Los Alamos NATIONAL LABORATORY

3D Radio Frequency Mapping and Polarization Observations Indicate Lightning Flashes were Ignited by Cosmic-ray Showers

Xuan-Min Shao,

Daniel Jensen, Cheng Ho, Michael Caffrey, Eric Raby, Paul Graham, Brian Haynes, William Blaine

Los Alamos National Laboratory

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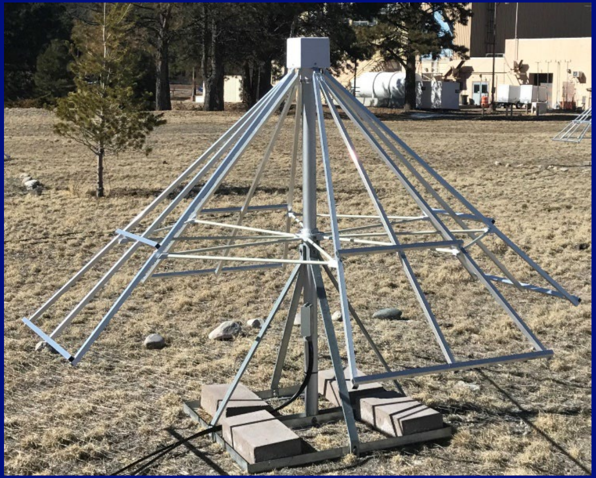
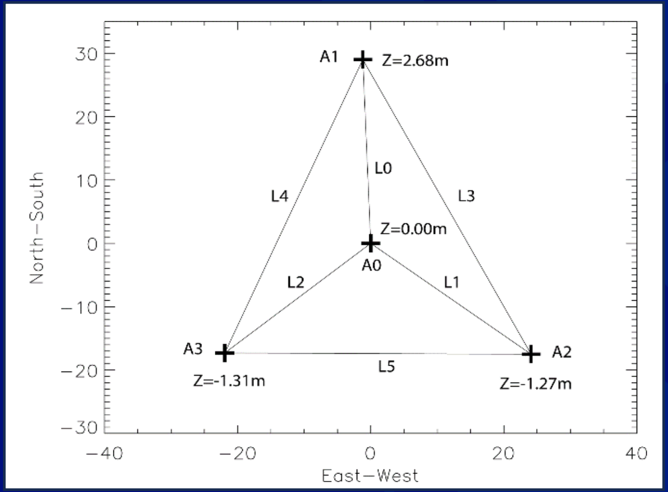
BIMAP-3D: 3-Dimensional Broadband Interferometric Mapping and Polarization system (*Shao et al., JGR, 2023*)

Typical processing time window and time step: 0.5μs, 20ns

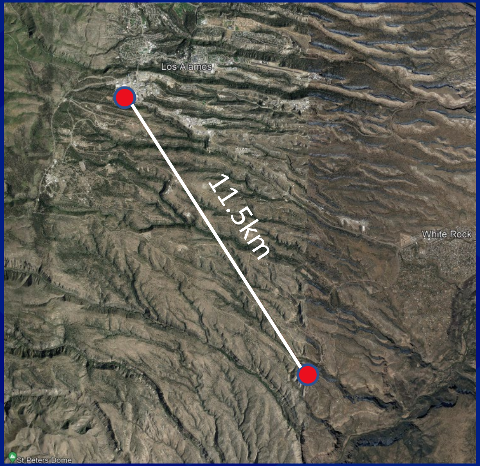
Broadband (20-80 MHz), dual-polarization antenna



Each BIMAP station consists of 4 antennas for 2D source and polarization

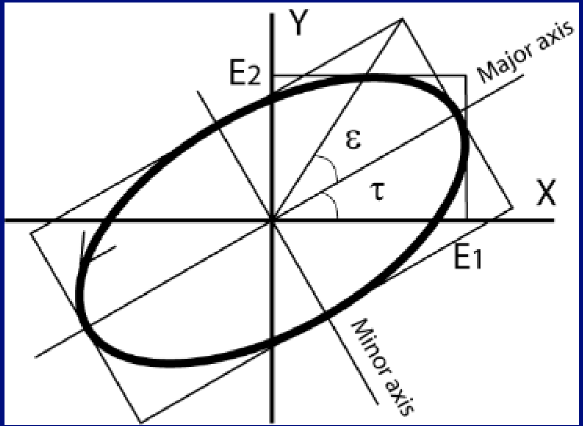


2 stations for 3D source and polarization



Polarization analysis with Stokes parameters

Signal detected by two orthogonal and phased-synchronized antennas X and Y



Stokes parameters for polarization analysis for a monotonic signal

$$I = \langle E_1^2 \rangle + \langle E_2^2 \rangle = P_0,$$
$$Q = \langle E_1^2 \rangle - \langle E_2^2 \rangle = P_0 \langle \cos 2\varepsilon \cos 2\tau \rangle,$$
$$U = 2\langle E_1 E_2 \cos(\delta_x - \delta_y) \rangle = P_0 \langle \cos 2\varepsilon \sin 2\tau \rangle,$$
$$V = 2\langle E_1 E_2 \sin(\delta_x - \delta_y) \rangle = P_0 \langle \sin 2\varepsilon \rangle,$$

Degree of polarization

$$d = \frac{\sqrt{Q^2 + U^2 + V^2}}{I},$$

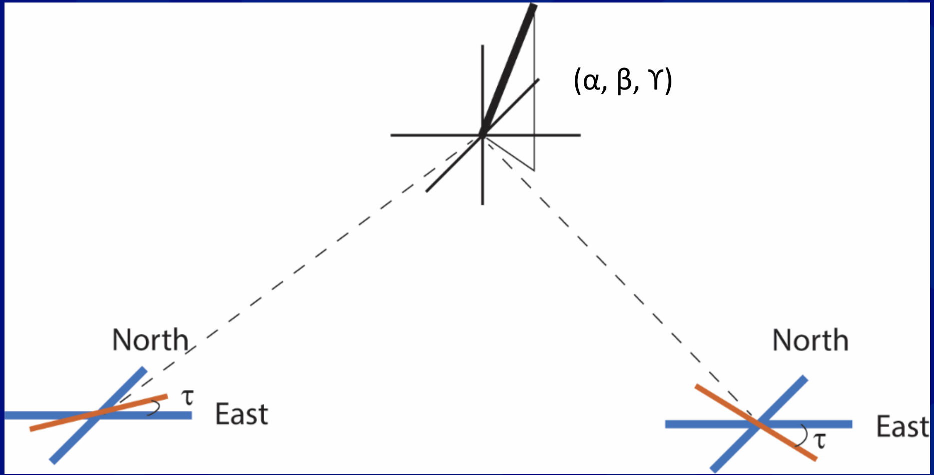
For linearly polarized signal, 3D orientation can be determined from two-station observations (*Shao et al., JGR, 2023*)

For one station observation

$A\alpha + B\beta + C\gamma = 0$ $[\alpha, \beta, \gamma]$: polarization orientation unit vector

$$A = (\cos^2\theta \cos^2\varphi + \sin^2\varphi) \sin\tau + \sin^2\theta \sin\varphi \cos\varphi \cos\tau$$
$$B = -(\cos^2\theta \sin^2\varphi + \cos^2\varphi) \cos\tau - \sin^2\theta \sin\varphi \cos\varphi \sin\tau$$
$$C = \sin\theta \cos\theta \sin(\varphi - \tau)$$

(φ, θ): source direction; τ: tilt angle from East

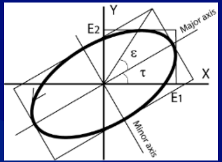


With two station observations

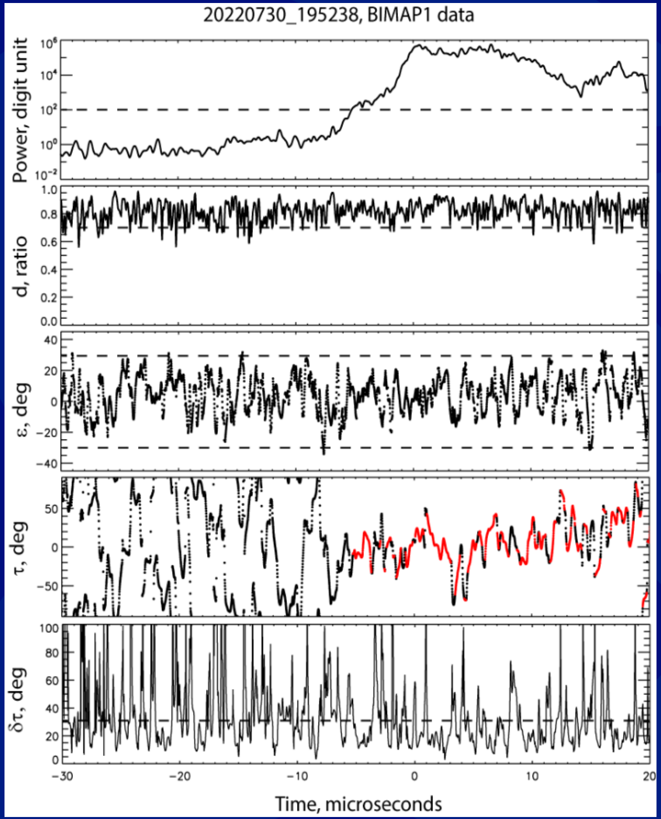
$\boldsymbol{V}_1 = (A_1, B_1, C_1)$ $\boldsymbol{V}_2 = (A_2, B_2, C_2)$

$$\begin{bmatrix}\alpha \\ \beta \\ \gamma\end{bmatrix} = \frac{\pm \boldsymbol{V}_1 \times \boldsymbol{V}_2}{|\boldsymbol{V}_1 \times \boldsymbol{V}_2|}$$

Single station polarization process



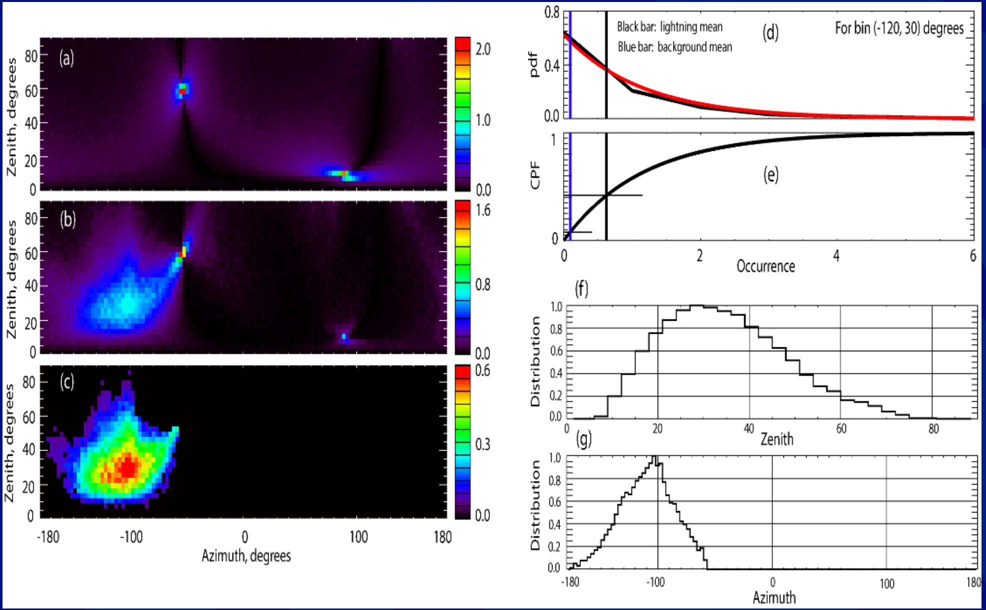
- FFT of EW (X) and NS (Y) signals (96 points with Hanning window)
- Slide FFT window forward (2 points)
- Average stokes parameters for each frequency over 24 FFT windows
- Effective time resolution: 500ns
- Use 64-76 MHz band (7 discrete frequencies) for analysis
  - Interference at 60 MHz at BIMAP2 at the time
  - Higher frequencies lead to better statistics on stokes parameters
  - Higher frequencies related to smaller scale discharge processes
- Determine RF power *I*, average *d*, median ε, and weighted τ and standard deviation $\delta\tau$ (with degree of polarization *d*) among 7 discrete frequencies in 64-76 MHz band
- Select τ above *I*, *d*, ε, $\delta\tau$ thresholds for later 3D process



Statistical analysis of 3D polarization vector for discharge process

Two unknowns for unit vector, two measurement τs -> a solution even if τs are not correlated

1. Compute 3D solution distribution with random and independent pairs of τs (10^6) for a chosen source location
2. Compute distribution for measured lightning sources. Each pair of lightning τs are computed 10^3 times with variations of δτs
3. Compare each bin (solution) in the distributions to examine if probability for lightning solution is greater than background
4. Select bins for those that their means are > 10% more likely above background level
5. Subtract background from selected lightning solution bins

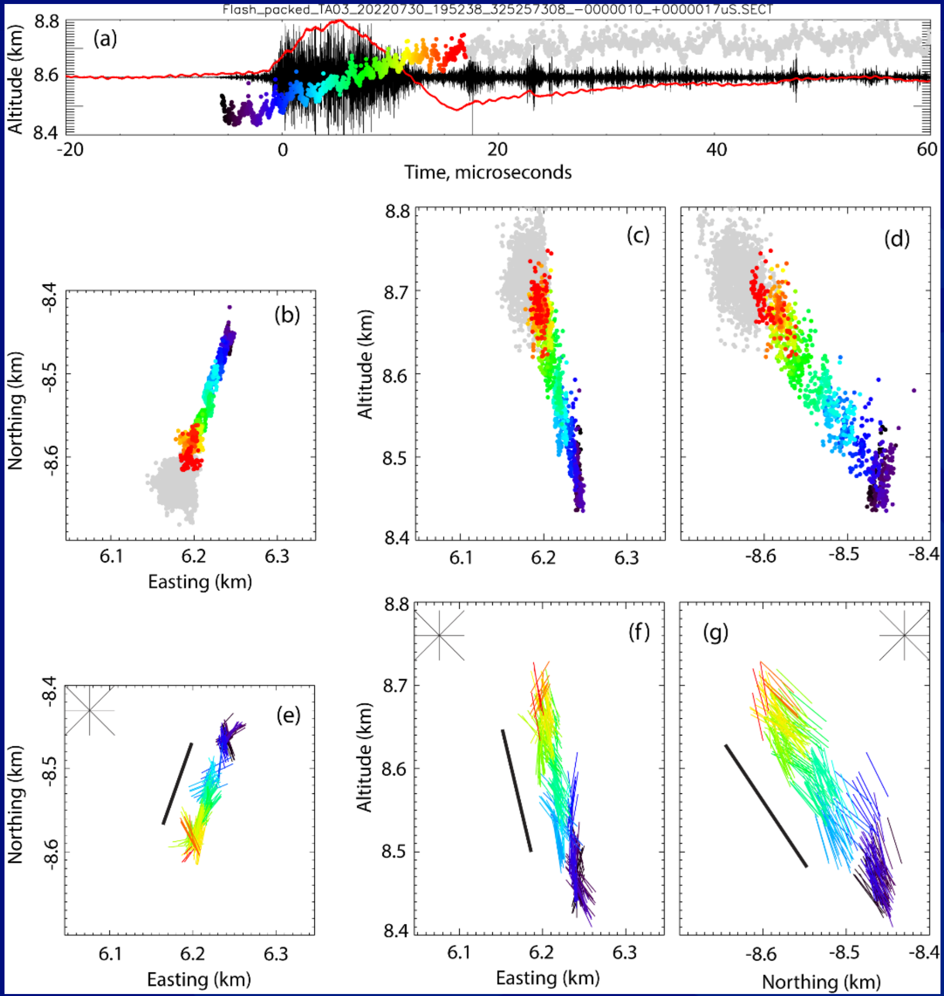


(a). Background distribution due to random coincidences. (b) distribution for an initial 23μs fast negative breakdown. (c) difference between (b) and (a). (d) Black curve: pdf for a selected bin in (b); red curve: exponential fit. (e) CPF based on exponential fit. Blue and black bars in (d) and (e) are background level and mean value for lightning. A bin is selected if mean lightning value is >10% more probable than background. (f) and (g) 1D distributions for zenith and azimuth angles based on (c).

3D results for an initial fast negative breakdown (FNB) process

Flash: 20220730_195238

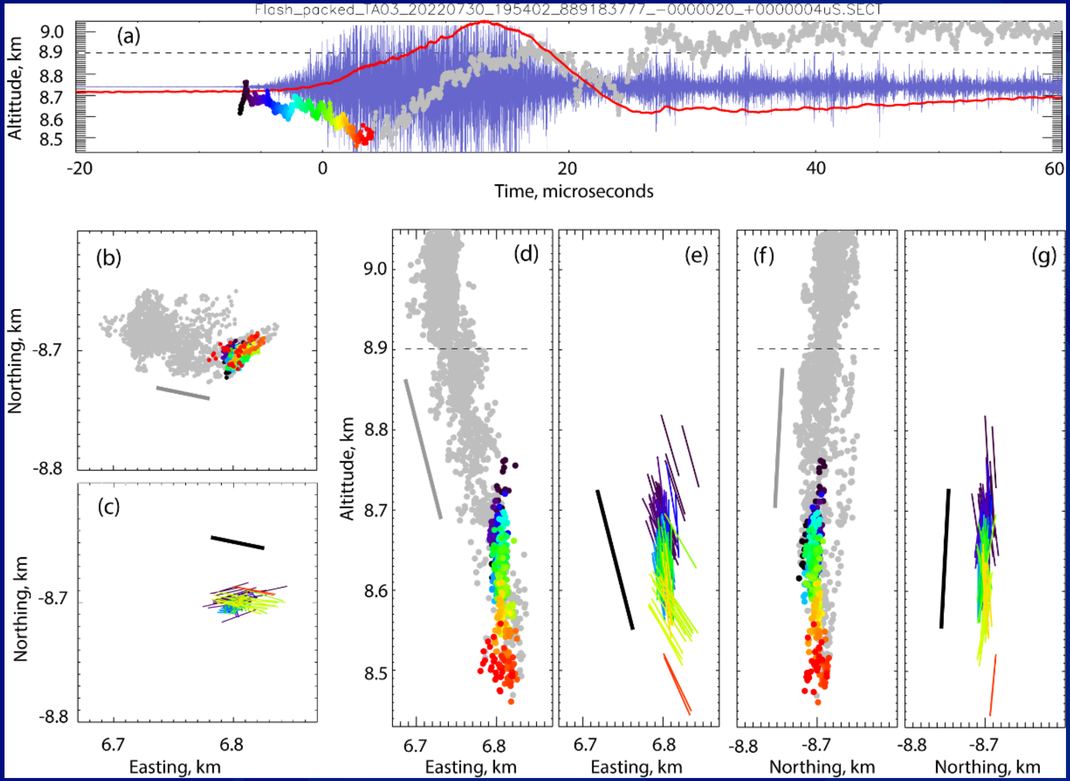
- Lightning started with apparent FNB (1.4×10^7m/s) in initial 23μs along ~300m straight path
- Followed by normal 10^5m/s and scattered negative breakdown (gray dots)
- Averaged polarization orientation parallel to breakdown path
- Propagation direction (-109°, 34°). Local geomagnetic field direction (-98°, 26°). FNB nearly in parallel to B



3D results for initial fast positive breakdown (FPB)
Flash: 20220730_195402

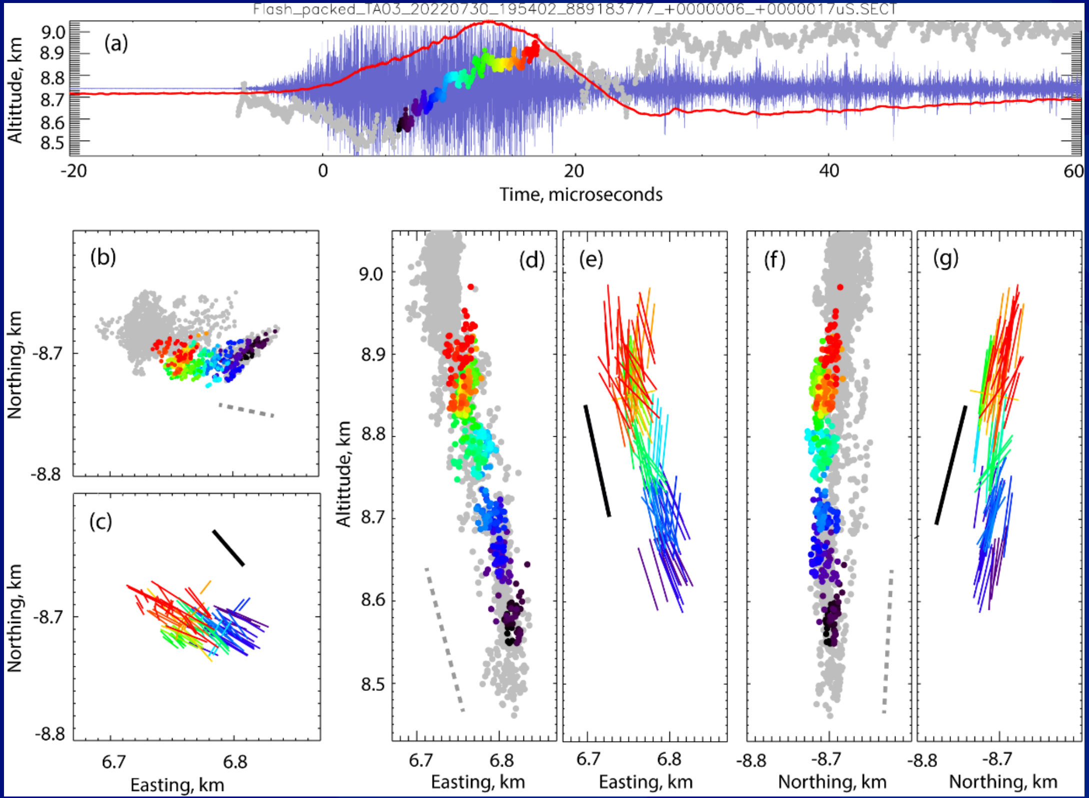
- Sources propagating vertically downward (-4° from zenith), at average speed $1.8x10^7$ m/s, in initial 11 μs along a path of ~250 m
- Average polarization direction: (170-180°, 8-15°), having a preferred EW component (c, e), away from vertical source propagation direction
- Polarization orientation parallel to path followed **later** by upward FNB (grey dots below 8.9km) which tilted to west and slightly to north

- Questions:
  - Why are polarizations consistently tilted away form source propagation direction?
  - Why the tilt orientation in parallel to **later** upward FNB?



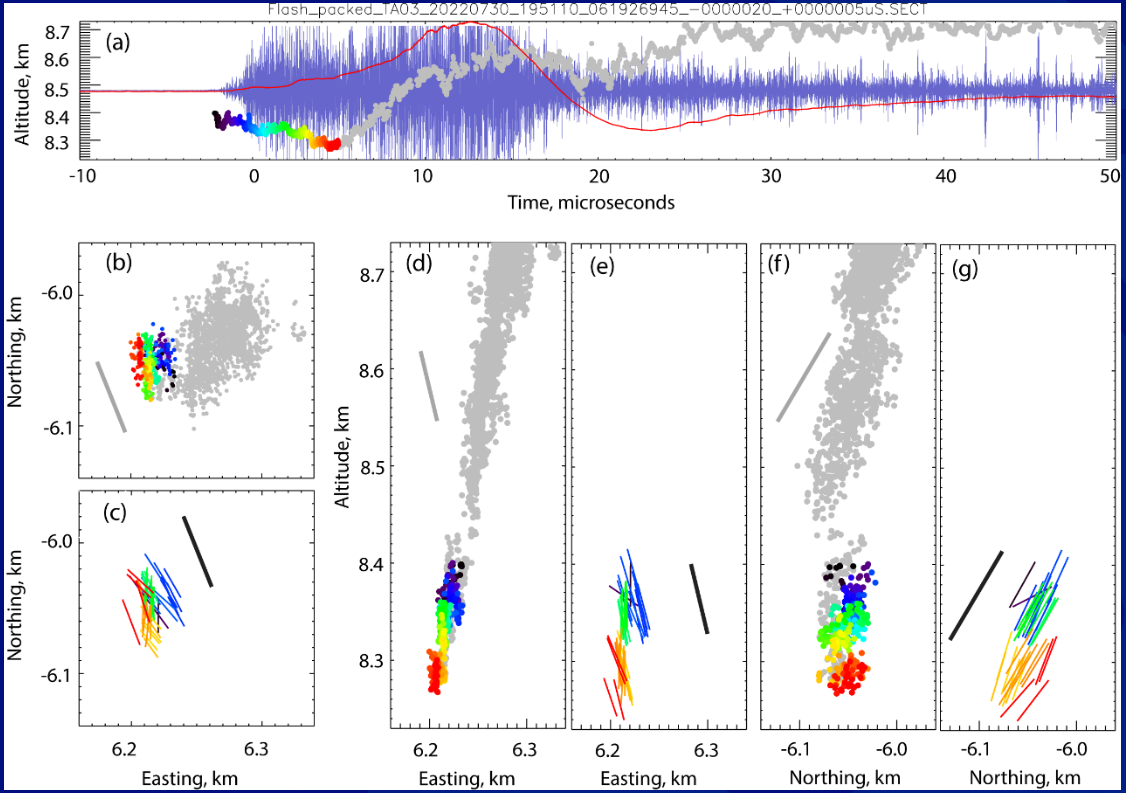
3D result for subsequent FNB. Flash: 20220730_195402

- Source propagation upward along a tilted path (179°, 12°) of ~350m at faster speed of 3.1×10^7m/s in 11μs.
- VxB: 23μT, -165° (near EW direction)
- Polarization in general parallel to source propagation
- Polarization in XY plane turned clockwise 30-40°
- Note: high-energy (>MeVs) e^- would experience a 15°-25° clockwise gyro-rotation before totally stopped in the air at this altitude



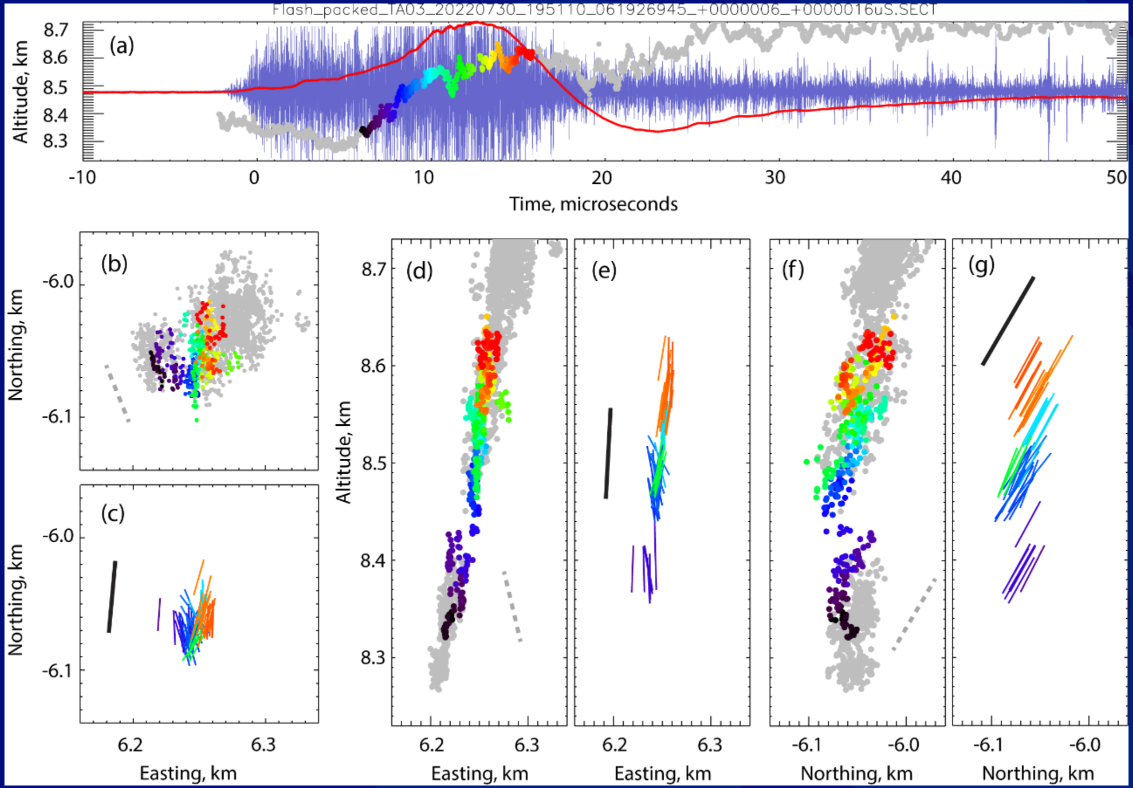
3D results for initial FPB. Flash: 20220730_195110

- Sources propagate downward in direction (-150°, -12°) at average speed of 1.4×10^7m/s in initial 7 μs over ~150 m
- Average polarization direction (110°-130°, 30°-35°), having a preferred NS orientation.
- Polarization in YZ plane roughly in parallel to **later** upward FNB source path
- Later upward FNB tilted toward north from downward FPB
- Polarization in XZ plane is different than the later FNB path direction?
- VxB for later FNB: 28μT, 160° (near EW). For high-energy e^-/e^+, B-field would deflect them toward EW direction



3D result for subsequent FNB. Flash 20220730_195110

- Sources propagate upward at faster $2.8x10^7$ m/s in 10μs along a ~300 m path, in average direction (33°, 10°)
- Sources in YZ plane (f) show fine structures that are in parallel to the more slanted polarization orientation
- Polarization in XZ plane roughly in same direction of source propagation
- Polarization in XY plane rotated clockwise about 25°-45° from initial FPB



Discussion

- 3D source development and polarization features in 2nd and 3rd flashes can not be explained by conventional breakdown or RREA process, in which both should be driven by ambient E-field, and should be in parallel directions
- The only plausible explanation for 2nd and 3rd flashes is that they were ignited by cosmic-ray showers.
- FPB and FNB in 2nd flash can be explained by (a)
- FPB and FNB in 3rd flash can be explained by (b). The component in XZ (EW – Altitude) plane can be due to geomagnetic field effect on high-energy e^-/e^+ (20 MeV, average in CRS) that deflect e^-/e^+ toward EW direction
- The first flash started with an apparent FNB, and the polarization orientation is parallel to the source propagation. This appears to be consistent with a conventional process. However, conventional process can't explain its 10^7m/s speed and even its existence (due to higher field threshold for negative breakdown). CRS can establish an ionized path and enhance the local field to start the FNB. Since the path is nearly parallel to the geomagnetic field and the path and polarization are expected to be in parallel.