In Situ Measurements to Investigate Transient Luminous Events Above Thunderstorms

Jeremy N. Thomas

USGS Golden, CO

NOAA SEC Seminar July 12, 2007

Acknowledgments

•Bob Holzworth, Michael McCarthy, Erin Lay, Tim Chinowsky, and John Chin (University of Washington, Seattle)

•Mike Taylor, Dominique Pautet, and Matt Bailey (Utah State University)

•Osmar Pinto, Jr. and other members of the ELAT team (INPE, Brazil)

•Natalia Solorzano (Digipen Institute of Technology)

•Ben Barnum (Johns Hopkins Applied Physics Laboratory)

•NSF USA / FAPESP Brazil

Outline

I. Transient Luminous Events (TLEs): What are sprites, jets, and elves?

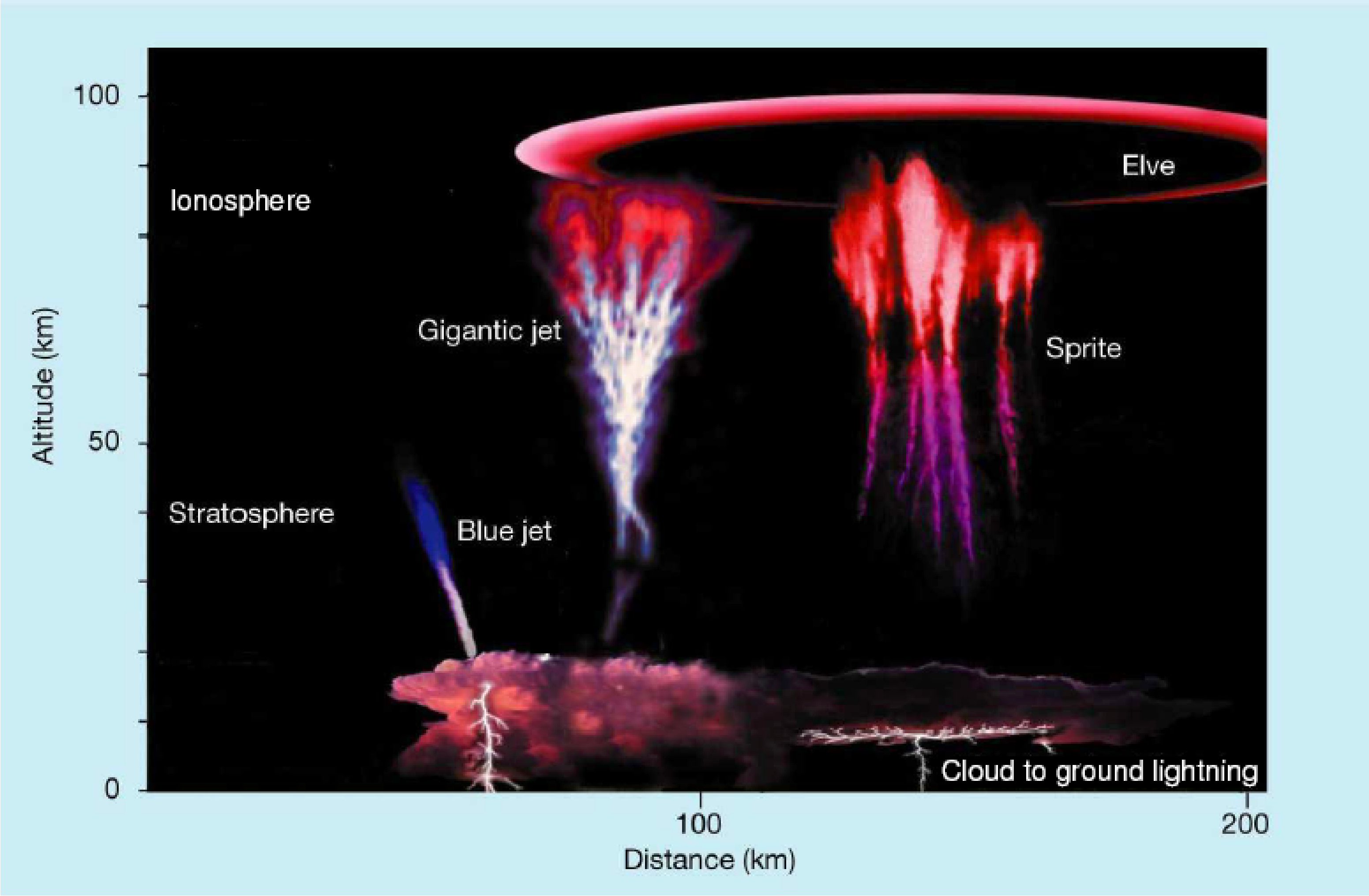
II. Why do we study these high altitude optical discharges?

III. What causes sprites, jets, and elves?

IV. In situ balloon and rocket measurements above thunderstorms

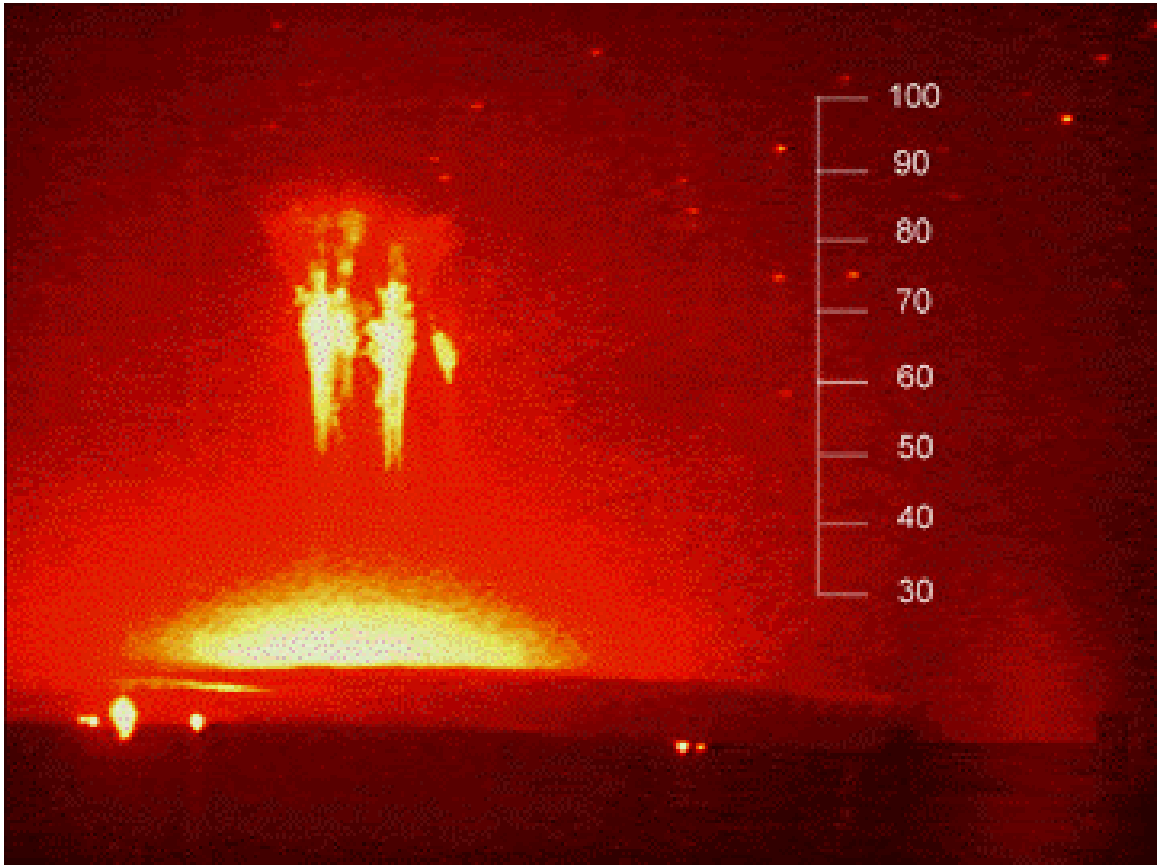
V. Electric fields at sprite and elve altitudes

Lightning-Related Middle Atmospheric Transient Luminous Events



[Lyons et al., BAMS, 84, 445, 2003; Pasko, Nature, 423, 927, 2003]

Sprite Properties



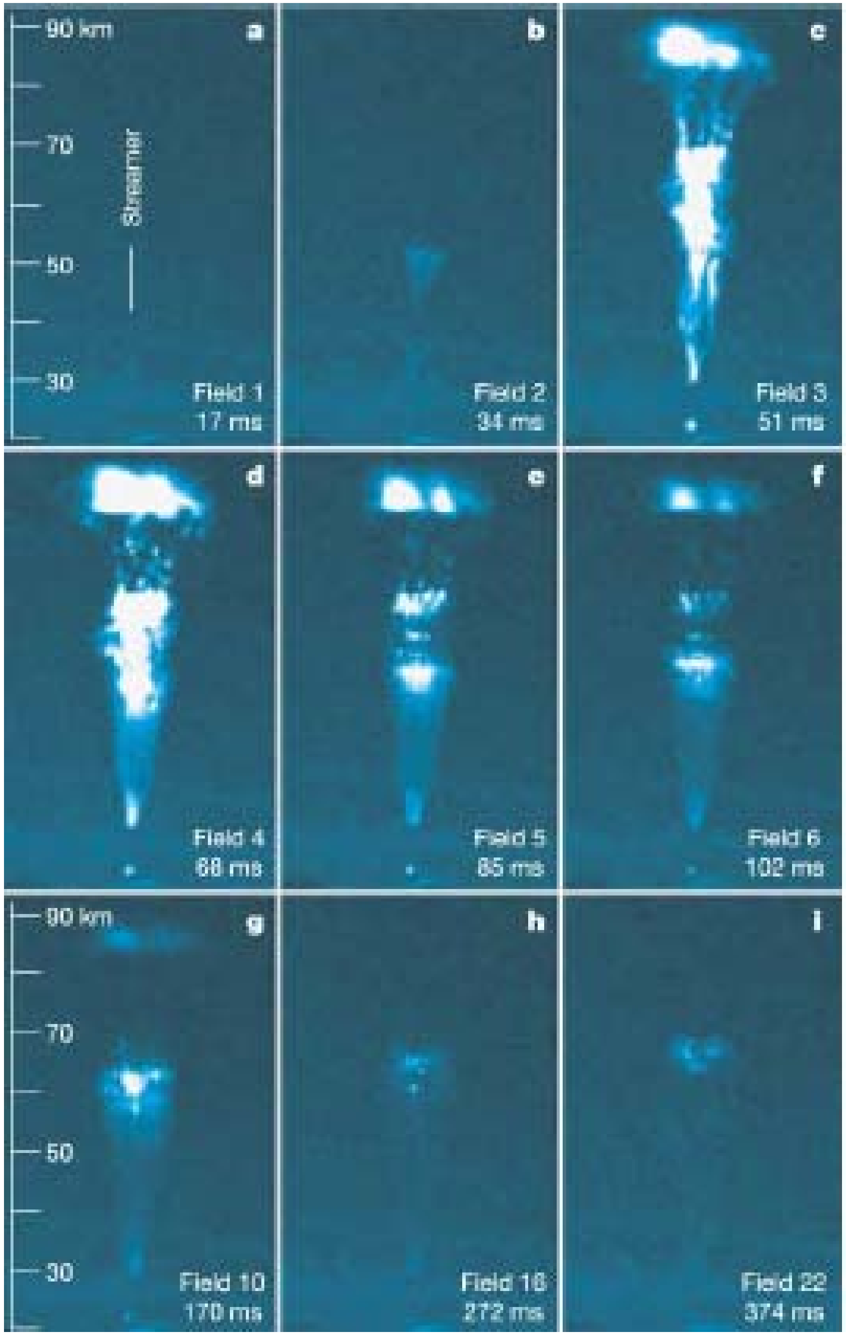
Ground Based Sprite Image from Fort Collins, CO 1995 (Courtesy of the Geophysical Institute, the University of Alaska)

Sprites Captured By An Aircraft Over the Midwestern U.S. in 1994
(Courtesy of the Geophysical Institute, University of Alaska)

Sprite-Halo over Argentina Feb.23, 2006

What are Jets?

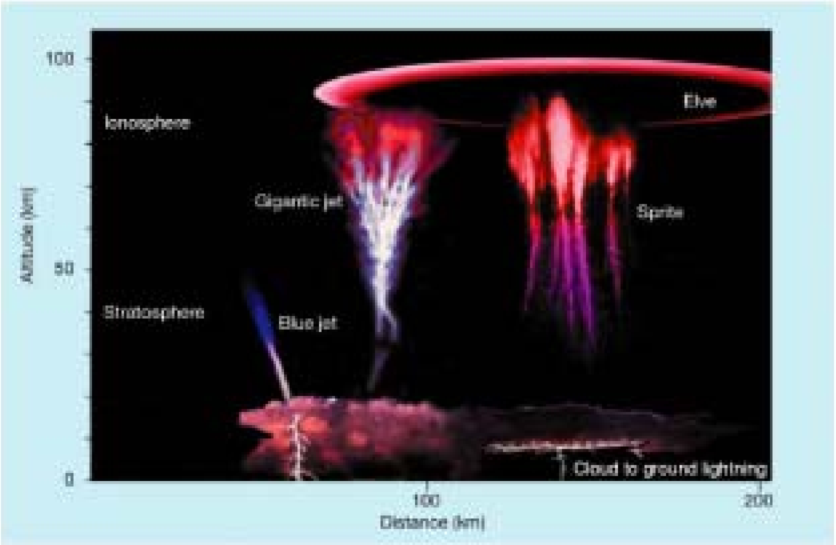
A gigantic jet reaching from the top of the thundercloud to the ionosphere over the South China Sea imaged from Taiwan (reproduced from Su et al. [2003]).



Jet Captured By An Aircraft Over the Midwestern U.S. in 1994
(Courtesy of the Geophysical Institute, University of Alaska)

What are Elves?

Lightning-Related Middle Atmospheric Transient Luminous Events



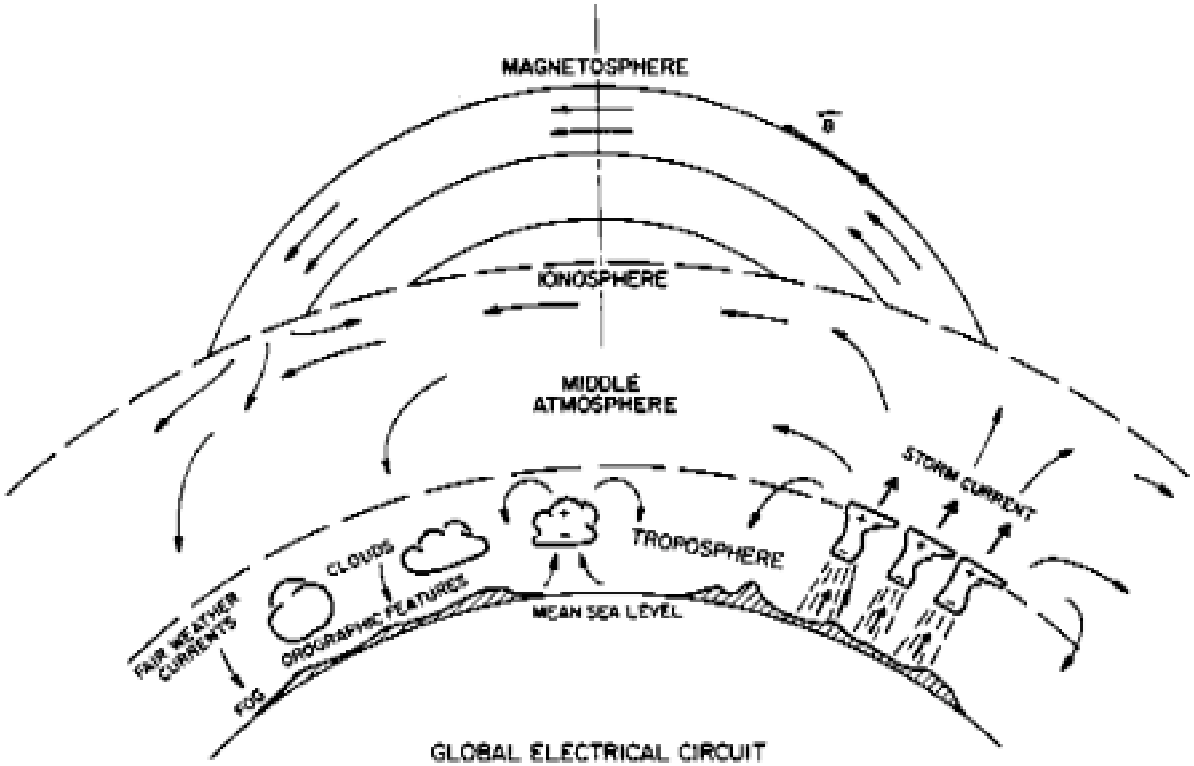
[Lyons et al., BAMS, 84, 445, 2003; Pasko, Nature, 423, 927, 2003]

An elve imaged over Europe in Nov. 1999 by M. J. Taylor and L. C. Gardner of Utah St. U.

Why Study High Altitude Discharges?

- Global electrodynamic circuit
- Energy transfer between lower and upper atmosphere
- Atmospheric chemistry (NOx)
- Perturbations of the ionosphere
- Terrestrial gamma ray flashes
- Aircraft/spacecraft safety
- Communications

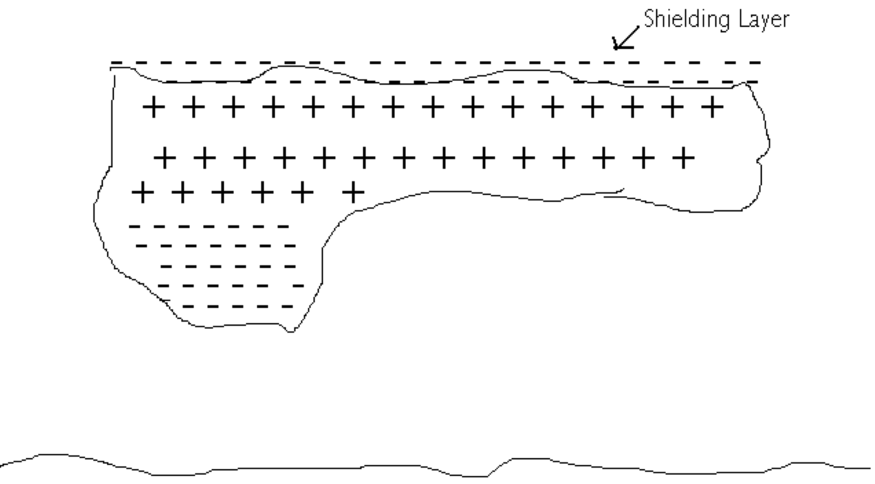
Why Study High Altitude Discharges?



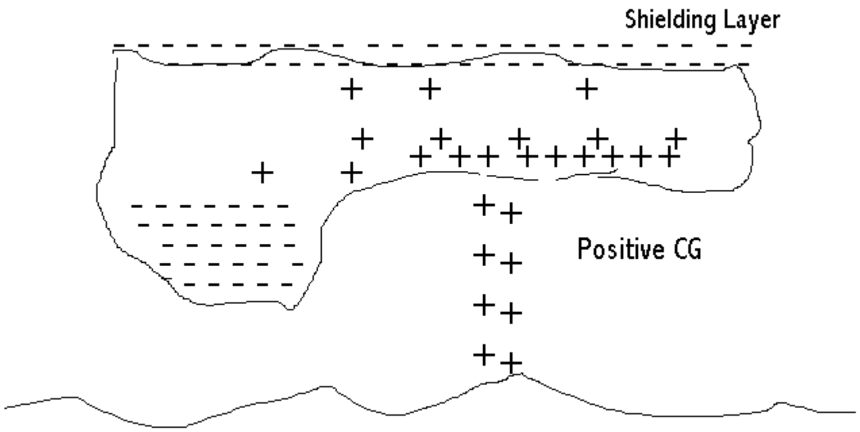
Adapted from Roble and Tzur, 1986

What causes Sprites?

The Quasi-static Electric Field Model

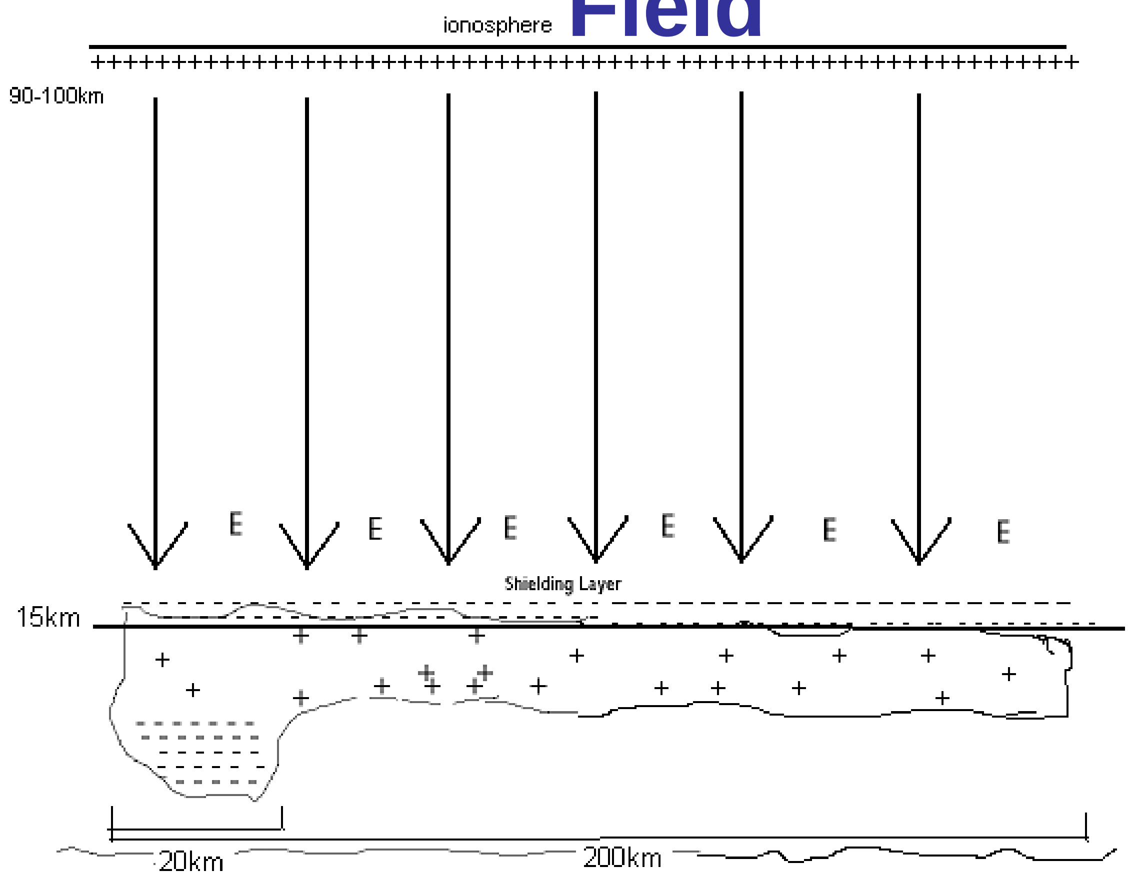


1. The cloud charges up before the lightning discharge inducing a negative shielding layer



2. The positive CG removes positive charge but the negative shielding layer remains over a much longer time scale

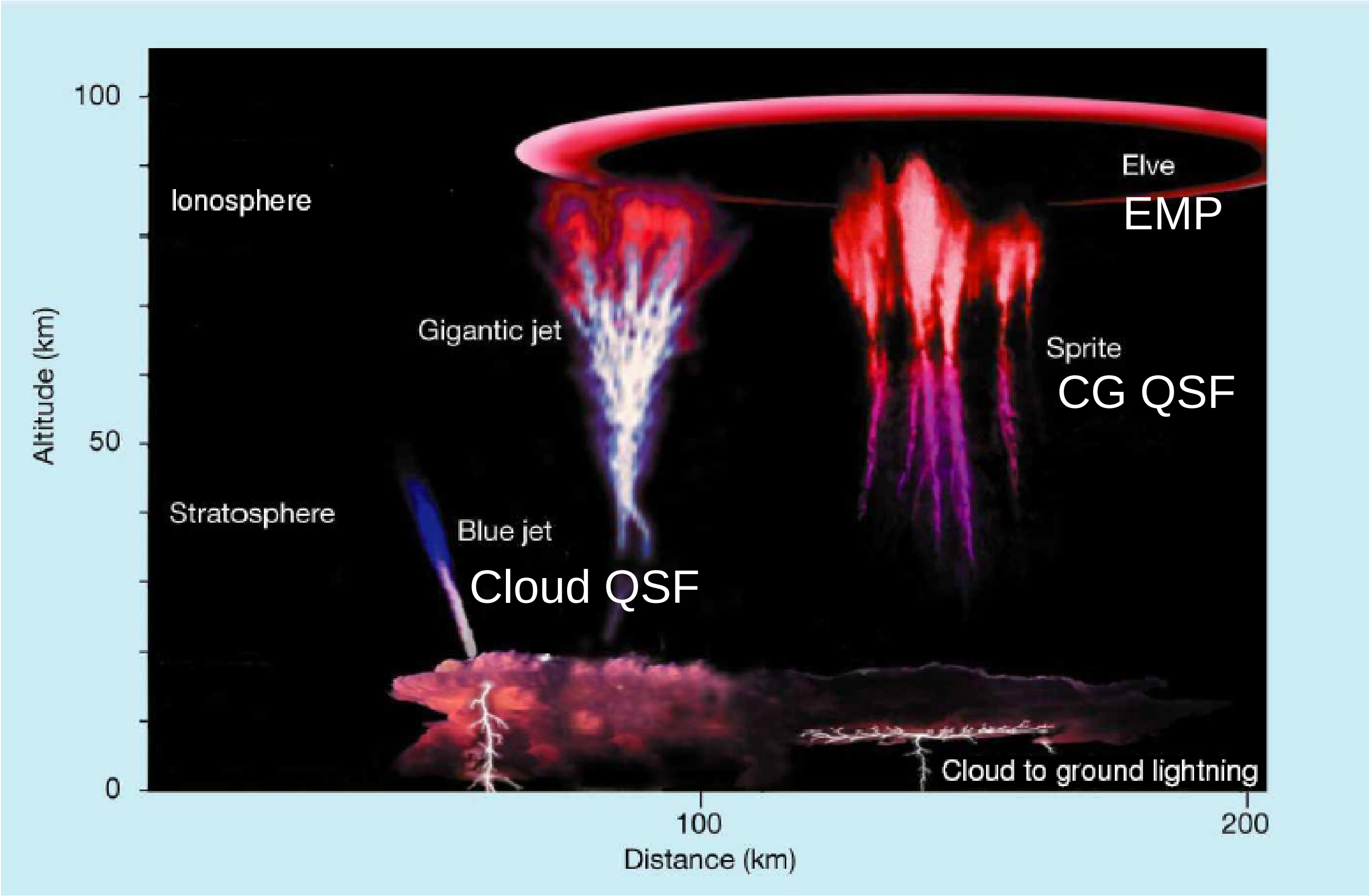
Sprite Models: The Quasi-static Electric Field



3. The negative shielding layer remains after the discharge causing polarization in the atmosphere and a quasi-static E-field. This can be likened to a giant parallel plate capacitor as shown above. This strong E-field causes electrical breakdown producing sprites.

What Causes Jets and Elves?

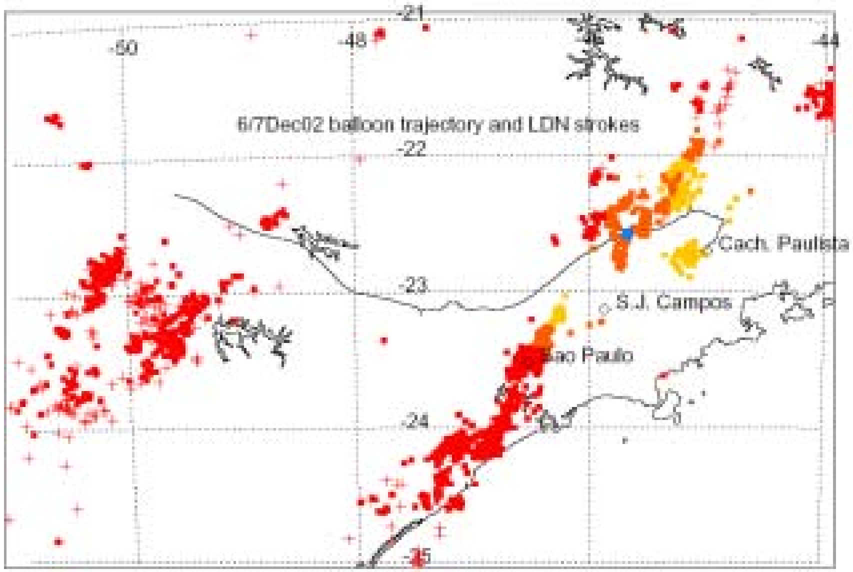
Lightning-Related Middle Atmospheric Transient Luminous Events



[Lyons et al., BAMS, 84, 445, 2003; Pasko, Nature, 423, 927, 2003]


The Sprite Balloon Campaign
Brazil 2002-2003
DC/AC Vector E-field
(0 to 200V/m)
± polar conductivity
DC/AC Magnetic Field
up/dn Optical Power
up/dn X-rays
External air Temperature
3MBPS digital telemetry
vector search coil
HV Probes
low voltage probes

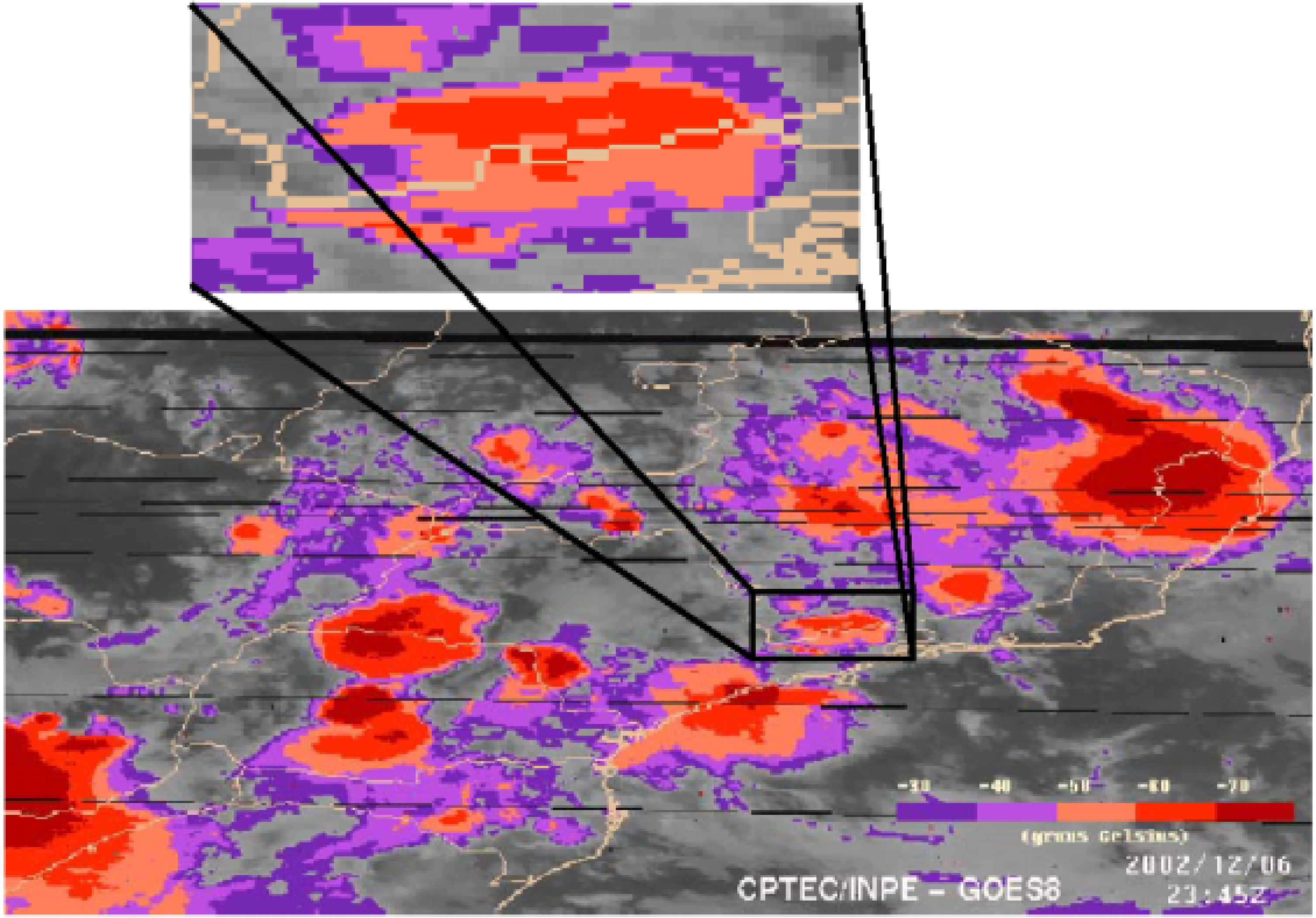
Nearby (< 75 km) Quasi-Electrostatic Field Changes due to Lightning



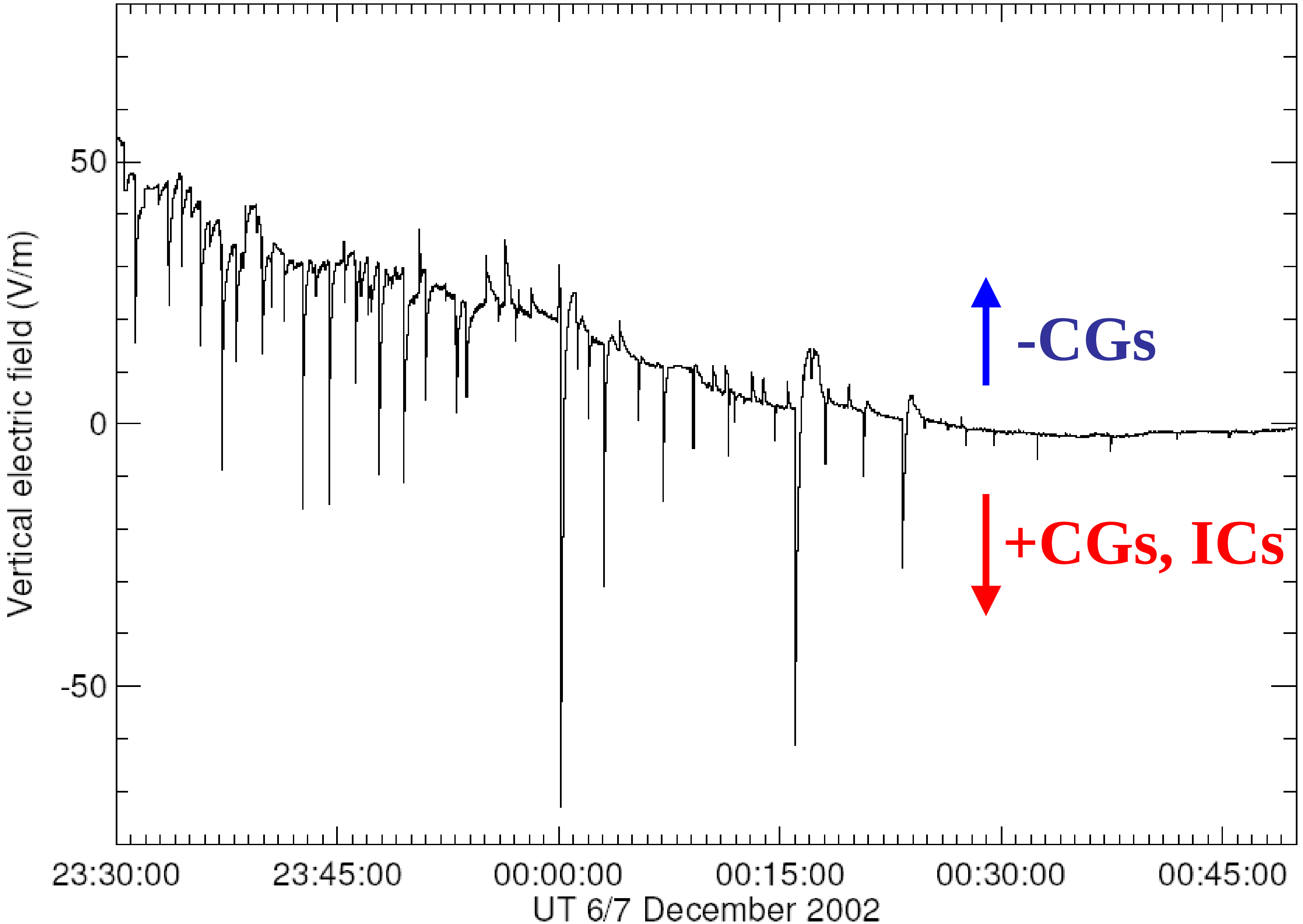
Flight 1 Trajectory and BIN CGs

- 38 electric field changes greater than 10 V/m were measured above 30km in alt.
- Location of strokes: Brazilian Integrated Ground Based Lightning Network (BIN)
- Sprites not ruled out, although none were confirmed optically

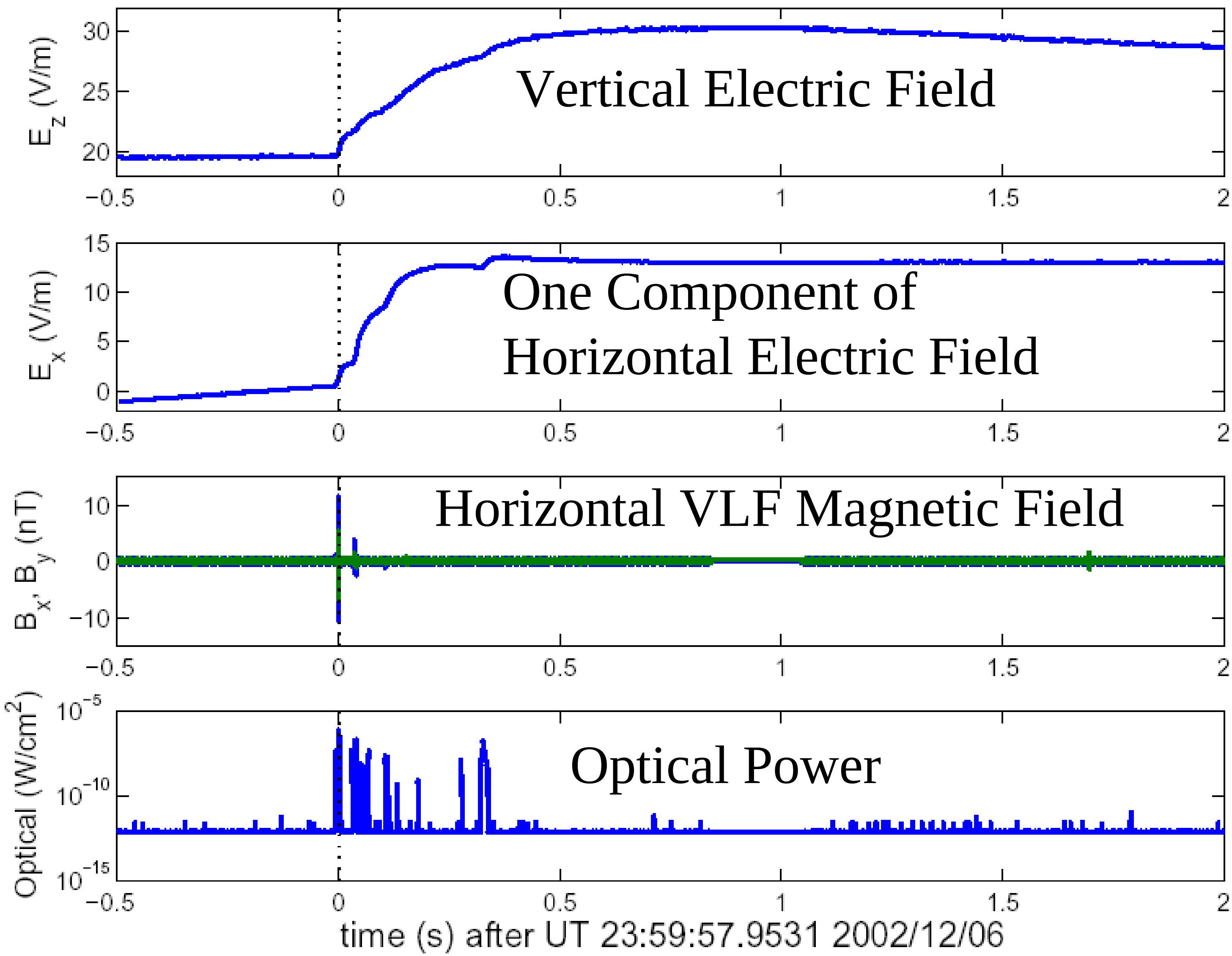
GOES8 Satellite IR image from 23:45 UT Dec. 6, 2002 for the southeast of Brazil



80 minutes of vertical dc electric field data during Flight 1

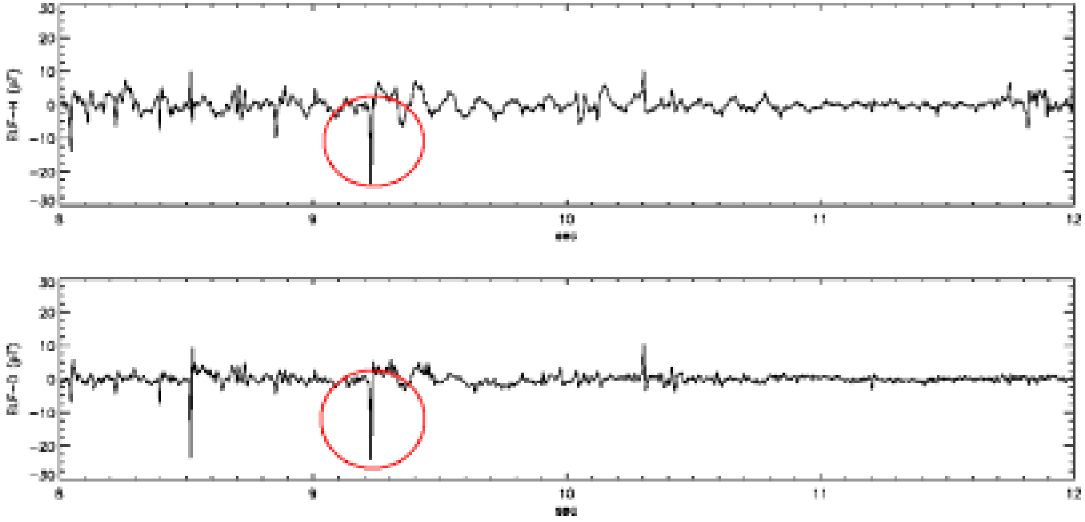


Largest typical –CG driven electric field change measured at the payload: -72 kA Peak Current, 39.2 km horizontal distance



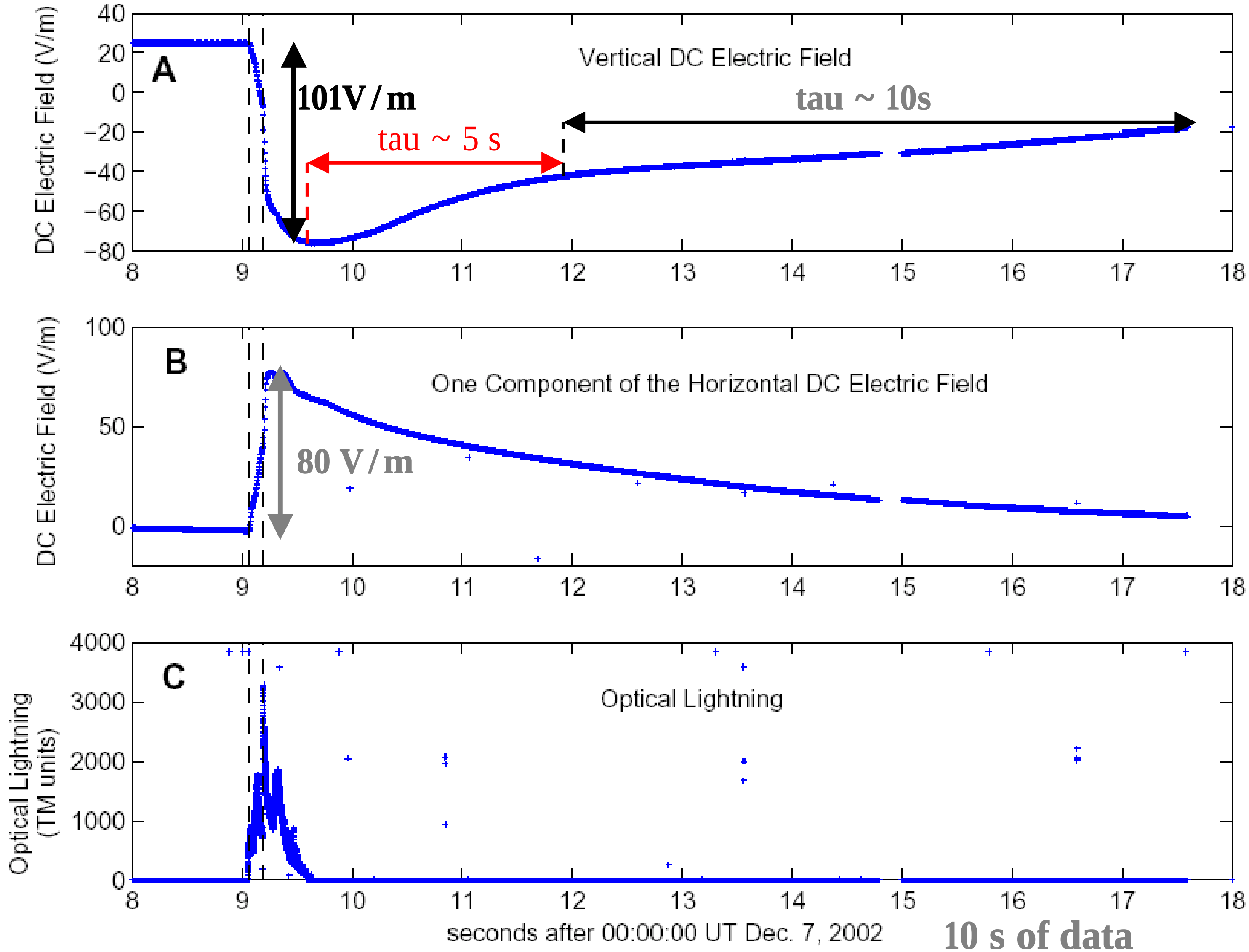
Case Study: A Large +CG Event

- Two positive cloud-to-ground (+CG) strokes 140ms apart 34 km hor. distance from the balloon payload (alt=34km)
- Charge moment: 329-1683 C-km estimated from remote ELF (extremely low frequency) magnetic field measurements (M. Sato)

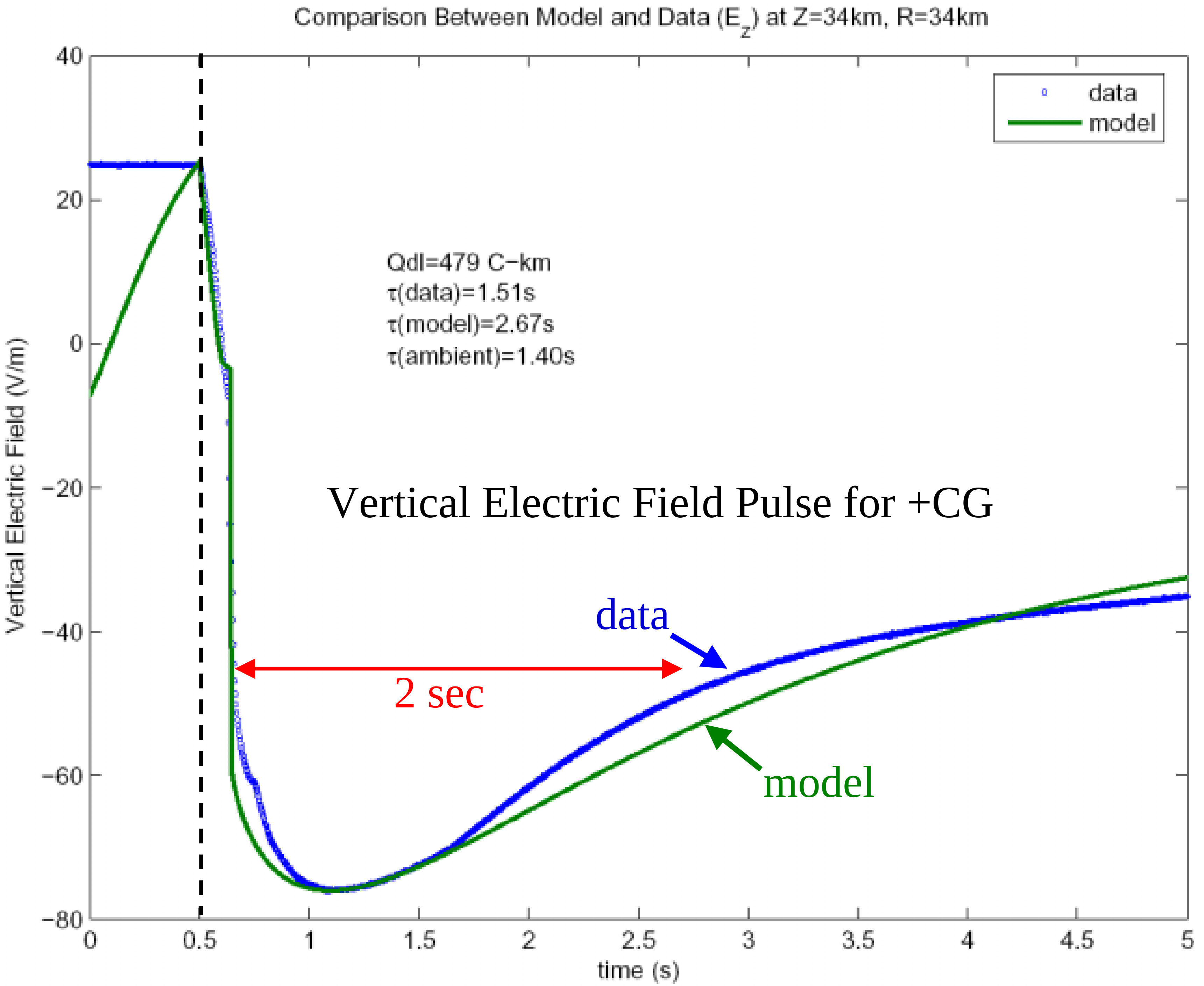


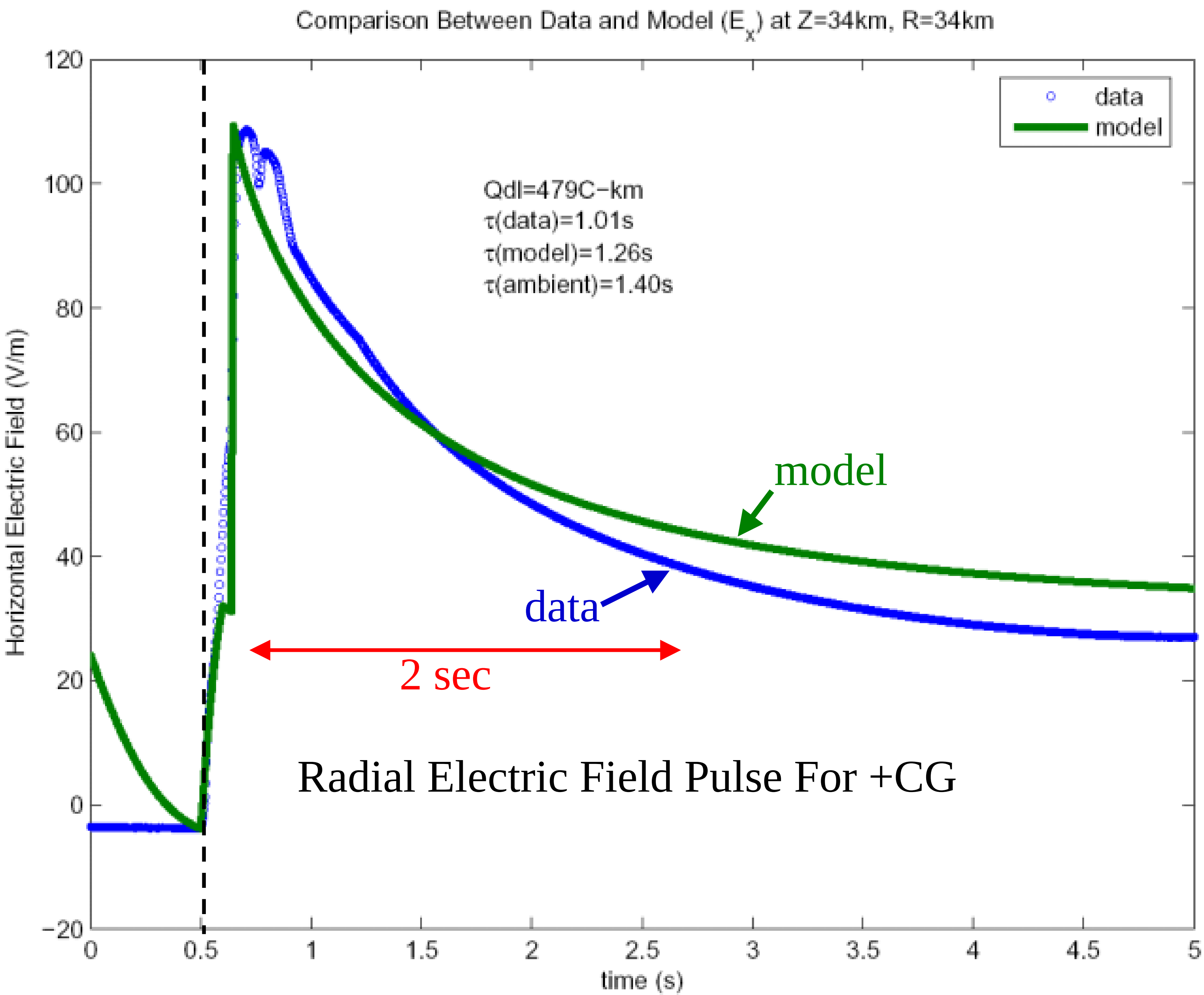
ELF Data from Syowa, Antarctica

DC Electric Field Change Driven by +CG (Probable Sprite Event)



In-situ data: Two lightning events, +15kA and +53kA (436 C-km), at ~00:00:09 UT Dec. 7 both less than 40 km from the balloon payload.


Comparison Between Model and Data (E_z) at Z=34km, R=34km
Vertical Electric Field (V/m)
time (s)
data
model
Qdl=479 C−km
τ(data)=1.51s
τ(model)=2.67s
τ(ambient)=1.40s
Vertical Electric Field Pulse for +CG
data
2 sec
model
40
20
0
−20
−40
−60
−80
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Comparison Between Data and Model (E_x) at Z=34km, R=34km
data
model
Qdl=479C−km
τ(data)=1.01s
τ(model)=1.26s
τ(ambient)=1.40s
model
data
2 sec
Radial Electric Field Pulse For +CG
Horizontal Electric Field (V/m)
time (s)
120
100
80
60
40
20
0
−20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

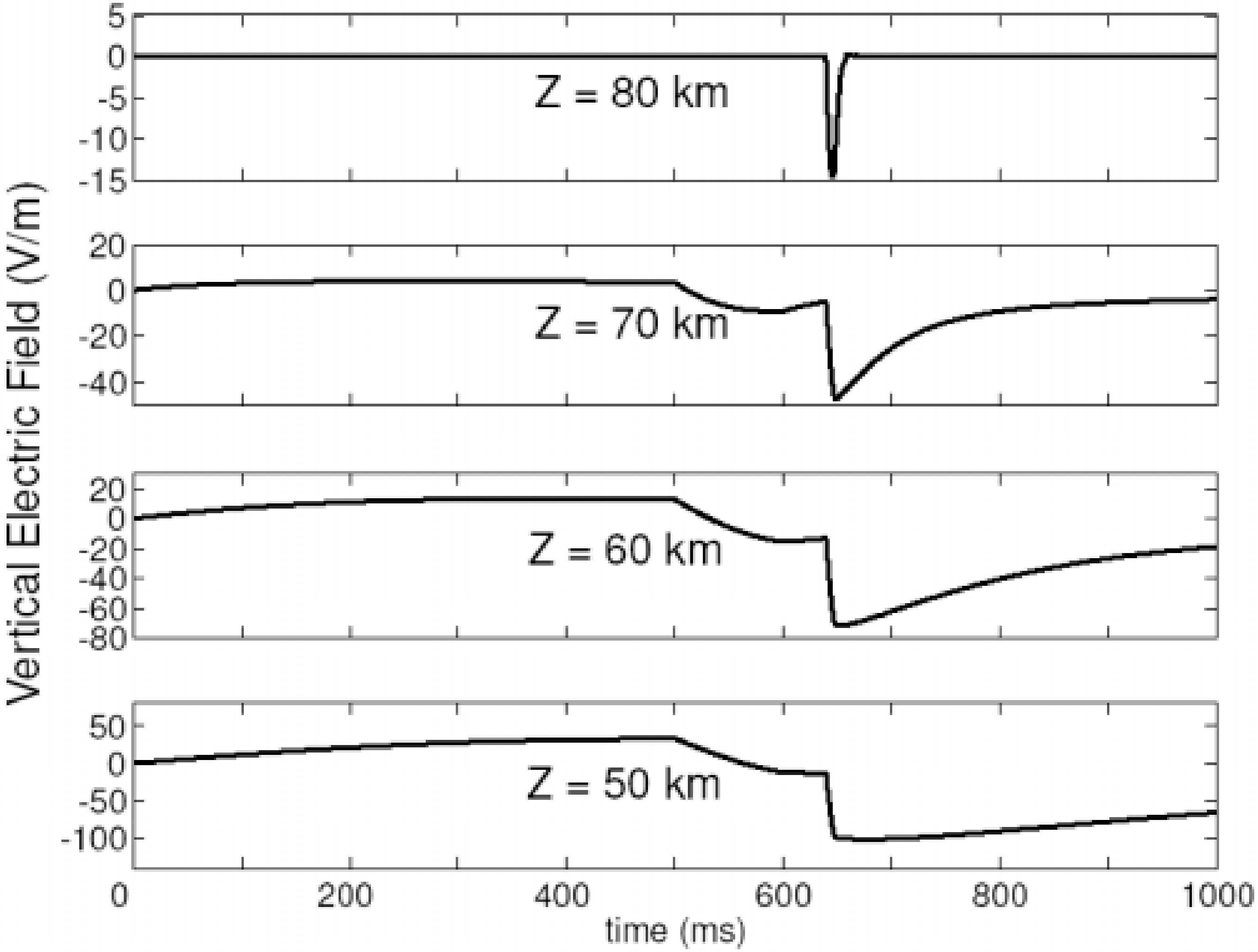
Breakdown Thresholds

- Conventional Breakdown (E_k): electric field magnitude when ionization rate surpasses the attachment rate, $E_k = 3.2 \times 10^6$ V/m at STP.

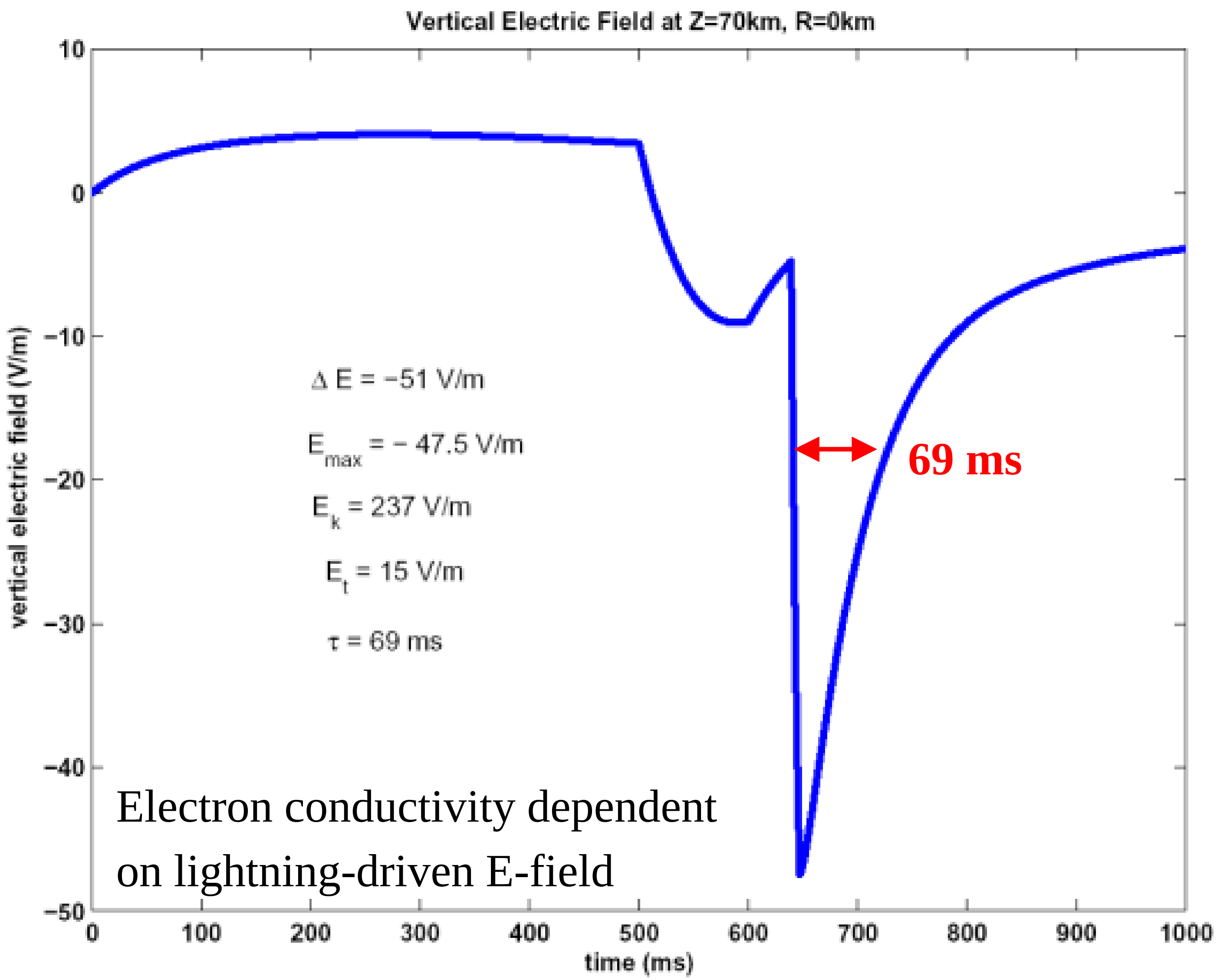
- Relativistic Runaway (E_t): electric field magnitude needed for a 1 MeV electron to initiate a electron avalanche, $E_t = 2 \times 10^5$ V/m at STP.

- Positive (Negative) Streamer Breakdown (E_{cr}^+, E_{cr}^-): electric field magnitude needed for an ionized filament to continue to propagate in the direction (opposite direction) of the field, $E_{cr}^+ = 4.4 \times 10^5$ V/m and $E_{cr}^- = -1.25 \times 10^6$ V/m at STP.

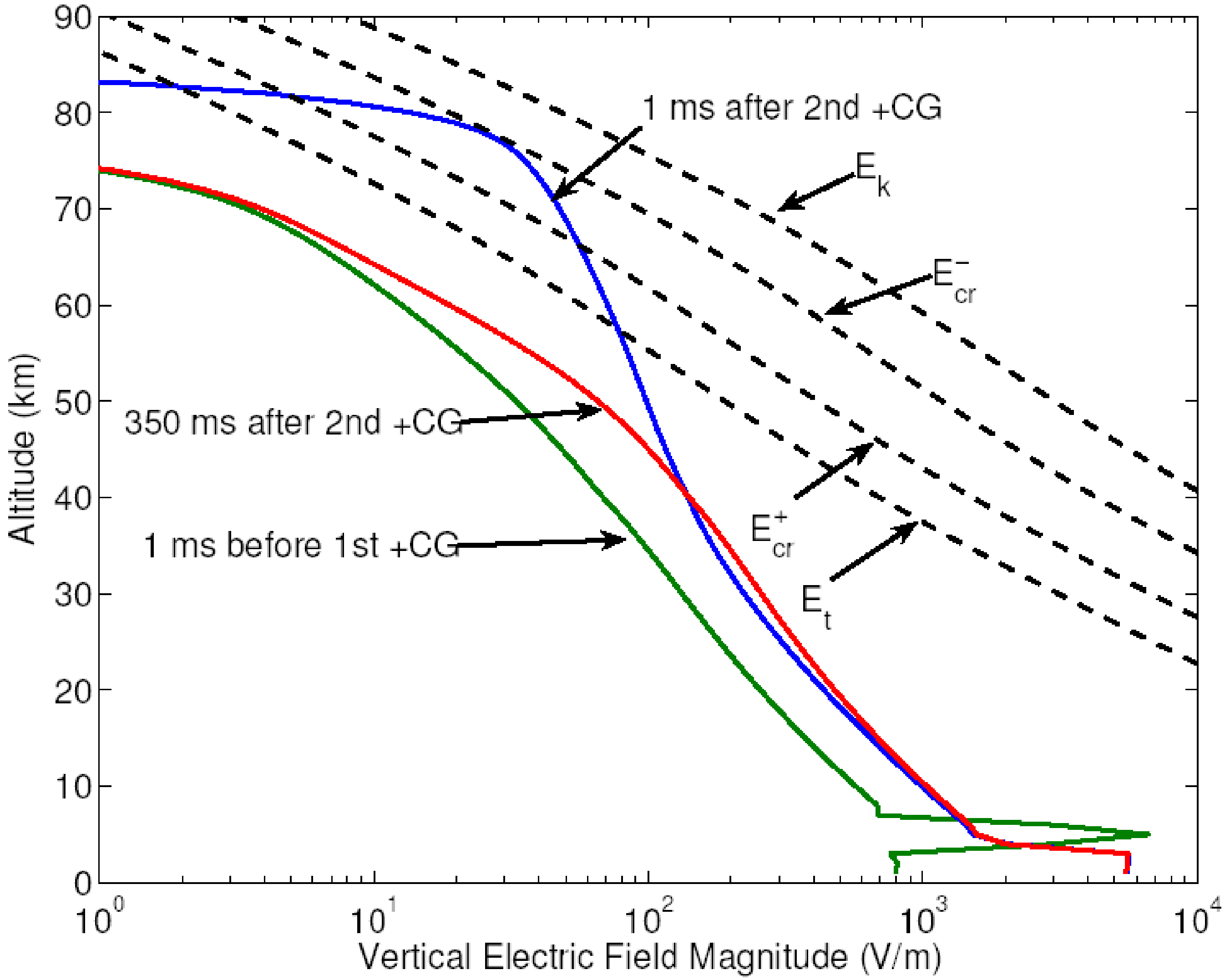
Model Output: Predicted lightning-driven electric fields at sprite altitudes (Z=50-80km)



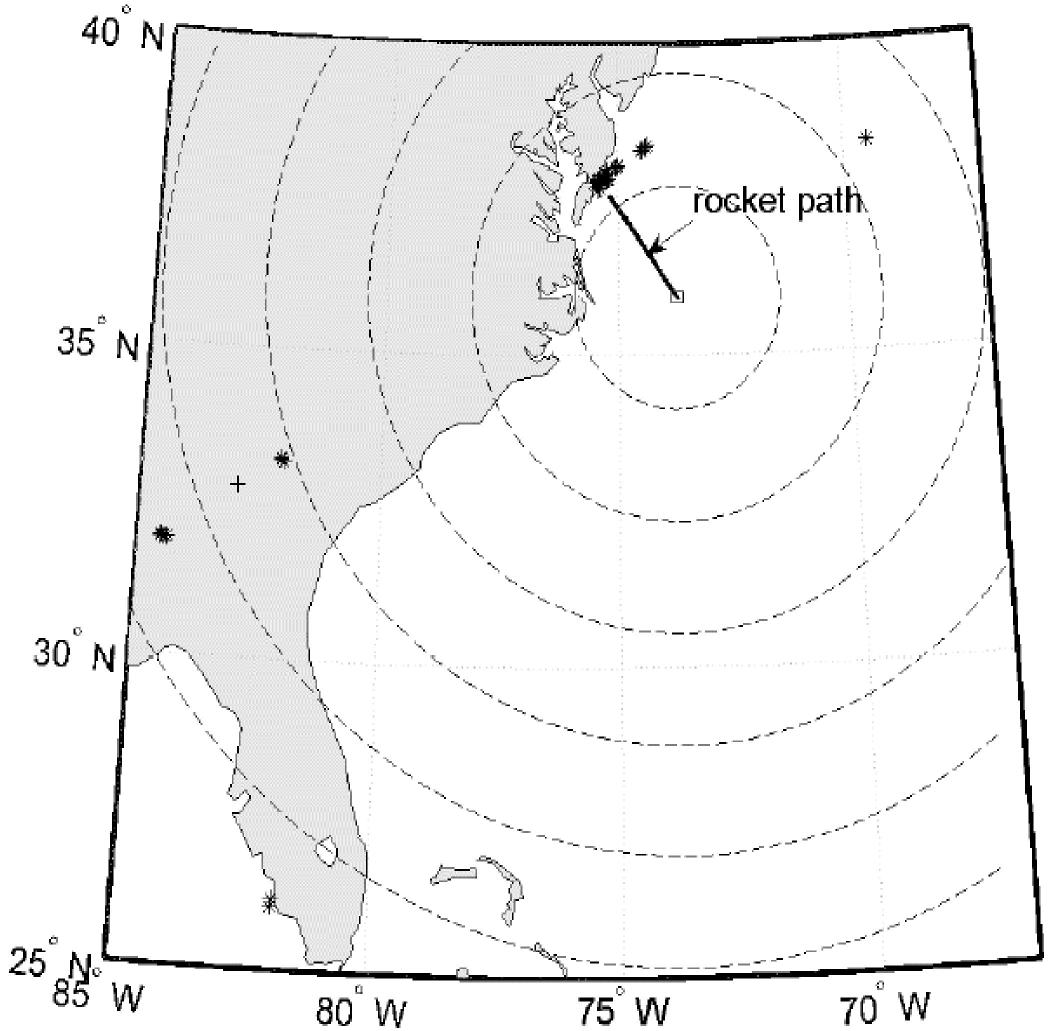
Model Output: Predicted lightning-driven electric fields at sprite altitudes (Z=70km)



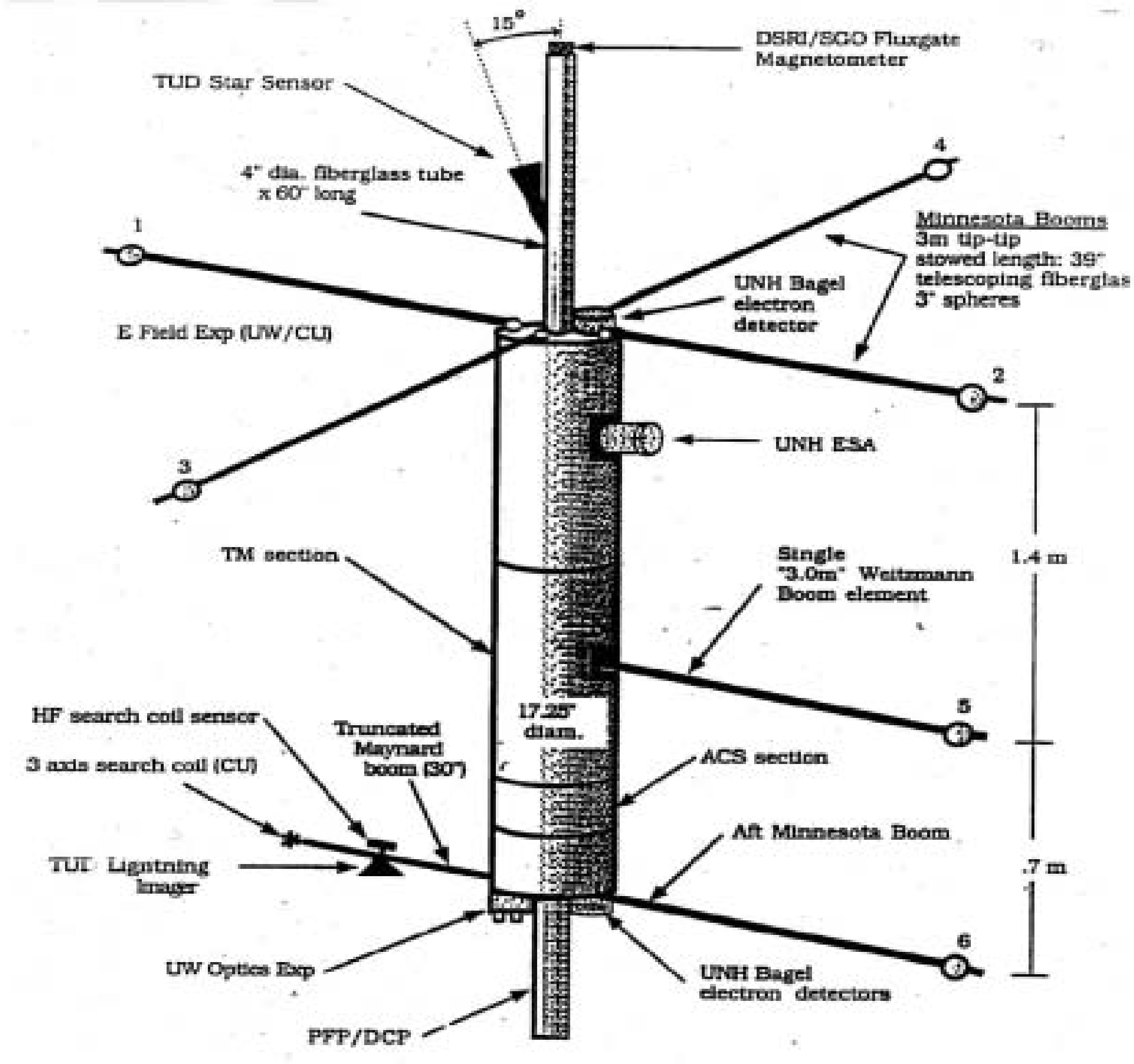
Model Output: Vertical electric field vs. altitude at R=0 km

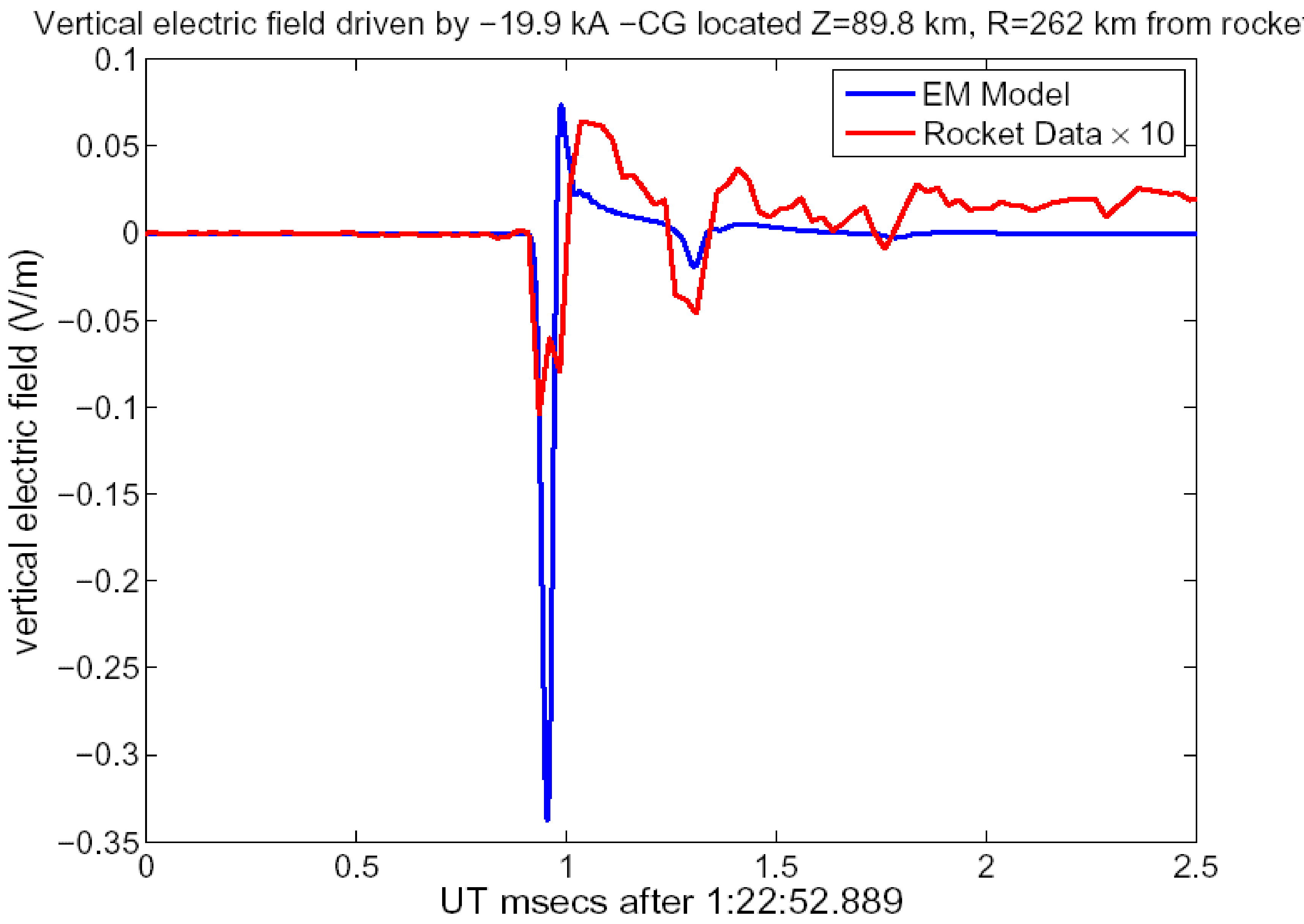


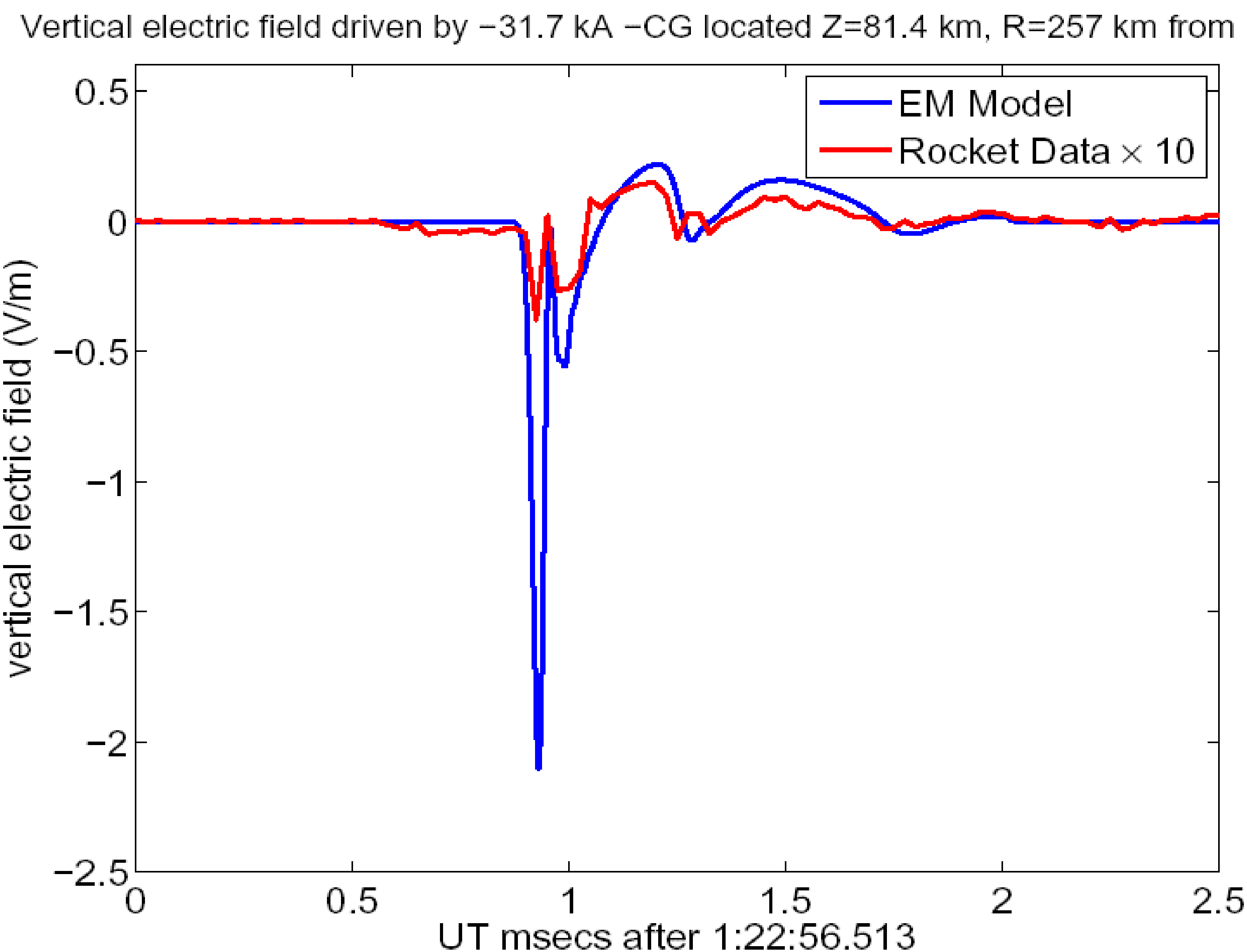
Thunderstorm-III Rocket Campaign
Sept.1 1995



Thunderstorm-III Payload

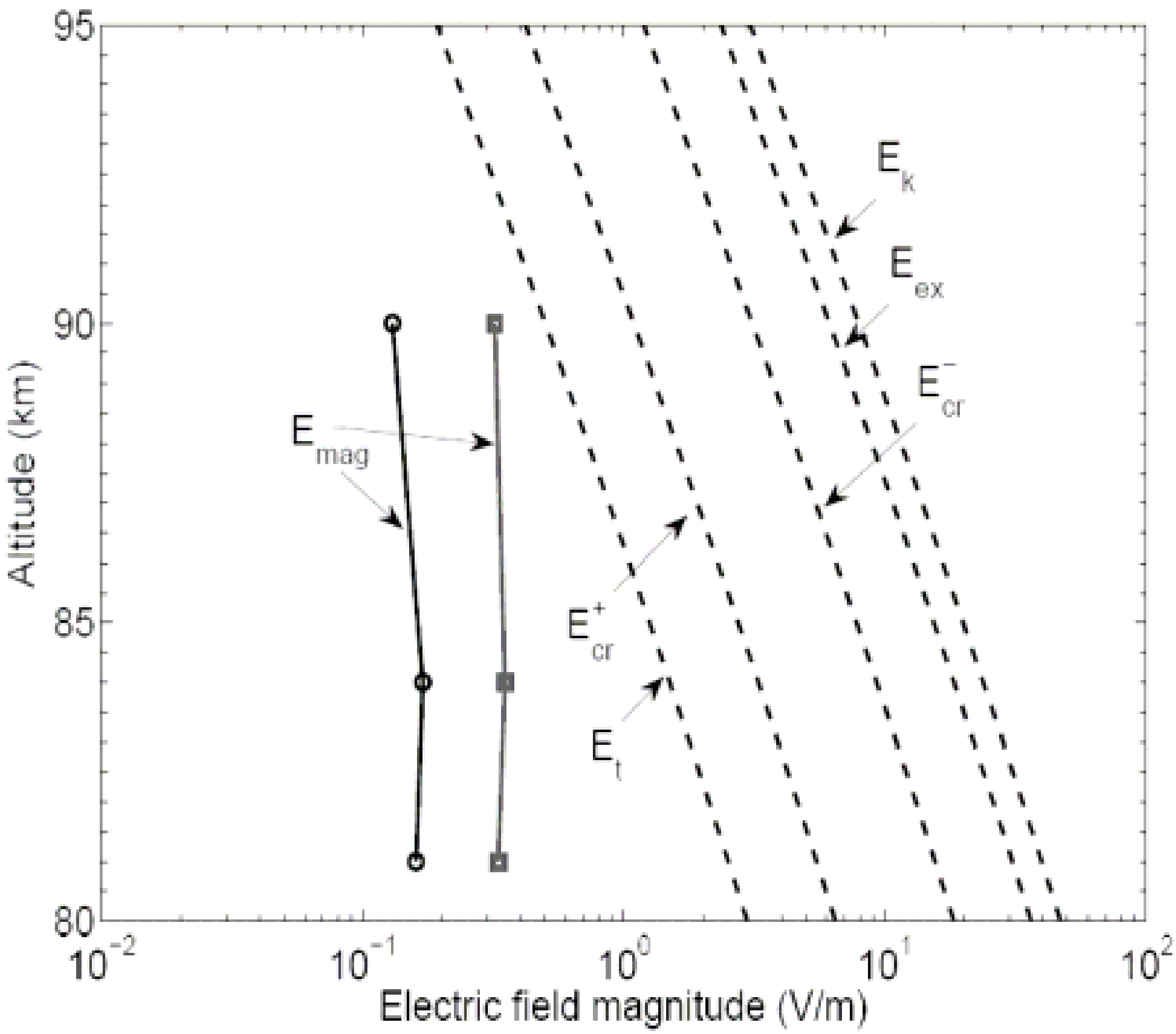



Vertical electric field driven by −19.9 kA −CG located Z=89.8 km, R=262 km from rocket
EM Model
Rocket Data × 10
vertical electric field (V/m)
UT msecs after 1:22:52.889
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
−0.3
−0.35
0
0.5
1
1.5
2
2.5



Vertical electric field driven by −31.7 kA −CG located Z=81.4 km, R=257 km from rocket
EM Model
Rocket Data × 10
vertical electric field (V/m)
UT msecs after 1:22:56.513
0.5
0
−0.5
−1
−1.5
−2
−2.5
0
0.5
1
1.5
2
2.5

Predicted Field at Elve Altitudes for 100 kA CG



Conclusions

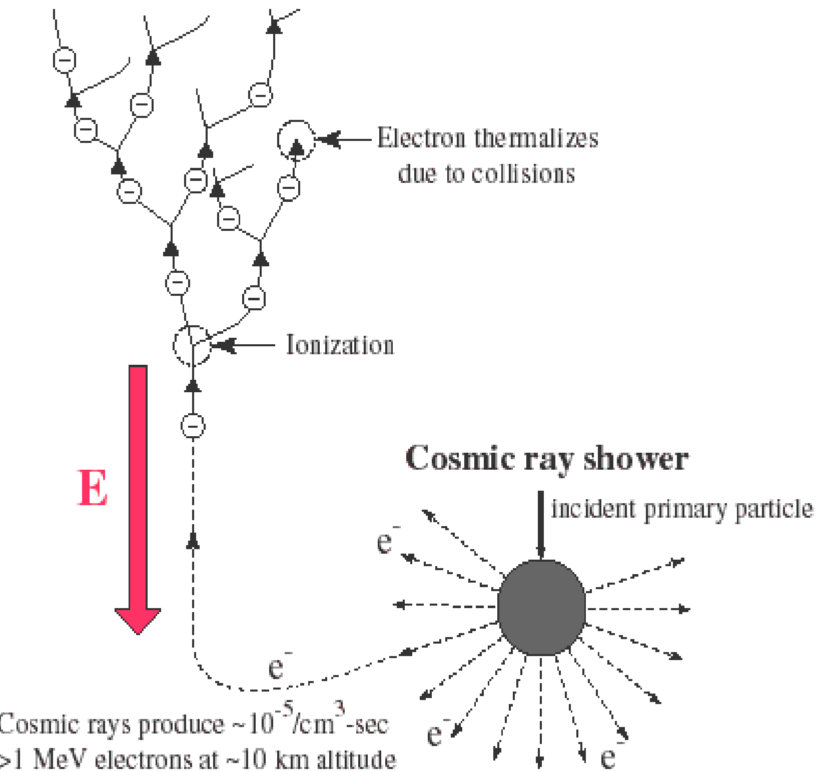
- Balloon measurements at 35 km generally agree with quasi-static electric field model
- Rocket measurements at 80-100 km are more than 10 times smaller than predicted by electromagnetic model
- Better understanding of conductivity in the middle atmosphere is central to understanding TLEs
- In situ measurements needed during confirmed sprite and elve events to verify generation mechanisms

What are Sprites?

Historically:

- Reports of optical phenomena above thunderstorms where first published in scientific literature in the late 19^{th} century (Toynbee and Mackenzie, 1886, Everett and Everett, 1903)
- In the 1950's the first airborne observation was reported from a commercial airlines pilot over Fiji (Wright, 1950)
- CTR Wilson was the first to predict the existence of high altitude discharges (Wilson, 1956)
- Not until 1989 were these phenomena captured on film. A group from the University of Minnesota recorded a twin upward flash from distant cloud tops while testing a low light level TV camera intended for sounding rockets (Franz,et al 1989)

What causes sprites?
Runaway Electron Breakdown Model



Cartoon of Runaway Electron Breakdown
(Courtesy of Star Laboratory, Stanford)

- High energy electrons produced by cosmic rays are accelerated by the quasi-static electric field.
- Through collisions, these electrons produce ions and new electrons.
- Below 1MeV the stopping power decreases with increasing electron energy. The higher energy electrons are able to gain more energy from the electric field than they lose due to collisions with neutrals. Thus, the population of electrons grows exponentially (runaway)

Predicting Electric Fields at Sprite Altitudes

- The parameters that best fit the quasi-static field model to the balloon data are used to predict the electric field perturbation at sprite altitudes (50-80km)
- These electric field pulses are compared to the electrical breakdown thresholds (conventional, relativistic, streamer)
- The duration of the pulse is compared to the duration of observed sprites