Chapters 4.7 – 4.12 of Rakov and Uman, 2003
(About everything that happens after 1st return stroke)

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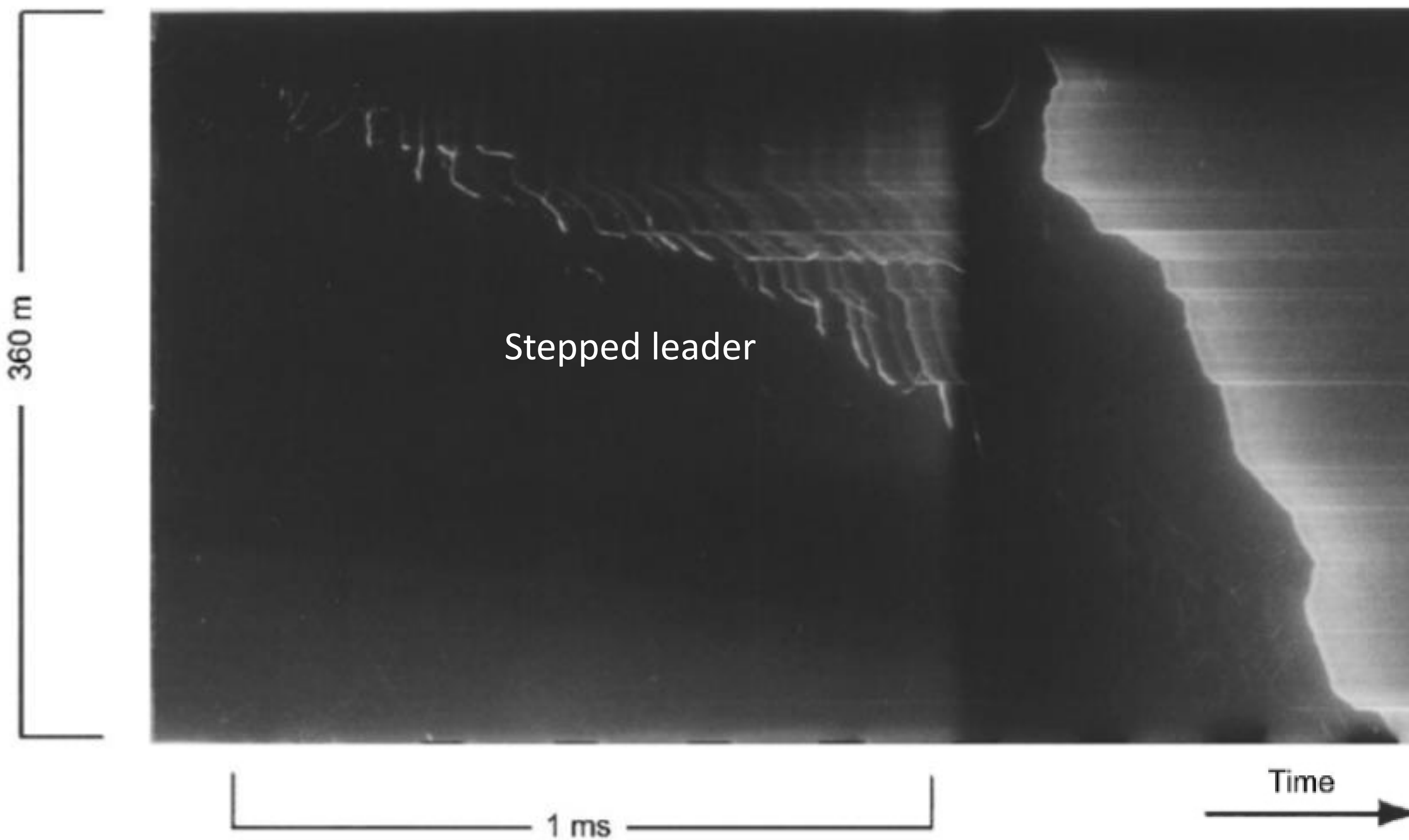
4.7 Subsequent leader

→ Following return stroke, inter-stroke interval some 10s of ms.
→ Dart leader: appears to move smoothly along path of previous leader activity, unlike stepped leader, ~10^7 m/s, ~1 ms duration.



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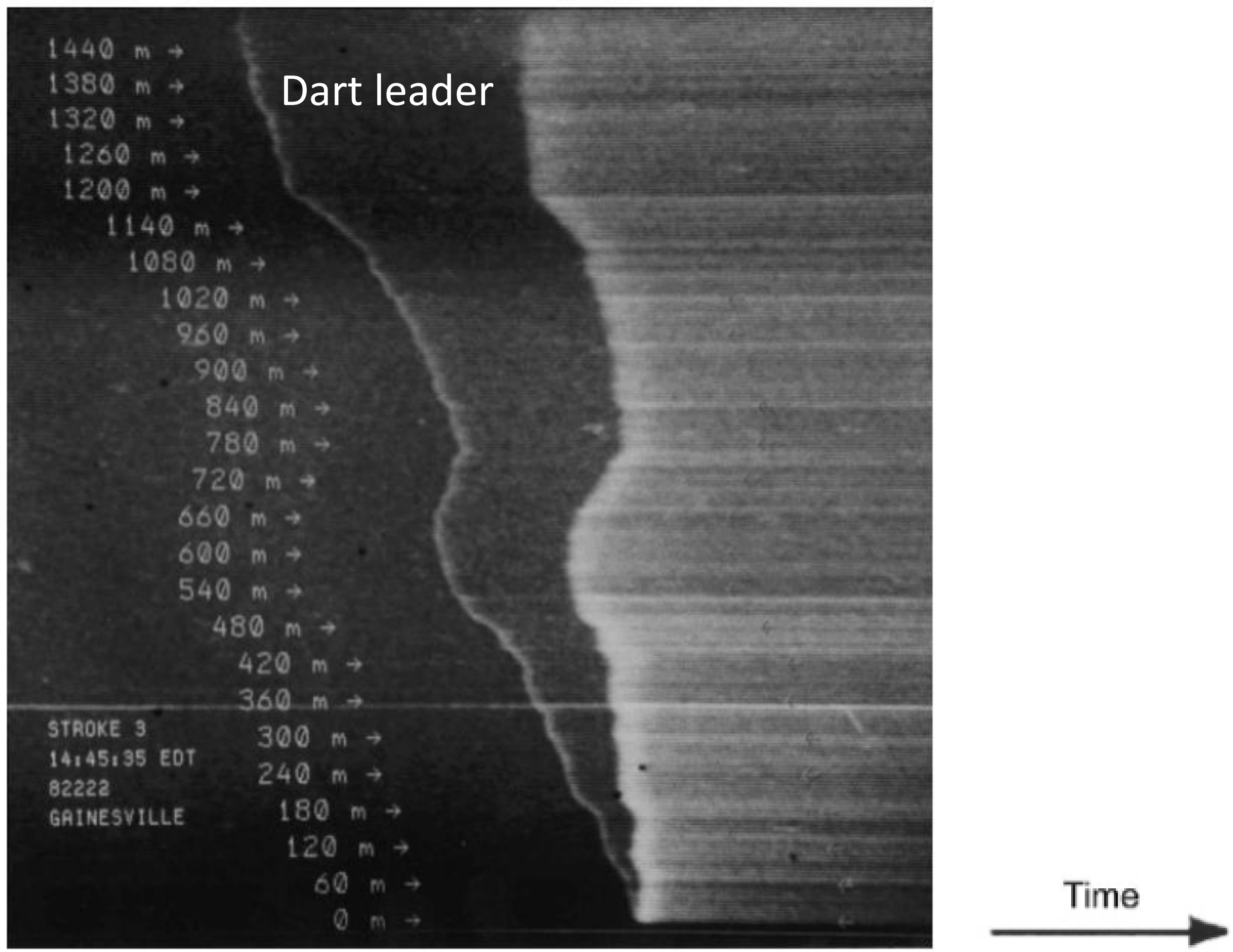

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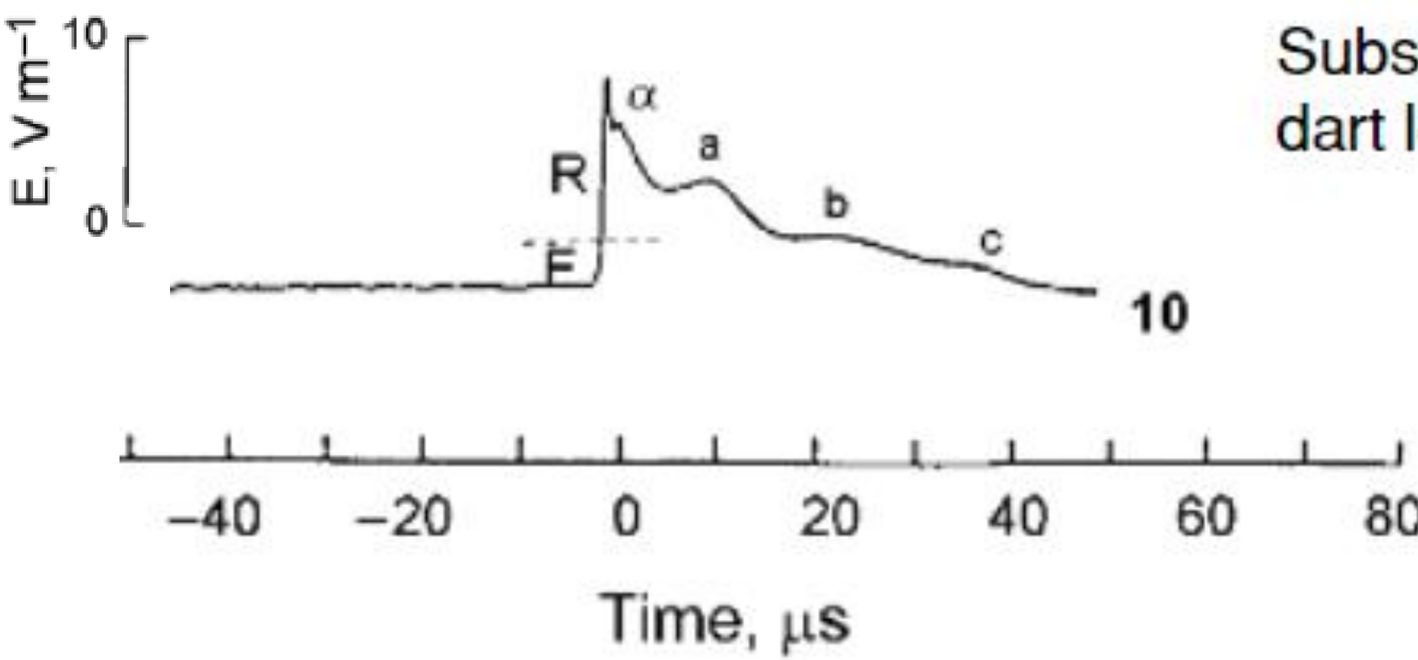

Subsequent with dart leader

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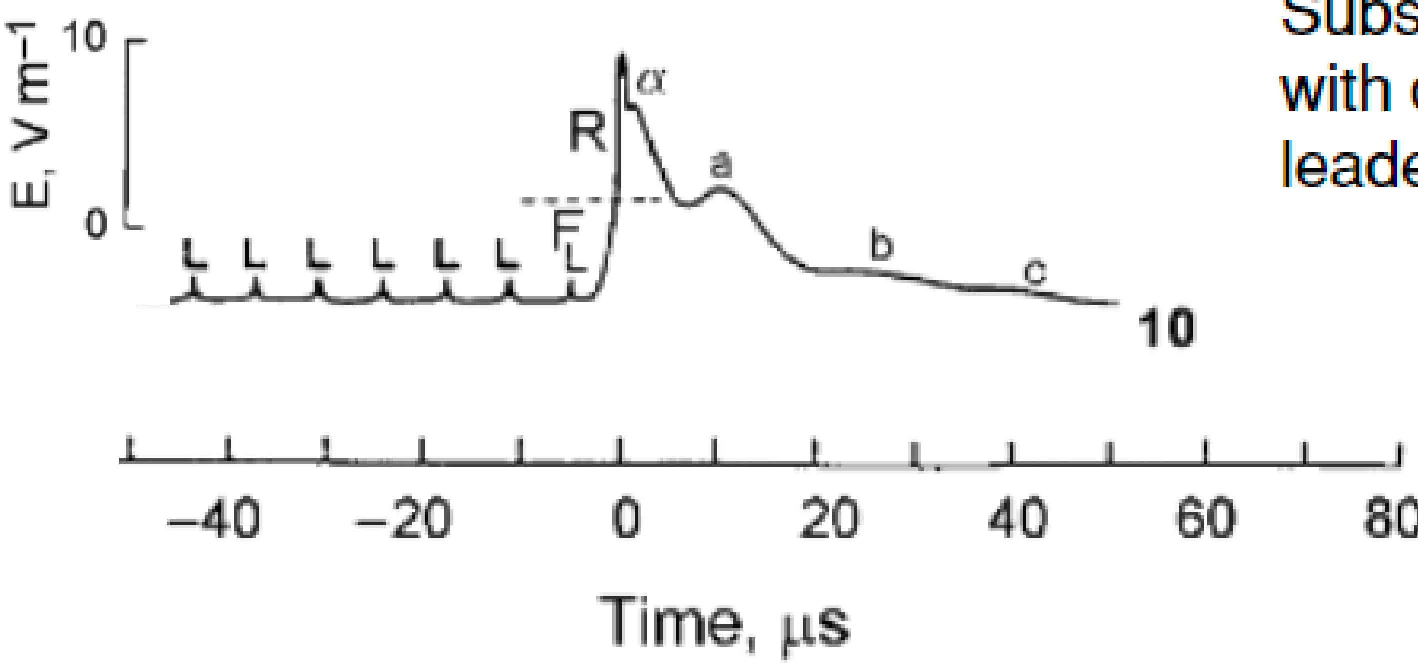

Subsequent with dart-stepped leader

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→ Chaotic leaders: creates irregular E pulses.

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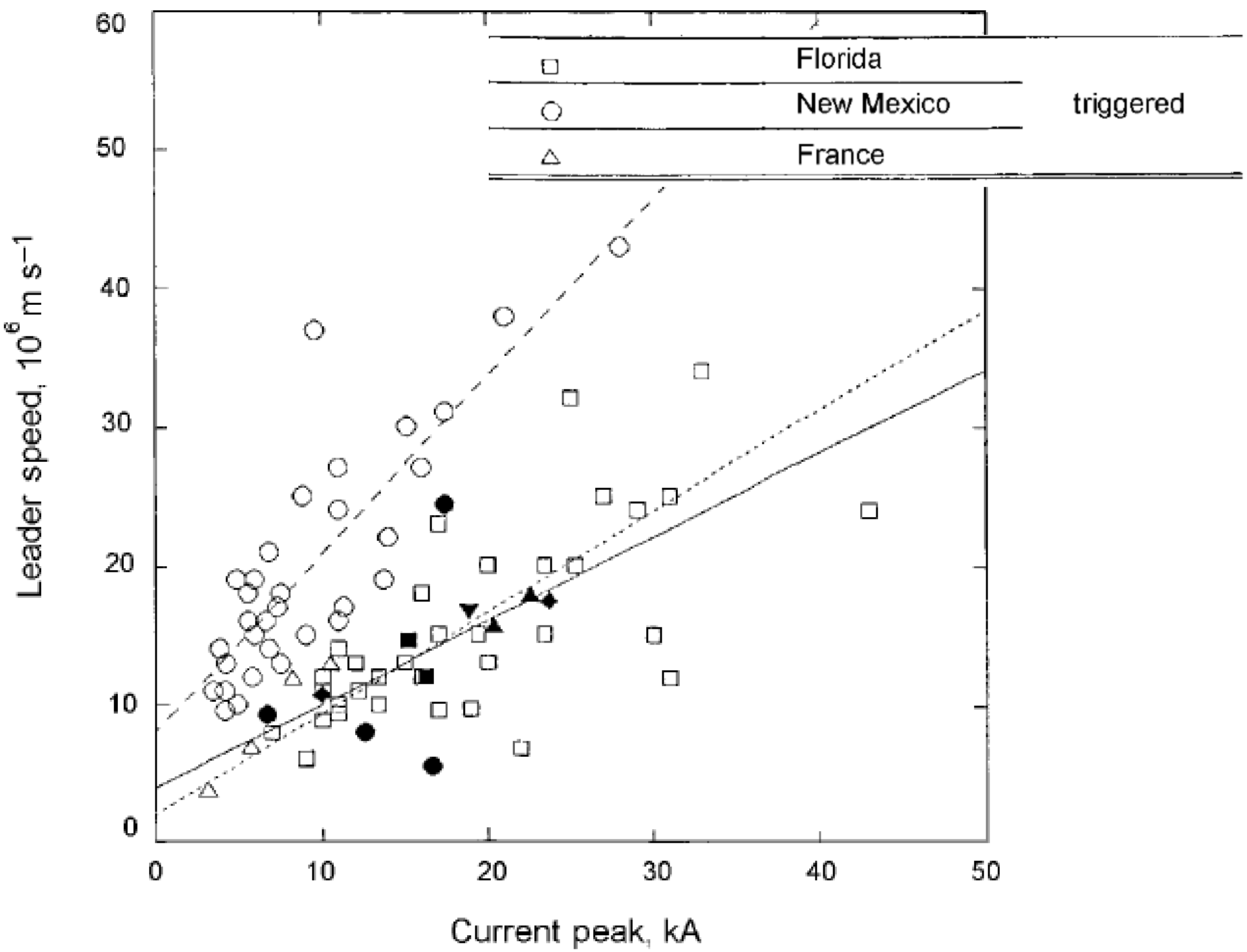
Dart and dart-to-stepped leader

→ Dart leader speed and the following RS current peak are positively correlated (for both natural and triggered lightning).



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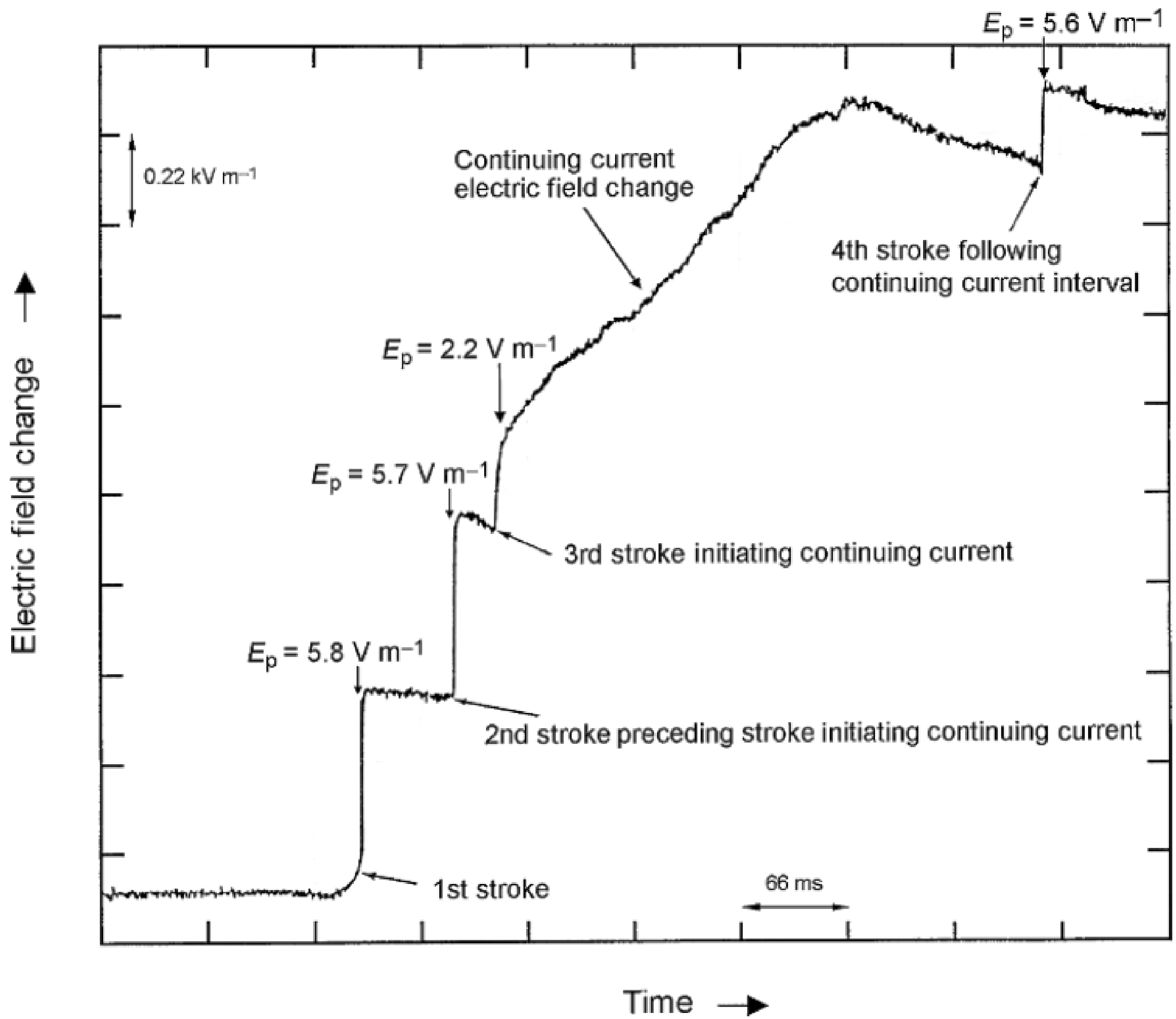
Dart and dart-to-stepped leader

→ Dart leader speed and the following RS current peak are positively correlated (for both natural and triggered lightning).
→ Dart-to-stepped leader comparable to stepped leader.
→ 100 A to some kA’s current.
→ Peak optical radiation intensity 10 times smaller than for RS.
→ Subsequent leader duration, i.e., leader length, increases with stroke order.

4.8 Continuing current (CC)

→ Following RS, slow (10s-100s milliseconds) current (10s-100s A).



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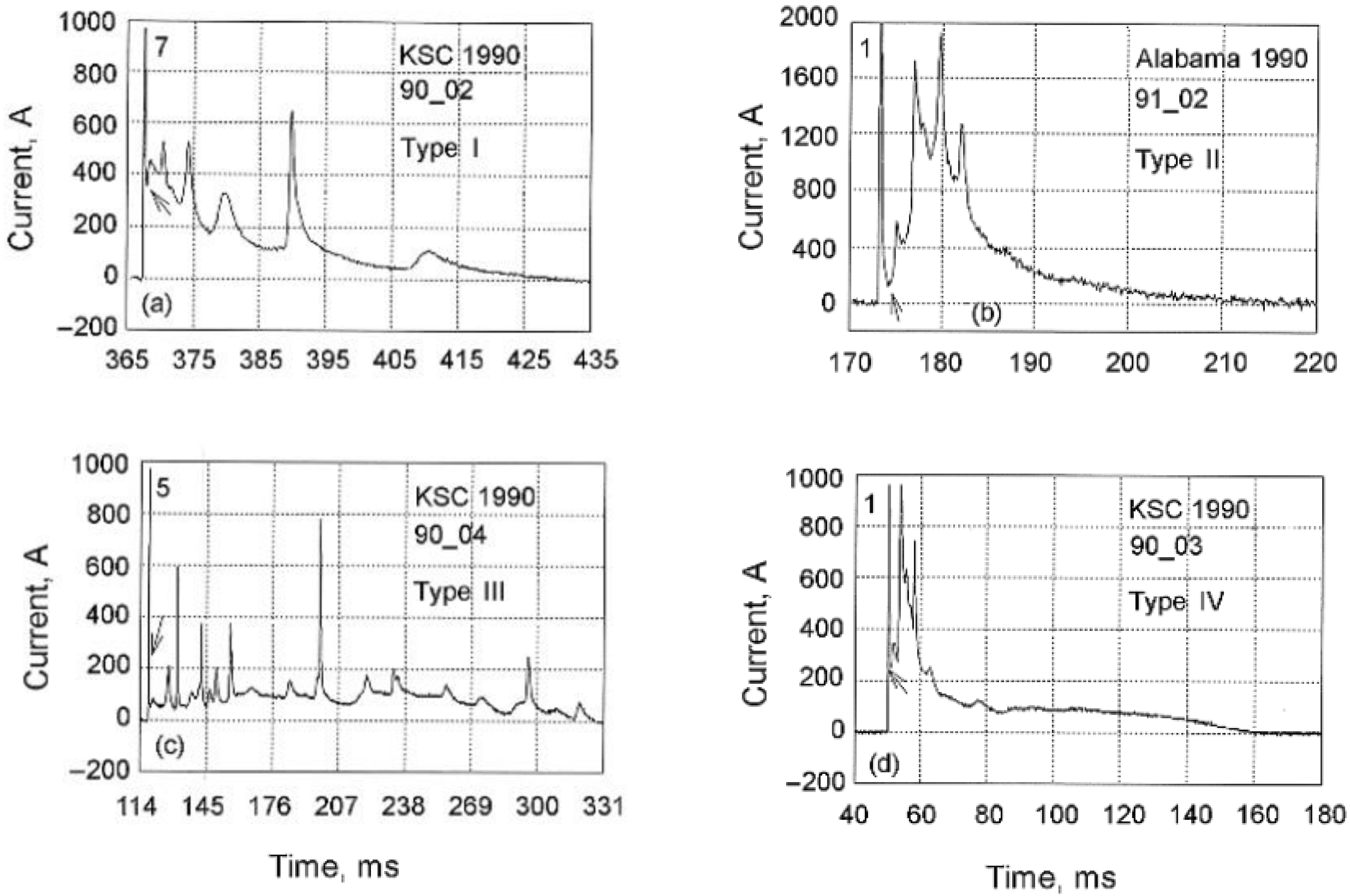

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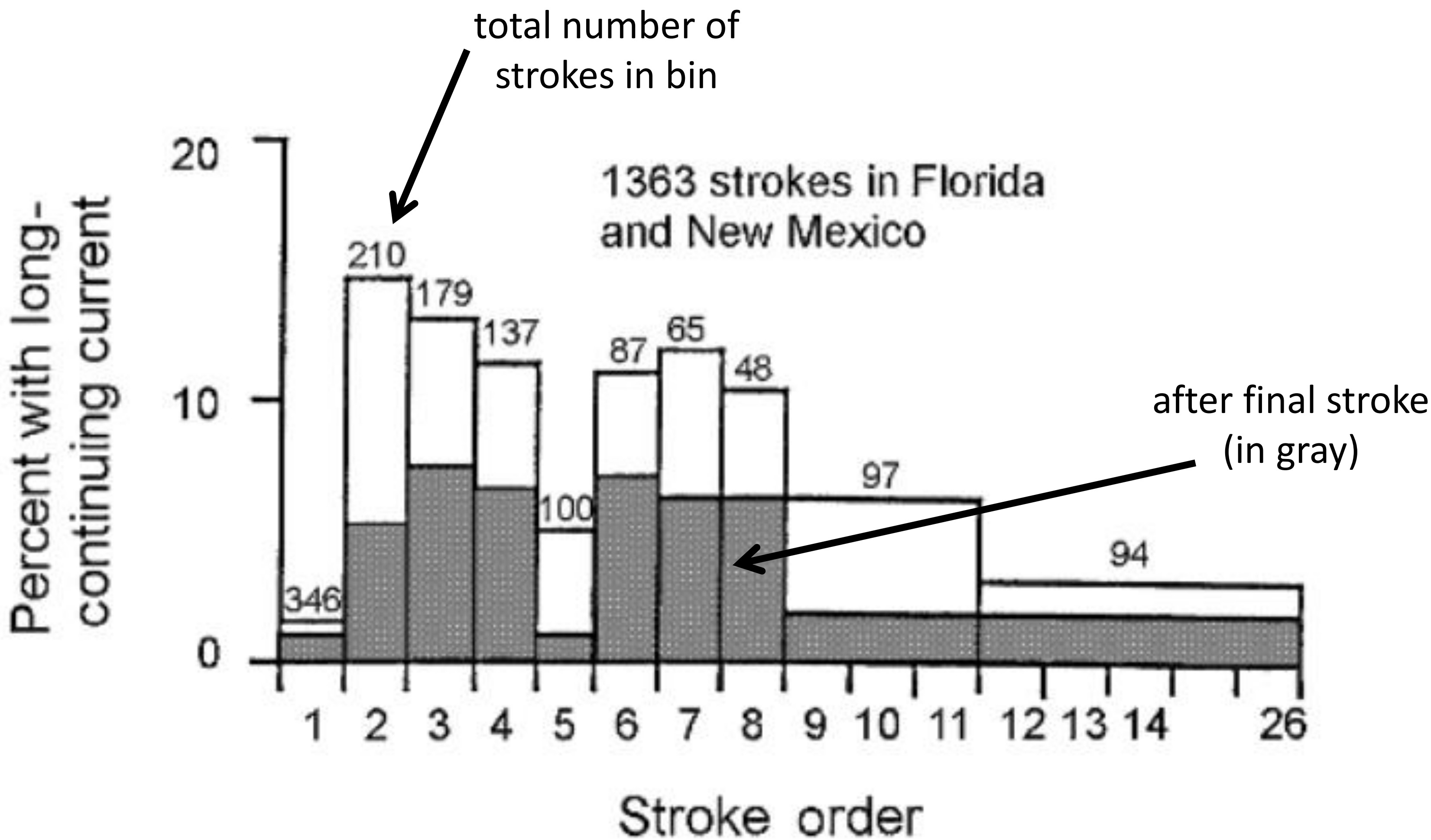

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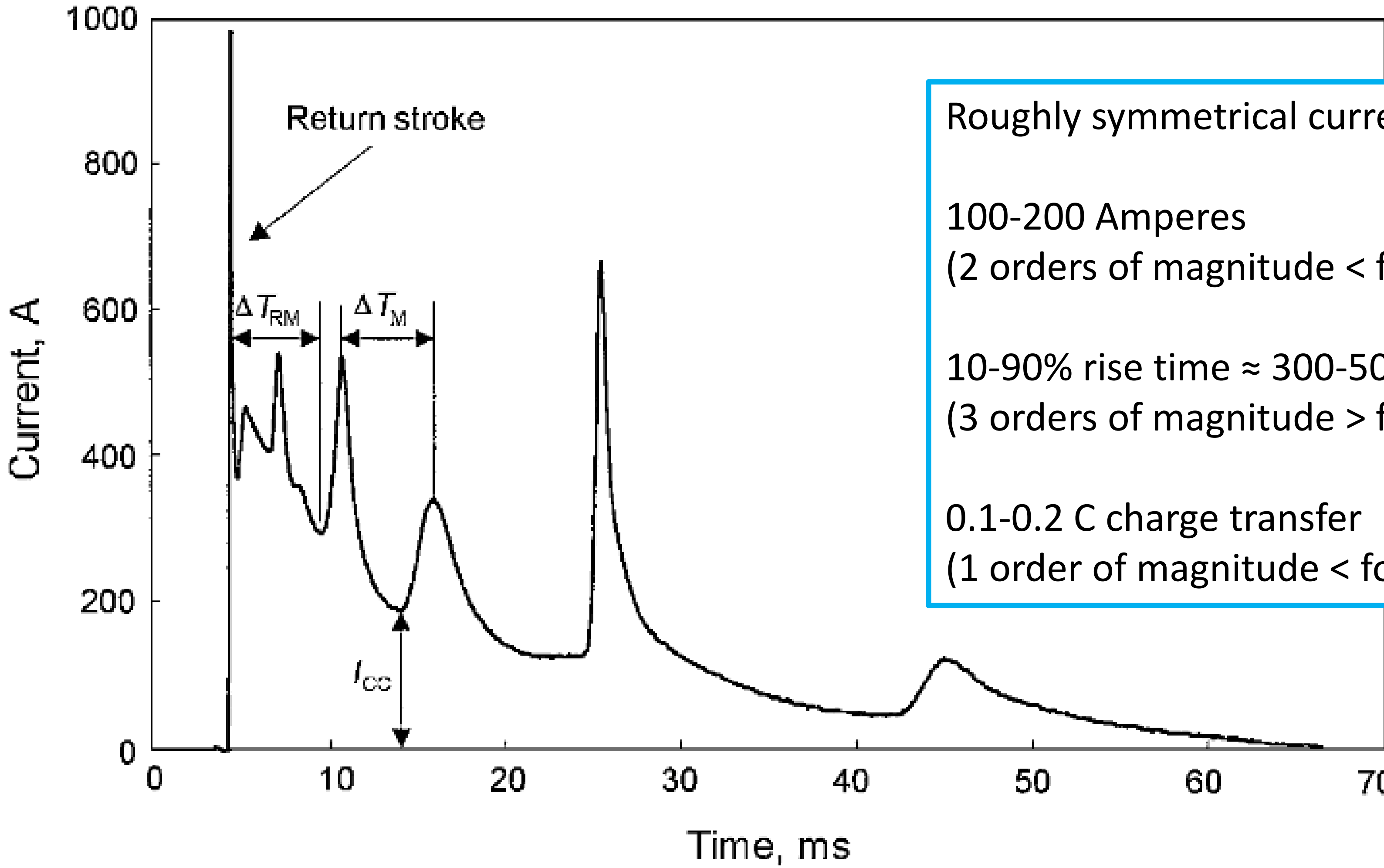
→ Large charge transfer → damage due to thermal effects.
  Example: can burn through aircraft metal skins.
  Example: can cause forest fires.
→ CC established by extensive (~10x10x10 km^3 volume) branching in cloud → "Q-noise" or VHF radiation sometimes accompanying CC → initial part of K-process/recoil process.

4.9 M-components

→ Short (~1 millisecond) perturbations in CC.
→ Named after D. J. Malan, who first studied the process in 1937.



Roughly symmetrical current pulse

100-200 Amperes
(2 orders of magnitude < for RS)

10-90% rise time ≈ 300-500 μs
(3 orders of magnitude > for RS)

0.1-0.2 C charge transfer
(1 order of magnitude < for RS)

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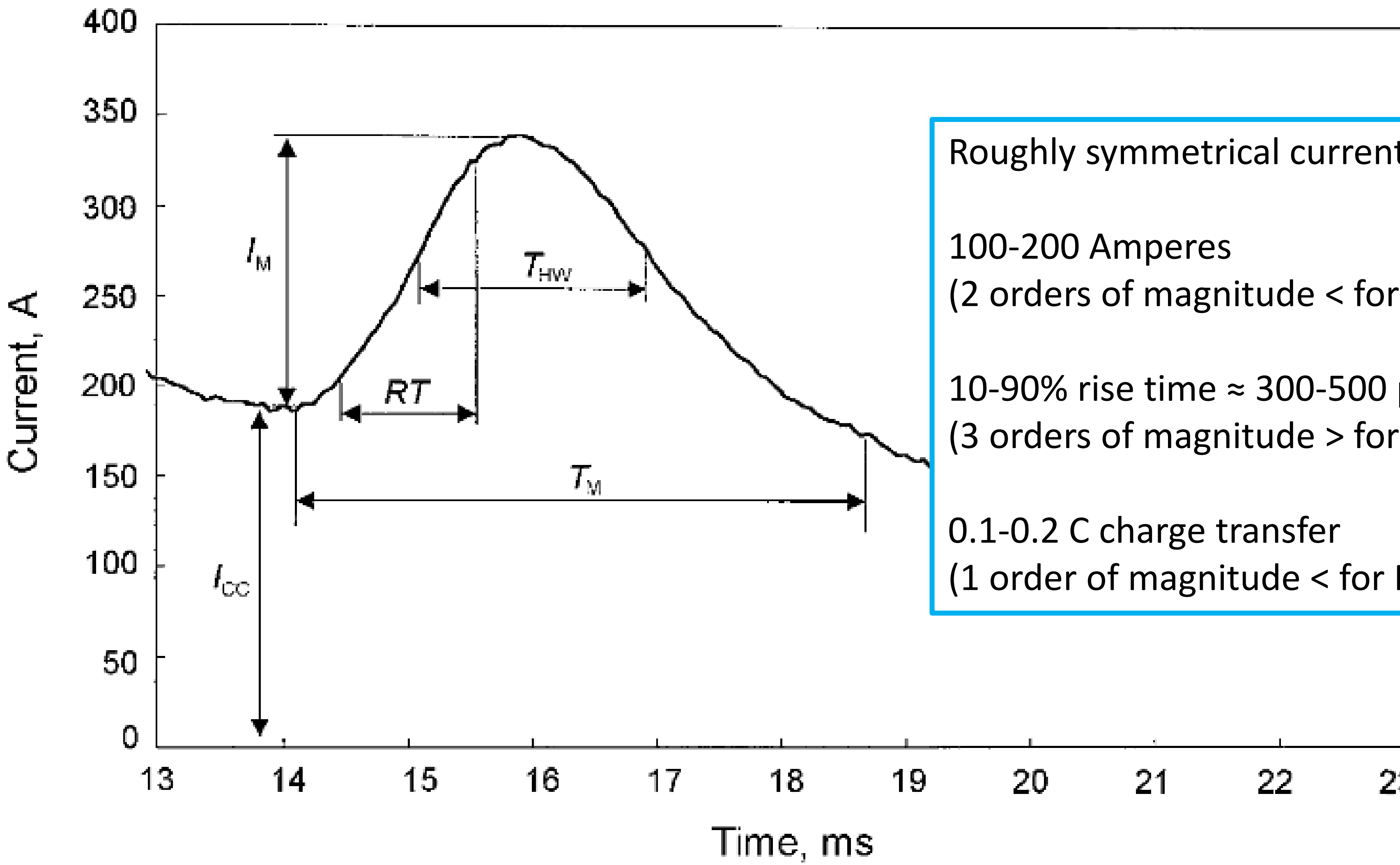

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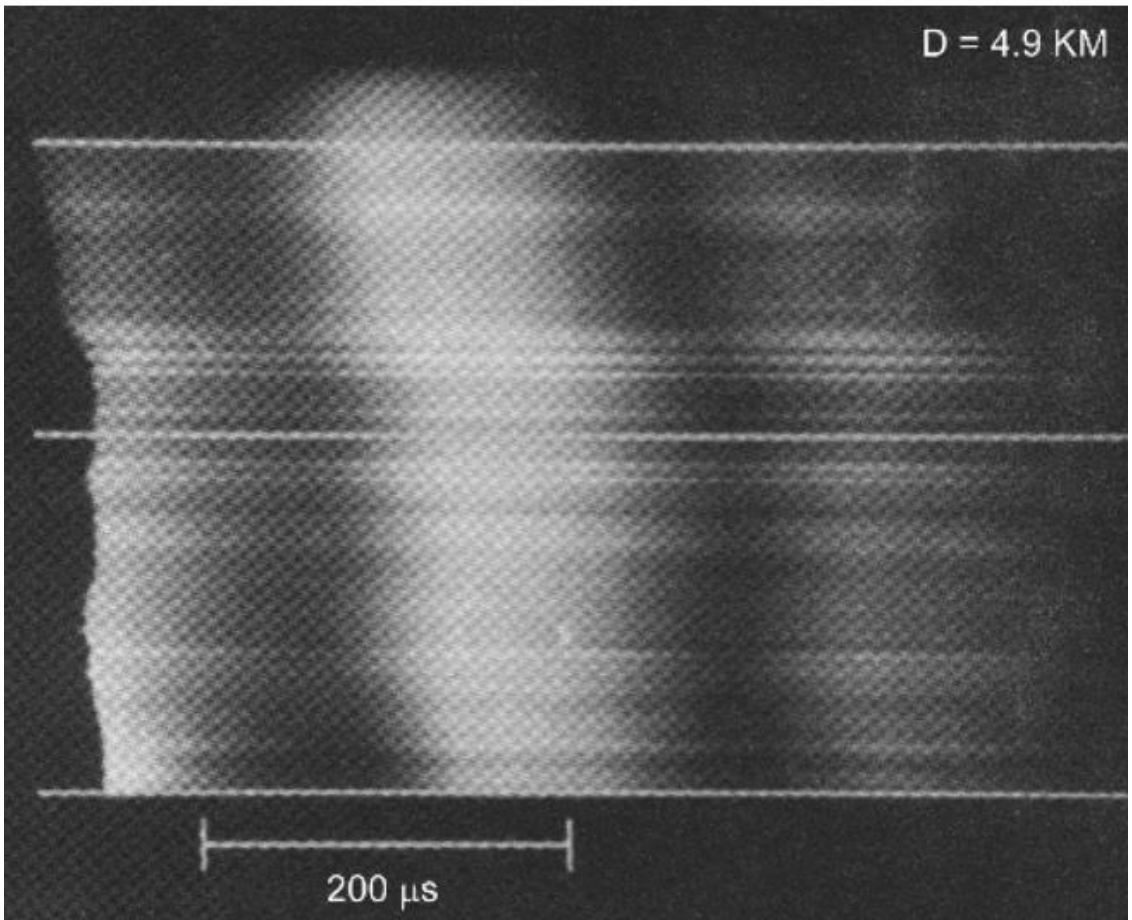

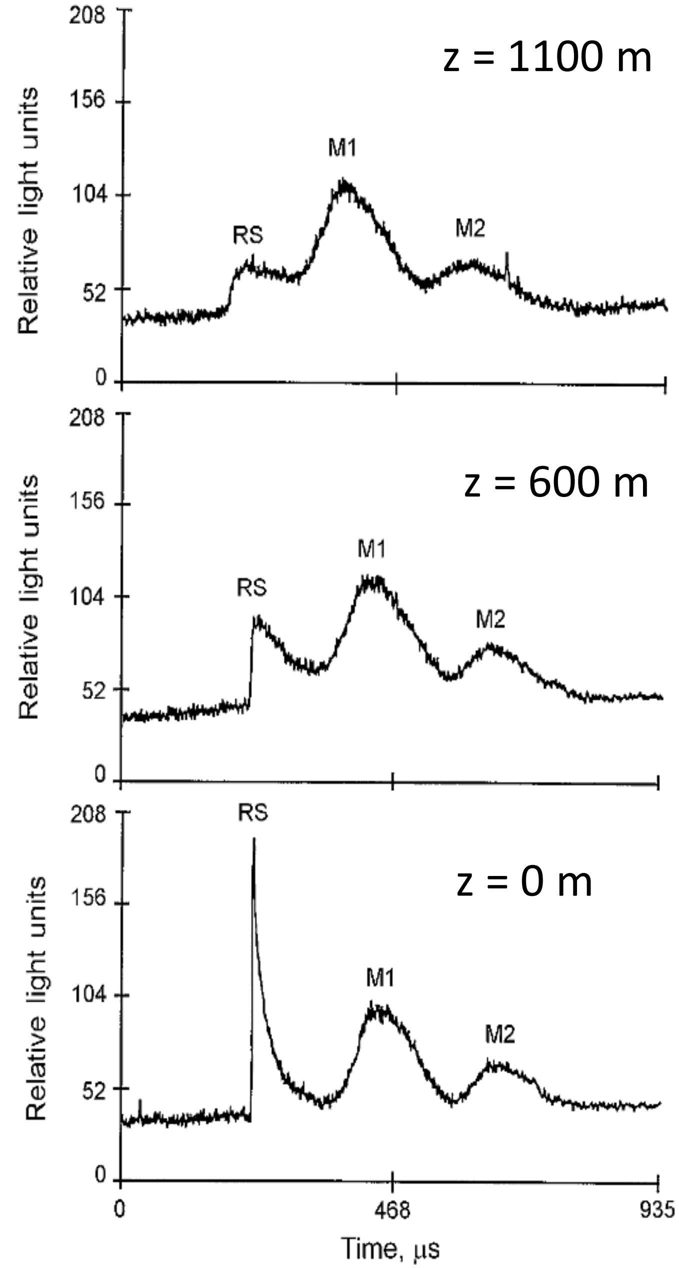

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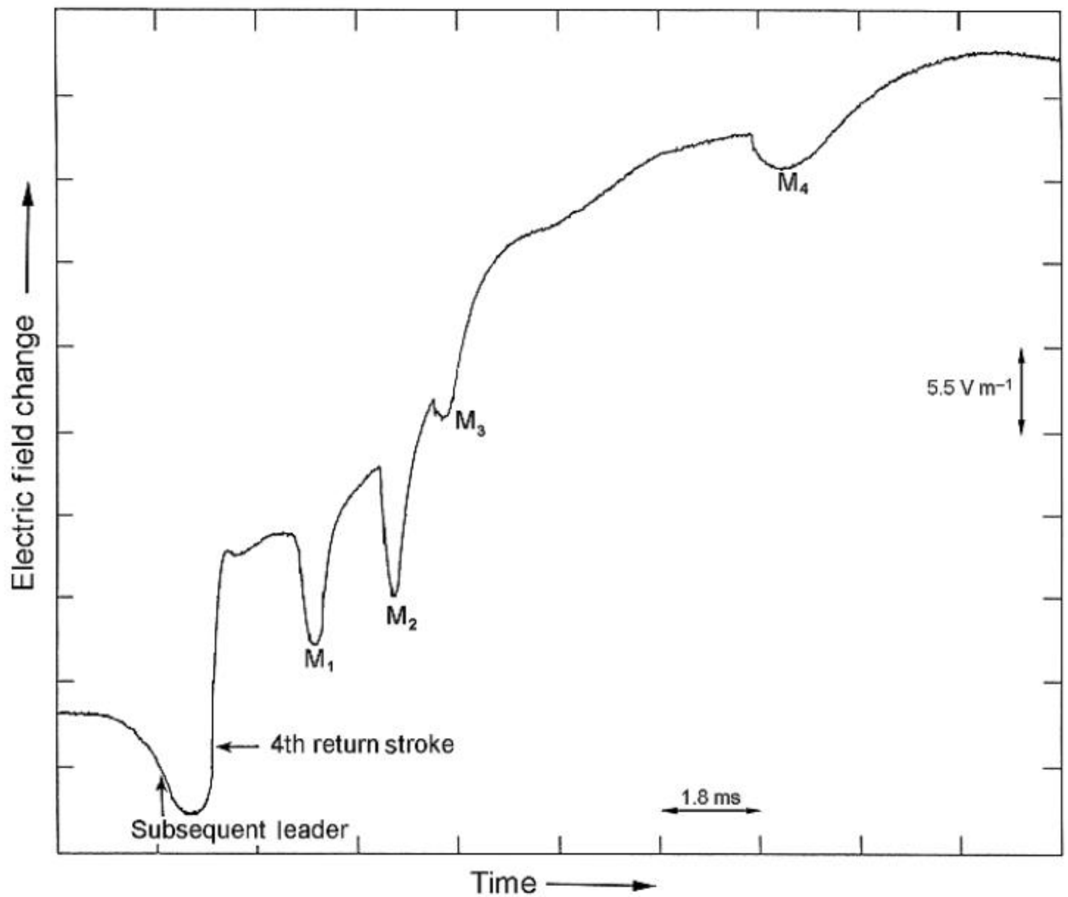
→ Characteristic hook-shaped ΔE waveform when τ_{sensor} ~ 1 ms.



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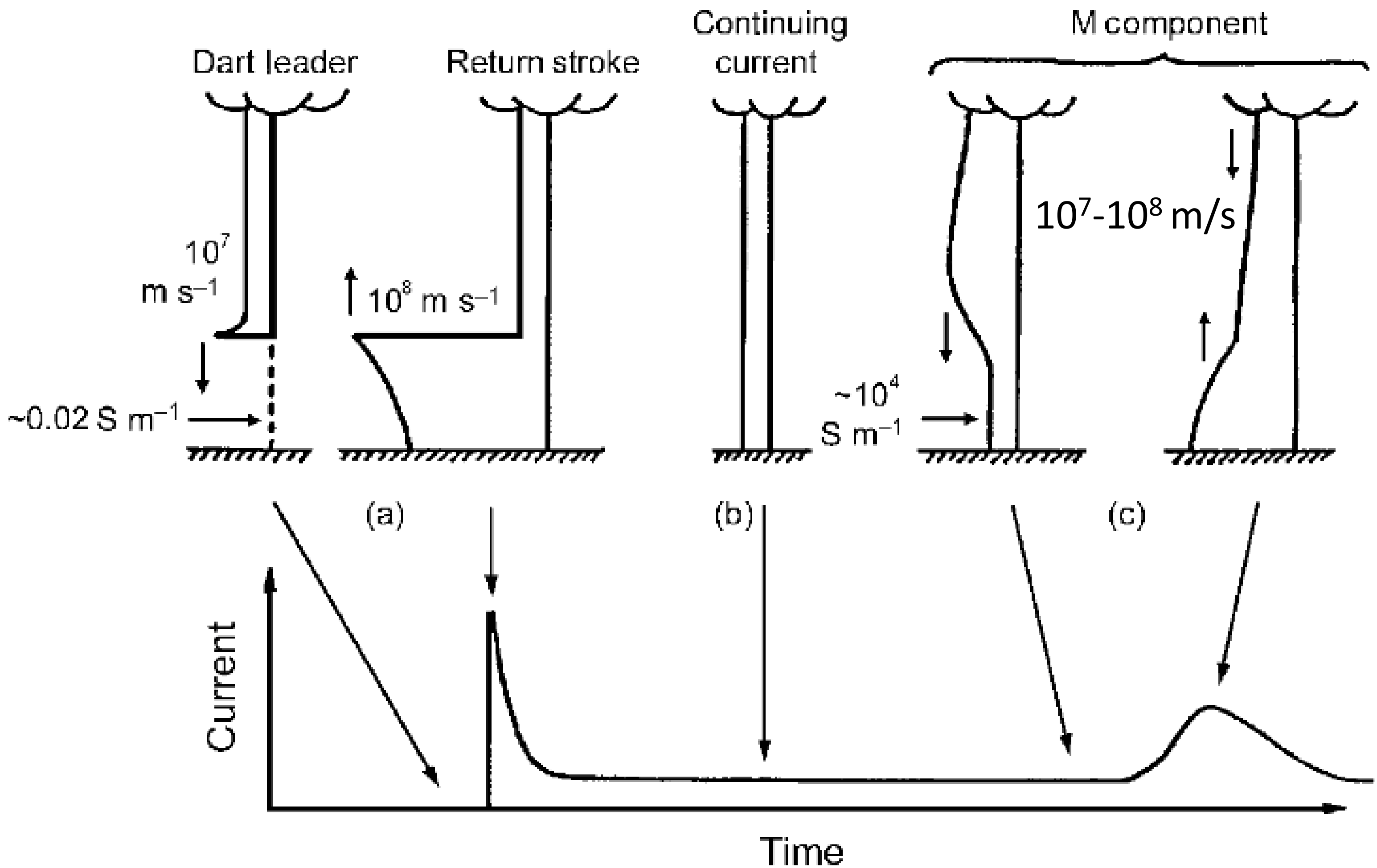
→ Luminosity perturbation.
→ Characteristic hook-shaped ΔE waveform when τ_{sensor} ~ 1 ms.
→ VHF-UHF imaging reveals fast (10^6-10^7 m/s) breakdown at upper extremities of conducting channel → previous RS deposited positive charge there (M-comps themselves not imaged).

4.9 M-components

→ Guided wave process → need current-carrying channel to ground.
→ Line charge density ~0 at ground, increases with height → $E_M(r) \sim \ln(kr^{-1})$



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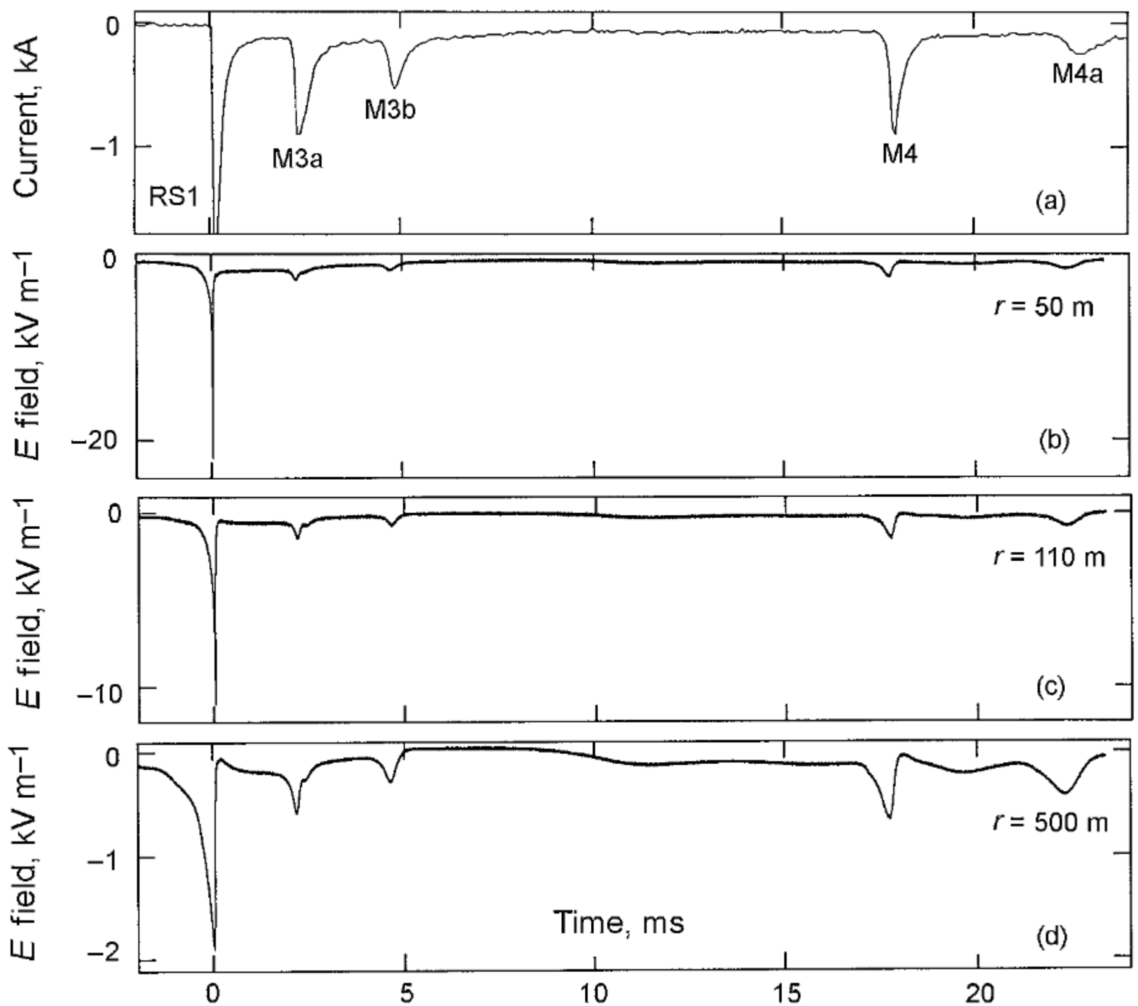

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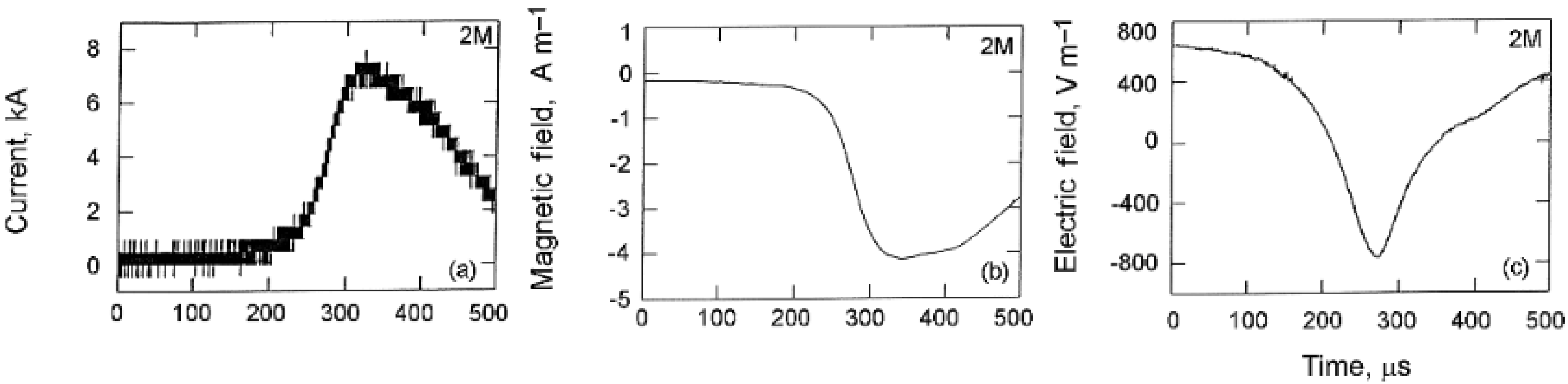
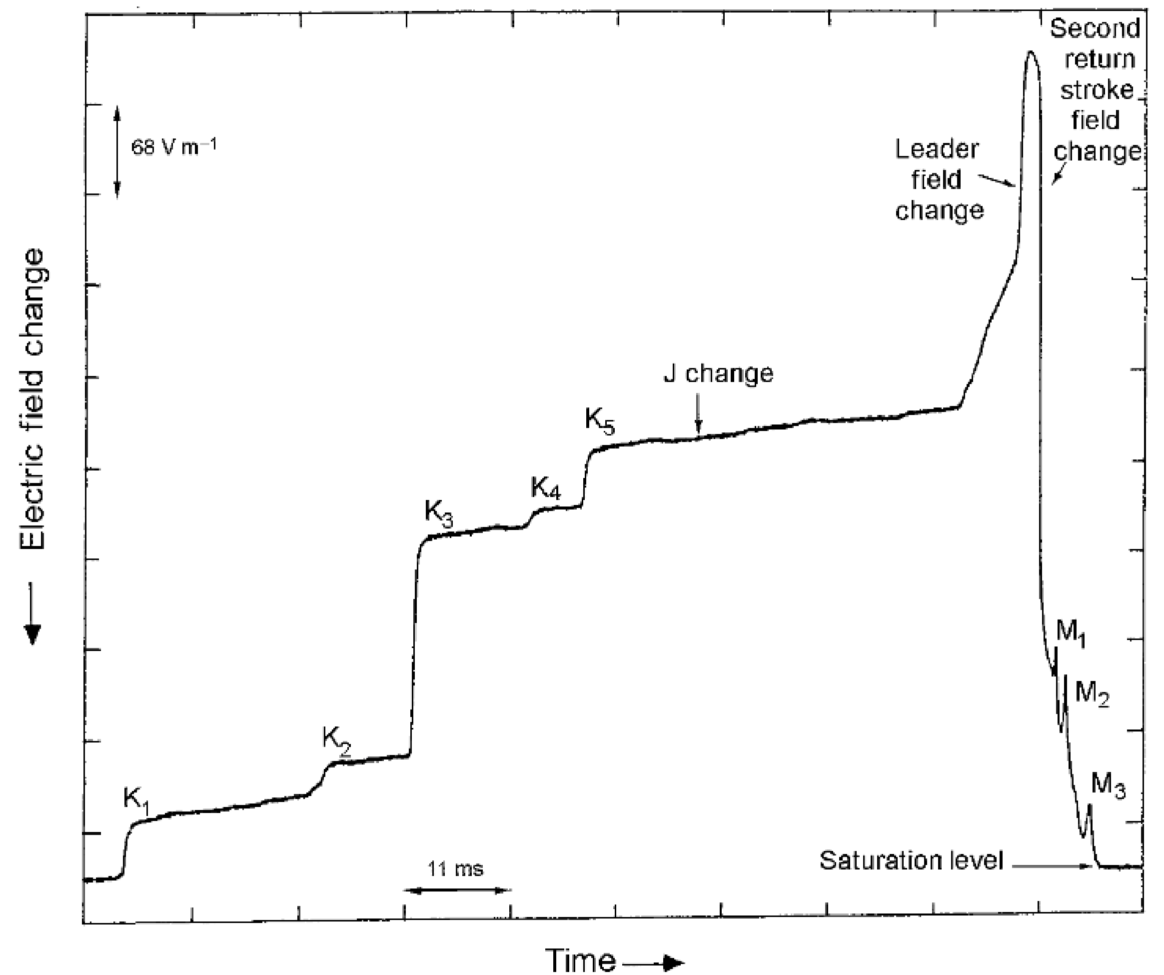
→ E_M/E_{RS} gets larger with distance ($E_{RS} \sim r^{-1}$)
→ Currents add during reflection → $B_M \sim I_{base}$
→ Charge densities subtract during reflection → $E_M \sim dI_{base}/dt$



4.10 J- and K-processes

- → J-process: steady E change, between strokes, 10s of milliseconds long, associated with in-cloud positive leader extension.
- → K-process: named after Kitagawa and Kobayashi (1977), step-like E change, ~1 ms long, superimposed on J-change, may occur when positive leader reaches concentrated negative charge; an unsuccessful dart leader.



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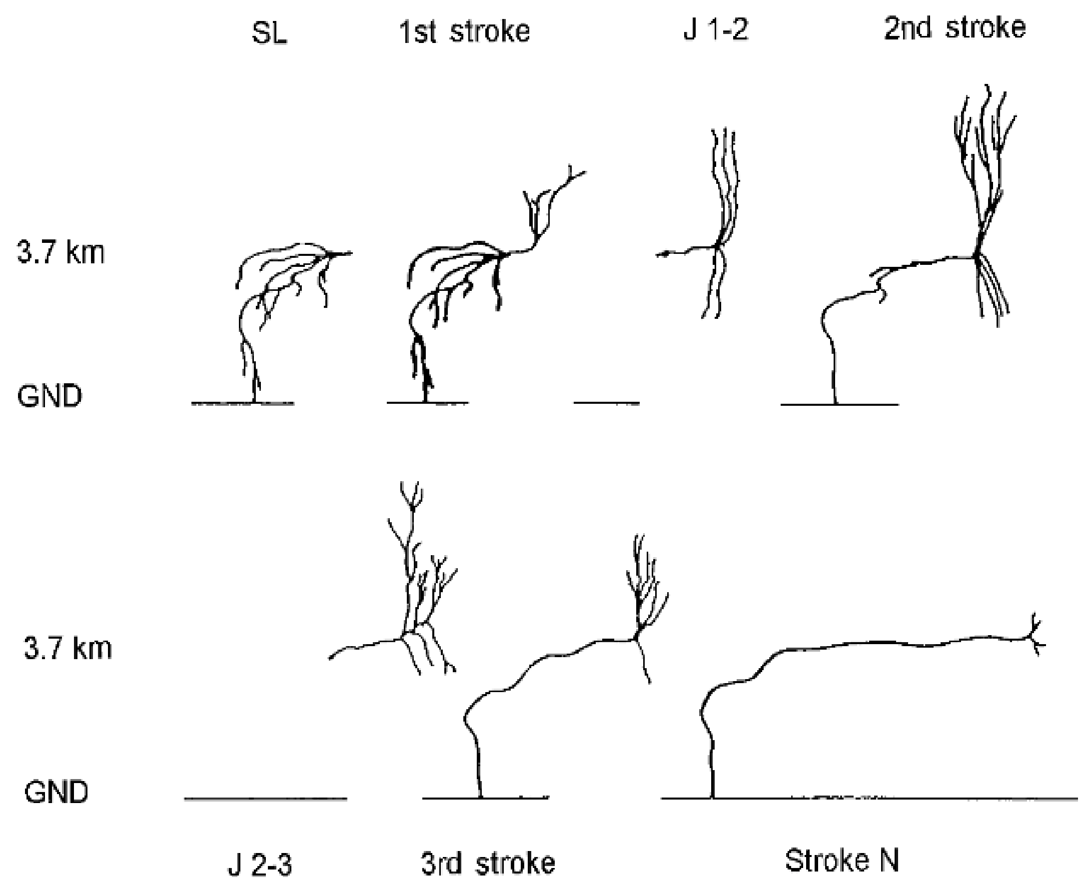

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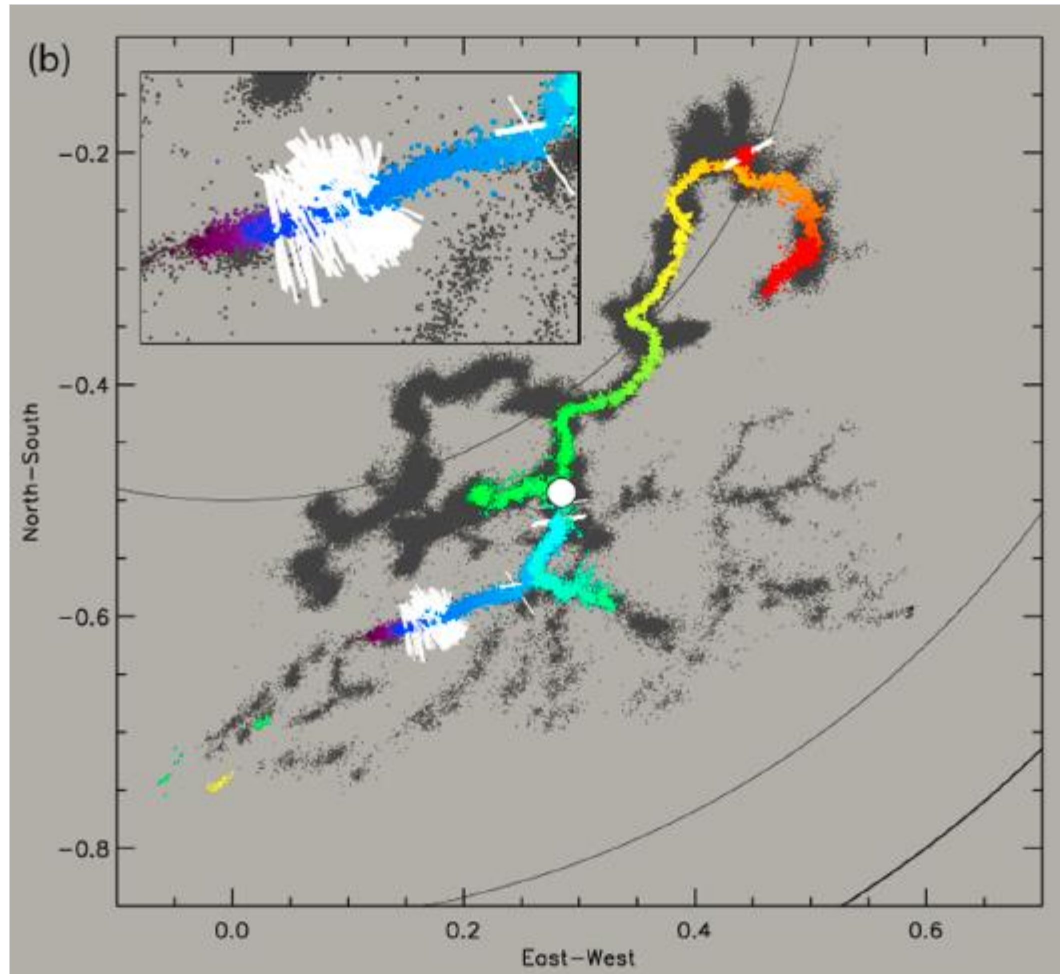
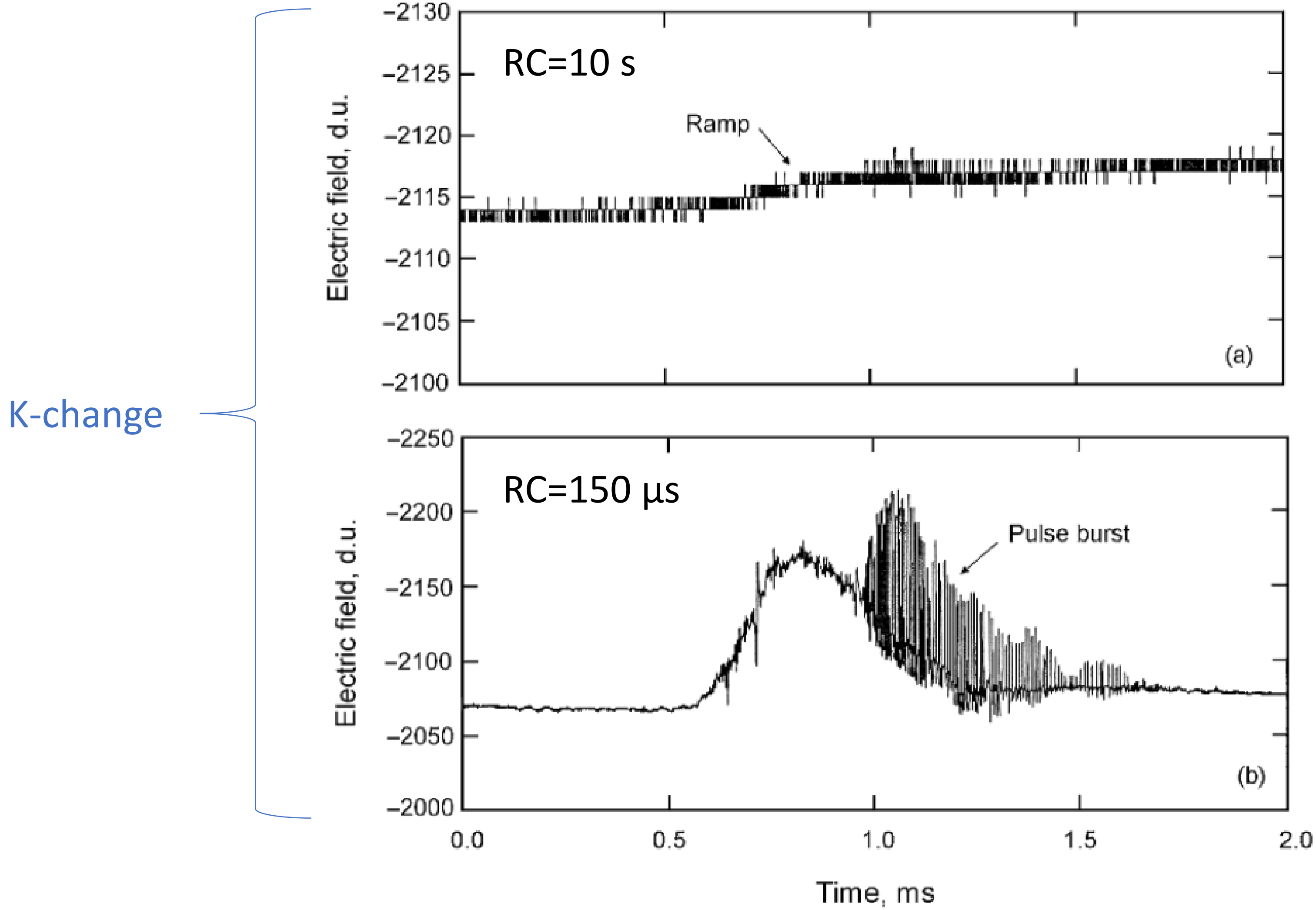


Shao et al., 2018

4.11 Regular pulse bursts

→ Microsecond-scale pulse train superimposed on K-change / M-component.



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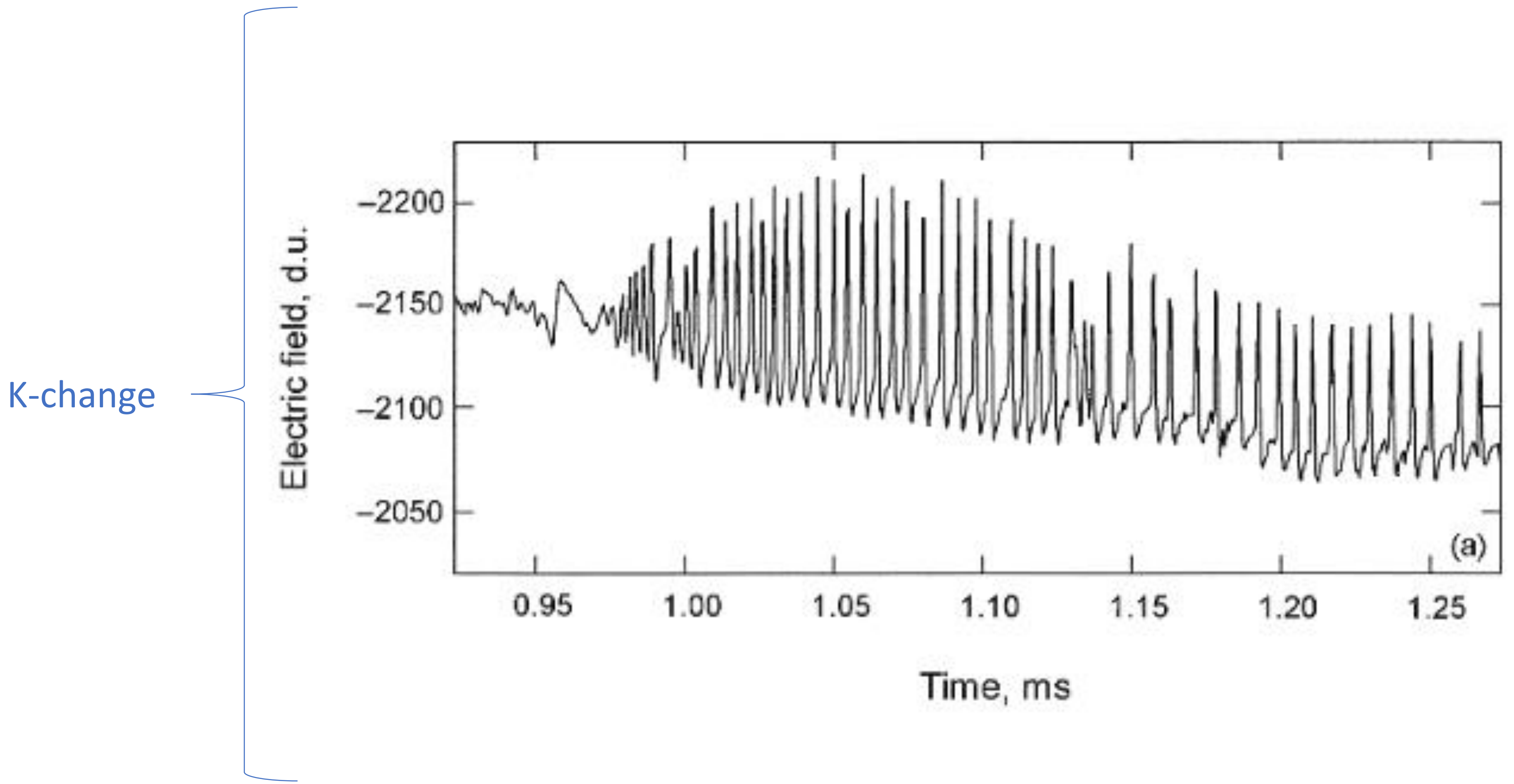

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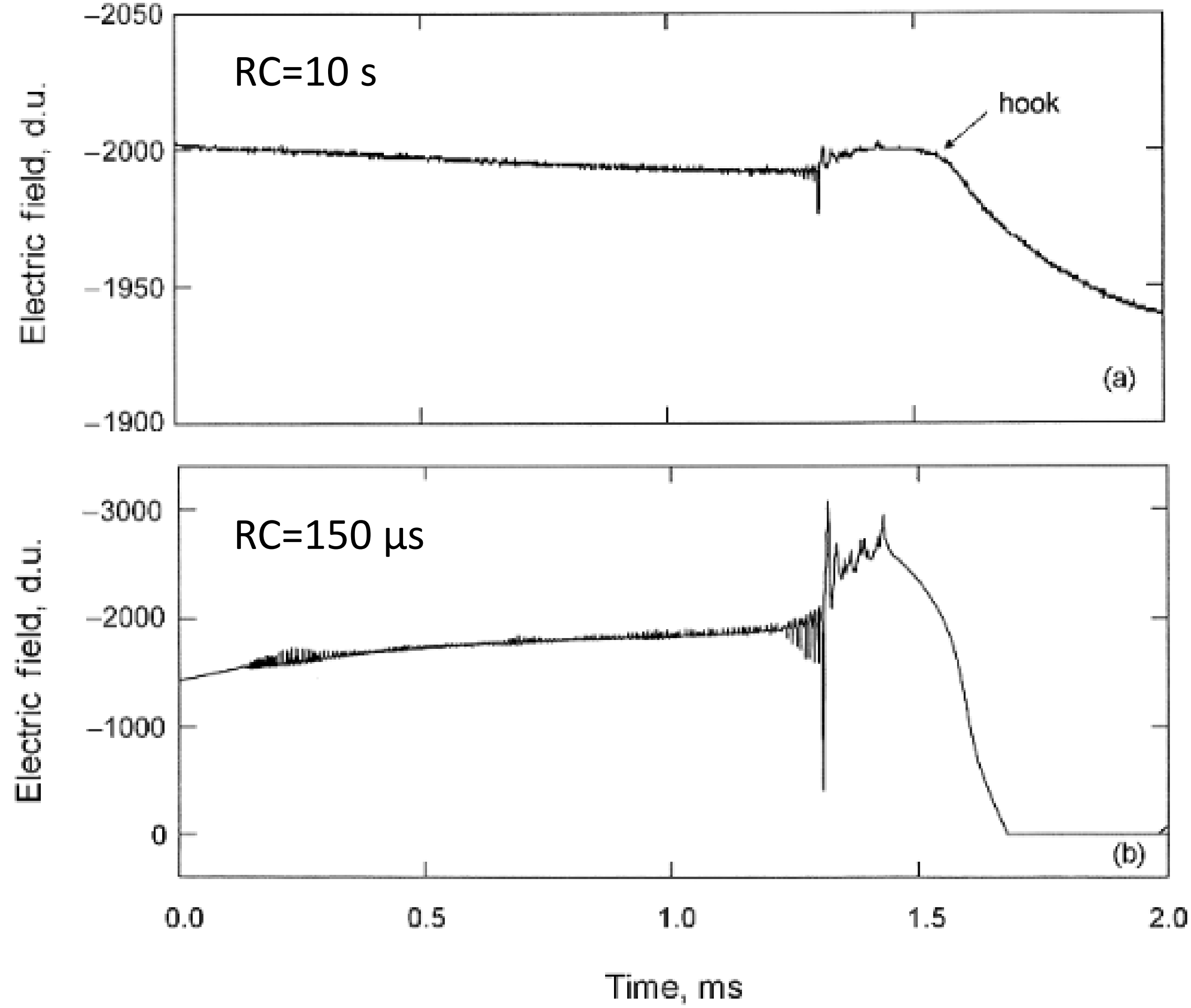
M-component



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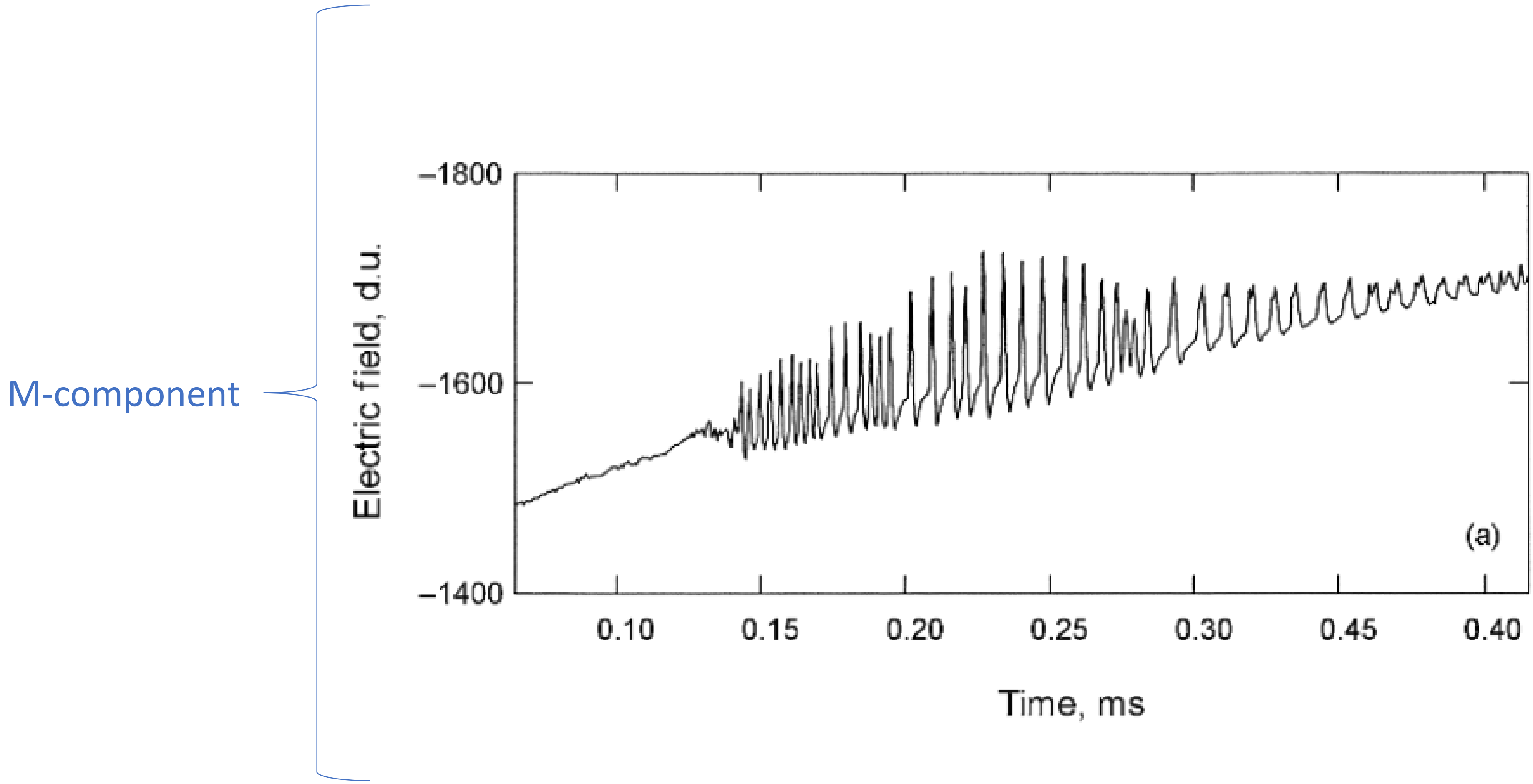

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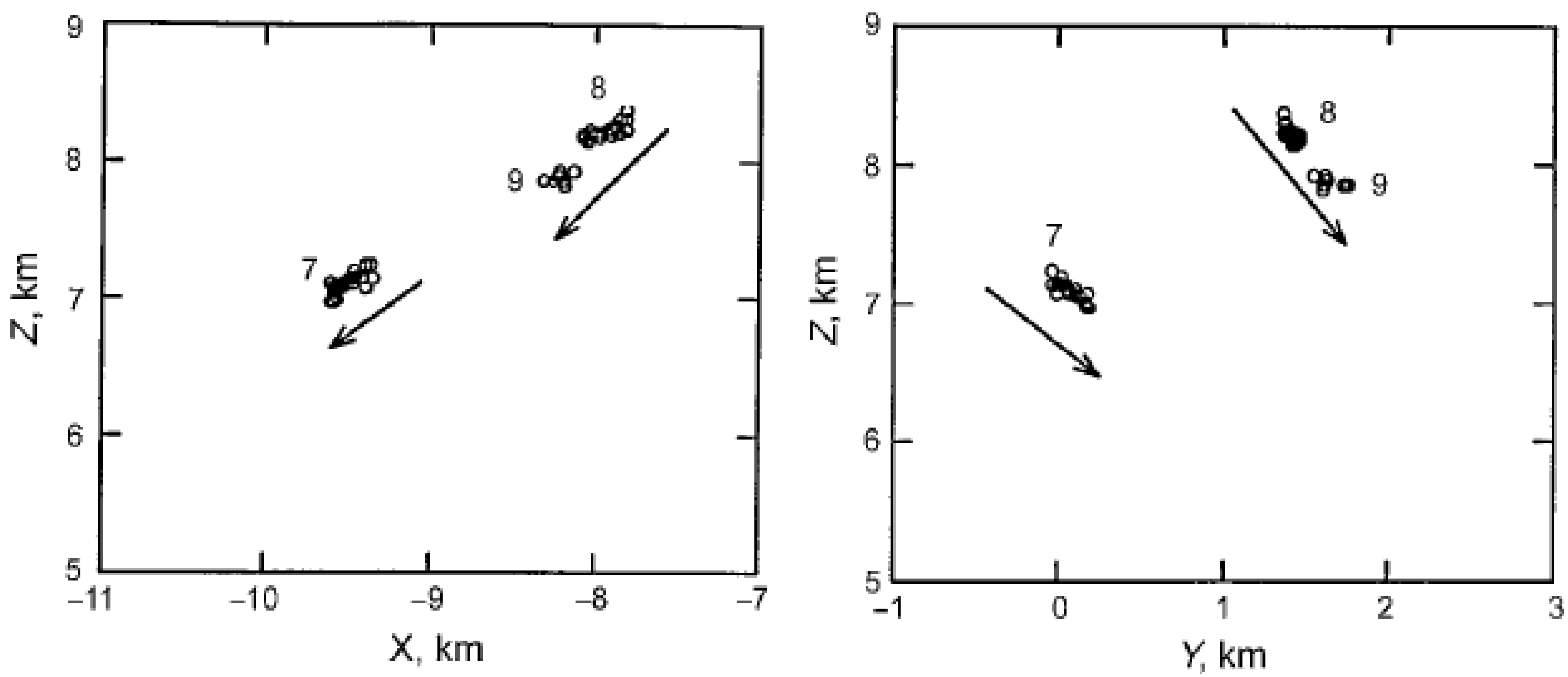
→ Microsecond-scale pulse train superimposed on K-change / M-component.
→ Similar to dart-stepped leader, with ~10^6 m/s.



4.12 Summary (of cloud-to-ground flashes)

→ 100s of milliseconds duration, 10s of Coulombs lowered to ground.
→ Flash initiated between charge regions in cloud.
→ Initial stepped leader: 2×10^5 m/s, 100-1000 A, ~1 μs step duration, 10s of meters step length, 20-50 μs inter-step interval, ≥1 kA /step.
→ Return strokes: $c/3$ to $c/2$, ~30 kA peak current reached in μs, heats channel to 30,000 K with channel pressure ≥10 atm.
→ Typically 3-5 strokes per flash (max 26 observed).
→ >80% flashes have >1 RS (after cessation current to ground).
→ Continuing current: 10s-100s of Amperes, up to 100 ms.
→ Dart leader: ~10^7 m/s, peak current ~1 A, deposits ~1 C.
→ ~50% have >1 termination point to ground (many kms between).
→ M-components: transient processes during continuing current.
→ Both J- and K-process serve to transport negative charge into existing/remnant channel.