Experimental Studies of Lightning Leaders in Natural and Triggered Lightning

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Physics Department Colloquium

October 30, 2025

LANGMUIR LABORATORY

FOR ATMOSPHERIC RESEARCH

(Photo courtesy of Harald Edens)

A HIGHLY COLLABORATIVE EFFORT!

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BIMAP-3D

Xuan-Min Shao, Daniel Jensen

Outline

What are lightning leaders?

Why are they important?

What behaviors do they display?

How do we know?

Initial results summer 2025

Outline

What are lightning leaders?

Why are they important?

What behaviors do they display?

How do we know?

Initial results summer 2025

What's a leader?

Roughly 3-Million volts/m is necessary to break down virgin air at STP.

A thundercloud may be at 100 Million volts with respect to ground.

What's a leader?

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But it's much higher than 33 meters.

So how do you break down a one kilometer, or three kilometer, or ten kilometer, or hundred kilometer path in virgin air?

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A little bit at a time

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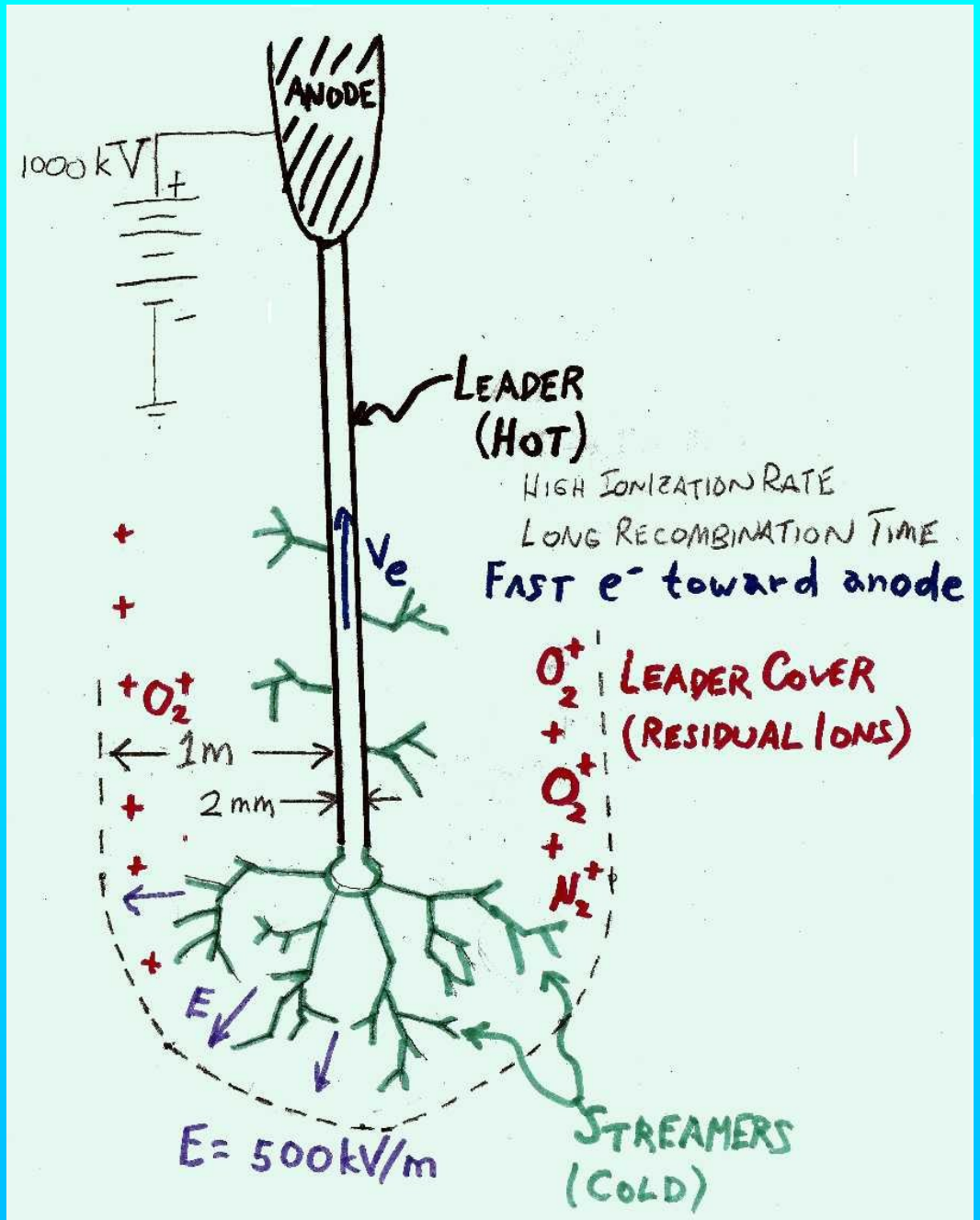
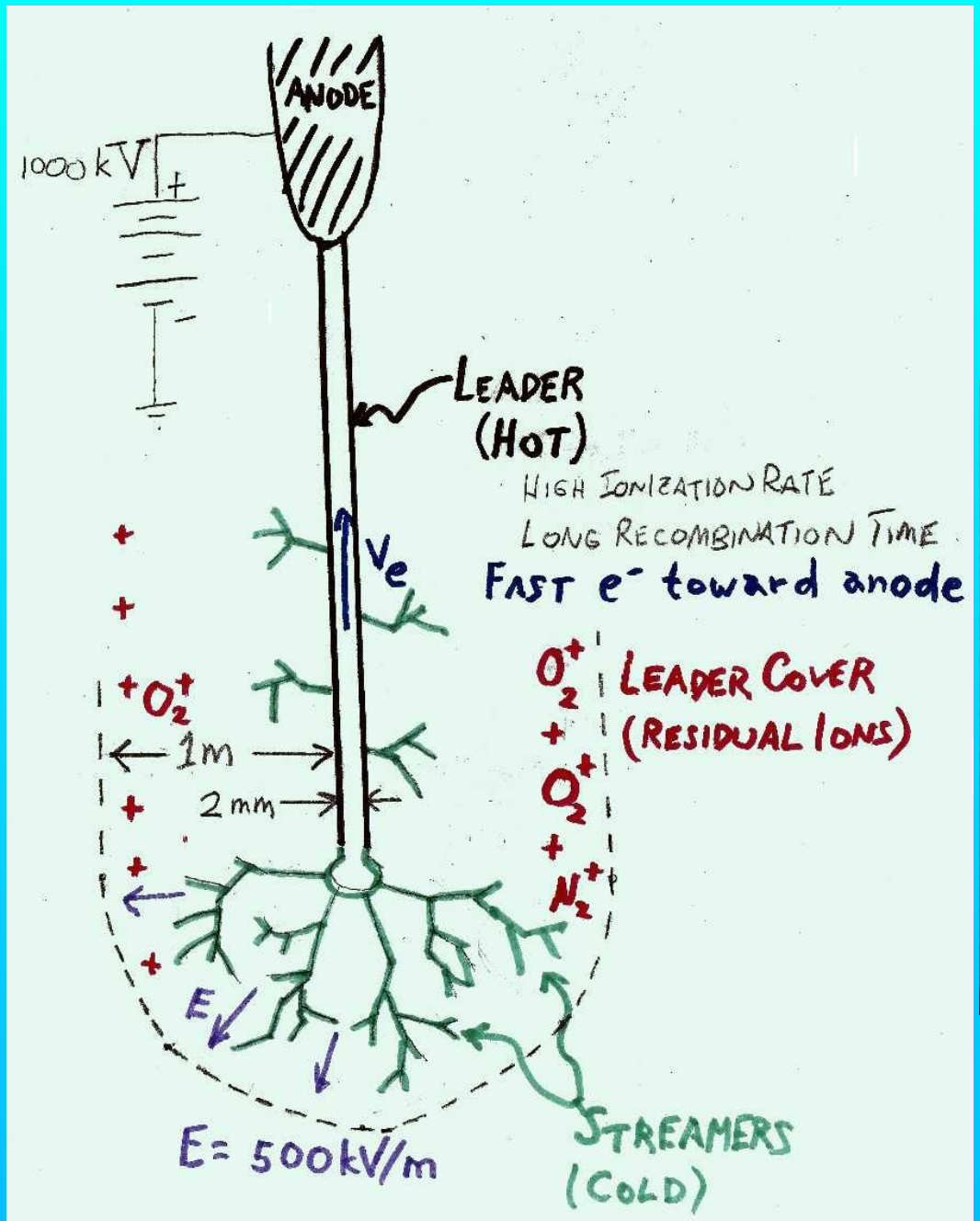
A little bit at a time

With a "leader"


ANODE
1000 kV
+
-
LEADER
(HOT)
HIGH IONIZATION RATE
LONG RECOMBINATION TIME
FAST e⁻ toward anode
V_e
O_2^+
1m
2mm
O_2^+
LEADER COVER
(RESIDUAL IONS)
O_2^+
N_2^+
E
E= 500kV/m
STREAMERS
(COLD)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LEADER COVER
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1m
2mm
E
E= 500kV/m
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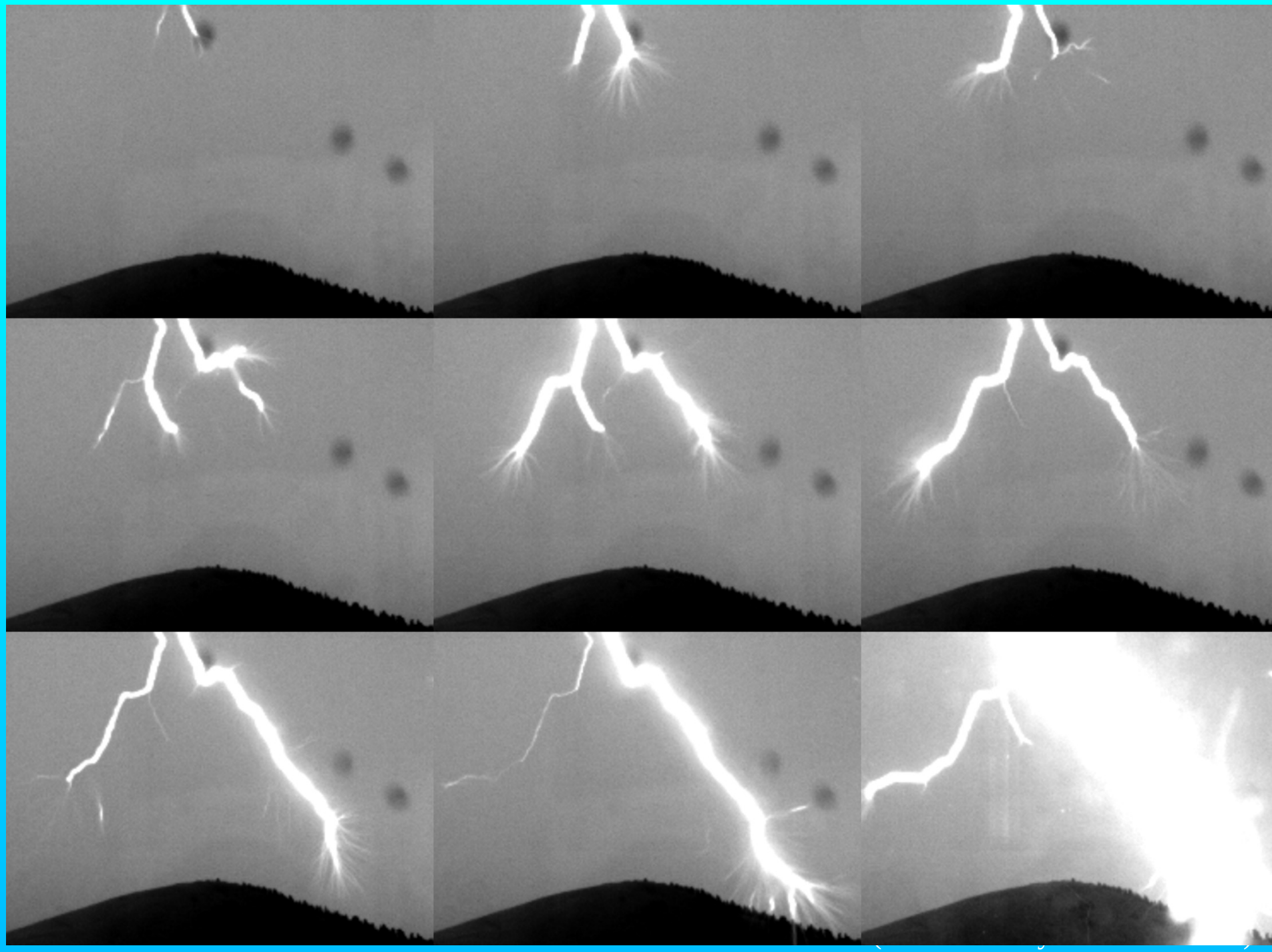
(COLD)



How does lightning happen?

Leaders, streamers, and waves

Outline

What are lightning leaders?

Why are they important?

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How do we know?

Initial results summer 2025

Stepped and dart leaders

Negative stepped leader – Virgin air breaks down in "steps". Steps are 10-300 m long. The leader often branches at multiple scales.

Velocity: $5 \times 10^4 - 3 \times 10^5$ m/s
~60 MHz power: 10 to 30 dBW $(10 - 1000$ Watts$)$

Negative dart leader – Pre-ionized air (20-200 ms later) breaks down faster, with higher current and fewer branches.

Velocity: $1 \times 10^6 - 2 \times 10^7$ m/s
~60 MHz power: highly variable

Positive leaders

Do they step? – They emit weak RF pulses. Bright tips are not apparent. They are slower than negative leaders.

Velocity: $1 \times 10^4 - 2 \times 10^4$ m/s (Mach 50)
~60 MHz power: -20 to 0 dBW $(10 - 1000\,\mathrm{mW})$

Positive dart leader? – Not much data

Outline

What are lightning leaders?

Why are they important?

What behaviors do they display?

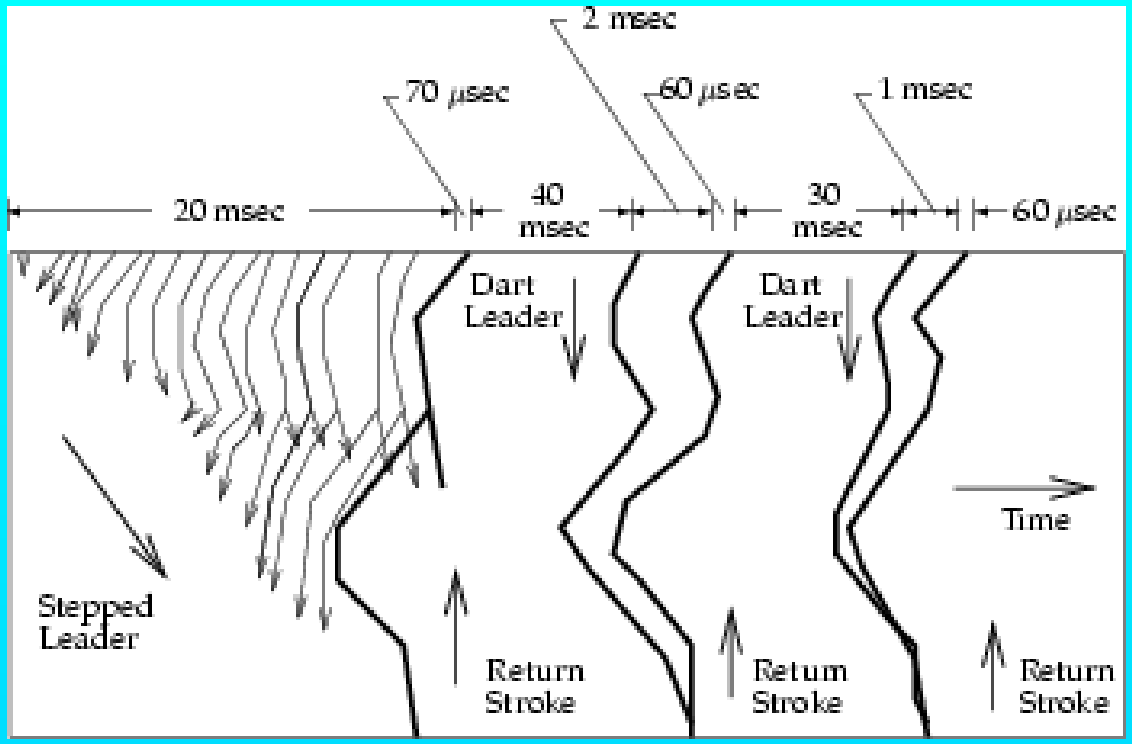
How do we know?

Why do they display these behaviors?

What's next?

Ancient results

$v_s \simeq 10^5 \ \mathrm{m/s}$



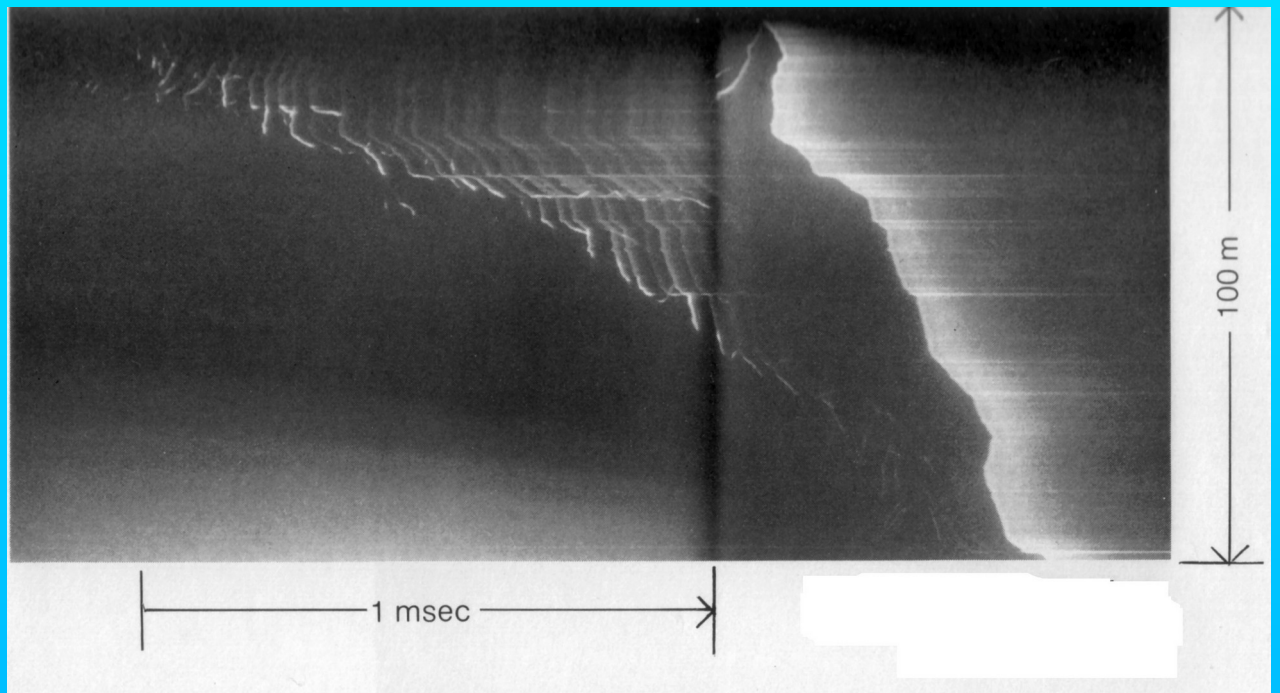


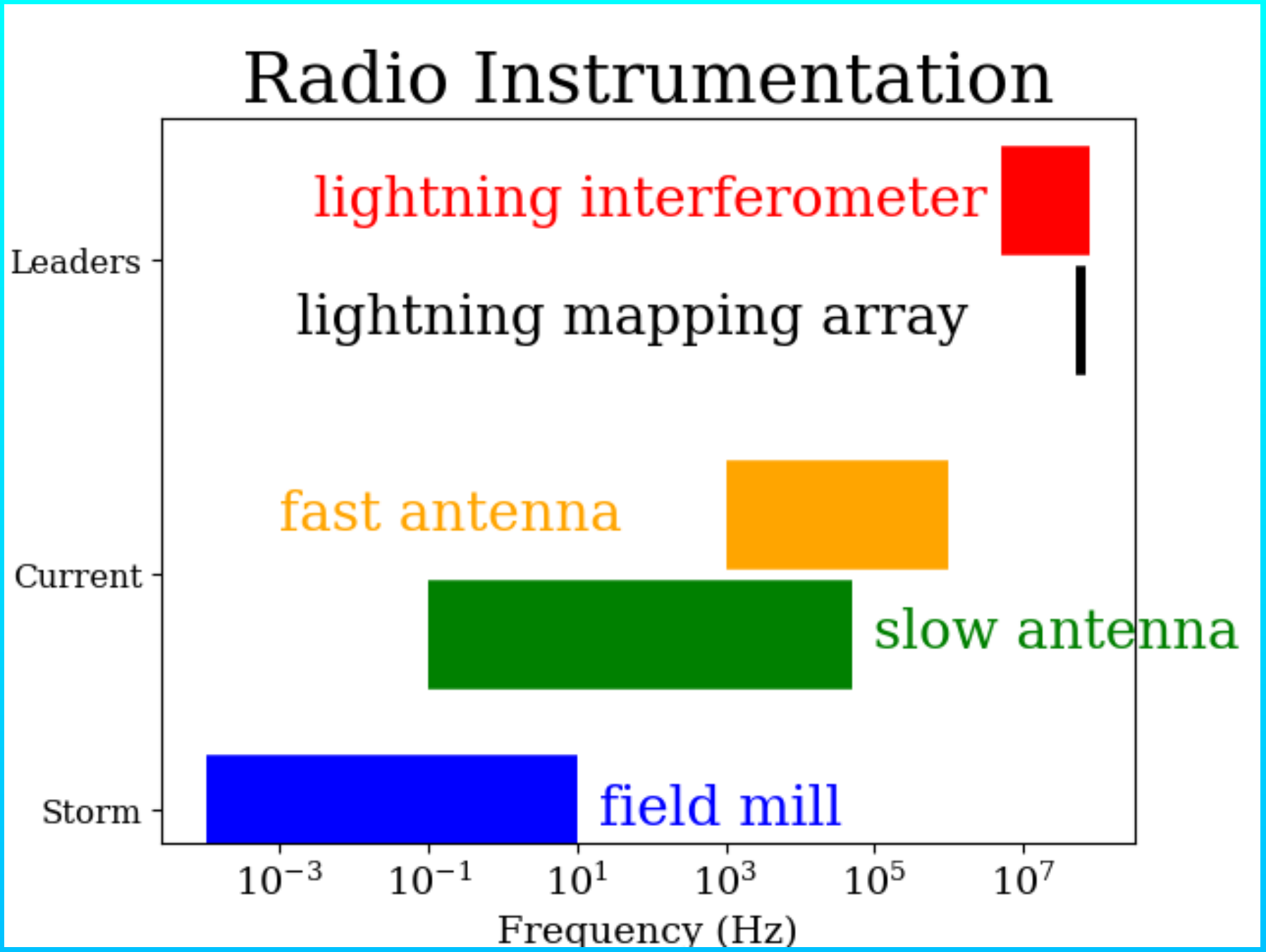
Table 1

The Range of Maximum and Minimum Dart (and K) Leader Velocities Reported by Selected Studies, and Compared to This Study

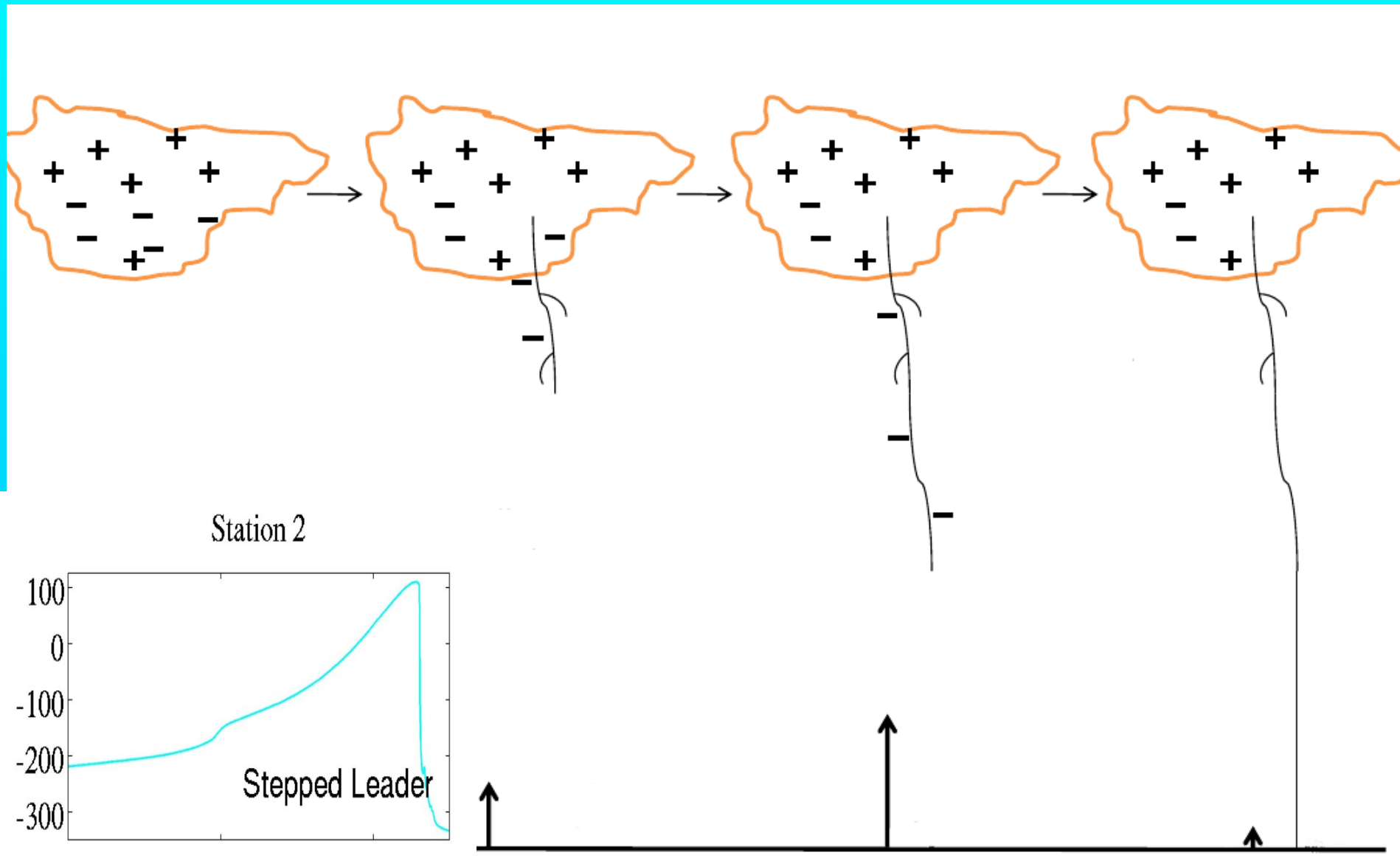
Paper	Leader velocities (m/s)	Leader type
Schonland et al. (1935)	1×10^6 to 23×10^6	Dart
Loeb (1966)	2×10^6 to 20×10^6	Dart
Jordan et al. (1992)	6×10^6 to 50×10^6	Dart
Shao et al. (1995)	1×10^6 to 10×10^6	Dart
M. G. Stock et al. (2014)	3×10^6 to 17×10^6	K leader
This study	2×10^6 to 20×10^6	Dart & K

Jensen, Shao, Sonnenfeld – J. Geophys. Res. 2023, 10.1029/2023JD039104

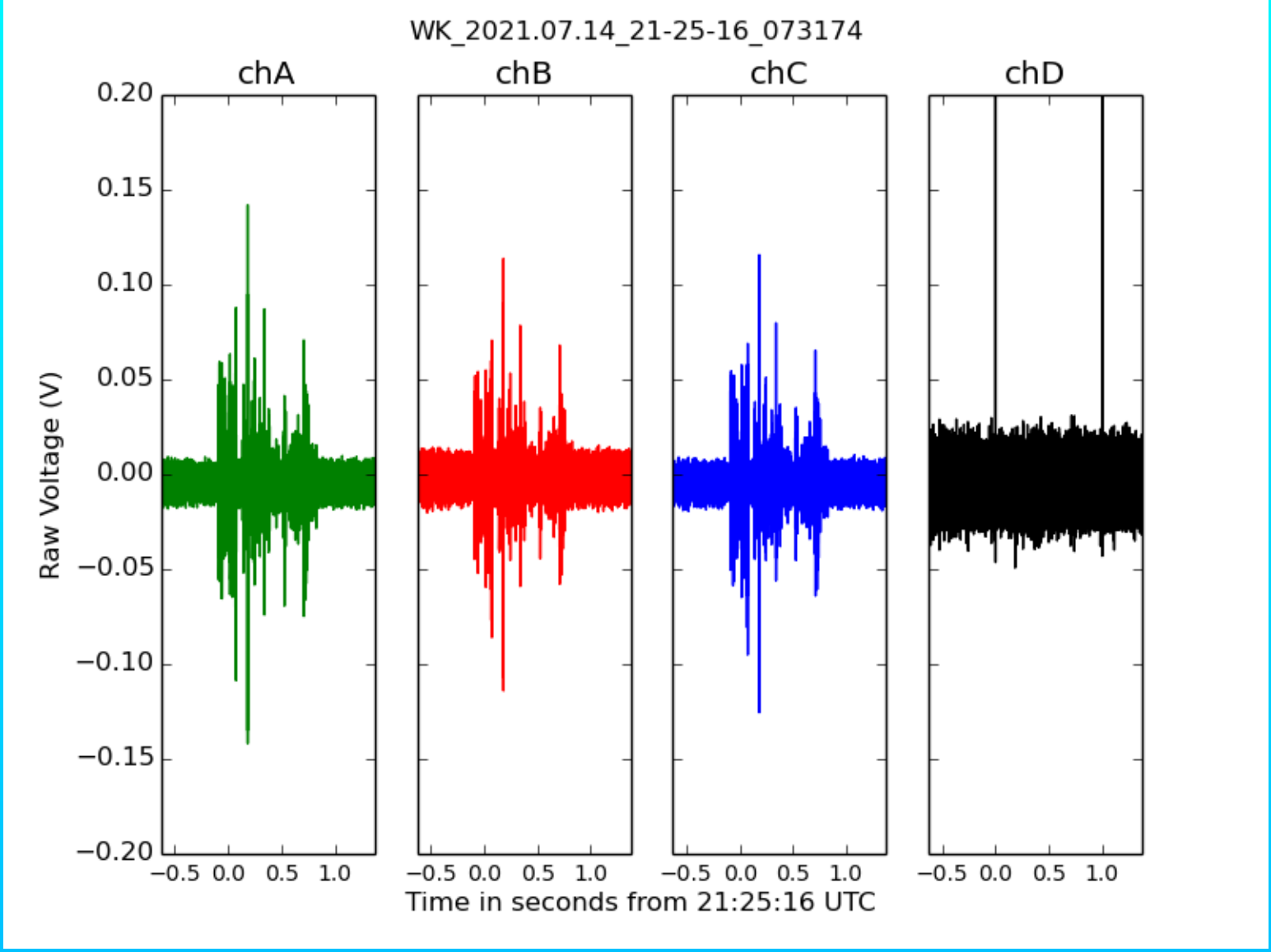

– 40 °C
~ 8 km
0 °C


Radio Instrumentation
lightning interferometer
lightning mapping array
fast antenna
slow antenna
field mill
Leaders
Current
Storm
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
Frequency (Hz)

Cartoon of a CG flash



Lightning interferometer (5-80 MHz), and LMA (~60 MHz)



Radio interferometric observations of cloud-to-ground lightning phenomena in Florida

X. M. Shao,[1] P. R. Krehbiel, R. J. Thomas, and W. Rison

Langmuir Laboratory for Atmospheric Research, Geophysical Research Center

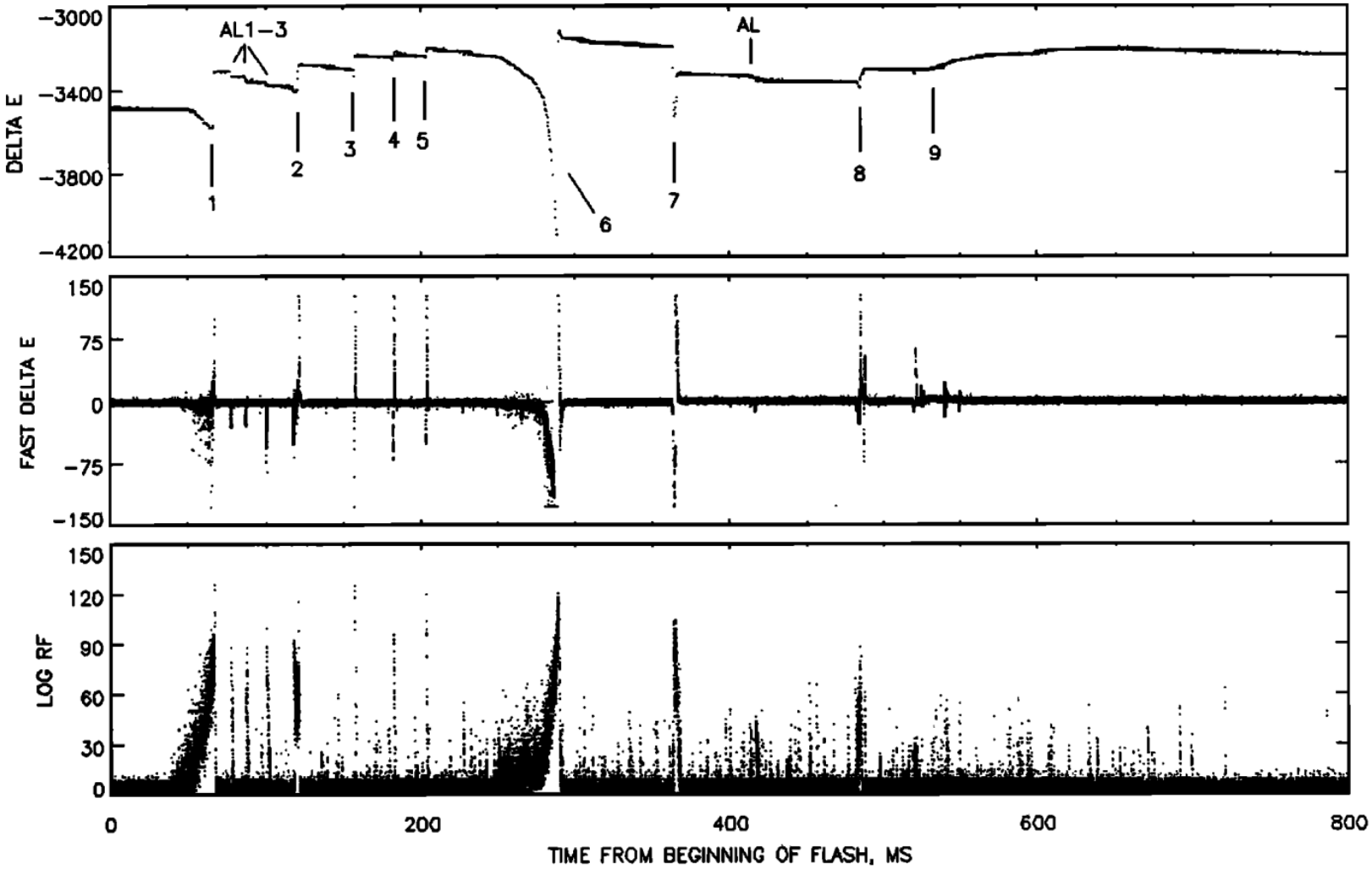
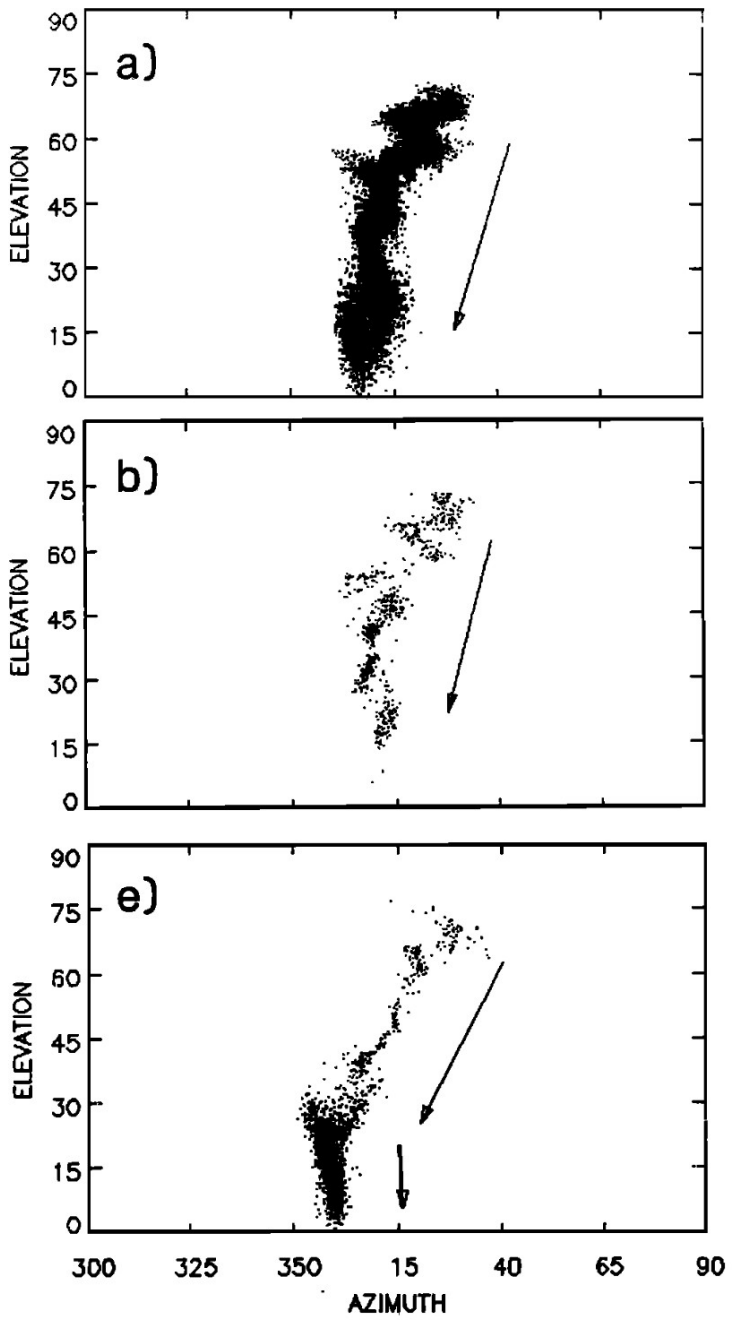
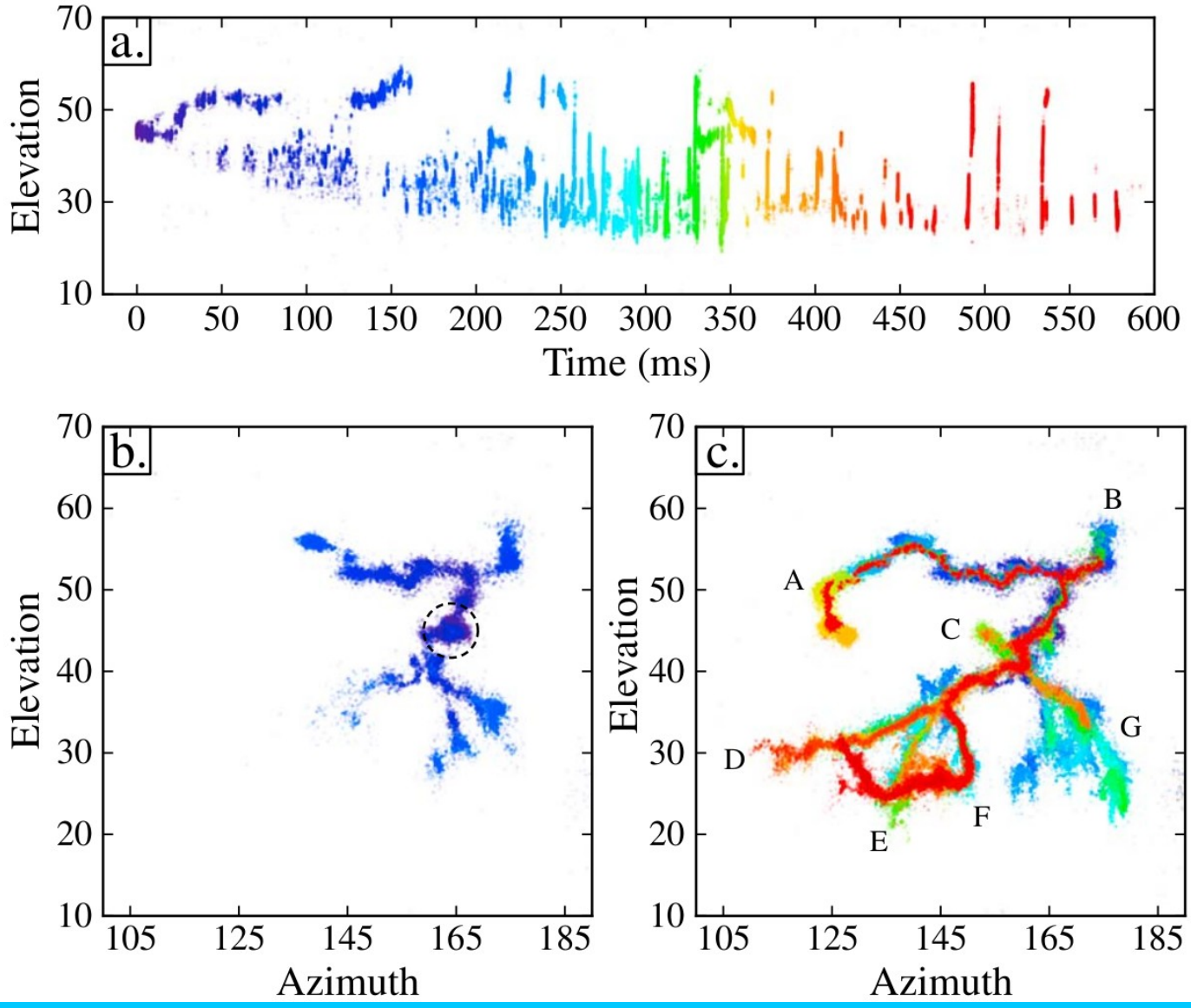
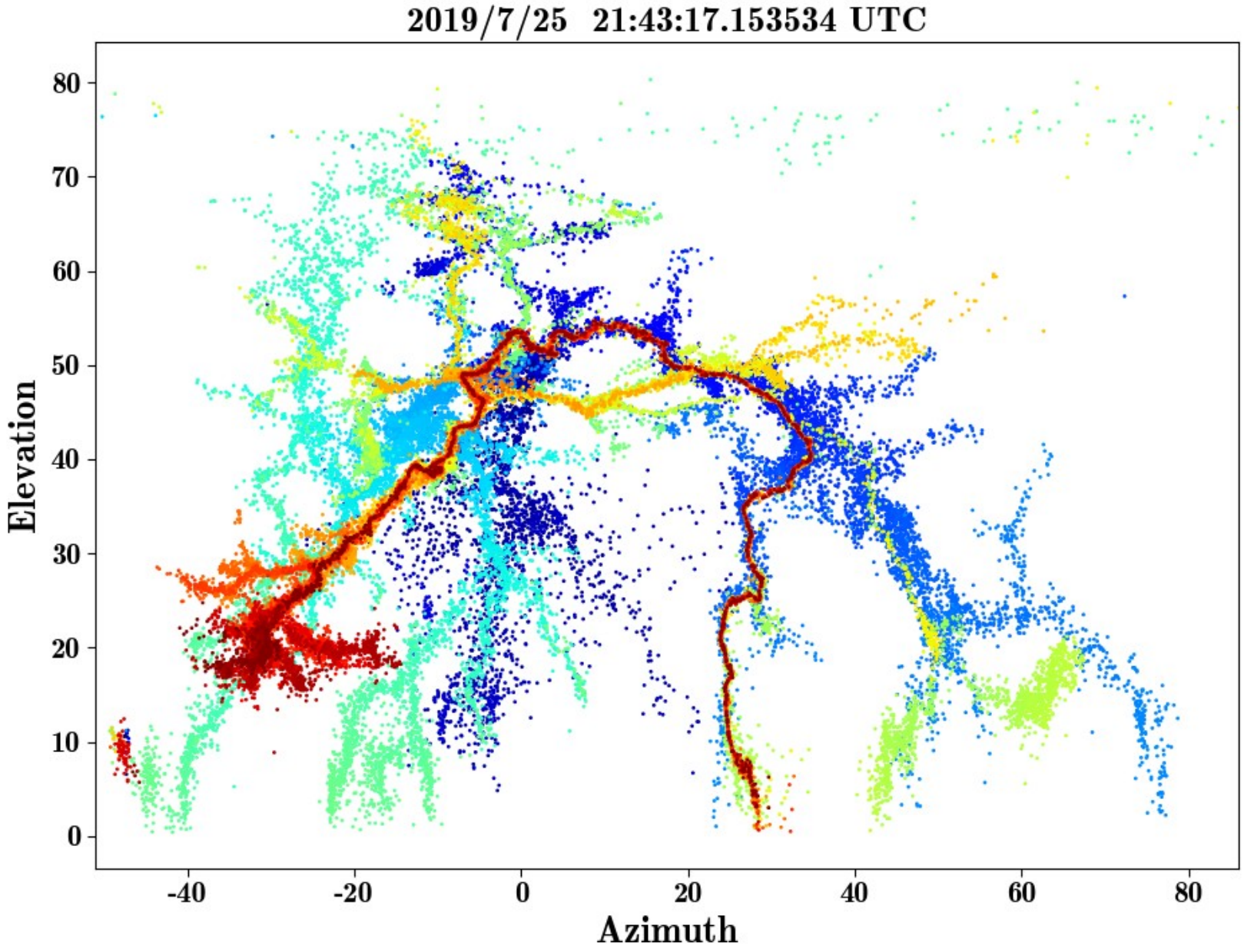


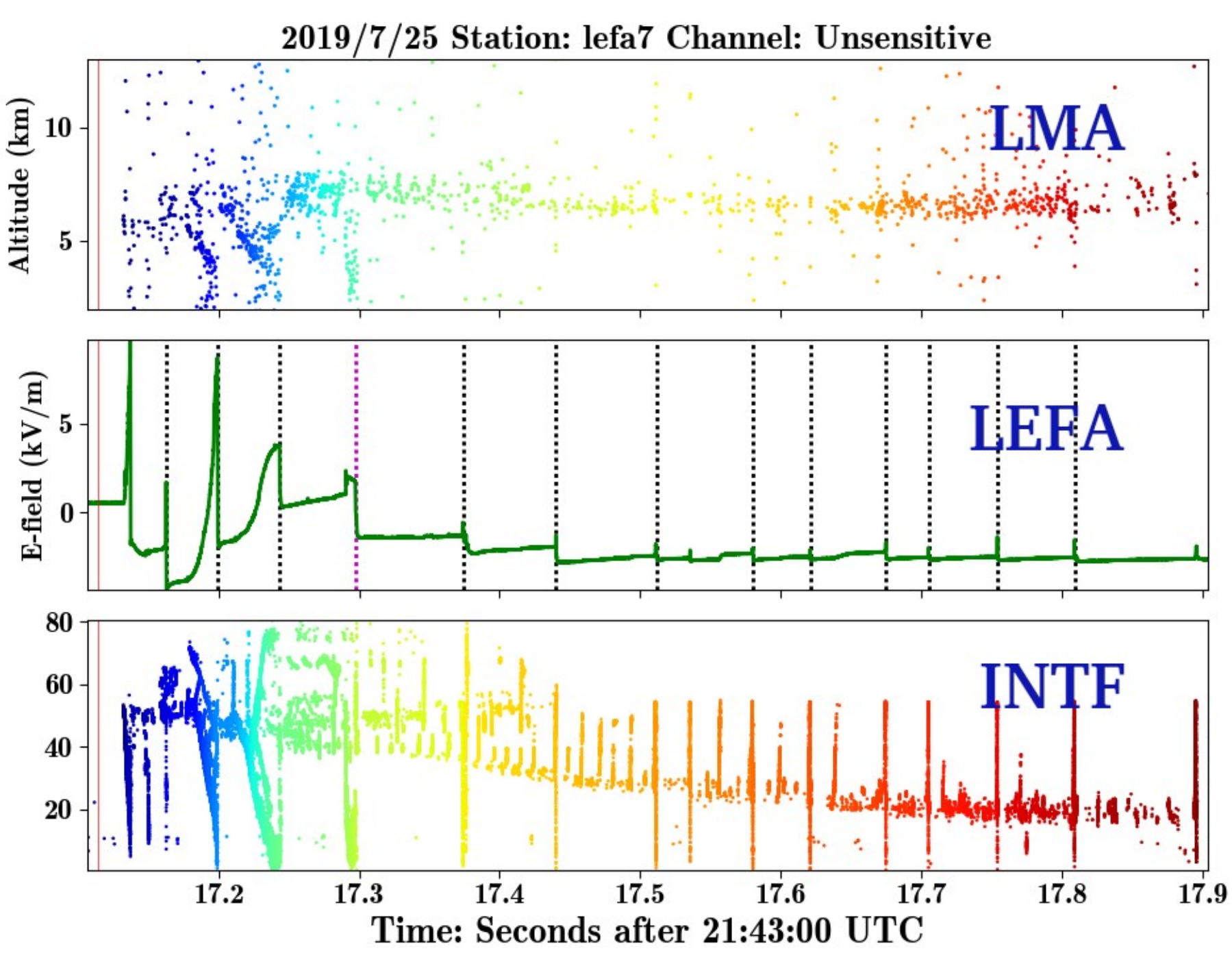
Figure 4. Overall time waveforms for flash 203100 of Figures 1 to 3. The flash produced nine strokes to ground and a final attempted leader (AL4) following the seventh stroke.

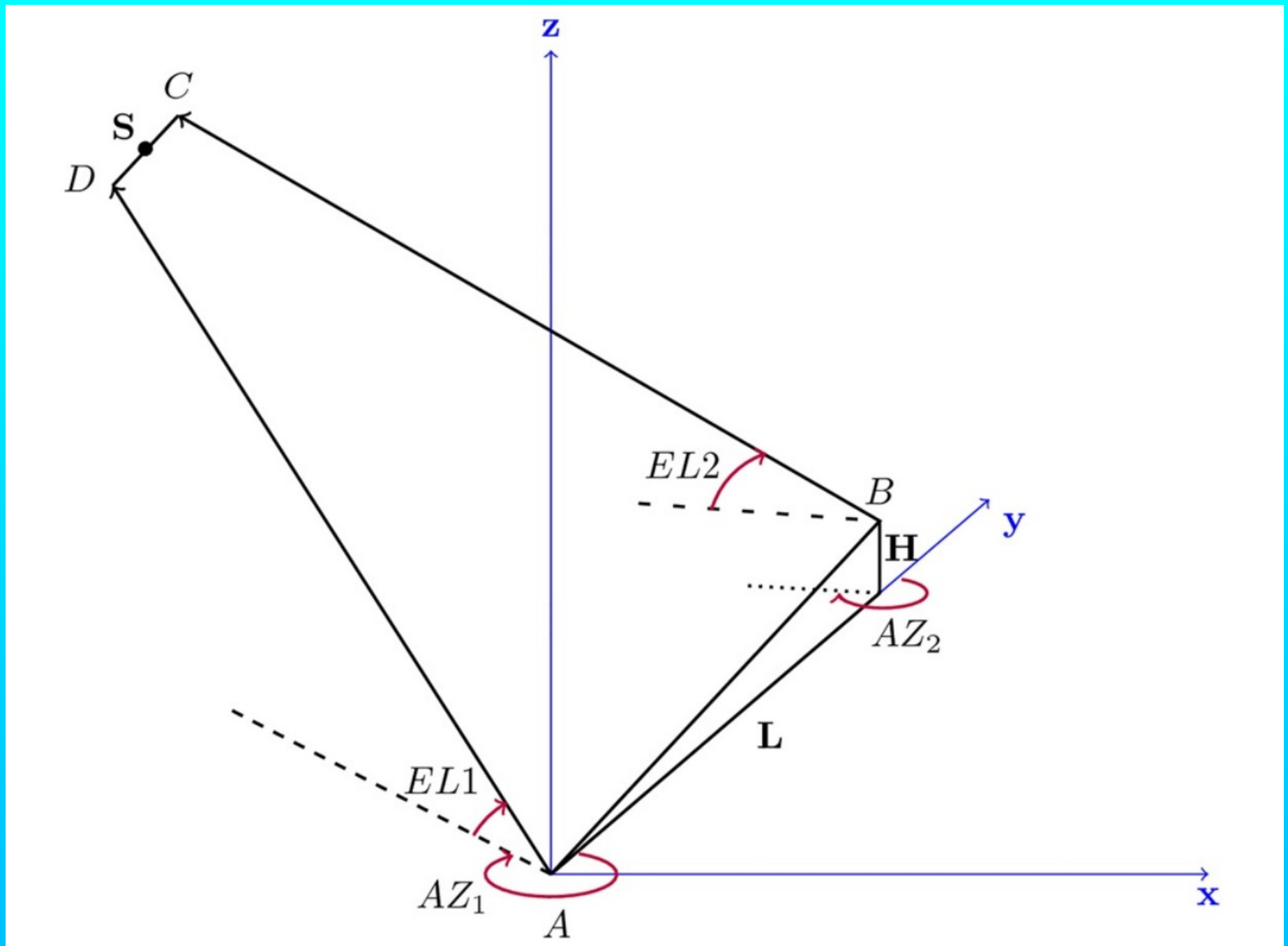

a)
b)
e)
ELEVATION
90
75
60
45
30
15
0
300
325
350
15
40
65
90
AZIMUTH

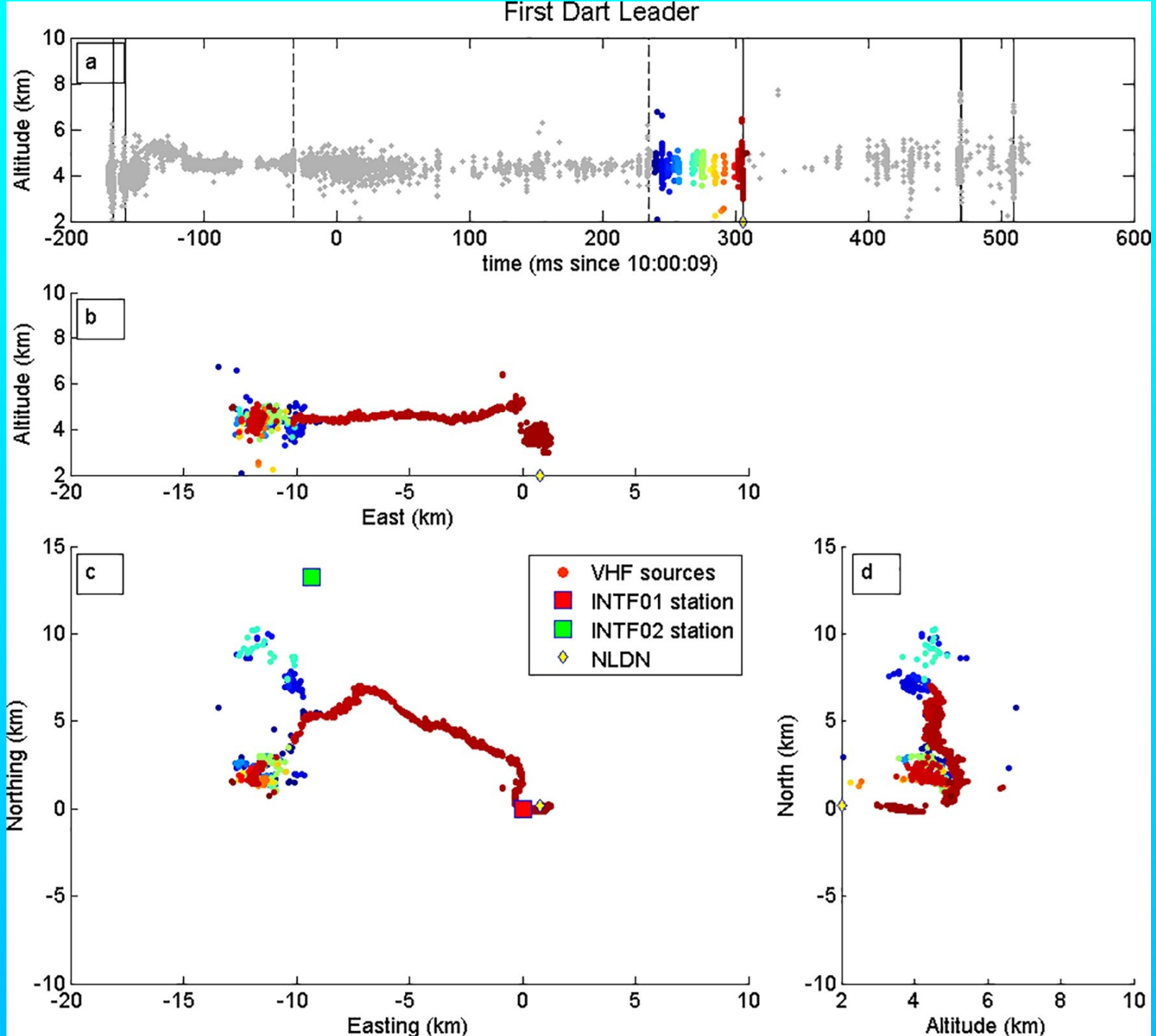


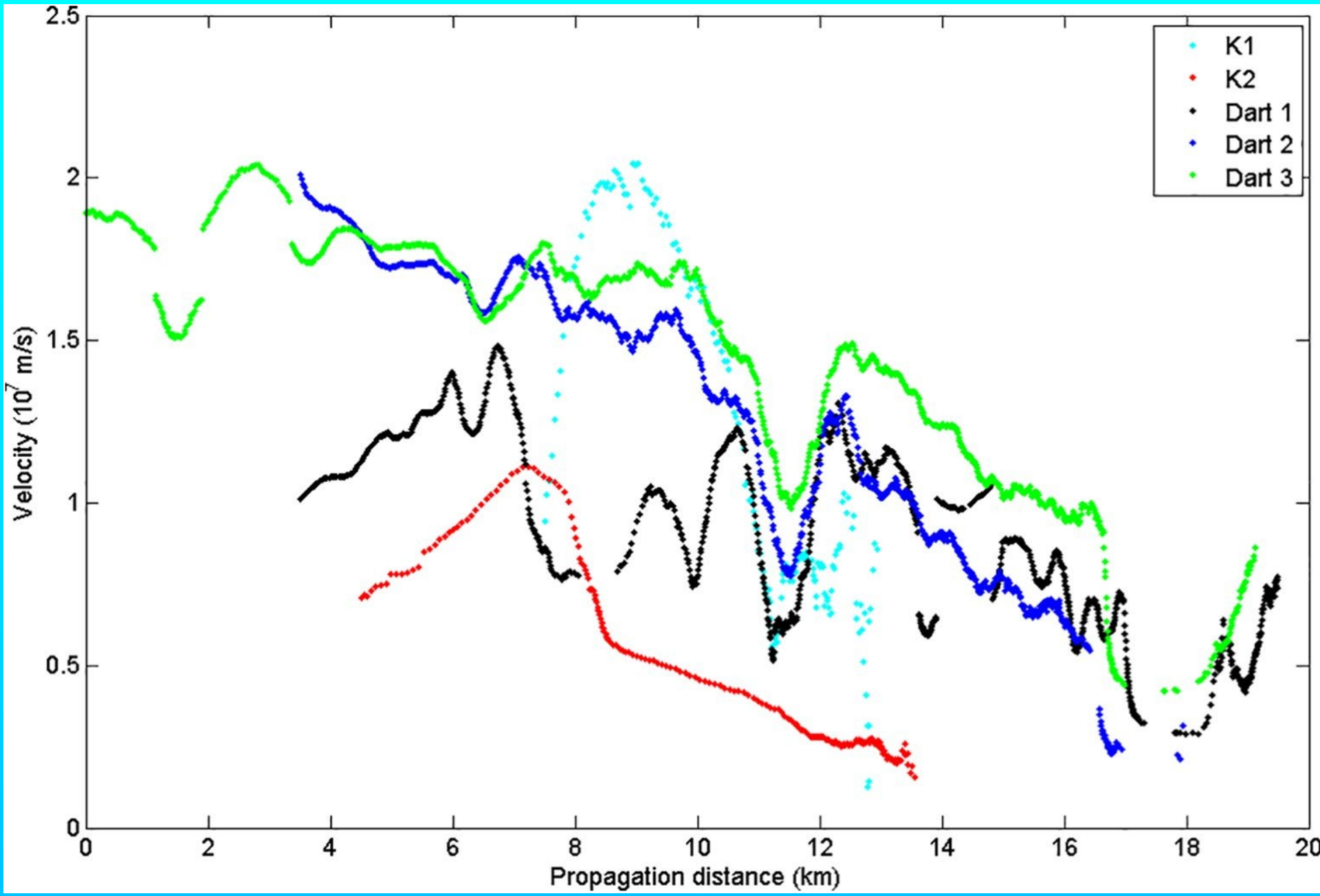
Stock et al. – J. Geophys. Res. 2013, 10.1002/2013JD020217


2019/7/25 21:43:17.153534 UTC
Elevation
Azimuth
80
70
60
50
40
30
20
10
0
-40
-20
0
20
40
60
80

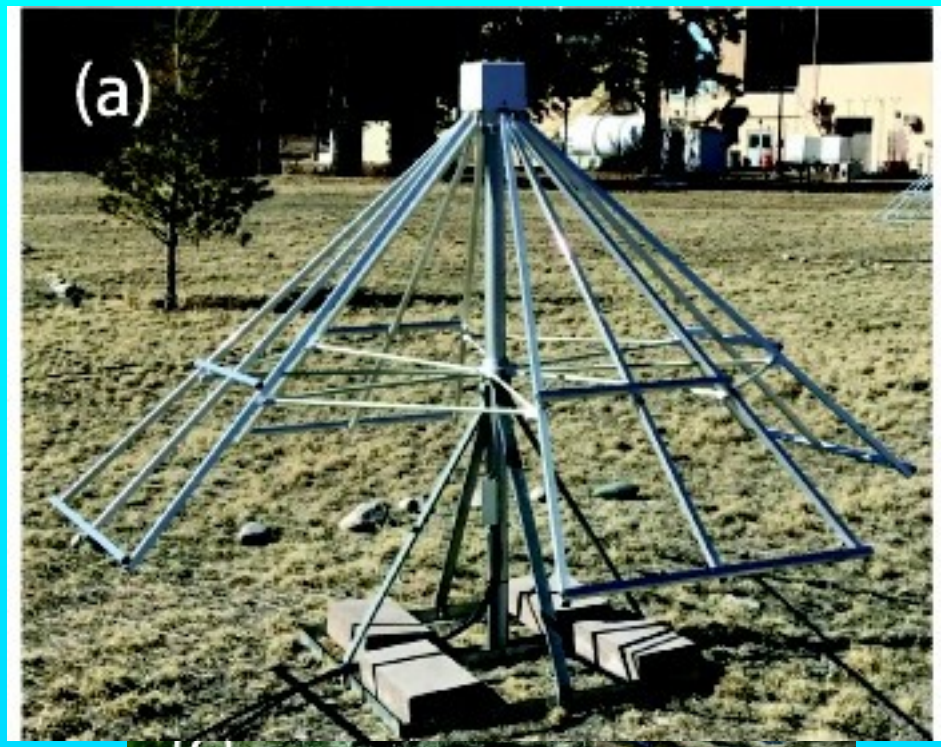

2019/7/25 Station: lefa7 Channel: Unsensitive
Altitude (km)
10
5
LMA
E-field (kV/m)
5
0
LEFA
80
60
40
20
INTF
17.2
17.3
17.4
17.5
17.6
17.7
17.8
17.9
Time: Seconds after 21:43:00 UTC

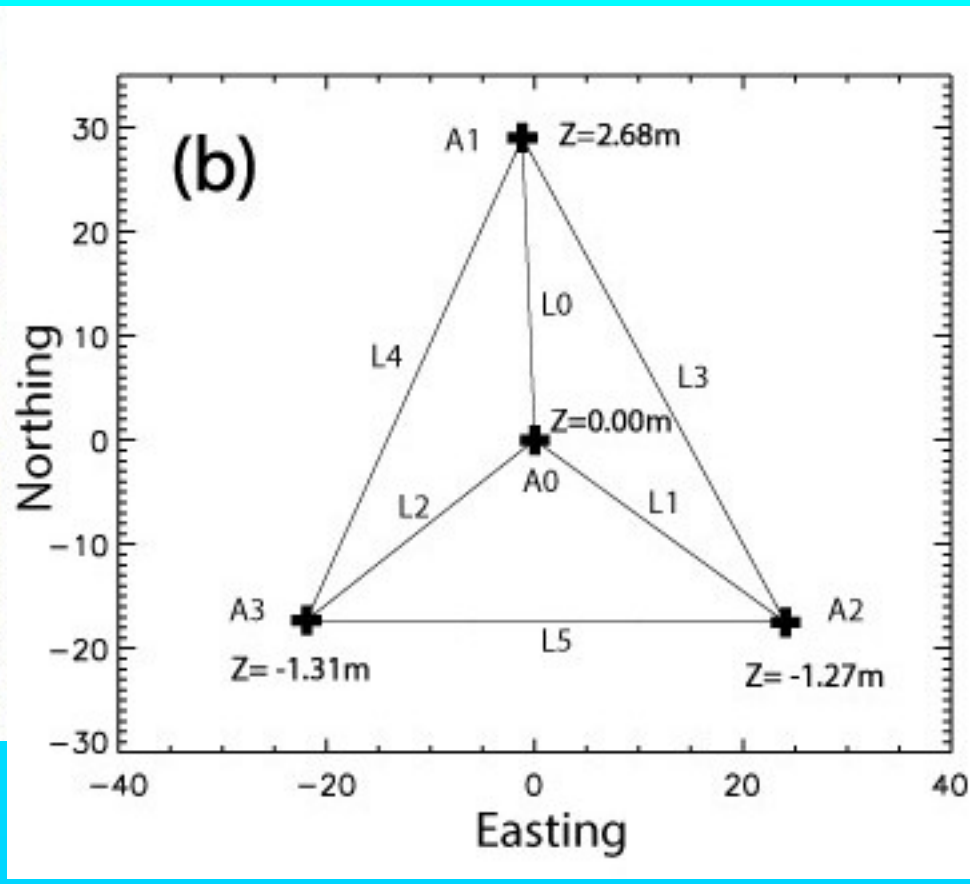

z
C
S
D
EL2
B
y
H
AZ2
L
EL1
AZ1
A
x

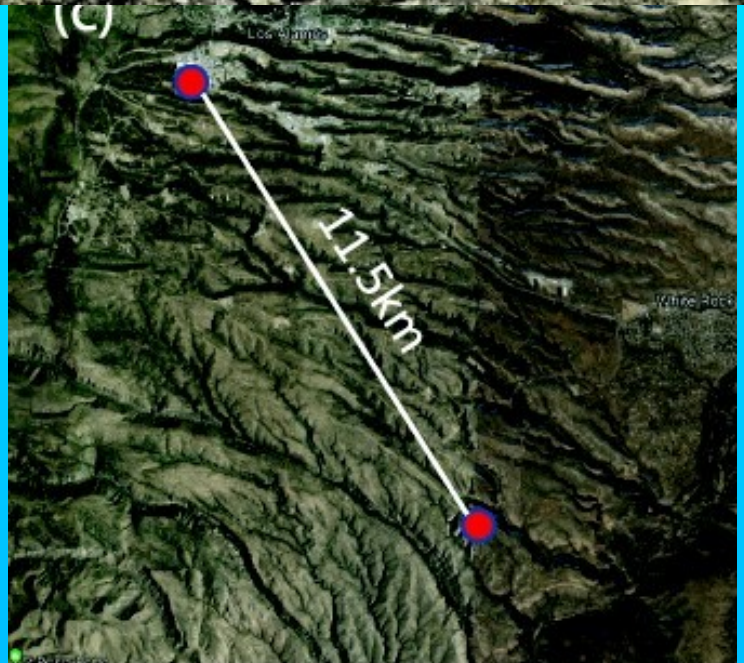

First Dart Leader
a
Altitude (km)
time (ms since 10:00:09)
b
Altitude (km)
East (km)
c
Northing (km)
Easting (km)
VHF sources
INTF01 station
INTF02 station
NLDN
d
North (km)
Altitude (km)

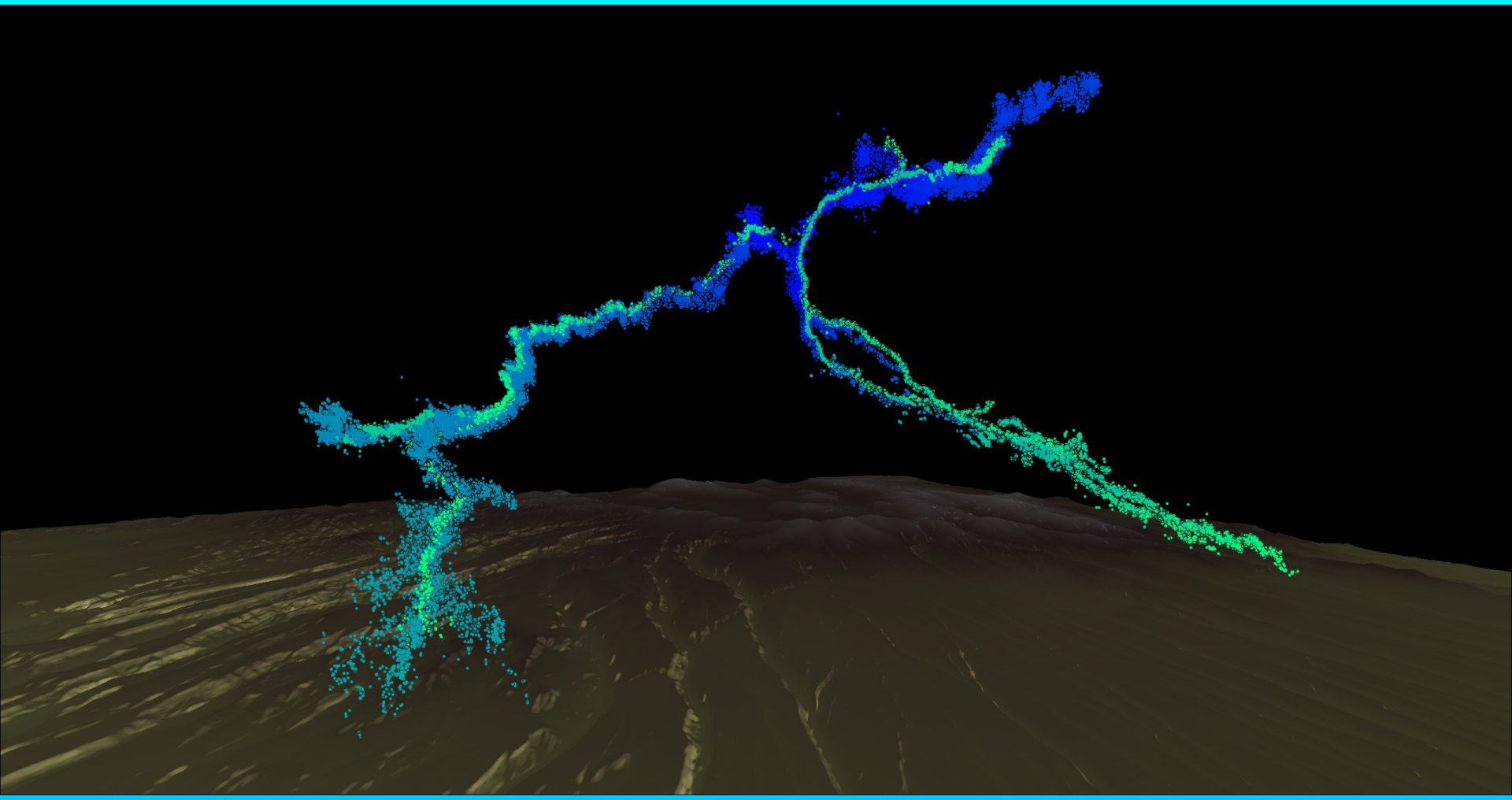


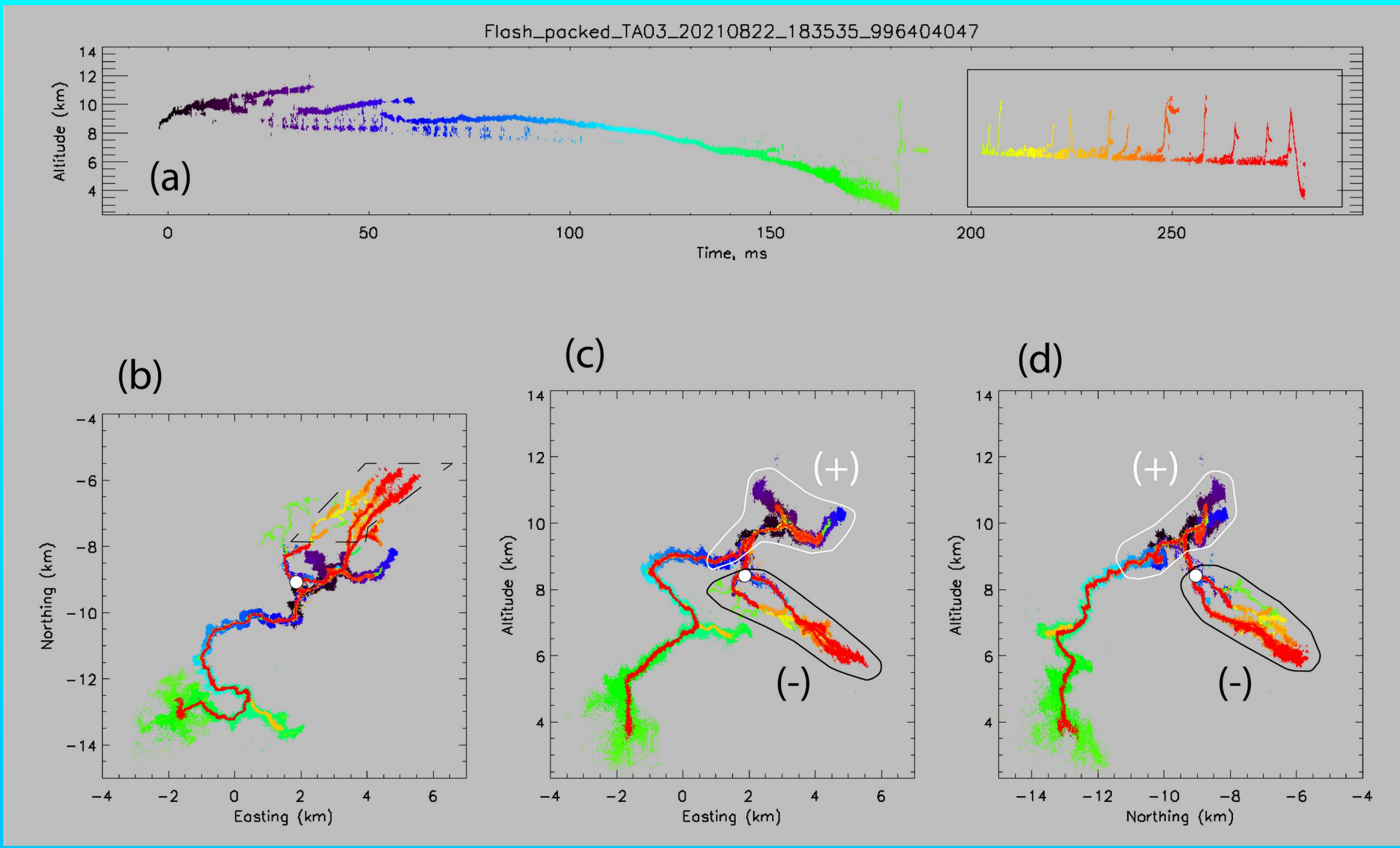
Jensen, Sonnenfeld, et al. J. Geophys. Res, 10.1029/2020JD034309

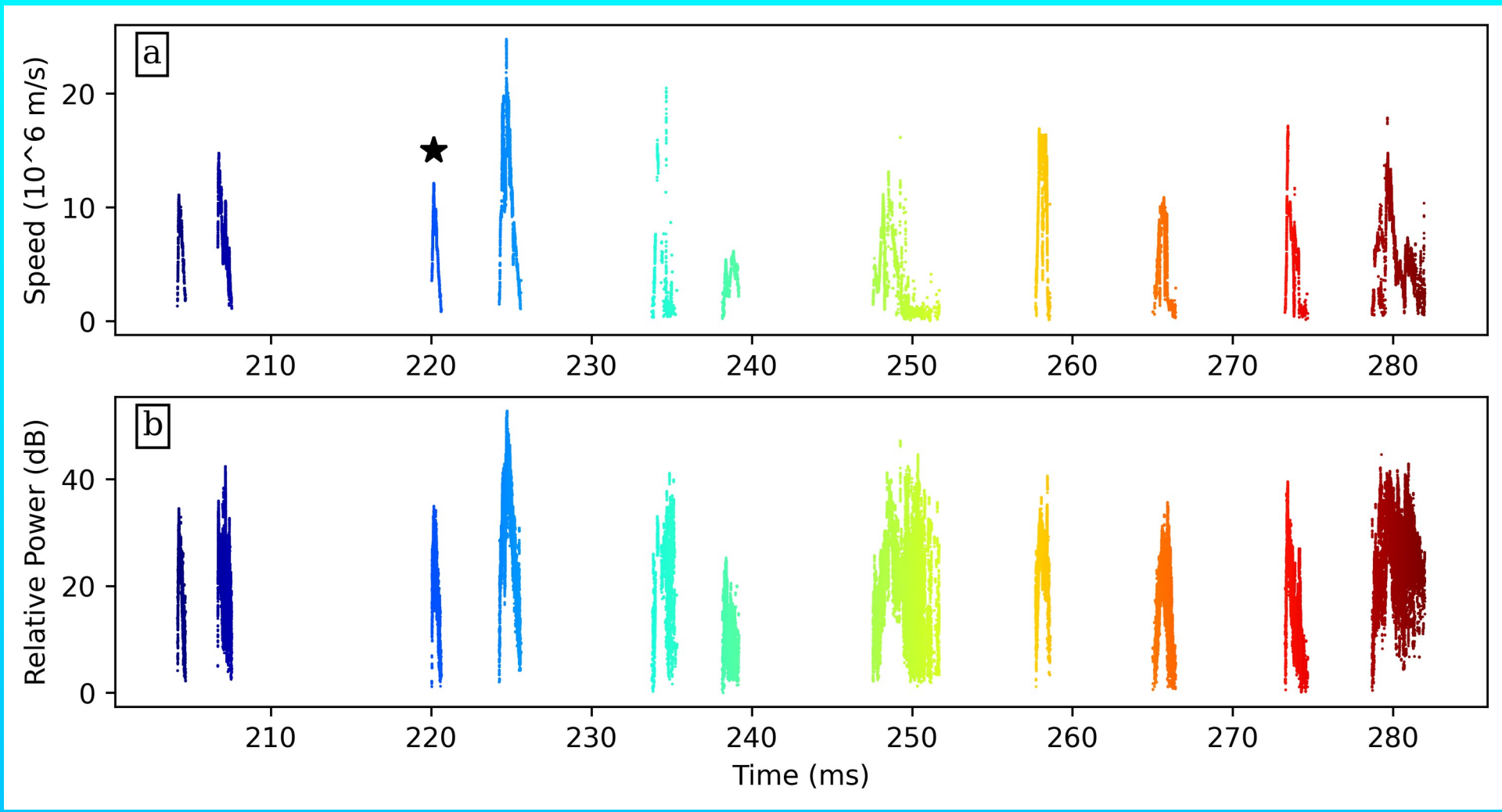

(a)


(b)
A1
Z=2.68m
L0
L4
L3
Z=0.00m
A0
L2
L1
A3
A2
L5
Z= -1.31m
Z= -1.27m
Northing
Easting
30
20
10
0
−10
−20
−30
−40
−20
0
20
40

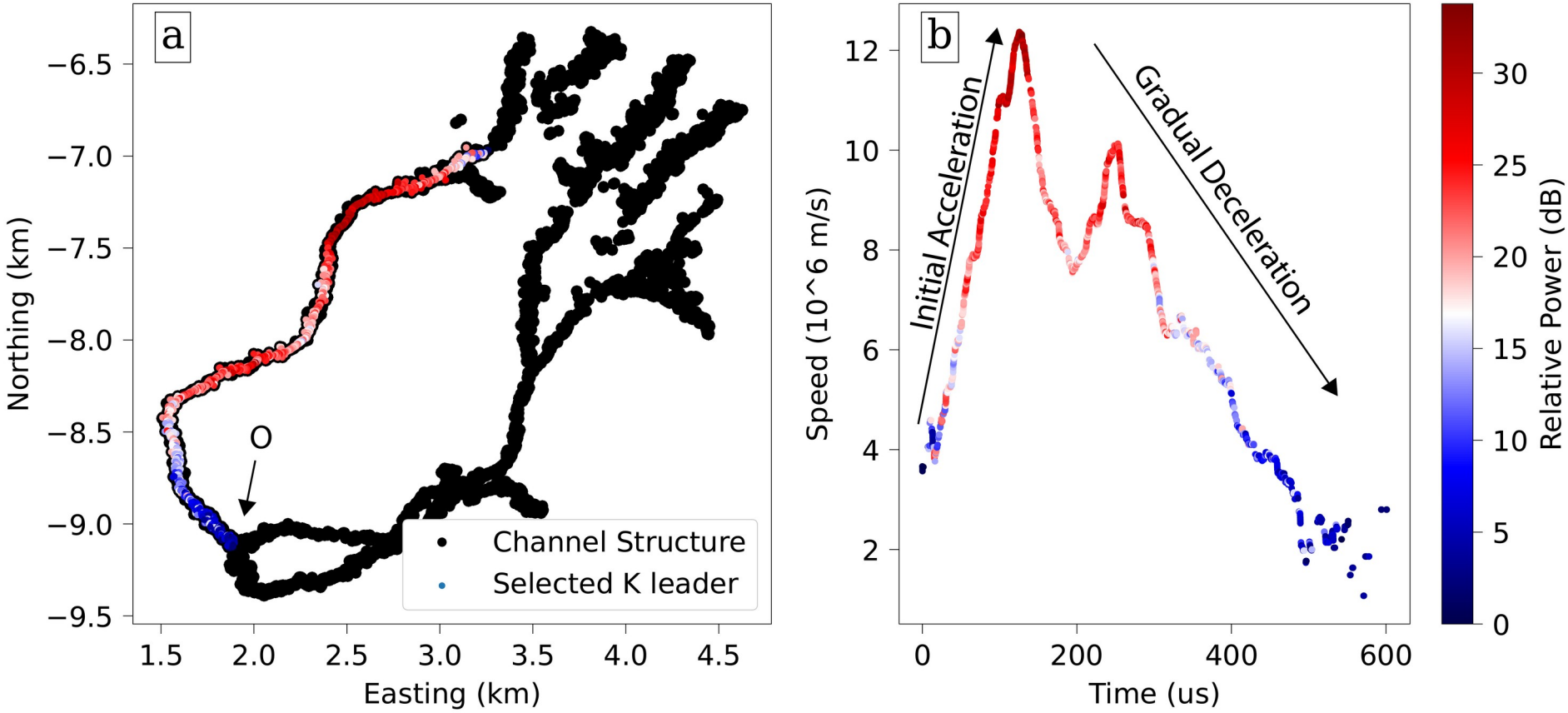

(c)
11.5km

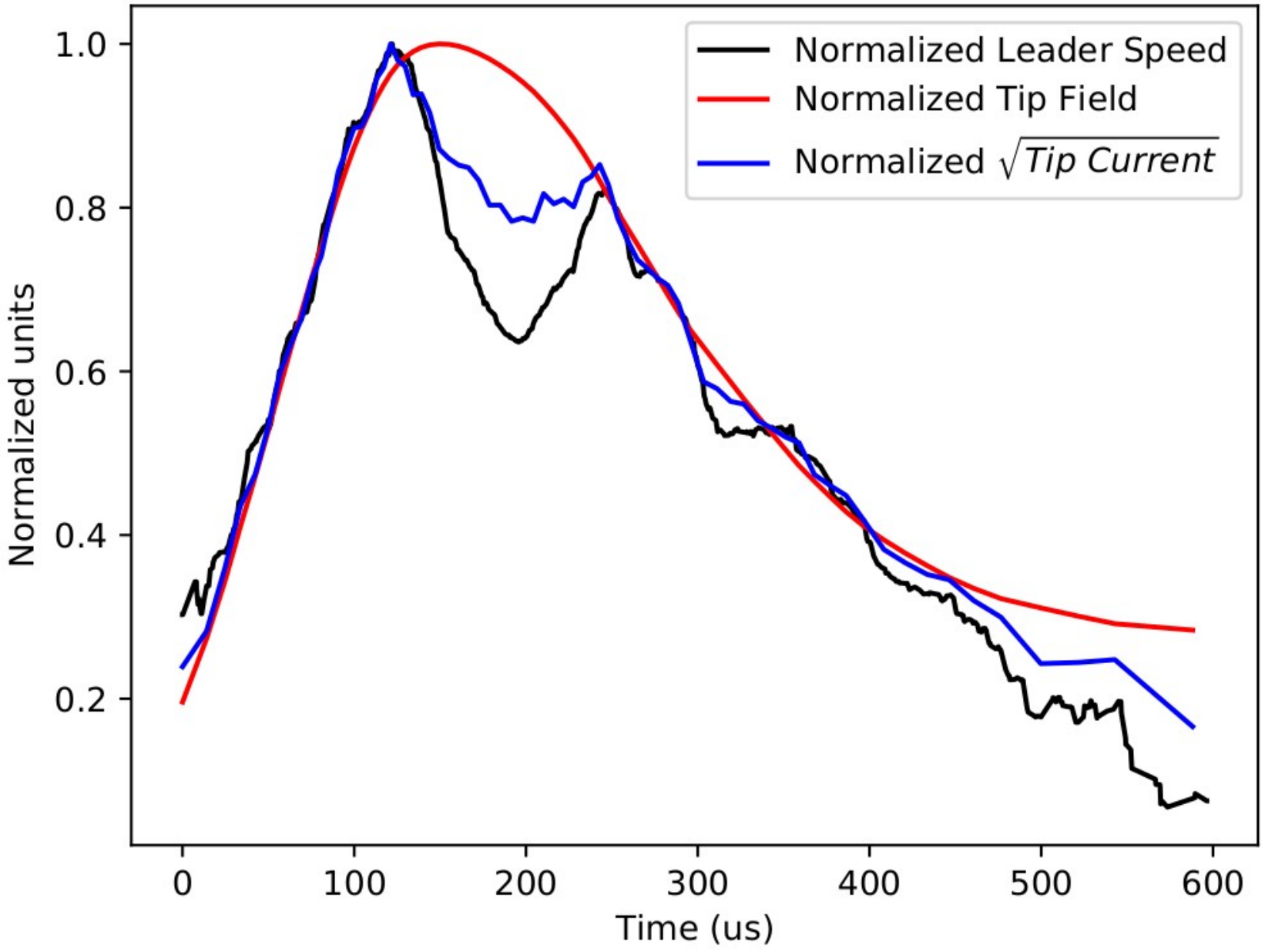


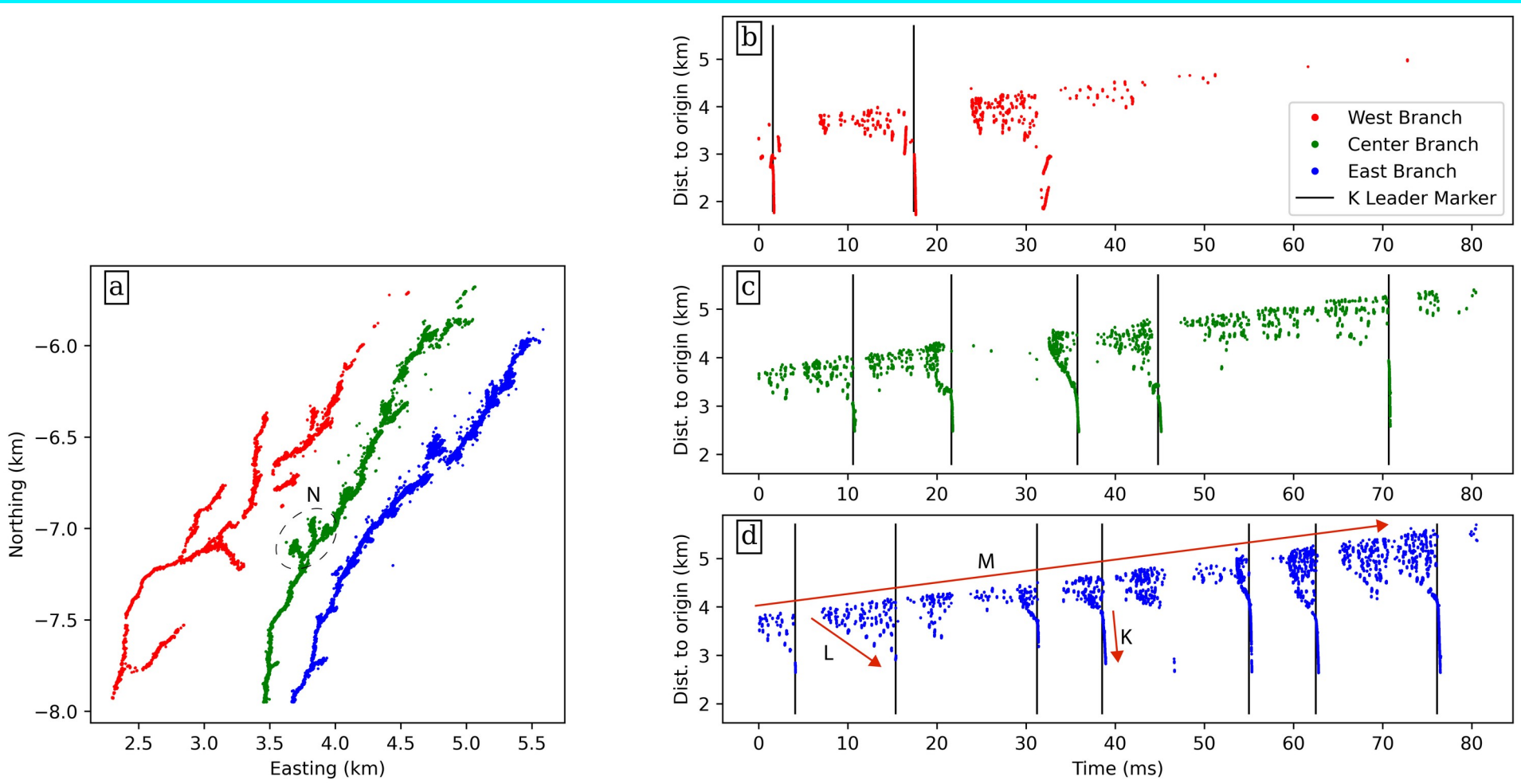

Flash_packed_TA03_20210822_183535_996404047
(a)
Altitude (km)
Time, ms
(b)
Northing (km)
Easting (km)
(c)
Altitude (km)
Easting (km)
(+)
(-)
(d)
Altitude (km)
Northing (km)
(+)
(-)

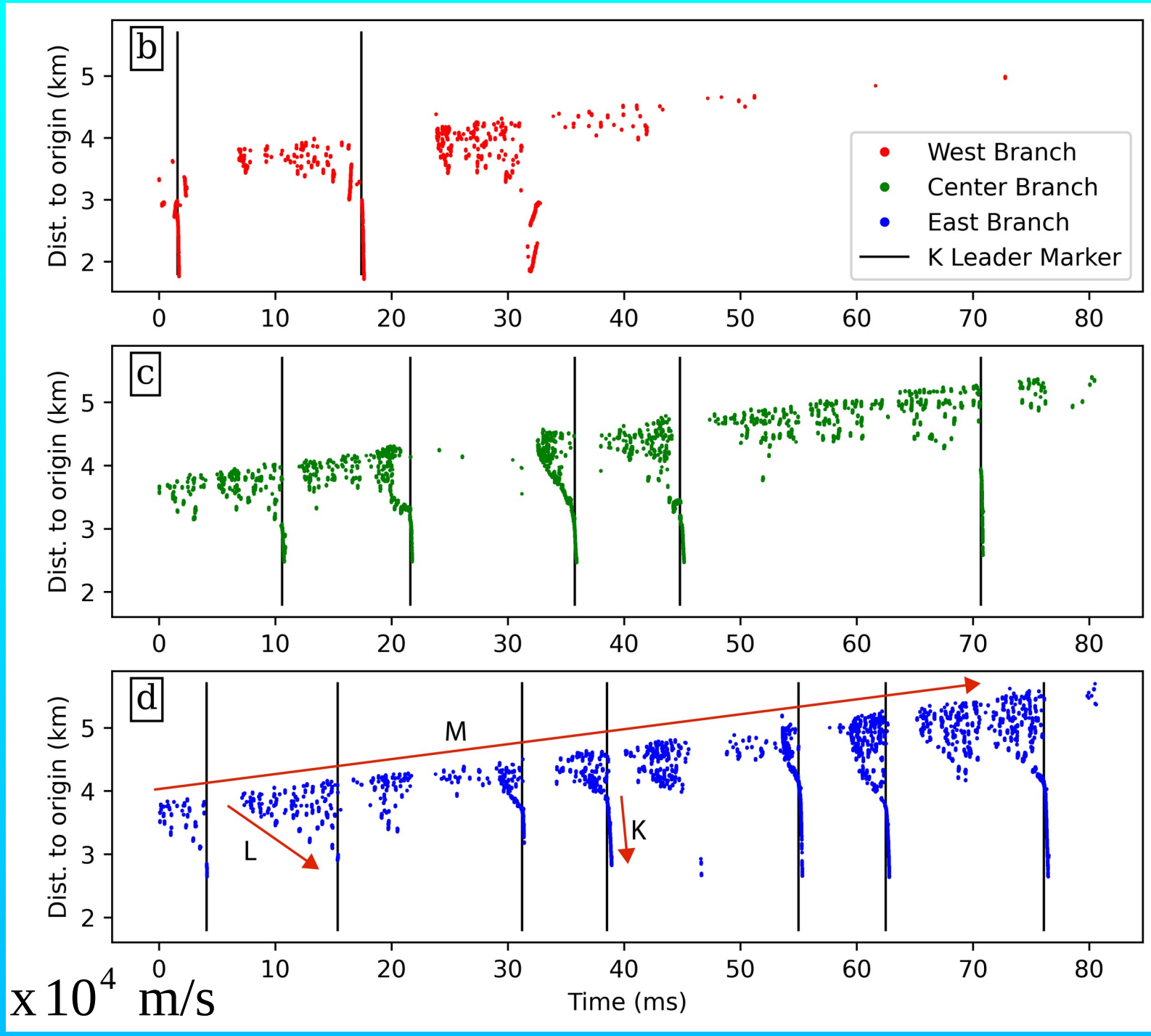

a
Speed (10^6 m/s)
0
10
20
210
220
230
240
250
260
270
280
b
Relative Power (dB)
0
20
40
210
220
230
240
250
260
270
280
Time (ms)

$$v_d = 0.2 - 1.2 \times 10^7 \text{ m/s}$$




Normalized Leader Speed
Normalized Tip Field
Normalized $\sqrt{Tip\ Current}$
Normalized units
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
Time (us)


a
N
Northing (km)
Easting (km)
b
c
d
Dist. to origin (km)
West Branch
Center Branch
East Branch
K Leader Marker
M
L
K
Time (ms)



$v_p = 1 - 2 \times 10^4$ m/s

Outline

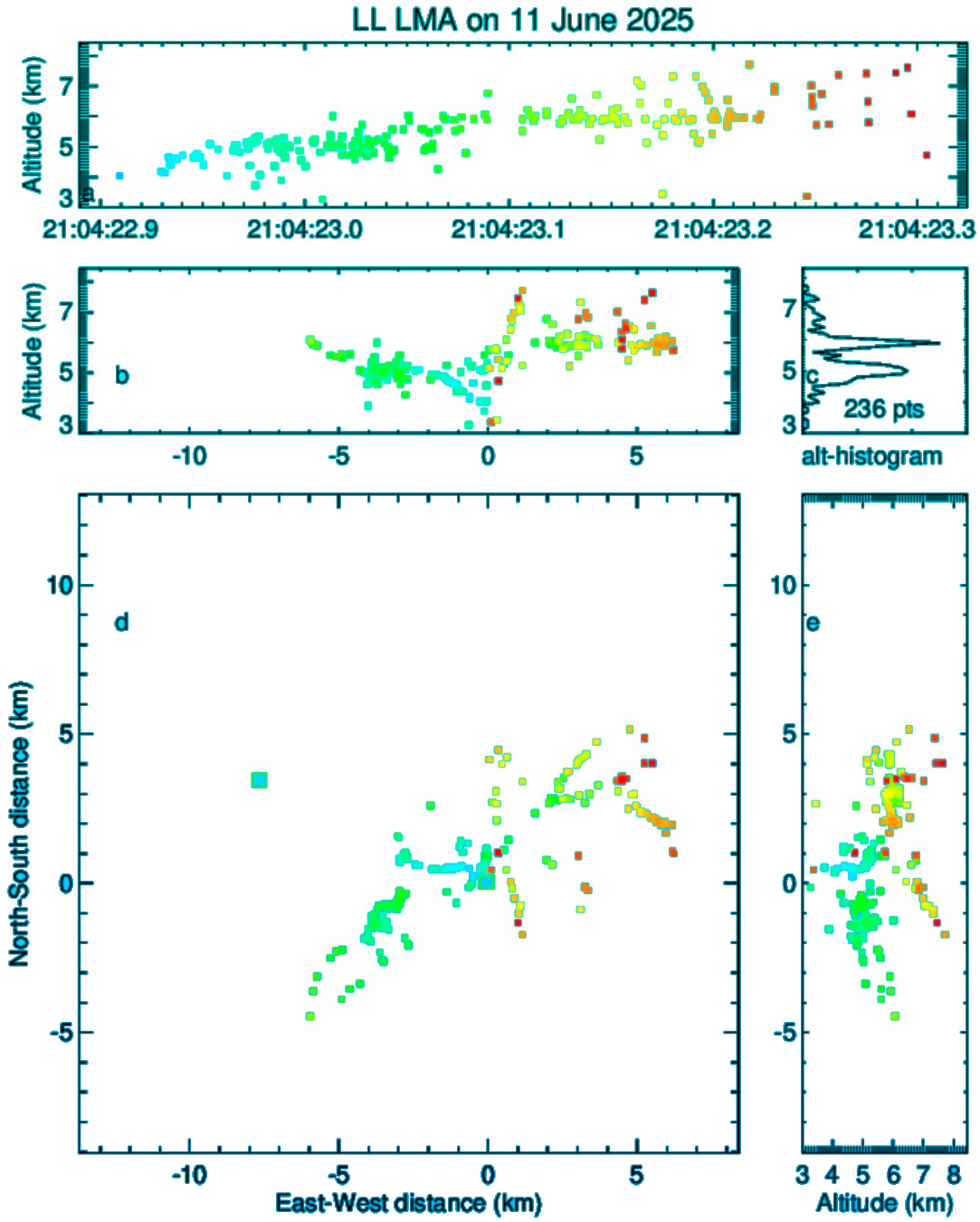
What are lightning leaders?

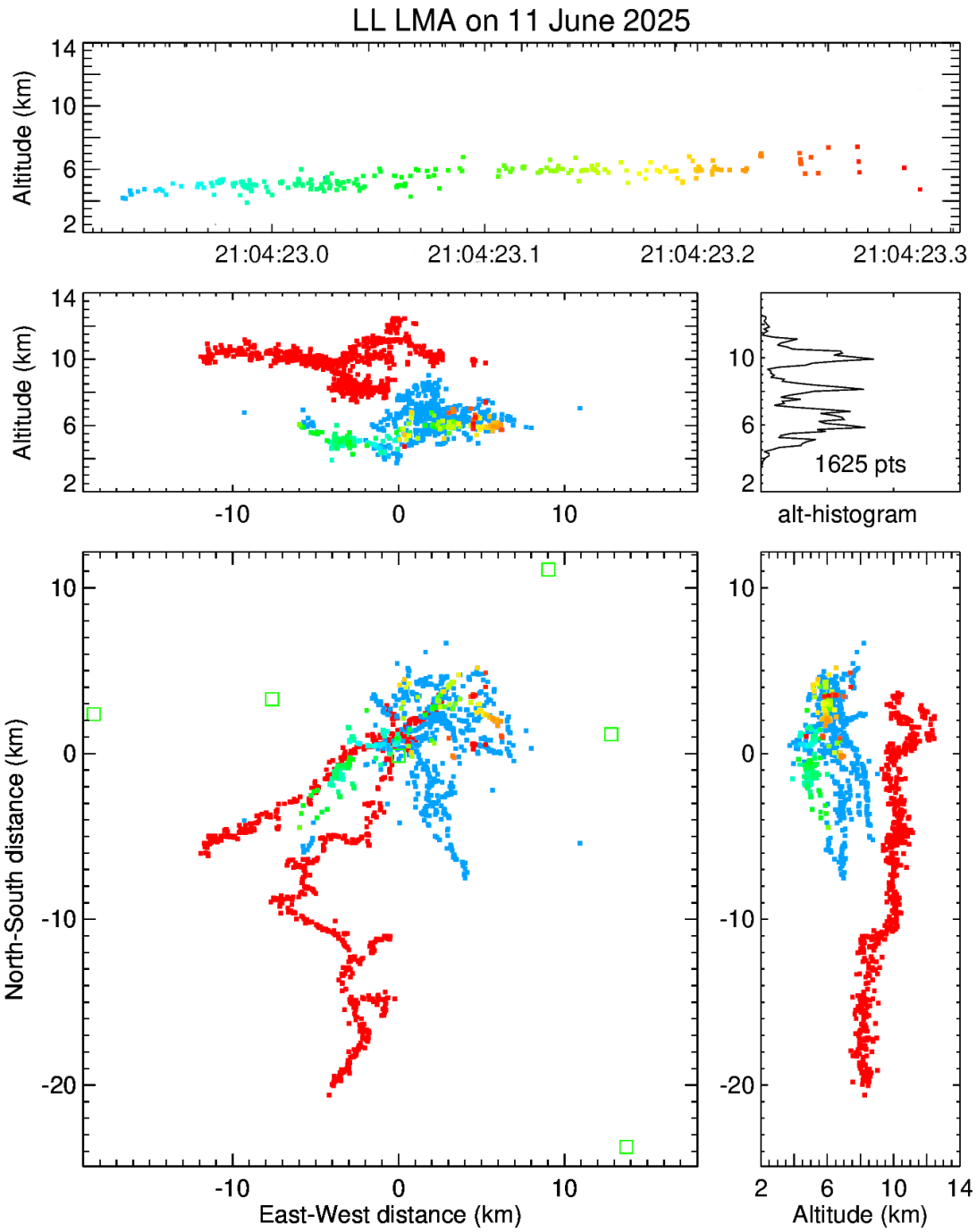
Why are they important?

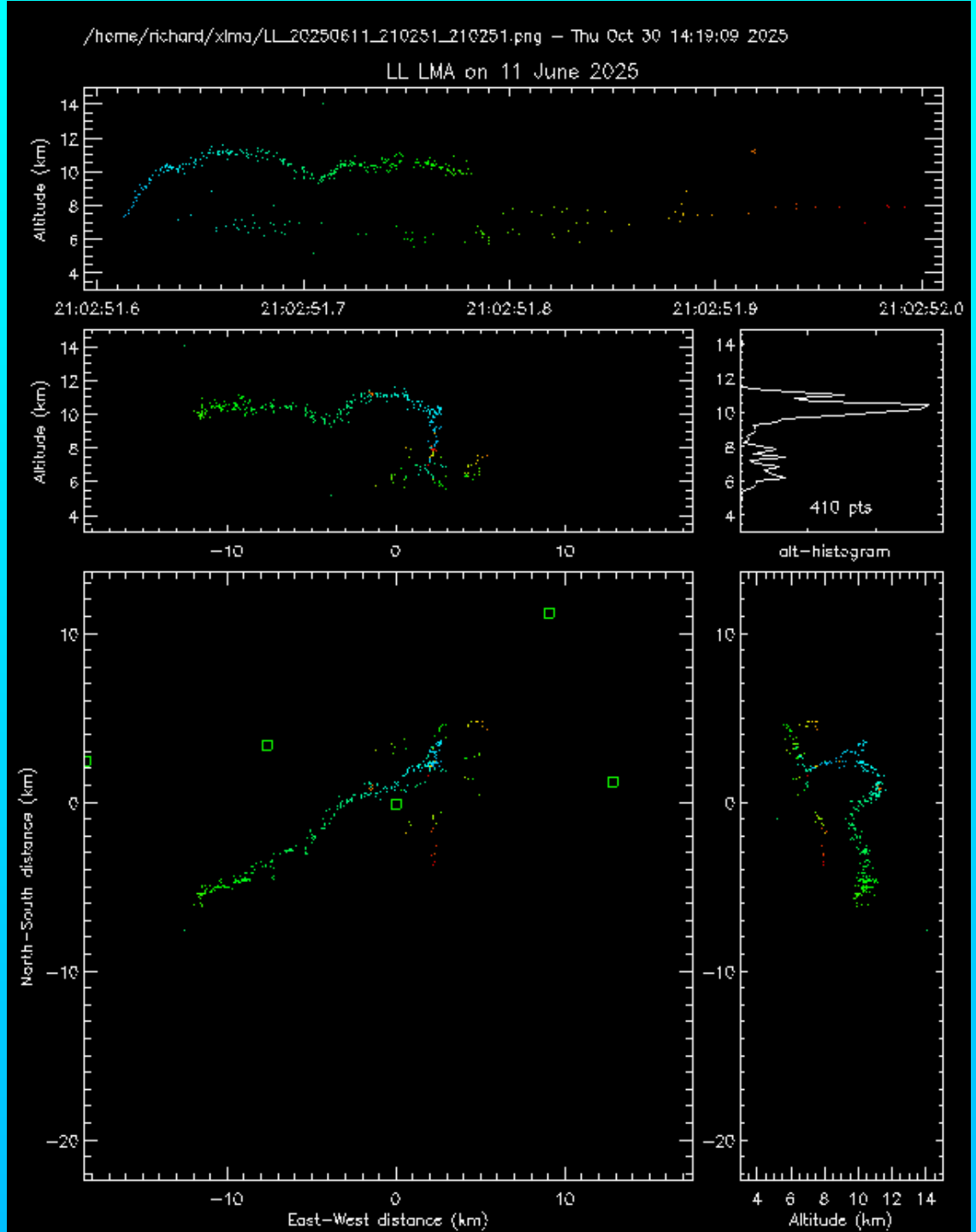
What behaviors do they display?

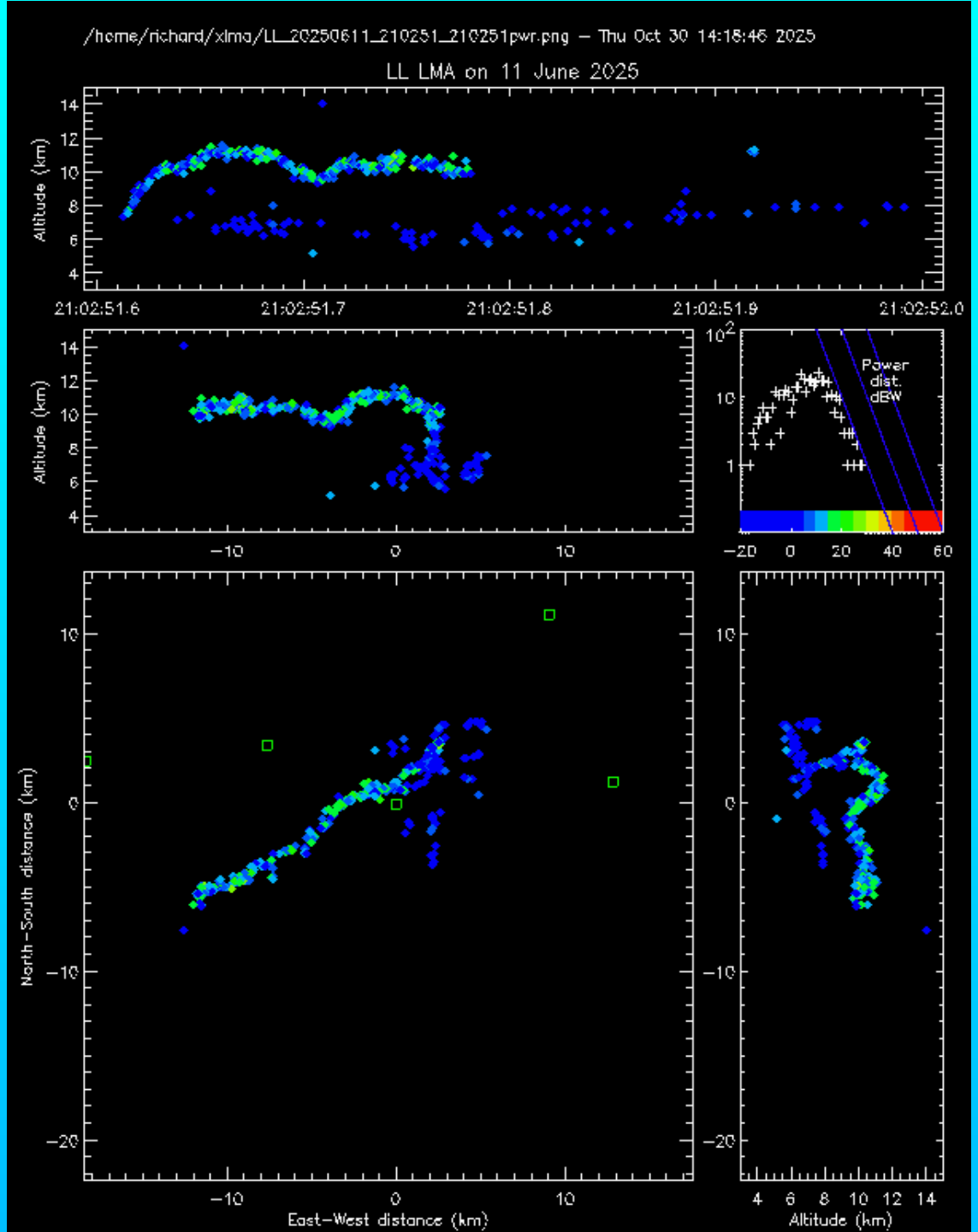
How do we know?

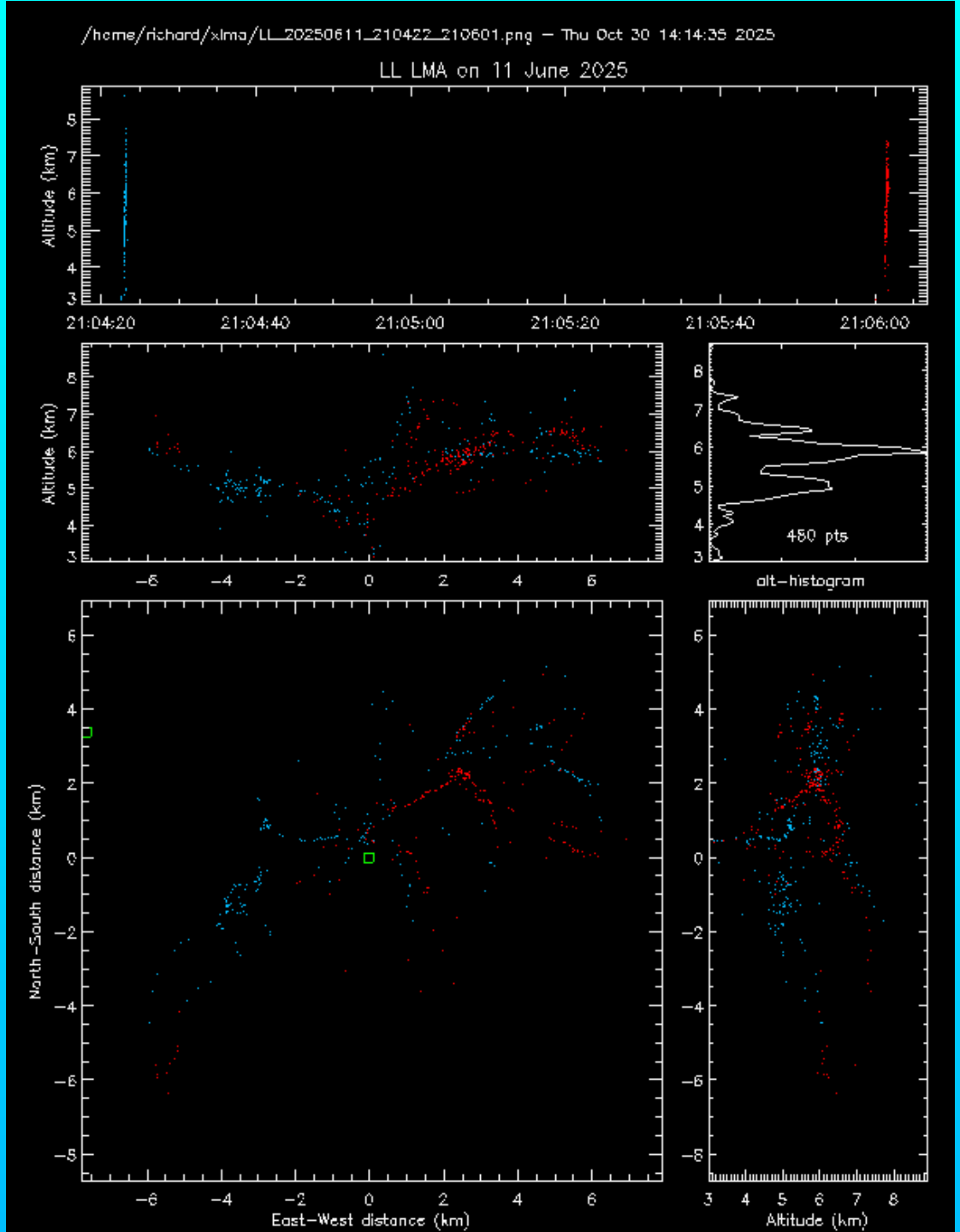
Initial results summer 2025

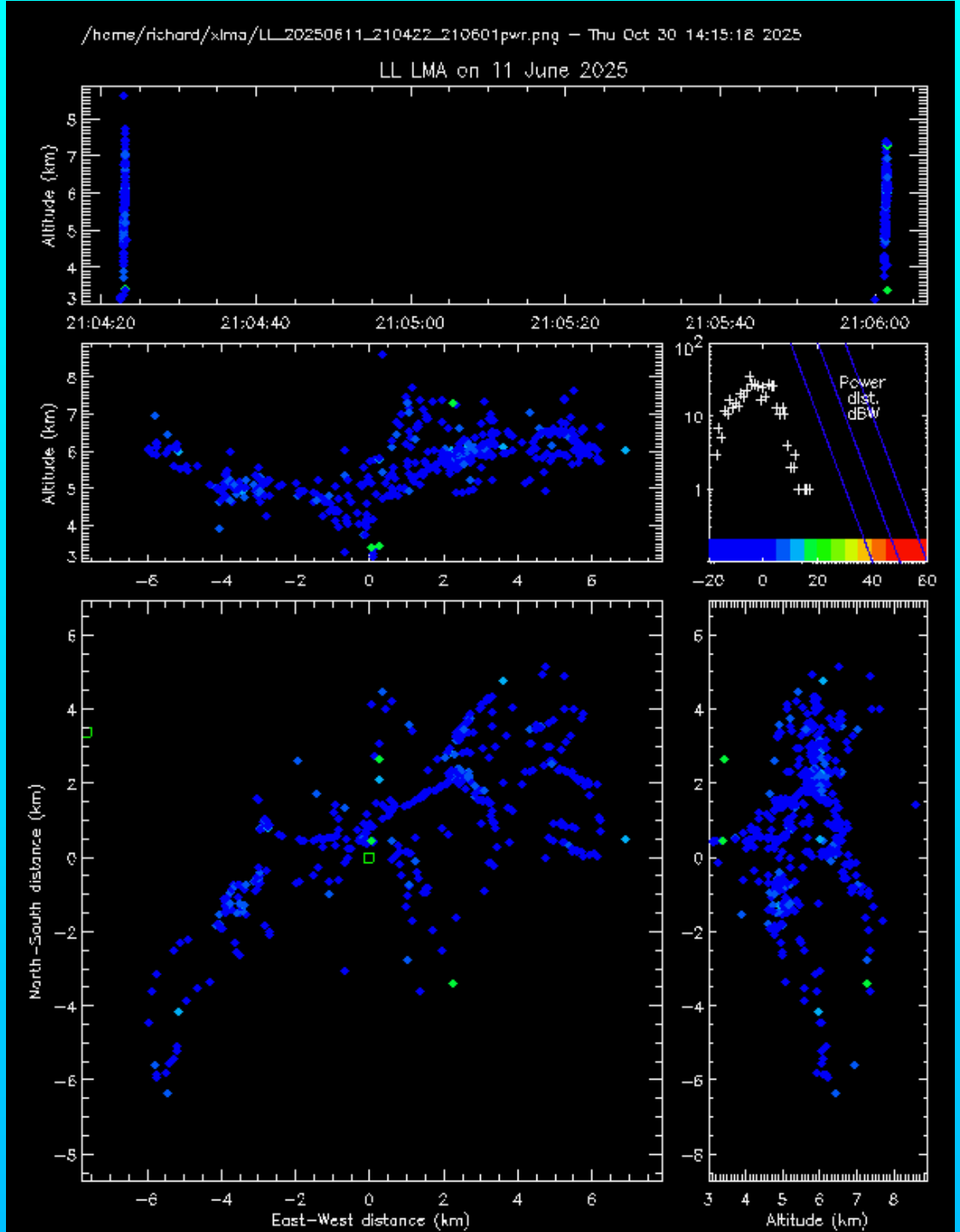

LL LMA on 11 June 2025
Altitude (km)
7
5
3
a
21:04:22.9
21:04:23.0
21:04:23.1
21:04:23.2
21:04:23.3
Altitude (km)
b
-10
-5
0
5
c
236 pts
alt-histogram
North-South distance (km)
d
10
5
0
-5
East-West distance (km)
e
3 4 5 6 7 8
Altitude (km)

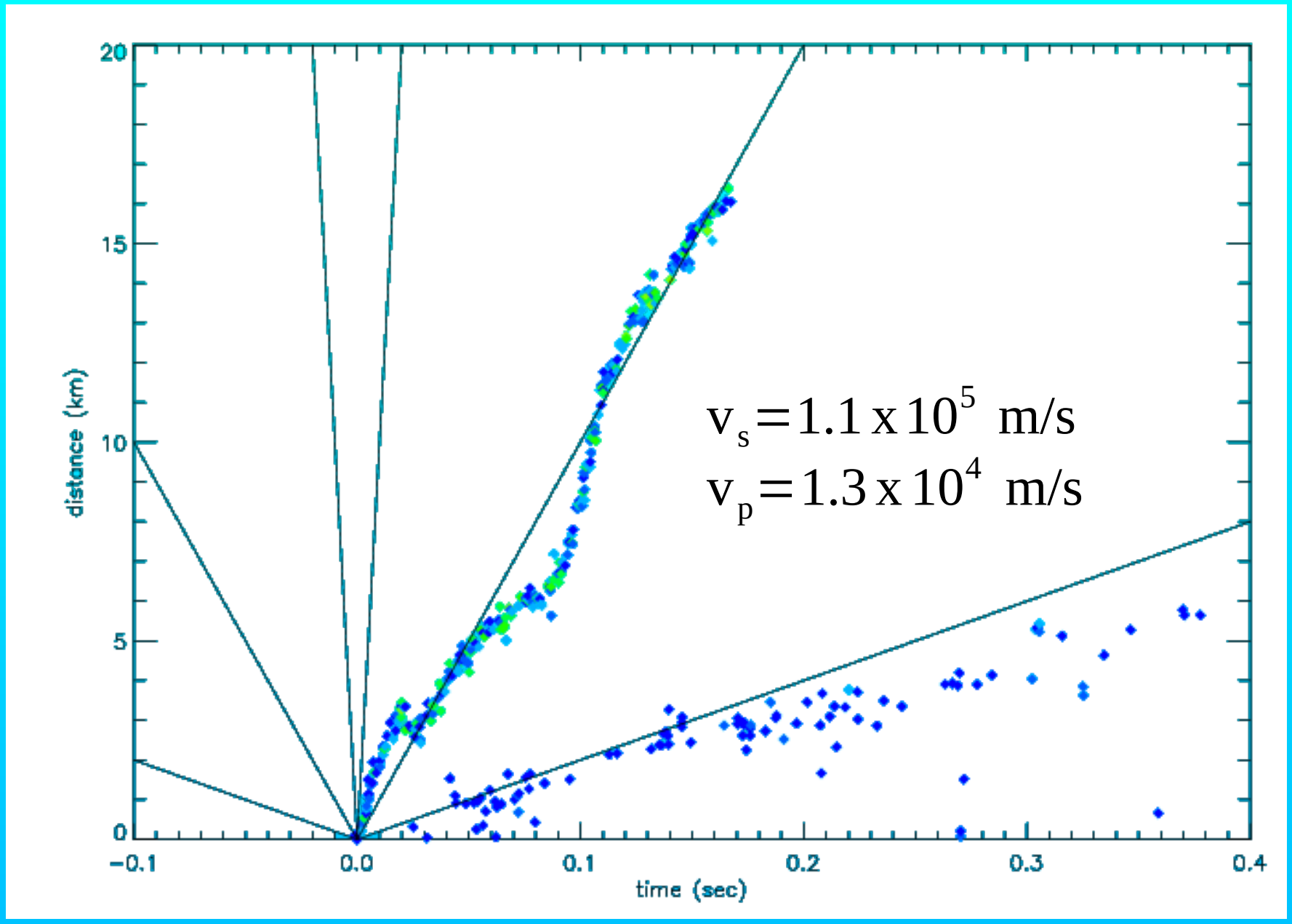

LL LMA on 11 June 2025
Altitude (km)
14
10
6
2
21:04:23.0
21:04:23.1
21:04:23.2
21:04:23.3
Altitude (km)
-10
0
10
1625 pts
alt-histogram
North-South distance (km)
East-West distance (km)
Altitude (km)
-20


/home/richard/xlma/LL_20250611_210251_210251.png – Thu Oct 30 14:19:09 2025
LL LMA on 11 June 2025
Altitude (km)
21:02:51.6
21:02:51.7
21:02:51.8
21:02:51.9
21:02:52.0
410 pts
alt-histogram
North-South distance (km)
East-West distance (km)
Altitude (km)

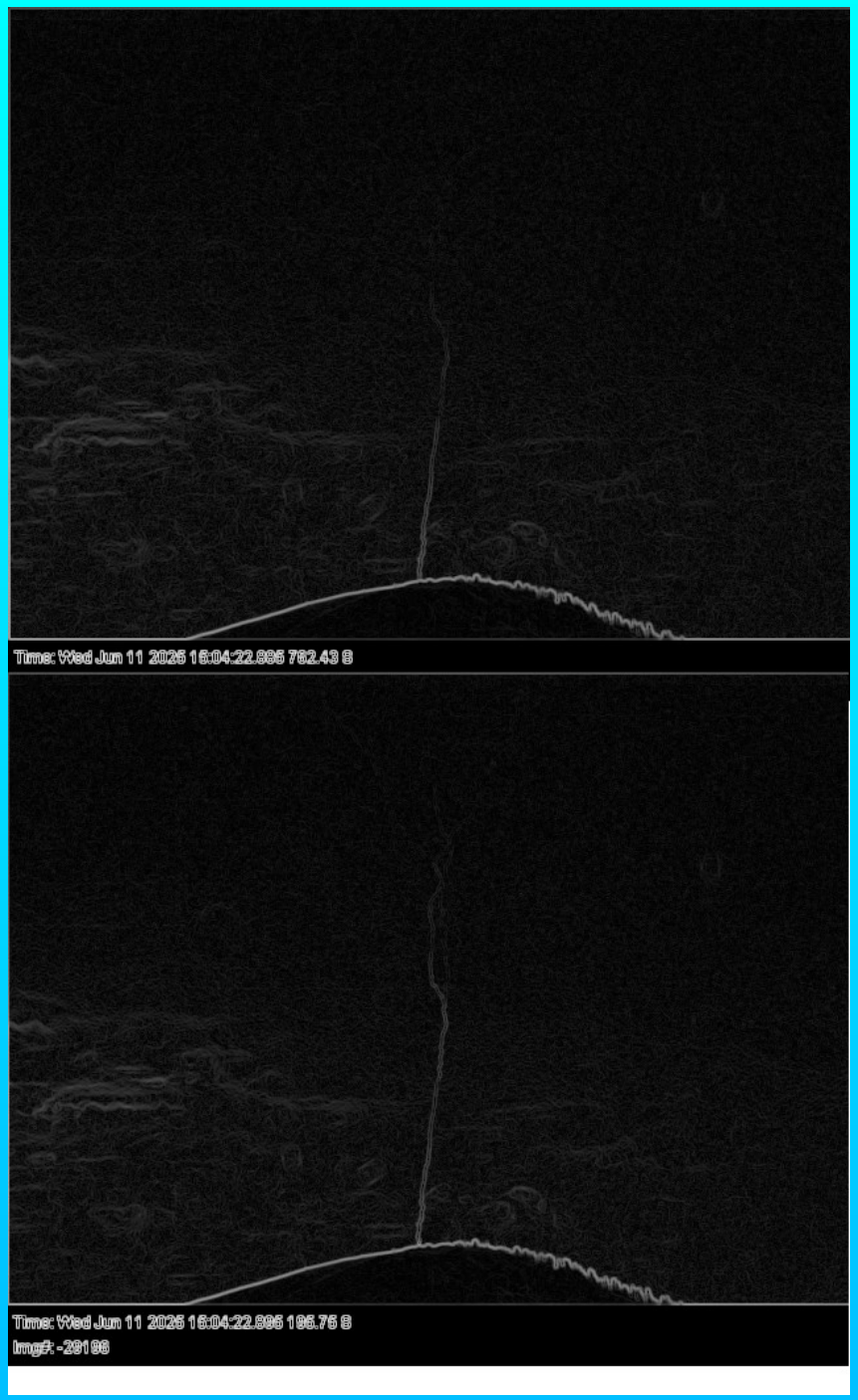

/home/richard/xlma/LL_20250611_210251_210251pwr.png – Thu Oct 30 14:18:46 2025
LL LMA on 11 June 2025
Altitude (km)
21:02:51.6
21:02:51.7
21:02:51.8
21:02:51.9
21:02:52.0
Power dist. dBW
North–South distance (km)
East–West distance (km)
Altitude (km)

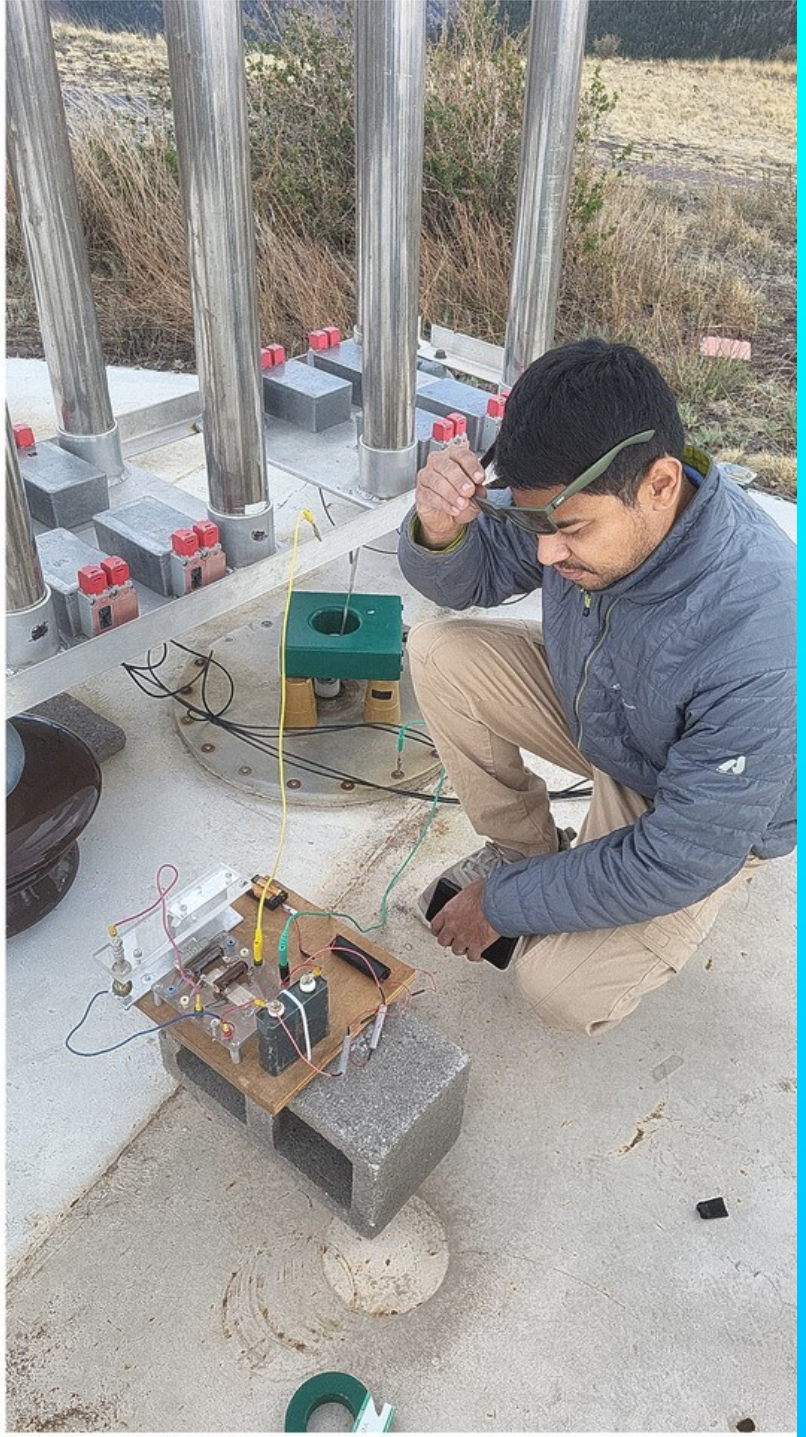

/home/richard/xlma/LL_20250611_210422_210601.png – Thu Oct 30 14:14:35 2025
LL LMA on 11 June 2025
Altitude (km)
21:04:20
21:04:40
21:05:00
21:05:20
21:05:40
21:06:00
Altitude (km)
480 pts
alt-histogram
North-South distance (km)
East-West distance (km)
Altitude (km)


/home/richard/xlma/LL_20250611_210422_210601pwr.png – Thu Oct 30 14:15:18 2025
LL LMA on 11 June 2025
Altitude (km)
21:04:20
21:04:40
21:05:00
21:05:20
21:05:40
21:06:00
Power dist, dBW
North-South distance (km)
East-West distance (km)
Altitude (km)


20
15
10
5
0
distance (km)
−0.1
0.0
0.1
0.2
0.3
0.4
time (sec)
$v_s = 1.1 \times 10^5$ m/s
$v_p = 1.3 \times 10^4$ m/s

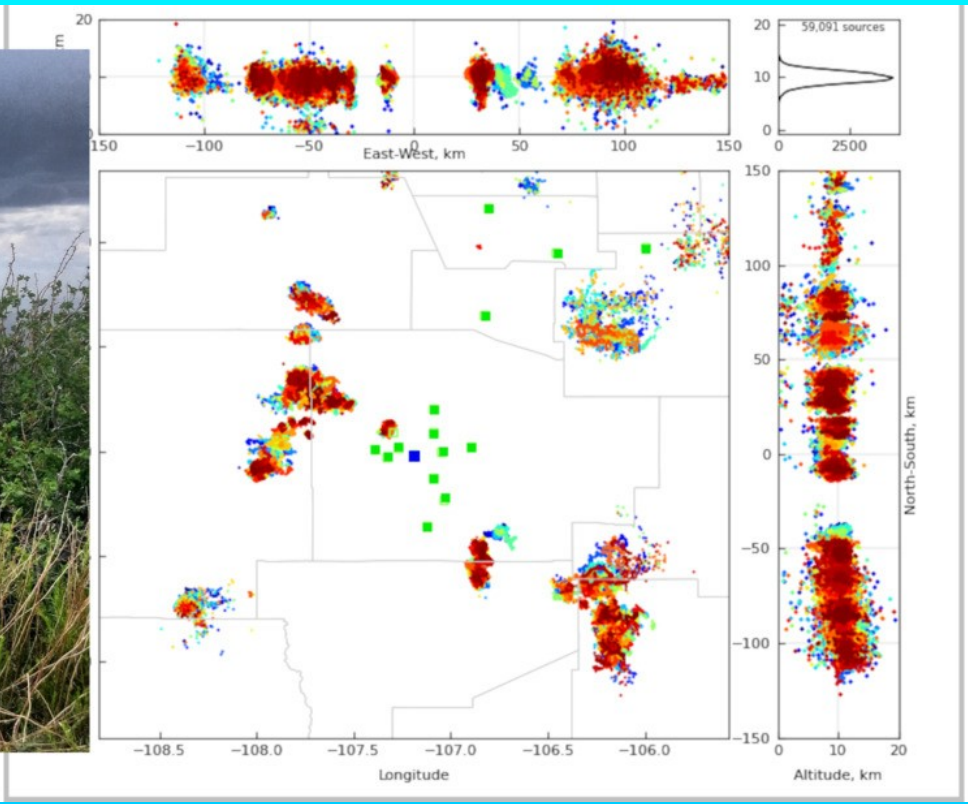
$$v_p = 1 - 2 \times 10^4 \text{ m/s}$$






DANGER
HIGH VOLTAGE


PHYSICS


59,091 sources
East-West, km
Longitude
Altitude, km
North-South, km

Summary

A lot of the “physics of lightning” is in the streamer/leader process.

Leaders make lightning “go”.

There are two polarities of leader and they behave differently.

State of art RF techniques continue to increase our knowledge of leaders.

Natural positive leaders are dimmer and harder to see, so they are still a frontier of understanding.


AMAZONIA