Measuring electric and magnetic fields high above thunderstorms:

Implications for sprites, jets, and elves

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Outline

I. Introduction: What are sprites, jets, and elves?

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

III. What causes sprites, jets, and elves?

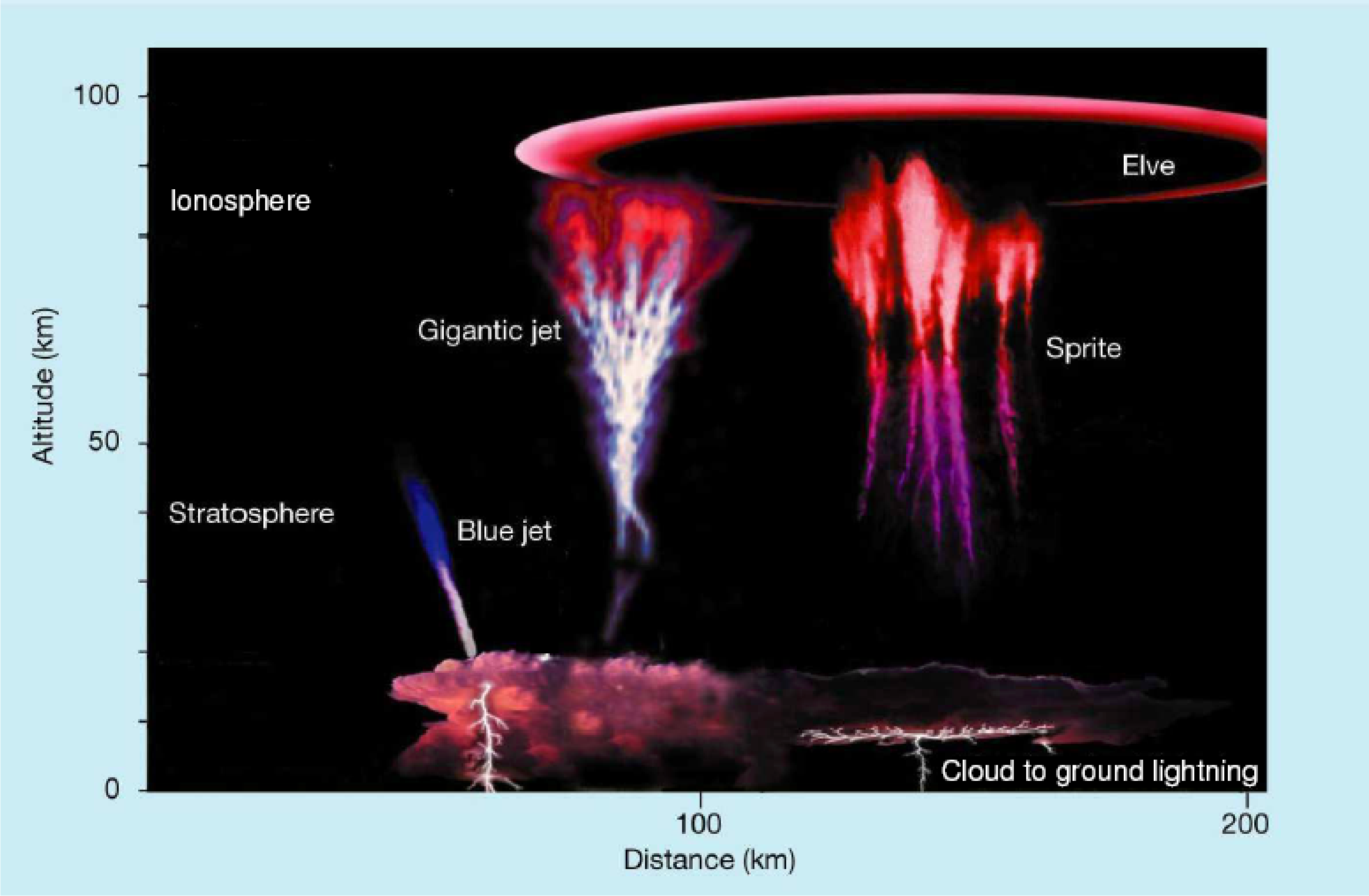
IV. In situ balloon measurements above thunderstorms

V. Predicting electric fields at sprite altitudes

VI. ELF/VLF electromagnetic field from distant lightning

VII. Update from south Brazil balloon campaign 2006

Lightning-Related Middle Atmospheric Transient Luminous Events



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

What are Sprites?

Historically:

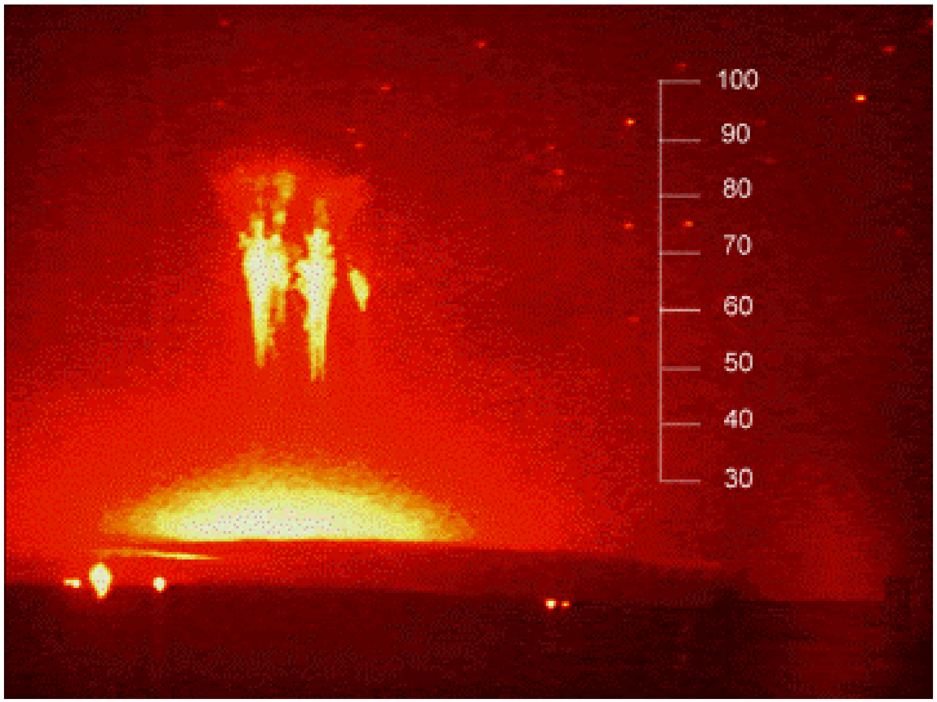
- Reports of optical phenomena above thunderstorms where first published in scientific literature in the late 19^{th} century (Toynbee and Mackenzie, 1886, Everett and Everett, 1903)

- 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)

Sprite Properties

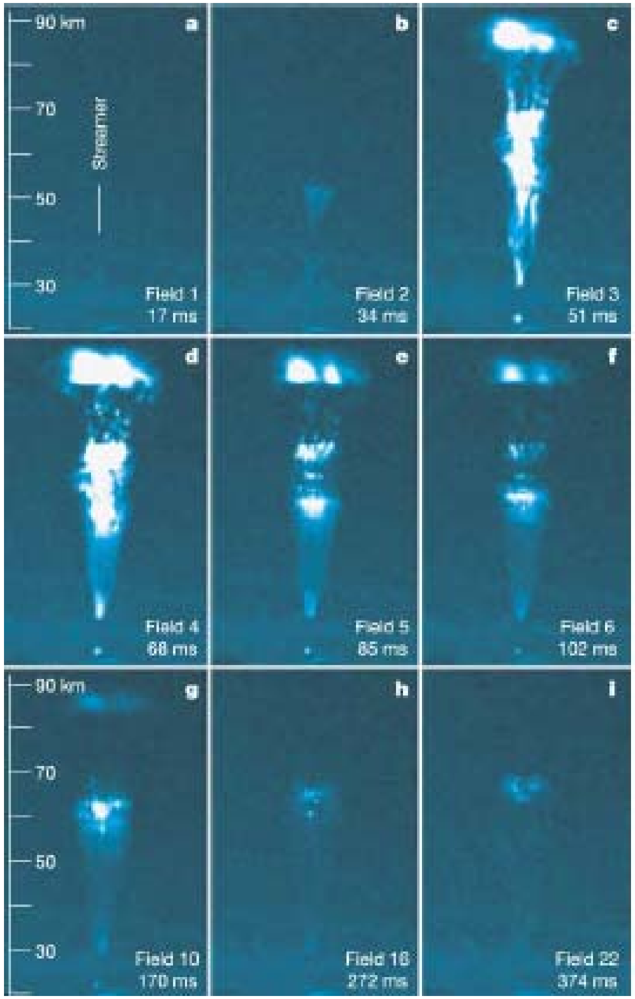


Ground Based Sprite Image from Fort Collins, CO 1995 (Courtesy of the Geophysical Institute, the University of Alaska)

- Associated with positive cloud-to-ground (+CG) lightning discharge, and they last from about 5ms to 300ms.
- Often have a column-like composition, with fine structure. They extend from about 30-40km to about 80-90km, with a primary body at about 50-70 km. Their horizontal extent is about 25-50km, with a bright core <10km wide

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

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]).

- Blue optical discharges that propagate from the top of a thundercloud upward into the stratosphere and mesosphere
- Sometimes connect with the ionosphere at about 90 km in altitude (gigantic jet)
- Unlike sprites which are correlated with +CG strokes, jets are not correlated with individual strokes.

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

What are Elves?

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

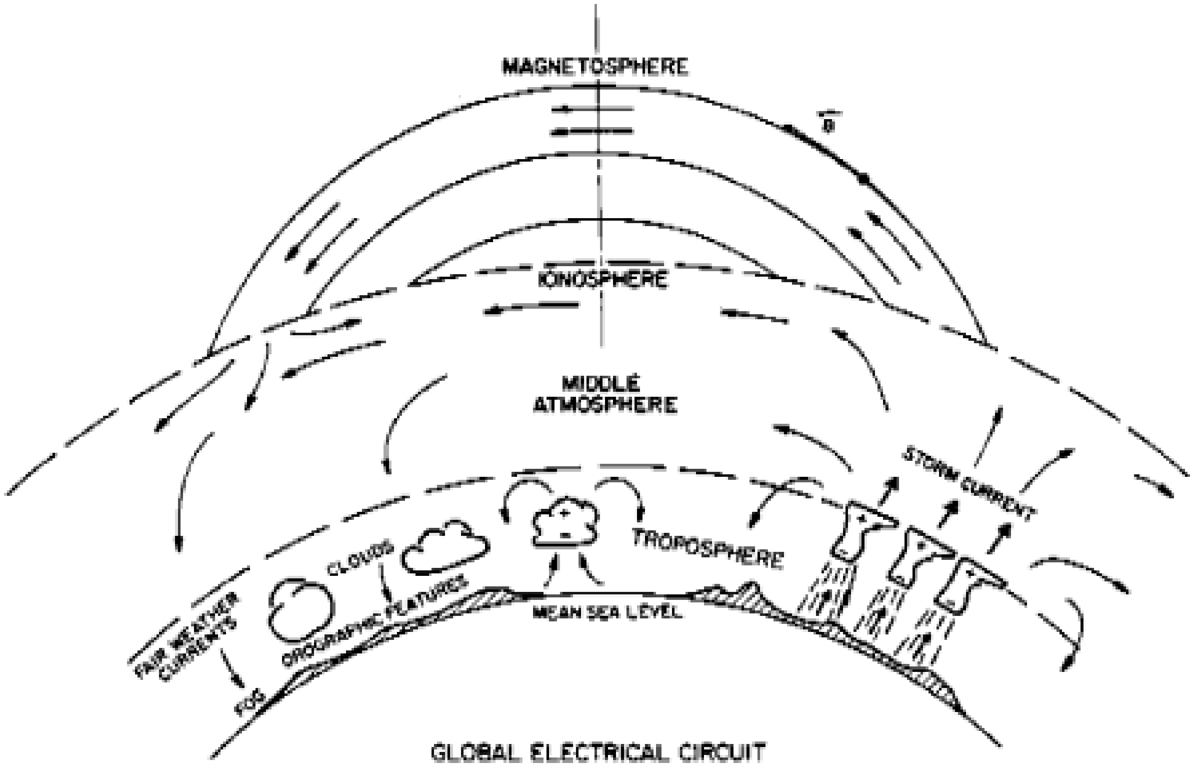
•Elves are an expanding disks of optical emissions that occur in the lower ionosphere (90-100km) after large peak current (> 60kA) CGs of both negative and positive polarity

•Unlike sprites and jets which are likely caused by quasi-electrostatic fields, elves are likely the result of the lightning return stroke generated electromagnetic pulses (EMP)

Why Study High Altitude Discharges?

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

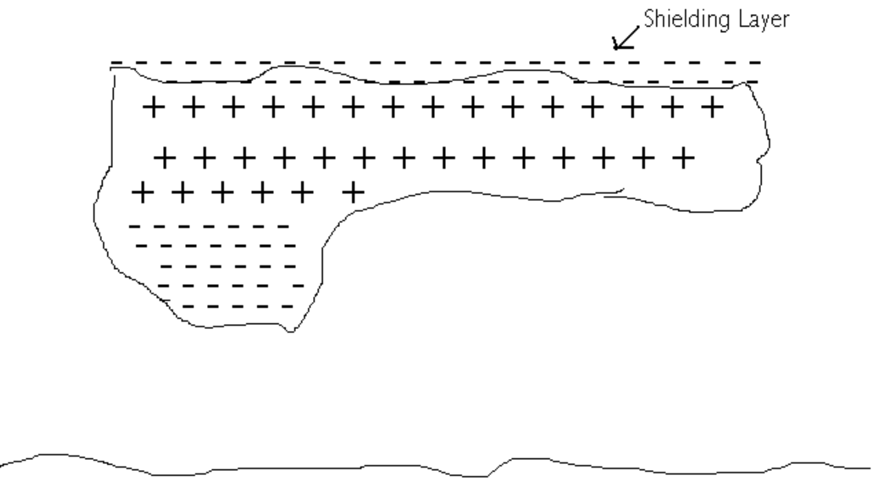
Why Study High Altitude Discharges?

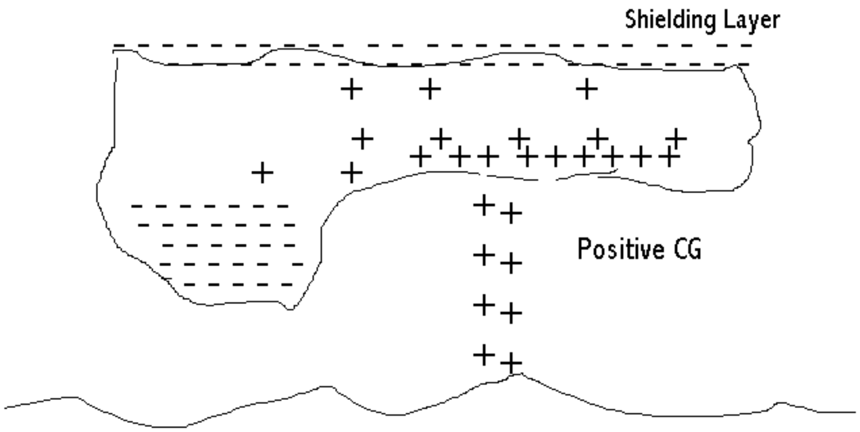


Adapted from Roble and Tzur, 1986

What causes Sprites?

The Quasi-static Electric Field Model

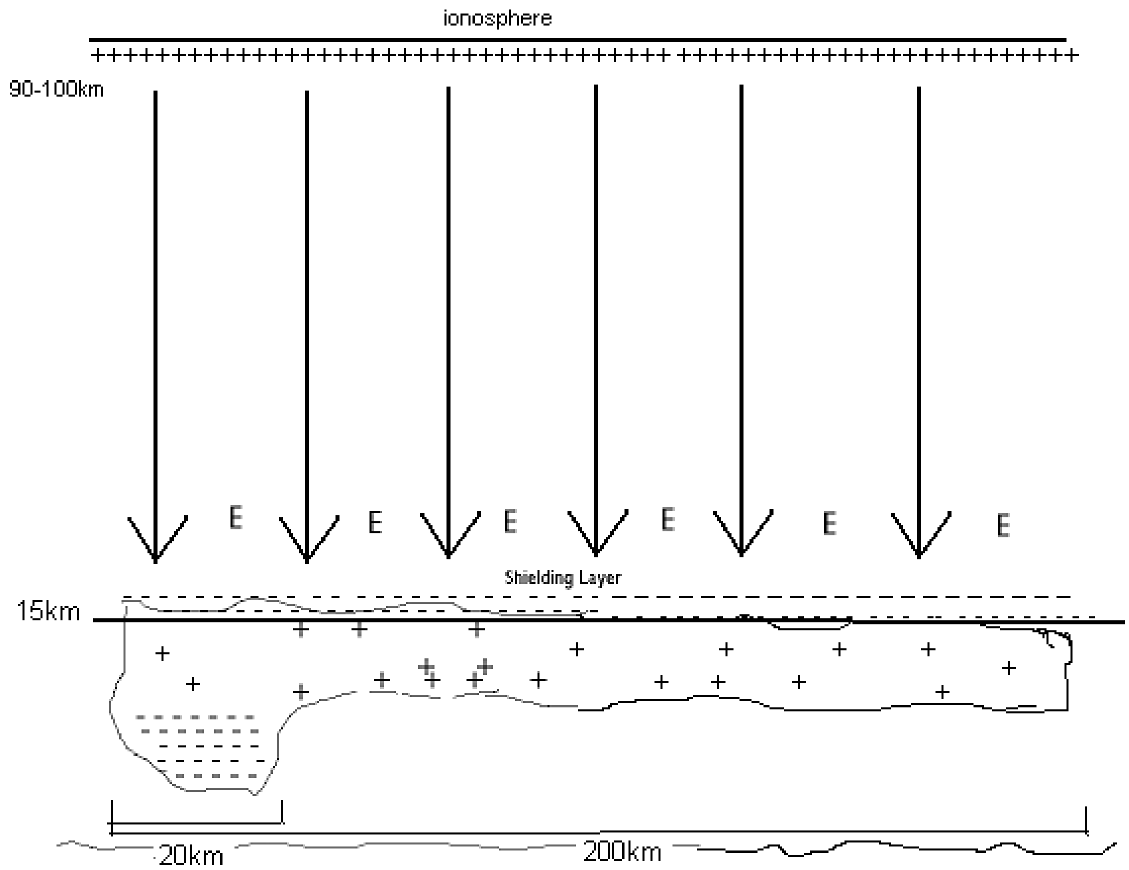




1. The cloud charges up before the lightning discharge inducing a negative shielding layer

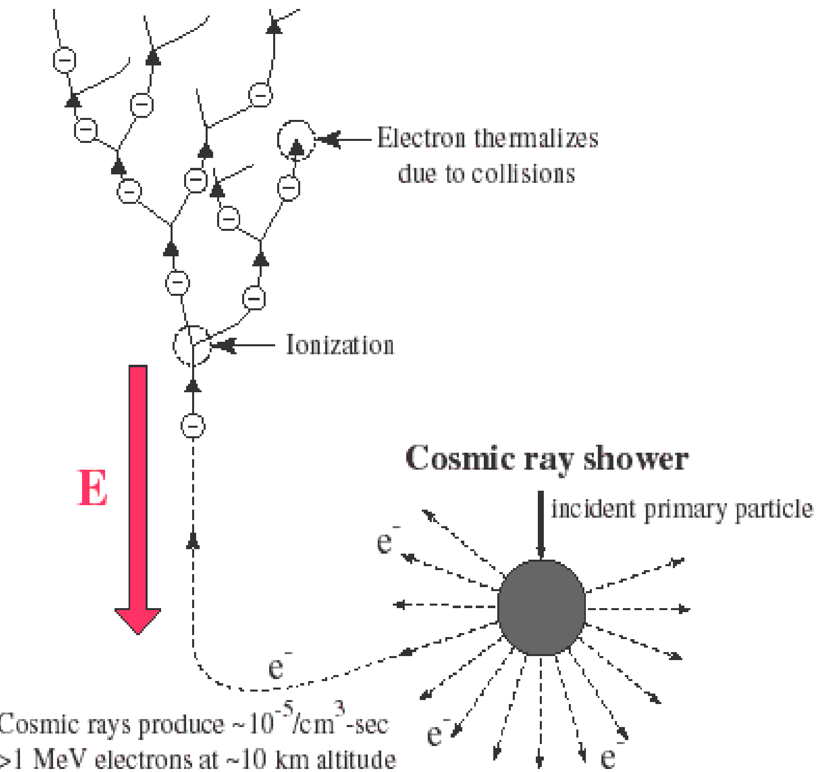
2. The positive CG removes positive charge but the negative shielding layer remains over a much longer time scale

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 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)

What Causes Jets and Elves?

•Unlike sprites which are correlated with +CG strokes, jets are not correlated with individual strokes. Thus, jets are likely due to large electrostatic fields, resulting from the cloud charge distribution, surpassing breakdown inside and above thunderclouds

•Unlike sprites and jets which are likely caused by quasi-electrostatic fields, elves are likely the result of the lightning return stroke generated electromagnetic pulses (EMP)

In situ Measurements above Thunderstorms: The 2002-03 Brazil Balloon Campaign

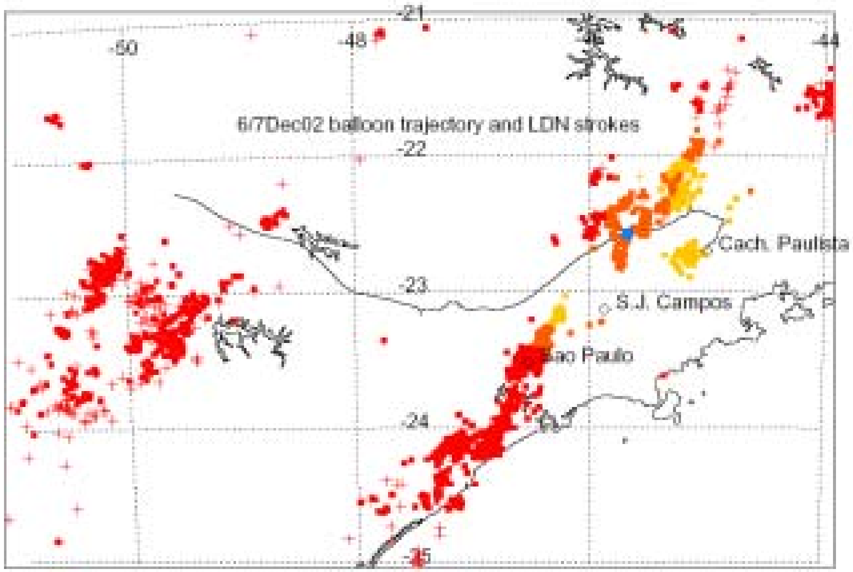
UW/USU/INPE Collaboration

- Goal: Measure at 35km altitude the nearby (<75km) electric and magnetic fields and x-ray production of sprites and their parent lightning strokes
- 2 balloon flights from Cachoeira Paulista, approximately 200km northeast of Sao Paulo
- Launches occurred around sunset with flights lasting from 10-12 hours throughout the night.

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

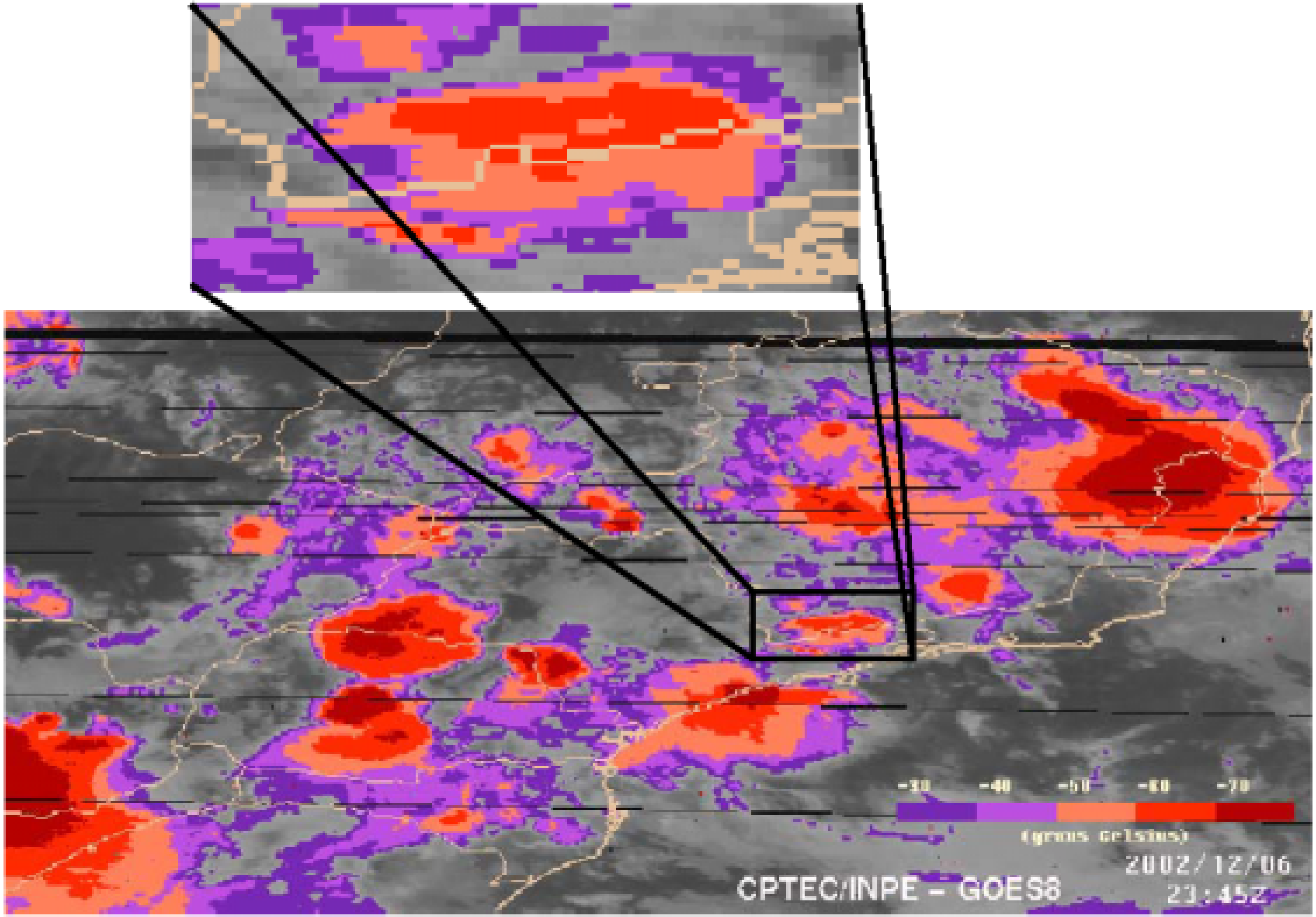
Nearby (< 75 km) Quasi-Electrostatic Field Changes due to Lightning



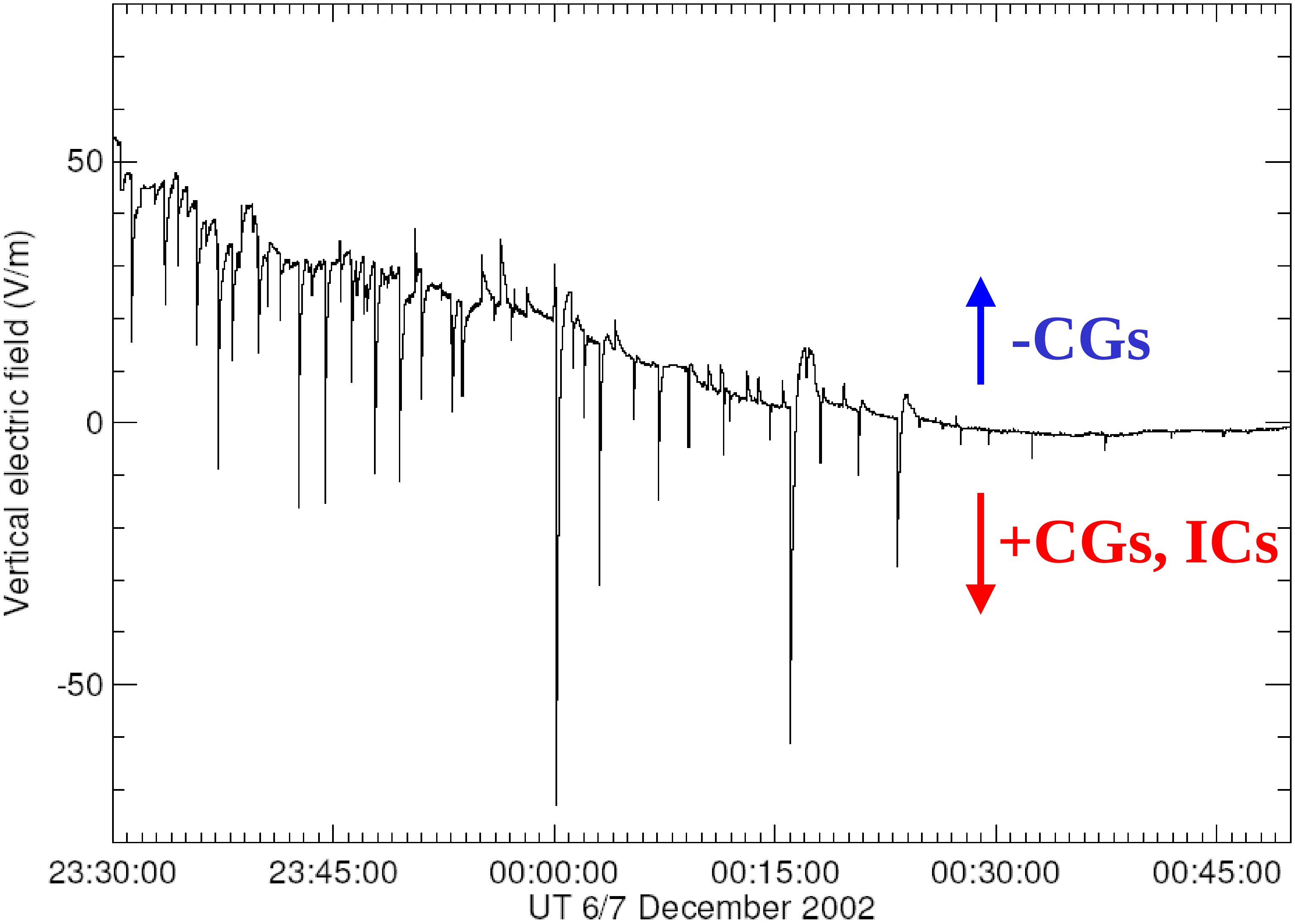
Flight 1 Trajectory and BIN CGs

- 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

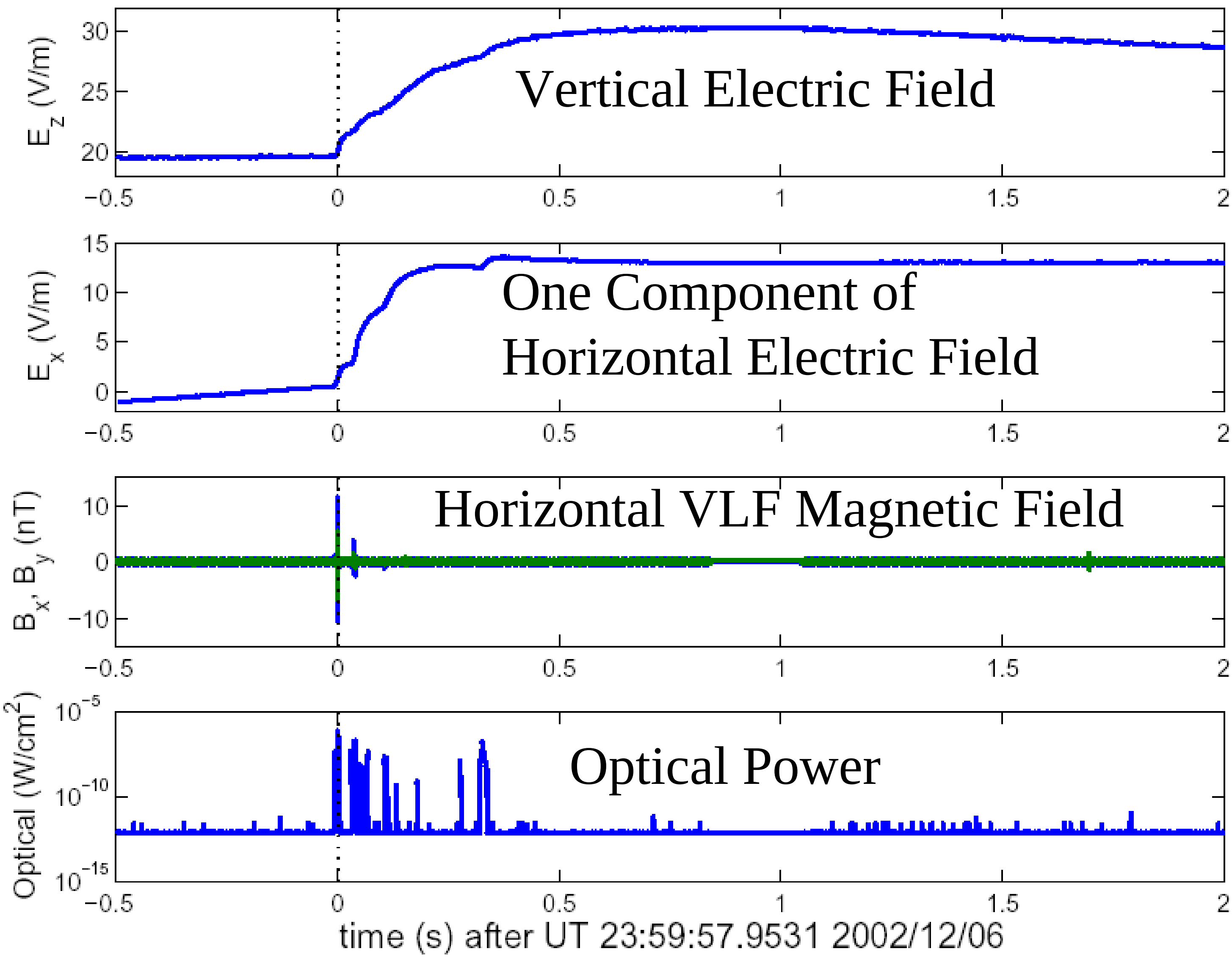
GOES8 Satellite IR image from 23:45 UT Dec. 6, 2002 for the southeast of Brazil



80 minutes of vertical dc electric field data during Flight 1

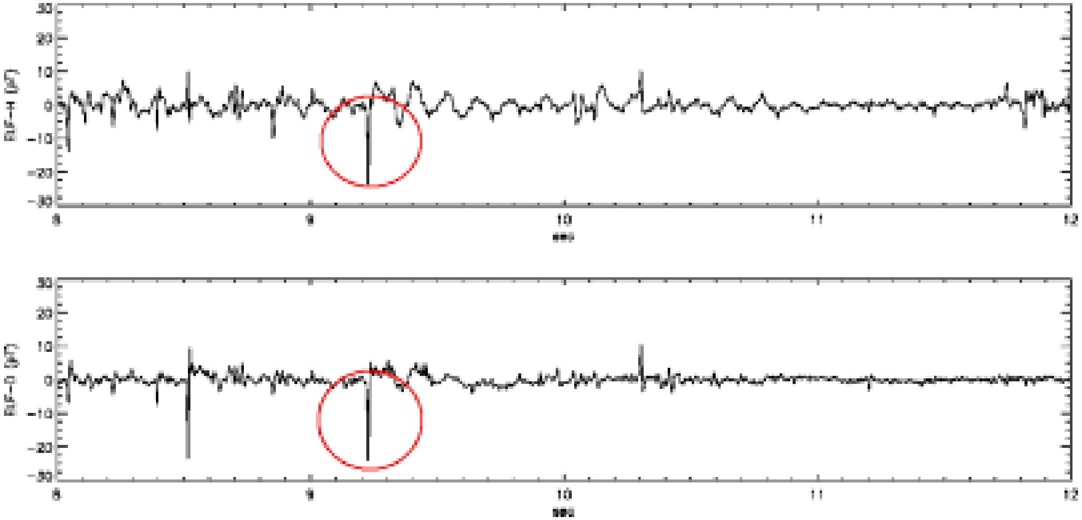


Largest typical –CG driven electric field change measured at the payload: -72 kA Peak Current, 39.2 km horizontal distance



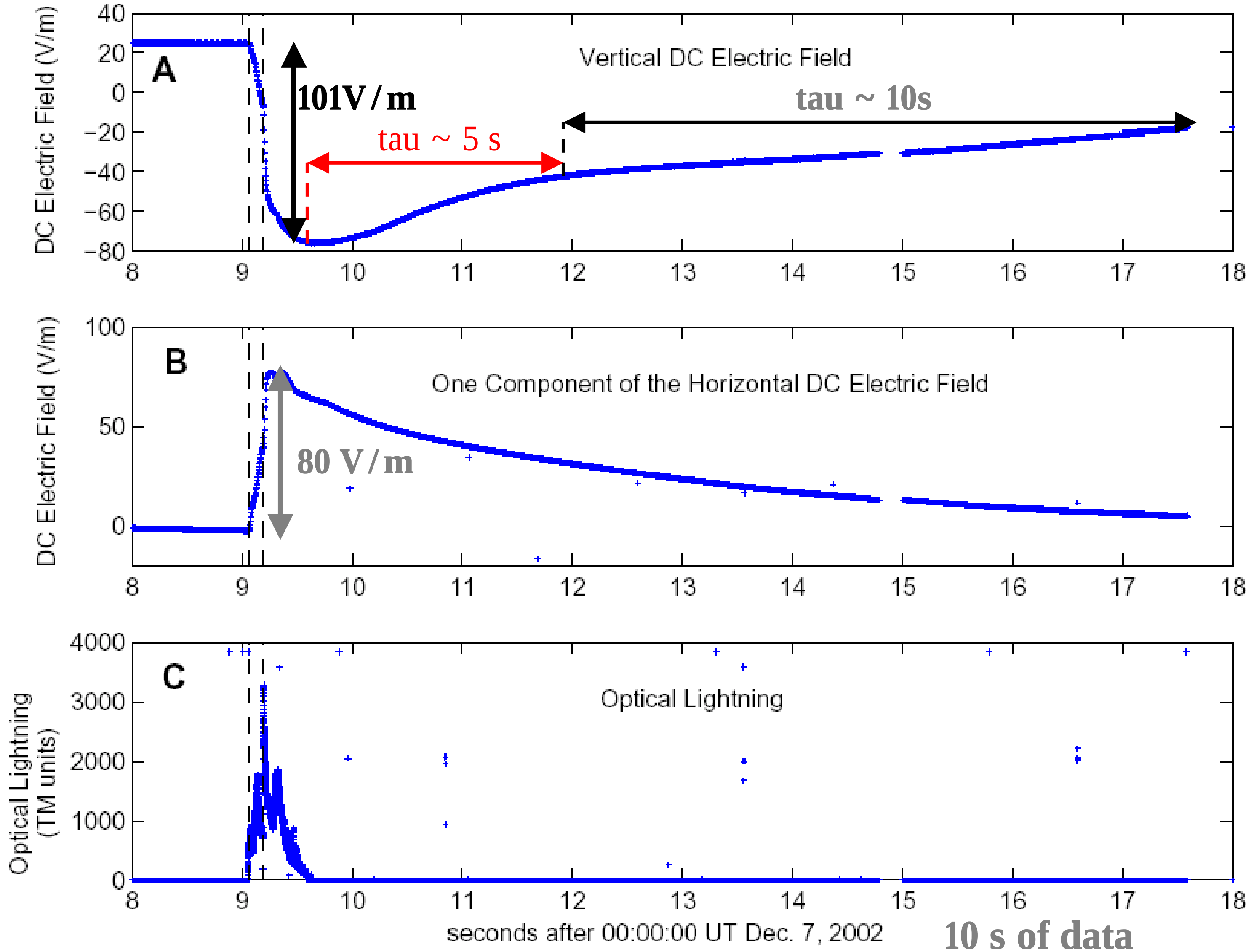
Case Study: A Large +CG Event

- 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)

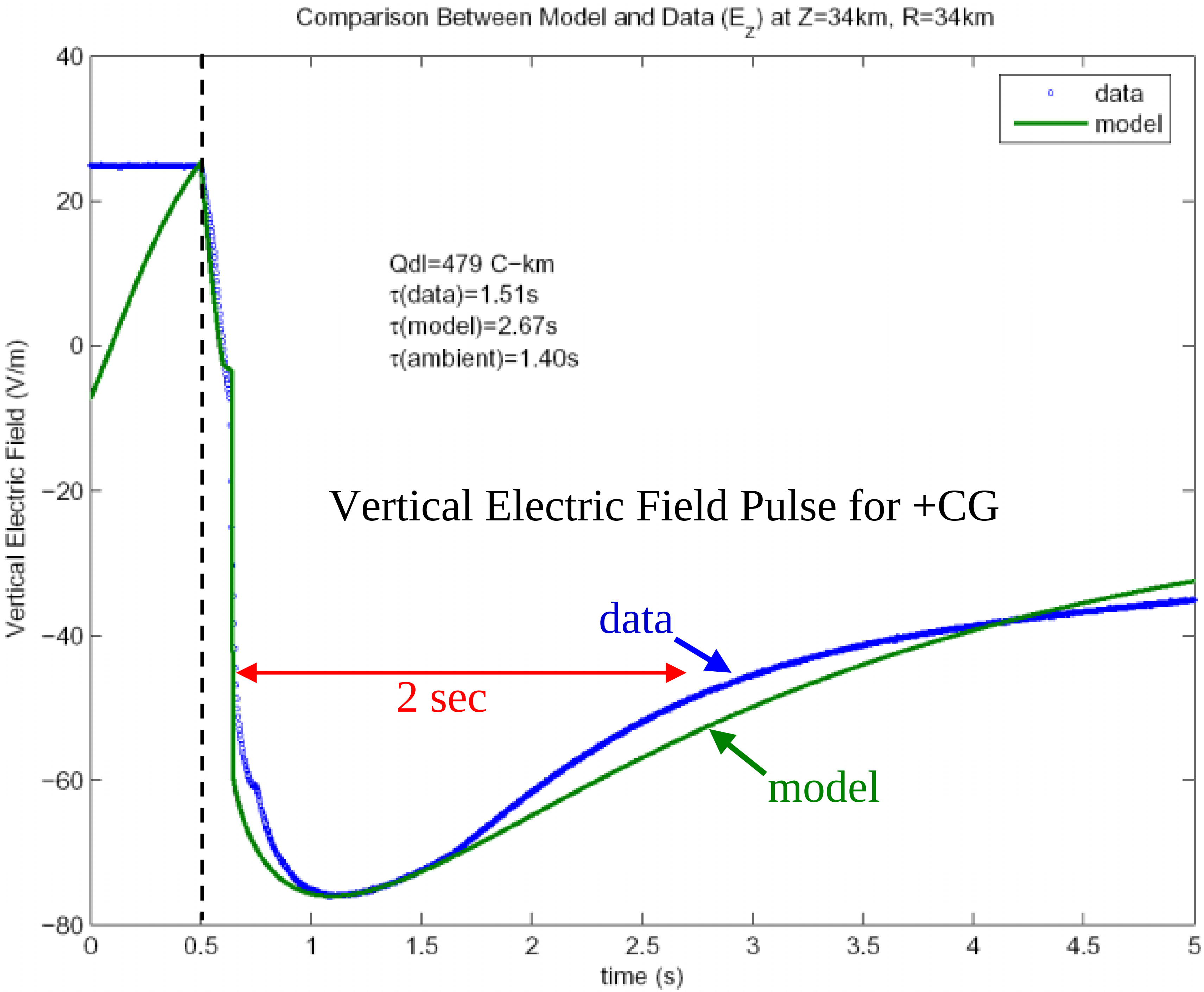


ELF Data from Syowa, Antarctica

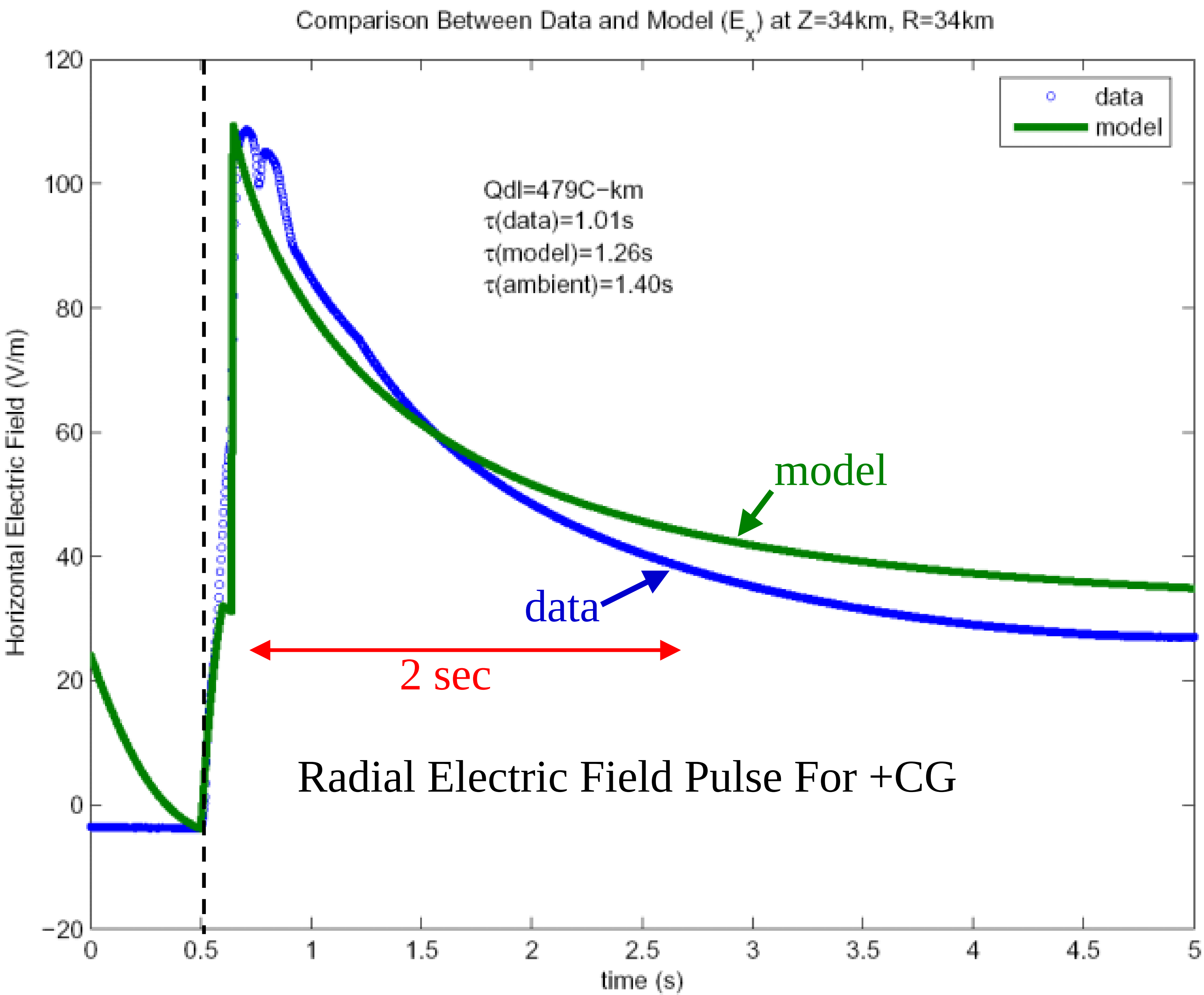
DC Electric Field Change Driven by +CG (Probable Sprite Event)



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
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
Vertical Electric Field (V/m)
time (s)
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

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

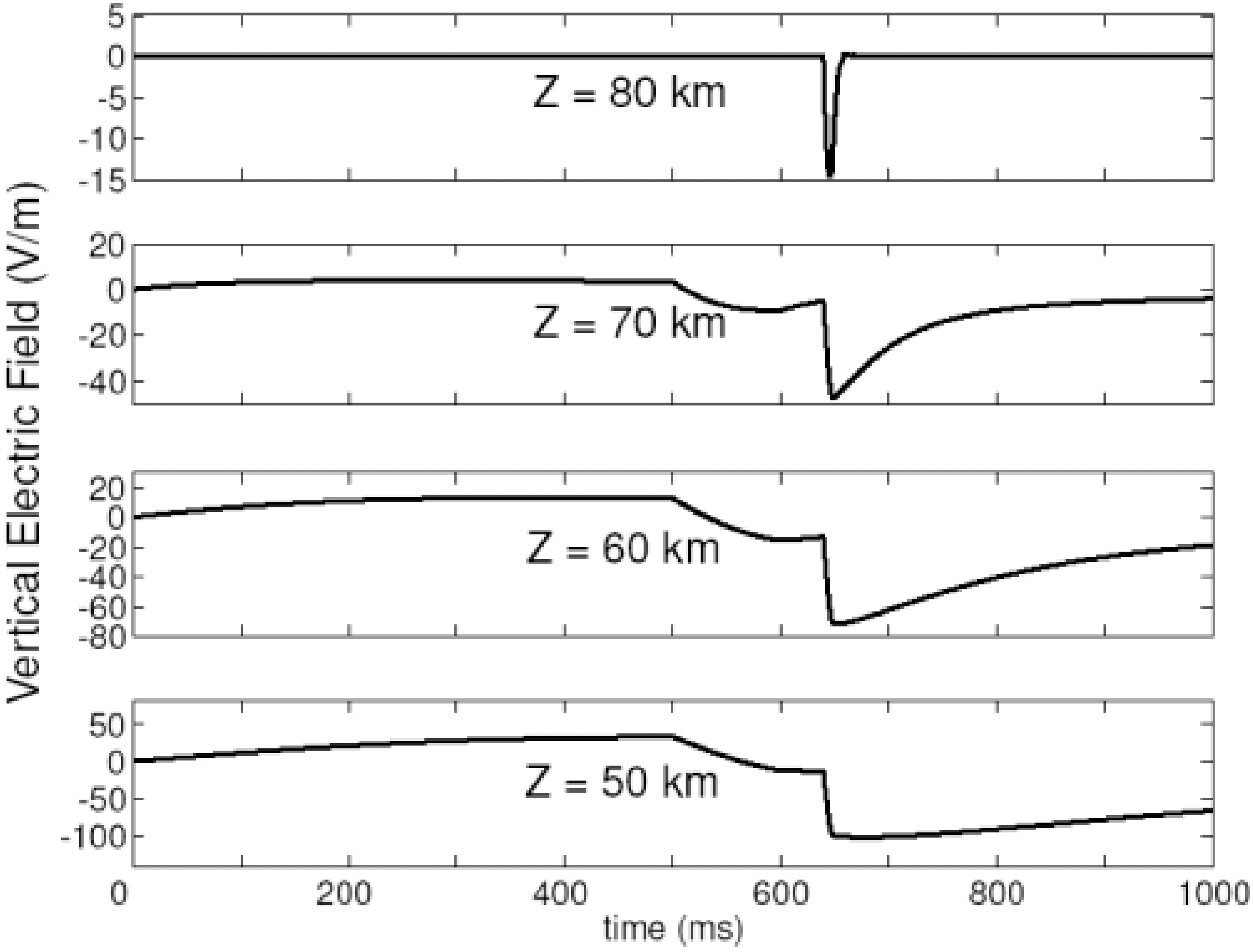
Breakdown Thresholds

•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.

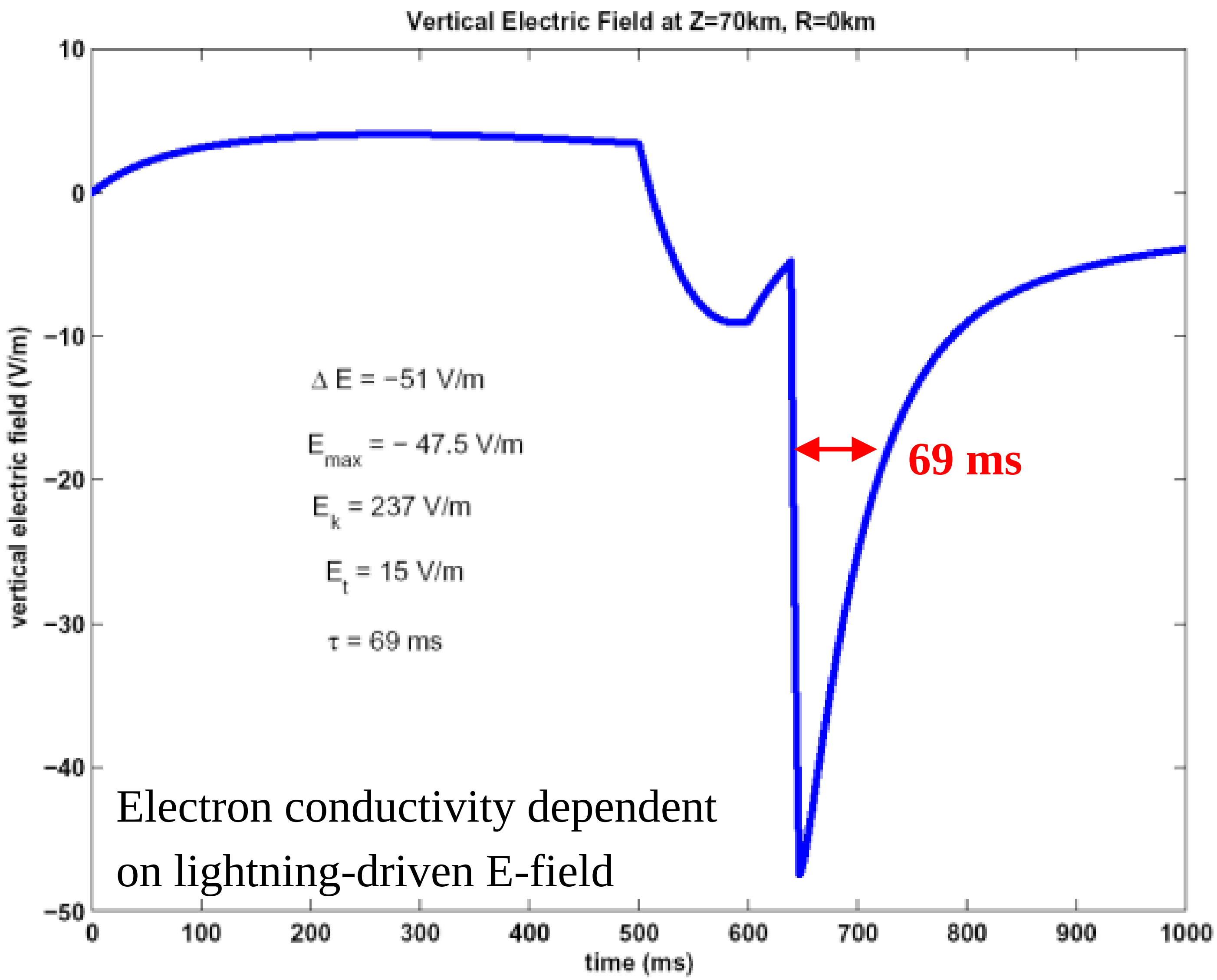
•Relativistic Runaway (E_t): electric field magnitude needed for a 1 MeV electron to initiate a electron avalanche, $E_t = 2 \times 10^5$ V/m at STP.

•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.

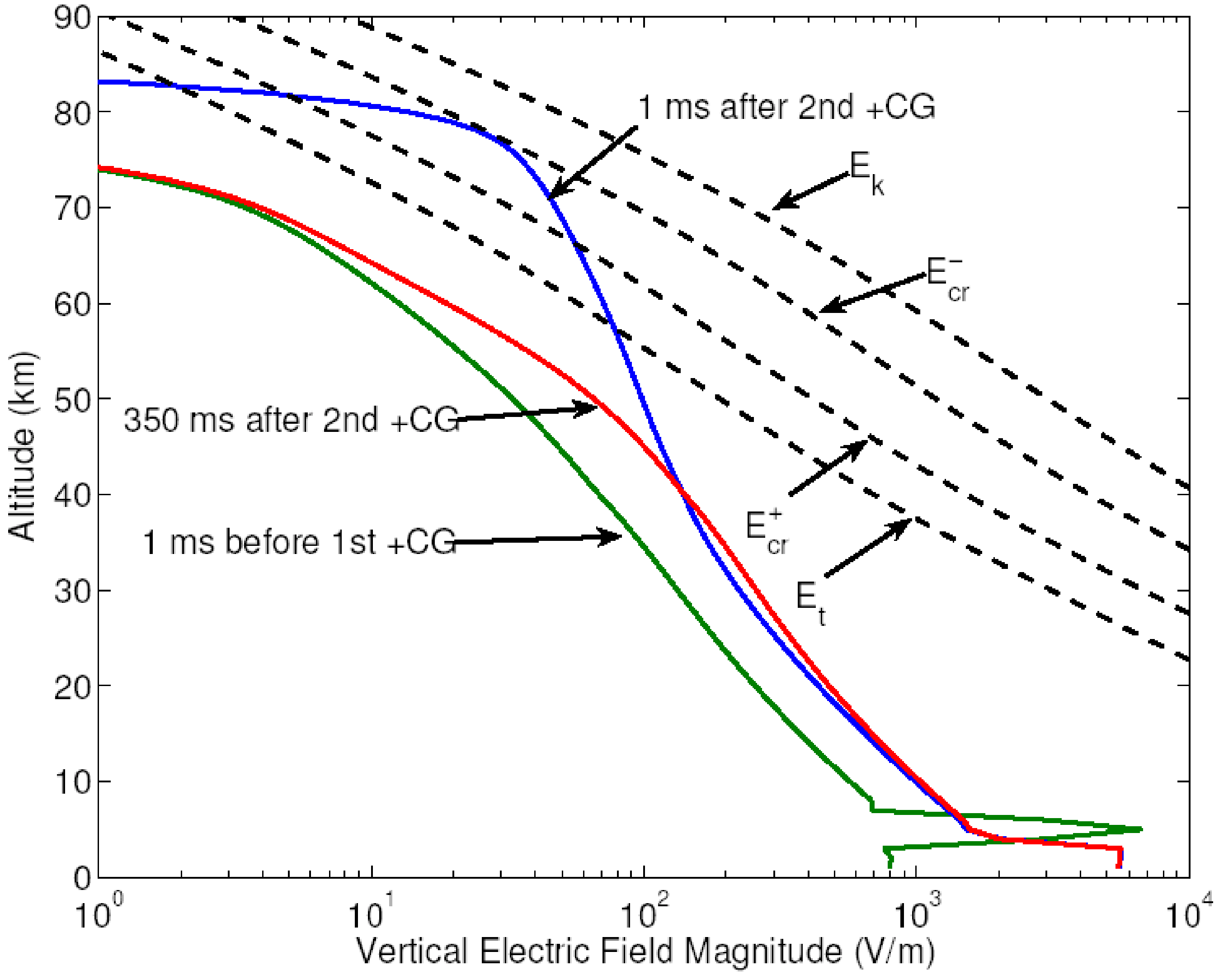
Model Output: Predicted lightning-driven electric fields at sprite altitudes (Z=50-80km)



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



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



Case Study Conclusions

- QSF approach is valid for modeling lightning-driven fields
- The electric field never surpasses the conventional electrical breakdown but does surpass the relativistic breakdown and positive streamer threshold.
- The duration of the electric field pulse at sprite altitudes is relatively long (τ = 69 ms at 70 km).
- Better electron conductivity profiles are needed to more accurately model these electric field pulses at sprite altitudes

ELF to VLF electric and magnetic fields from distant (75-600 km) CG lightning

•Electric field measured in 25 Hz - 8 kHz band

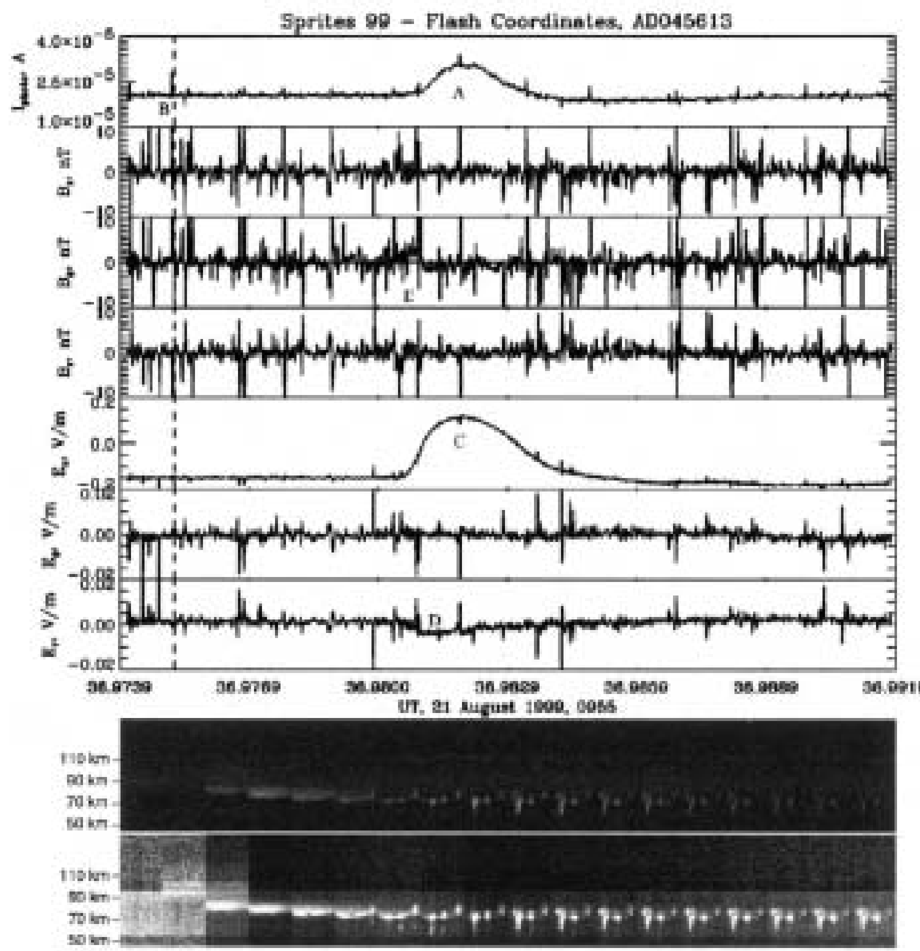
•Magnetic field measured in 300 Hz - 8 kHz band

•Electric field changes were measured for each of the 2467 CG strokes measured by a ground-based network.

•Magnetic field changes were measured for 35% of these CG strokes. High background noise prevented magnetic field measurements for all the CGs.

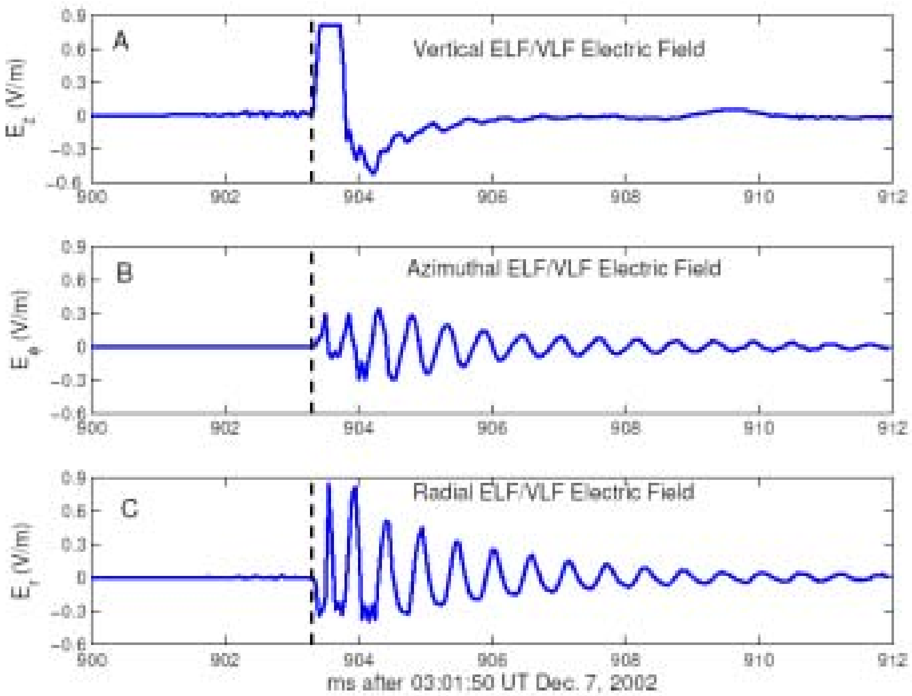
Previous stratospheric ELF measurements during Sprites99

Sprites99 rarely measured the CG sferic but often measured CG delayed pulses which were sometimes correlated with sprites and halos.

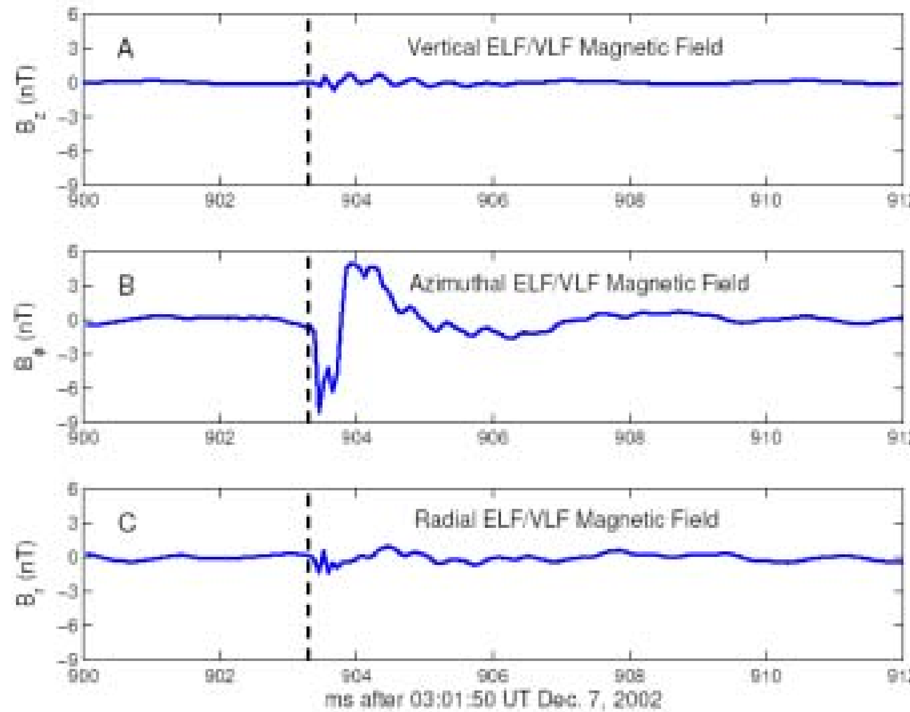


A delayed pulse correlated with sprites [Bering et al., Adv. Space Res., 34, 1782, 2004].

ELF to VLF electric and magnetic fields from a +111 kA CG stroke 328 km from payload



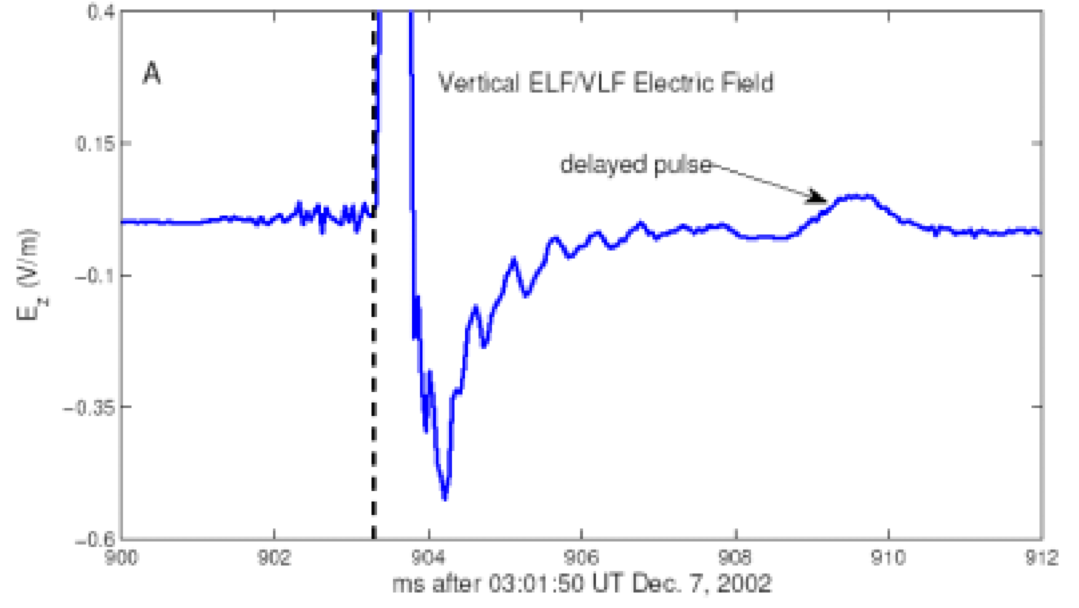
Electric Field

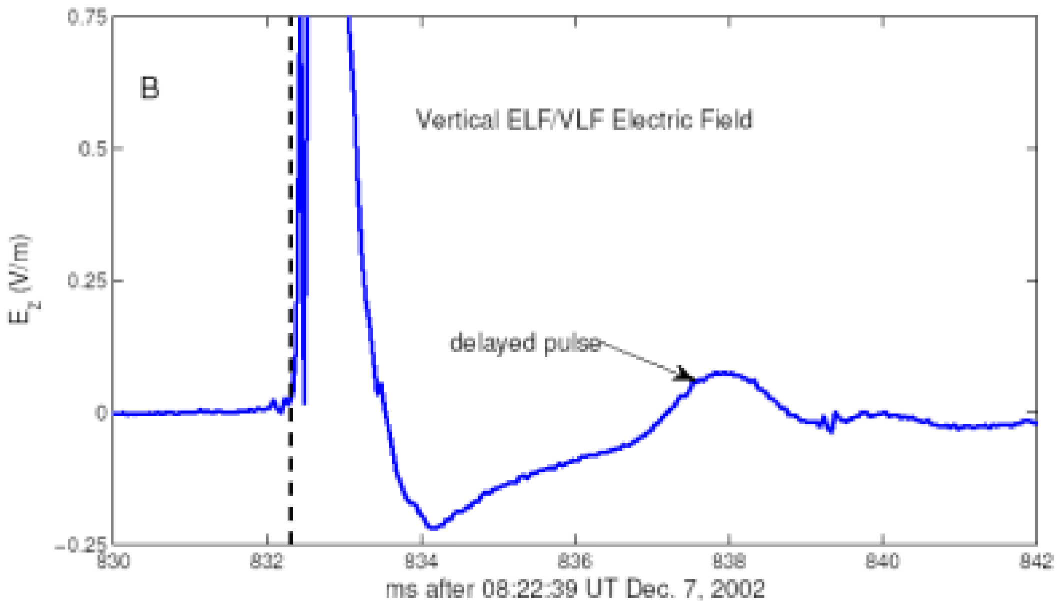


Magnetic Field

CG delayed pulses: Possible evidence of mesospheric currents

+111 kA CG
328 km from
payload





+101 kA CG 410 km
from payload (after
sunrise)

Summary of ELF to VLF electric and magnetic fields from distant (75-600 km) CG lightning

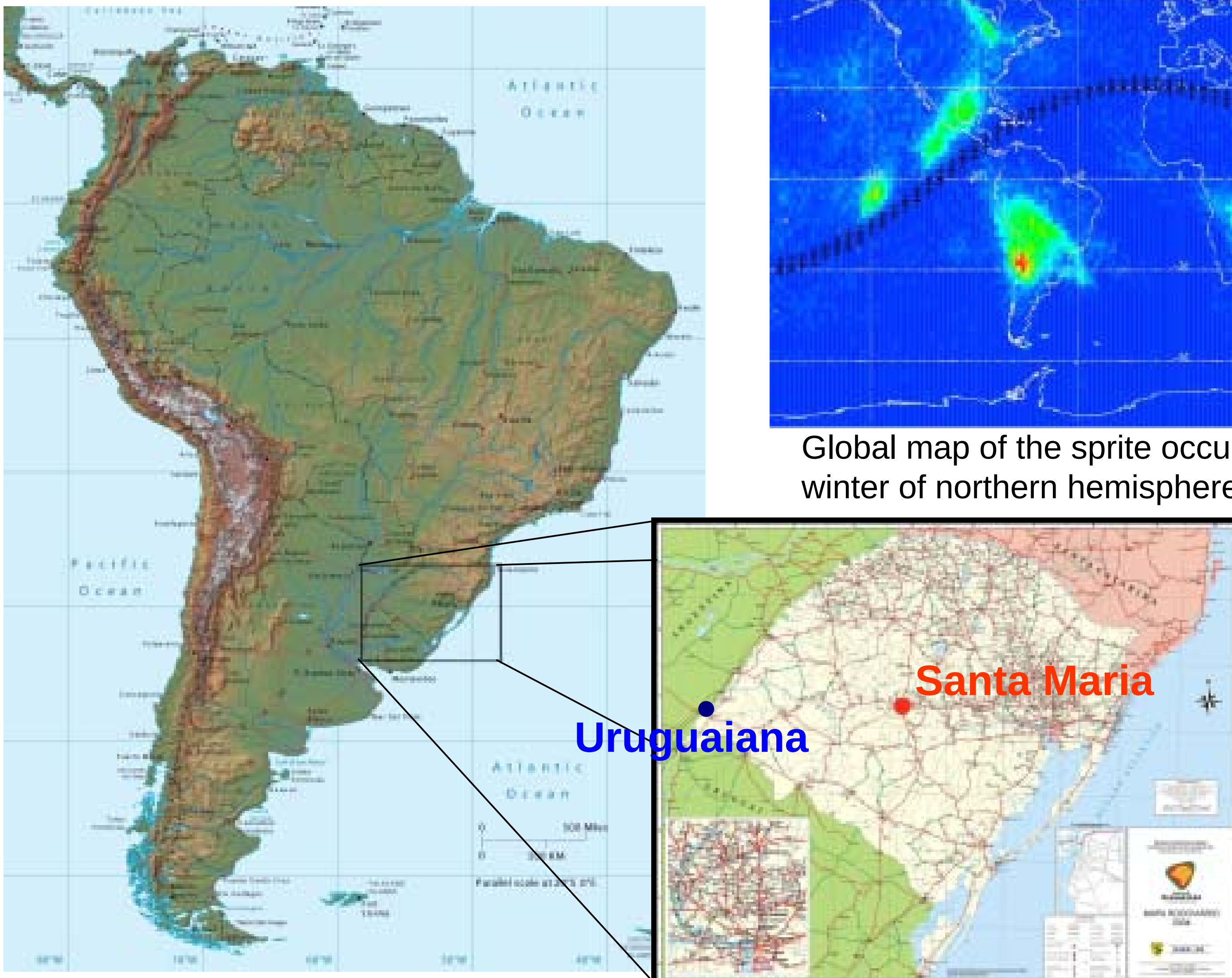
•ELF to VLF fields were measured for every CG stroke detected by the ground-based network. For 2% (15/750) of -CGs and 17% (31/184) of +CGs a CG delayed pulse was measured which may indicate mesospheric current.

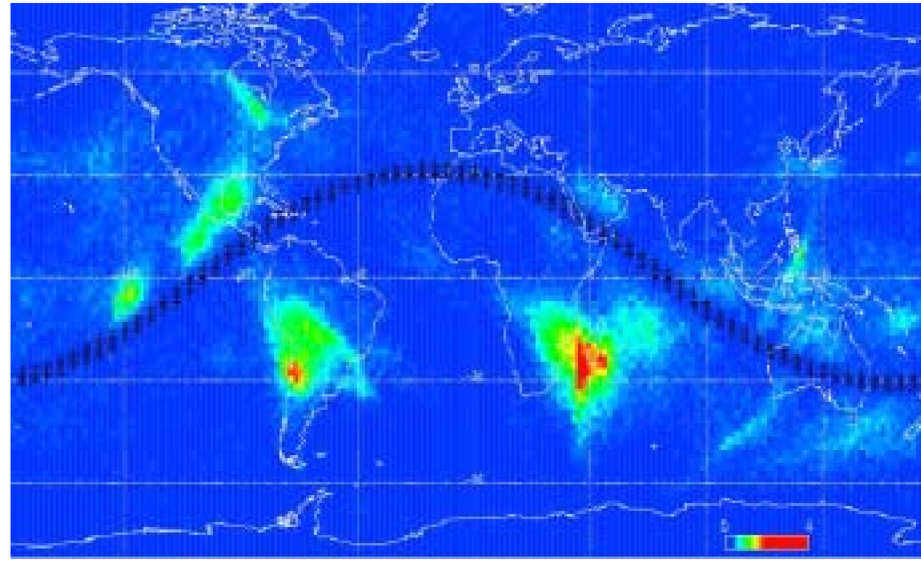
•This bias to +CGs suggests that mesospheric currents are driven by large charge moment strokes and that the QSF from these strokes initiate the mesospheric breakdown.

•This disagrees with the Sprites99 payloads which rarely measured the CG sferics but for 90% of CG strokes measured a delayed ELF pulse [Bering et al., Adv. Space Res., 34, 1782, 2004; Bhusal et al., Adv. Space Res., 34, 1811, 2004].

South Brazil Sprites Campaign 2006

UW/USU/INPE/Duke





Global map of the sprite occurrence regions in fall and winter of northern hemisphere (Sato & Fukunishi, 2003)


Front
(card)
Side
02/14/2006