Lightning Modeling Workshop
Albuquerque, NM, 1-3 April 2024

# Radio Frequency and Optical Emissions from Lightning

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Los Alamos NATIONAL LABORATORY

LA-UR-24-22788

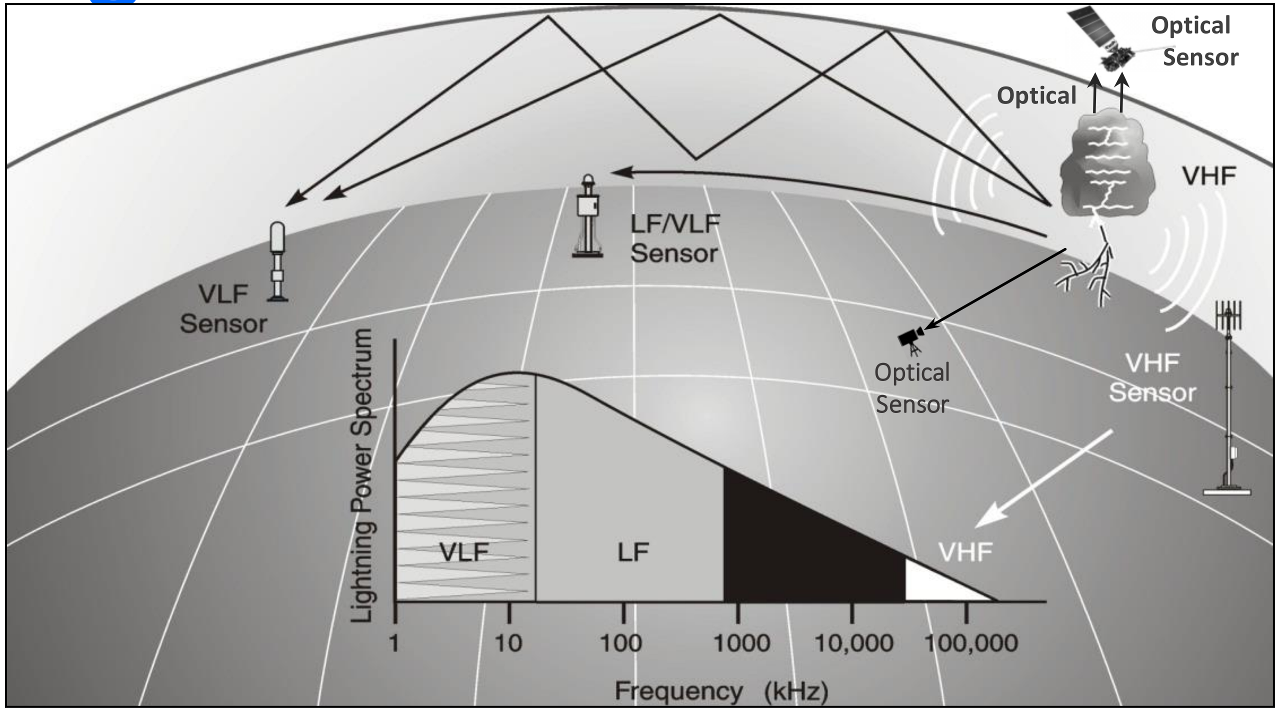
# Radio Frequency and Optical Emissions from Lightning

- Introduction/Overview of Lightning Emissions
- Ground and Space Based Measurements
- Modeling Techniques for Return Strokes and other EMPs
- Summary

# Lightning Electromagnetic Emissions

- Cloud and cloud-to-ground flashes may have durations of a second or more and individual processes within a particular flash may last from a few hundred milliseconds to a few microseconds or less.

- These processes produce electromagnetic signatures in the range from a few hertz (long continuing currents) to $10^{20}$ Hz (hard x-rays) [Rakov, 2008].




| Frequency Range | Wavelength Range | Discharge Processes | Mode of Signal Propagation |
|---|---|---|---|
| VLF | 10 – 100 km | CG return strokes, large amplitude cloud pulses including PB and CIDs | Ground wave and earth-ionosphere waveguide (affected by dispersion due to finite soil conductivity and characteristics of ionosphere) |
| LF and MF | 0.1 – 10 km | CG leader steps, CG return strokes, M-components, cloud pulses including PB, CIDs, and K-changes | |
| HF | 10 – 100 m | Various in-cloud and leader processes | Line of sight (affected by blockage due to presence of objects in line of sight), trans-ionospheric |
| VHF | 1 – 10 m | Breakdown of "virgin air" during channel formation, streamer-dominated processes, dart leaders, and K-changes | |
| Optical (Far UV to Near IR) | $10^{-7}$ – $10^{-6}$ m | Hot current-carrying channels, streamer-based processes | Line of sight (affected by scattering in clouds), trans-ionospheric |

# Lightning Geolocation Techniques

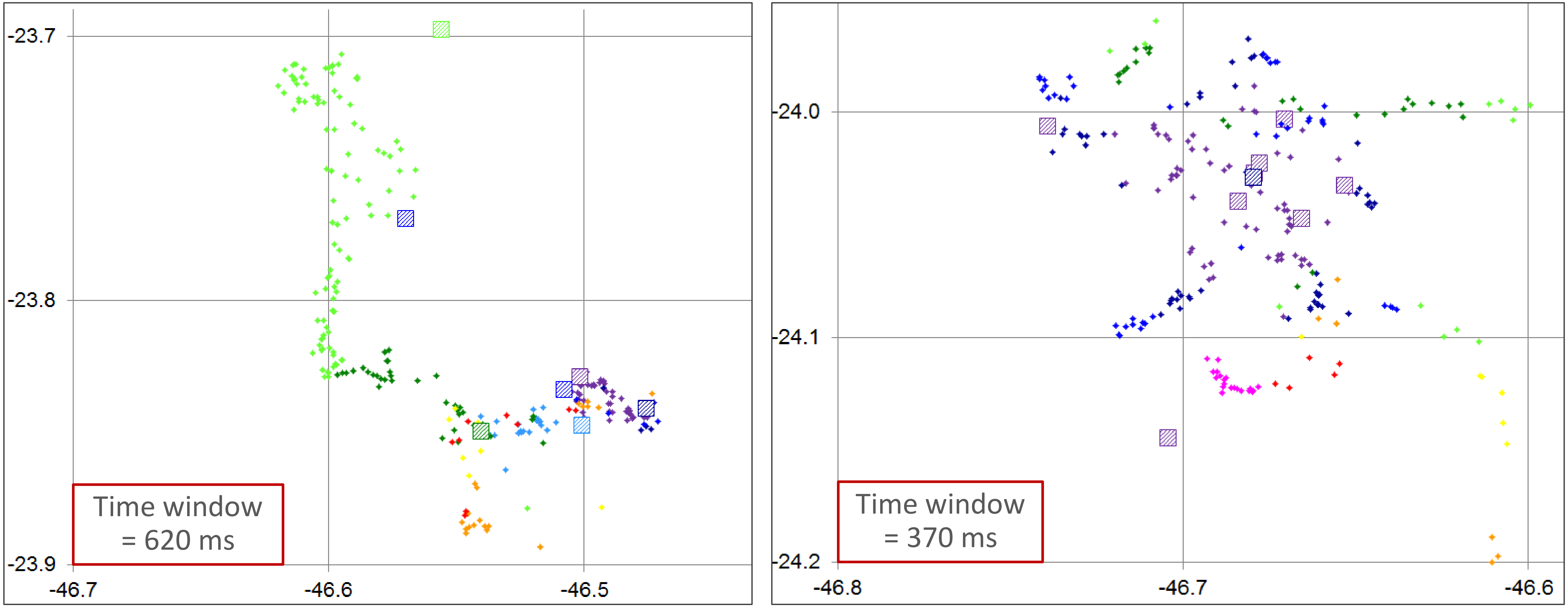
- **Ground Based LLSs**
    - Typically, a network of a minimum of 4 to 5 sensors and a central processor.
    - Each sensor, operating in a part of the ELF to VHF range, measures the EM signal produced by a lightning process (or event) and sends back key information to the central processor.
    - In the central processor, information from multiple sensors about the same lightning event along with one or more techniques can be used to geolocate the lightning event.

      Time of arrival (TOA)
      - Dispersion correction for long range LLSs

      Direction Finding (DF)
      - Magnetic Direction Finding (MDF)
      - Interferometry (ITF)

- **Space Based LLSs**
    - Modern satellite-based LLSs use CCD-array-based optical imagers on board low earth orbiting satellites [e.g. Boccippio et al., 2002].
    - Non-interferometric VHF direction-finding systems [e.g. Jacobson et al., 2011] or broadband VHF interferometry in combination with optical imaging [Morimoto et al., 2011] on board low-earth orbiting satellites have also been used.
    - Geostationary satellite-based LLS on-board the GOES-R (Geostationary Lightning Mapper, GLM) provides data over roughly the western hemisphere.

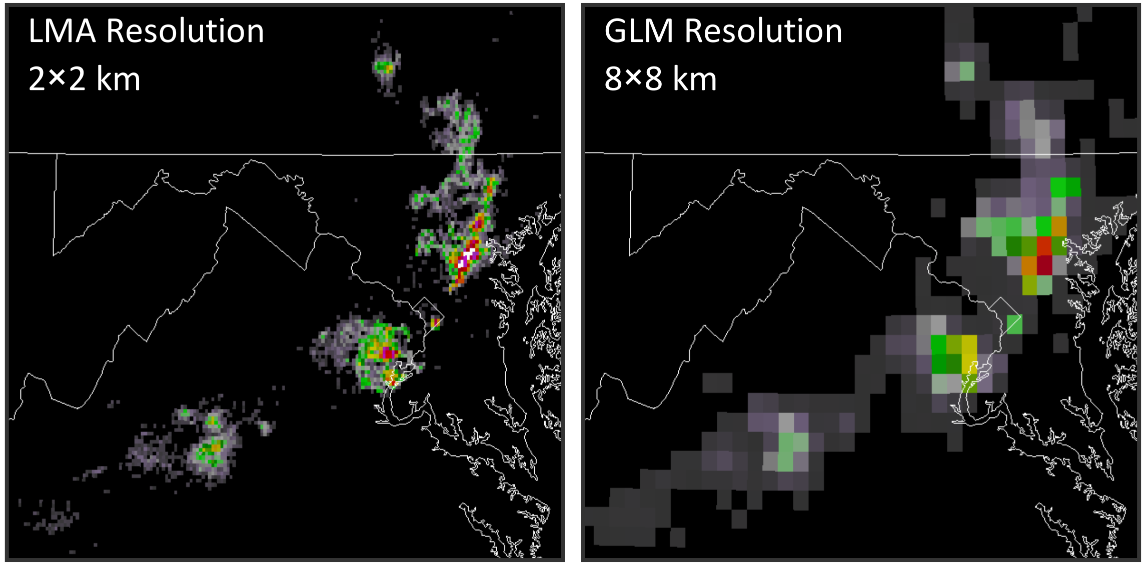
# Lightning Geolocation at LF and VHF



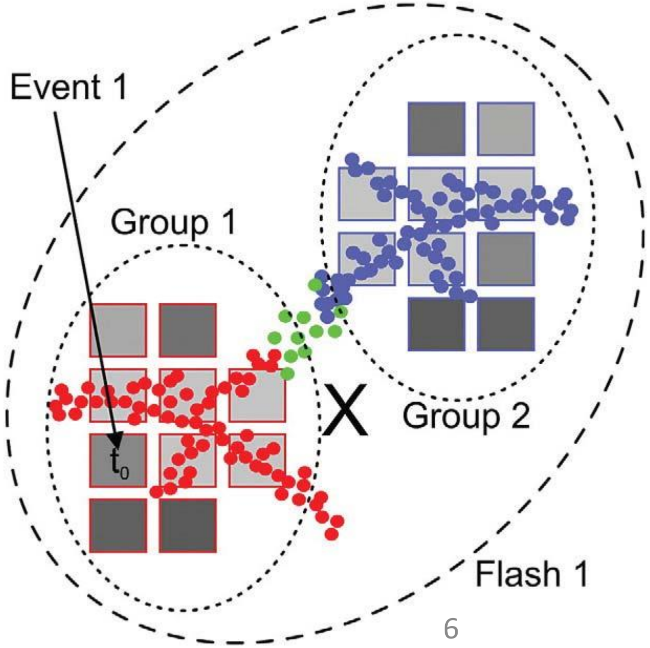

Lat, lon plots of two flashes
(VHF = small dots, LF IC = squares, color = time, with purple at start, red/pink at end)

# Space-based Lightning Detection

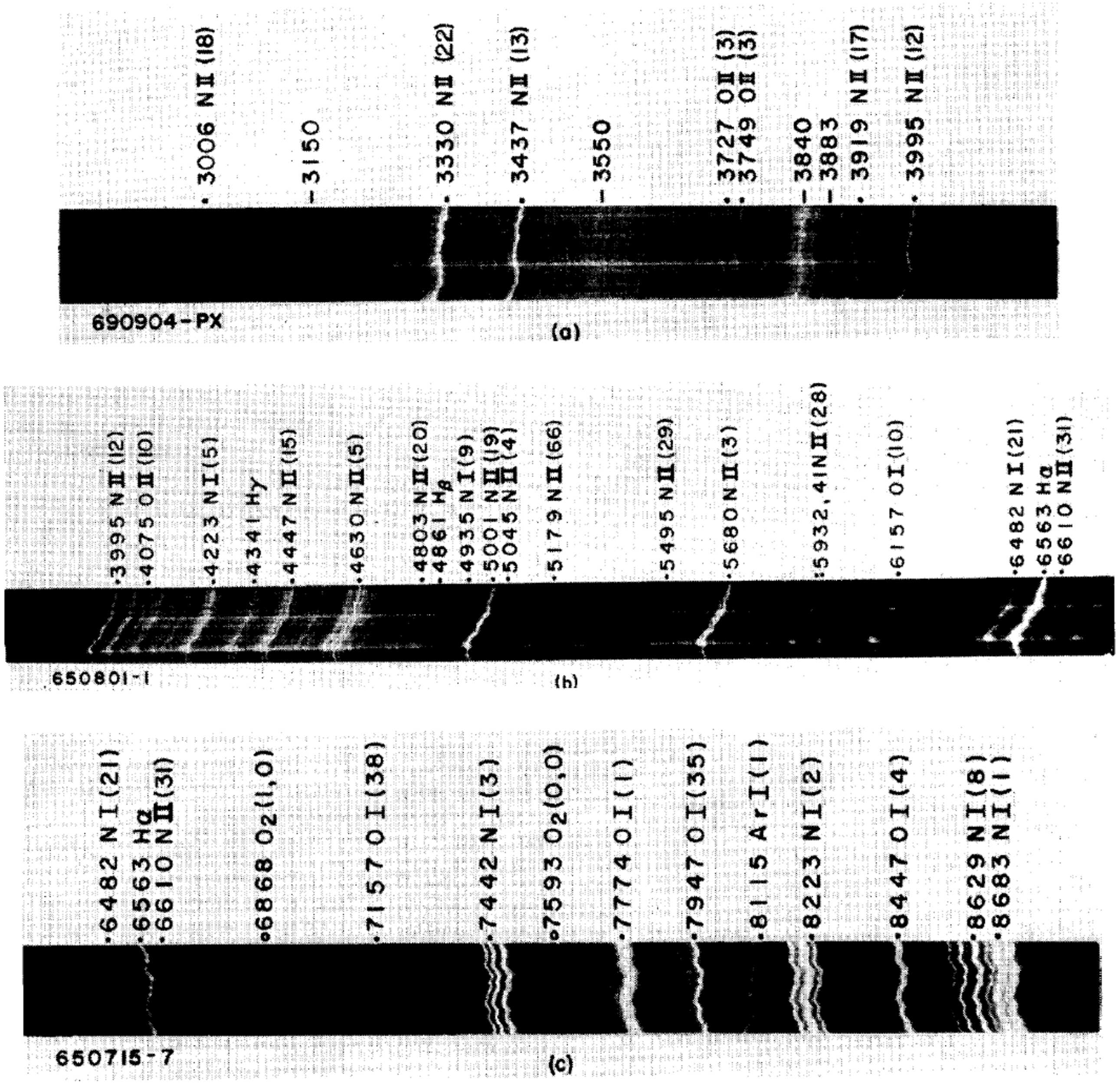

GOES-R Geostationary Lightning Mapper (GLM)



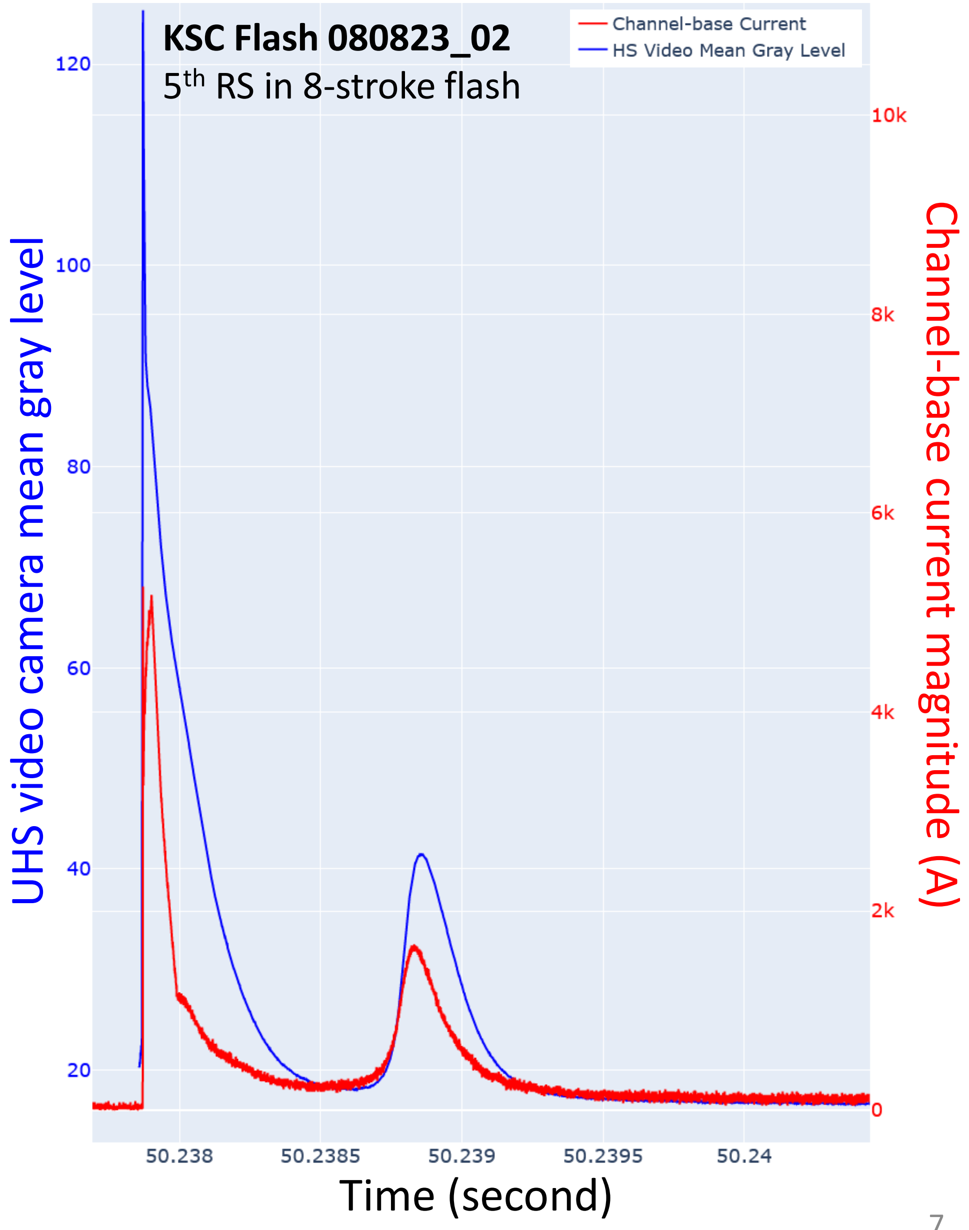

Goodman et al., 2013 and Goodman (personal communication)



# Lightning Optical Emissions




Taken from Krider (1973), Orville and Salanave (1970).




Adapted from Mark et al. (2024).

# Lightning Optical Emissions

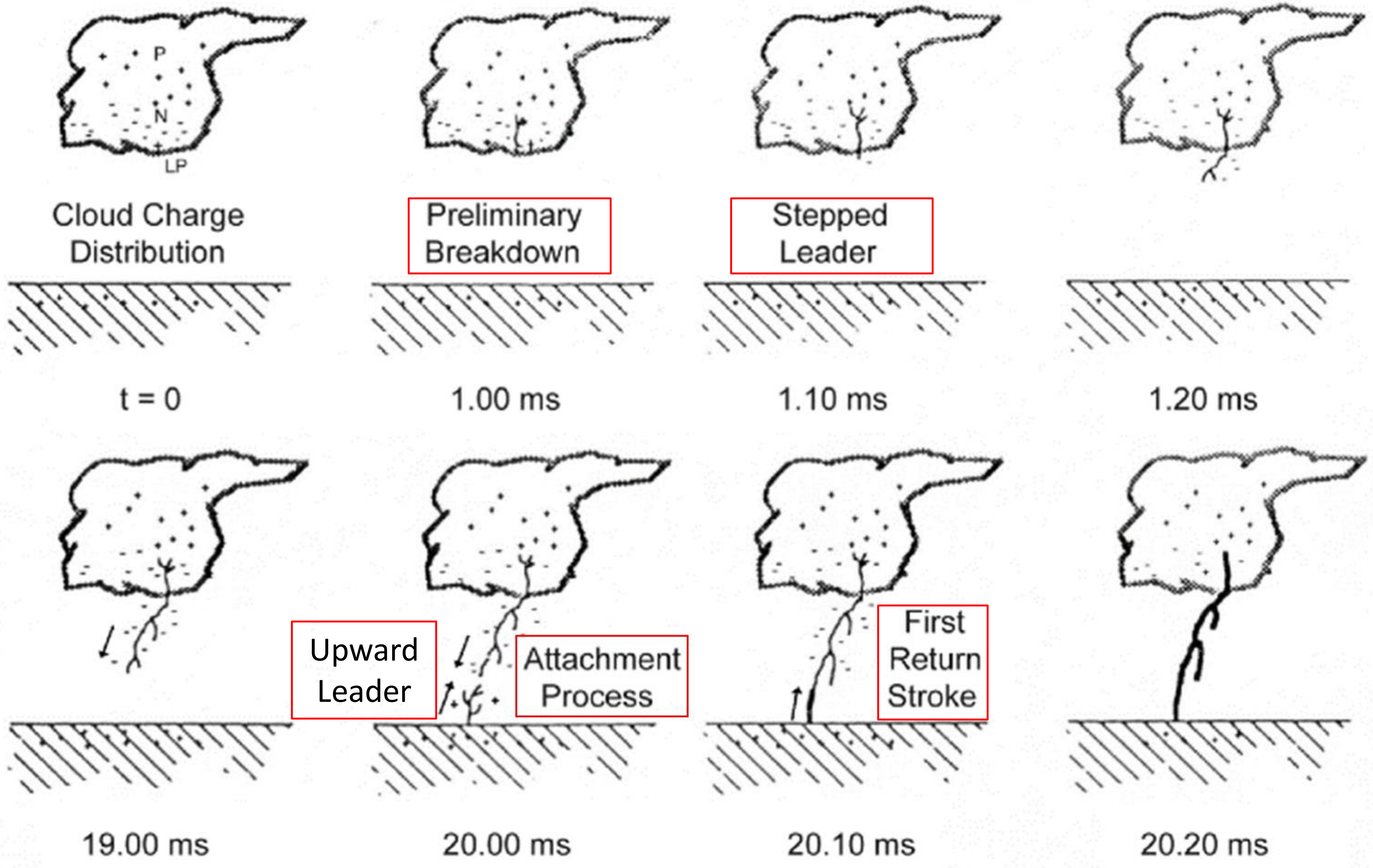
## Summary of characteristics for return stroke channel-segments

- The risetime and peak of an irradiance waveform in the 0.4-1 μm range are determined primarily by the RS current and by the geometrical growth and total length of channel (Quick and Krider, 2017).
- Current and optical irradiance agree well up to initial peak after which the irradiance decays faster than the current and then plateaus.
- Average and peak optical power per unit length are proportional to the square of the channel base peak current.
- The initial optical radiation during return strokes is likely dominated by ionized atomic species radiated at higher temperatures (NII lines between 450 and 600 nm) while the later optical radiation is likely due to neutral atomic species radiated at lower temperatures (e.g., H-alpha at 656.3 nm, OI at 715.7 nm and 777.4 nm, and the NI at 744.4 nm).

## Summary of observations for cloud lightning

- Apart from lightning observations centered around the dominant 777.4 nm wavelength above and below thunderclouds, observations at the 337 nm wavelength have also been performed.
- Emissions in the 337 nm range (called BLUEs) have been associated with transient corona discharges and streamer-based emissions from lightning processes such as compact intracloud discharges or narrow bipolar events (CIDs/NBEs).
- For corona discharges, an average global nighttime occurrence rate of 11 per/second was reported.

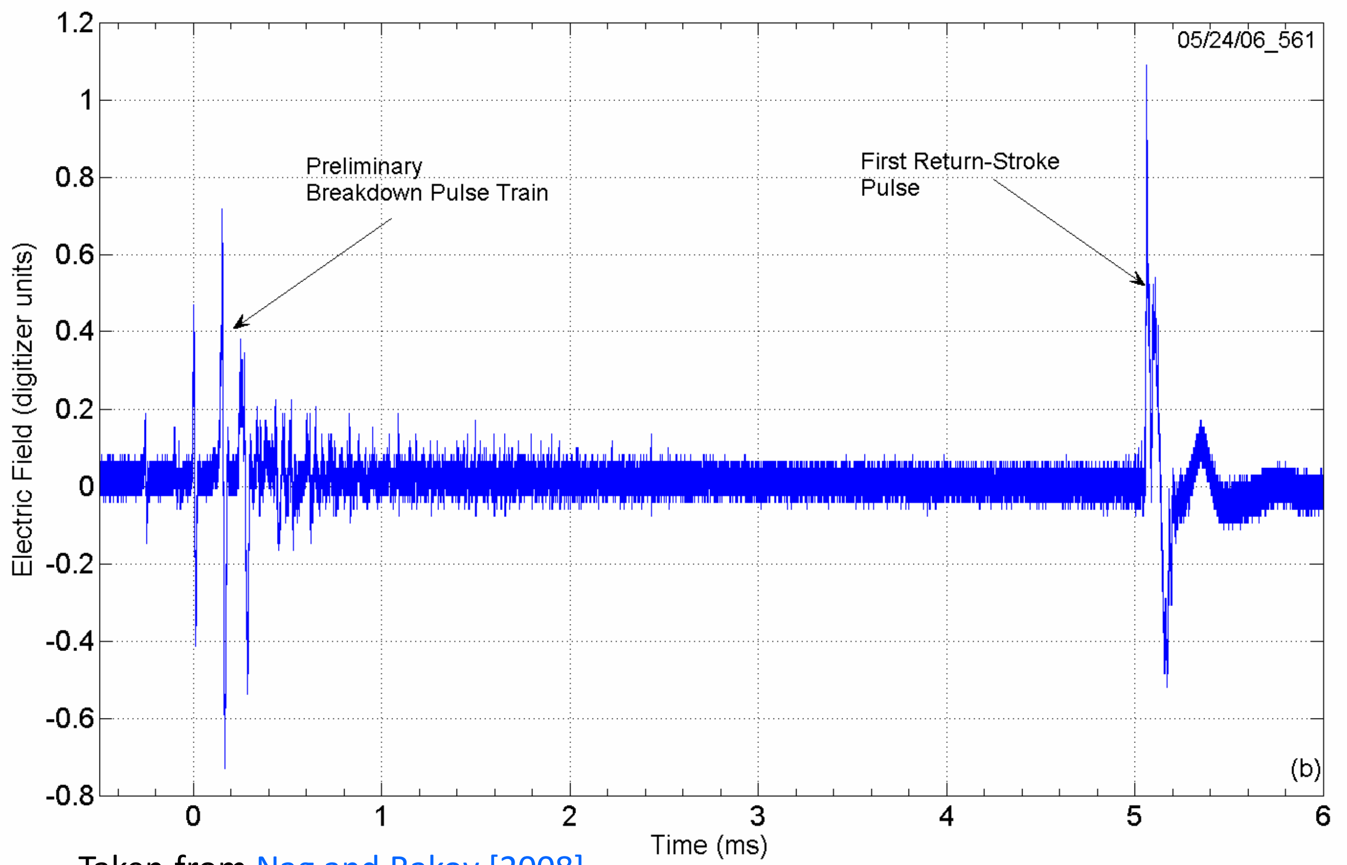
# CG Lightning Processes






Adapted from Uman [1987]

# Preliminary Breakdown




Taken from Nag and Rakov [2008].

- The overall negative cloud-to-ground (CG) lightning discharge consists of typically three to five component strokes. Each stroke is composed of a downward-moving leader and an upward-moving return stroke (RS). [Rakov and Uman, 2003]

- Leader initiating the first stroke in a flash is stepped and is preceded by the initial or preliminary breakdown (PB).

- Thus, a stepped leader is preceded (initiated) by PB (not always detectable) and followed by first RS.

# Return Stroke (RS) Modeling Techniques

- **Gas dynamic models** – Track the radial evolution of short segment of lightning channel and associated shock wave by solving gas dynamic/hydrodynamic equations.

- **Electromagnetic models** – Lightning channel approximated as a lossy thin-wire antenna and Maxwell's equations solved to find current distribution along channel from which remote electromagnetic fields can be computed.
  - **Distributed circuit models** – Lightning discharge represented as a transient process on an R-L-C transmission line to determine current as a function of height and time from which remote electromagnetic fields can be computed.
  - **Engineering models** – Lightning current or line charge density distribution as a function of height and time is specified based on measured/observed RS channel base current measurements, RS front propagation speed along channel, and channel luminosity profile. Emphasis is placed on obtaining good match between computed electromagnetic fields (derived from Maxwell's equations) and measured fields at different distances.

# Return Stroke (RS) Modeling Techniques

## Calculating electromagnetic fields from currents

Specify longitudinal channel current, *i(z, t)*, based on lightning channel representation (e.g., as a transmission line) or from observations

Calculate fields from the magnetic vector potential for a vertical dipole with a time-varying source and Lorenz gauge over perfectly conducting ground.

Perform spatial integration for a vertical lightning channel with specified current velocity and channel length to obtain fields on surface of perfectly conducting ground.

Computed fields which can be compared to measured fields at different distances

Revise input parameters

Revise input parameters

## Calculating currents from measured electromagnetic fields

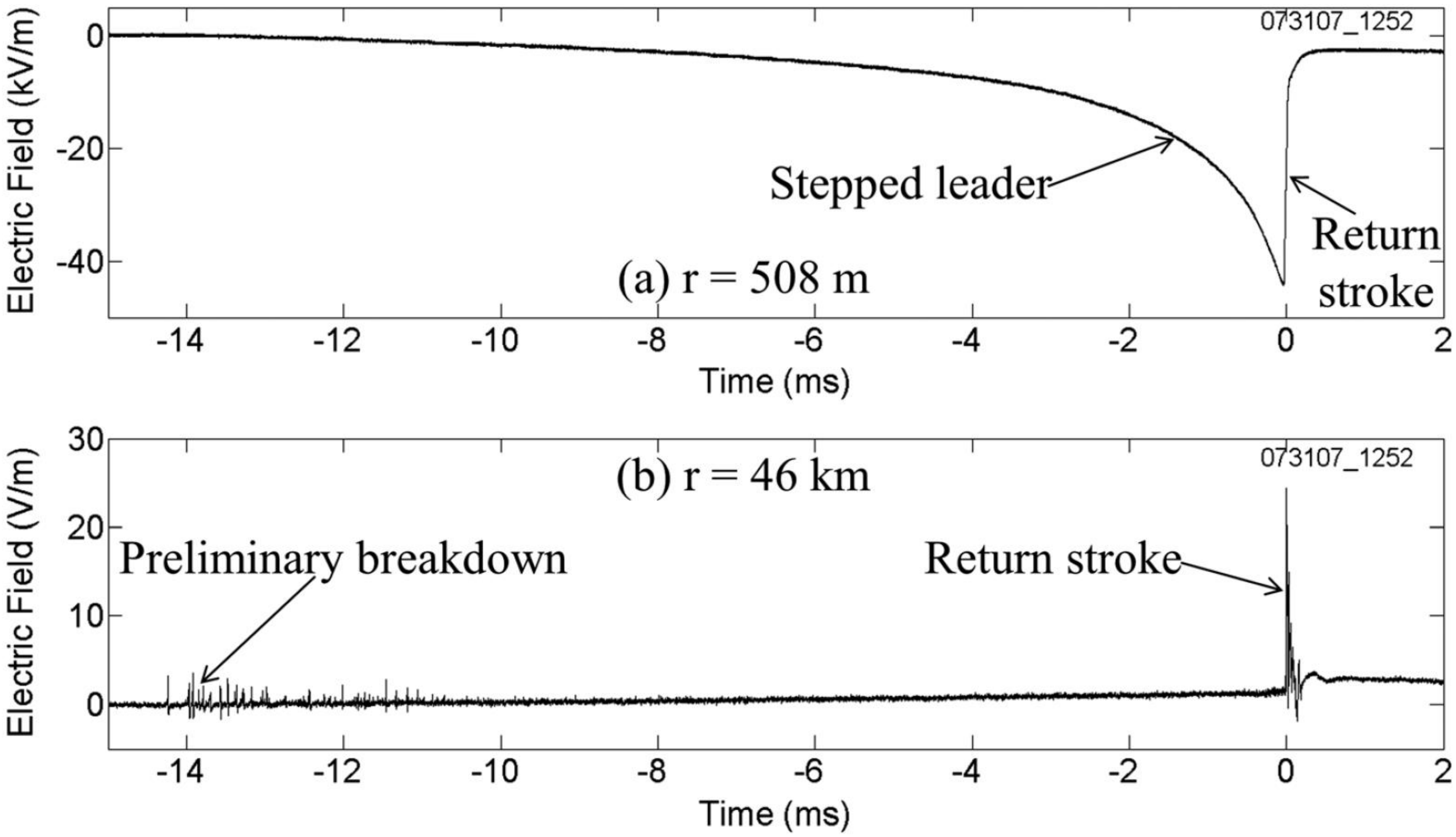
Relate *i(z, t)* to current at the lightning channel base, *i(0, t-z/v)*

Solve for current in equation relating magnetic field at measurement point to temporally retarded current at various heights

Computed current from measured field (simple relationship for measured radiation fields).

So-called “Transmission Line (TL)” model (e.g., Uman and McLain, 1969)

# Measured Leader-RS Field Changes and EMPs




Electric field waveforms of the first stroke of a negative cloud-to-ground flash shown on a 17-ms time scale, measured at distances of (a) 508 m (near station) and (b) 46 km (far station) in Florida. National Lightning Detection Network-reported return stroke peak current is 41 kA.

# Modeling of Leader EMPs and Field Changes

## Unified engineering model of the first stroke in downward negative lightning

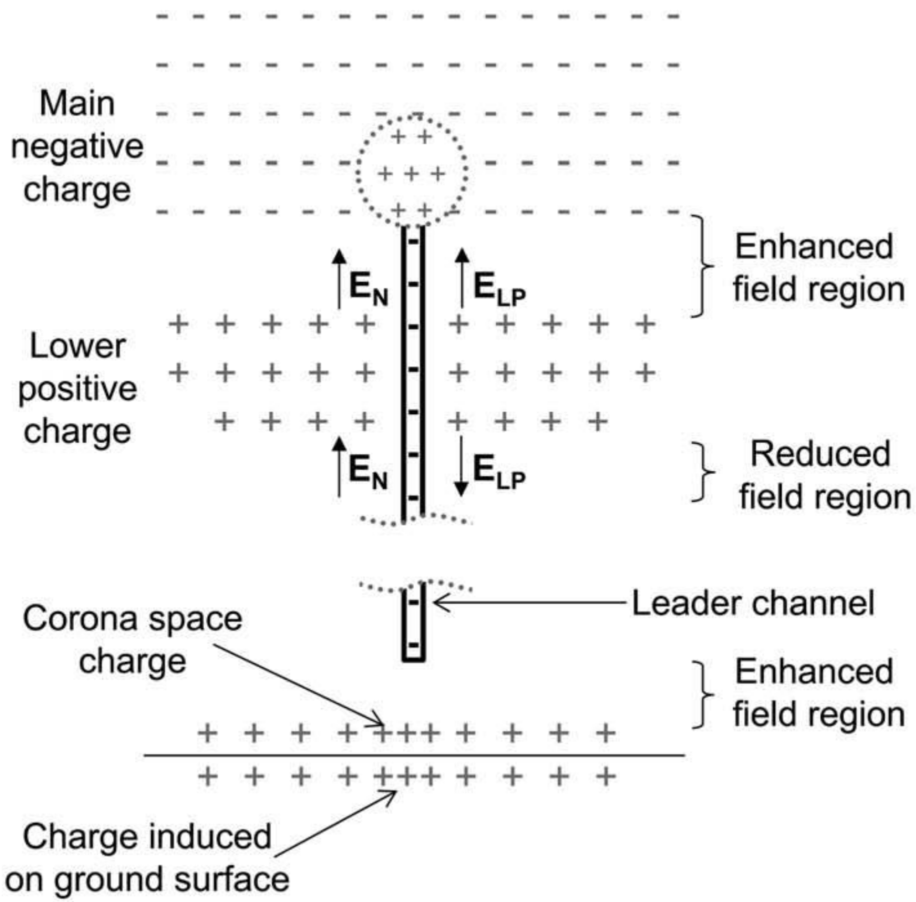
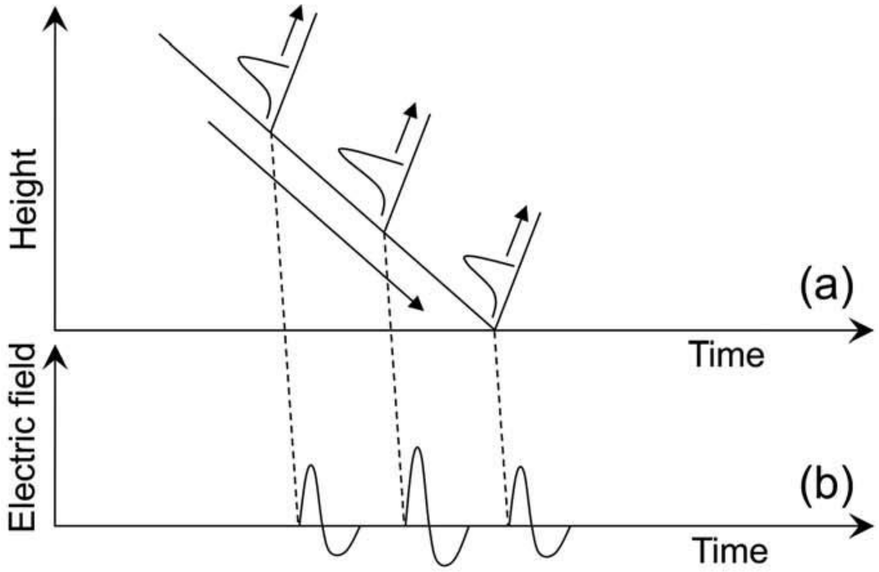



Illustration (not to scale) of electric field enhancement and reduction effects of the lower positive charge region below the main negative charge region. The main positive charge region is not shown.




Schematic representation of stepping process in negative ground flashes.

(a) Each current pulse originates at the tip of downward extending channel and propagates upward (positively sloped arrows).

(b) (b) A sketch of expected electric field record of resultant pulse train.

Adapted from Nag and Rakov (2016).

# Modeling of Leader EMPs and Field Changes

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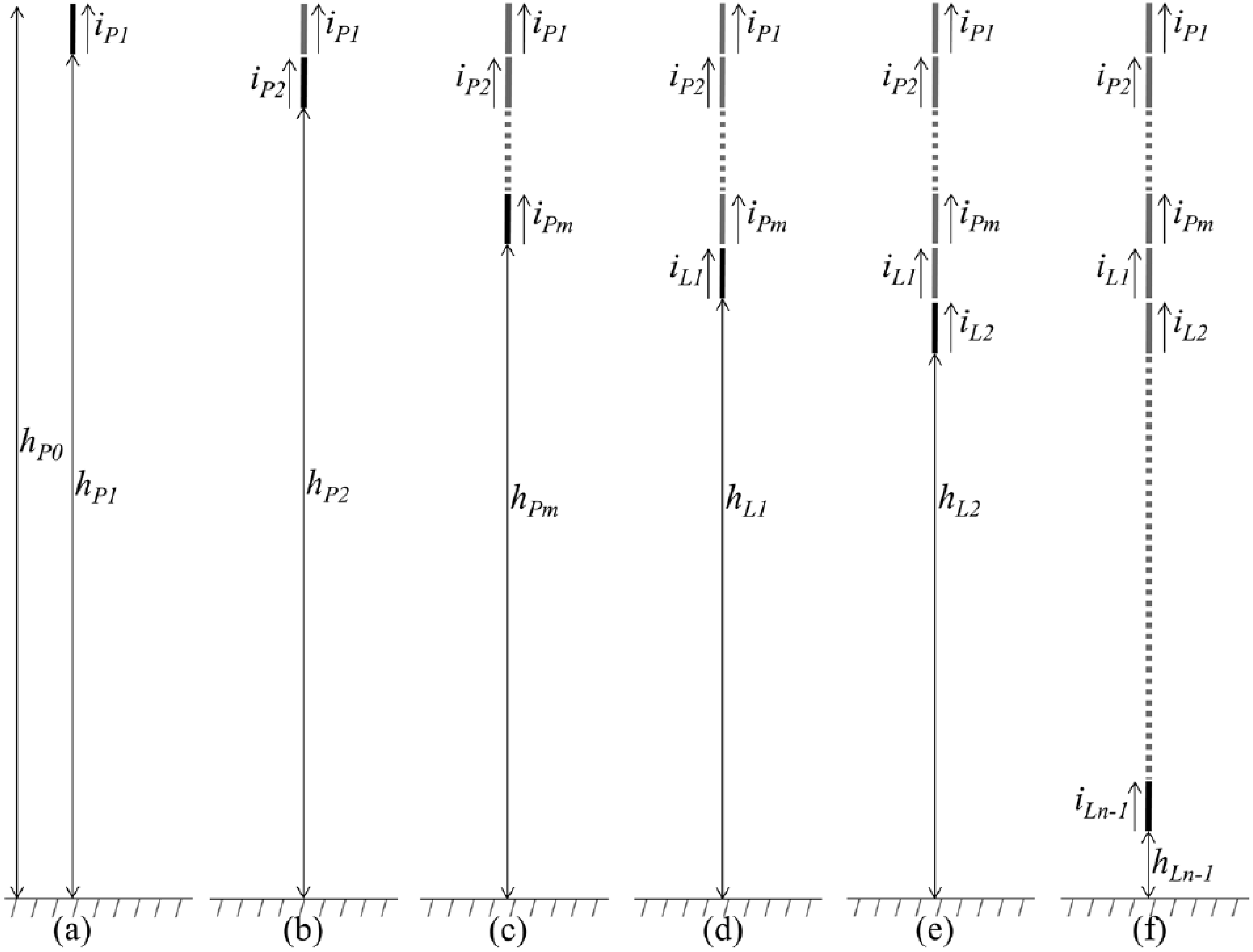



Illustration of the downward extension of the lightning channel in a stepwise fashion for (a–c) m steps during the preliminary breakdown stage and (d–f) (n – 1) steps during the stepped leader stage. Taken from Nag and Rakov (2016).

# Modeling of Leader EMPs and Field Changes

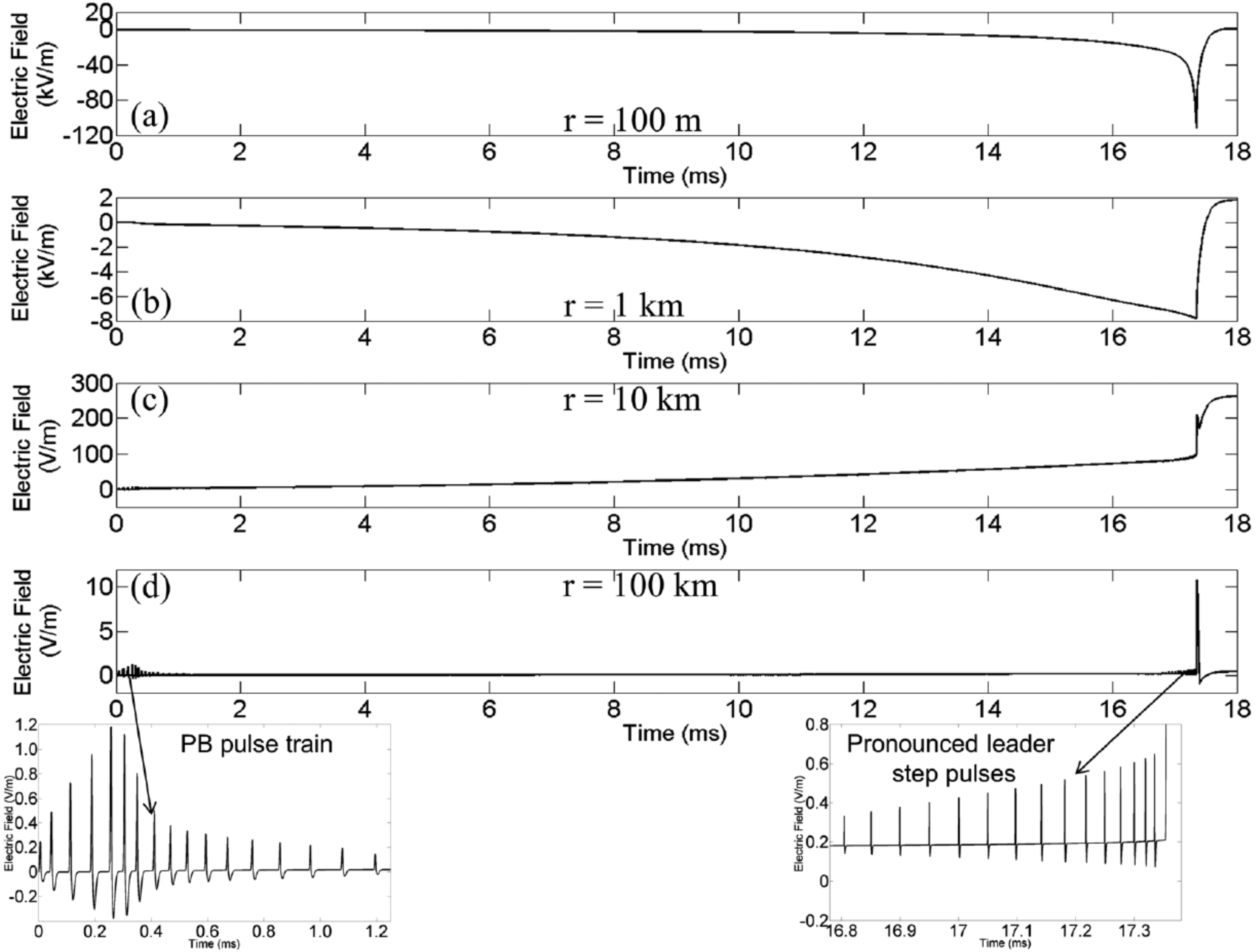
**Table 2.** Summary of the Values of Model Input Parameters Used in Computing Electric Field Waveforms Shown in Figure 7[a]

| Lightning Process | | Height Range | Number of Steps[b] | Step/Channel Length[b] | Downward Channel Extension Speed (m/s) | Step/RS Current Upward Propagation Speed (m/s) | Step/RS Current Peak at the Origin (kA) | Current Waveform Parameters | Current Decay With Height |
|---|---|---|---|---|---|---|---|---|---|
| Preliminary breakdown | Between main negative and lower positive charge centers (higher field region) | 5.25–6 km | 5 | Increasing with decreasing height from 50 to 250 m | $1.3 \times 10^6$–$5.2 \times 10^6$ | $1.2 \times 10^8$ | 35[c] | Equation (8), $A = 35$ kA, $\alpha = 0.33 \times 10^6\ s^{-1}$, $t_1 = 8.5\ \mu s$, and $t_2 = 35\ \mu s$ (see Figure 6a) | Exponential with decay constant of one quarter of step length |
| | Immediately below lower positive charge center (lower field region) | 4.3–5.25 km | 12 | Decreasing with decreasing height from 235 to 25 m | $2.6 \times 10^5$–$5.1 \times 10^6$ | | | | |
| Stepped leader | Middle altitudes | 410 m–4.3 km | 389 | 10 m | $2.5 \times 10^5$ | $1.2 \times 10^8$ | 1[c] | Equation (8), $\alpha = 3.17 \times 10^6\ s^{-1}$, $t_1 = 1\ \mu s$, and $t_2 = 5\ \mu s$ | Exponential with decay constant of one quarter of step length |
| | Close to ground (higher field region) | 0–410 m | 16 | Increasing with decreasing height from 12 to 40 m, except for the last step, which is 20 m long | $2.6 \times 10^5$–$4.1 \times 10^6$ | | 10[c] | | |
| Return stroke | | 0–6 km | N/A | 6 km | N/A | $1.5 \times 10^8$ | 37 | Equation (9), $I_0 = 20$ kA, $\eta = 0.5$, $n = 10$, $\tau_1 = 4\ \mu s$, and $\tau_2 = 100\ \mu s$ (see Figure 6b) | Linear (current vanishes at the top of the channel) |

[a]Using the engineering approach, values of parameters are selected such that the model-computed field characteristics agree with pertinent measurements available in the literature. RS = return stroke; N/A = not applicable.
[b]The number of steps is determined by the total channel length associated with each process and the length of individual steps.
[c]*A* in equation (8).

# Modeling of Leader EMPs and Field Changes

## Unified engineering model of the first stroke in downward negative lightning




The computed electric fields at distances of (a) 100 m, (b) 1 km, (c) 10 km, and (d) 100 km for a typical first stroke in downward negative lightning. The atmospheric electricity sign convention is used.

Insets show the PB pulse train on a 1.25 ms time scale and the leader stepping immediately prior to the return stroke on a 0.6 ms time scale. Taken from Nag and Rakov (2016).

# Return Stroke (RS) Modeling Techniques

- Advantages of the Engineering Models:
  - Intrinsically validation-driven. Model acceptance depends upon ability to reproduce measured fields.
  - Relatively low number of tunable model-parameters (current waveform, propagation speed, and channel length).
  - Large number of practical applications:
    - Lightning protection systems and EMC applications, parameters derived from this approach used in IEC, CIGRE and other international standards.
    - Ground-based lightning locating systems

- Disadvantages of the Engineering Models:
  - Assumptions of perfectly vertical channel and perfectly conducting ground not suitable in reality.
  - Masks the detailed physics of channel formation and variations in channel properties all of which get "lumped" into an "equivalent" channel base/bottom current waveform and a limited set of input parameters.

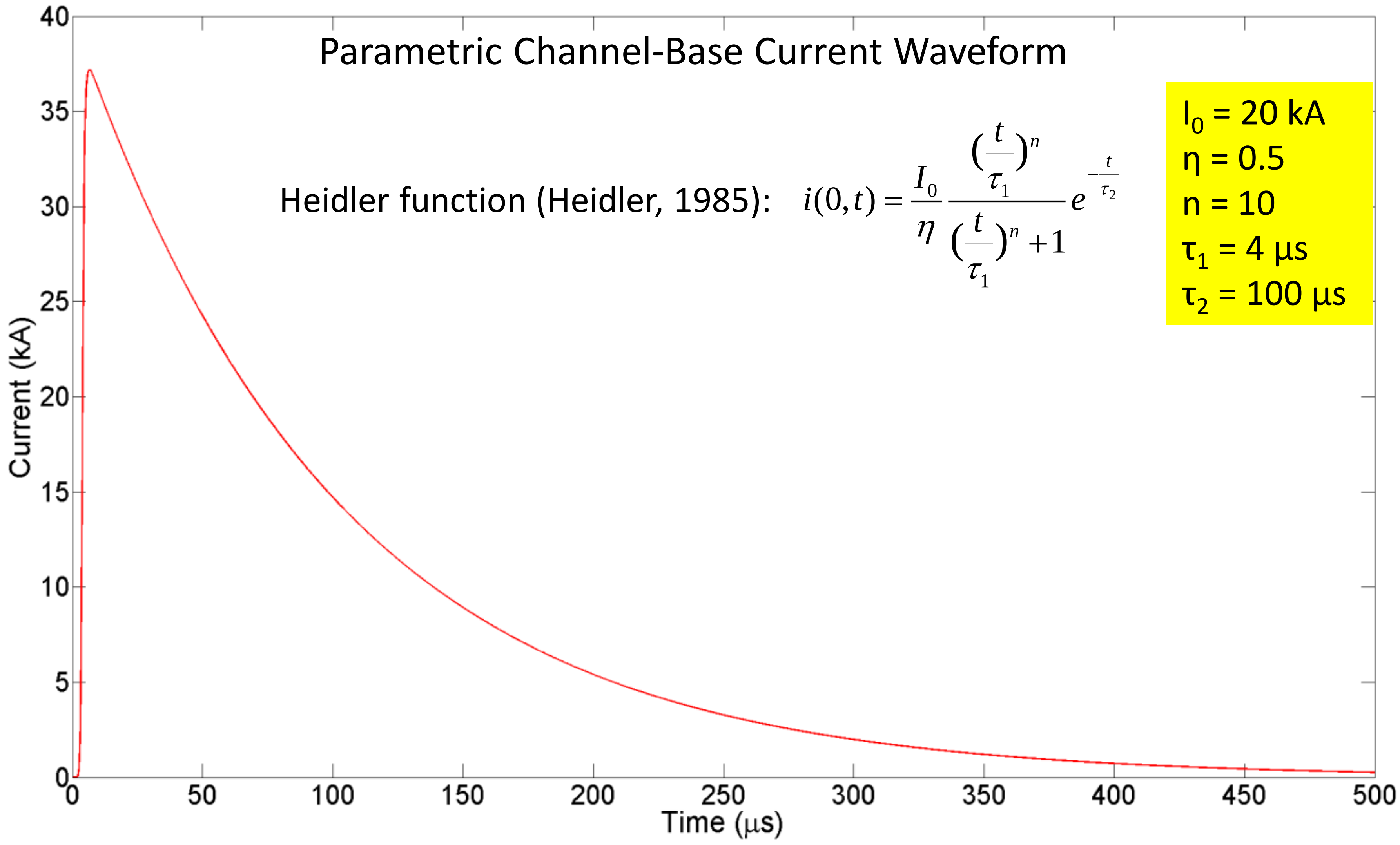
To address these drawbacks, this approach has been modified in various ways with more realistic channel parameter representations. Some examples are shown next.

# Return Stroke (RS) Modeling Techniques
## Summary of model modifications/augmentation

A variety for modifications have been introduced to augment the engineering model over the years by various studies. These include:

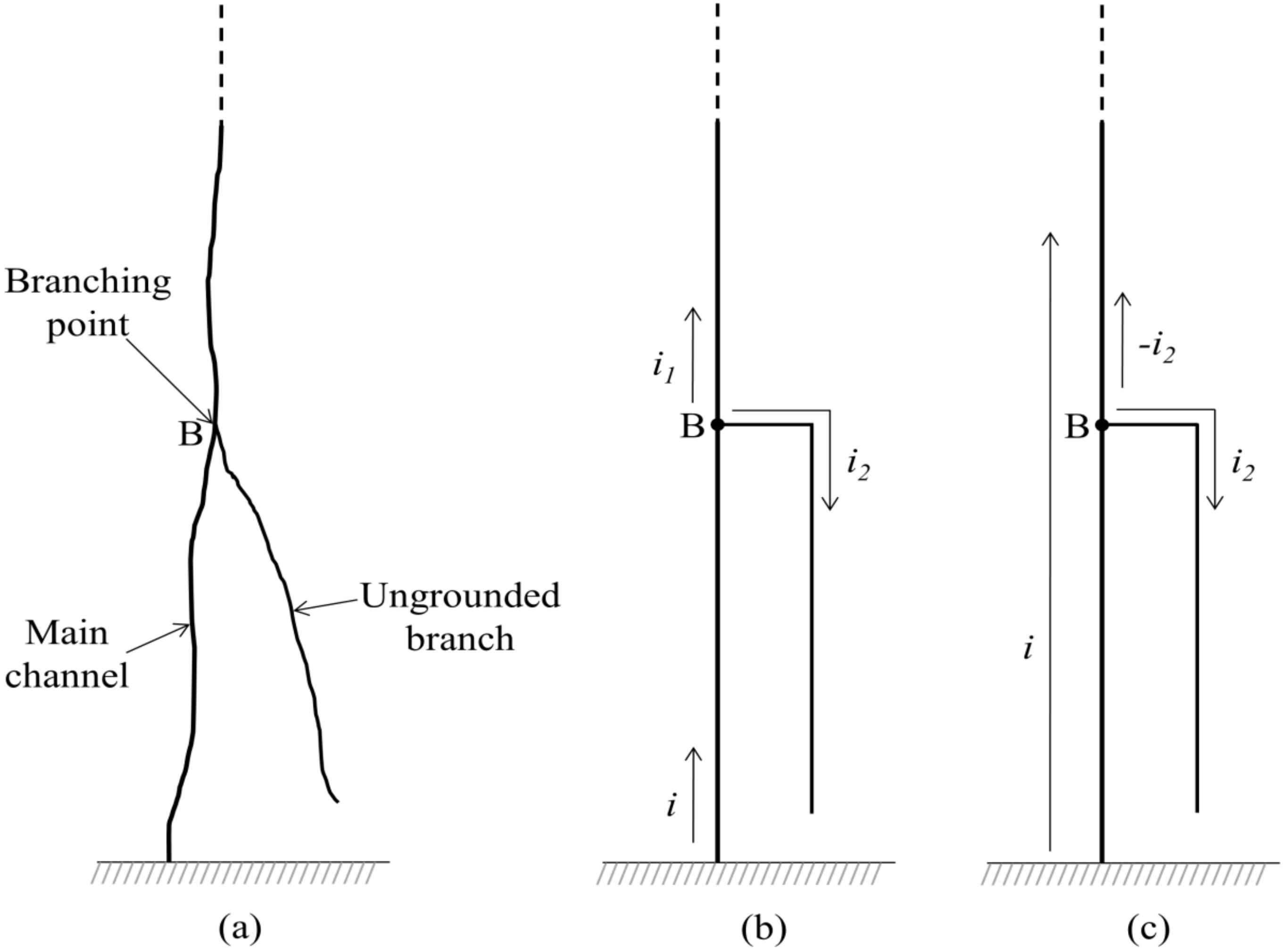
- Variation of current amplitude as a function of channel height (e.g. with linear and exponential decays).
- Variation of current propagation speeds as a function of channel height.
- Effect of channel branching and tortuosity.
- Effect of altitude of upward and downward leader attachment point above ground.

# Branching of Return Stroke Channel – Channel Geometry




The incident return stroke current waveform computed using the Heidler function that is used in this study shown on a 500 μs timescale. The current peak is about 37 kA and the zero-to-peak risetime is 6.6 μs. The half-peak width is 72 μs. This current waveform is representative of negative first return strokes.

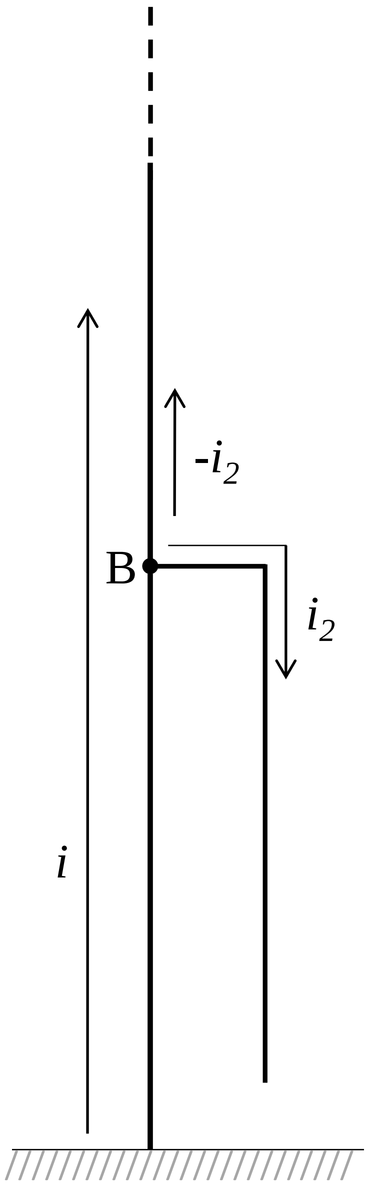
# Branching of Return Stroke Channel – Channel Geometry

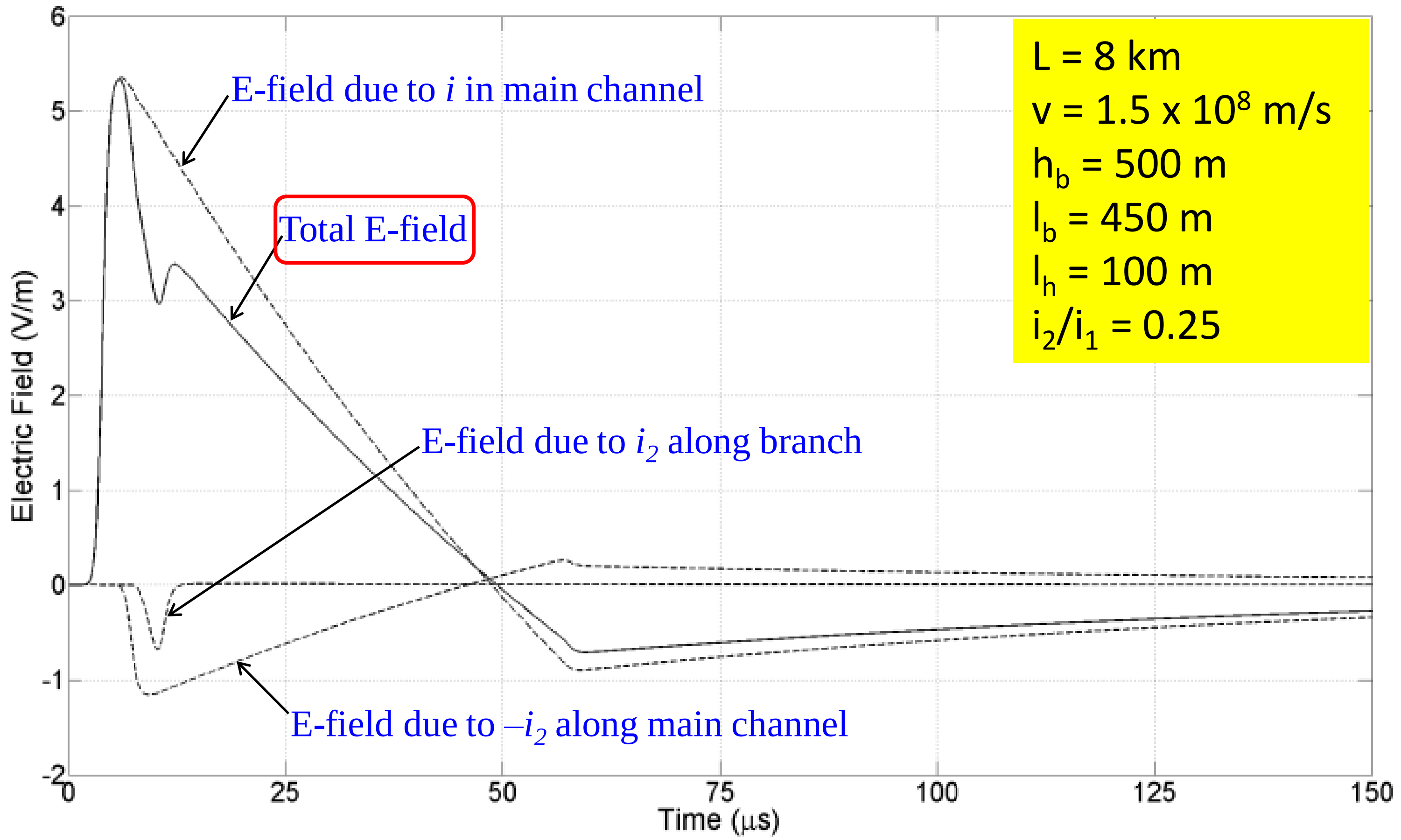



The channel consists of a main channel that extends between the ground and the cloud charge source, and additionally, includes an ungrounded branch. (b) The simplified version of the channel geometry shown in (a). Both the main channel and the branch are considered to be vertical and separated by a short horizontal channel segment. (c) Configuration equivalent to (b) that was used in computing fields.

Taken from Nag and Rakov (2015)

# Branching of Return Stroke Channel – Channel Geometry



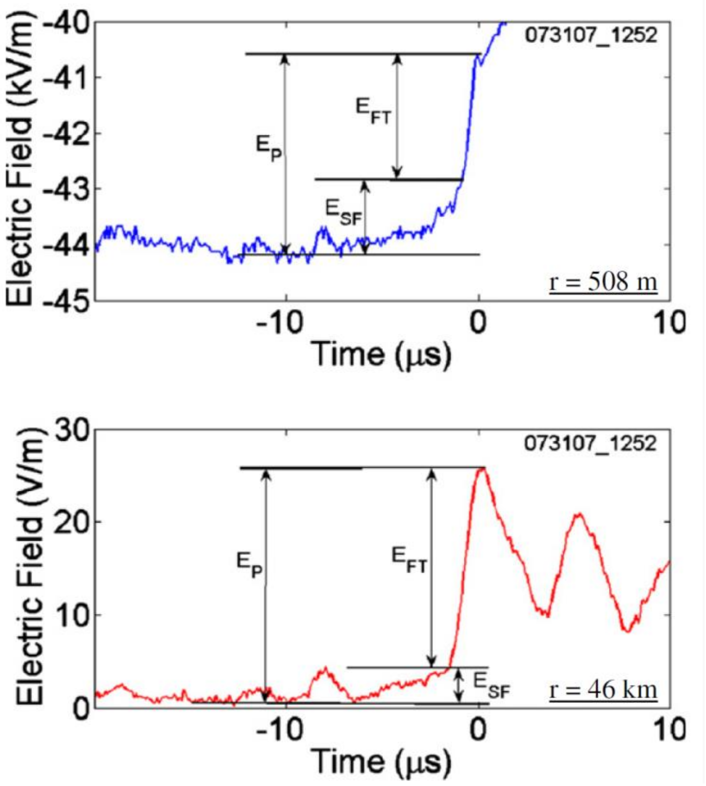



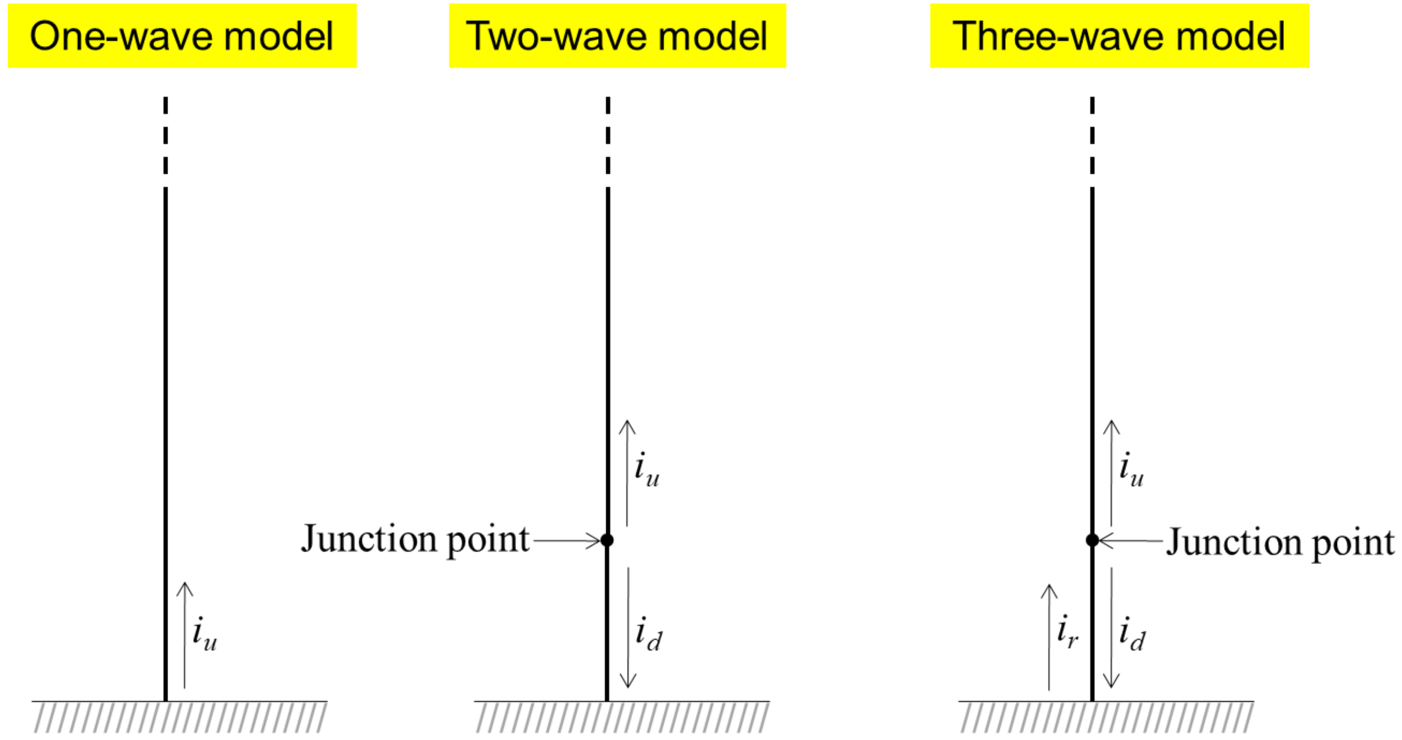

The contributions to the total electric field from the individual current components (waveforms shown with dashed lines). The time interval between the primary and secondary peaks depends upon the height of the branching point above ground and the speed at which the incident current moves upward from the ground.

Taken from Nag and Rakov (2015)

# Modeling of Return Stroke Risetime – Slow Front

- The rising portion of the return stroke EMP consists of the slow front (SF) and the fast transition (FT) which is time-coincident with the attachment of upward and downward leaders.
- The SF is the relatively-slowly rising portion of the RS field waveform, is about 2−8 μs in duration, and constitutes as much as roughly half the return-stroke peak field amplitude.
- The FT follows the SF and is an abrupt transition to peak and has a 10-to-90% risetime of 0.1-0.2 μs or less for first strokes.



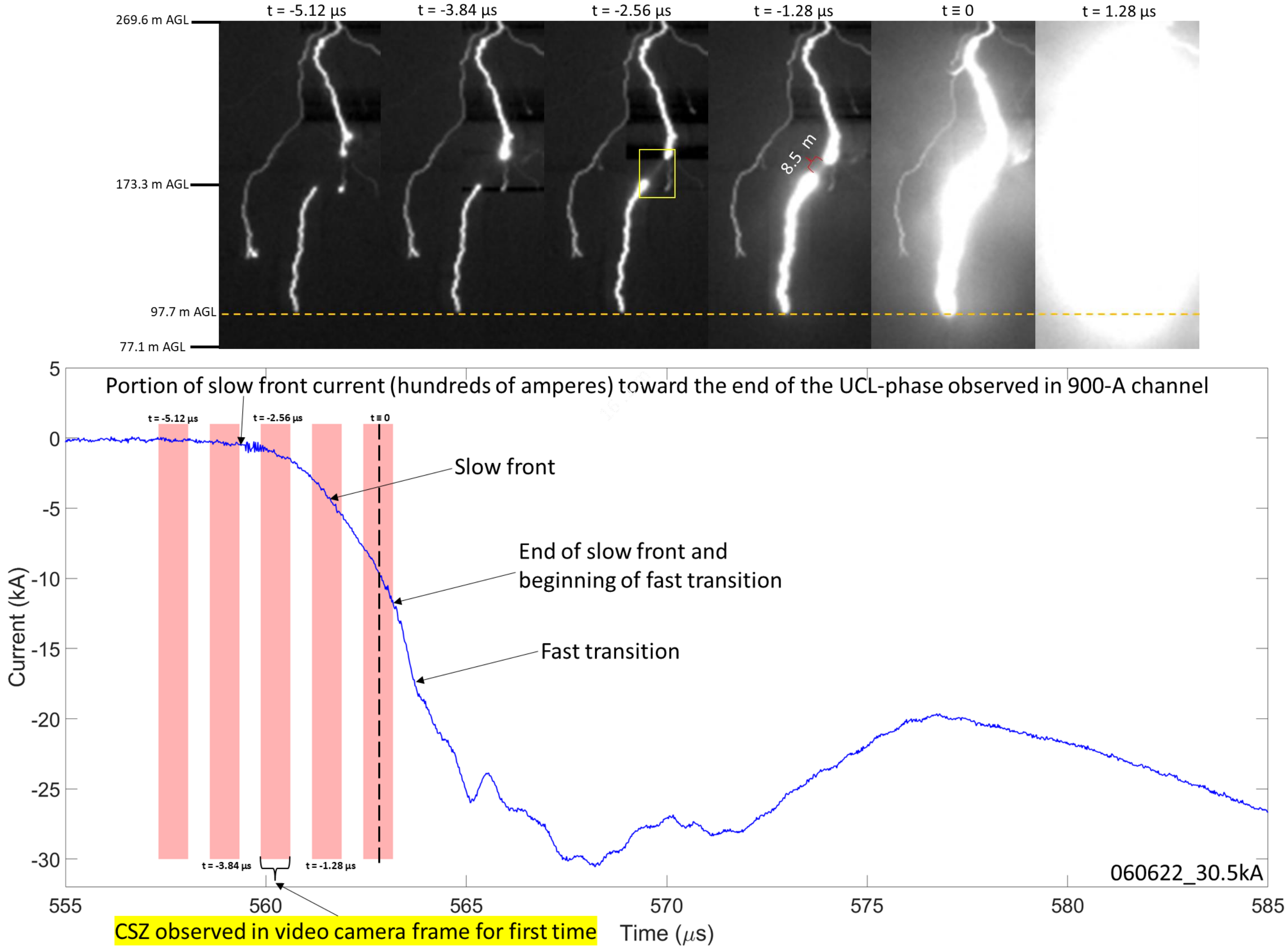

- Based on some limited observational evidence (Willett et al., 1989) attempt was made to see if the presence of the upward leader and the height of the attachment point resulted in a slow front in the field without a corresponding slow front in the current.

- Modelling showed that this was not possible.



Taken from Nag et al. (2012).

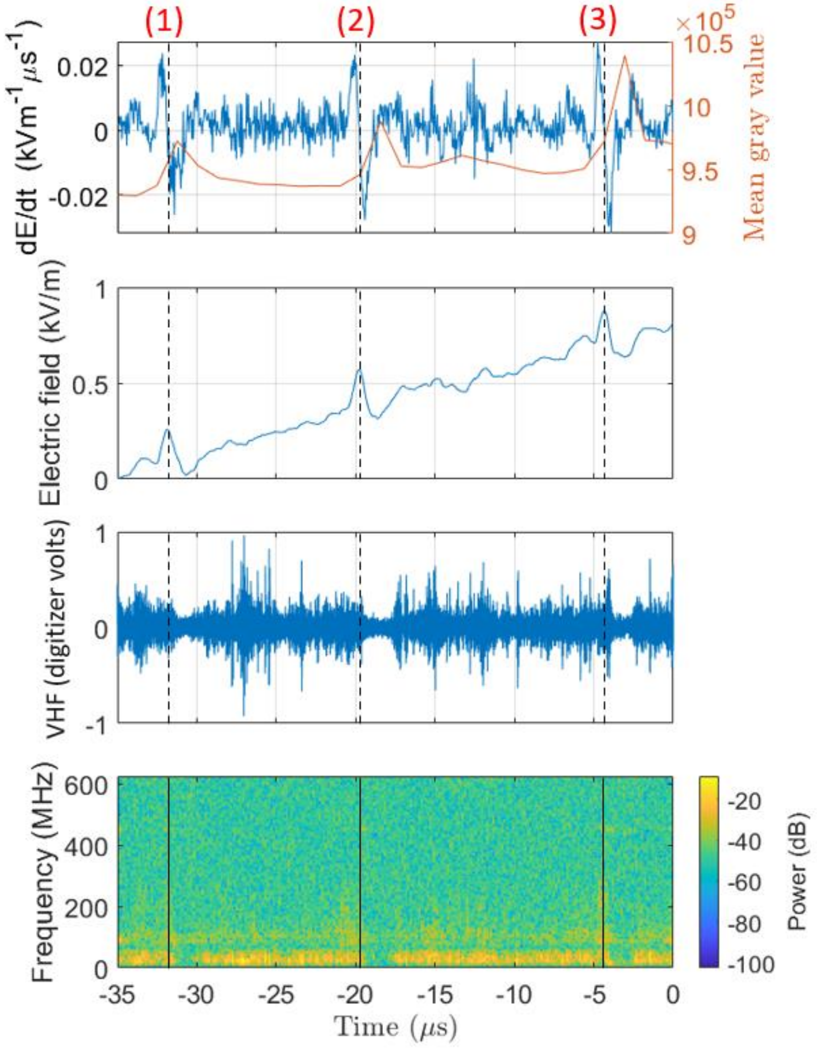
# Return Stroke Risetime – Slow Front

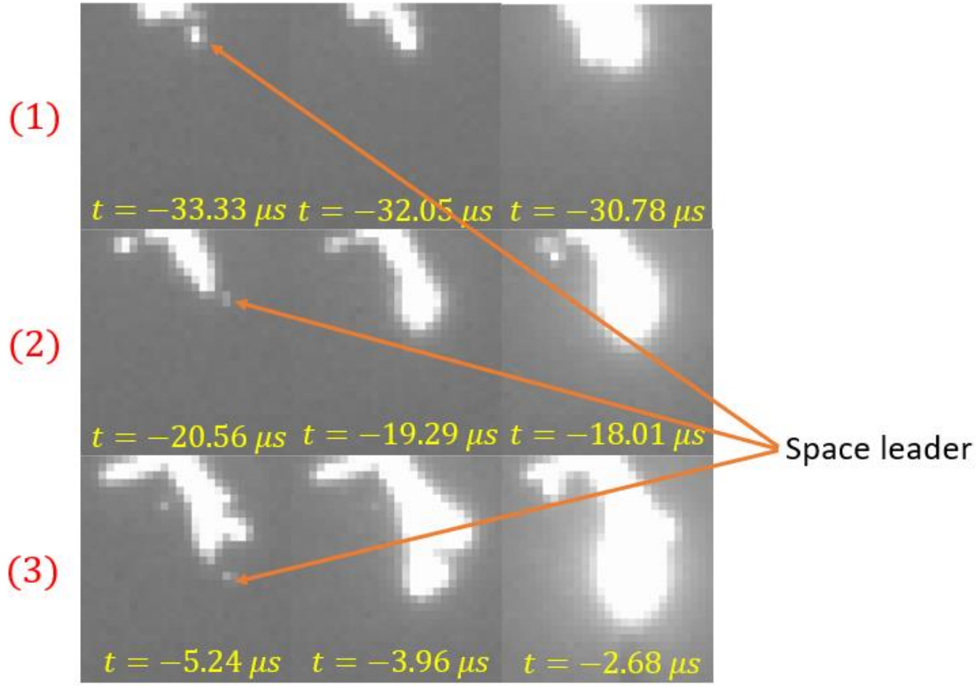



Overlay of the exposure times of our video camera frames (indicated by pink rectangles) on top of the current waveform (shown on a 30-µs time window). Adapted from Plaisir et al. (2023).

# Step Formation

- Step formation in downward negative stepped leader occurs via the formation of space stem/leaders that ahead of the leader tip.
- The space leaders propagate back to the pre-existing leader channel and attach to it resulting in the forward progression of the leader.




Taken from Goldberg et al. (2024).

# Possible Future Improvements

Possible future improvements to the engineering model include:

- Adding/considering the physics of the attachment process/slow front formation in return stroke models.
- Considering the effect of branching on estimation of first stroke peak currents.
- Integration of leader stepping mechanism
- Improvement of microsecond-scale (fine-structure) representation using breakdown parameters.
- Better representation of the channel-top and integration of post-return stroke processes

# References (incomplete list)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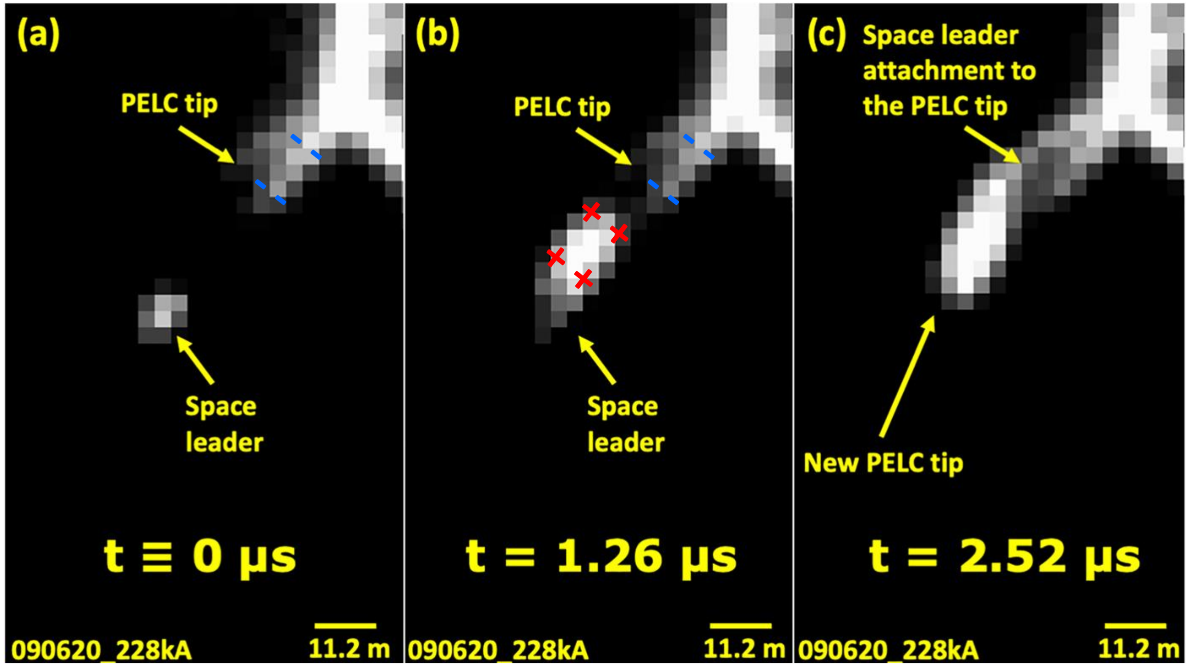
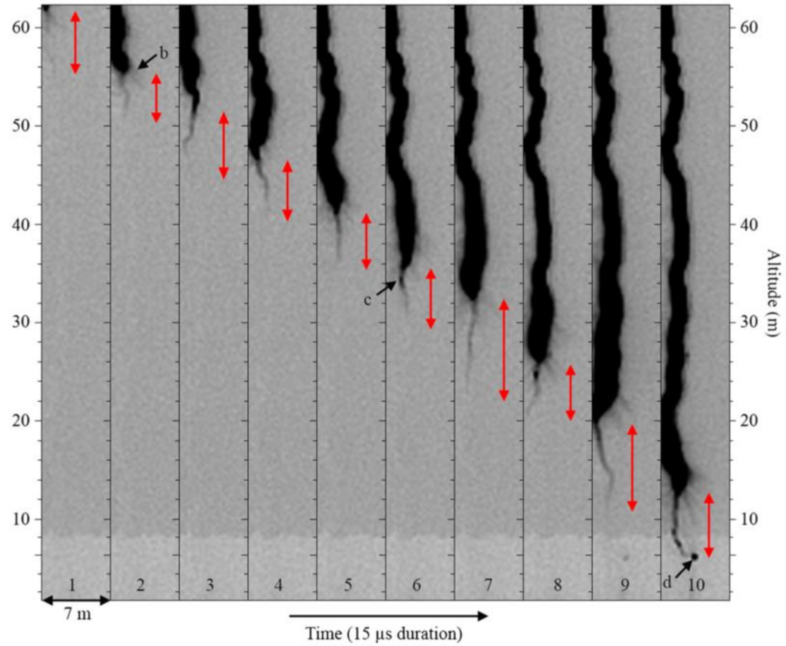
## Agencies that have funded (this flavor of) lightning modeling work in the past:

NSF, Air Force, DARPA, EPRI, ONR, DOE.

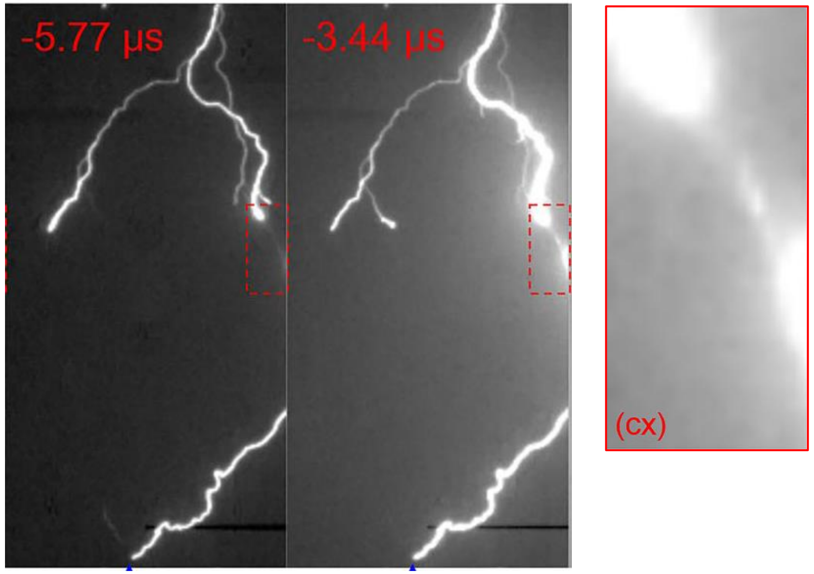
# Negative Leader Stepping and Propagation within CSZ




Step formation in downward negative stepped leader captured in Melbourne, Florida. Images show consecutive video-camera frames (exposure time of 0.74 μs) showing inception (a), progression (b), and attachment (c) of a space leader that attached to the pre-existing leader channel (PELC) tip.
Taken from Khounate et al. (2021).

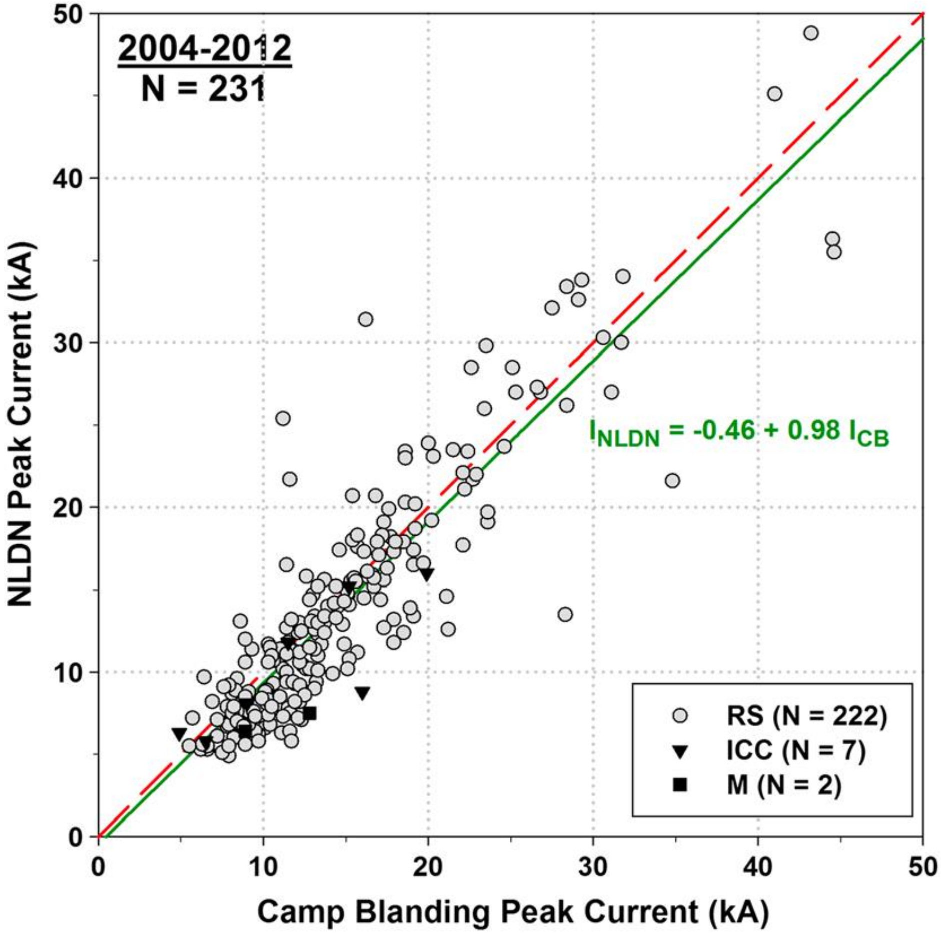


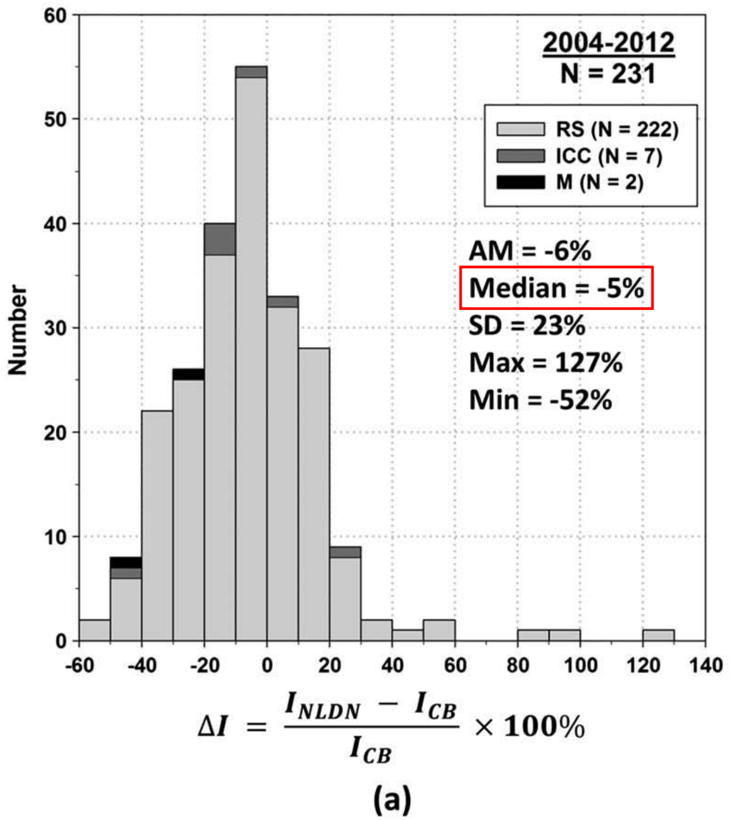

Taken from Gamerota et al. (2015)

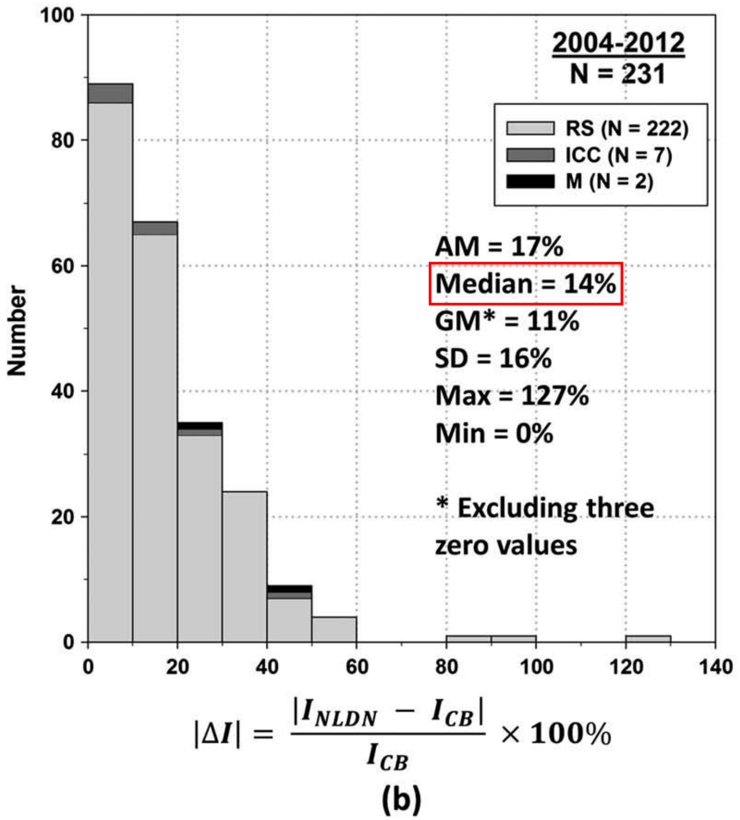



Taken from Jiang et al. (2021)

# Calculating Currents from Measured Electromagnetic Fields




Taken from Mallick et al. [2014].

(Left) NLDN-reported peak current versus peak current directly measured at Camp Blanding for 231 events in 80 flashes triggered in 2004–2012. Different plot symbols are used for return strokes (RS), ICC pulses (ICC), and M components (M).

(Right) Histograms of (a) signed and (b) absolute NLDN peak current estimation errors, given as a percentage of the directly measured Camp Blanding current ($\Delta I\% = 100\Delta I/I_{CB}$, where $\Delta I = I_{NLDN} - I_{CB}$) for 231 events in 80 flashes triggered in 2004–2012.

# Characteristics of Lightning Data from Different LLSs

| LLS Type | | Sensor Baseline Distance/ Optical Imager Field of View | Detection Efficiency | | | Median Location Accuracy/ Spatial Resolution | Temporal Resolution | CG Stroke Peak Current, Polarity Estimation Error | CG Stroke Location and Multiplicity | Lightning Type Classification Accuracy |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | CG Stroke | CG Flash | IC Flash | | | | | |
| Ground Based | Long-range (VLF) | Several thousand kilometers | 3-40% | 10-70% | Few to less than 10% | 2 km to more than 10 km | Ten to several tens of microseconds | 25-30%, 1-4% | Yes | NA |
| | Medium-range (ELF-HF) | 150-400 km | 70-90% | 85% to more than 95% | 40-50% | About 100 meters to less than 1 kilometer | Several tens of nanoseconds | 15-20%, negligible | Yes | 48-96% |
| | Short-range (ELF-HF) | 50-75 km | Greater than 90% | Greater than 95% | About 75% | About 100 meters to few hundred meters | Several tens of nanoseconds | 15-20%, negligible | Yes | 48-96% |
| | VHF mapping | 10-40 km for TOA, 150 km or less for interferometry | Total flash DE of greater than 95% | | | Several tens to few hundred meters | Ten microseconds or more for TOA), 100 µs for interferometry | NA | NA | NA |
| Satellite Based | Low earth orbit optical imaging/ mapping | 600 x 600 km to 1300 x 1300 km areas for 90 s to a few minutes | Total flash DE of 38 to 88%, depending upon instrument and time of day | | | Ten to a few tens of kilometers | 2 ms | NA | NA | NA[a] |
| | Geo-stationary optical imaging/ mapping | Two optical imagers on board two satellites (east and west) staring continuously at the Americas and nearby oceans | Flash DE of ~50-90% depending upon flash type. | | | 8-14 km | 2 ms | NA | NA | NA |