Los Alamos NATIONAL LABORATORY

BIMAP-3D Observations Show Lightning Flashes Were Ignited by Cosmic-ray Showers

Full paper: Shao et al., JGR, 2025

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Lightning processes in initial microseconds

Observed with broadband RF INTF

- Lightning flashes commonly start with a positive fast discharge (+FD) (>10^7 m/s, Rison et al., 2016)
  - 82% ICs; 48% CGs
- Some flashes appeared to start with a negative fast discharge (-FD) (Tilles et al., 2019). However, later observations showed –FD commonly followed a weak and short +FD (Huang et al., 2021)

BIMAP-3D showed most flashes start with +FD. Its intensity varies in large range from flash to flash. Detection depends on +FD intensity and distance, and sensor sensitivity.

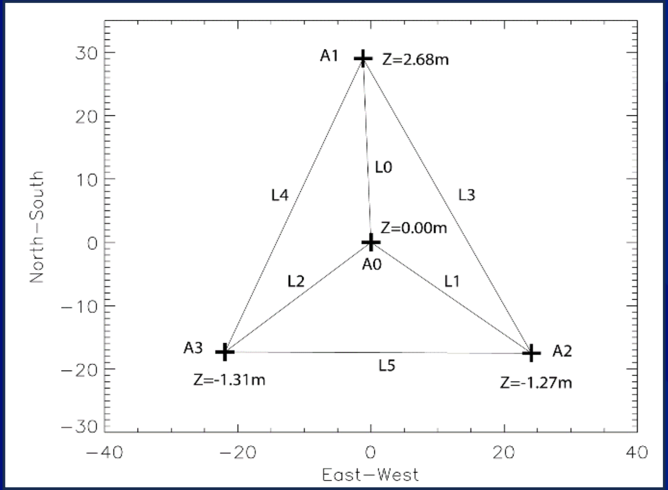
Among 46 fully developed flashes over BIMAP-3D in 07/30/2022 storm

- 27 (59%) with +FD observed from both stations. RF intensity varies from noise floor to saturation level
- 10 (22%) with intense +FD/-FD sequence from both stations during intense storm stage
- 5 (11%) with weak +FD detected from one but not the other station (stations separated by 11.5km)
- 4 (8%) with no FD above noise from either station

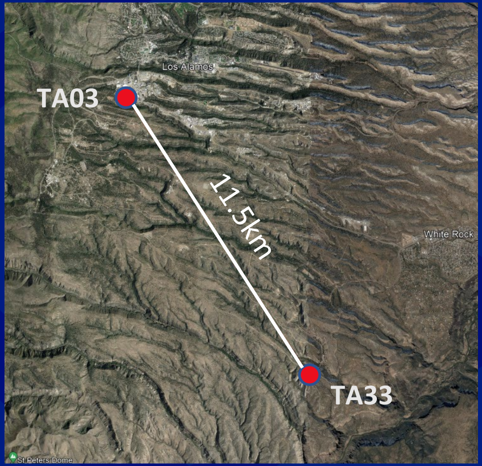
BIMAP-3D: 3-Dimensional Broadband Interferometric Mapping and Polarization system
(*Shao et al., JGR, 2023*)

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

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



2 stations for 3D source and polarization



For linearly polarized signal, its 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

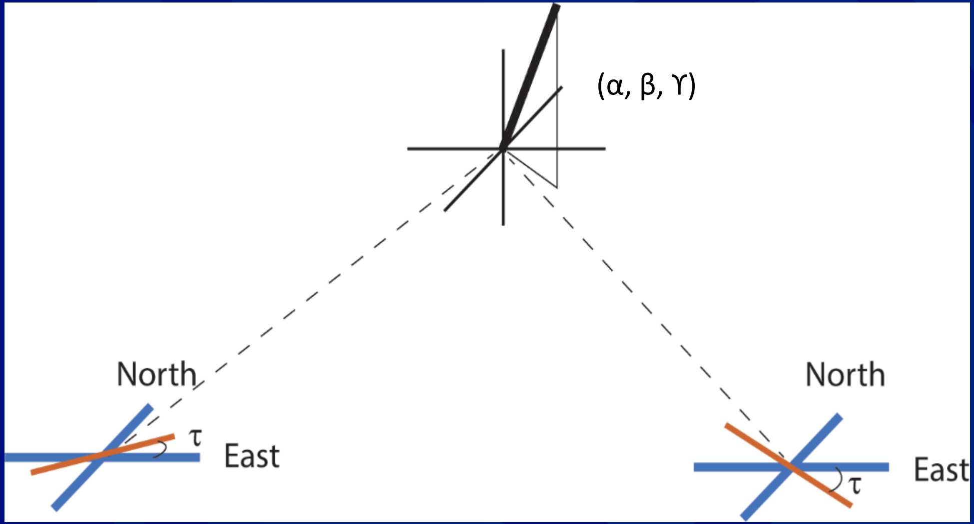
$$A = (\cos^2\theta \cos^2\varphi + \sin^2\varphi) \sin\tau + \sin^2\theta \sin\varphi \cos\varphi \cos\tau$$
$$B = -(\cos^2\theta \sin^2\varphi + \cos^2\varphi) \cos\tau - \sin^2\theta \sin\varphi \cos\varphi \sin\tau$$
$$C = \sin\theta \cos\theta \sin(\varphi - \tau)$$

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

With two station observations

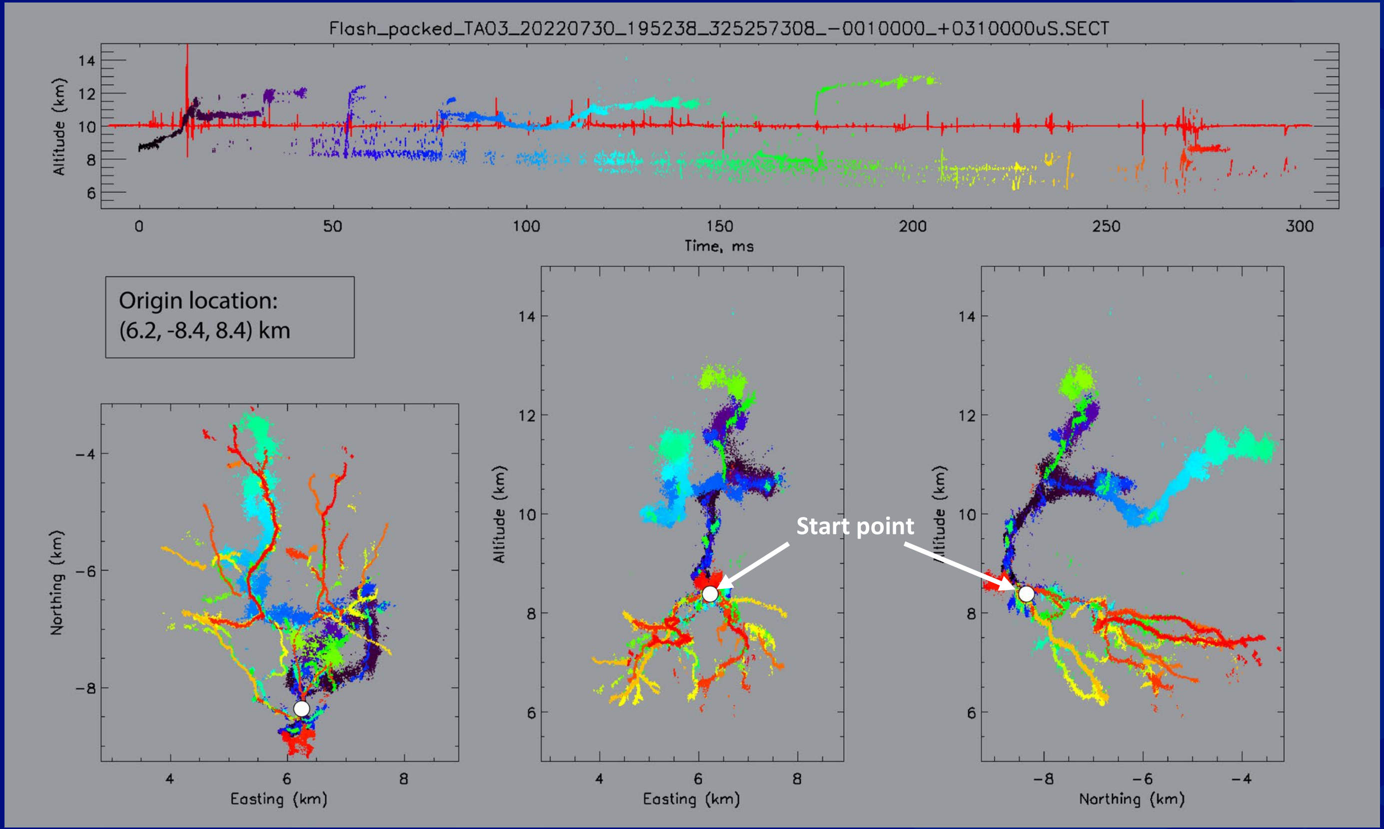
$\boldsymbol{V}_1 = (A_1, B_1, C_1)$ $\boldsymbol{V}_2 = (A_2, B_2, C_2)$

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



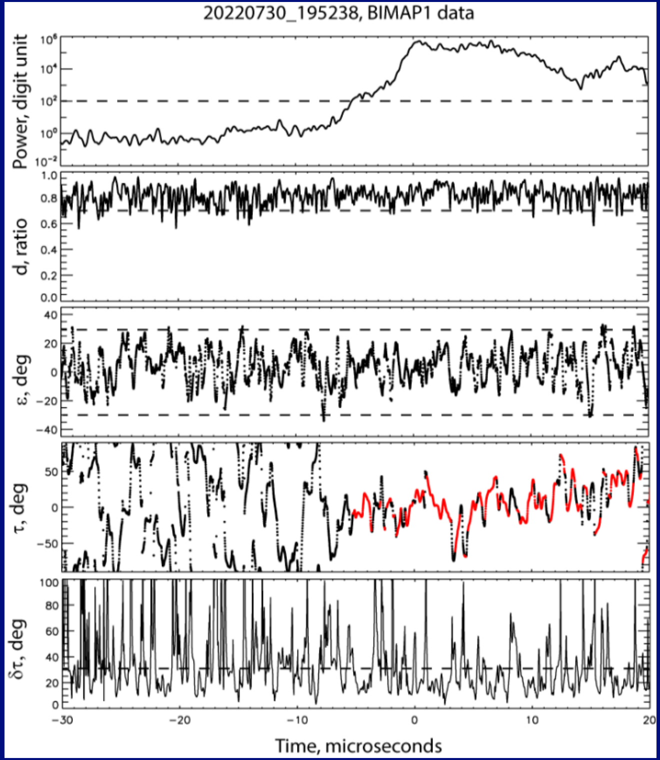
Overall structure and initiation location for Flash 1

Initial stage of this flash used to demonstrate polarization analysis

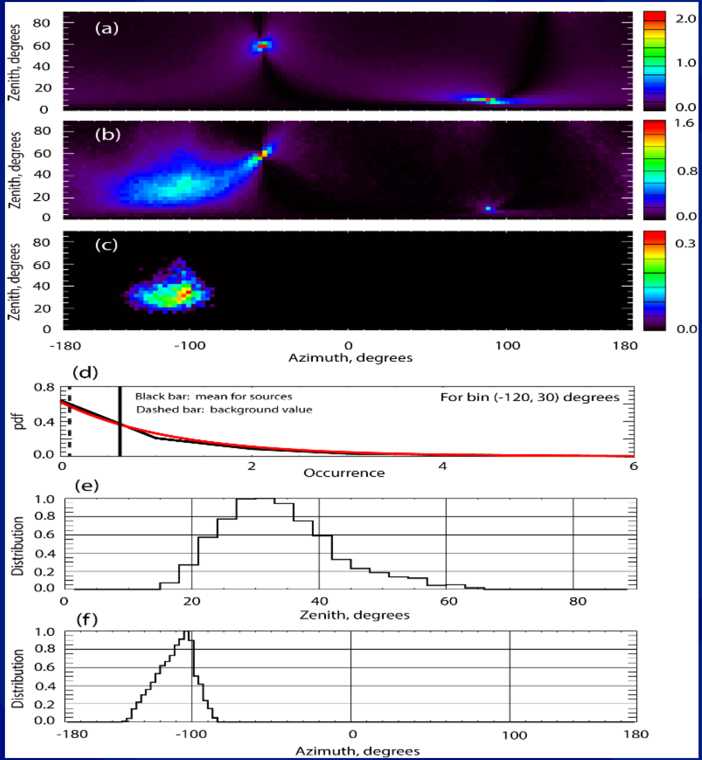


Statistical and noise-reduction analyses for 3D polarization construction

Single station 2D analysis to filter out noisy detection

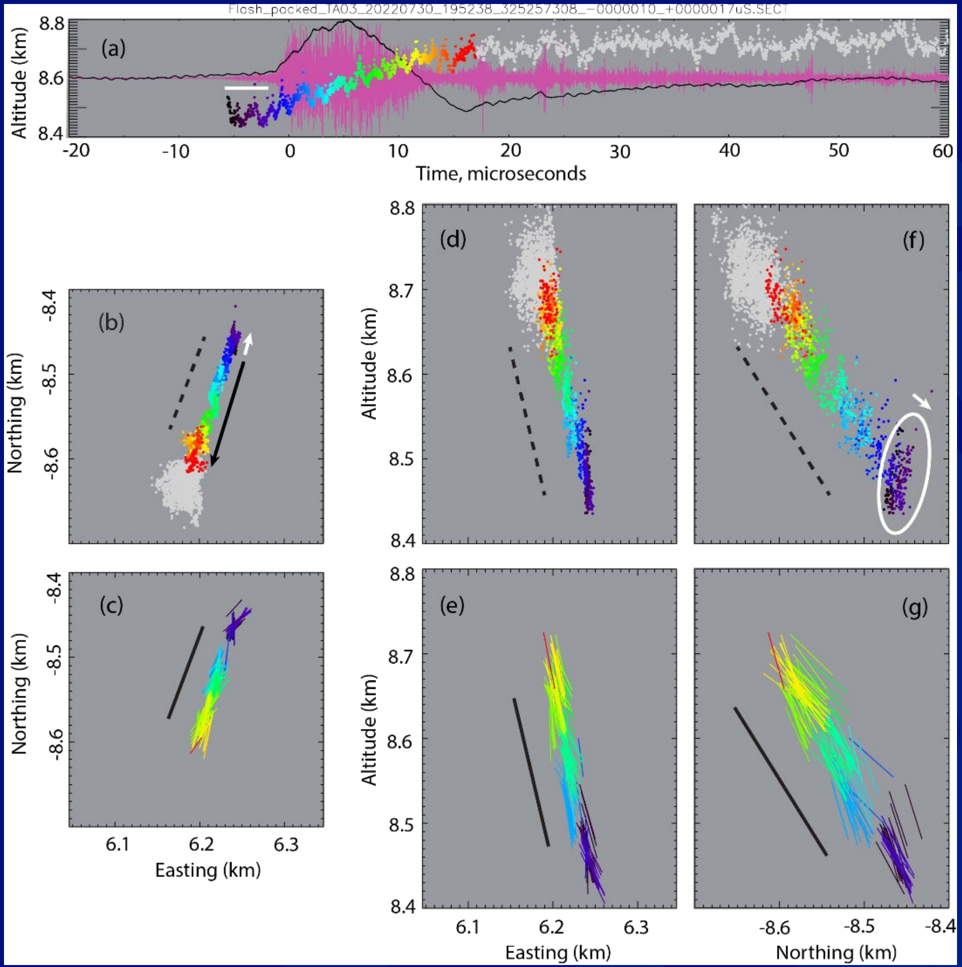


Two-station 3D analysis to remove background effect



Flash 1, 3D results for initial FD

- Lightning started with a short and weak positive discharge in first 3-4 μs
- Followed by a negative fast discharge(-FD) (1.3×10^7m/s) of 19 μs along ~300m straight path
- Averaged polarization parallel to discharge path
- Propagation direction (-109°, 34°). Local geomagnetic field direction (-98°, 26°). FD nearly parallel to B
- Polarization aligned with propagation path, but high propagation speed is not understood.



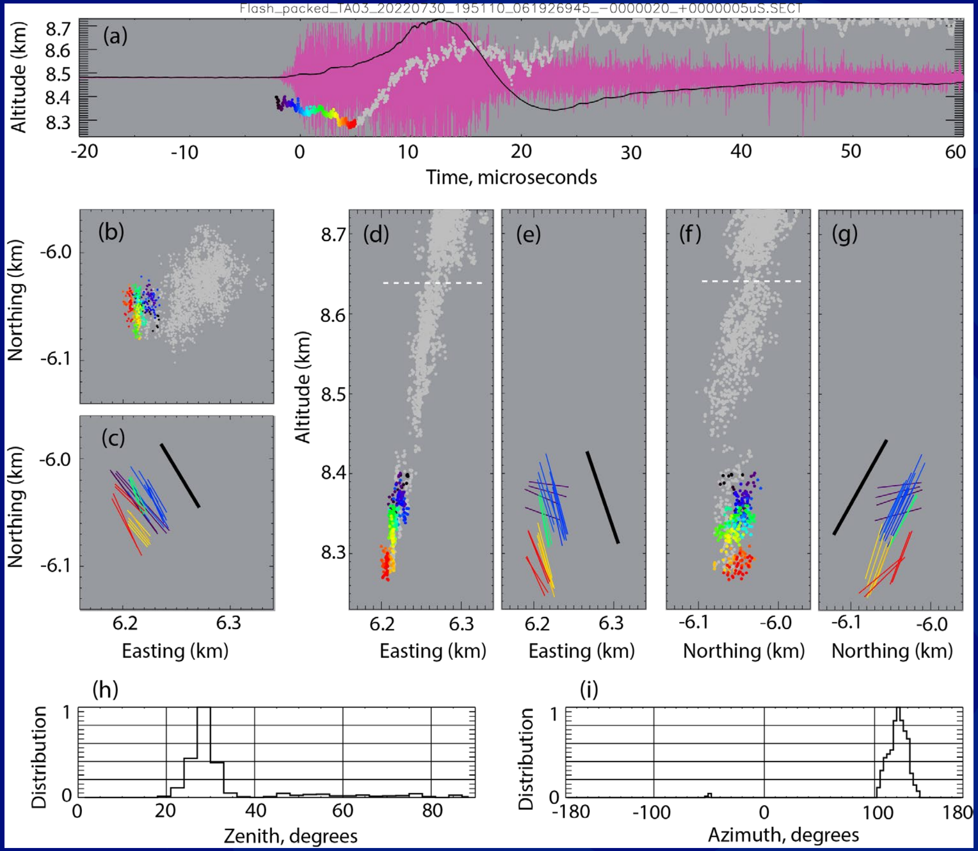
Flash 2: clear initial downward +FD

Source development:

- Duration: 7μs (black -> red)
- Length: 100 m
- Speed: 1.4×10^7 m/s
- Direction: (-150°, -12°)

Averaged polarization orientation

- (118°, 33°) or (-62°, -33°),
- Clearly tilted away from source propagation direction



Flash 2: -FD immediately after +FD

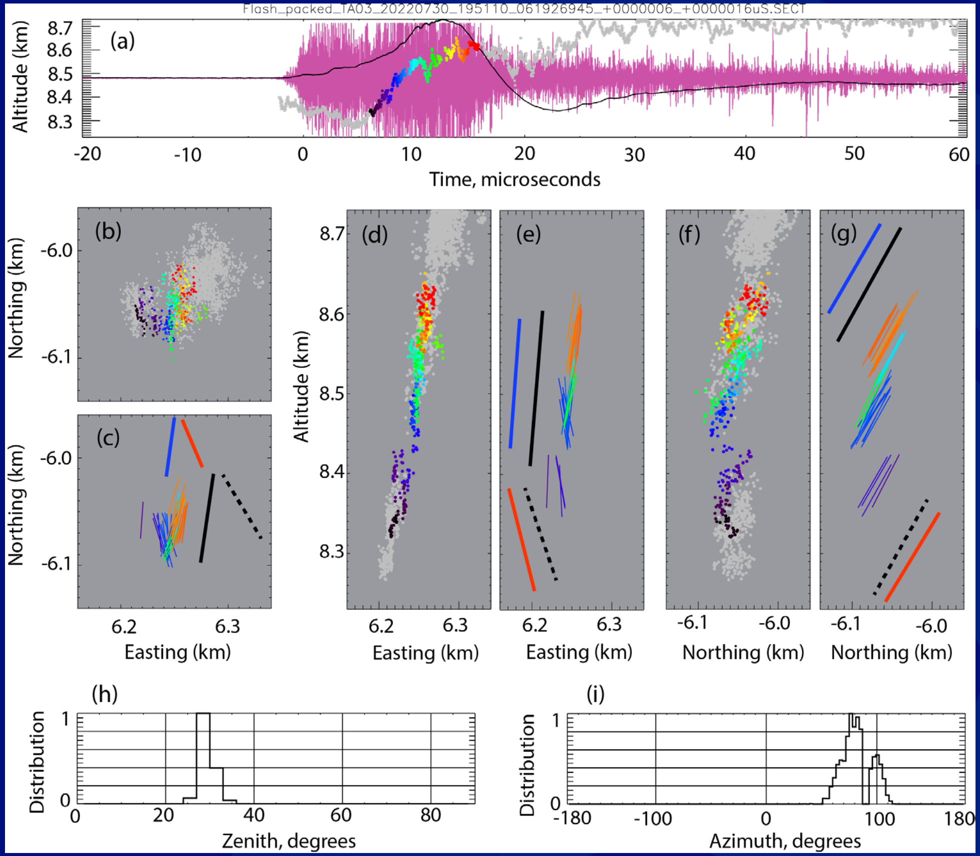
Source development

- Duration: 10 μs (black -> red)
- Length: 300 m
- Speed: 3.0×10^{7} m/s
- Direction: (33°, 10°)

Average polarization orientation:

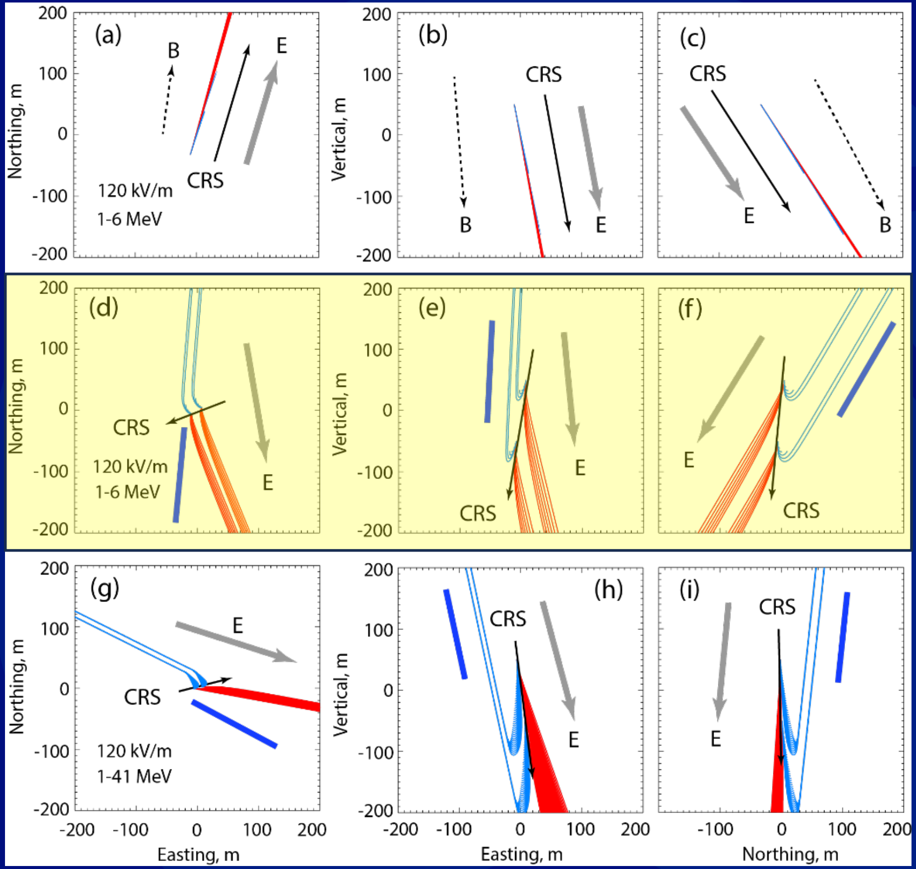
- (77°, 29°)
- tilted away from propagation direction.

In horizontal plane, -FD polarization rotates 40°-50° from +FD (from dashed to solid black lines)



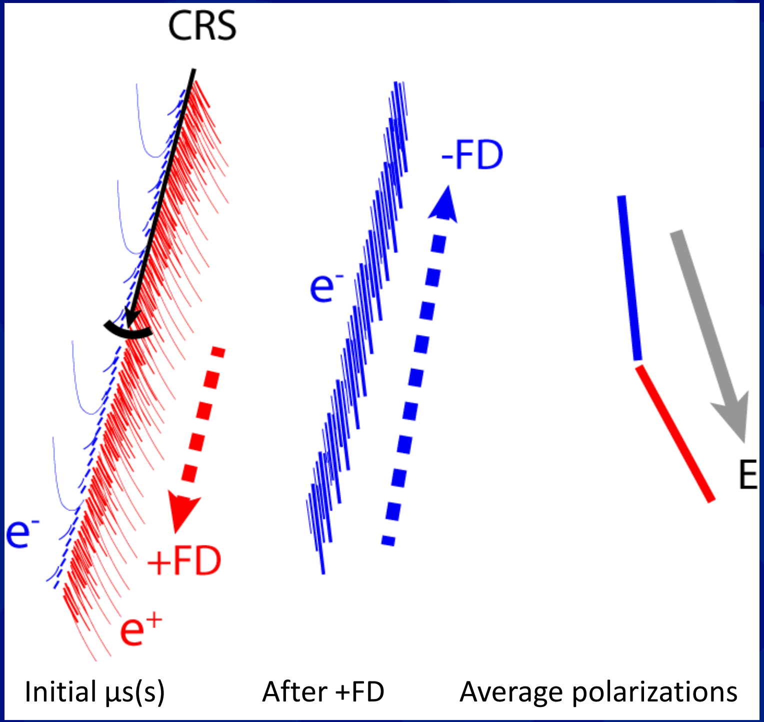
Deflection of high-energy e^- and e^+ as of CRS in E and B fields

- Assume CRS in direction between +FD and –FD propagation directions (thin black arrows), independent of E-field
- Assume E-field direction between +FD and –FD polarization orientations (gray arrows), with amplitude of 120 kV/m
- Atmosphere density at 8.5km
- Middle row related to **Flash 2**, shows e^+ (red) and e^- (blue) from 1 to 6 MeV
- All e^+ runaway and only >5 MeV e^- turn around and runaway at E of 120 kV/m (<RREA field)
- These runaway e^+/e^- leave 3300/m eV-level electrons along their traces, and are expected to guide the instantaneous discharge current direction (polarization) in later +FD/-FD processes
- Deflected e^+ and e^- directions agree with +FD and –FD polarizations (see last slide)



Time sequence of +FD and -FD related to CRS

- +FD starts at CRS front, propagates along ionized core behind the speed-of-light CRS front
  - ➢ straight and fast
- Immediately behind CRS front, ionization imprints from e^+ dominates
  - ➢ instantaneous discharge current (polarization) guided by imprints of deflected e^+
- After microseconds, CRS (and e^+) moves out of the region
  - ➢ only e^- (including more ionized e^-) left along path
  - ➢ FD discharge current (polarization) guided by imprint of deflected e^-

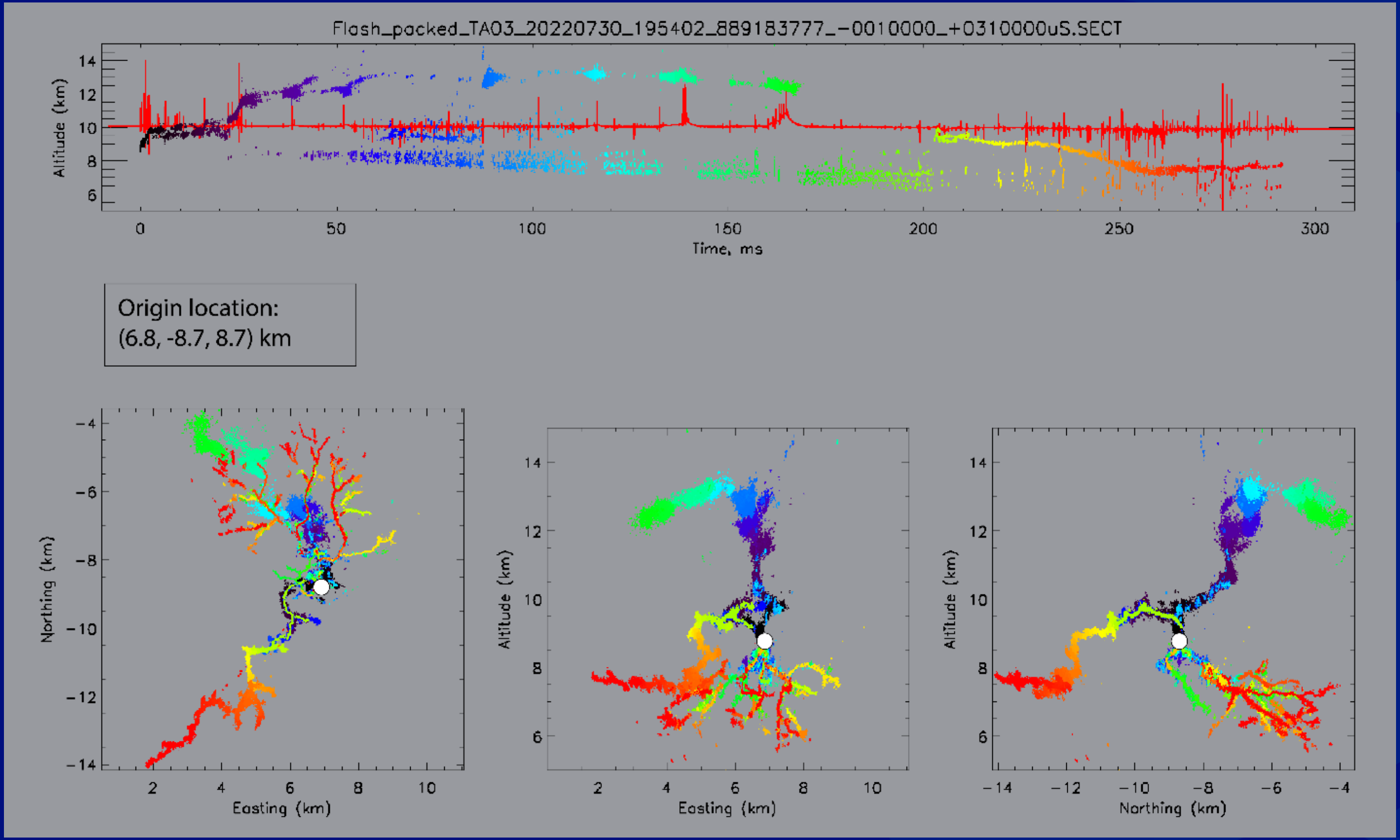


Conclusions

- High (>10^7 m/s) discharge speed suggests pre-ionized, RF invisible path before +FD/-FD
- Discharge path (+FD and –FD) not solely driven by cloud electric field. If so, discharge propagation and polarization would be along the same direction.
- Observations inconsistent with E-field-driven RREA since B-field effect on runaway electrons is <10% of RREA E-field effect, and polarization is expected to be nearly aligned with discharge direction, <7°.
- Like RREA, FRD is dominated by electrons, and its development is predominately driven by E-field
- With CRS, all observed features can be consistently explained, including that of Flash 1 and other more common cases that start with only a +FD
- Initiation depends on combined intensities and directions of E, CRS, and somewhat B. E-field does not have to be above RREA threshold.
- Full paper of *Shao et al*., 2025 reports more examples and detailed analyses

Backup slides

Overall structure and initiation location for Flash 3

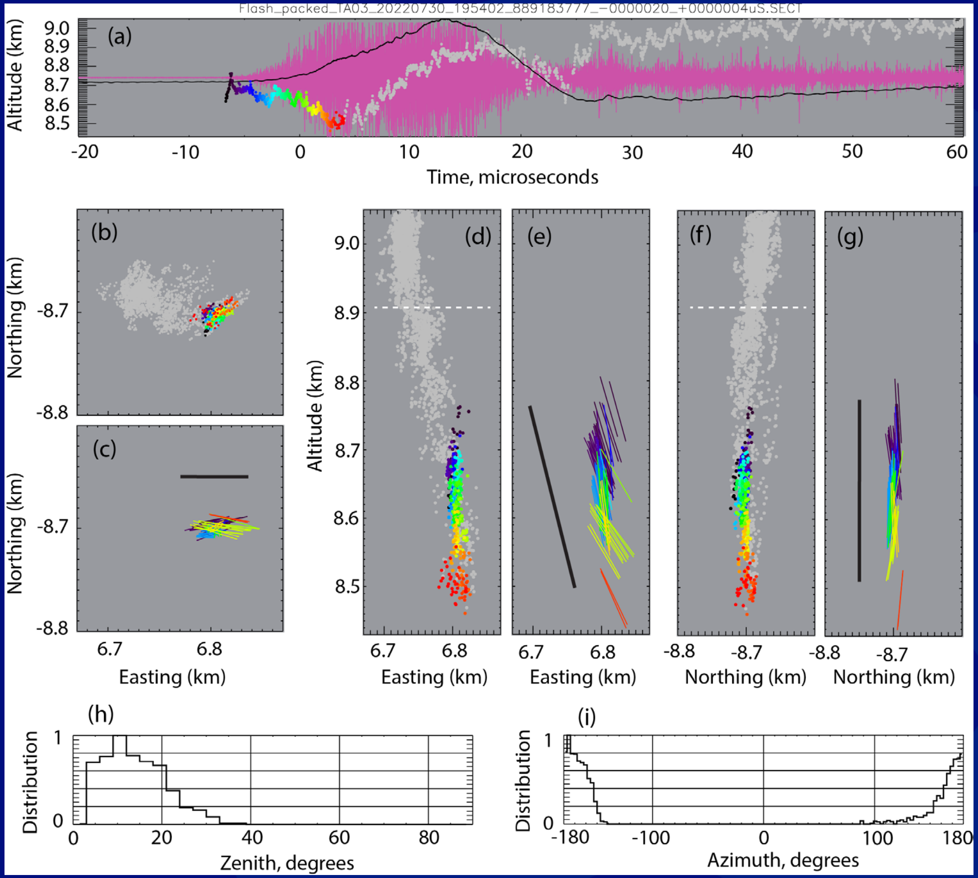


Flash 3: Clear and more extensive +FD

Source development

- Duration: 11 μs (black -> red)
- Length: 200 m
- Speed: 1.8×10^{7} m/s
- Direction: (27°, -4°), vertical

- Polarization orientation
  - (-179°, -14°)
  - Tilted away from propagation direction



Initial +FD followed immediately by –FD

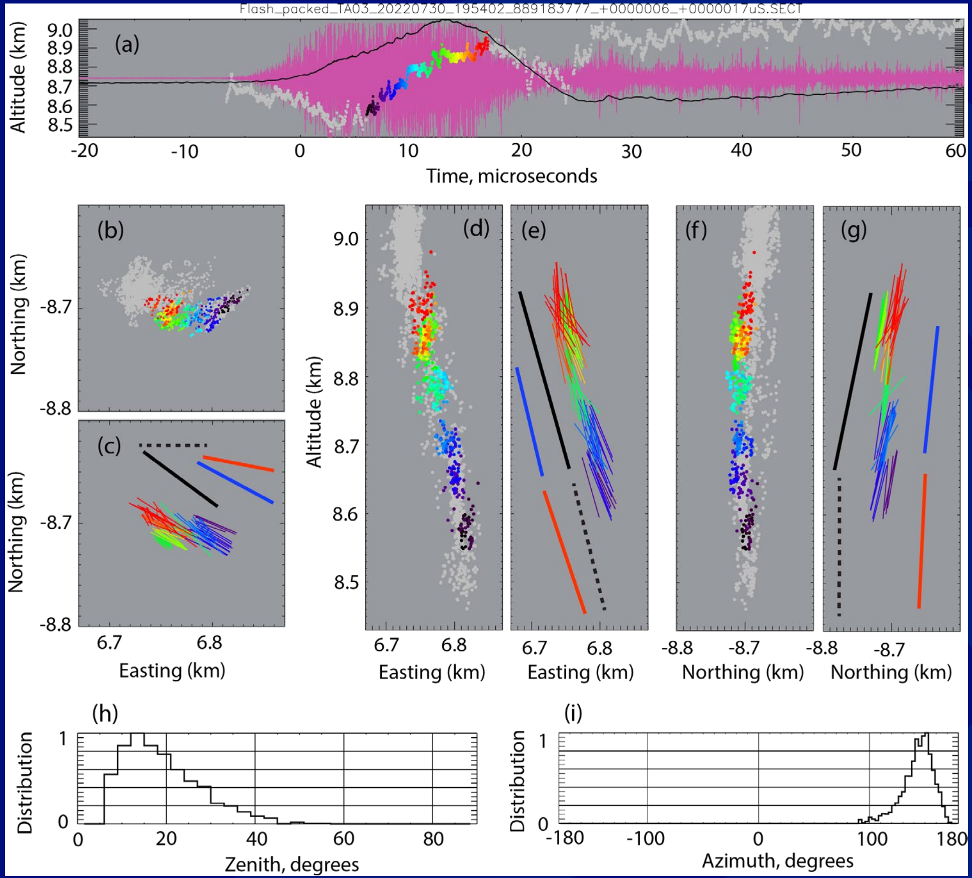
Source development

- Duration: 11 μs (black -> red)
- Length: 350 m
- Speed: 3.2×10^7 m/s
- Direction: (179°, 12°)

Polarization orientation:

- (144°, 19°)
- tilted away from propagation direction.

In horizonal plane, –FD polarization rotates 30°-40° from +FD (dashed and solid black lines)

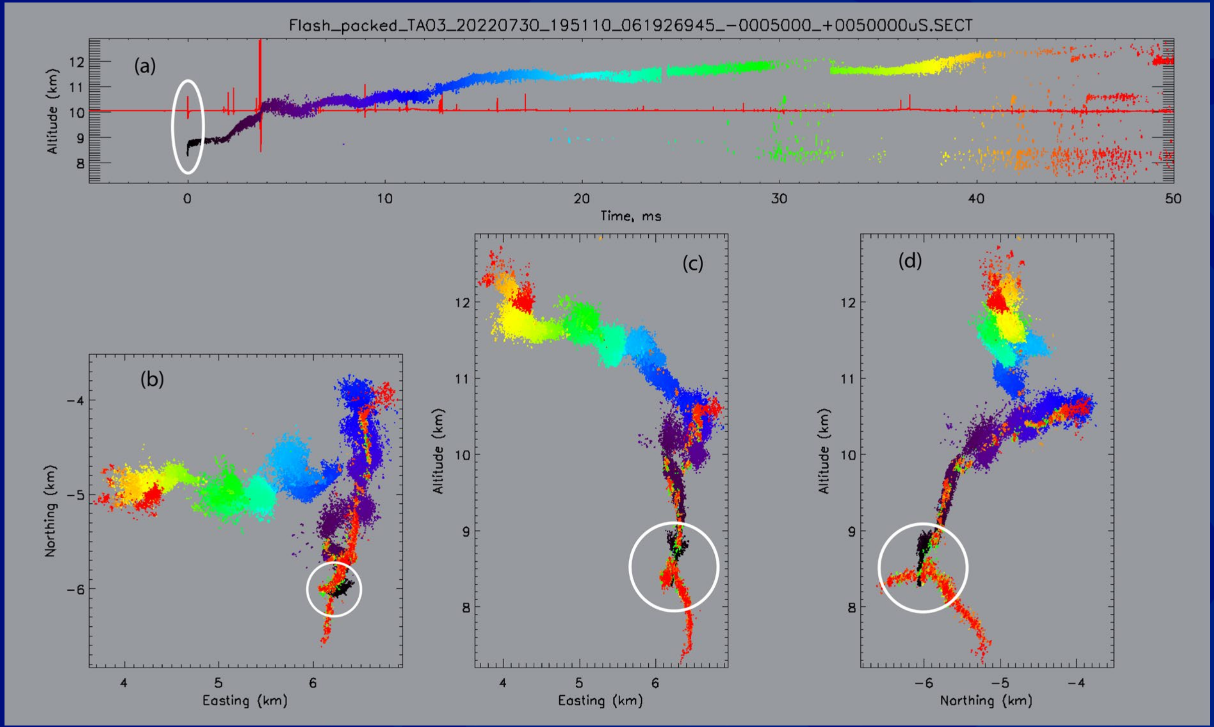


A cosmic-ray shower (CRS) pierces through cloud immediately prior to +FD/-FD process

- CRS with $>10^{15}$ eV arrive at $6.5/(km^2 s)$ rate, frequent enough for lightning rate
- CRS of 10^{15} eV leaves 10^7-10^8 /m^3 ionized eV-level electrons within 1-m radius at 8.5 km atmosphere, compared to $0.5/m^3$ in normal air
- CRS arrival direction independent of cloud E-field
  - pre-ionized path independent of E-field
- CRS provides equal number of high-energy e^- and e^+
  - e^- and e^+ deflected differently in E and geomagnetic field for polarization rotation between +FD/-FD

Later discharge in Flash 2 avoided the initial +FD/-FD path

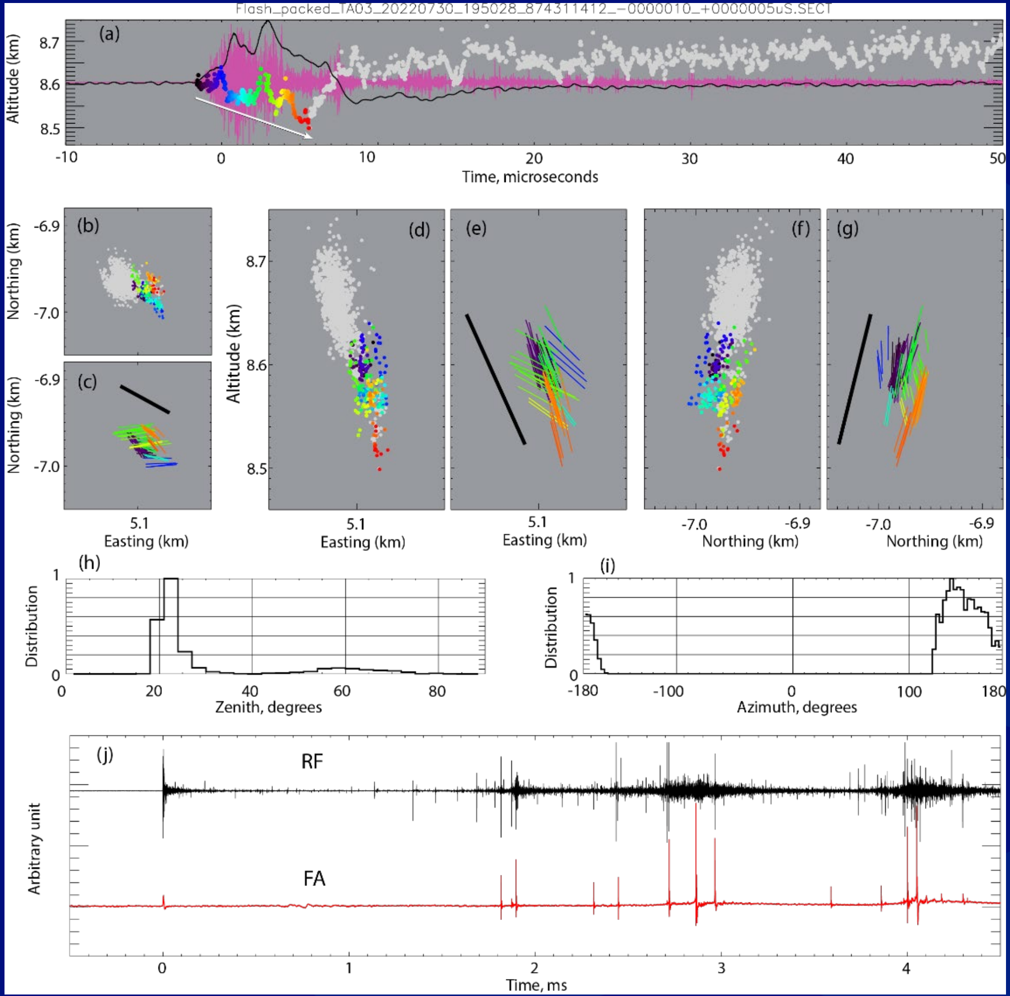
- Further indicates +FD/-FD path was not solely driven by E-field, otherwise they would fellow and extend along the same path
- Channel above +FD/-FD path (black dots in circle) tilted toward north, agreeing with inferred E-field direction for +FD/-FD analysis



Flash started with +FD

- +FD at 1.3 x 10^7 m/s
- Occasional –FD?, not extended beyond +FD.
- Average polarization slanted from source propagation direction

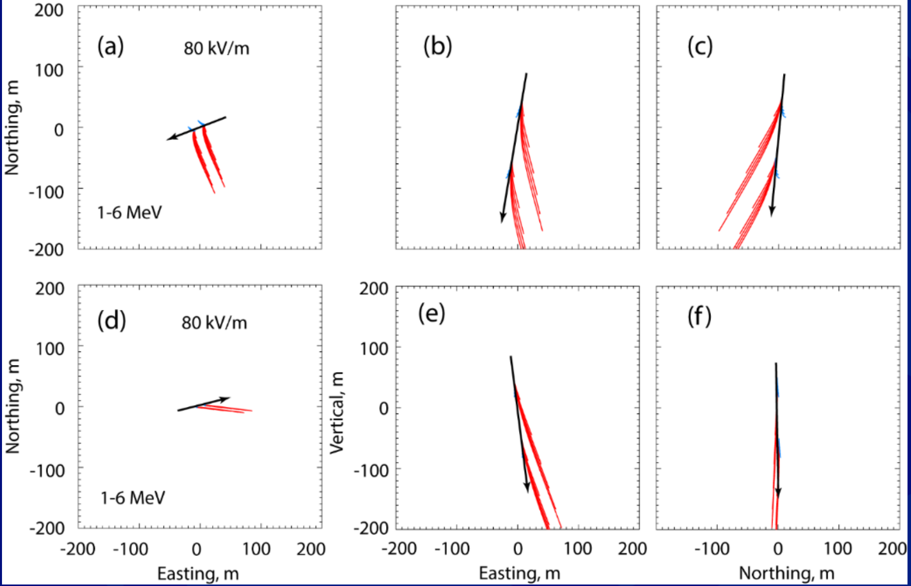
Same as +FD in other flashes.



Traces of e^- and e^+ in geomagnetic and lower E field

Occurrence of FD and ensuing lightning depends on the combined direction and intensity effects of CRS, E-field, and the geomagnetic field.

- E-field: 80kV/m instead of 120 kV/m
- Electrons less likely turn around and become runaway
- Ionization mostly due to downward positrons
- This would likely lead to +FD but not the following –FD, if +FD can occur at all from a given CRS



Why +FD polarization follows deflected e^+ traces and –FD polarization follows e^- traces?

- +FD likely starts at the front region of CRS core, since the electron density would be the highest at the position and time
- After +FD started, it will propagate downward behind the shower front in the direction where the positron ionization dominates, and the discharge current (polarization) is more influenced by the positron traces
- When –FD starts to propagate upward some microseconds later, more eV-level electrons due to positions would have attached to neutrals, and upward ionization is more attributed to upward propagating runaway electrons, from both CRS and secondary high-energy electrons, leading –FD polarization more influenced by high-energy e^- traces

Questions remain unanswered

- How the first RF visible discharge started by the CRS?
  - Likely in the front region of the CRS shower due to high density of free electrons
- How the discharge propagate at $>10^7$ m/s?
  - Even with 10^7-10^8 /m^3 eV-level electron density, it is still poorly ionized, and one can't apply typical plasma calculation for the propagation speed.