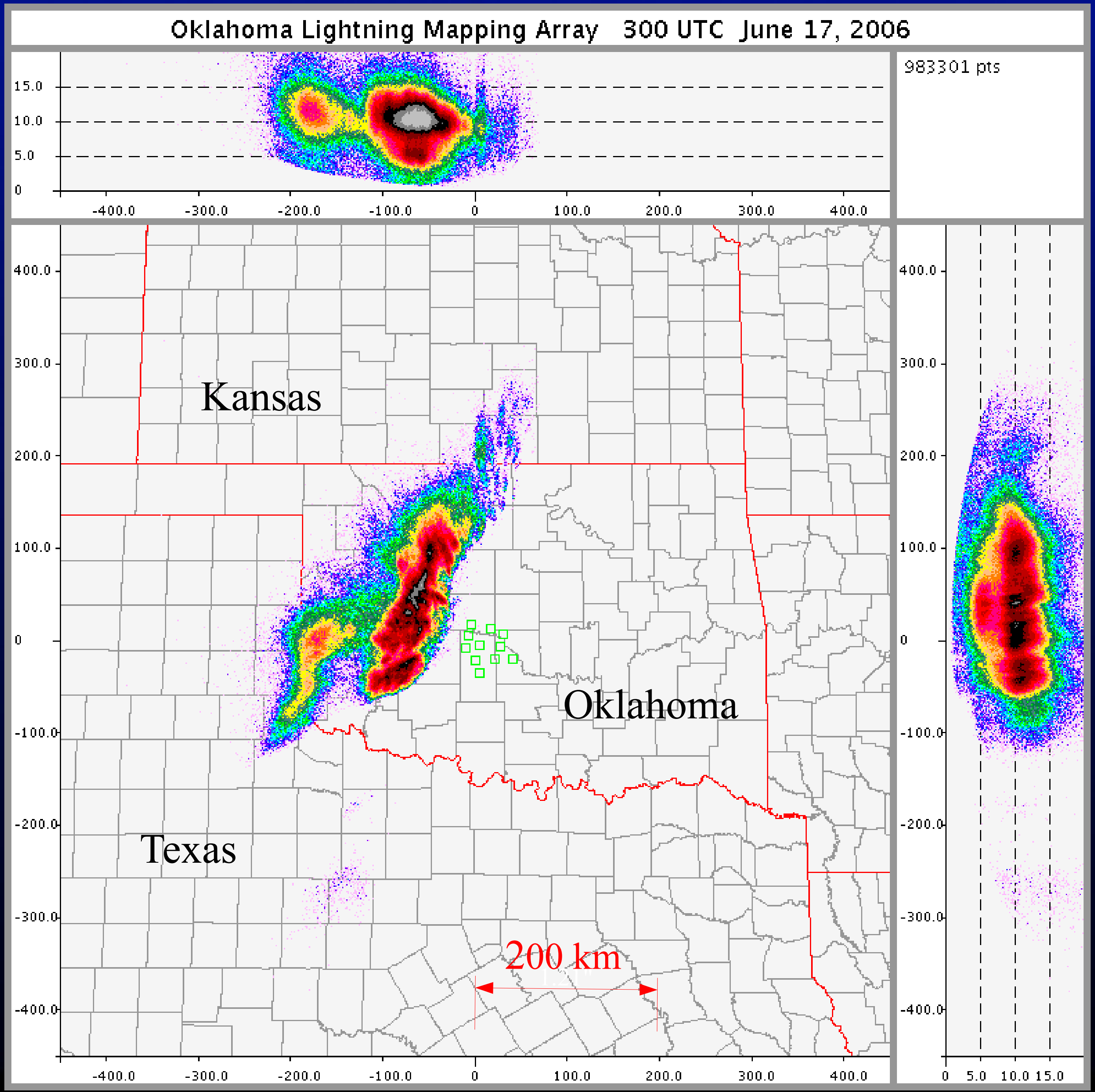
- Similar overall size (~60 km diameter).
- 1600 SD stations, vs. 8-12 stations for LMA.
- 2 LMA stations currently deployed (red circles).
- 6 stations planned, 12-13 stations eventually possible.

Adapted from J.L. Harton, Prospects for the Auger Observatory

Oklahoma Lightning Mapping Station (VHF TV Channel 3; 60-66 MHz)



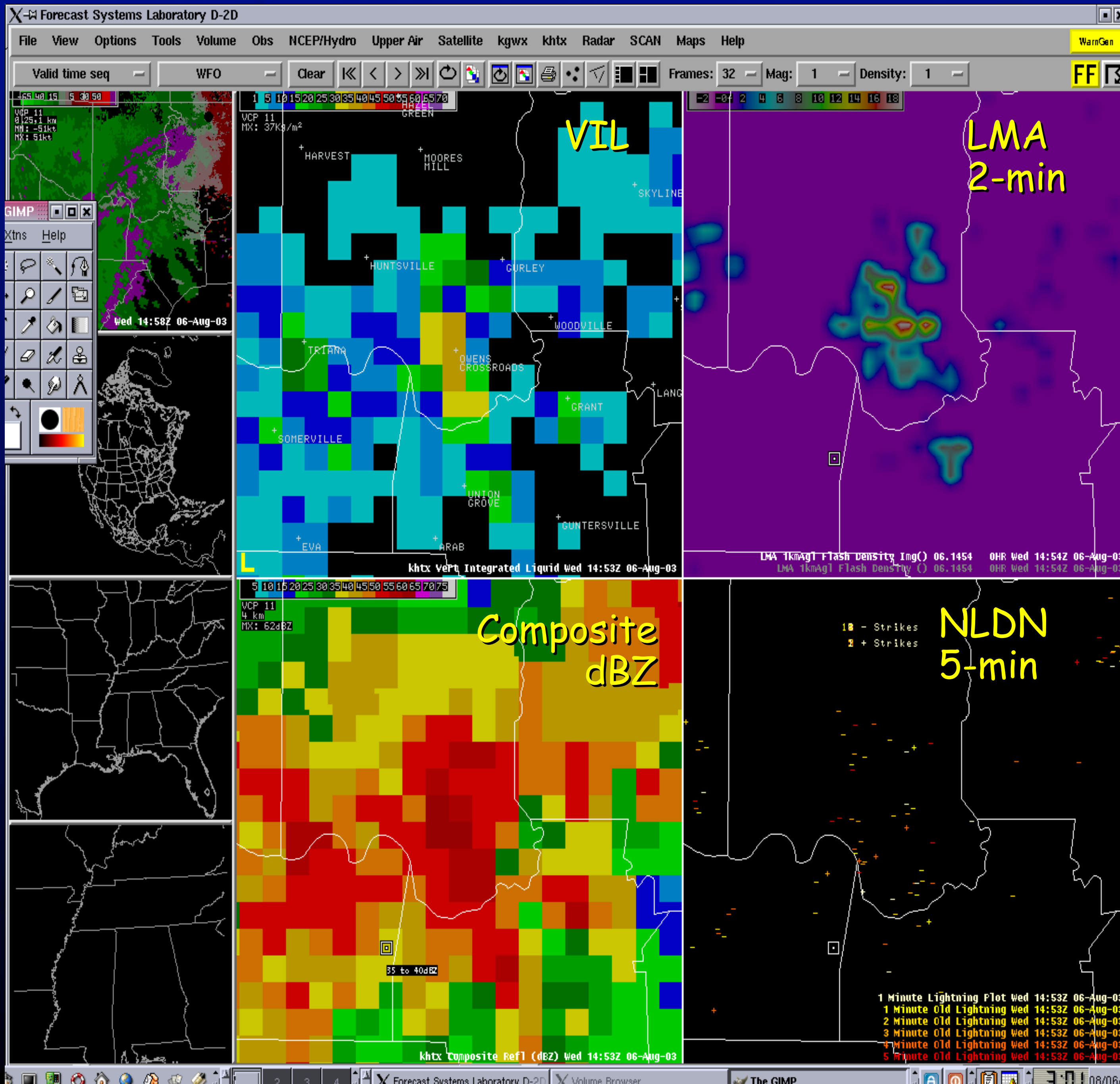
Real time display, Oklahoma LMA (Univ. of Oklahoma, National Severe Storms Lab)

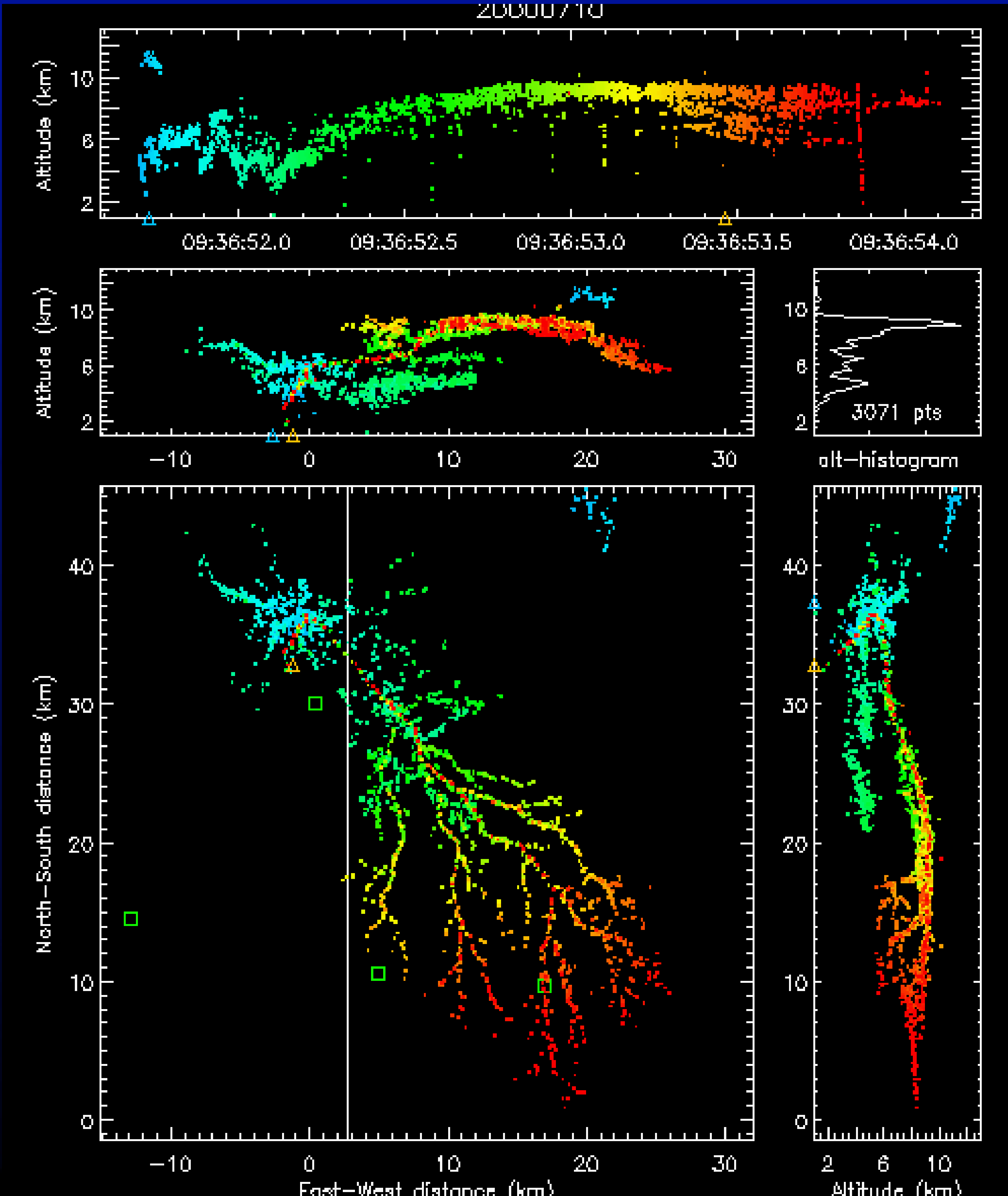


- One hour of data; 983,000 sources located.
- Large squall line approaching from the west.
- Data ingested over dedicated wireless links, processed in in real time, 1-2 minute updates.

(http://lightning.nmt.edu/oklma)

Forecast display, National Weather Service Off ce, Huntsville, Alabama (North Alabama LMA – NASA)





Highly Dendritic Negative Polarity Cloud-to-Ground Flash (-CG).

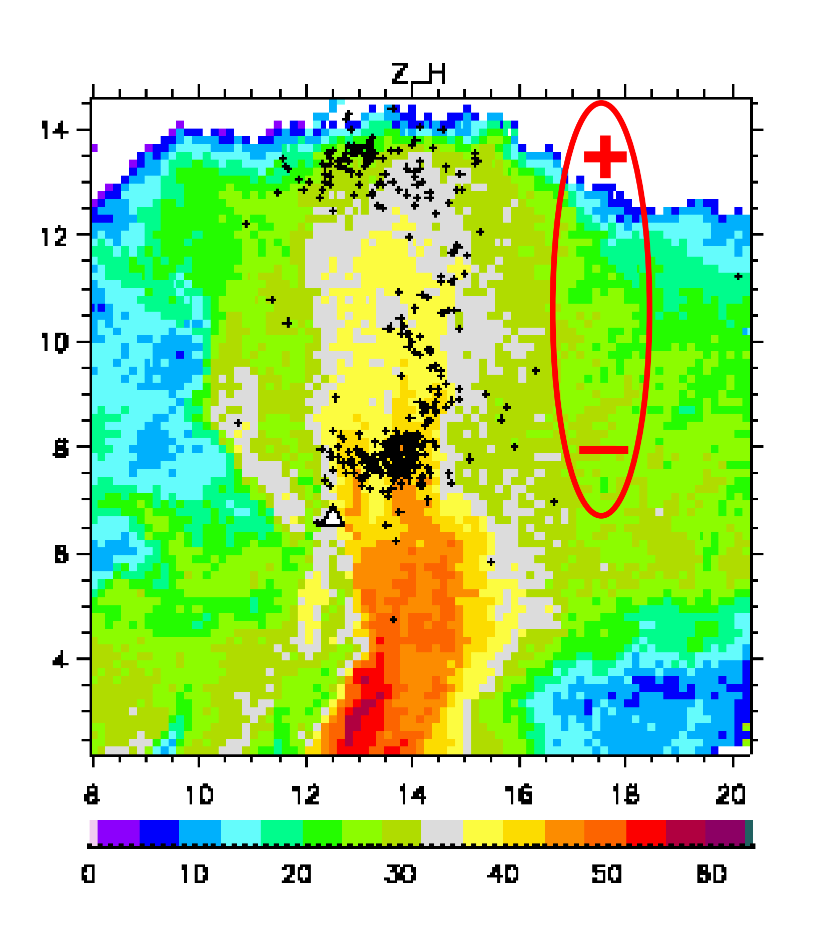
- 2.3 s duration;
- ~ 45 km horizontal extent
- 3000+ located sources

STEPS 2000 Field campaign (Kansas/Colorado)

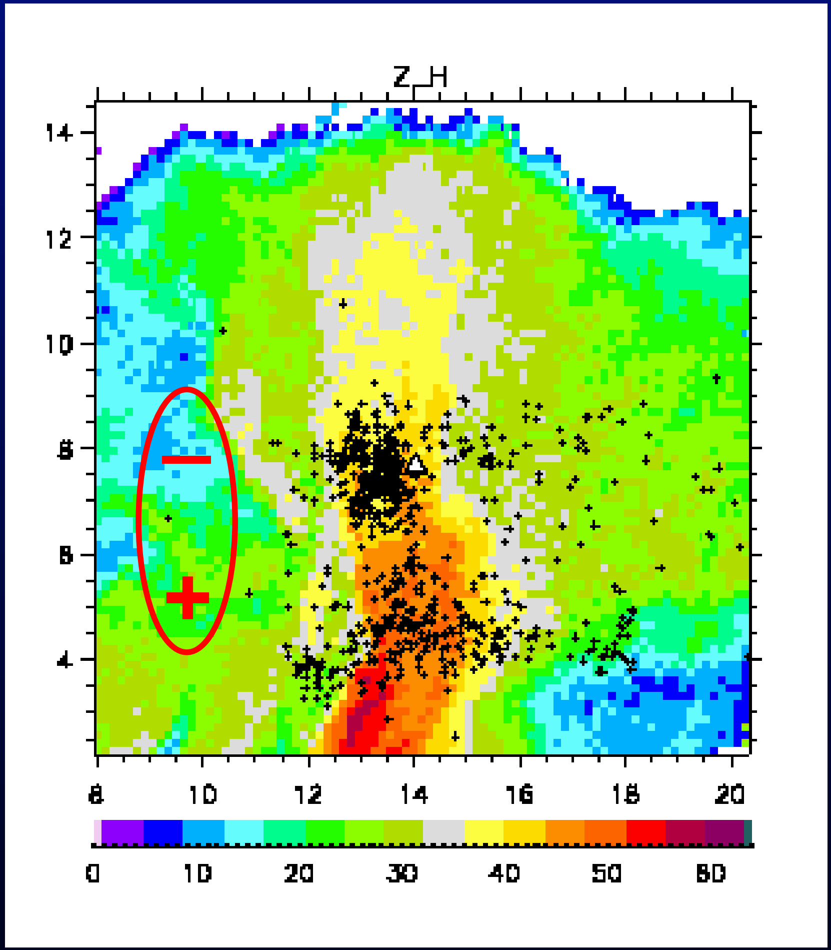
Flash Animation

Comparison of lightning with vertically scanning radar (Thomas et al., 2001)

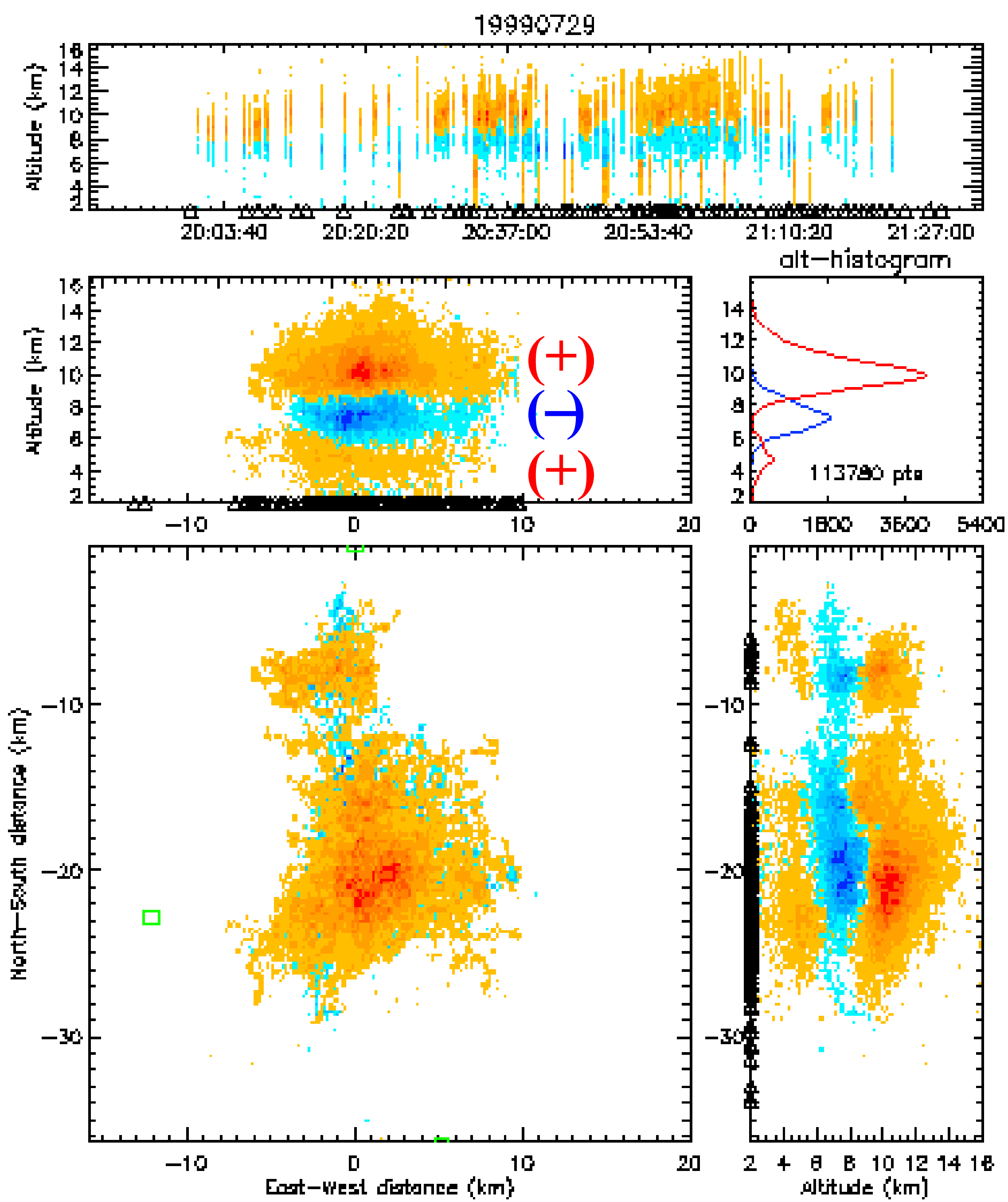
Intracloud (IC) flash



Cloud-to-ground (CG) flash



Classic tripolar charge structure, with dominant mid-level negative charge between upper and lower positive charges with precipitation (graupel/small hail) at storm mid-levels.

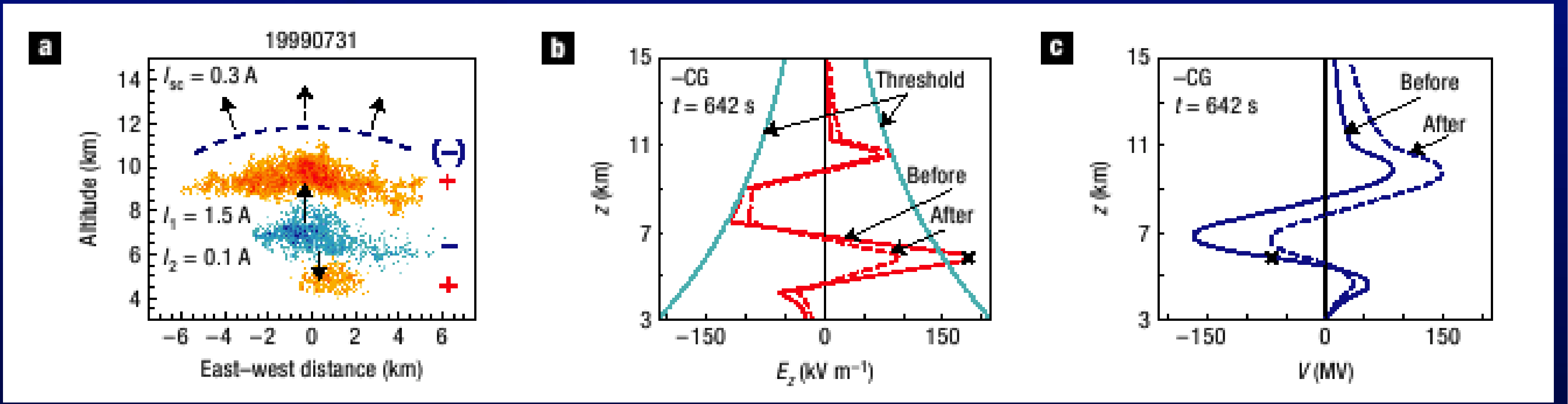


Storm charge structure inferred from lightning activity:

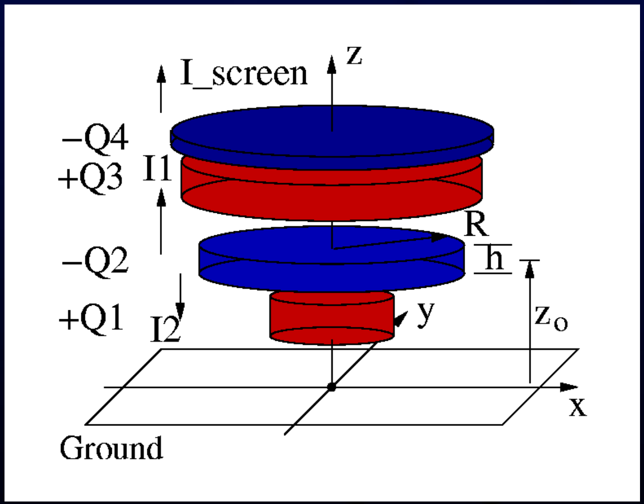
- 24 min of complete lightning activity in storm over Langmuir Laboratory.
- Classic tri-polar charge structure
- Dominant mid-level negative charge (blue)
- Upper and lower positive charge regions (orange)
- Parallel plate-like charge structure (horizontally extensive)

(Not sensed: Screening charges at upper and lateral cloud boundaries)

Lightning-inferred electric field and potential profiles in a small isolated storm, before and after a cloud-to-ground (CG) lightning discharge.



Cylindrical charge model



- Storm charges and charging currents estimated from lightning flashing rates and assumed breakdown threshold (panel b).
- Lightning assumed to occur when E exceeds runaway electron threshold value (maximum observed value in storms).
- ~200 MV potential difference between storm charge centers.

Energetic electron avalanche in strong electric field regions (J. Dwyer, initiated by a single 1 MeV seed electron)

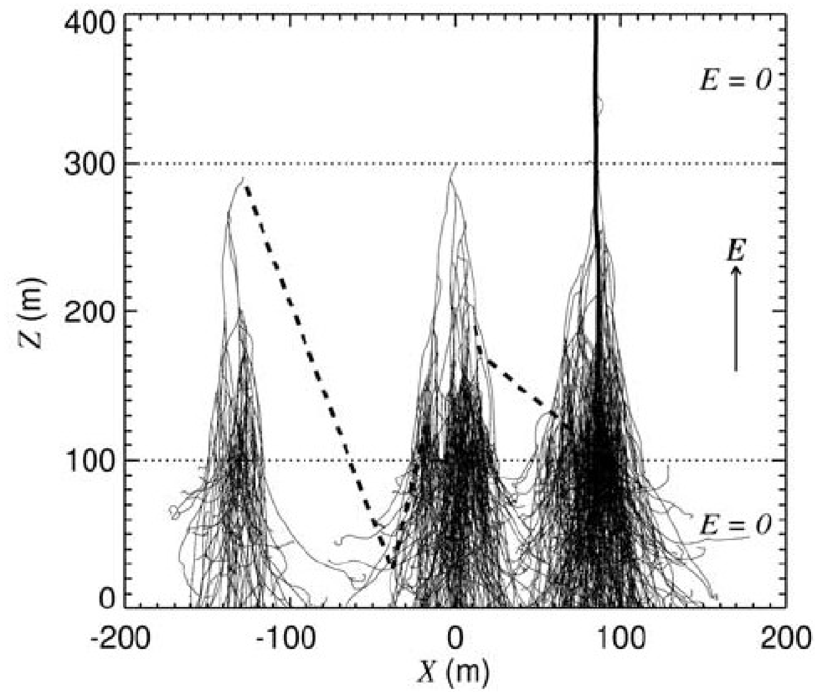
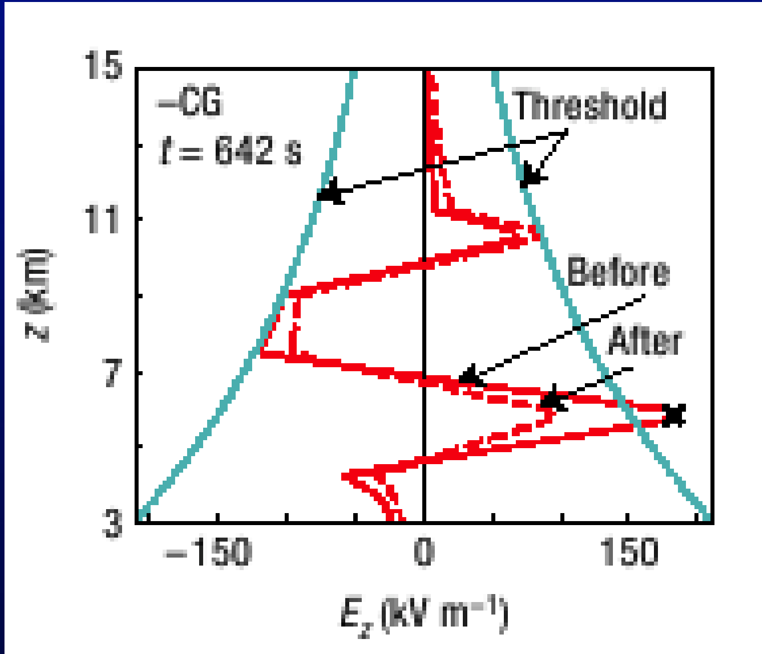


Figure 1. Partial results of the Monte Carlo simulation showing the runaway breakdown of air. The light tracks are the runaway electrons, the dashed lines are the gamma-rays and the dark track is a positron. The entire avalanche is initiated by one, 1 MeV, seed electron injected at the top center of the volume. The horizontal dotted lines show the boundaries of the electric field volume (E = 1000 kV/m). For clarity, only a small fraction of the runaway electrons and gamma-rays produced by the avalanche are plotted. The avalanches on the left and right illustrate the gamma-ray feedback and positron feedback mechanisms, respectively.



- Upward avalanches above main negative charge region (IC flashes); downward avalanches below negative charge region (–CG flashes).
- Avalanches will be field limiting (dissipative). Would they also be able to initiate lightning?
- Strong positive feedback from reverse propagation of gamma rays and positrons – horizontally broadening the discharge.

J.R. Dwyer, A fundamental limit on electric Fields in air, Geophys. Res. Letts., 2003

Enhanced VHF geomagnetic synchrotron radiation from accelerated electrons/positrons

S. Buitink et al., Amplified radio emission from cosmic ray air showers in thunderstorms, Astron. & Astrophys., 2007

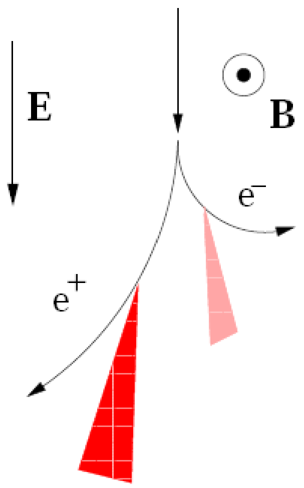
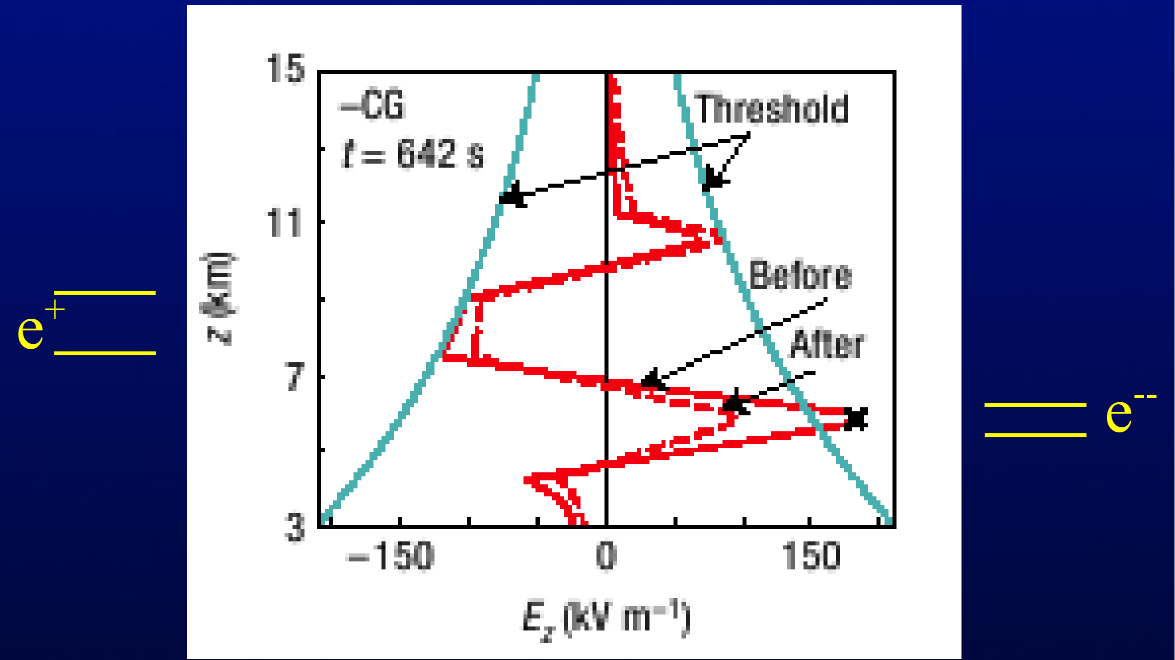
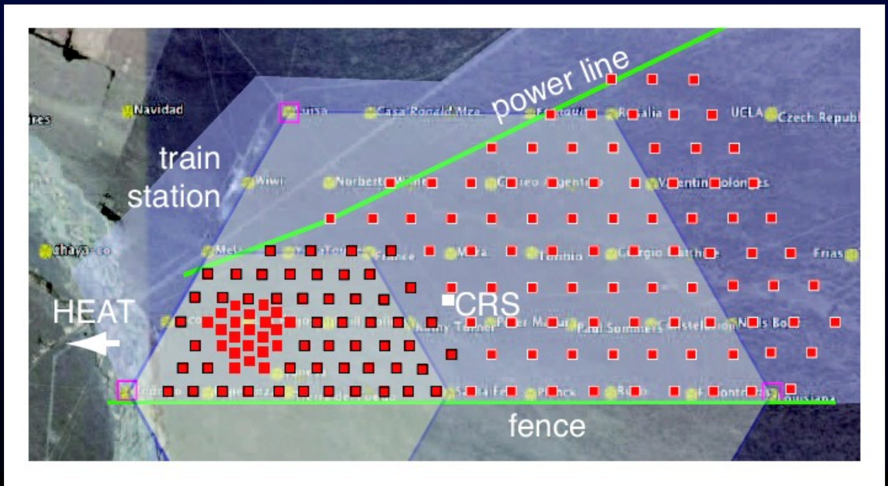


Fig. 2. The electrons and positrons make curved trajectories in the magnetic field. Under influence of a downward directed electric field, the positrons (electrons) are accelerated (decelerated). The asymmetry in the trajectories will be reflected in the radio emission.



- VHF radiation being studied with the Auger Engineering Radio Array (AERA) in Argentina, and by LOFAR and LOPES in Europe.
- AERA will be an area of concentration for the LMA studies – will detect lower energy cosmic rays.

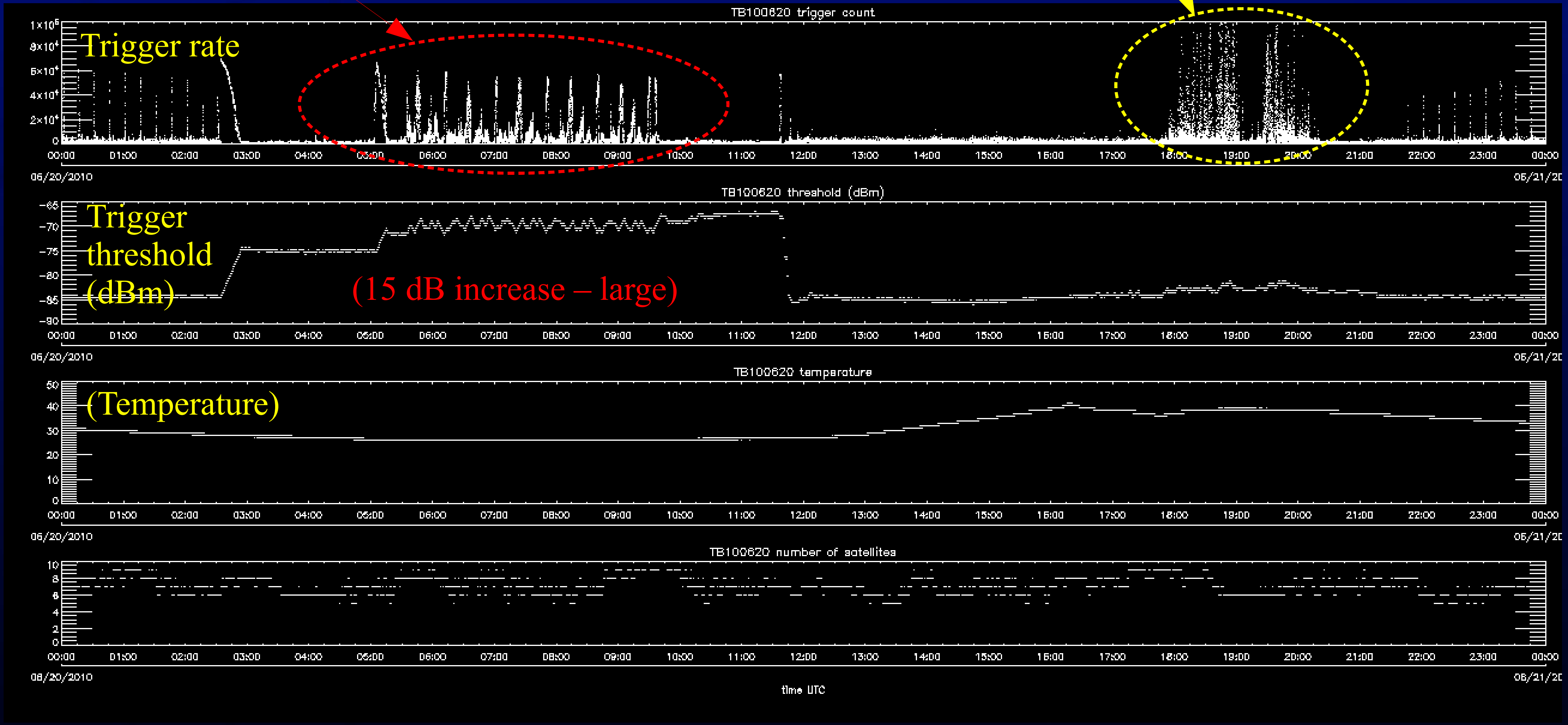


Two-Station Observations

Raw data from station B: Man-made and lightning- produced signals

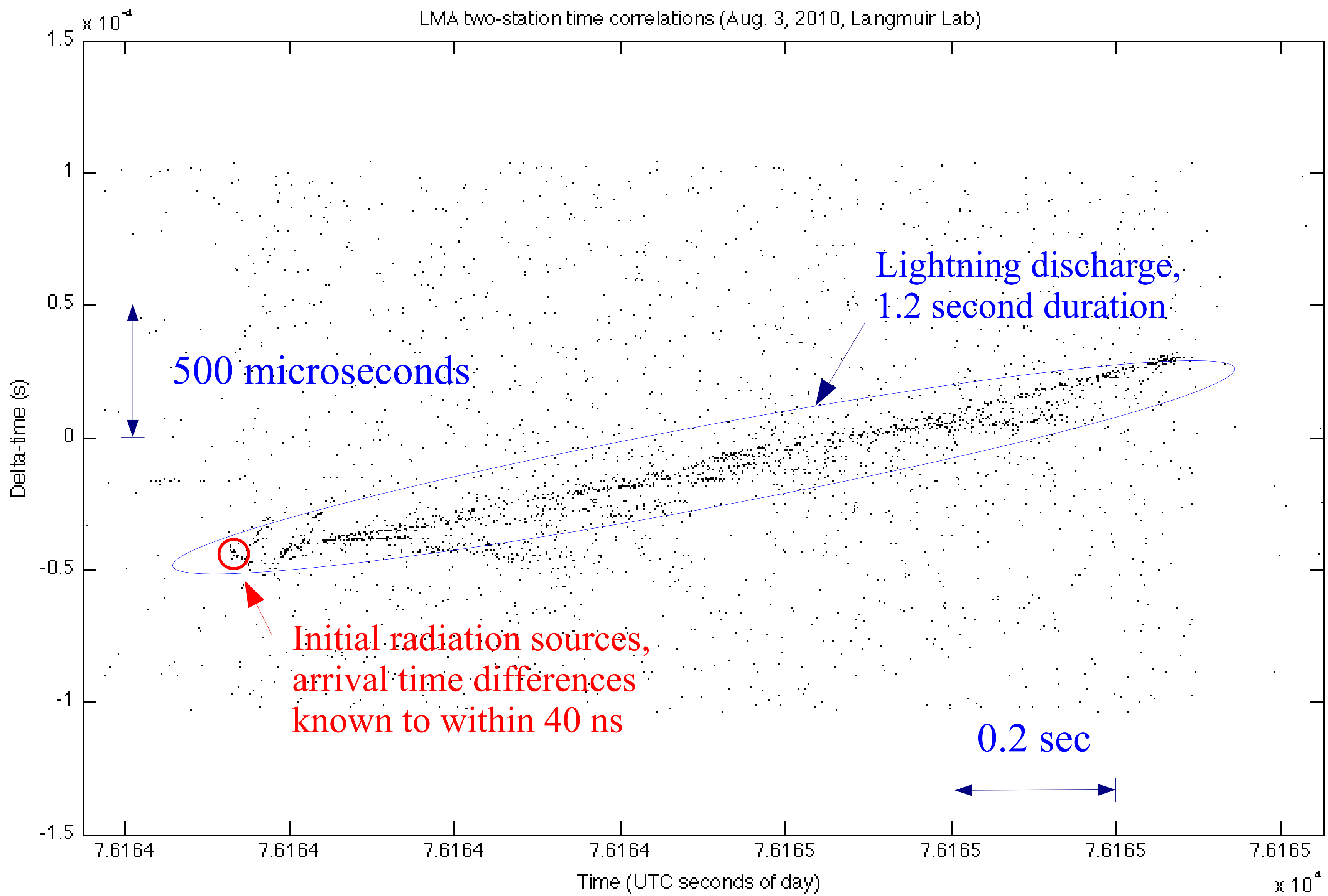
Local radio frequency interference (RFI) from Fluorescence Telescopes

Lightning signals from somewhere over/around Pierre Auger

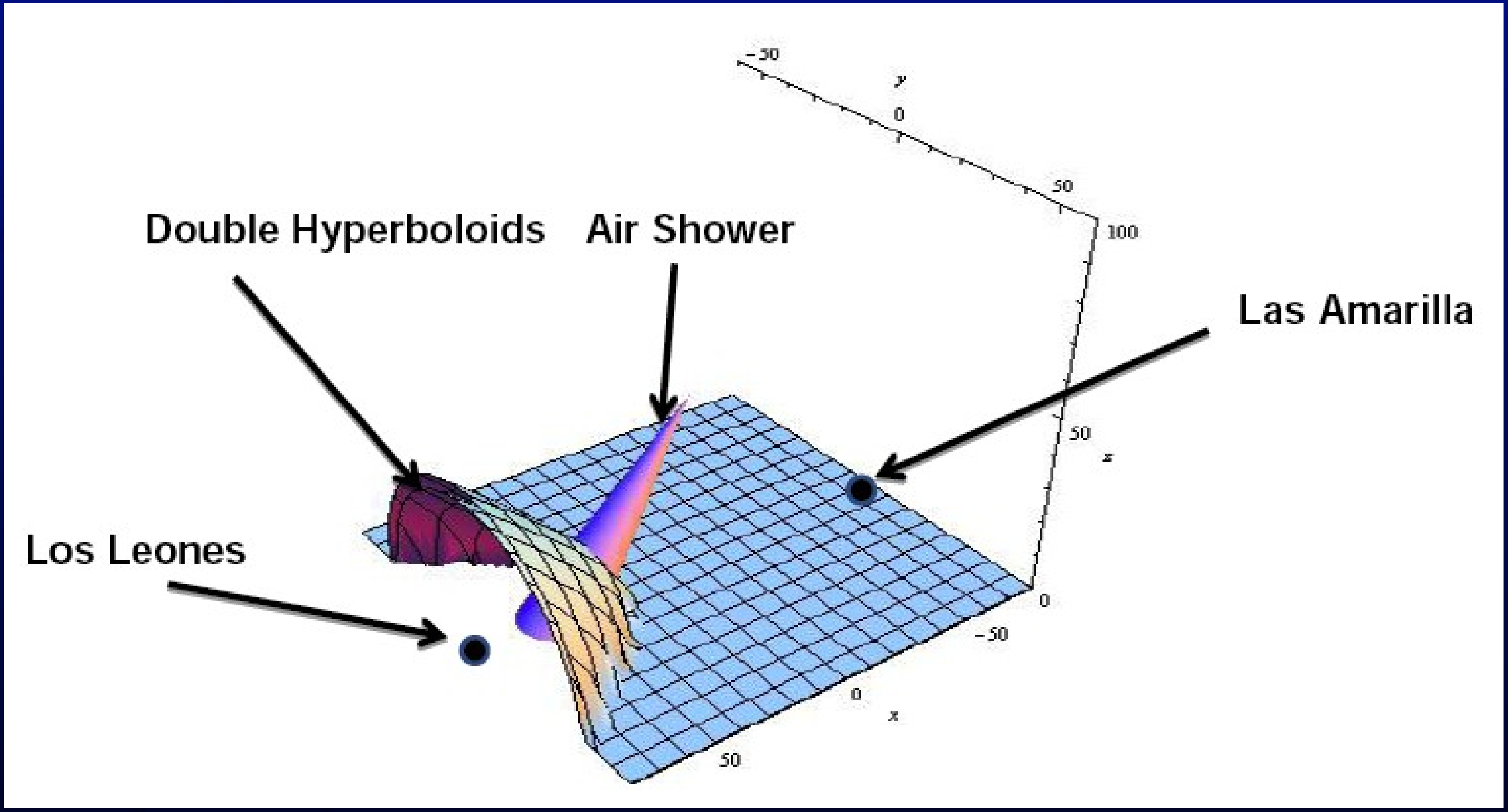


Can distinguish between lightning and local RFI noise by correlating signals from the two LMA stations

Time difference of arrival (TDOA), Station B – Station A

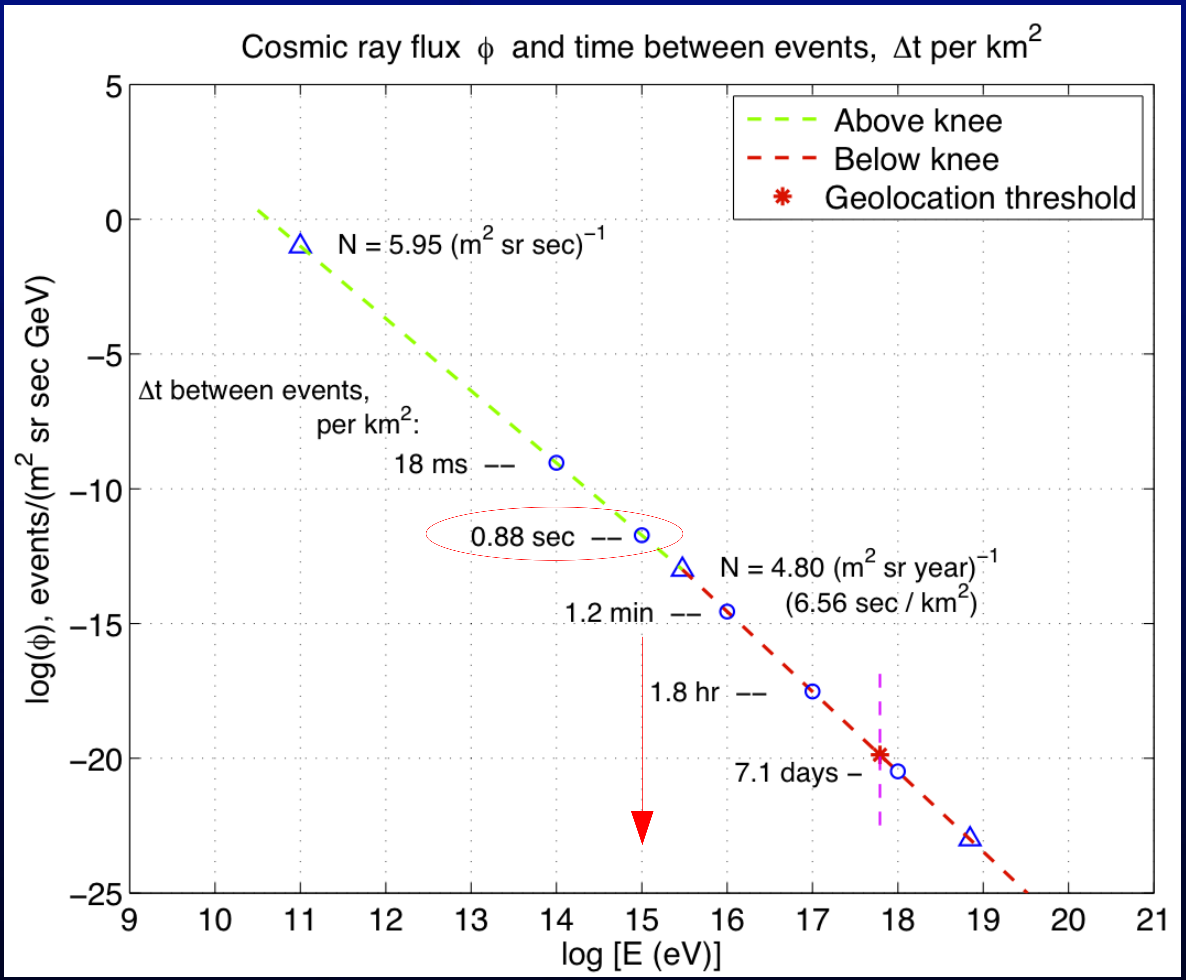


Time differences of arrival define hyperbolic surface of revolution about baseline between stations. Lightning would be initiated near intersection of air shower axis with the hyperboloid.



Basic Problem: Avalanche requires 1-2 ms or so to develop. This exceeds even the transit time across the array (60 km/3e8 m/s = 200 microsec). Need long (1-2 ms) time window to look for correlations. Accurate knowledge of initiation location does not help. Primarily time correlation, not space-time correlation.

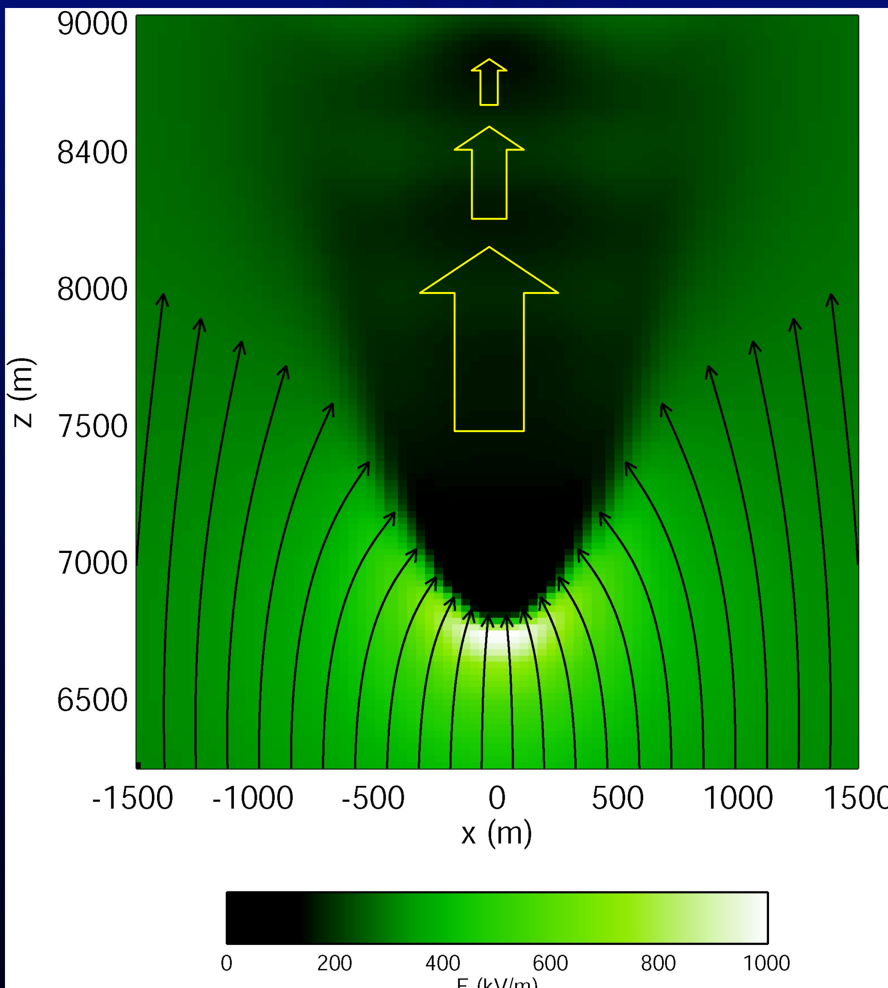
Cosmic ray flux versus primary energy

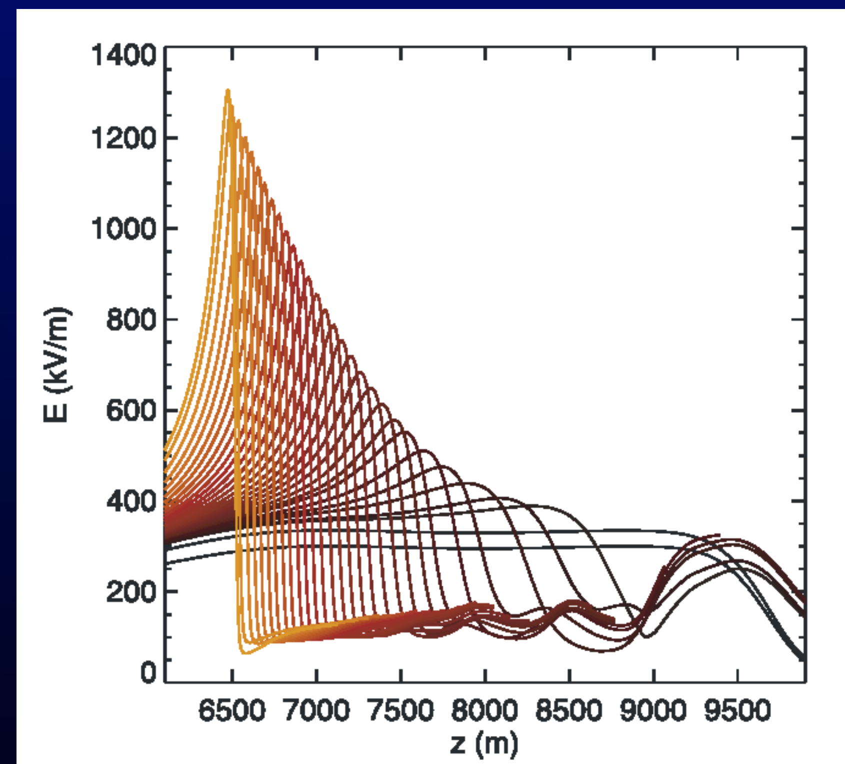


- Lightning rates are highly variable, but can reach one or more per second in large storms.
- Cosmic rays of about 10^15 eV would need to initiate individual discharges
- Incidence rate = ~1 per second per km^2
- Marginal in terms of numbers of seed electrons from individual cosmic rays.
- Background muon concentration much more prolific source of seed electrons (Dwyer, 2005).

Dwyer mechanism:

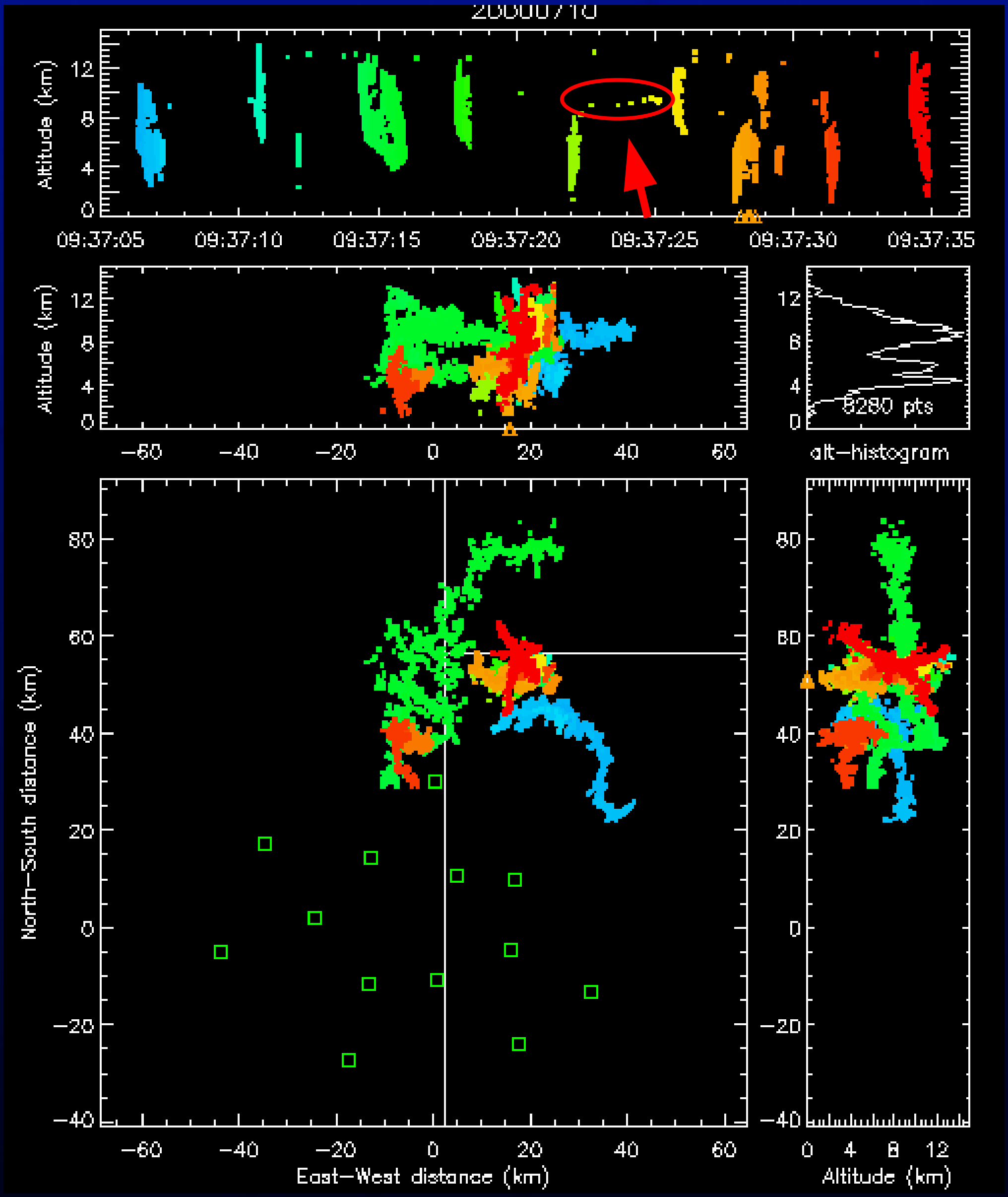
- Retrogressive downward cascade of upward avalanches above main (–) charge region.
- Substantially enhanced electric field as approaches mid-level negative charge.
- Local inhomogenieties lead to discharge initiation just above (–) charge region.
- Enhancement due to secondary electrons/ions becoming immobilized on cloud particles.
- Avalanche effects seen at ground??

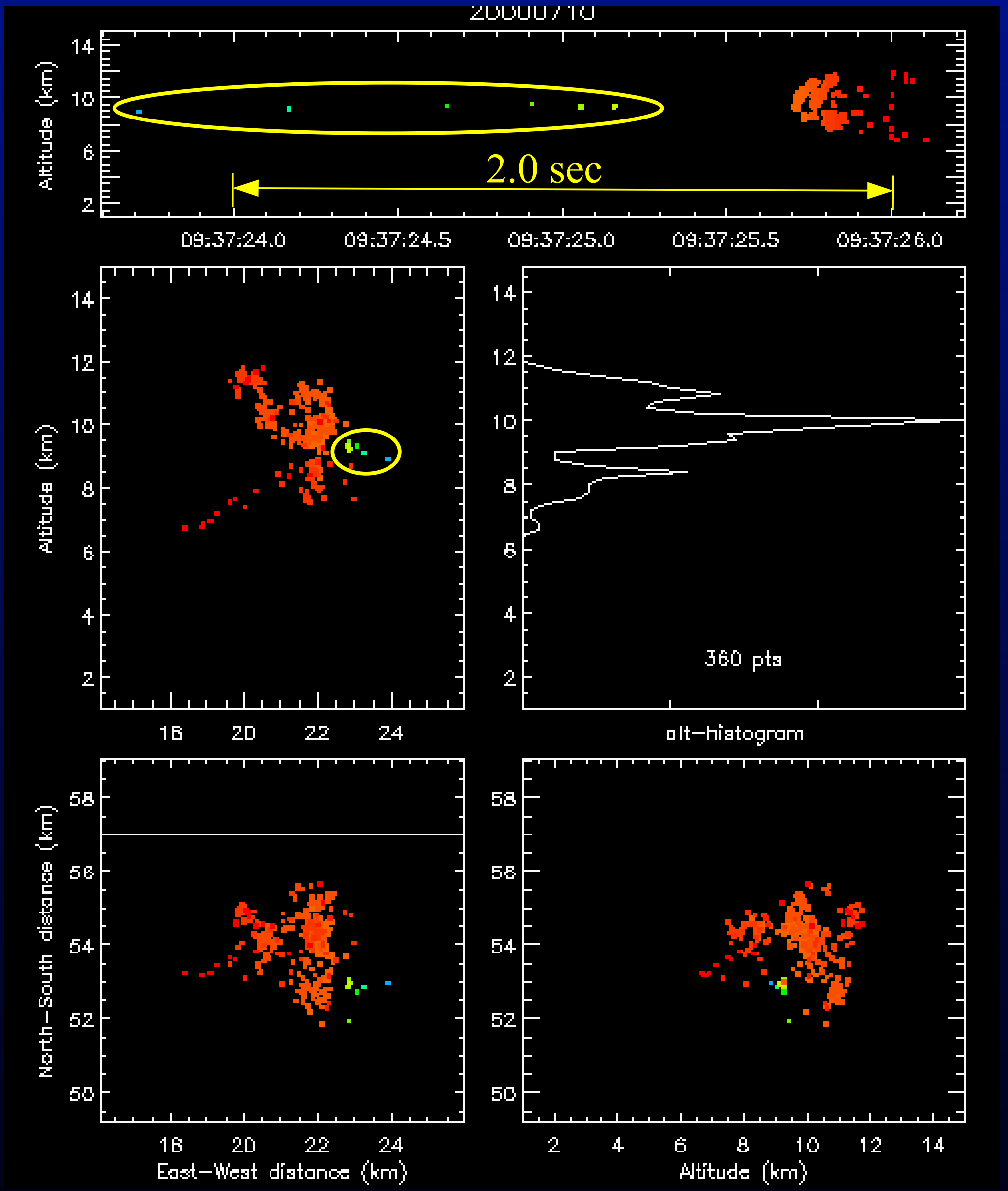




J.R. Dwyer, Initiation of lightning by runaway air breakdown, Geophys. Res. Letts., 2005

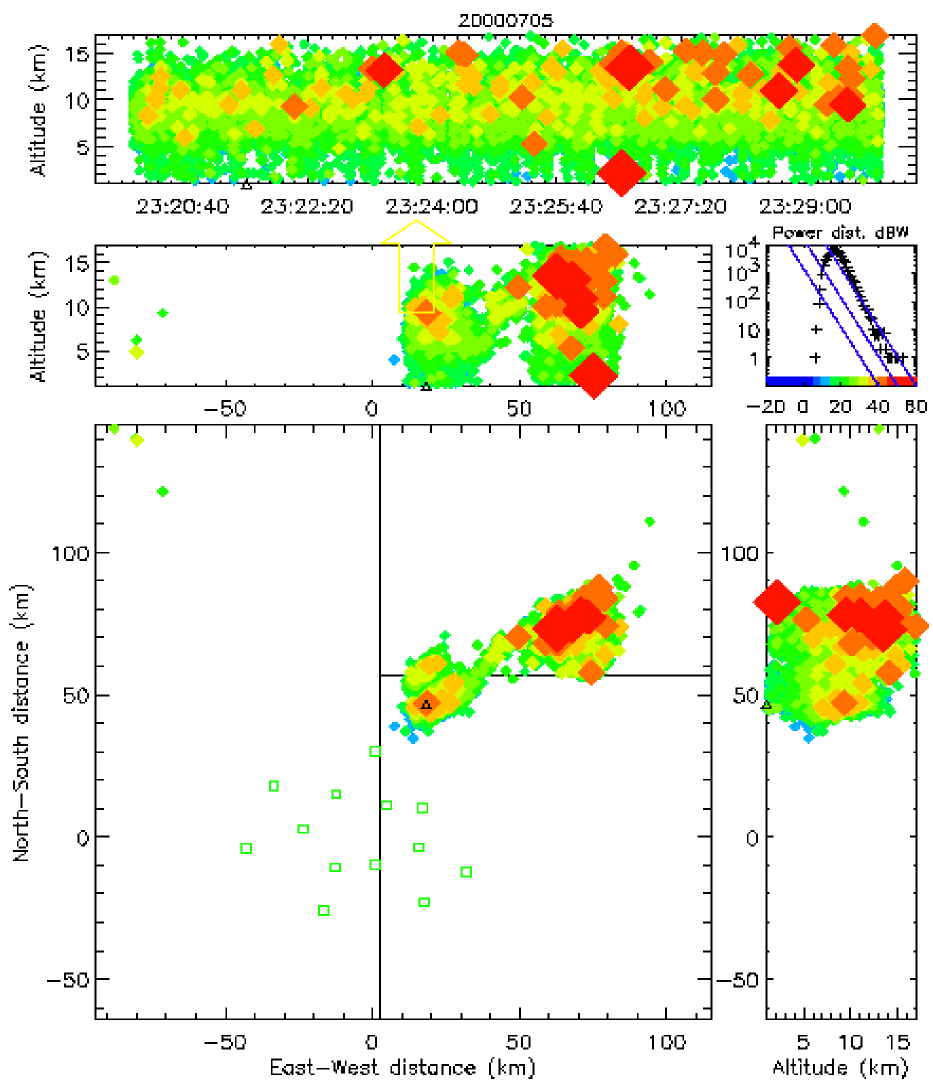
Precursor breakdown
(repeated unsuccessful avalanches)





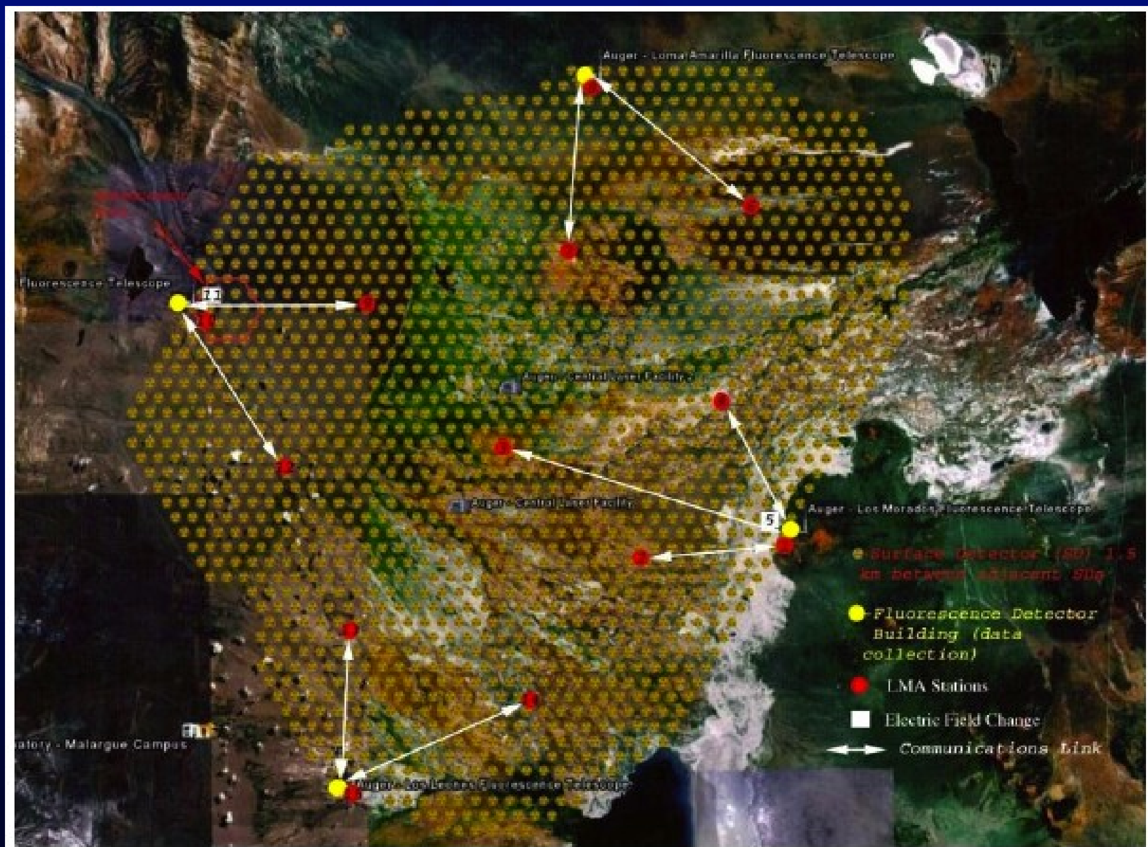
6 single-point radiation sources in 1.5 sec, ending 0.7 sec prior to full-fledged IC discharge. Precursors are commonly observed, probably not cosmic-ray initiated.

Energetic Narrow Bipolar Events (NBEs)



- Peak radiated source powers normally range from ~1 Watt to 10 kW (0 dBW to 40 dBW).
- The northeast storm was producing a number of highly energetic radiation events: 100 kW peak or more (50 dBW).
- Cause of these events is unknown.
- Are NBEs produced by energetic cosmic rays??

Possible 13-station LMA for Pierre Auger
(2 – 6 stations first)

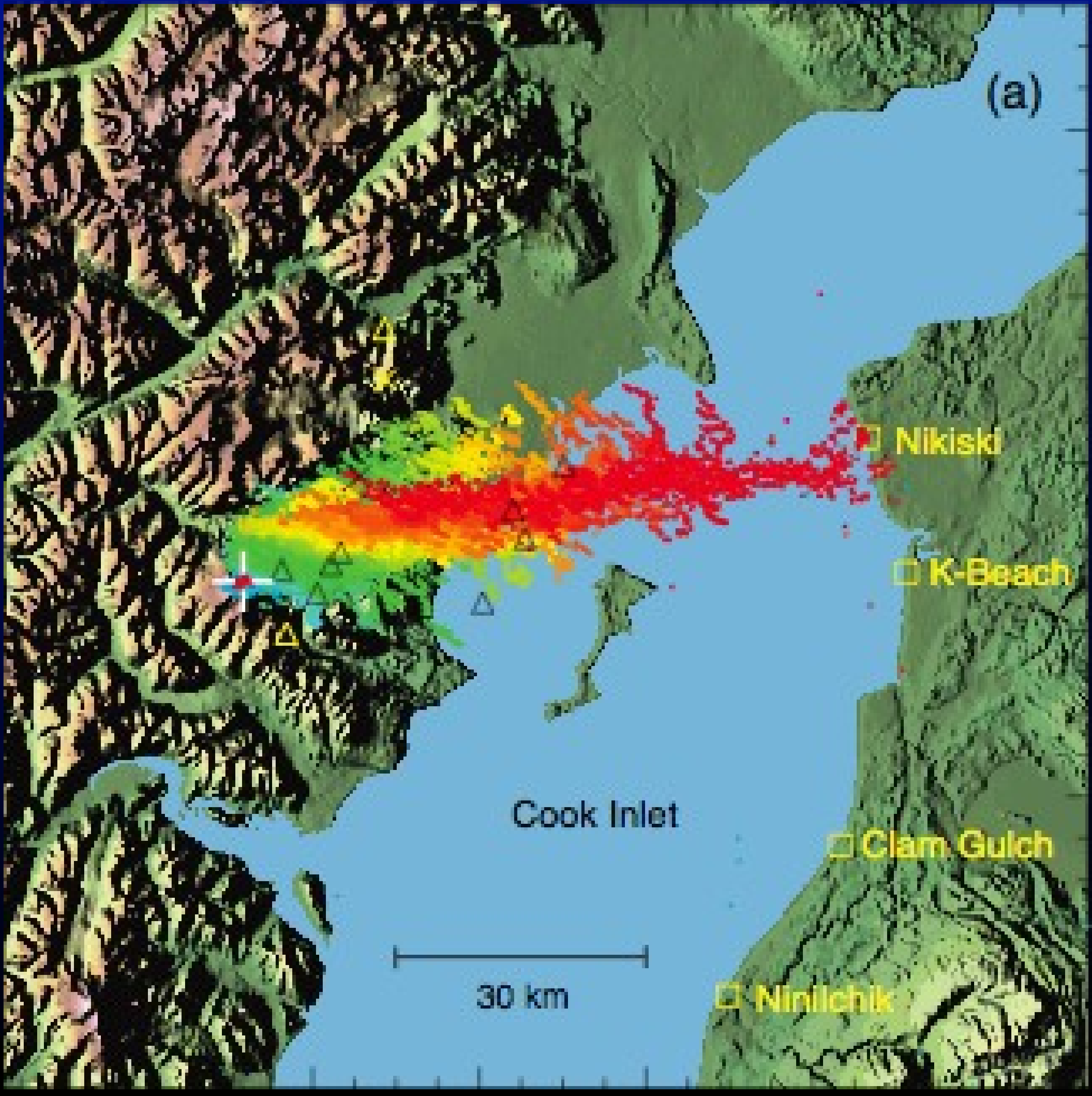


Solar-powered station

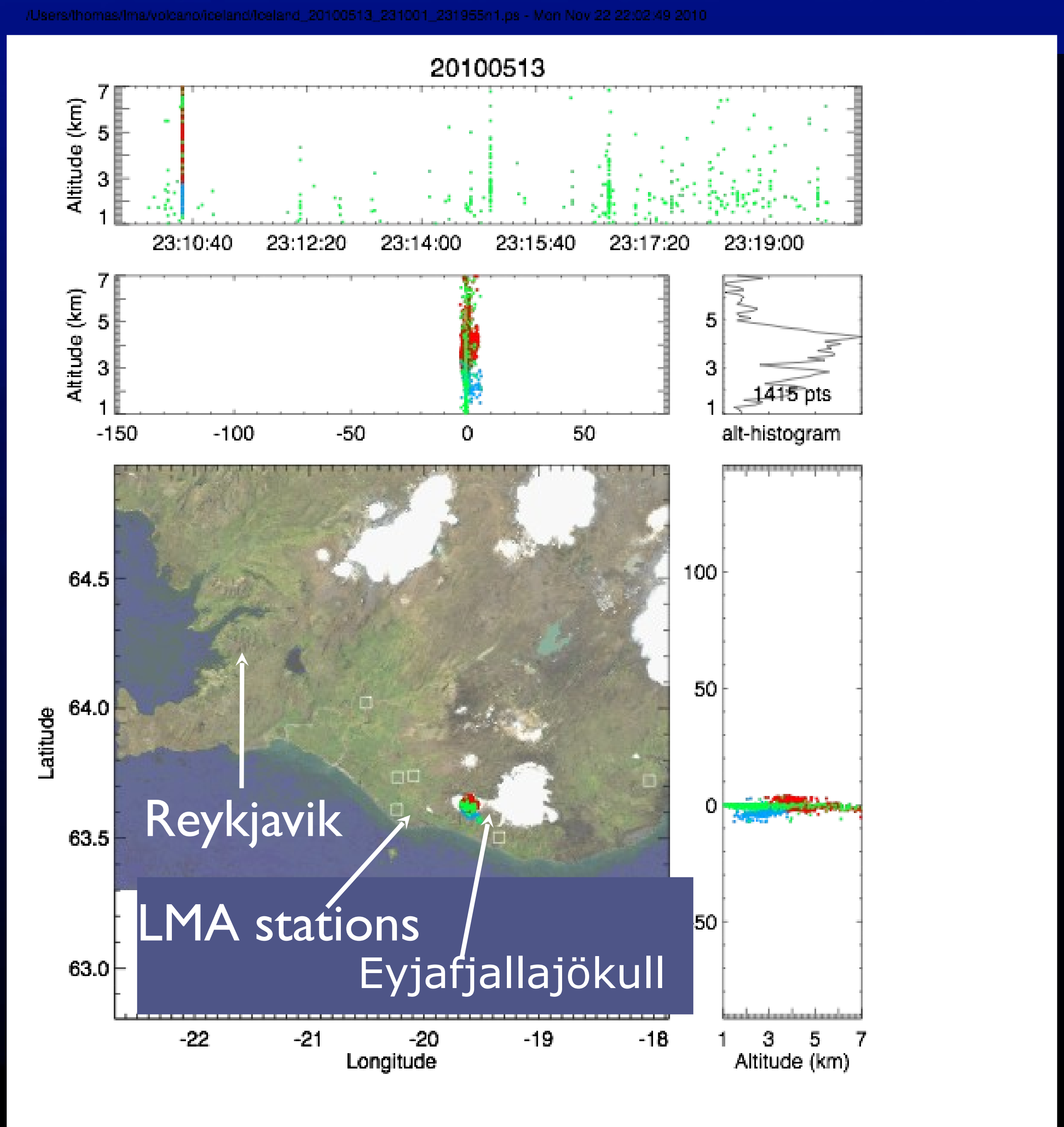
SUMMARY

- Lightning initiation part of study not easy. May obtain uncertain or negative result.
- Still working out statistics.
- Expect a couple of geolocated ultra high energy CRs through electrically active storms per year.   If individual CRs have an effect on storms these should.
- Serendipity Expected!

Eruption of Redoubt Volcano, March-April 2009

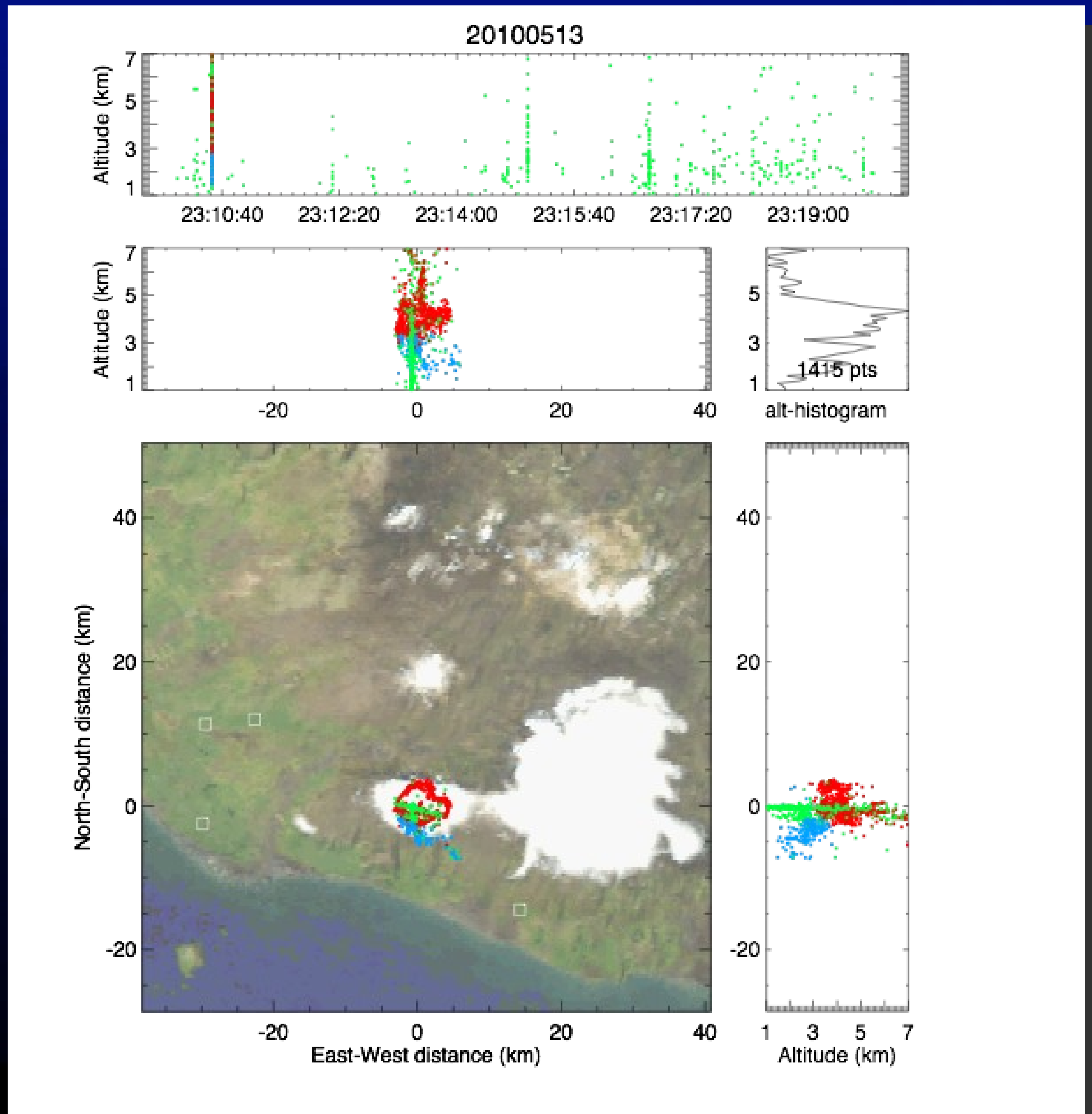


Eyjafjallajökull Eruption, Iceland 2010



Eyjafjallajökull Eruption, Iceland 2010

/Users/thomas/lma/volcano/iceland/iceland_20100513_231001_231955n2.ps - Mon Nov 22 22:06:23 2010



Eyjafjallajökull Eruption, Iceland 2010

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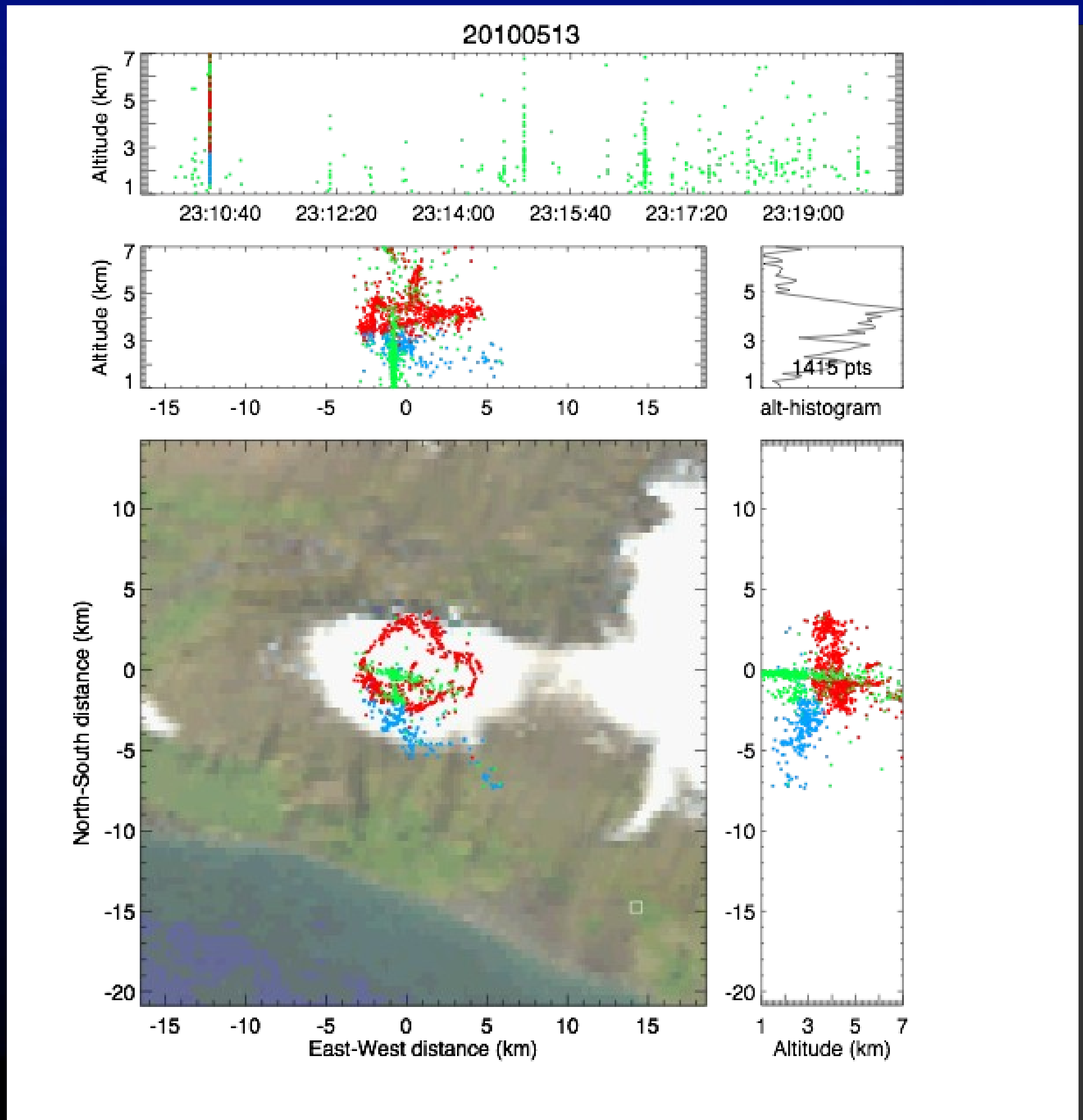
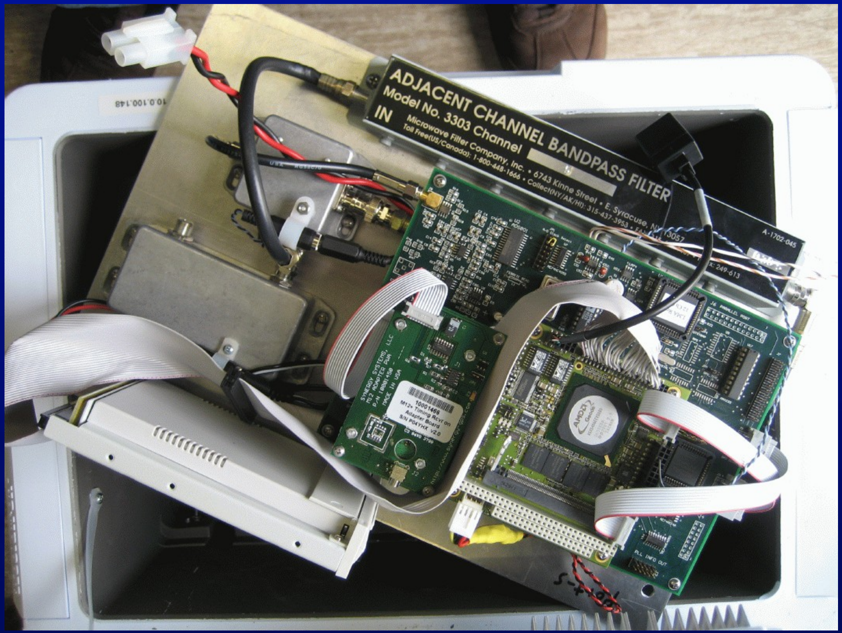


KASCADE Lightning Experiment
Summer, 2008

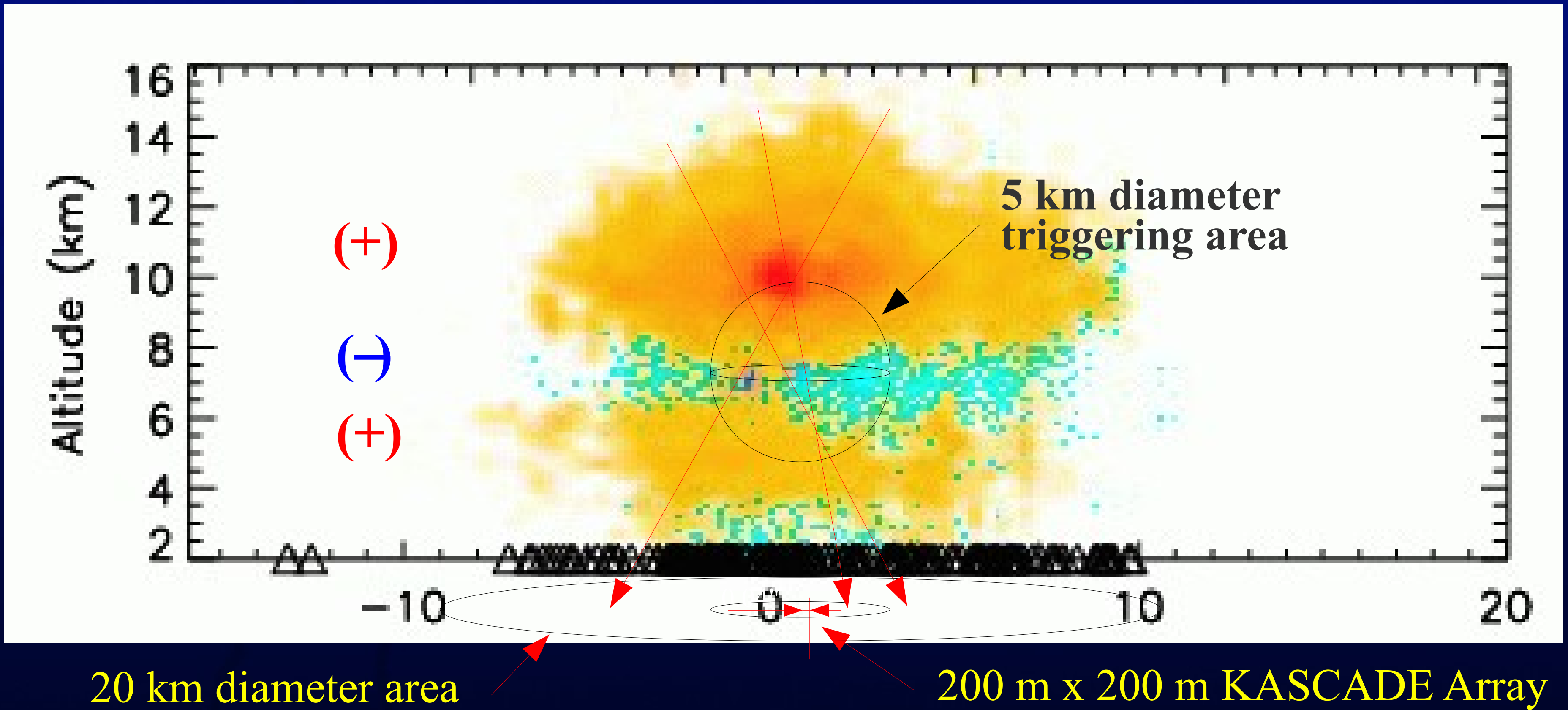
- Not attempting to image lightning in 3-D
- Instead, conduct a basic time-correlation experiment to start with.
- Measure electrostatic (‘slow’), radiation (‘fast’) electric field changes of lightning
- Single LMA station – peak VHF radiation event every 10 μ s (accurate to 40 ns)
- Look for time correlation of lightning initiation and cosmic ray event
- Do with ~1 microsecond time resolution

Electric field and field change sensors



LMA station
(U.S. TV Channel 5, 76–82 MHz)
–82 dBm sensitivity

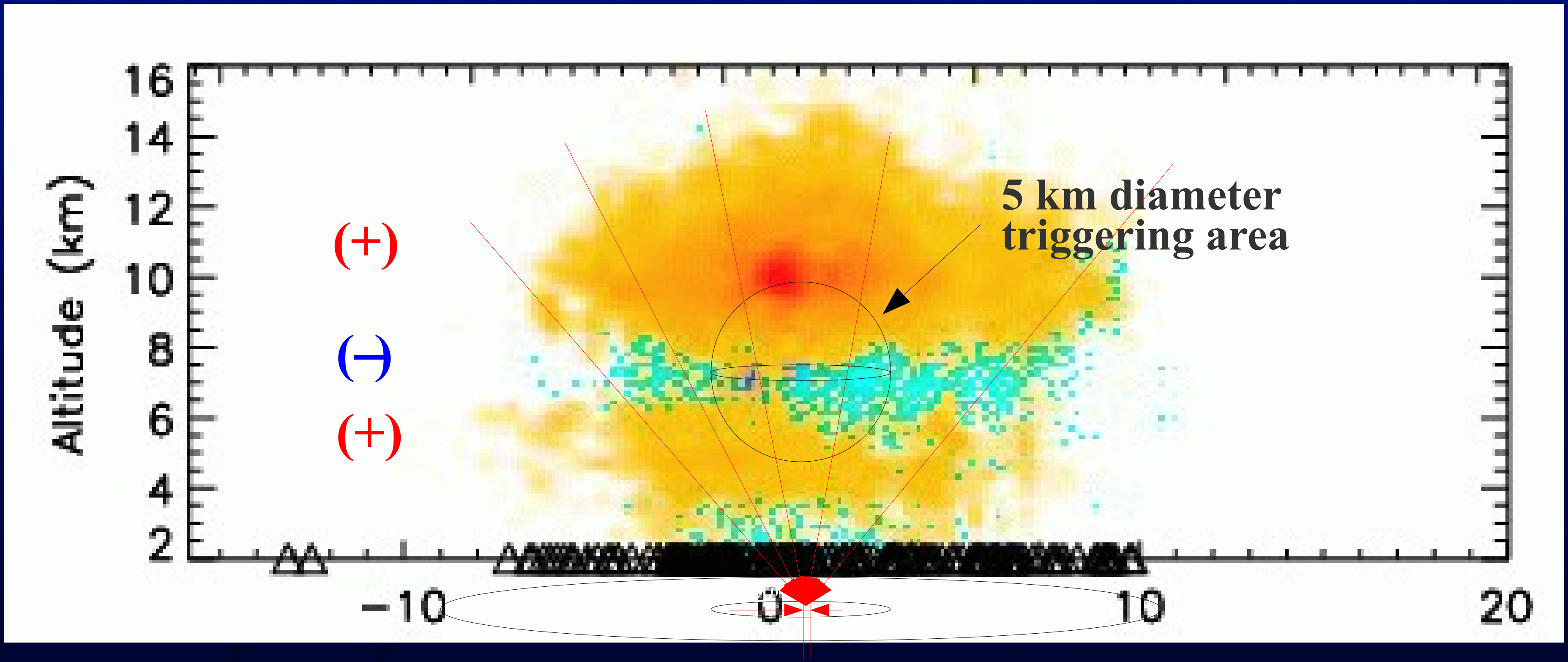
Probability of triggering cosmic ray hitting KASCADE



Prob ~ .04 km^2/300 km^2 ~ 1/10,000 (triggering cosmic ray hits ground in 20 km diameter area: 45 degree incidence)

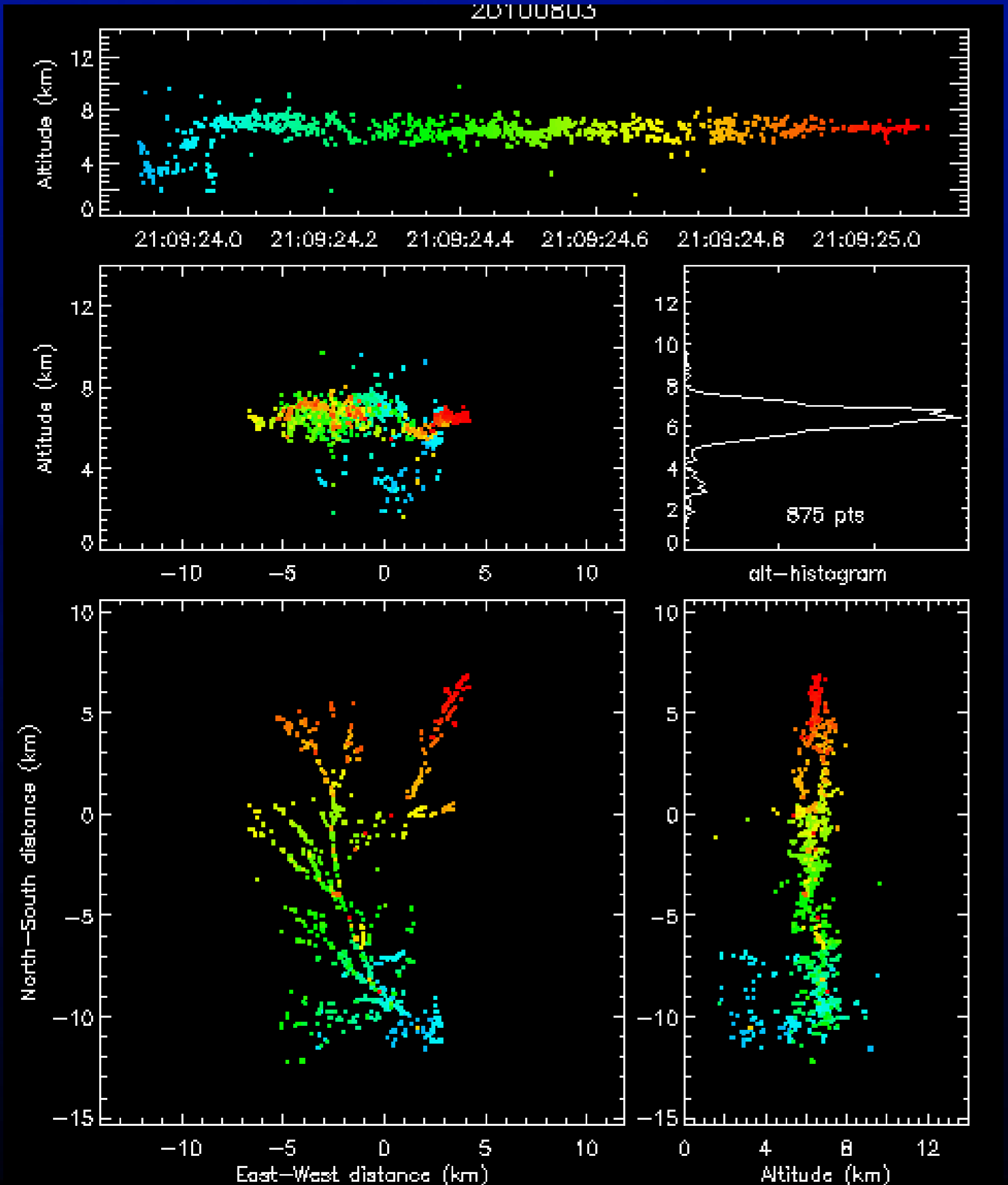
Prob ~ .04 km^2/20 km^2 ~ 1/500 (triggering cosmic ray hits ground in 5 km diameter area: vertical incidence)

Another way of looking at it:



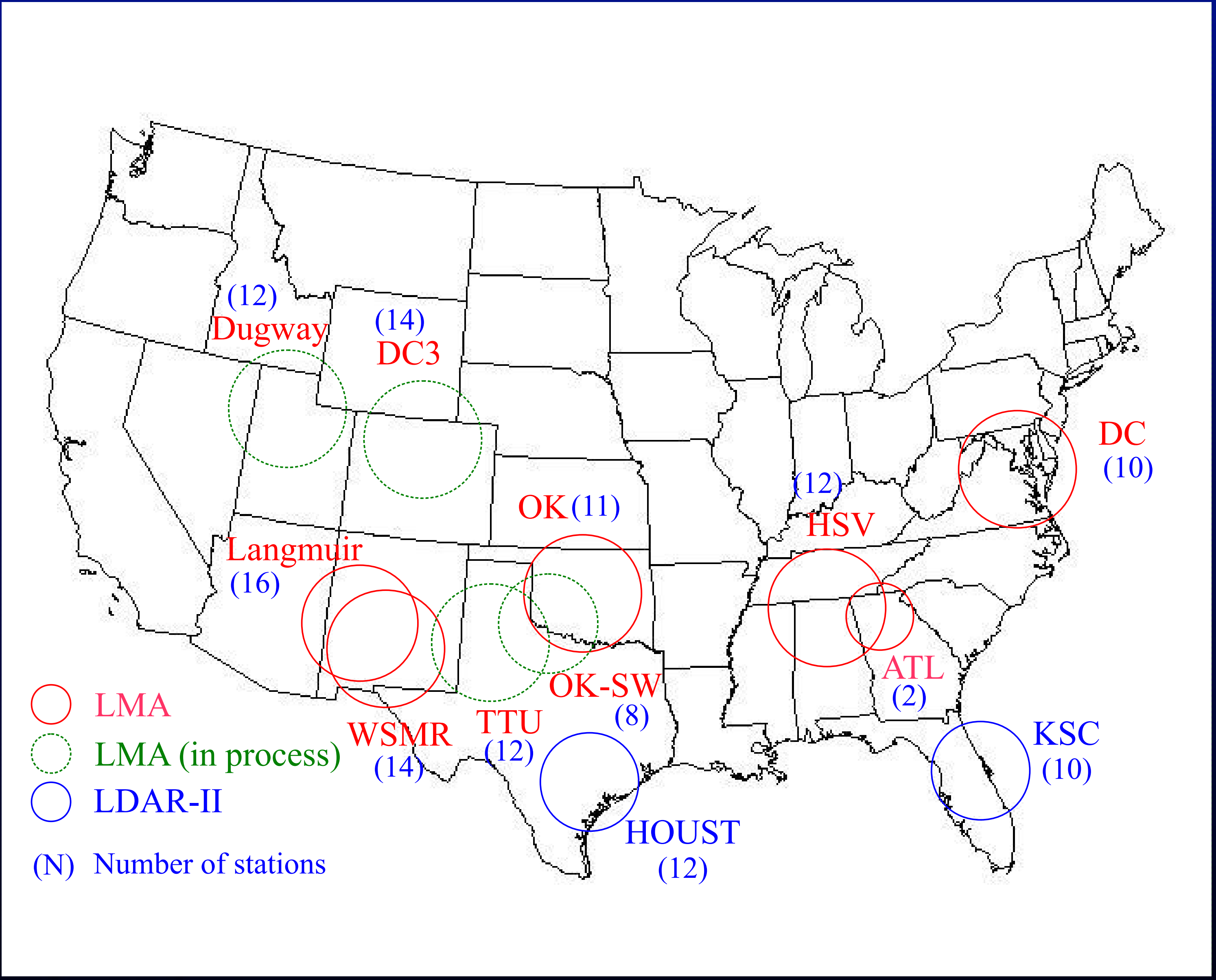
KASCADE array triggers 4.5 times/sec. For storms over the network, most of these cosmic rays will have passed through the storm. Sampling the storm with >10^14 eV cosmic rays ~4 times/second.

September 2007 storm: Lightning field change in same second as full array LOPES trigger for 2 out of ~11 flashes (!)

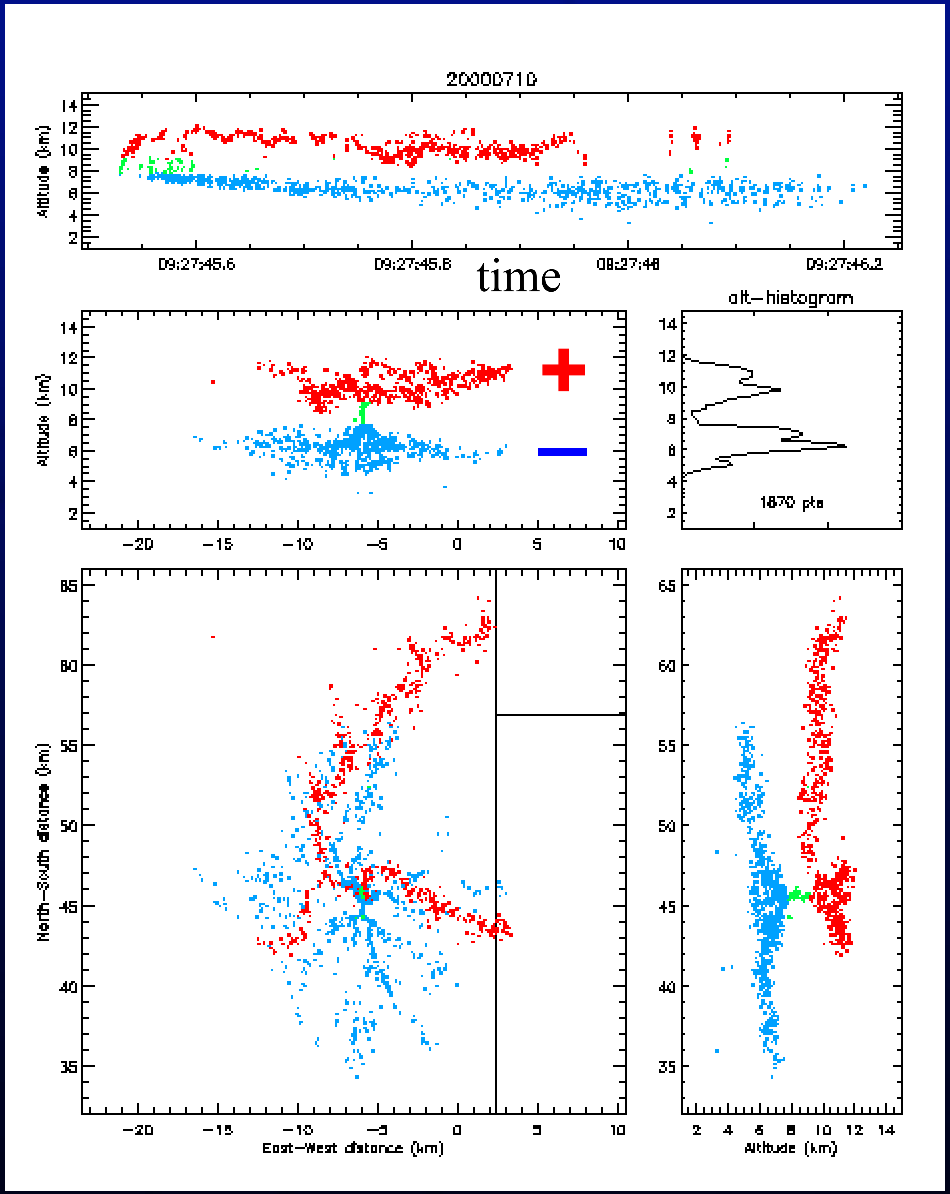


20100803
Altitude (km)
21:09:24.0
21:09:24.2
21:09:24.4
21:09:24.6
21:09:24.8
21:09:25.0
875 pts
alt-histogram
North-South distance (km)
East-West distance (km)
Altitude (km)
New Mexico Tech

VHF Time-Of-Arrival Total Lightning Mapping Systems



Polarity of intracloud lightning flashes



- Determined from asymmetries in the flash development .
- Initial VHF sources develop upward with time, away from negative storm charge into upper positive storm charge.
- Delayed onset of radiation sources in negative charge region.

Energetic Narrow Bipolar Event
~10 microsecond duration