1994 CEDAR Workshop Tutorial #3

Ionospheric Effects of Lightning Discharges

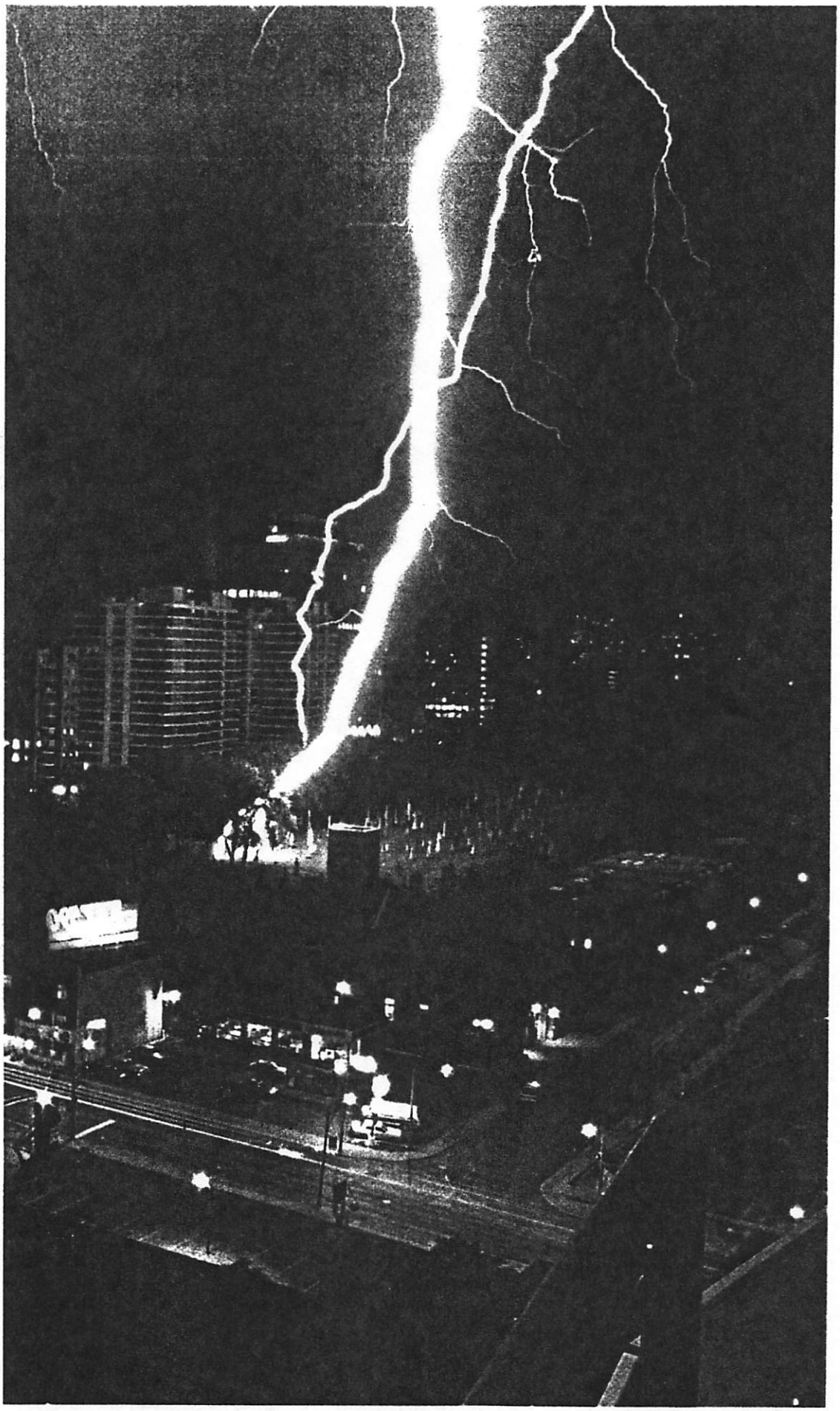
by Umran Inan / Stanford Univ.

Topics to be discussed:

* Lightning-induced electron precipitation (LEP)
* Lightning fields in the ionosphere
* Lightning-induced acceleration of ionospheric electrons
* Lightning-induced heating of the lower ionosphere
* Upward (cloud-to-stratosphere) lightning
* Intense ionospheric VHF fields
* Lightning-associated gamma ray flashes
* Ion heating above thunderstorms

Topics not discussed:

* Generation of magnetospheric hiss by lightning
* Quasi-static (dc?) electric fields
* Discharge physics
* Lightning and x-rays
* Planetary lightning
* Other



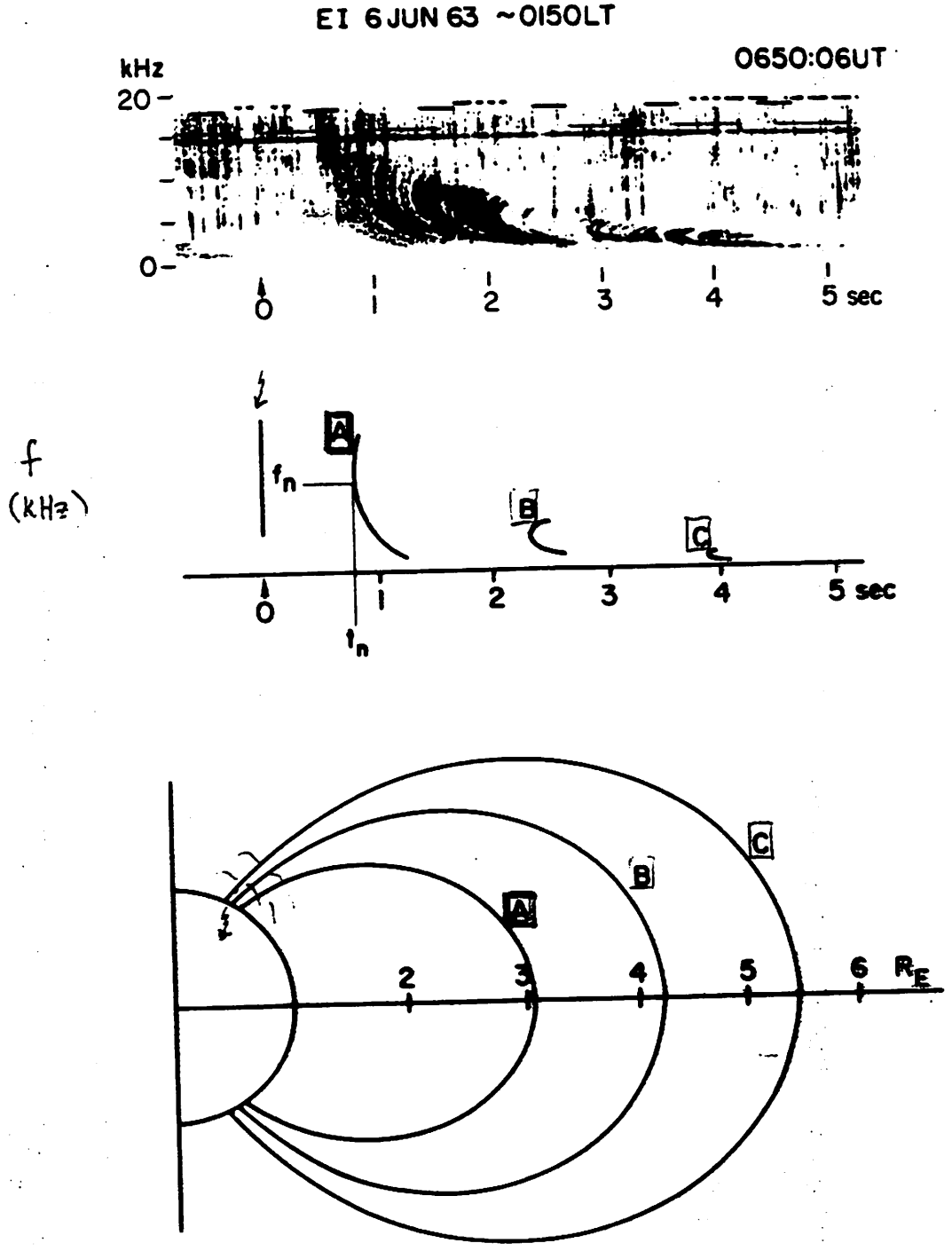


FIGURE 2.5 A TYPICAL WHISTLER EVENT. This event was observed at Eights (EI), Antarctica, on 6 June 1963 at 0150 Local Time (LT). This time corresponds to 0650:06 Universal Time (UT). The top panel shows the frequency time spectrogram. The middle panel is a sketch of the 'spheric' and three of the many individual traces of the whistler. The lower panel shows the magnetospheric paths traveled by the three traces [Park, 1972].

Helliwell [1965]

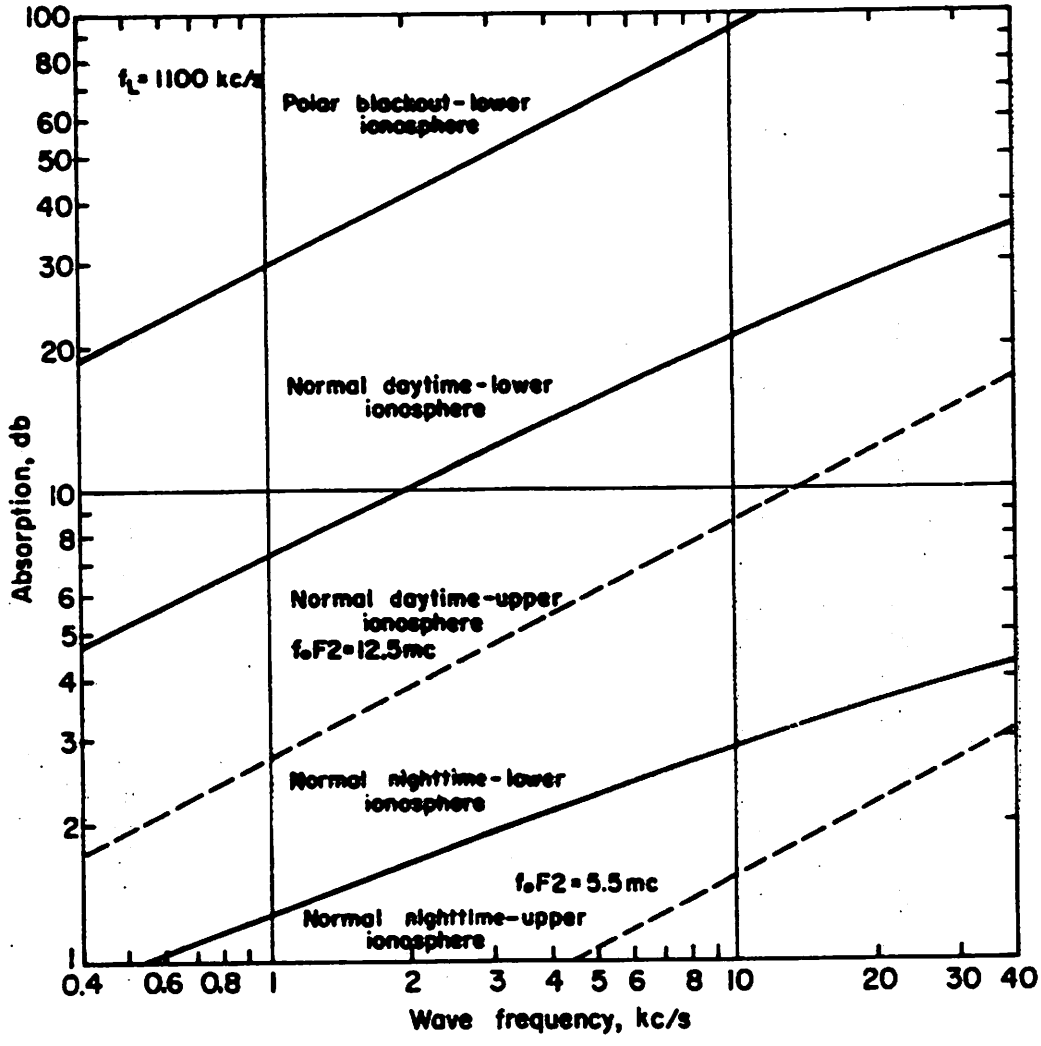
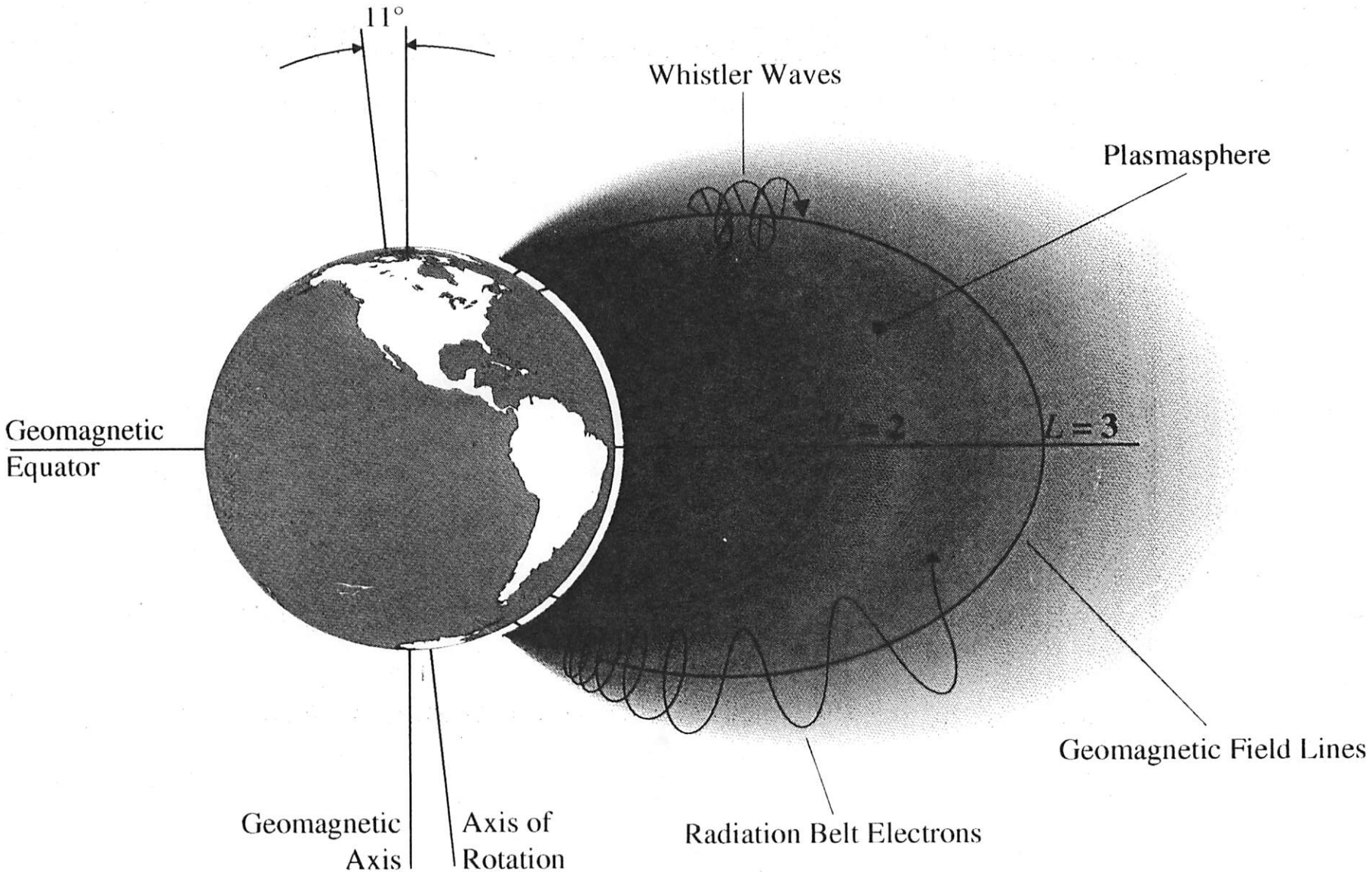
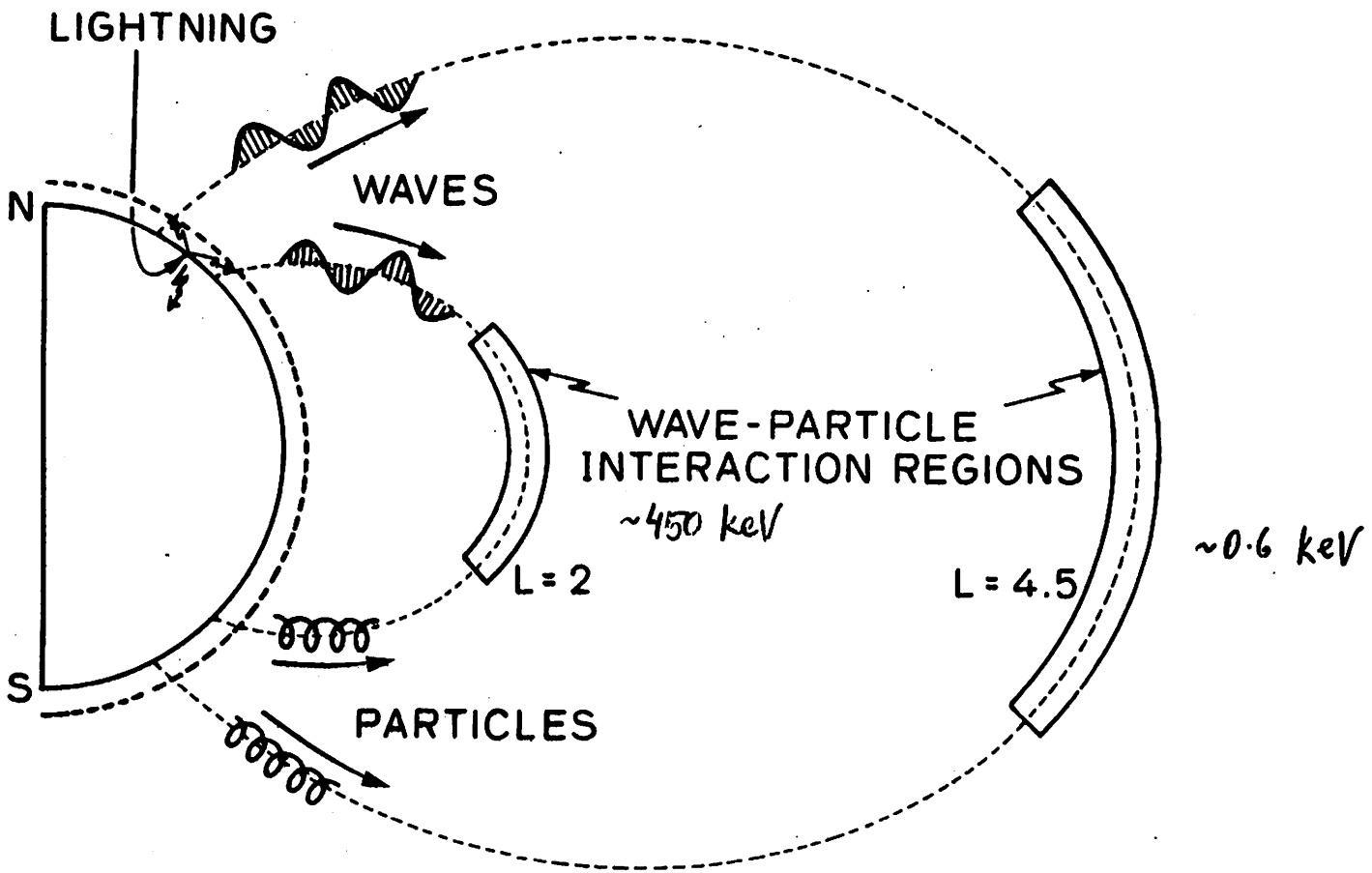
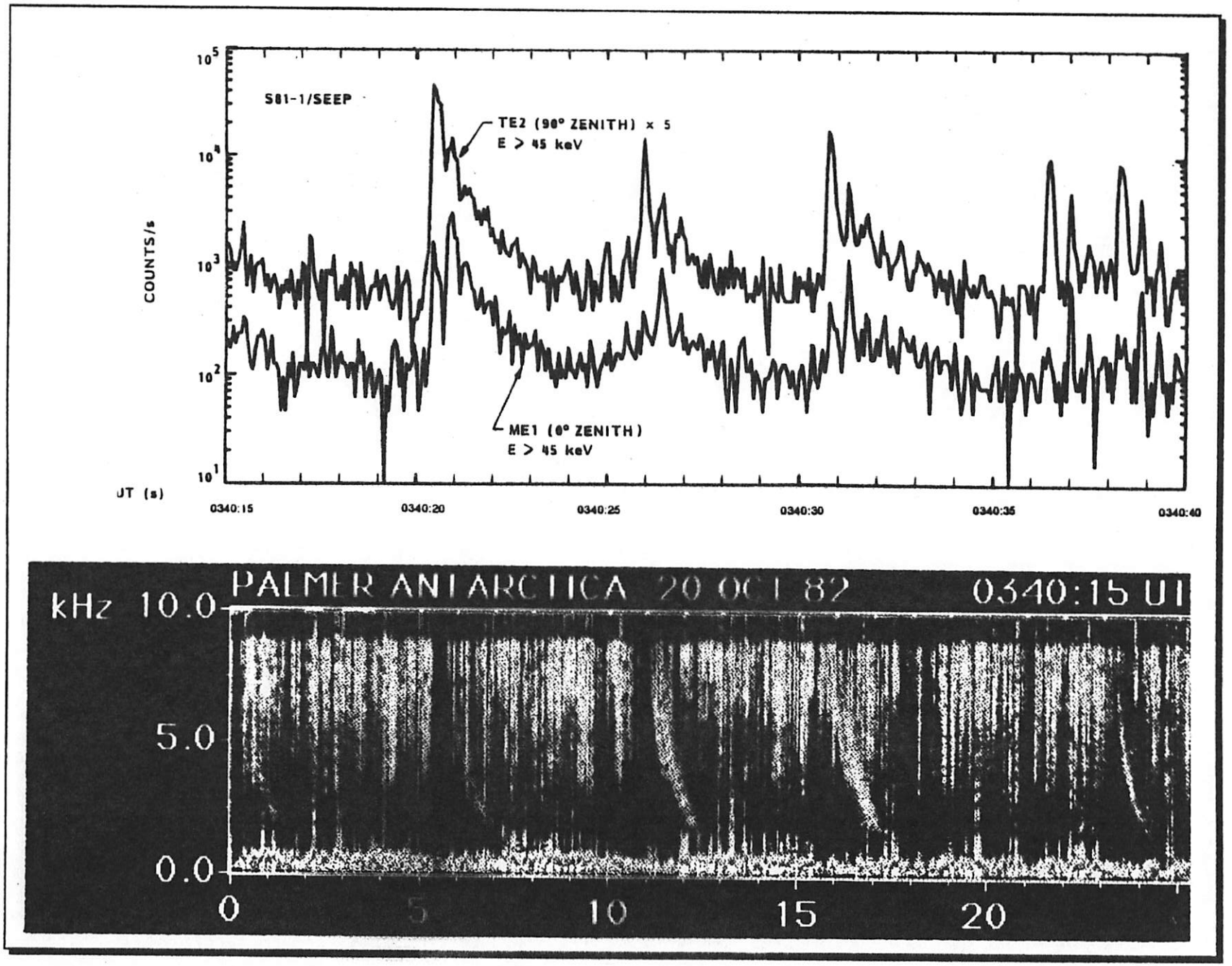


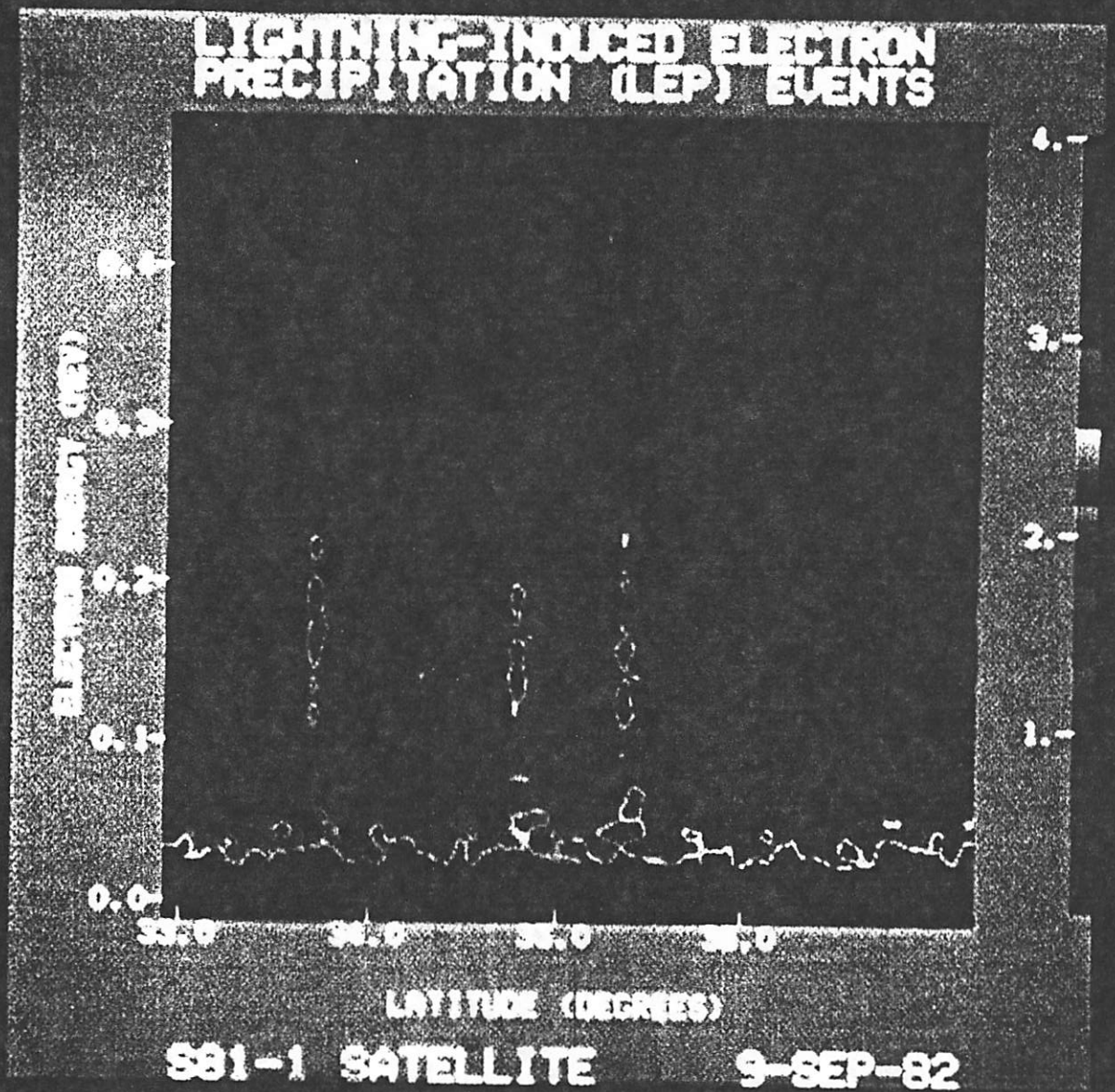
FIG. 3-31. Integrated absorption as a function of wave frequency for different models of the upper and lower ionosphere; normal daytime $f_0F2 = 12.5$ mc/s; normal nighttime $f_0F2 = 5.5$ mc/s.

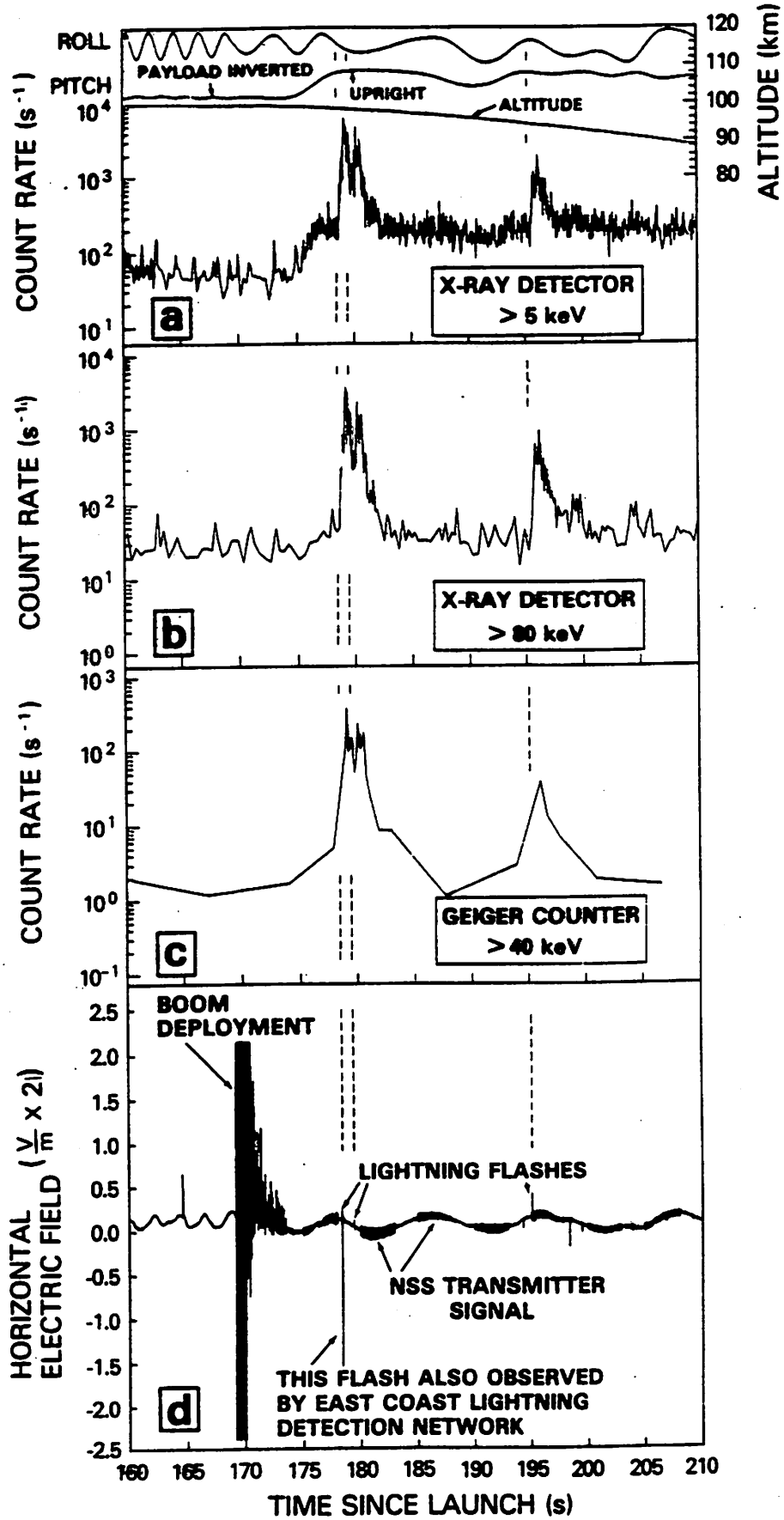

11°
Whistler Waves
Plasmasphere
Geomagnetic
Equator
L = 2
L = 3
Geomagnetic Field Lines
Geomagnetic
Axis
Axis of
Rotation
Radiation Belt Electrons

5 kHz


LIGHTNING
N
WAVES
WAVE-PARTICLE
INTERACTION REGIONS
~450 keV
L = 2
L = 4.5
~0.6 keV
S
PARTICLES

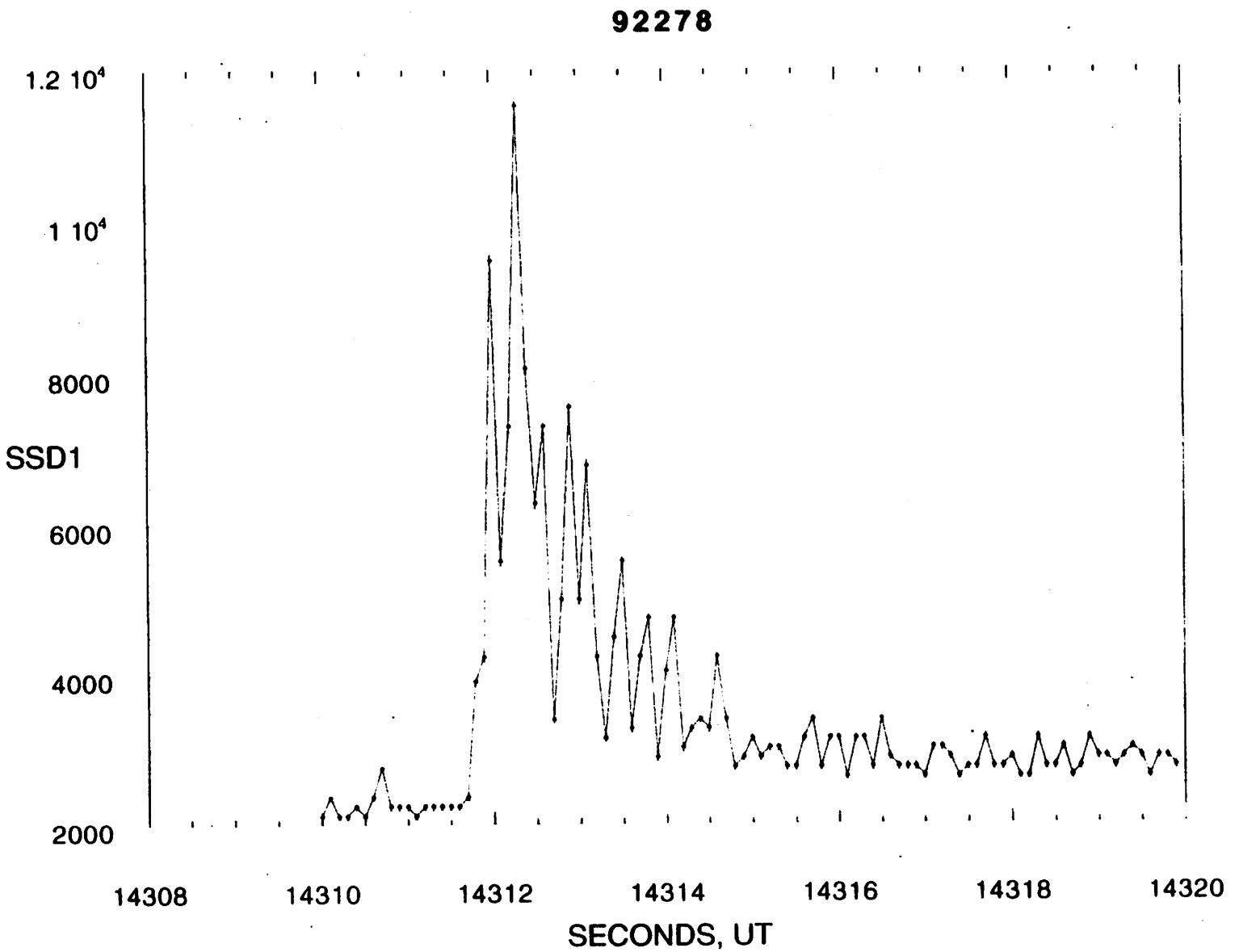

S81-1/SEEP
TE2 (90° ZENITH) x 5
E > 45 keV
ME1 (0° ZENITH)
E > 45 keV
COUNTS/s
UT (s)
0340:15
0340:20
0340:25
0340:30
0340:35
0340:40
PALMER ANTARCTICA 20 OCT 82
0340:15 UT
kHz 10.0
5.0
0.0
0
5
10
15
20

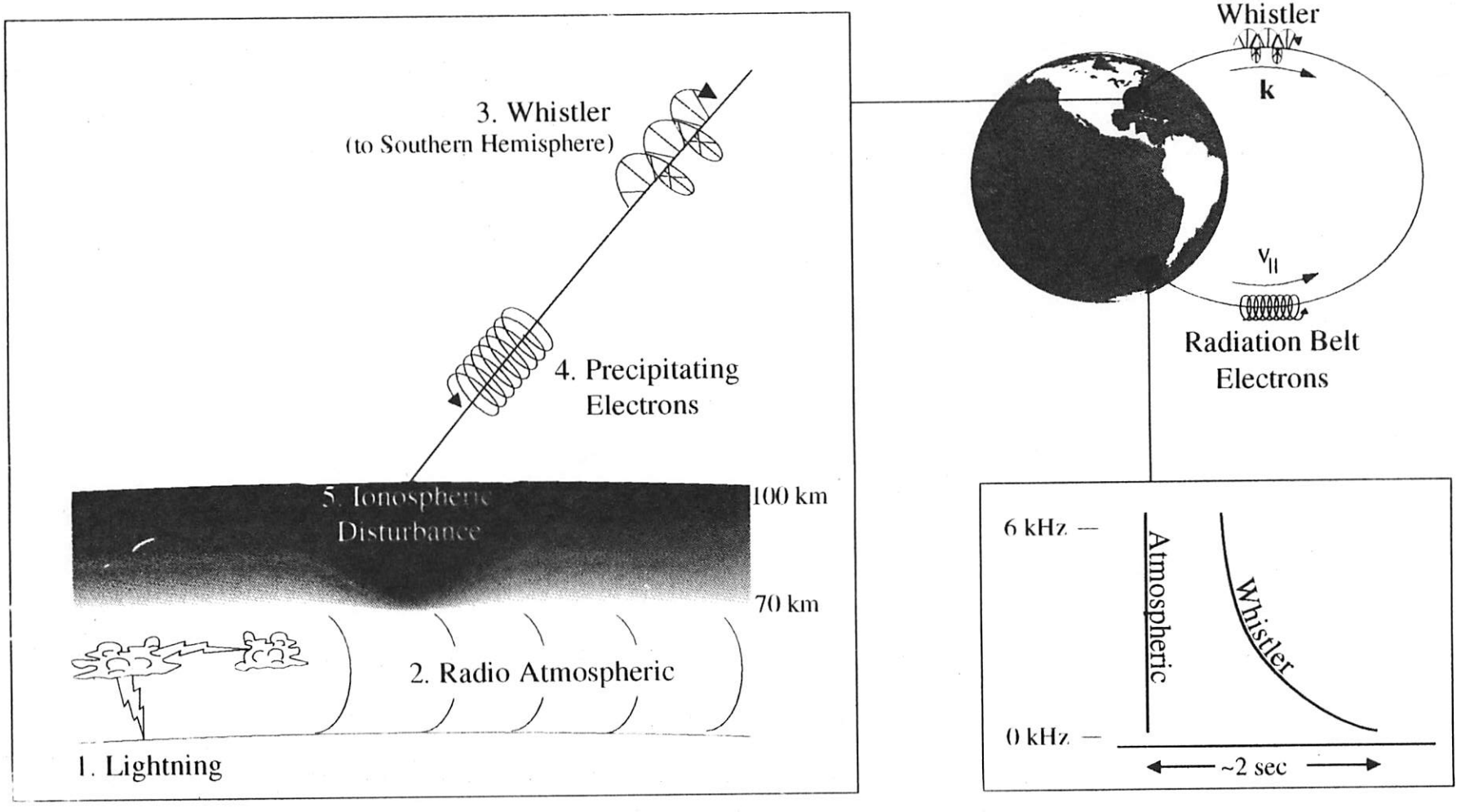

LIGHTNING-INDUCED ELECTRON
PRECIPITATION (LEP) EVENTS
0.4
0.3
0.2
0.1
0.0
4.
3.
2.
1.
LATITUDE (DEGREES)
S81-1 SATELLITE
9-SEP-82

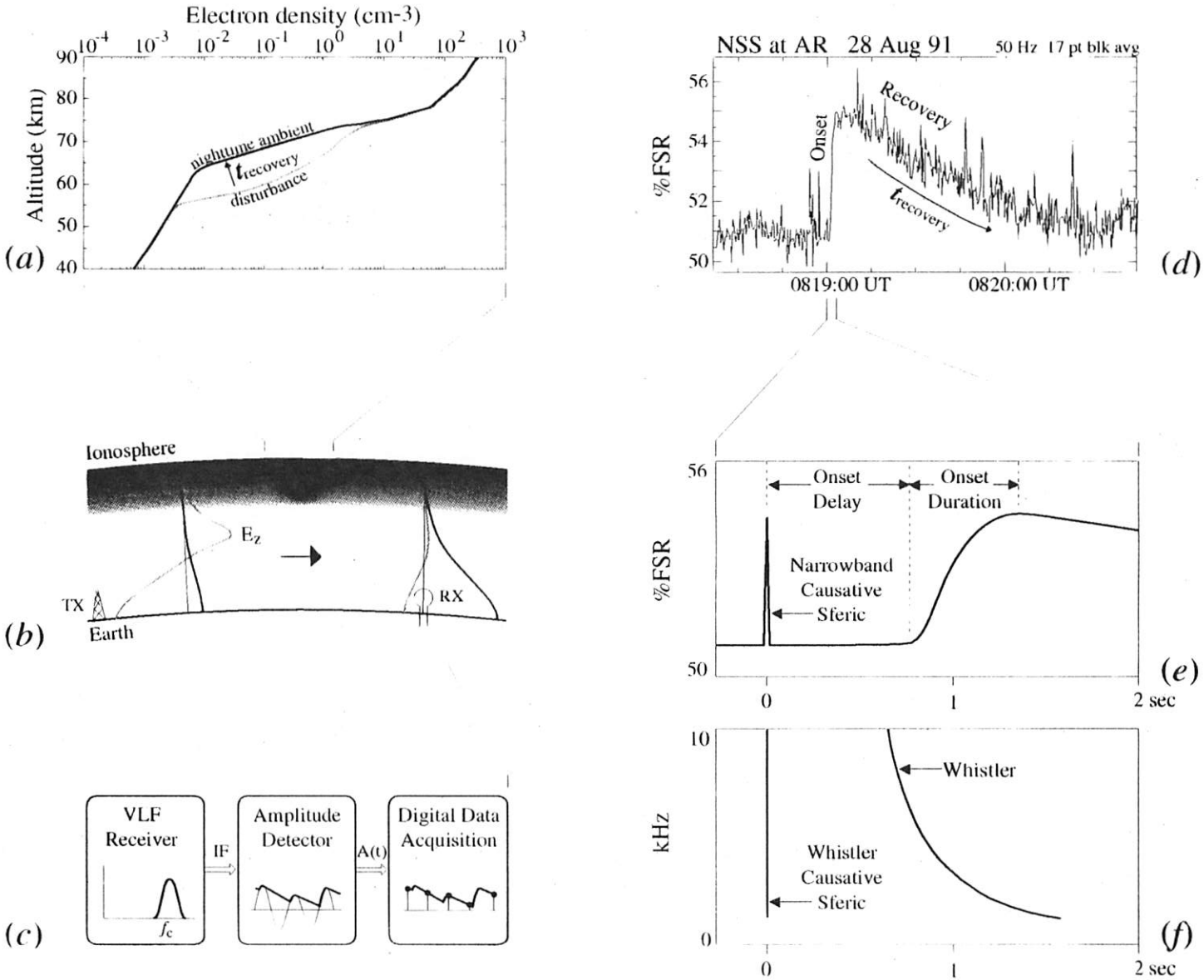

ROLL
PITCH
PAYLOAD INVERTED
UPRIGHT
ALTITUDE
120
110
100
90
80
ALTITUDE (km)
COUNT RATE (s⁻¹)
10^4
10^3
10^2
10^1
a
X-RAY DETECTOR
> 5 keV
10^4
10^3
10^2
10^1
10^0
b
X-RAY DETECTOR
> 80 keV
10^3
10^2
10^1
10^0
10^{-1}
c
GEIGER COUNTER
> 40 keV
HORIZONTAL ELECTRIC FIELD ($\frac{V}{m}$ x 2)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
BOOM DEPLOYMENT
LIGHTNING FLASHES
NSS TRANSMITTER SIGNAL
THIS FLASH ALSO OBSERVED BY EAST COAST LIGHTNING DETECTION NETWORK
d
160
165
170
175
180
185
190
195
200
205
210
TIME SINCE LAUNCH (s)

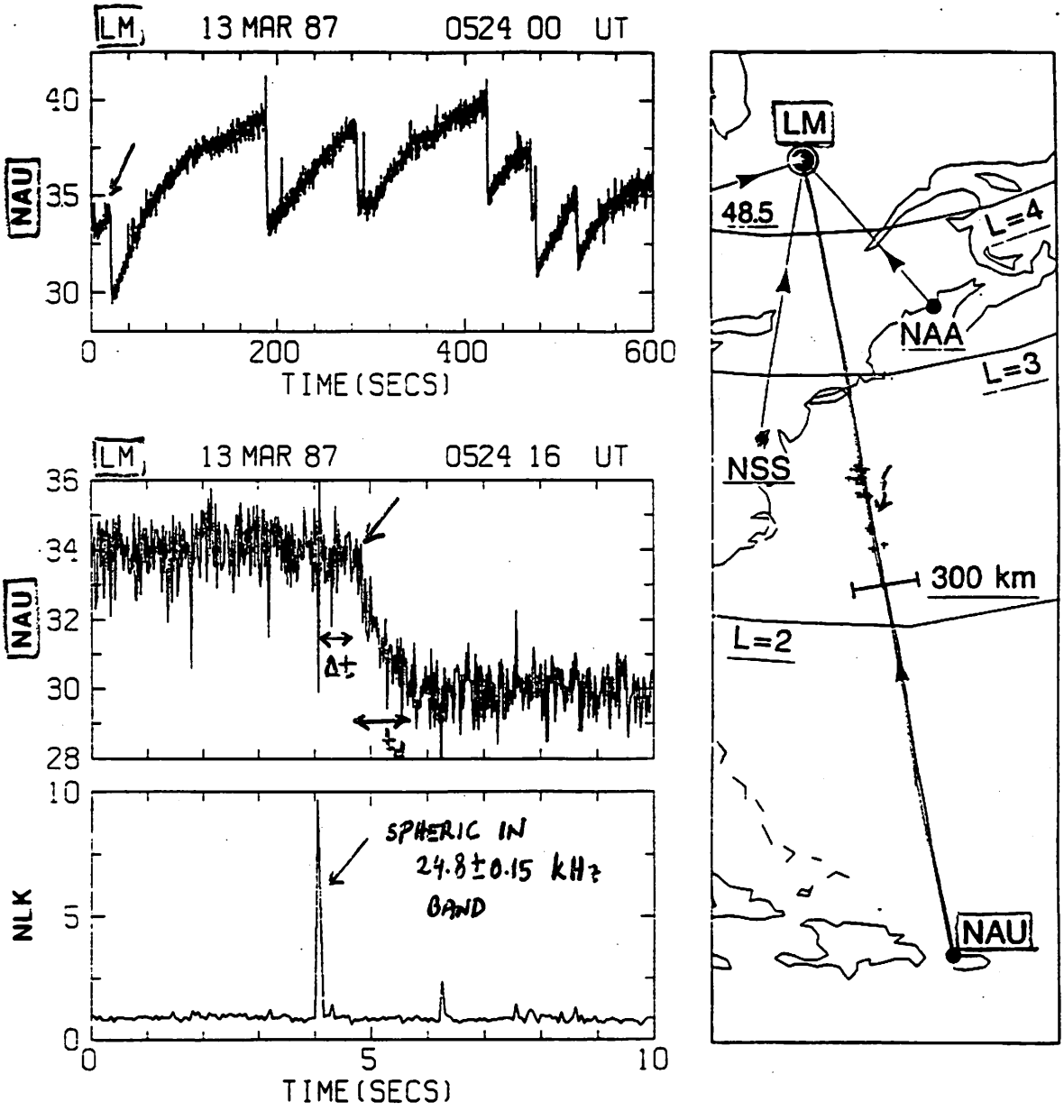
SAMPEX
Dr. B. Blake / Aerospace Corp.

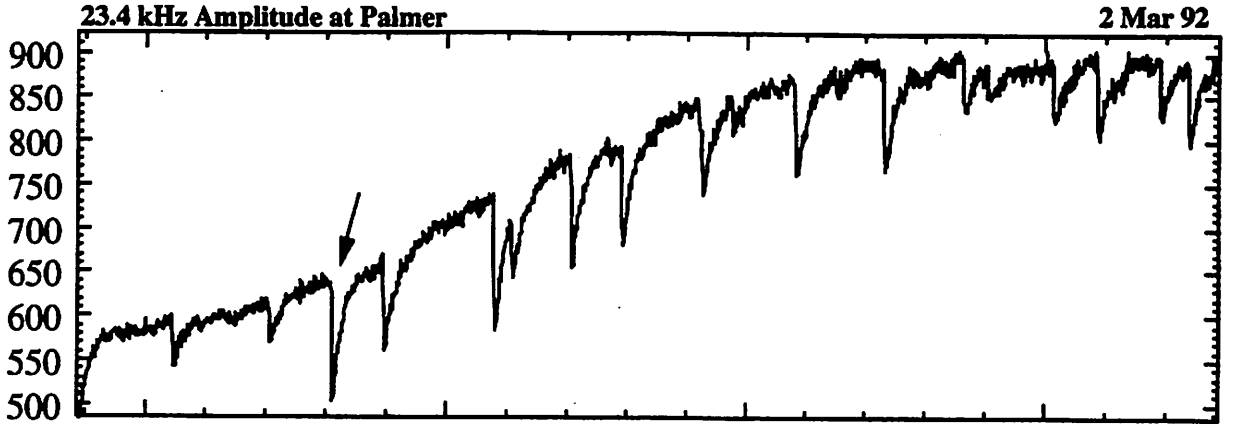
600-km/L=5

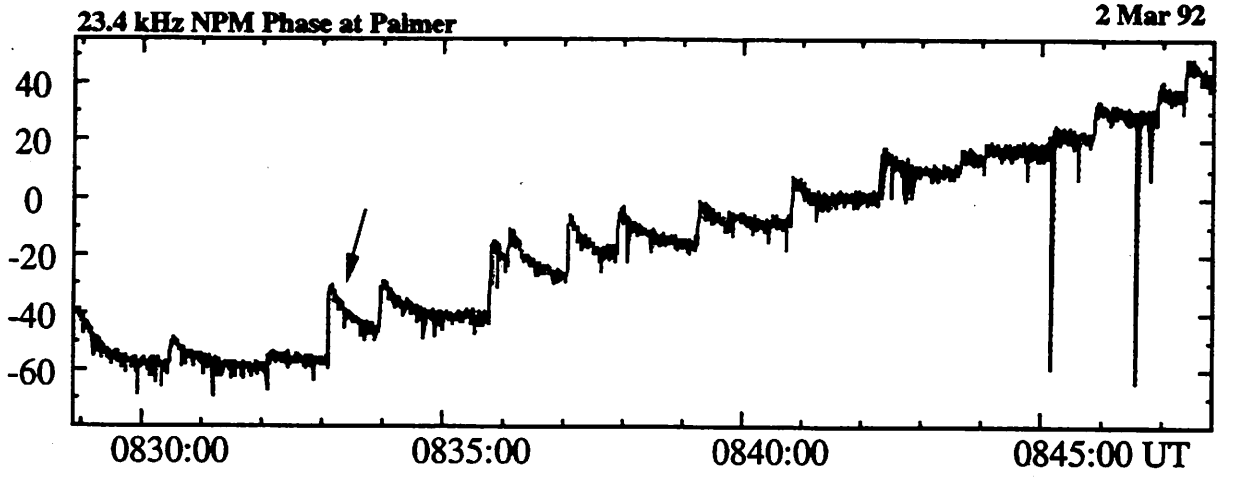


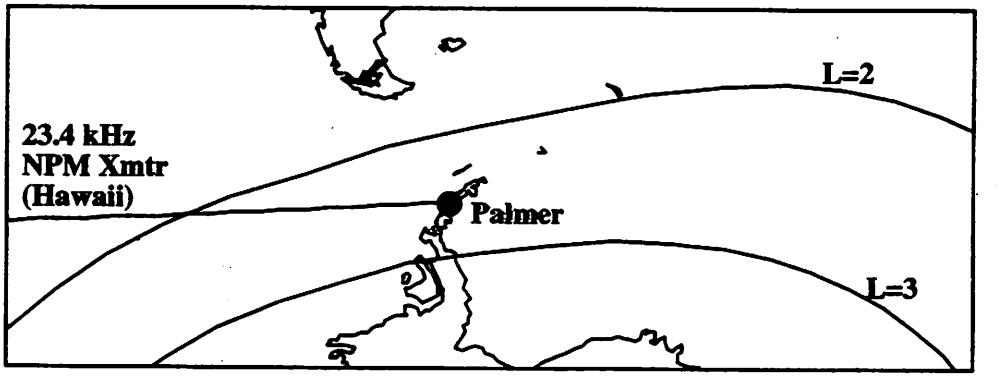

3. Whistler
(to Southern Hemisphere)
4. Precipitating
Electrons
5. Ionospheric
Disturbance
100 km
70 km
2. Radio Atmospheric
1. Lightning
Whistler
k
$v_{||}$
Radiation Belt
Electrons
6 kHz
0 kHz
Atmospheric
Whistler
~2 sec

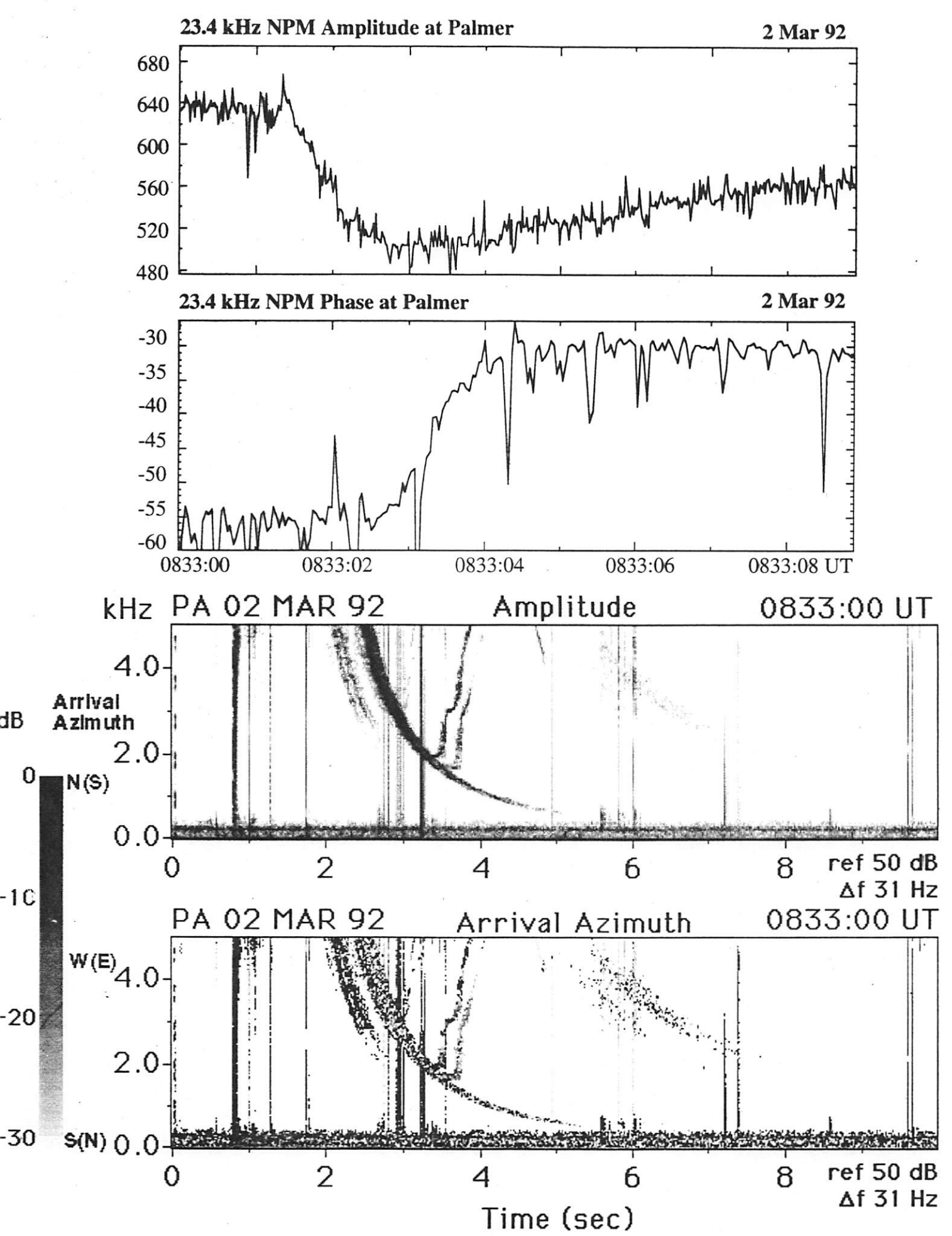

Electron density (cm-3)
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Altitude (km)
90 80 70 60 50 40
nighttime ambient
$t_{recovery}$
disturbance
(a)
Ionosphere
E_z
TX
RX
Earth
(b)
VLF Receiver
f_c
IF
Amplitude Detector
A(t)
Digital Data Acquisition
(c)
NSS at AR 28 Aug 91
50 Hz 17 pt blk avg
%FSR
56 54 52 50
Onset
Recovery
$t_{recovery}$
0819:00 UT
0820:00 UT
(d)
Onset Delay
Onset Duration
Narrowband Causative Sferic
0 1 2 sec
(e)
kHz
10 0
Whistler
Whistler Causative Sferic
0 1 2 sec
(f)

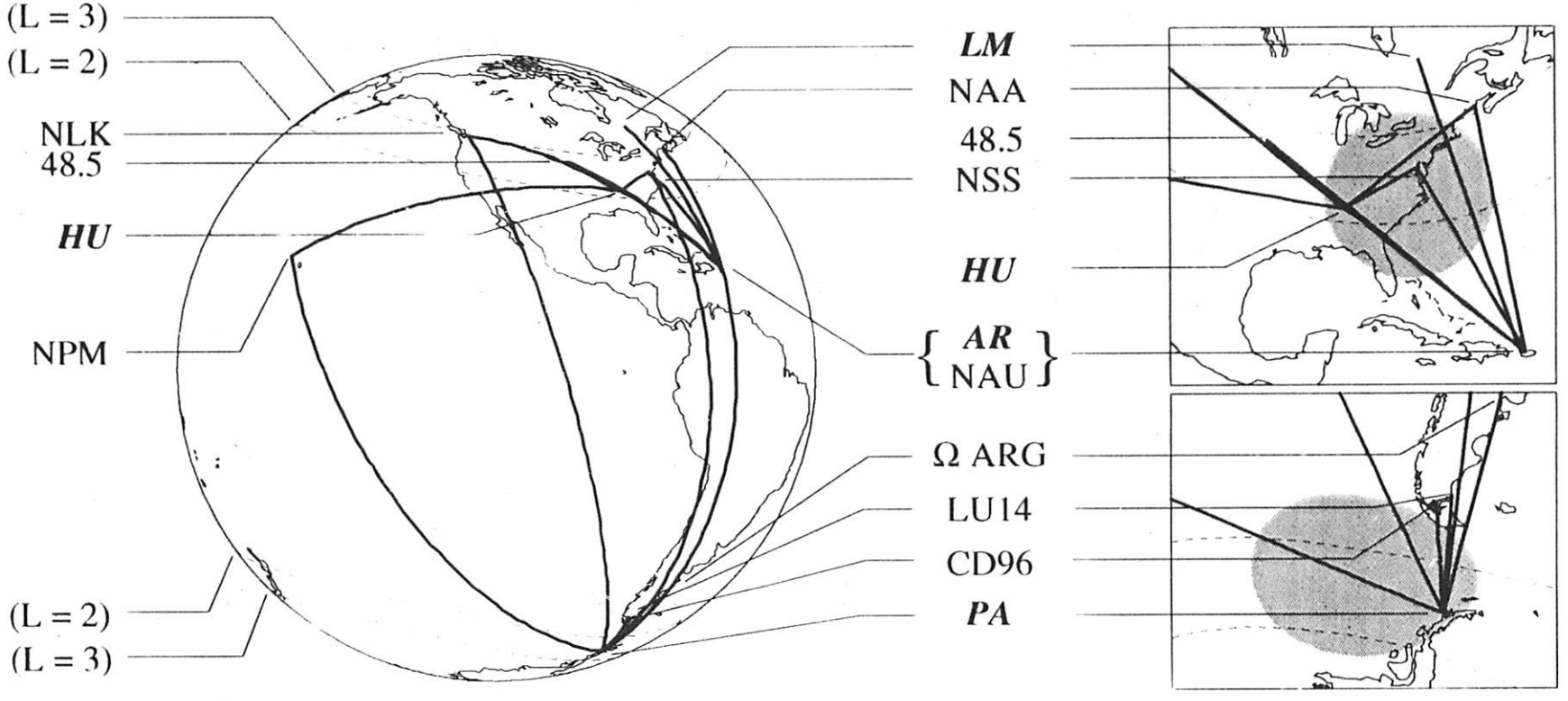

LM
13 MAR 87
0524 00 UT
NAU
40
35
30
0
200
400
600
TIME (SECS)
LM
13 MAR 87
0524 16 UT
NAU
36
34
32
30
28
Δt
Δt
NLK
10
5
0
SPHERIC IN
24.8±0.15 kHz
BAND
0
5
10
TIME (SECS)
LM
48.5
L=4
NAA
L=3
NSS
300 km
L=2
NAU

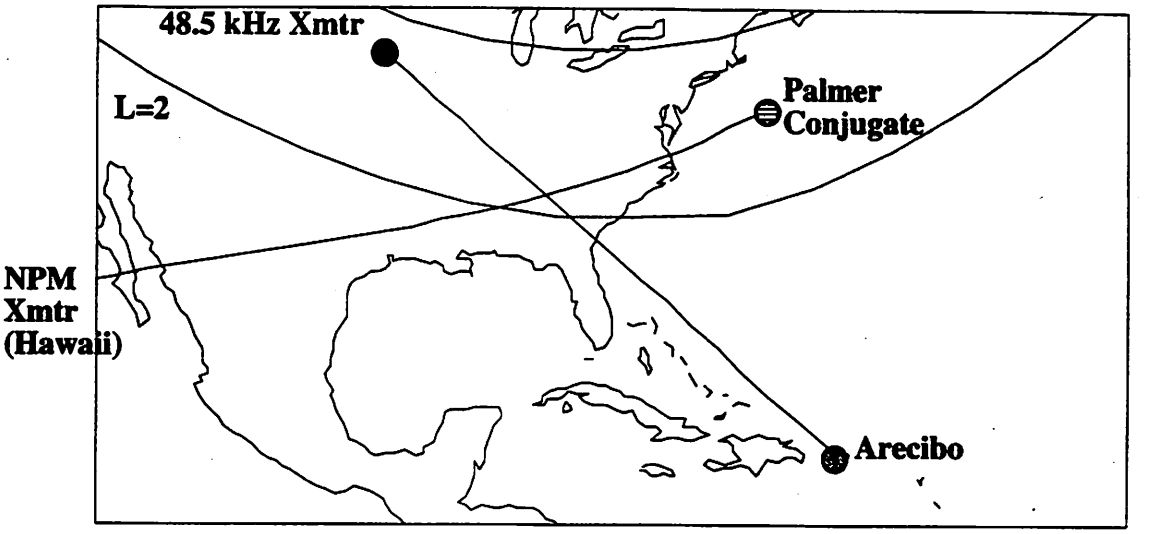

23.4 kHz Amplitude at Palmer
2 Mar 92
900
850
800
750
700
650
600
550
500

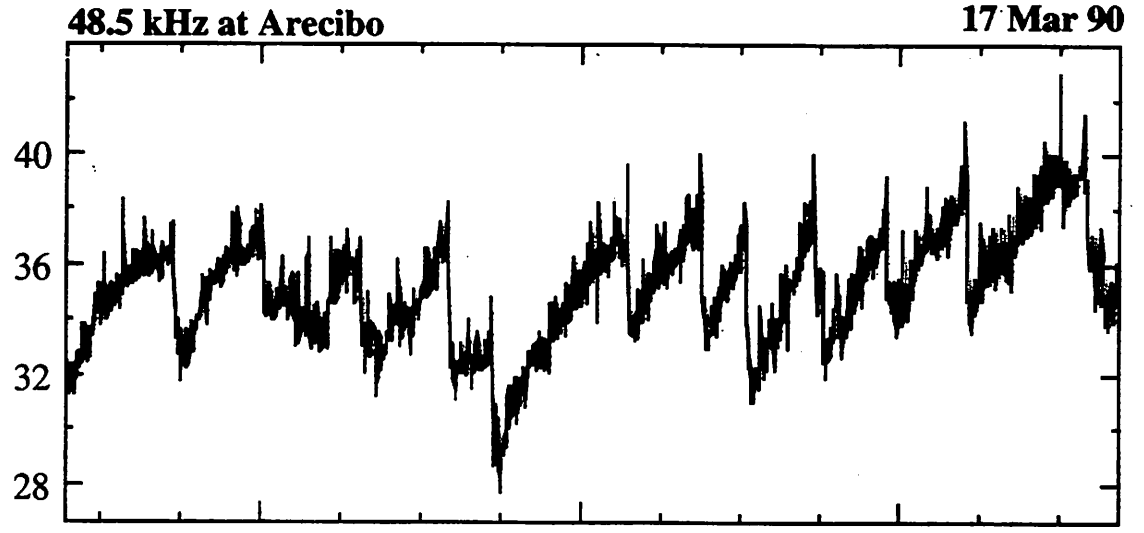

23.4 kHz NPM Phase at Palmer
2 Mar 92
40
20
0
-20
-40
-60
0830:00
0835:00
0840:00
0845:00 UT

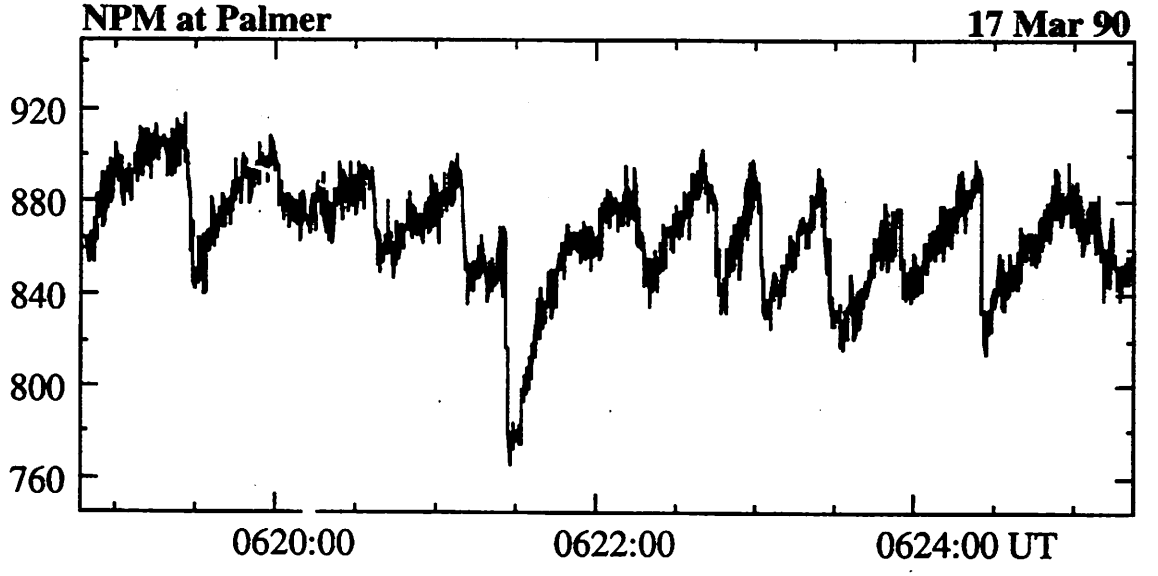

23.4 kHz
NPM Xmtr
(Hawaii)
L=2
Palmer
L=3

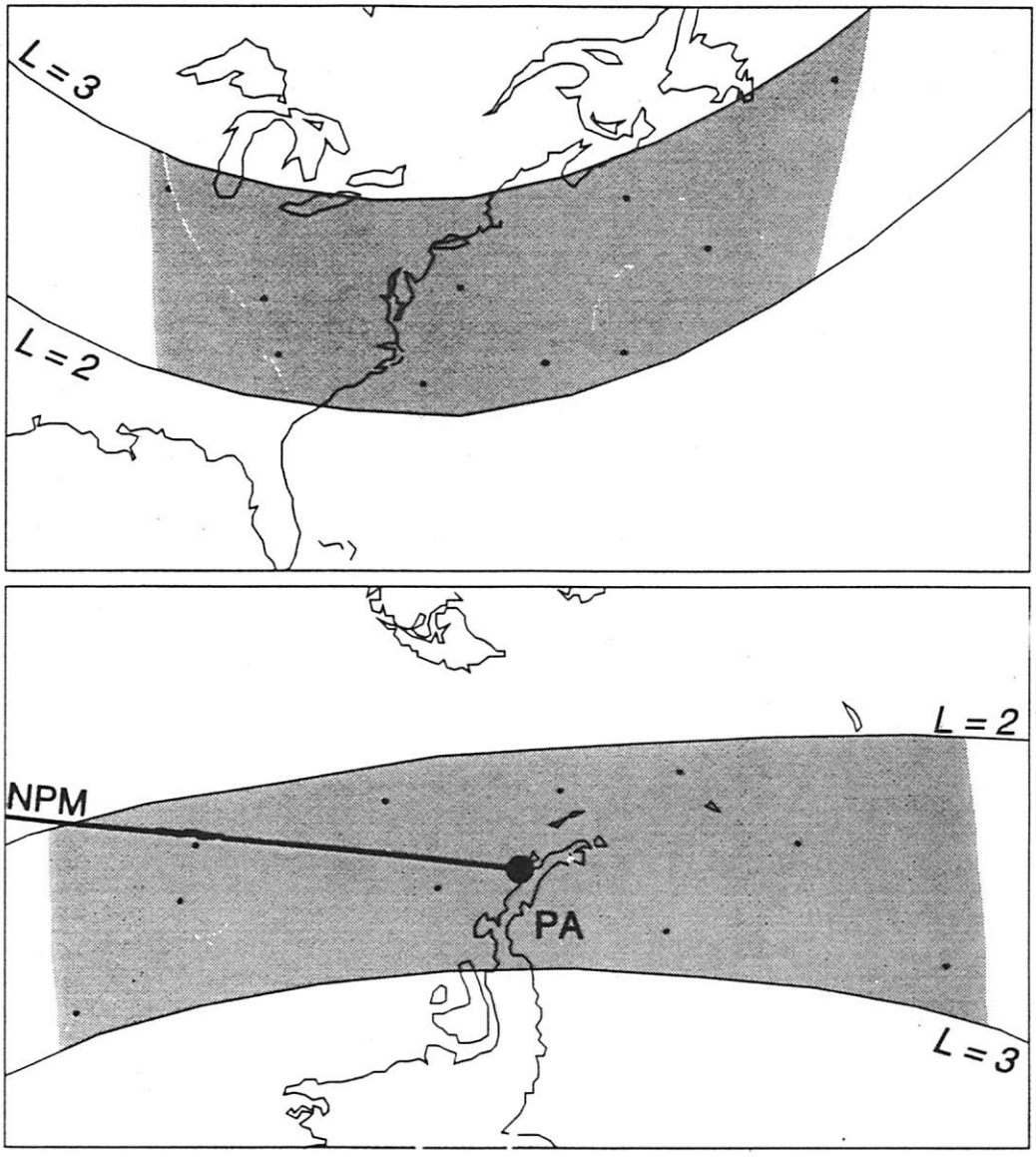

23.4 kHz NPM Amplitude at Palmer
2 Mar 92
680
640
600
560
520
480
23.4 kHz NPM Phase at Palmer
2 Mar 92
-30
-35
-40
-45
-50
-55
-60
0833:00
0833:02
0833:04
0833:06
0833:08 UT
kHz PA 02 MAR 92 Amplitude 0833:00 UT
4.0
2.0
0.0
0
2
4
6
8
ref 50 dB
Δf 31 Hz
dB
Arrival Azimuth
0
N(S)
-10
-20
-30
W(E)
S(N)
PA 02 MAR 92 Arrival Azimuth 0833:00 UT
4.0
2.0
0.0
0
2
4
6
8
ref 50 dB
Δf 31 Hz
Time (sec)


(L = 3)
(L = 2)
NLK
48.5
HU
NPM
(L = 2)
(L = 3)
LM
NAA
48.5
NSS
HU
AR
NAU
Ω ARG
LU14
CD96
PA

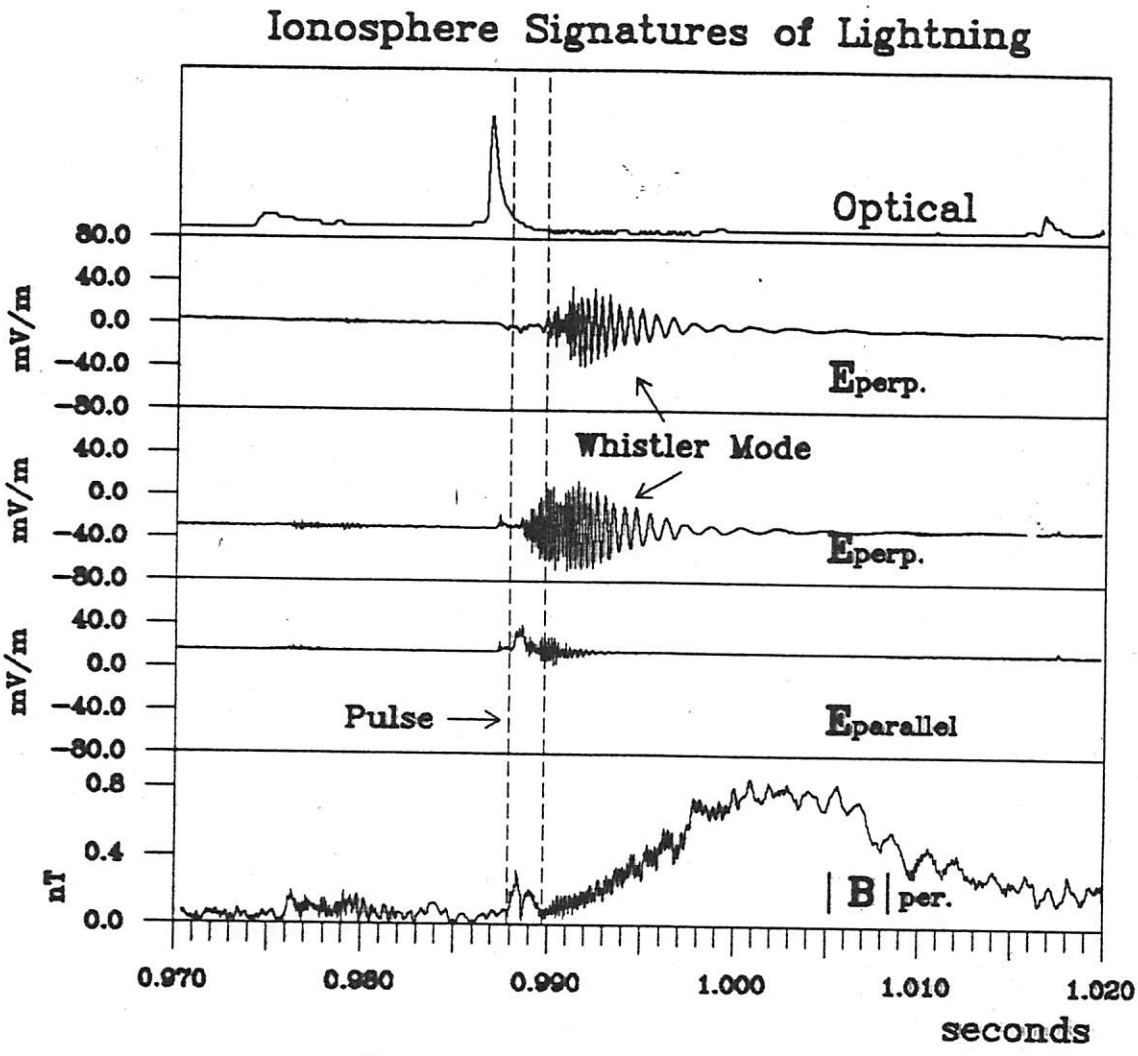

48.5 kHz Xmtr
L=2
Palmer
Conjugate
NPM
Xmtr
(Hawaii)
Arecibo

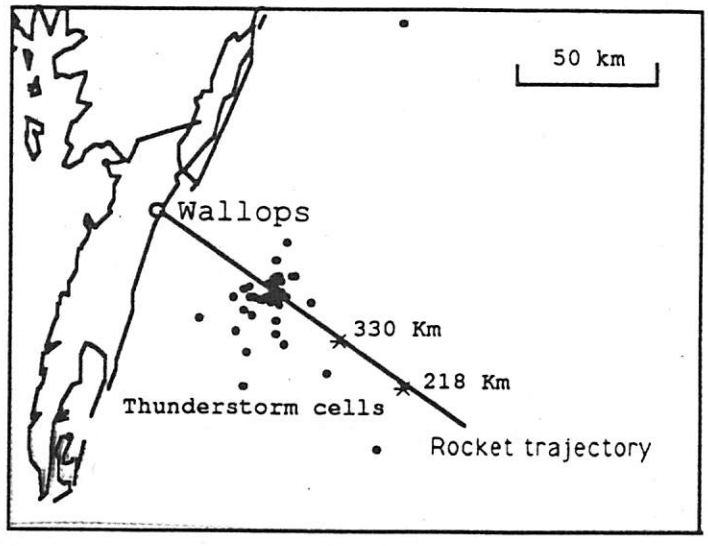

48.5 kHz at Arecibo
17 Mar 90
40
36
32
28

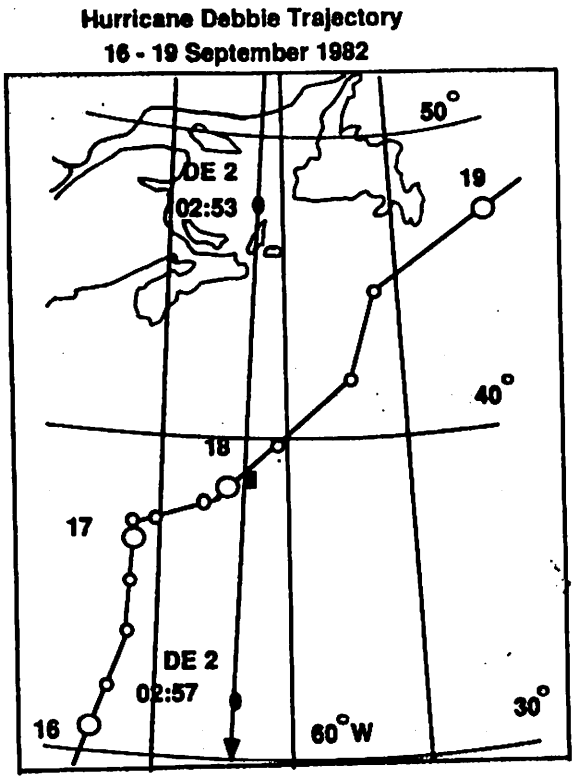

NPM at Palmer
17 Mar 90
920
880
840
800
760
0620:00
0622:00
0624:00 UT

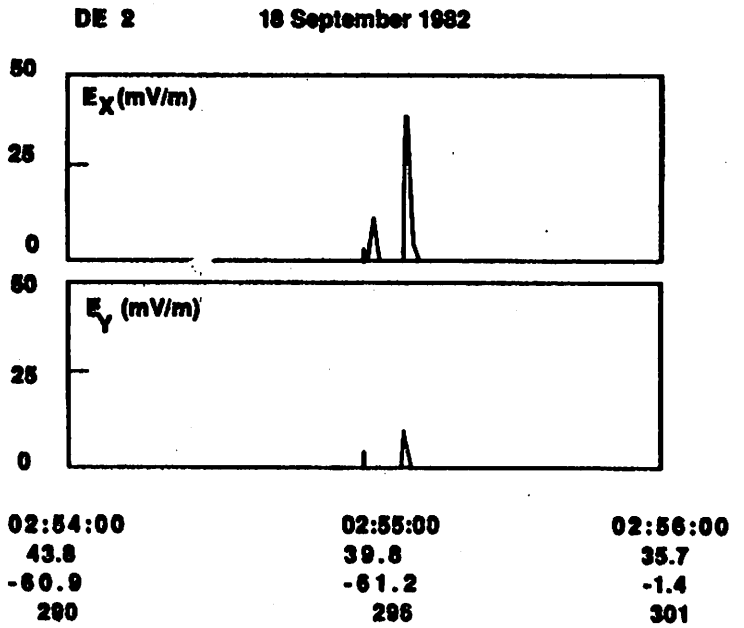


Approximate typical distribution of 'ducts' around Palmer and conjugate region.
[Burgess and Inan, 1993]

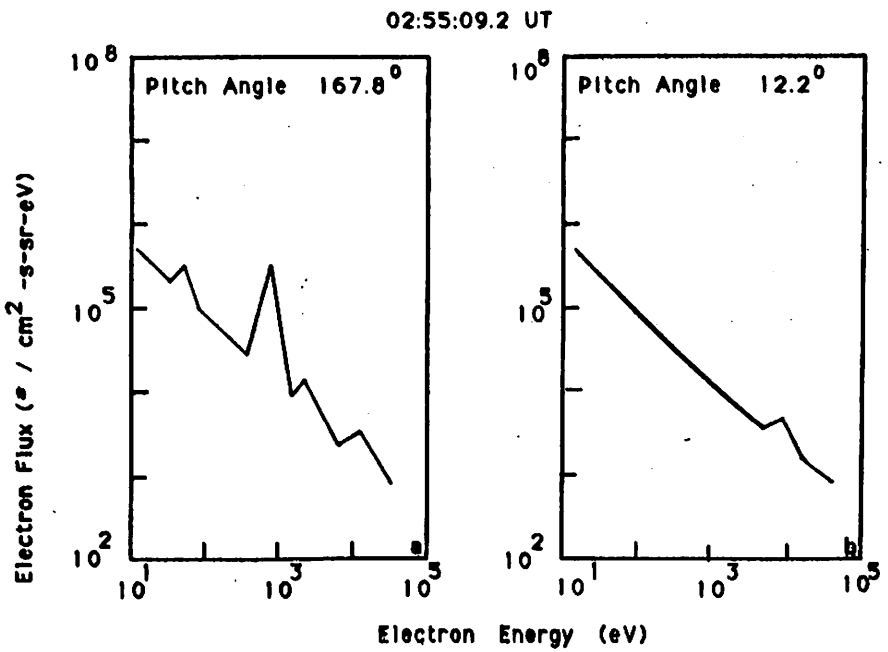

Ionosphere Signatures of Lightning
Optical
80.0
40.0
0.0
-40.0
-80.0
mV/m
Eperp.
Whistler Mode
Eperp.
Pulse
Eparallel
0.8
0.4
0.0
nT
| B | per.
0.970
0.980
0.990
1.000
1.010
1.020
seconds
Time 5:53:54.97 TO 55.02UT, Altitude 294km

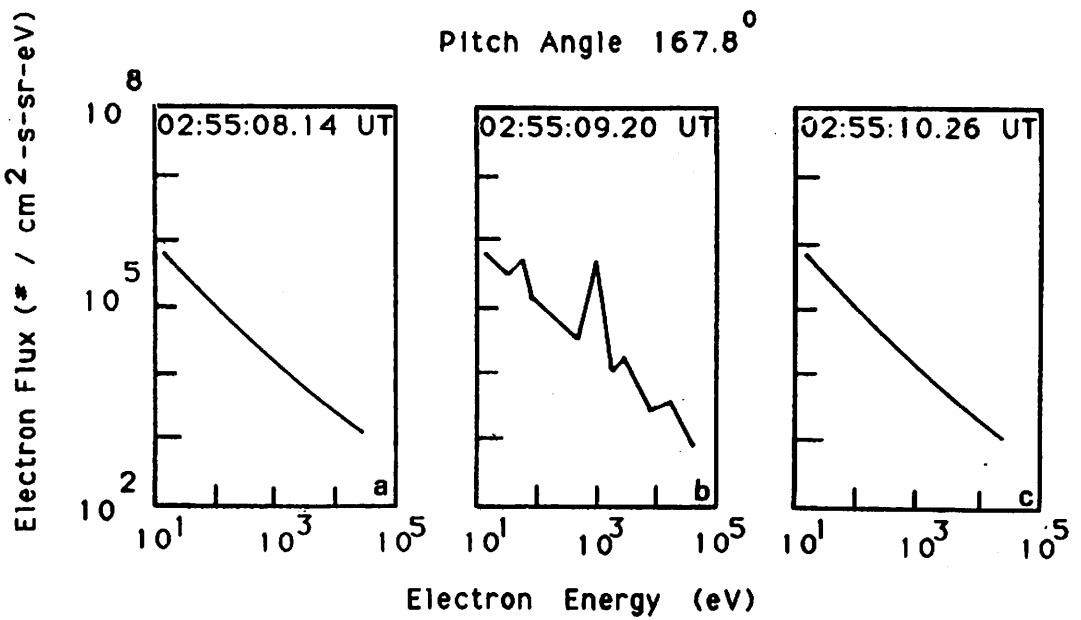

50 km
Wallops
330 Km
218 Km
Thunderstorm cells
Rocket trajectory

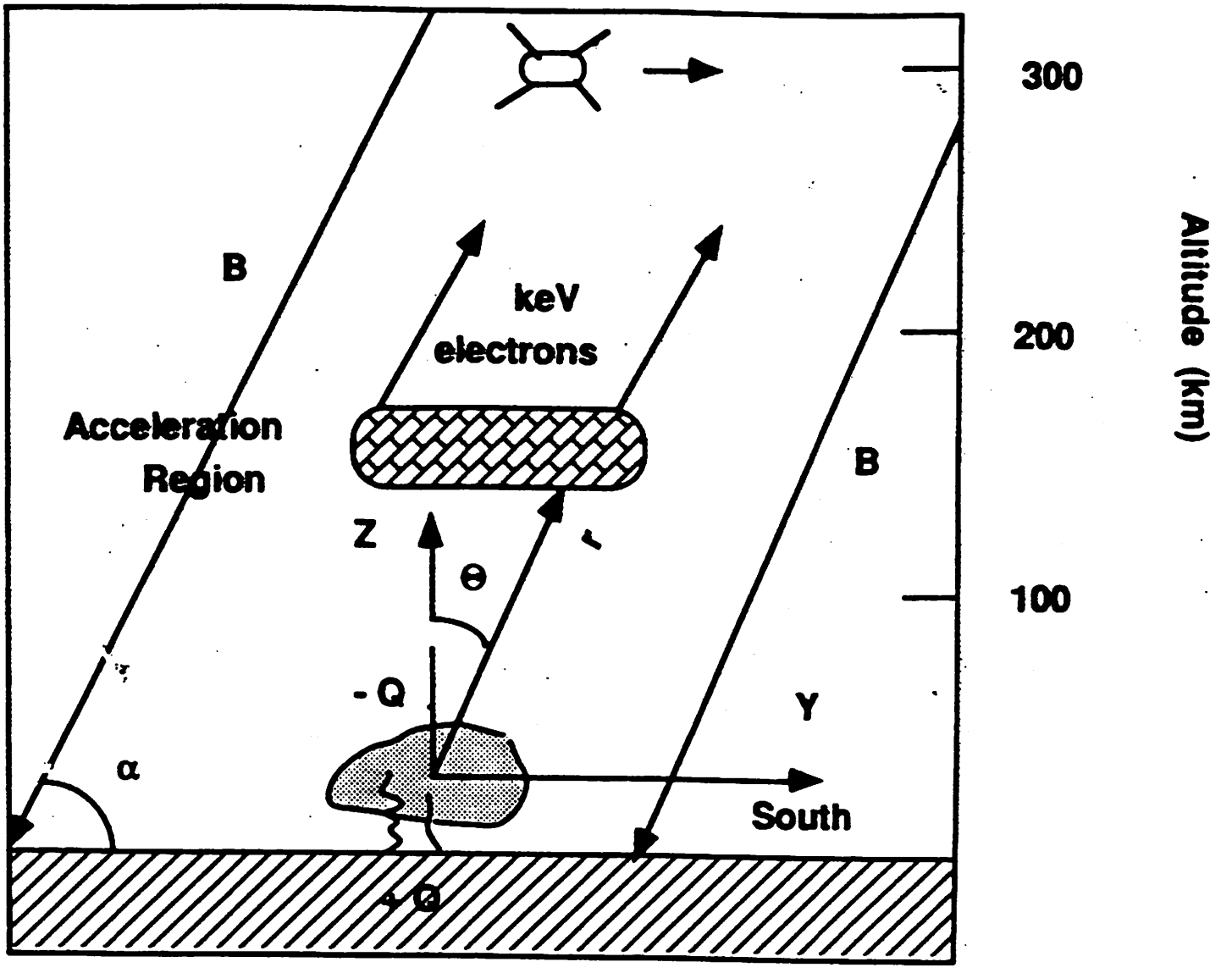


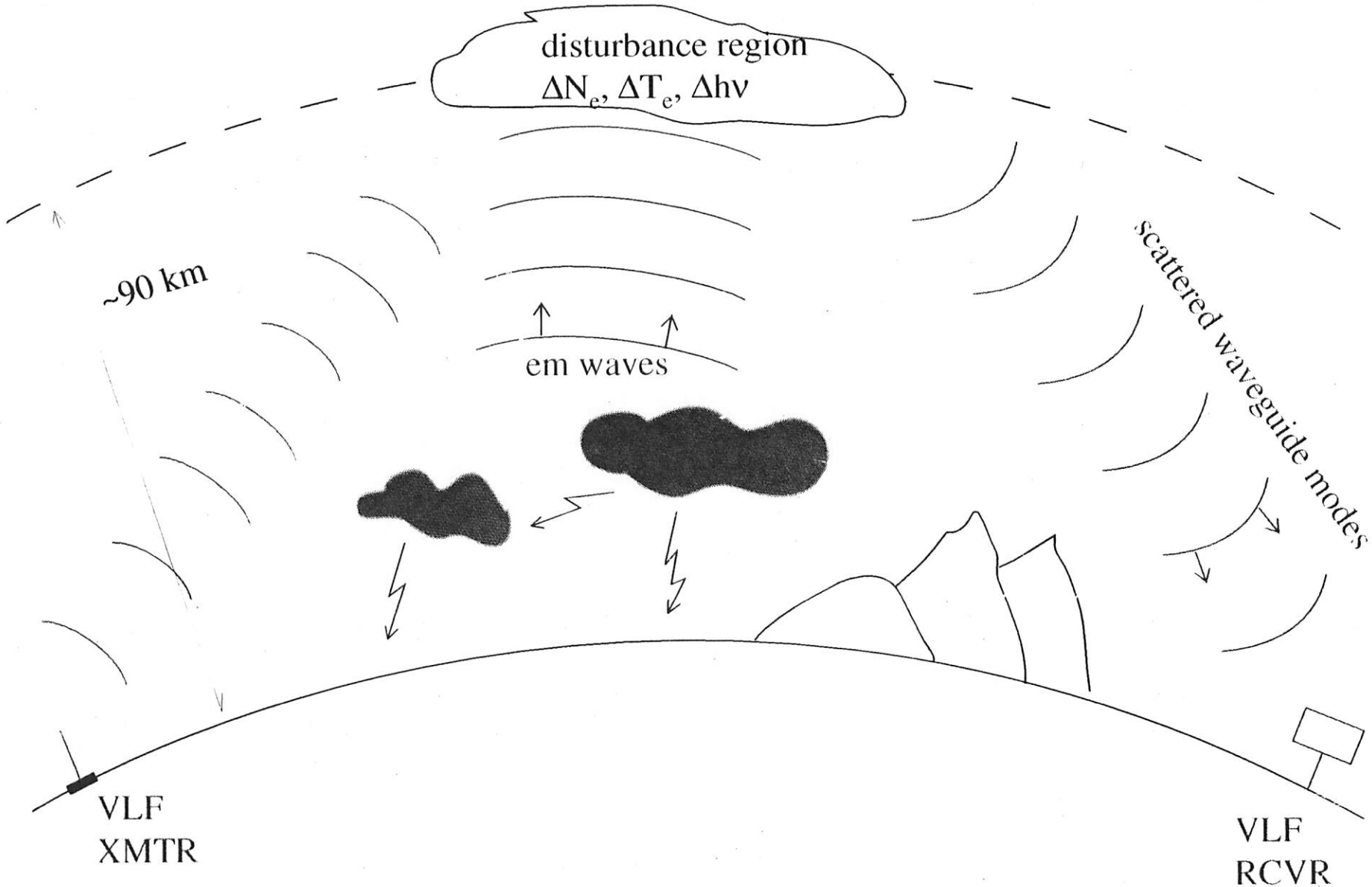


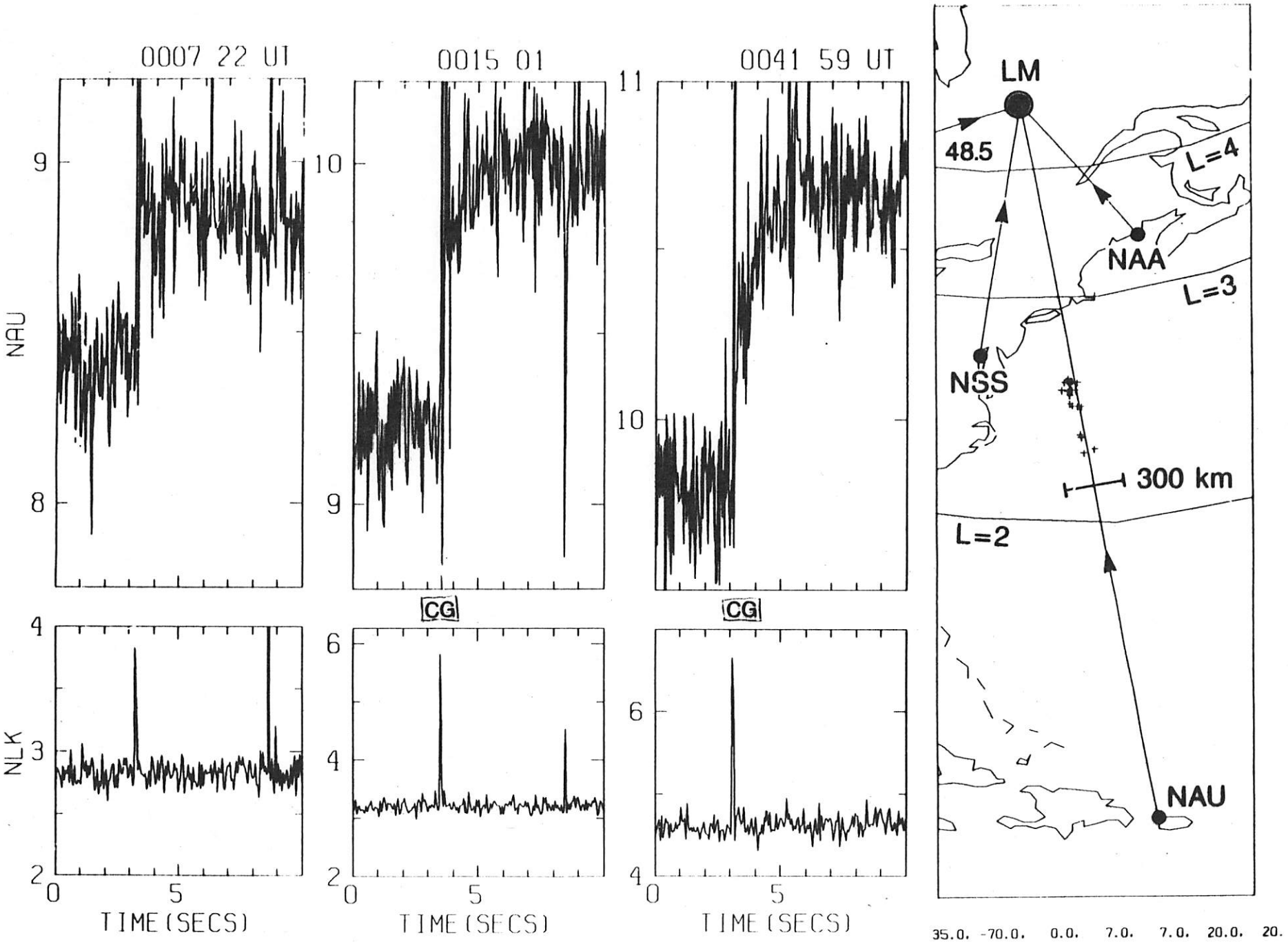
UT	02:54:00	02:55:00	02:56:00
GLAT	43.8	39.8	35.7
GLONG	-60.9	-61.2	-1.4
ALT	290	296	301

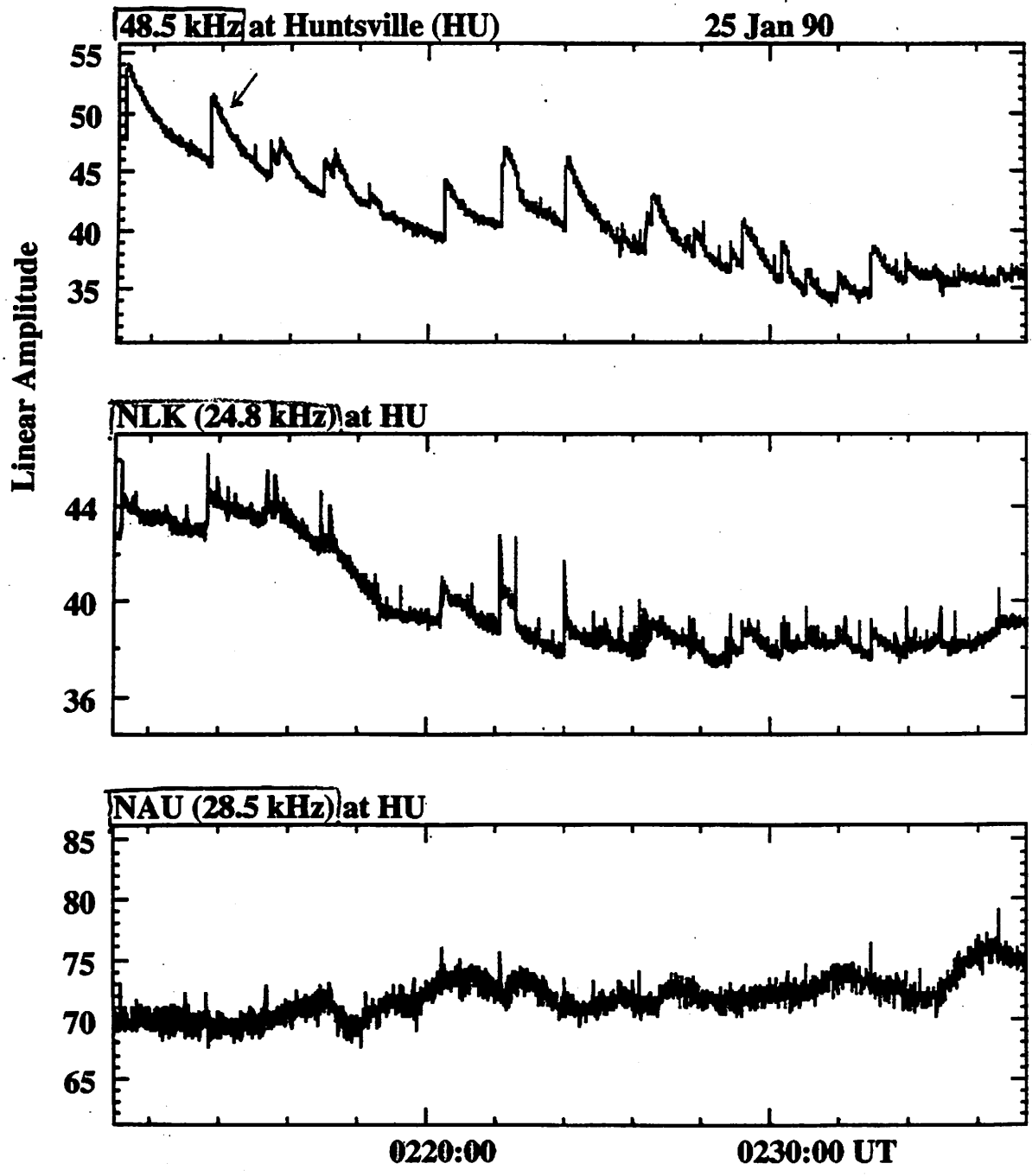


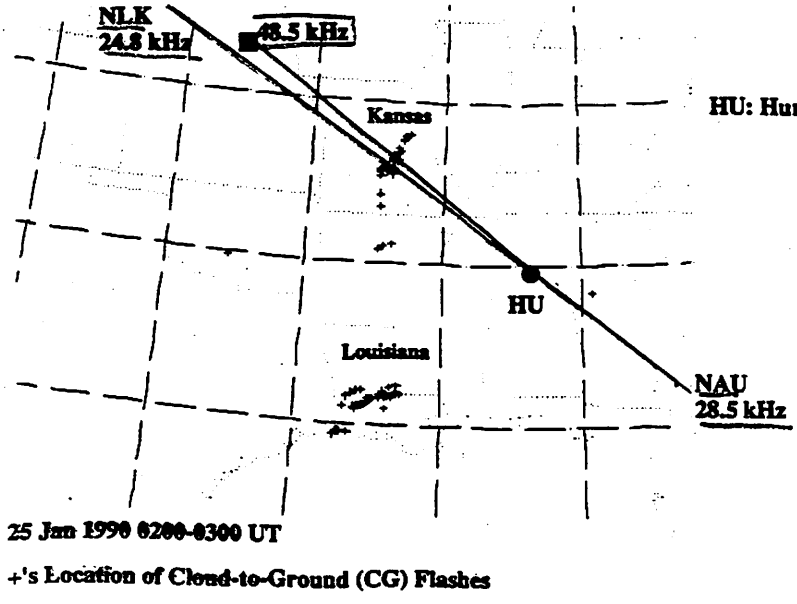



300
200
100
Altitude (km)
B
keV
electrons
Acceleration
Region
B
Z
Θ
-Q
Y
α
South
+Q

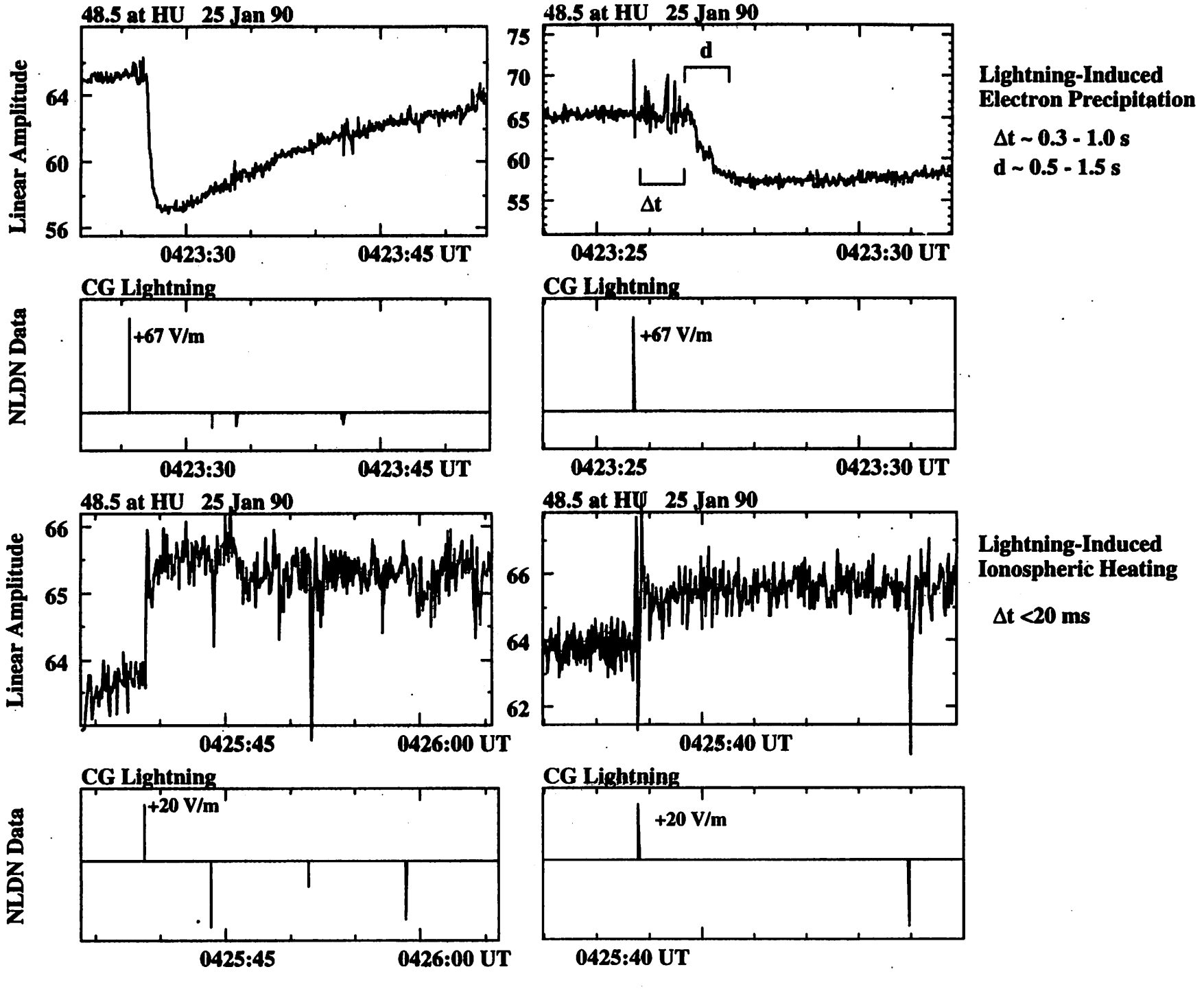

disturbance region
ΔN_e, ΔT_e, $\Delta h\nu$
~90 km
em waves
scattered waveguide modes
VLF
XMTR
VLF
RCVR

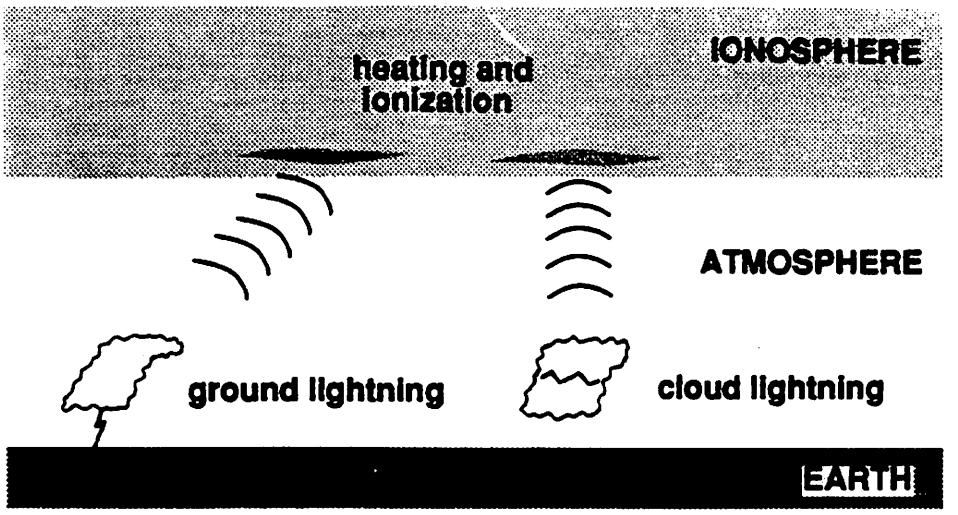

0007 22 UT
0015 01
0041 59 UT
NAU
NLK
CG
CG
TIME (SECS)
TIME (SECS)
TIME (SECS)
LM
48.5
L=4
NAA
L=3
NSS
300 km
L=2
NAU
35.0. -70.0. 0.0. 7.0. 7.0. 20.0. 20.



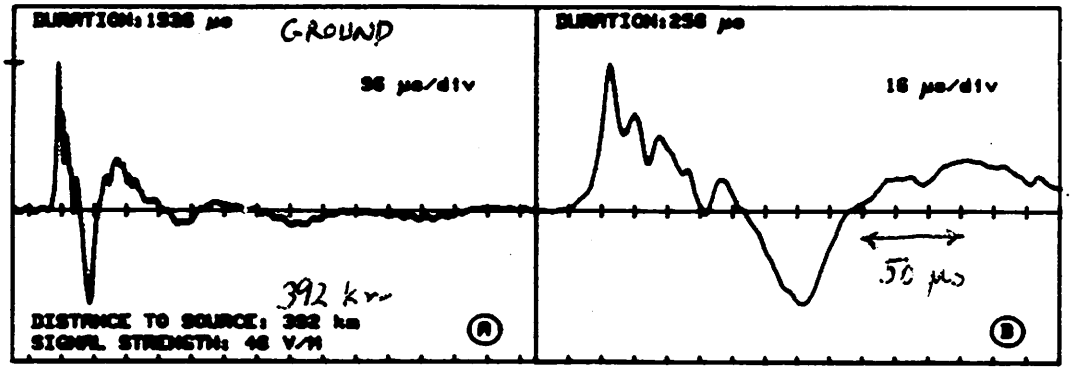


Inan et al.
GRL
Nov 1993


48.5 at HU 25 Jan 90
Linear Amplitude
64
60
56
0423:30
0423:45 UT
48.5 at HU 25 Jan 90
75
70
65
60
55
d
Δt
0423:25
0423:30 UT
Lightning-Induced
Electron Precipitation
Δt ~ 0.3 - 1.0 s
d ~ 0.5 - 1.5 s
CG Lightning
NLDN Data
+67 V/m
0423:30
0423:45 UT
CG Lightning
+67 V/m
0423:25
0423:30 UT
48.5 at HU 25 Jan 90
Linear Amplitude
66
65
64
0425:45
0426:00 UT
48.5 at HU 25 Jan 90
66
64
62
0425:40 UT
Lightning-Induced
Ionospheric Heating
Δt <20 ms
CG Lightning
NLDN Data
+20 V/m
0425:45
0426:00 UT
CG Lightning
+20 V/m
0425:40 UT



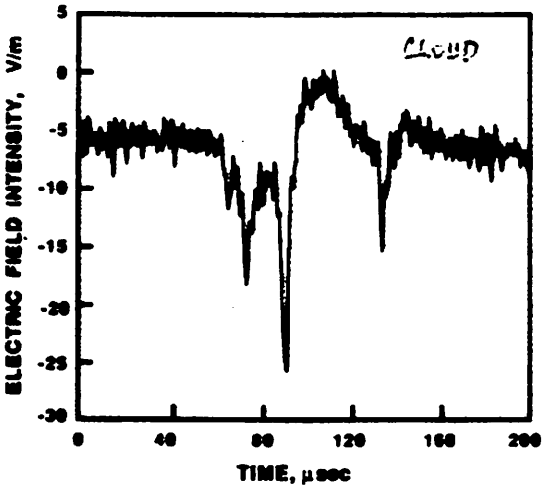
(a)



(b)

ground lightning

[Brook et al., 1989]



(c)

cloud lightning

MEAN ~5 V/m @ 100 km distance

10% ?25 V/m @ 100 km

[Krider and Guo, 1983]

Figure 3

50–100 μs duration

Inanenko et al., GRL 1993a

FORMULATION OF THE PROBLEM

- EM fields ($\vec{E}\&\vec{B}$) are described by Maxwell's equations:

$$\begin{aligned} \nabla \times \vec{B} &= \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c}\vec{J} \\ \nabla \times \vec{E} &= -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \end{aligned} \tag{1}$$

where c is the velocity of light in the vacuum, and $\vec{J}$ is the electric current density.

- Since the random electron velocity is much larger than the average directional velocity we can expand $f(\vec{r}, \vec{v}, t)$ in spherical functions of zero order [*Allis*, 1956]

$$f(\vec{r}, \vec{v}, t) = f_0(\vec{r}, v, t) + \frac{\vec{v} \cdot \vec{f}_1(\vec{r}, v, t)}{v} + \ldots \tag{2}$$

- The Boltzmann equation for the distribution function is reduced to the following [*Gurevich*, 1978]

$$\frac{\partial f_o}{\partial t} = \frac{\epsilon}{3mv^2}\frac{\partial}{\partial v}\left(v^2 \vec{E} \cdot \vec{f}_1\right) + \frac{1}{2v^2}\frac{\partial}{\partial v}\left[v^2 \delta \nu_{el}\left(\frac{T}{m}\frac{\partial f_o}{\partial v} + v f_o\right)\right] + S_o \tag{3}$$

$$\frac{\partial \vec{f}_1}{\partial t} = \frac{\epsilon \vec{E}}{m}\frac{\partial f_o}{\partial v} + \frac{\epsilon}{mc}\left[\vec{B}_o \times \vec{f}_1\right] - \nu f_1$$

$$S_o = S_o^{rot} + S_o^{vib} + S_o^{opt} + S_o^{dis} + S_o^{att} + S_o^{ion} \tag{4}$$

where $-\epsilon$ is electric charge and m is mass of an electron, T is the temperature of neutrals, δ is the average fraction of the energy lost in one elastic collision, $\nu_{el}(v)$ is frequency of elastic collisions, and $\nu(v)$ is the total collision frequency.

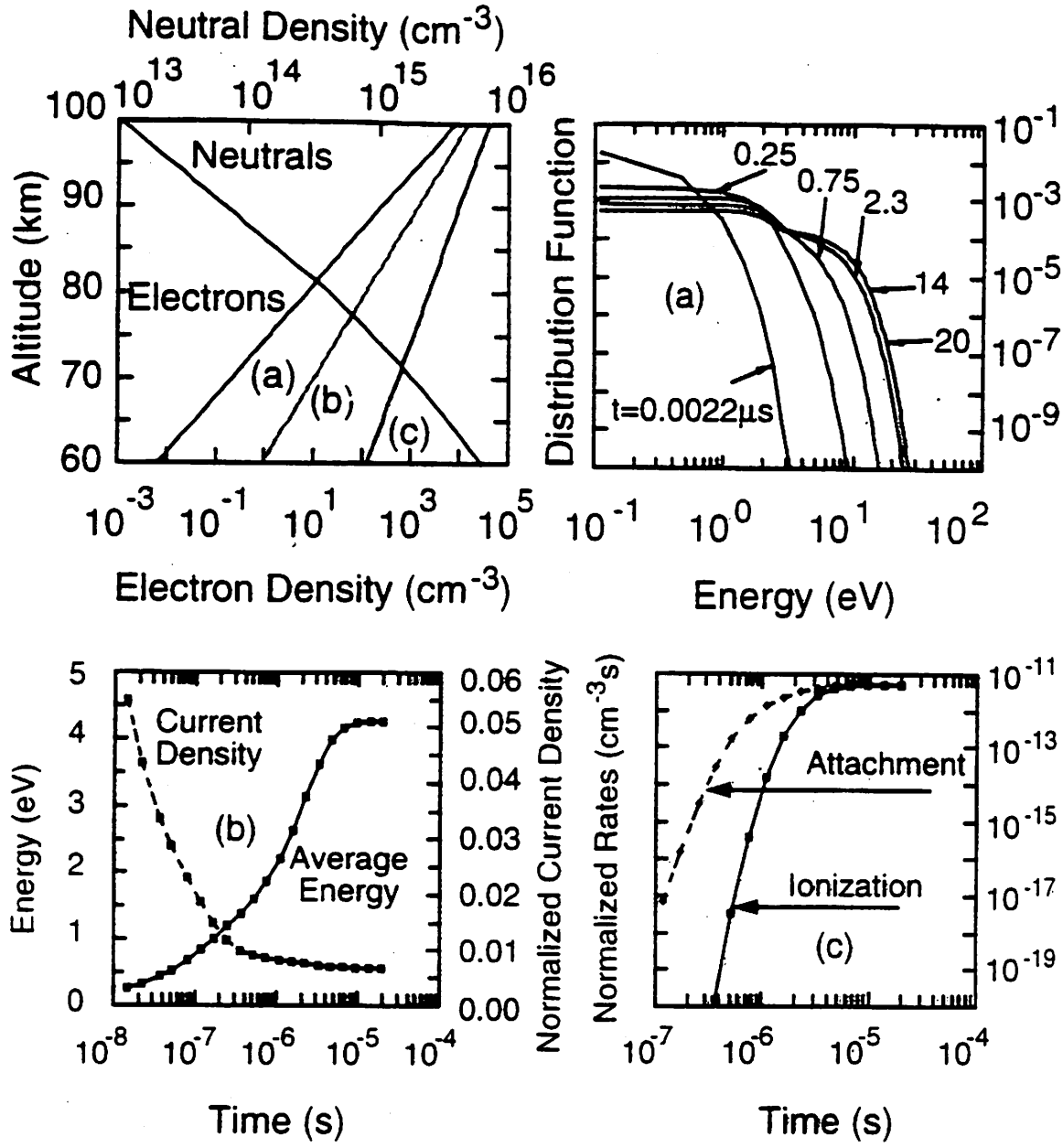


Fig. 1. (Top left) Ambient profiles of electron and neutral densities. Electron density profile (a) is for nighttime, profile (c) is for daytime, and profile (b) represents intermediate. Fig. 2. Time evolution at h = 90 km of (a) (top right) the electron distribution function, (b) (bottom left) the normalized electric current and average electron energy, and (c) (bottom right) the attachment and ionization rates.

$O_2 + e \longrightarrow O + O^-$ Attachment

$N_2 + e \longrightarrow 2e + N^+$ Ionization $\quad O_2 + e \longrightarrow 2e + O^+$

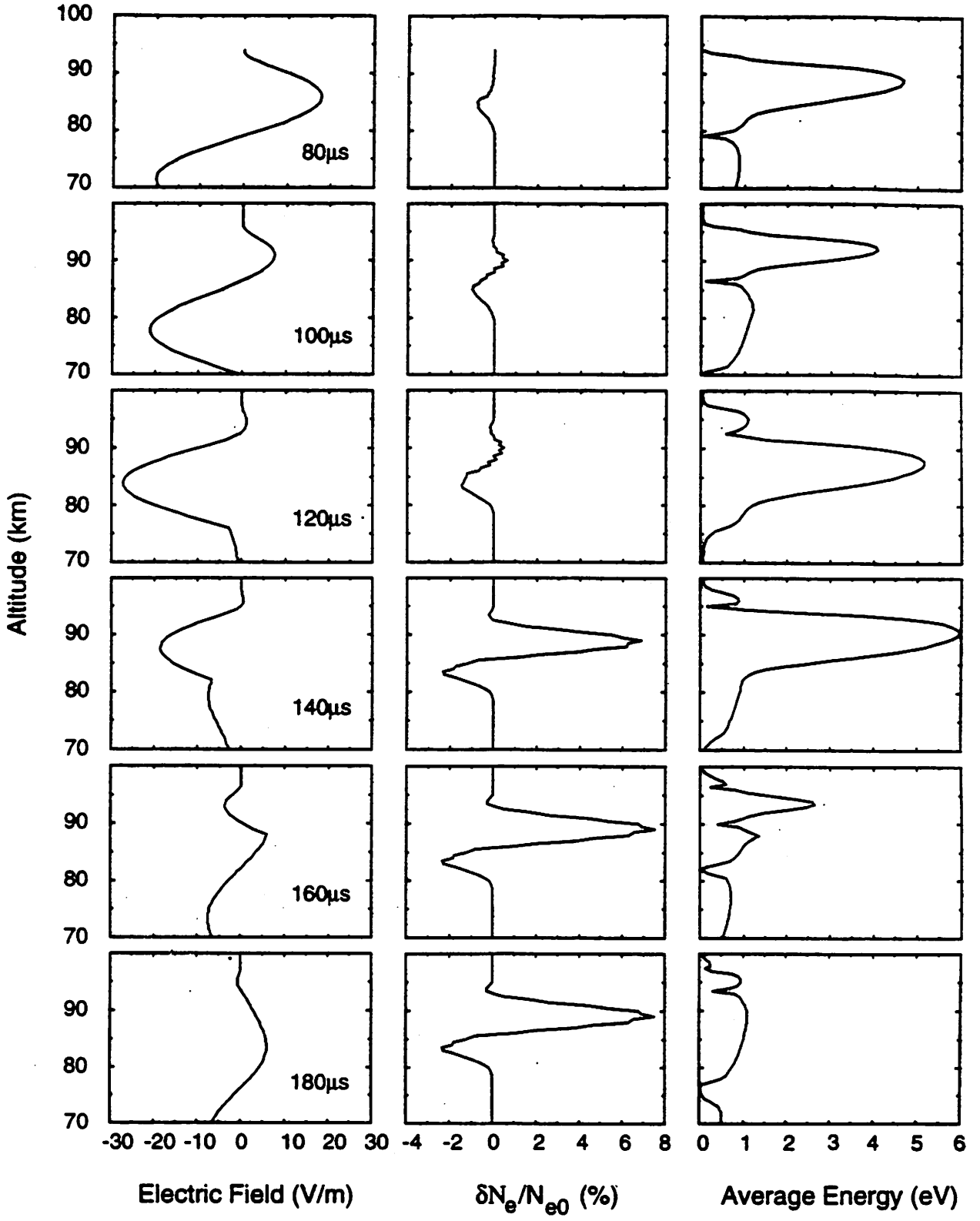


Fig. 3.1. Dynamics of the interaction of an EM pulse with the ionosphere. Snapshots of the electric field, normalized electron density change, and average electron energy covering the 80 to 180 μs time interval in 20 μs increments following the injection of a E_{inj} = 20 V/m EM pulse at 70 km under the 'tenuous' nighttime conditions (Figure 2.1 (a)).

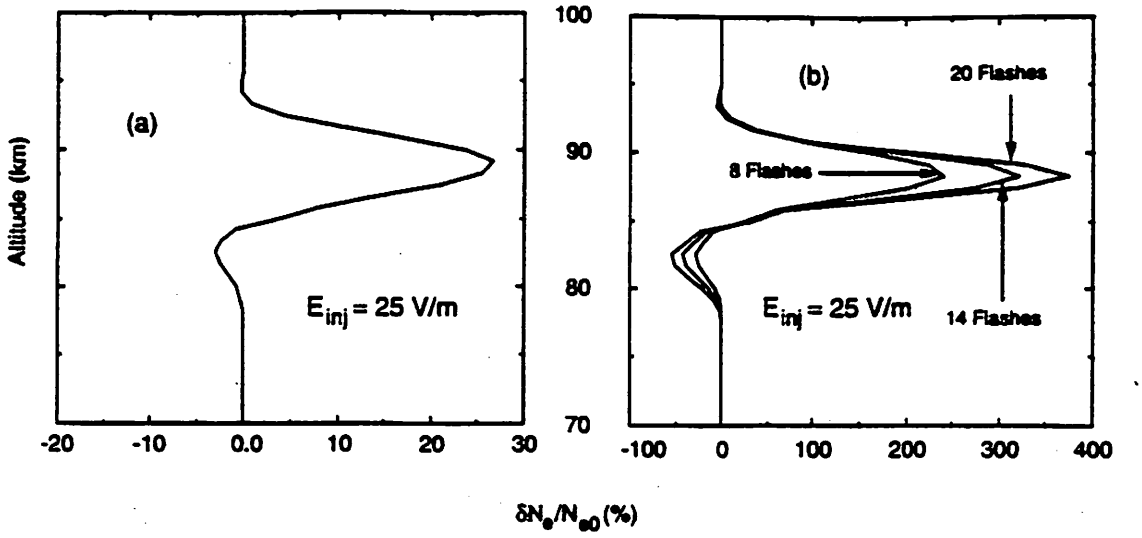


Fig. 3.3. Electron density changes. *(a):* The resulting density changes produced by a single EM pulse with E_{inj} = 25 V/m under 'tenuous' nighttime conditions (Figure 2.1 (a)). *(b):* The resulting density changes produced by a sequence of 8, 14, and 20 EM pulses with E_{inj} = 25 V/m under the same conditions.

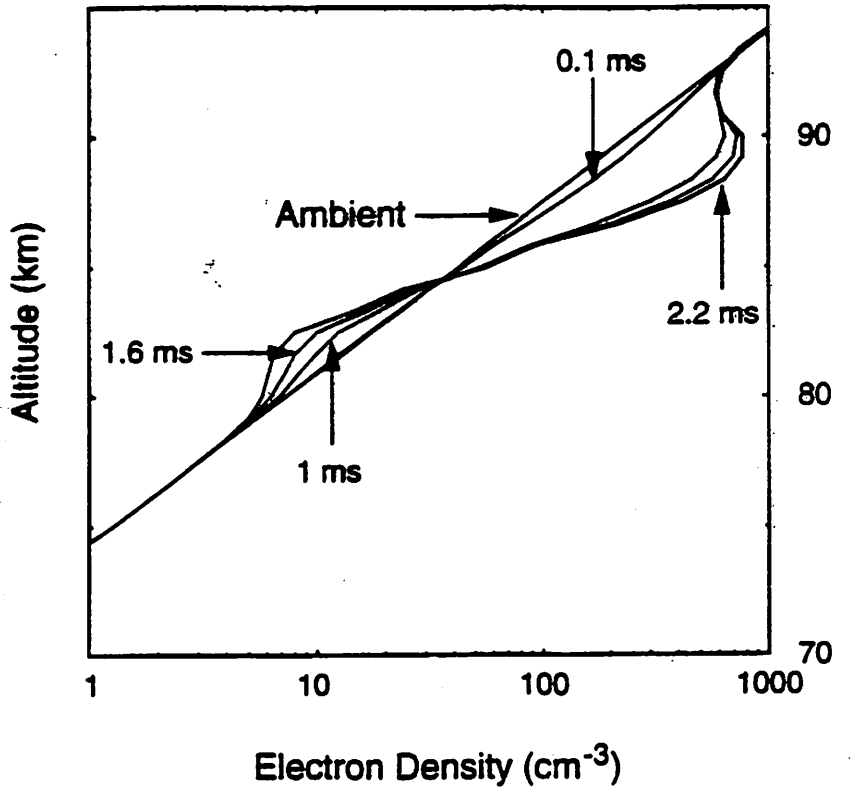
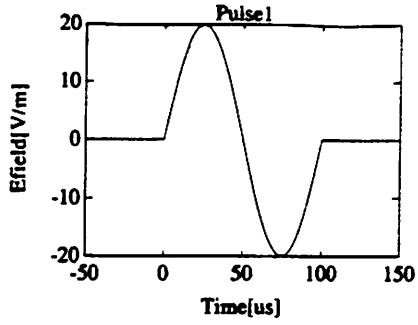
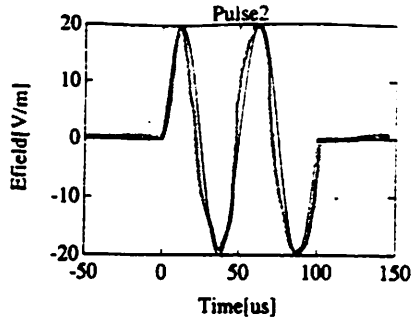


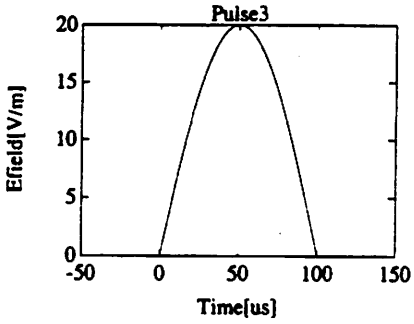
Fig. 5.1. Evolution of an electron density disturbance due to successive EM pulses from lightning. The disturbances were produced by an EM wave with E_{inj} = 25 V/m and different time durations of 0.1 ms (a single pulse), 1 ms (equivalent to a sequence of about 8 pulses), 1.6 ms (equivalent to a sequence of about 14 pulses), and 2.2 ms (equivalent to a sequence of about 20 pulses) under 'tenuous' nighttime conditions (Figure 2.1 (a)).

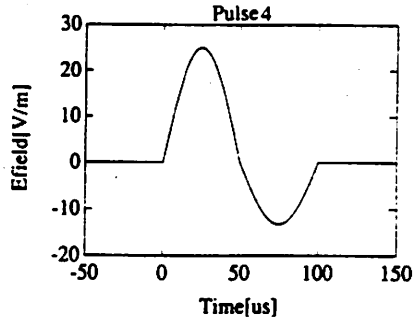
20 V/m

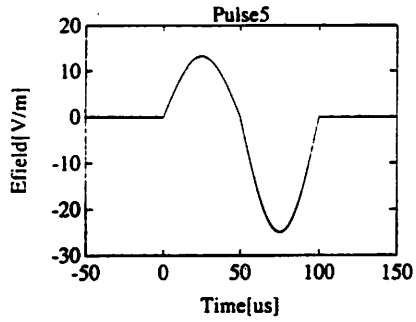
ALL WAVEFORMS HAVE EQUAL ENERGY

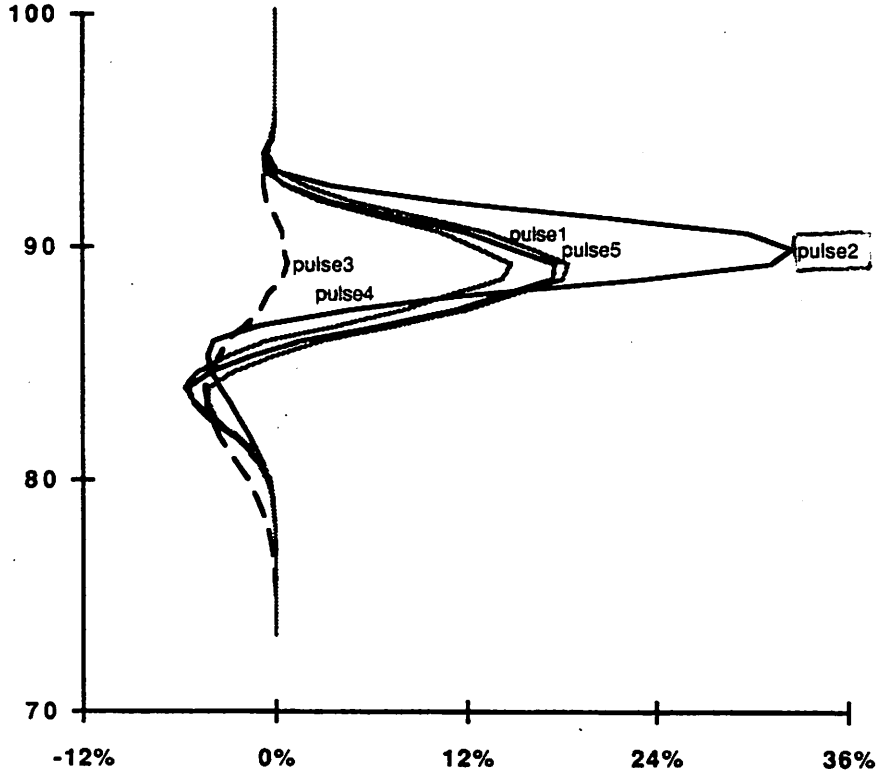


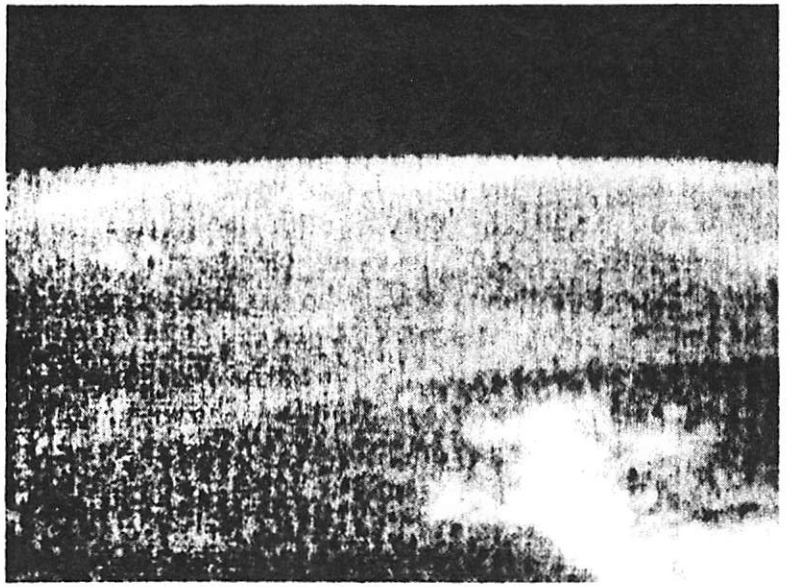


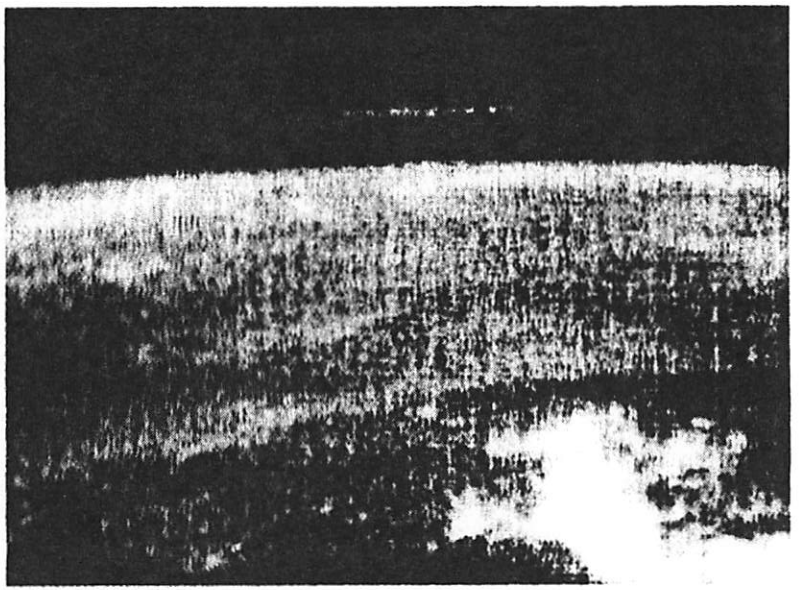


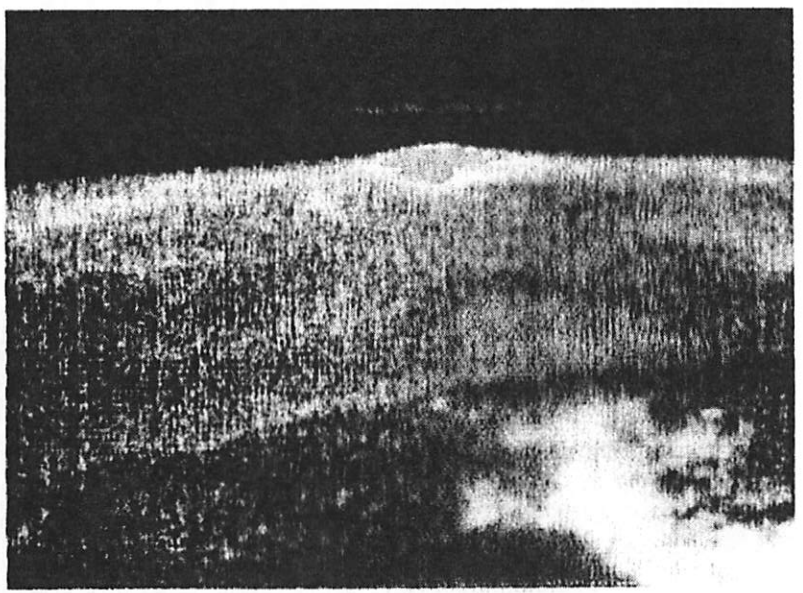


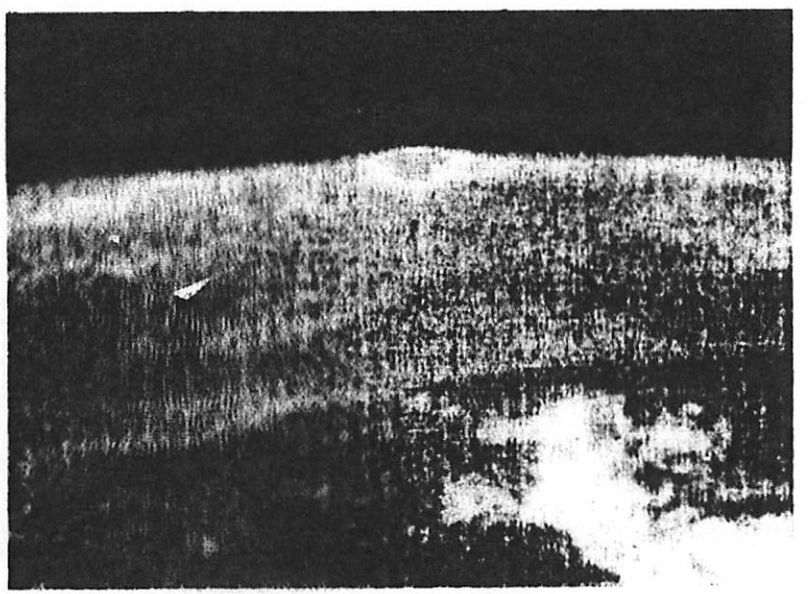


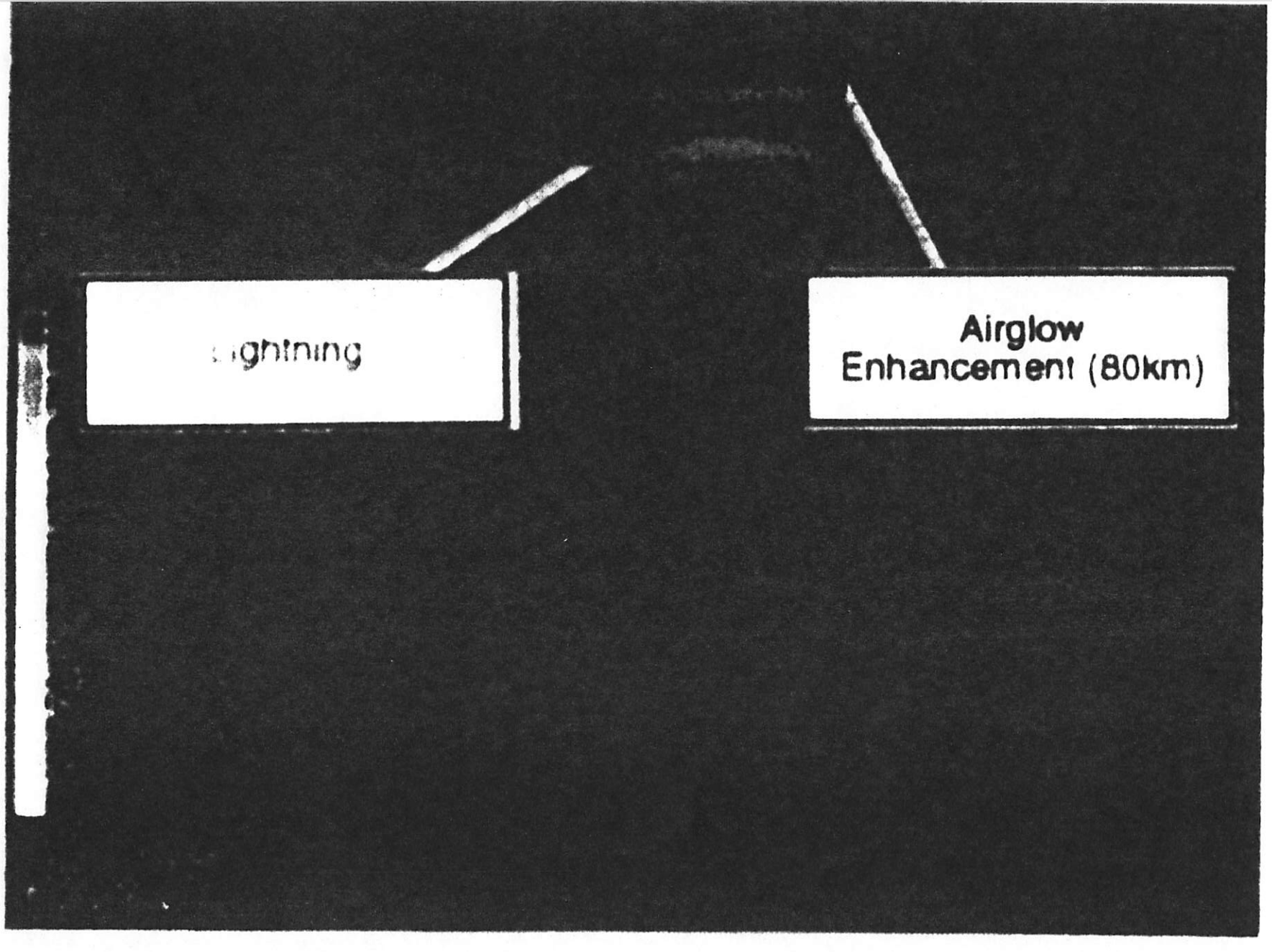











ghtning
Airglow
Enhancement (80km)

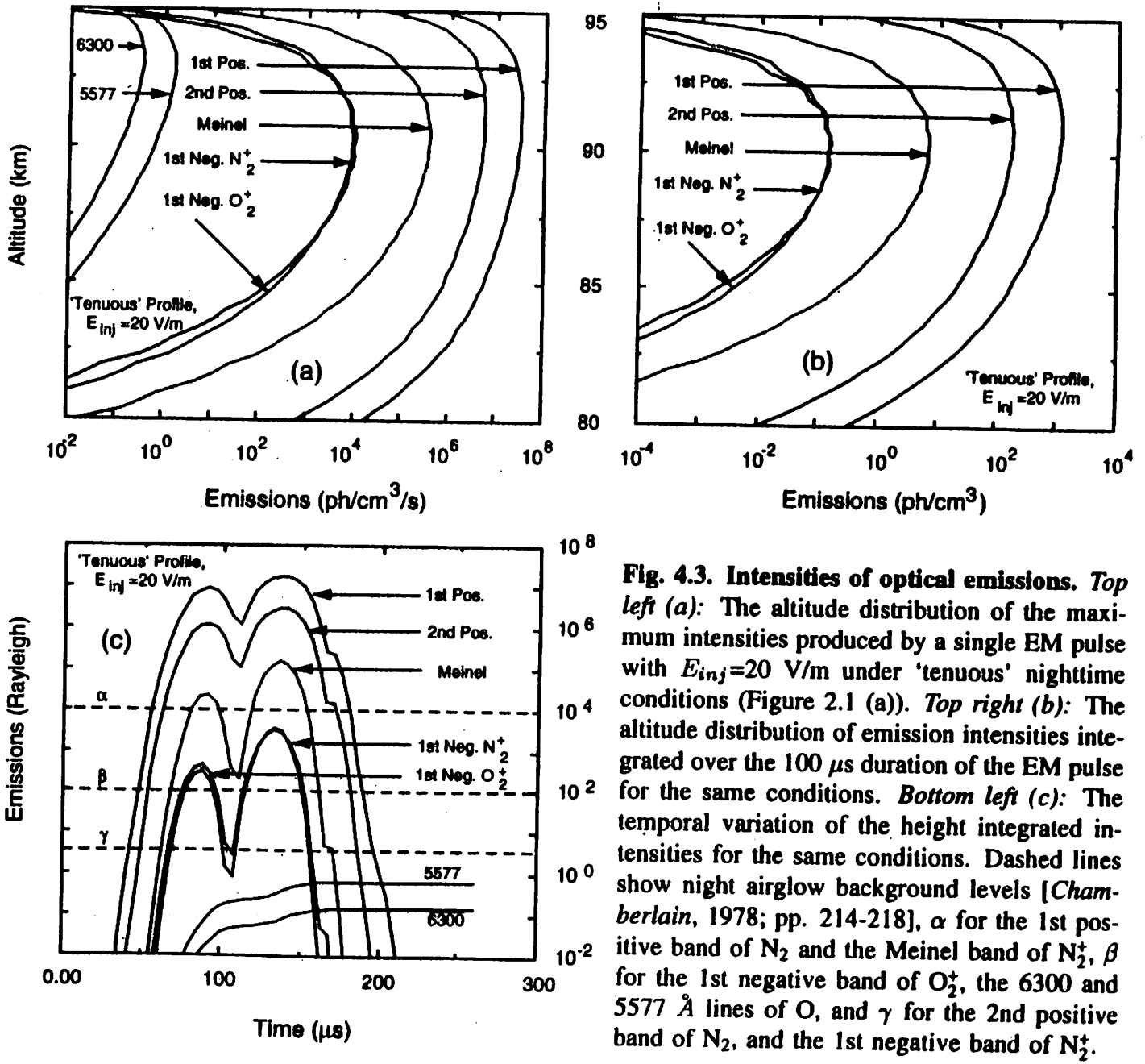
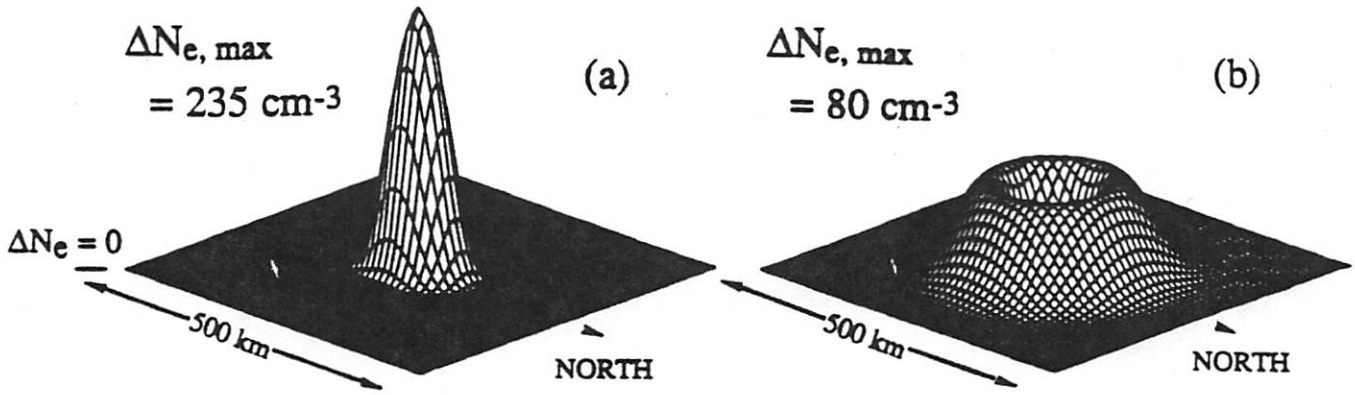


Fig. 4.3. Intensities of optical emissions. *Top left (a):* The altitude distribution of the maximum intensities produced by a single EM pulse with E_{inj}=20 V/m under 'tenuous' nighttime conditions (Figure 2.1 (a)). *Top right (b):* The altitude distribution of emission intensities integrated over the 100 μs duration of the EM pulse for the same conditions. *Bottom left (c):* The temporal variation of the height integrated intensities for the same conditions. Dashed lines show night airglow background levels [*Chamberlain*, 1978; pp. 214-218], α for the 1st positive band of N_2 and the Meinel band of N_2^+, β for the 1st negative band of O_2^+, the 6300 and 5577 $\AA$ lines of O, and γ for the 2nd positive band of N_2, and the 1st negative band of N_2^+.

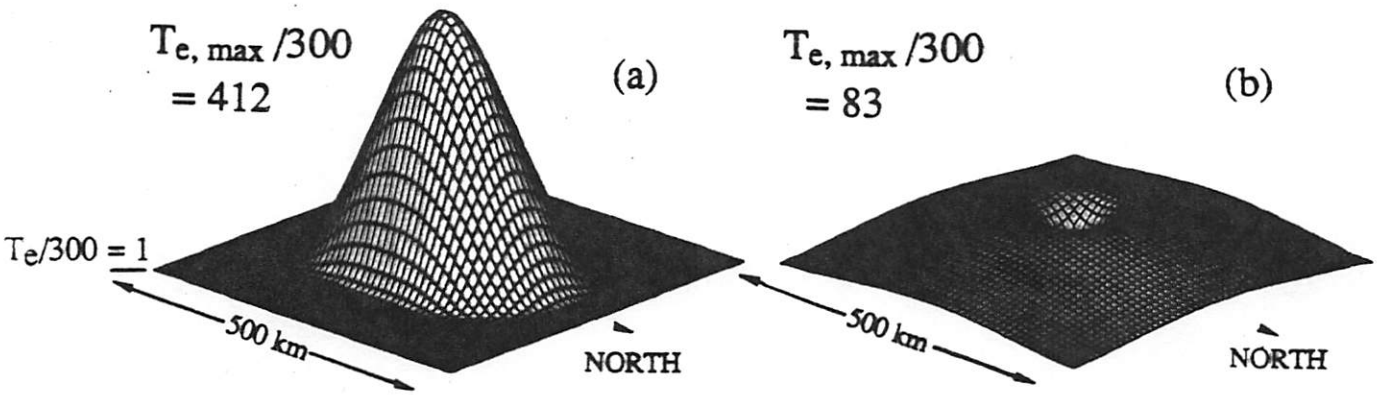


h = 94.3 km
E_{100} = 20 V/m

INTRACLOUD FLASH

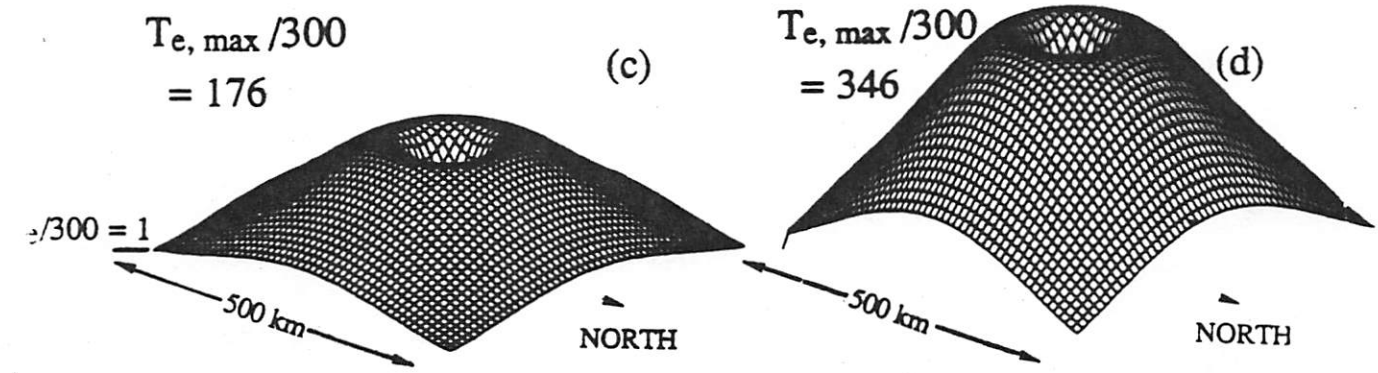
h = 92.9 km
E_{100} = 40 V/m

CLOUD-TO-GROUND FLASH



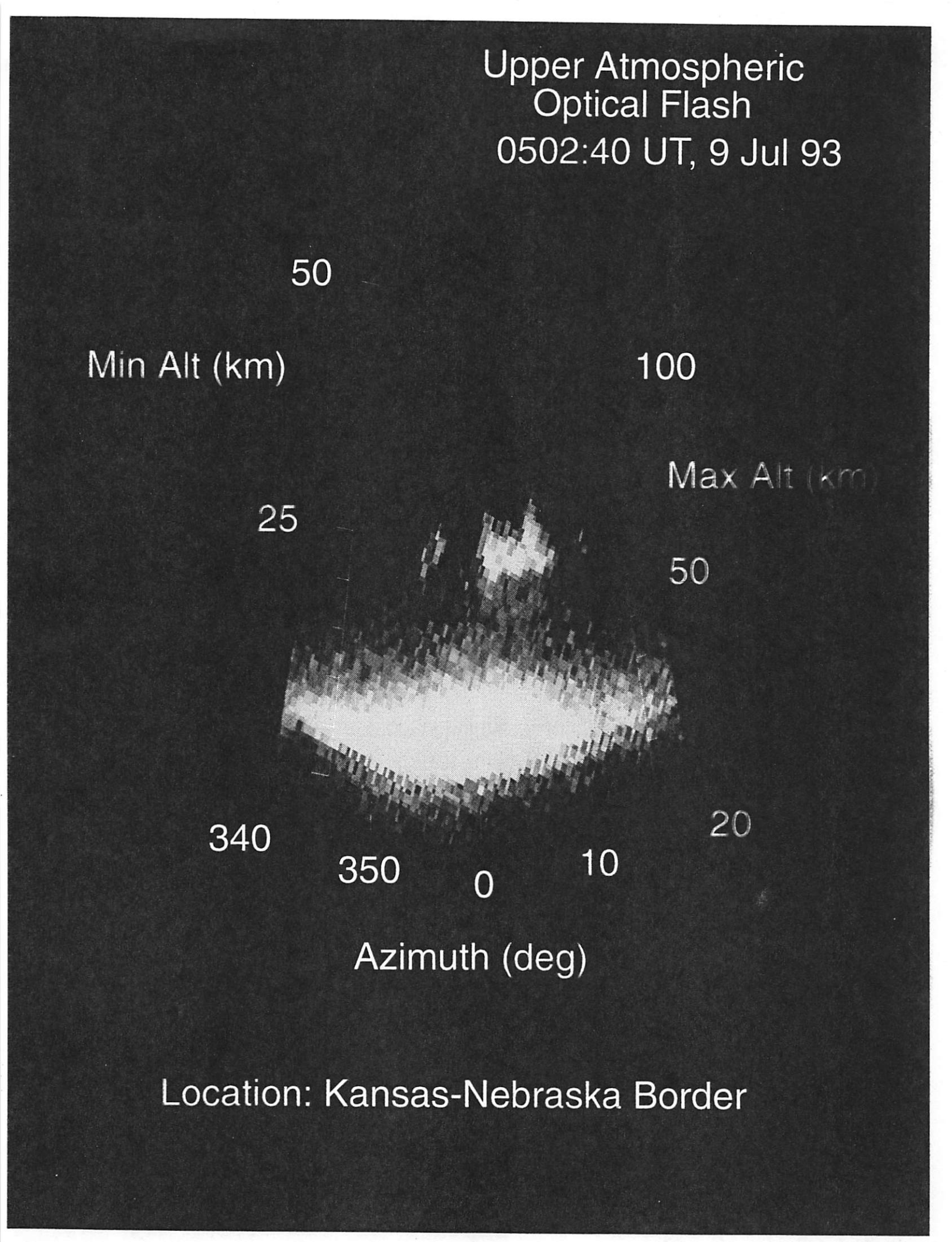
h = 93.0 km
E_{100} = 20 V/m

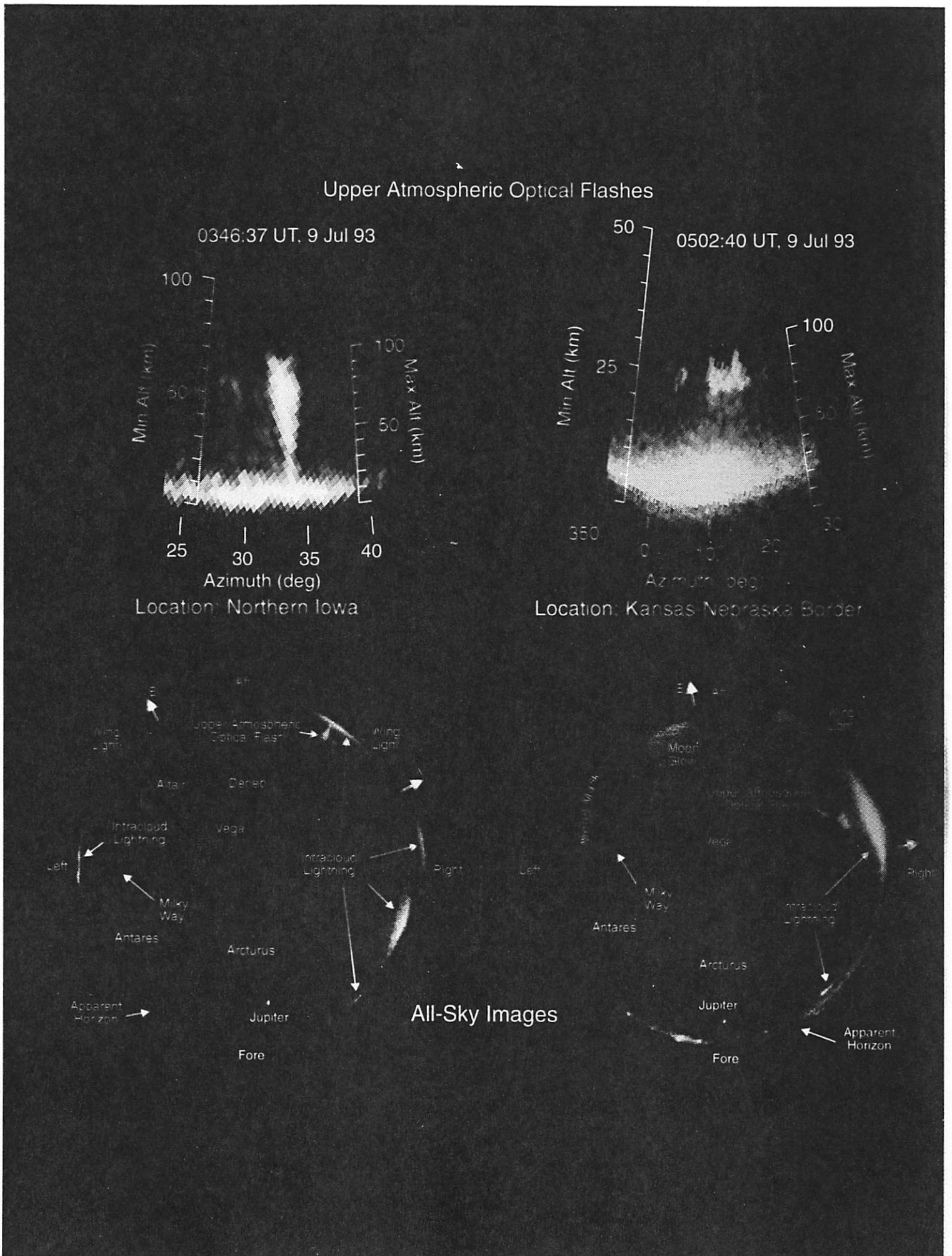
h = 87.4 km
E_{100} = 10 V/m



h = 89.9 km
E_{100} = 20 V/m

h = 91.5 km
E_{100} = 40 V/m


Upper Atmospheric
Optical Flash
0502:40 UT, 9 Jul 93
50
Min Alt (km)
100
Max Alt (km)
25
50
340
350
0
10
20
Azimuth (deg)
Location: Kansas-Nebraska Border


Upper Atmospheric Optical Flashes
0346:37 UT, 9 Jul 93
100
50
Min Alt (km)
100
50
Max Alt (km)
25
30
35
40
Azimuth (deg)
Location: Northern Iowa
50
25
Min Alt (km)
0502:40 UT, 9 Jul 93
100
Max Alt (km)
50
360
0
20
Azimuth (deg)
Location: Kansas Nebraska Border
Wing Light
Upper Atmospheric Optical Flash
Wing Light
Altair
Deneb
Intracloud Lightning
Vega
Left
Intracloud Lightning
Right
Milky Way
Antares
Arcturus
Apparent Horizon
Jupiter
Fore
All-Sky Images
Moon Glow
Milky Way
Antares
Arcturus
Jupiter
Apparent Horizon
Fore

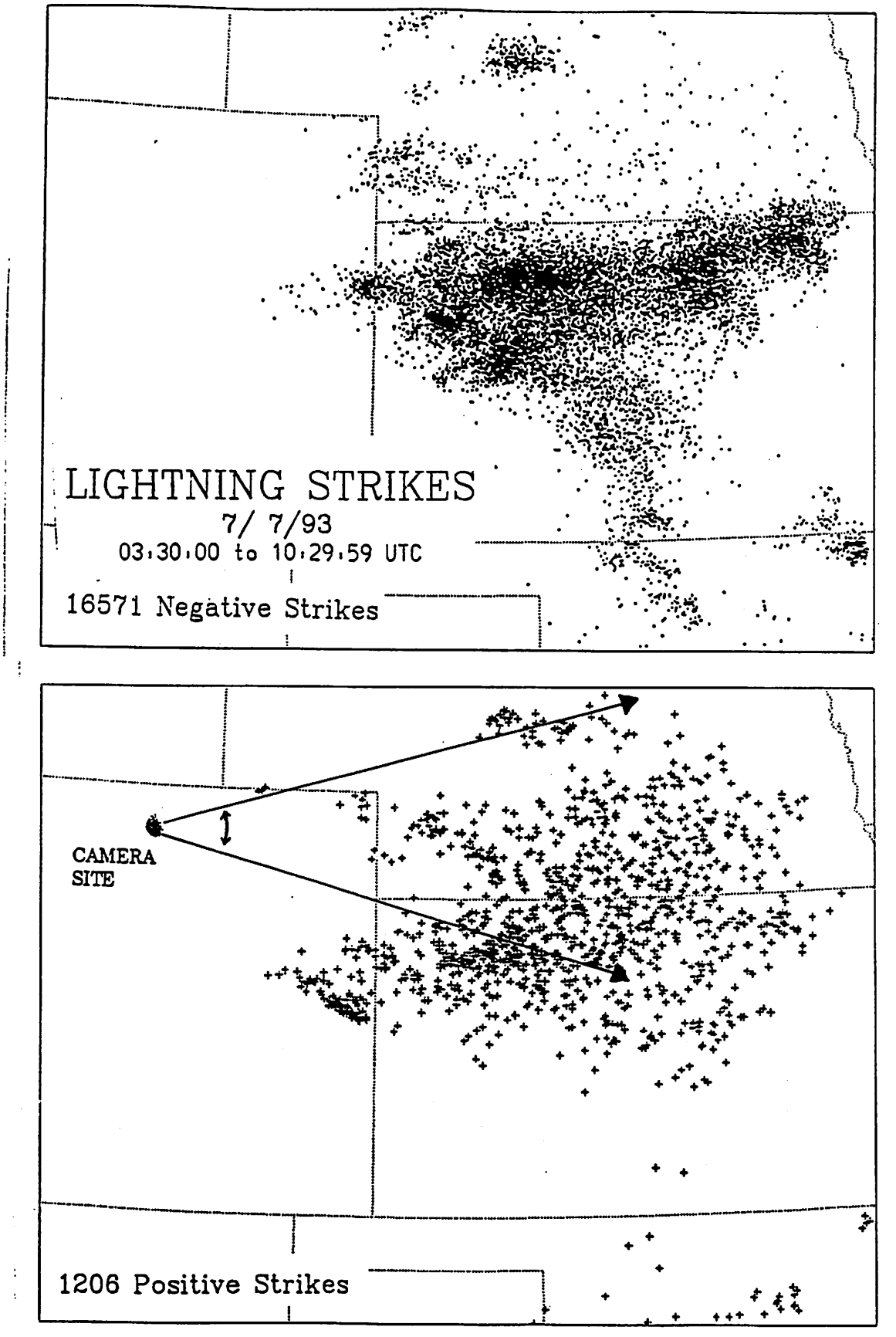
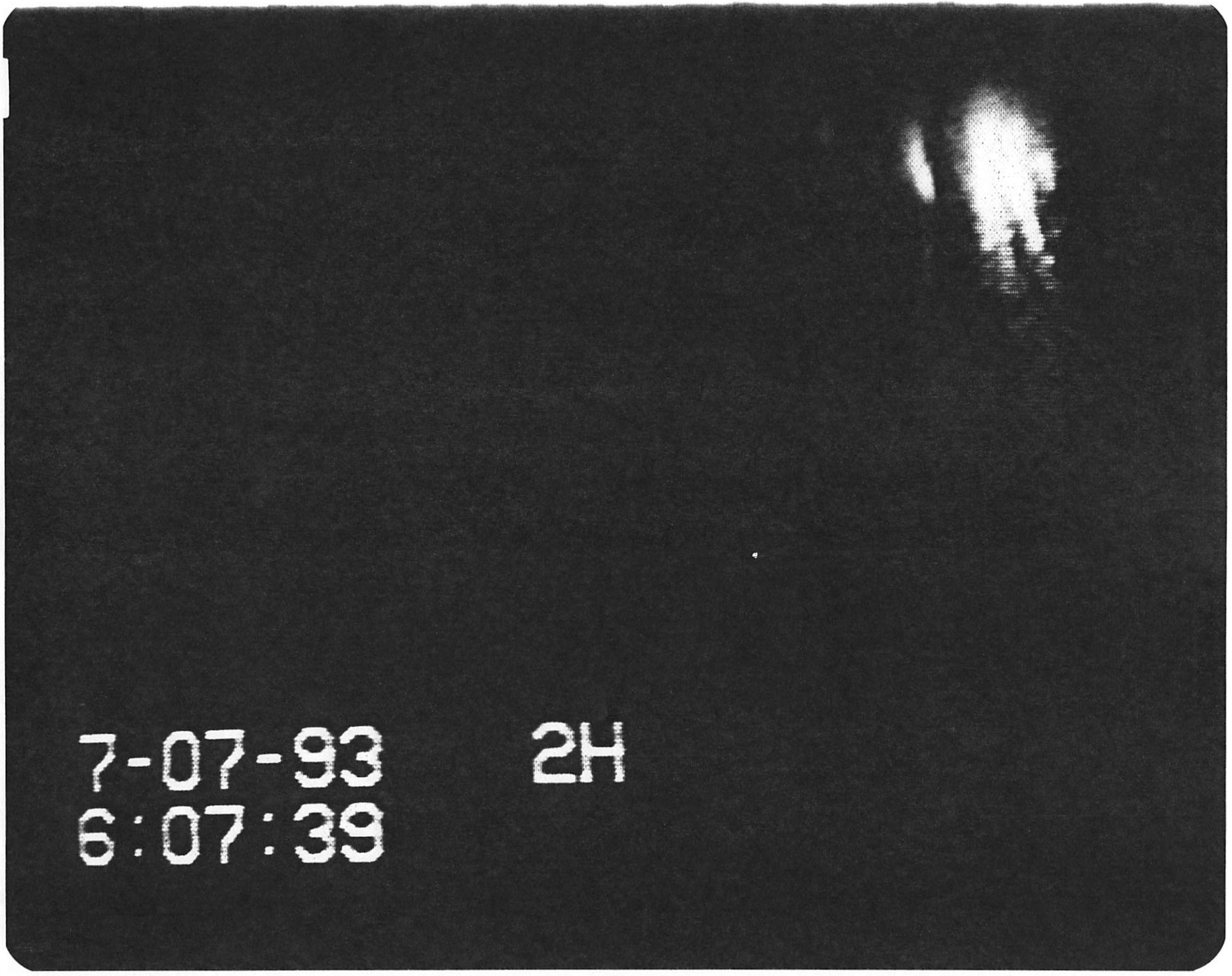
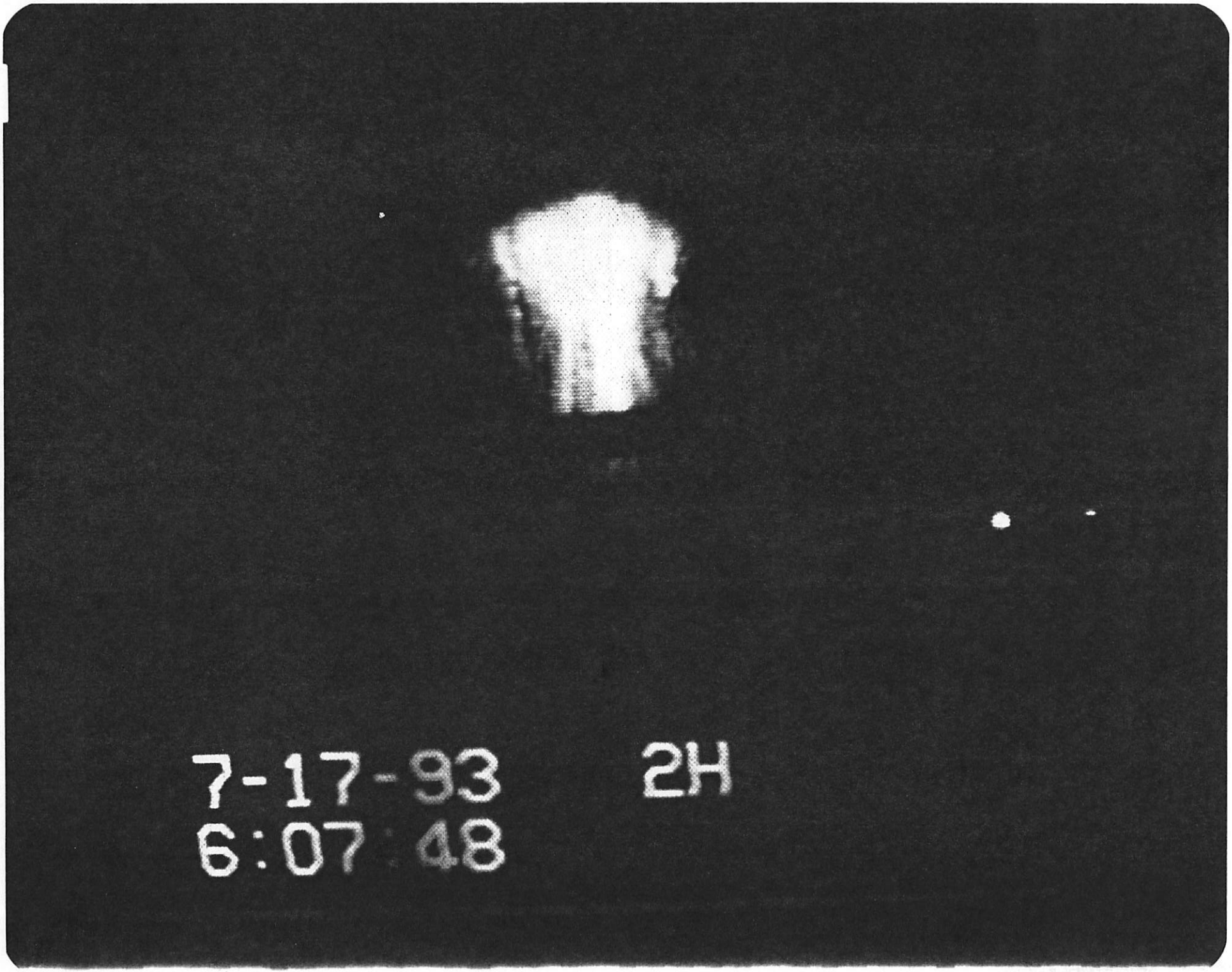


Fig. 1. Negative (top) and positive (bottom) CG flashes reported by the National Lightning Detection Network between 0300 and 1030 UTC 7 July 1993. The location and field of view of the low-light camera system is indicated.


7-07-93
6:07:39
2H


7-17-93 2H
6:07:48


7-16-93
4:11:39
2H

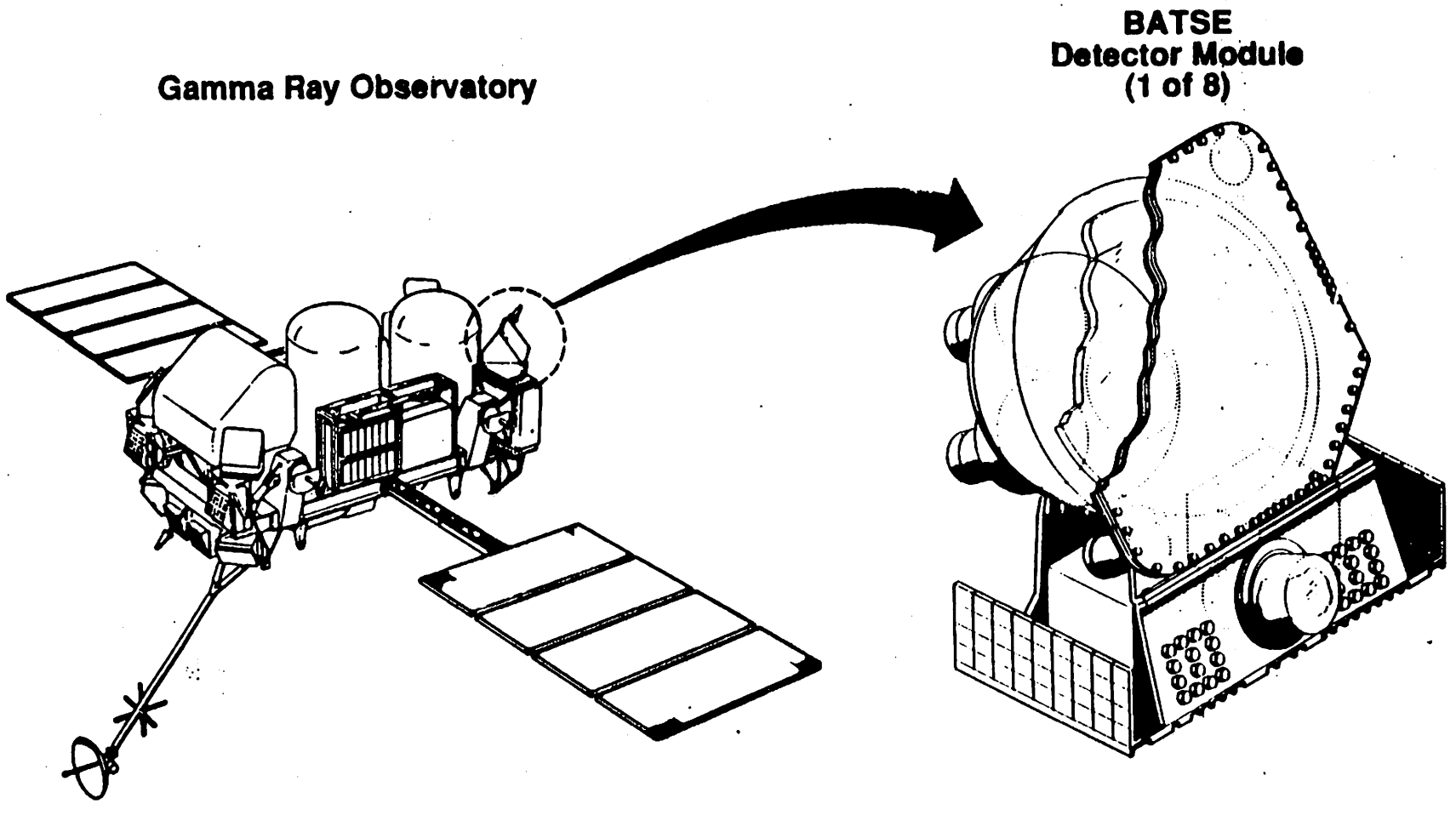
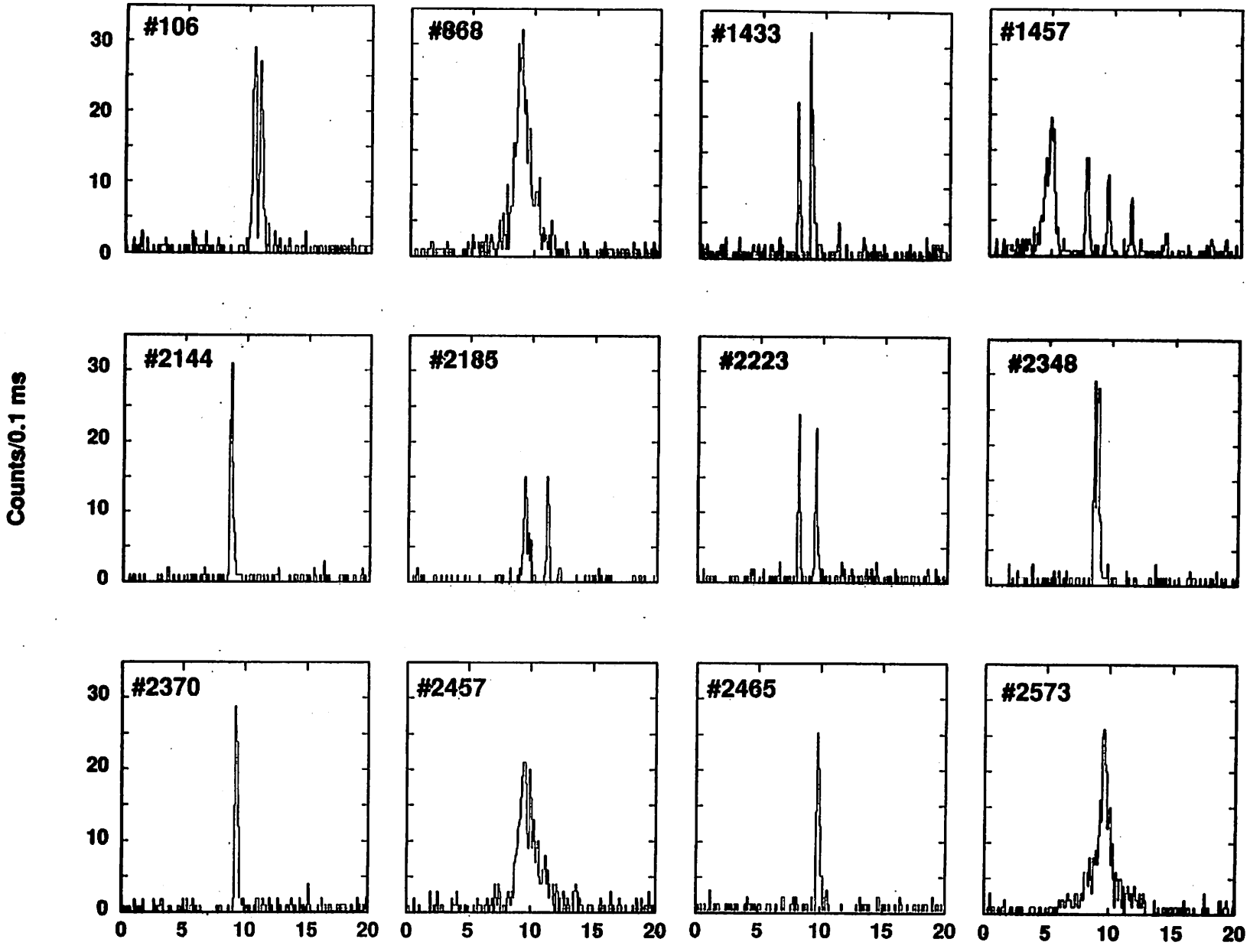
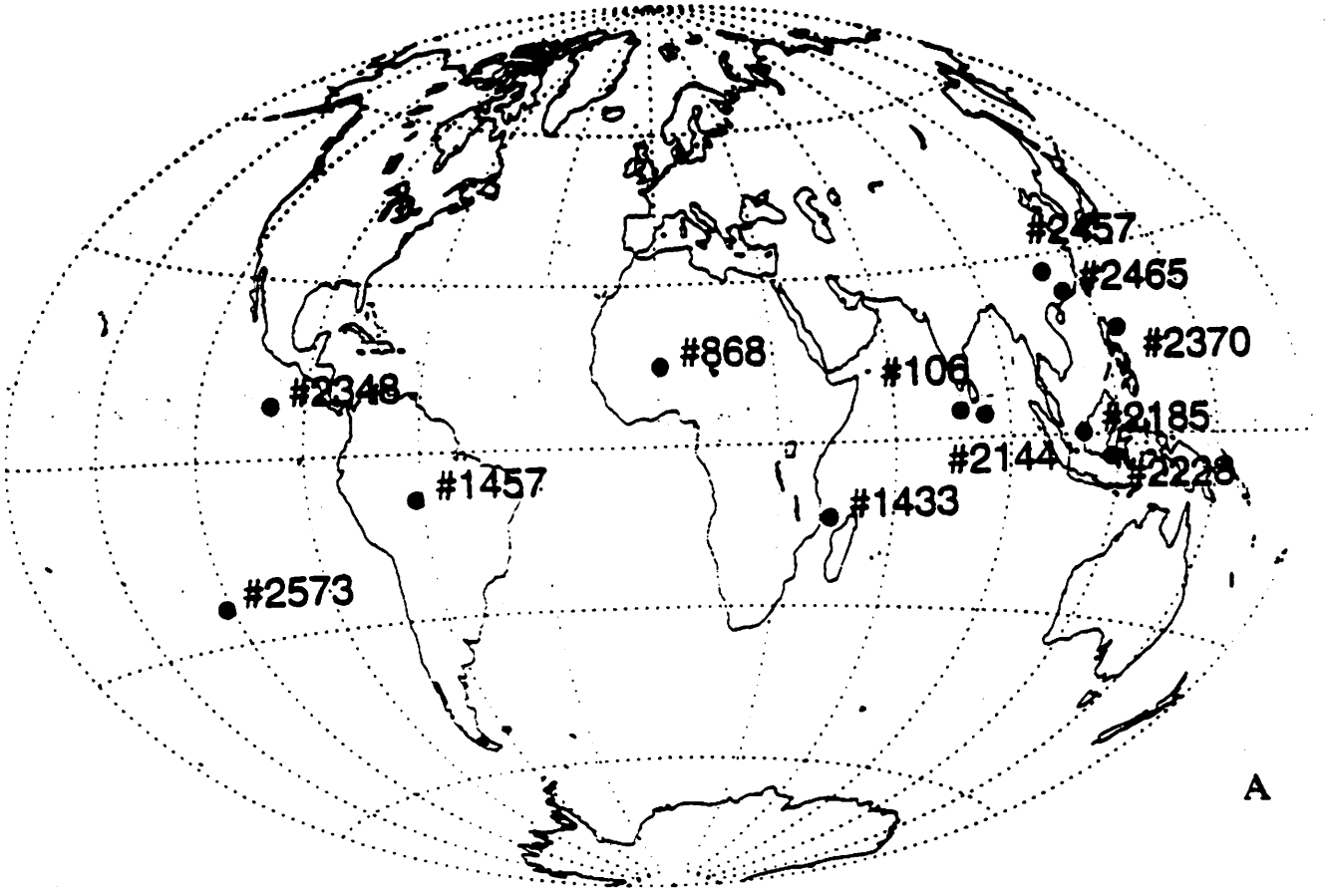


Figure 1


#106
#868
#1433
#1457
#2144
#2185
#2223
#2348
#2370
#2457
#2465
#2573
Counts/0.1 ms
t (ms)
0
10
20
30
0
5
10
15
20



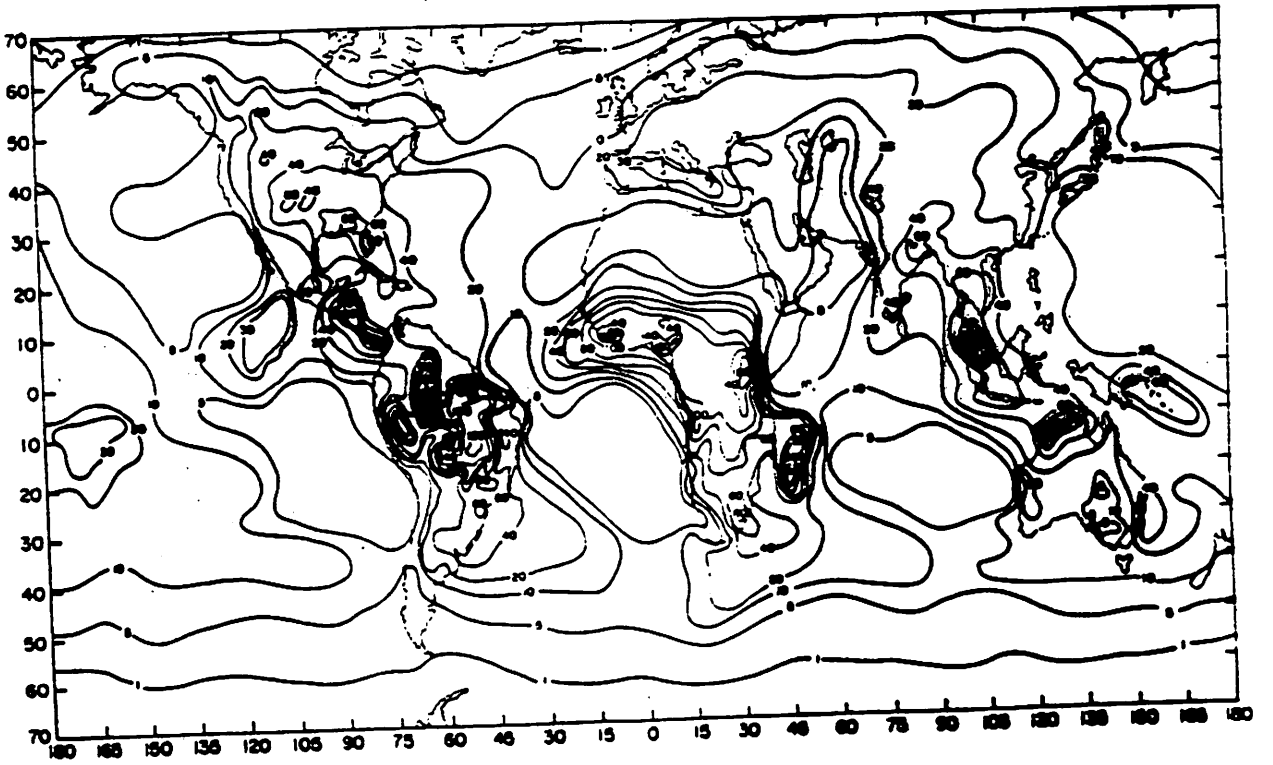
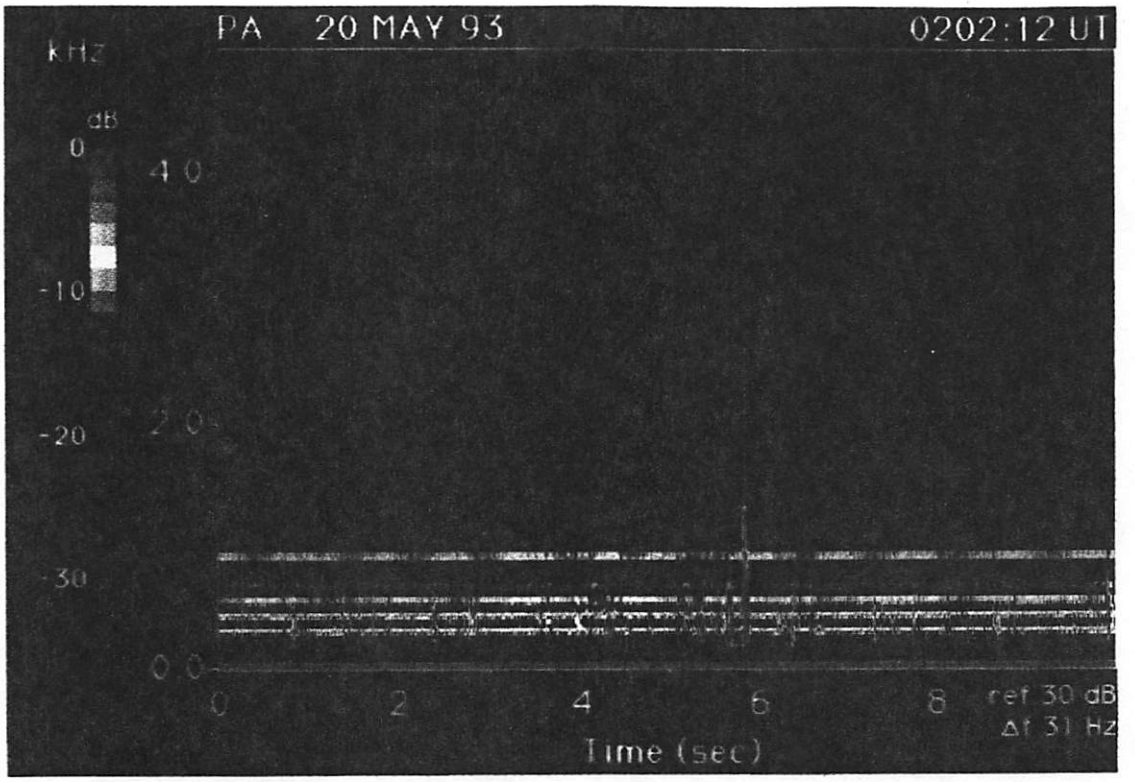
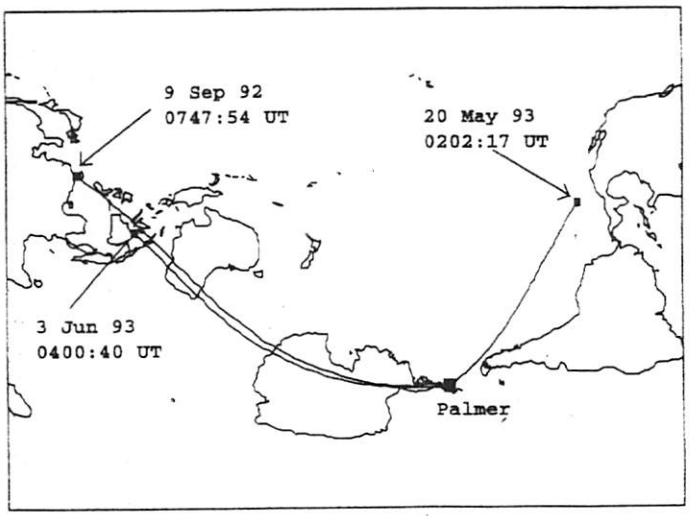
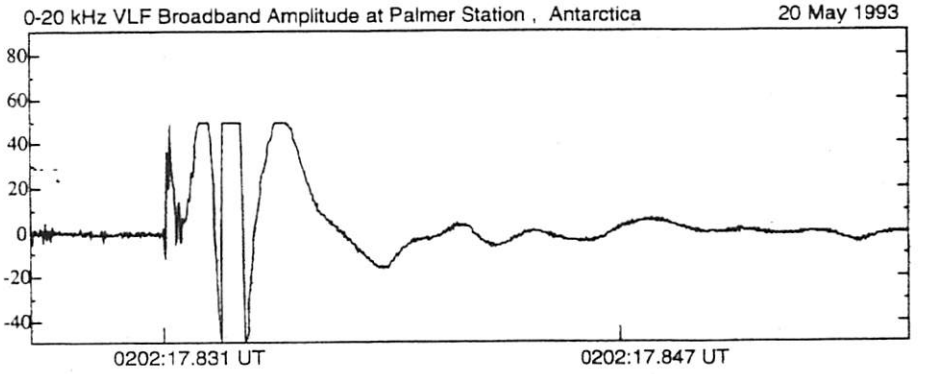


Figure 2

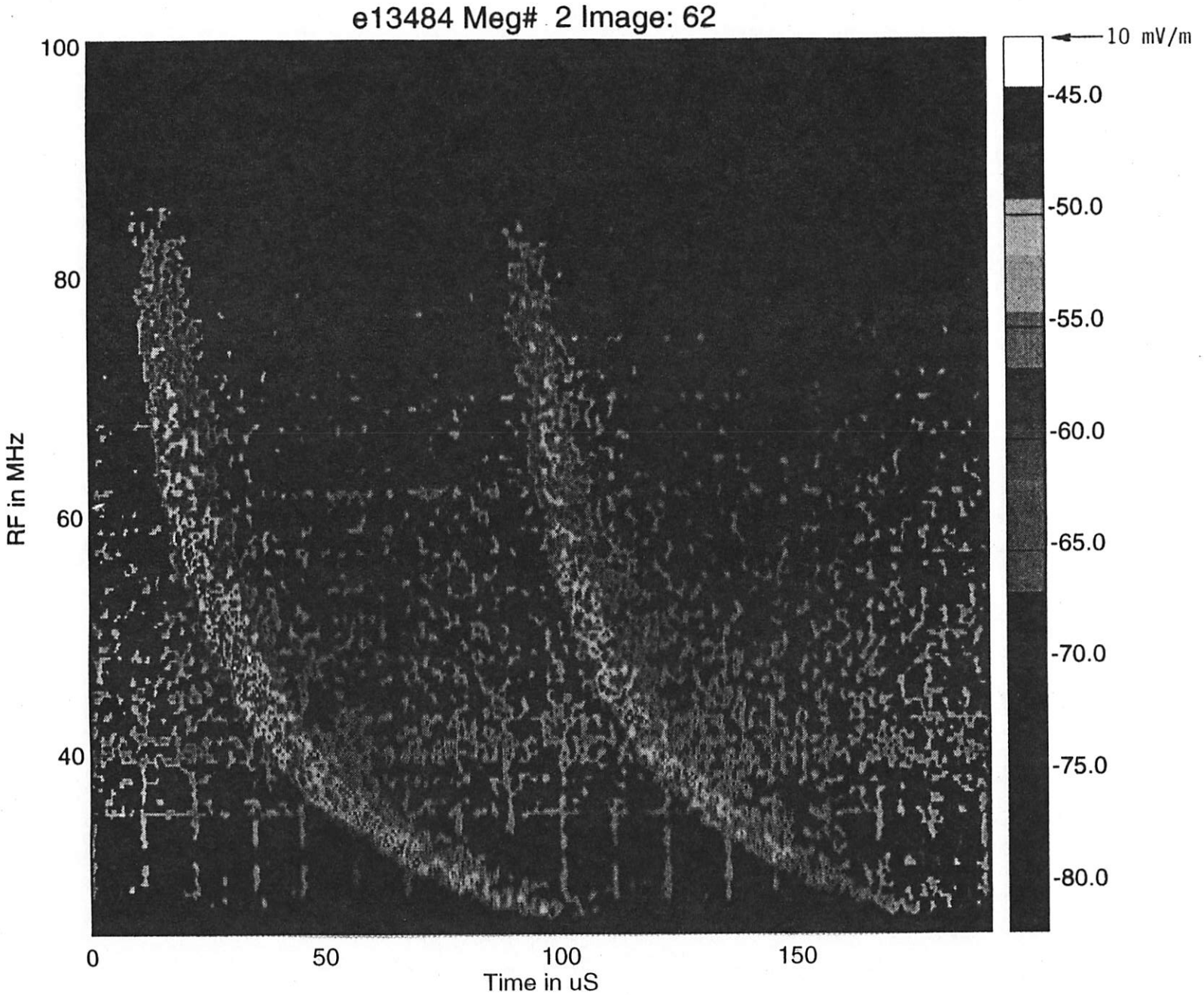


Great circle paths from gamma-ray "flash" locations to Palmer Station, Antarctica



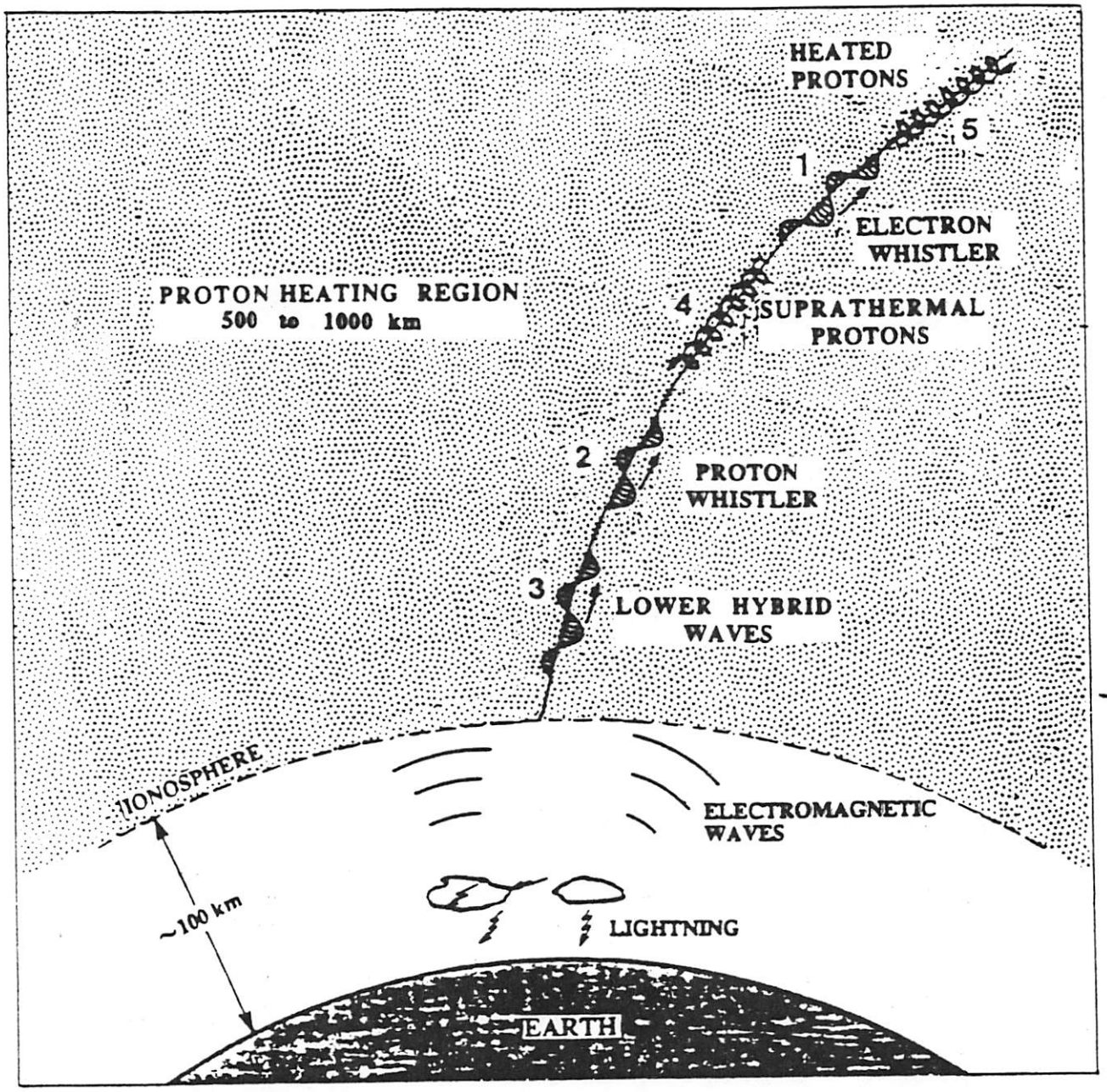


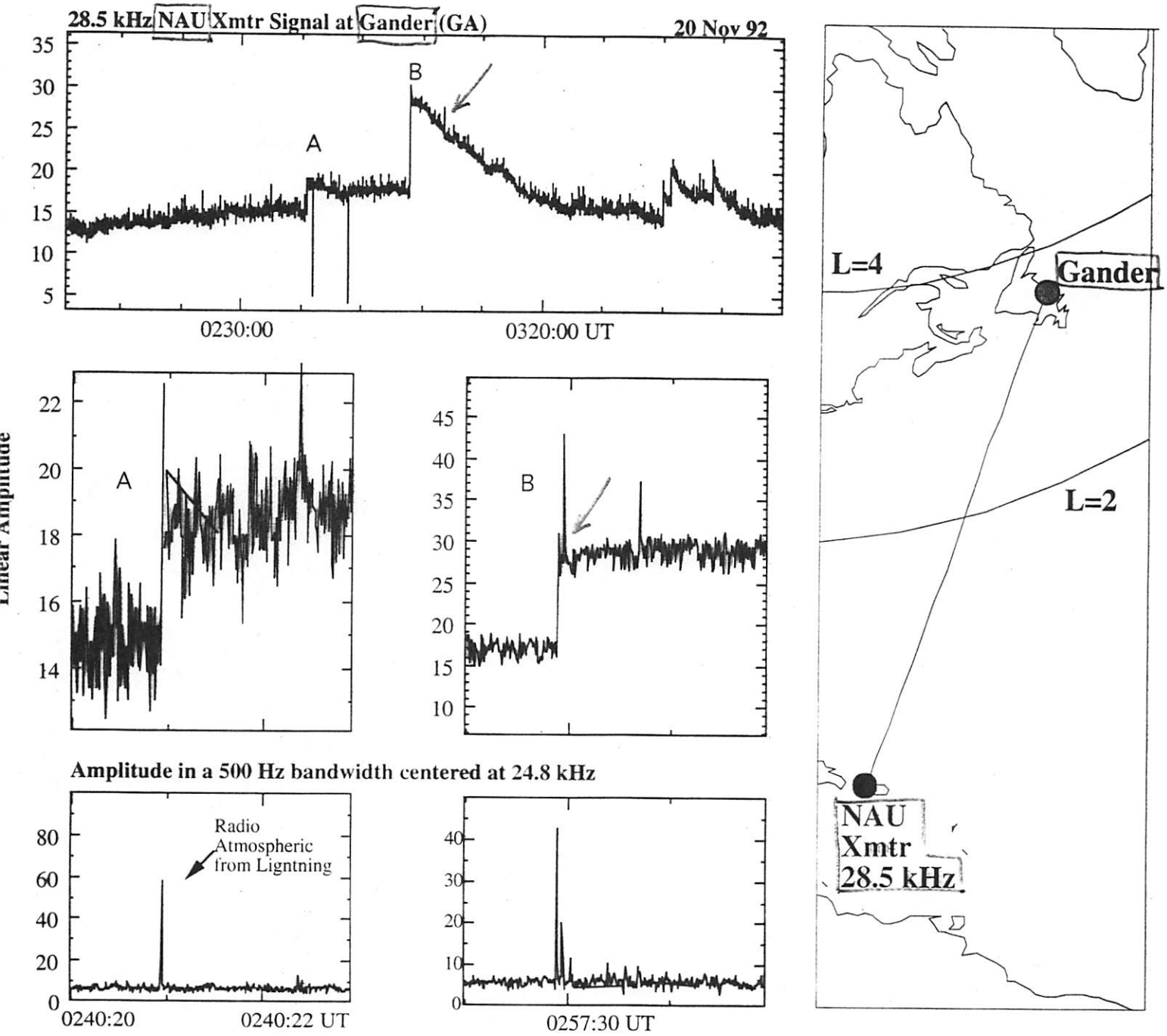
Dr.Daniel Holden/LLNL



Bell et al: The Heating of Ions above
Thunderstorm Cells

1993




28.5 kHz NAU Xmtr Signal at Gander (GA)
20 Nov 92
A
B
0230:00
0320:00 UT
Linear Amplitude
Amplitude in a 500 Hz bandwidth centered at 24.8 kHz
Radio
Atmospheric
from Lightning
0240:20
0240:22 UT
0257:30 UT
L=4
Gander
L=2
NAU
Xmtr
28.5 kHz