CHAPTER 1
INTRODUCTION

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1.1 Historical overview: Ancient times

Lightning playing a part in the origin of life: producing molecules

Mythological view of lightning by ancient civilizations

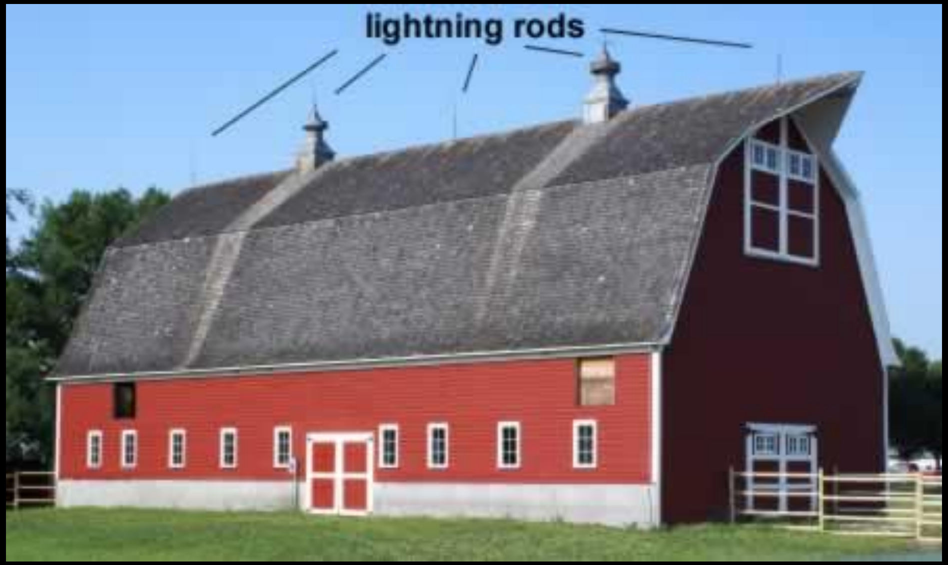
Seth – Egypt
Tien Mu – China
Zeus – Greek
Thor - Scandinavia

1.1 Historical overview: lightning damage to tall structures

Damage to churches

Ringing belts

Damages to ships

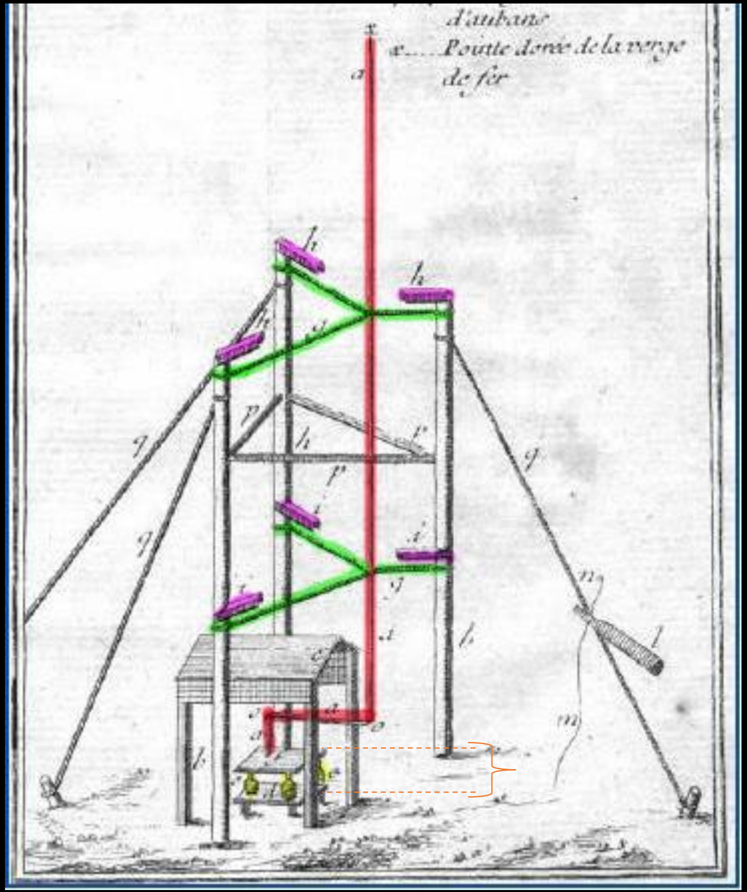


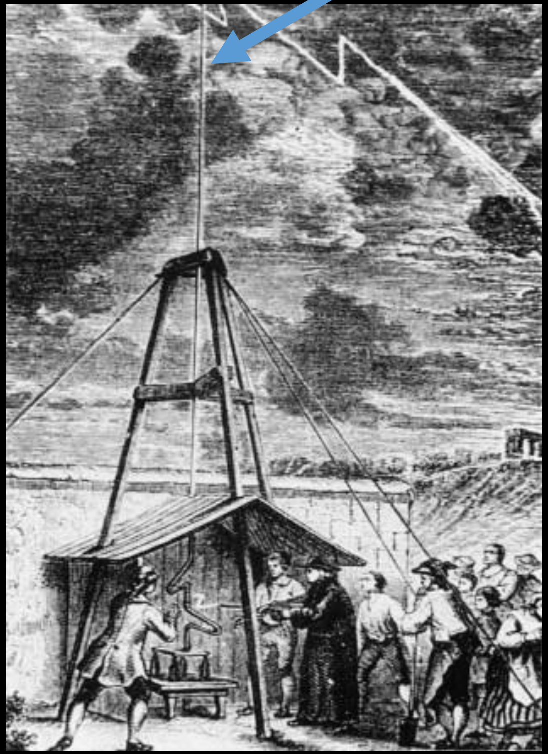
Some buildings no seriously damaged by lightning: Similar system than the Franklin rod system

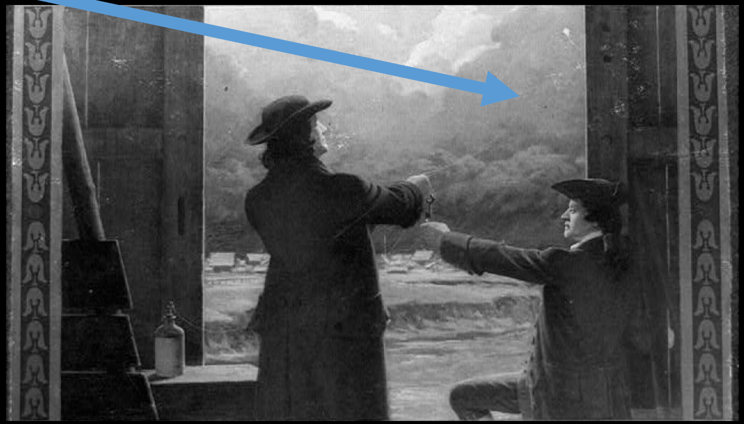
1.1 Historical overview: Systematic tudies of thunderstorm electricity

The conductor is polarized by the electric field of the cloud

Marly experiment







First direct proof that thunderclouds contain electricity

When the **gap** decrease, a spark discharge occur, with scale and effect orders of magnitude smaller than those of lightning.

Experiment design:
Not consider the possibility of direct strike to rod or kite.

1.1 Historical overview: Lightning protection

Conducting string are extended into the electrified cloud by kites, balloons, rockets, etc

Franklin showed that C-G lightning are "commonly negative"

Lightning road dual purpose
- Discharge a thunder cloud
- **Offers a preferred attachment for lightning and then a safe path to ground**

Faraday cage

In practice, a combination of Faraday cage and Franklin rode is used

For sensitive electronics, a topological shielding with surge suppression is used (generalization of Faraday cage concept)

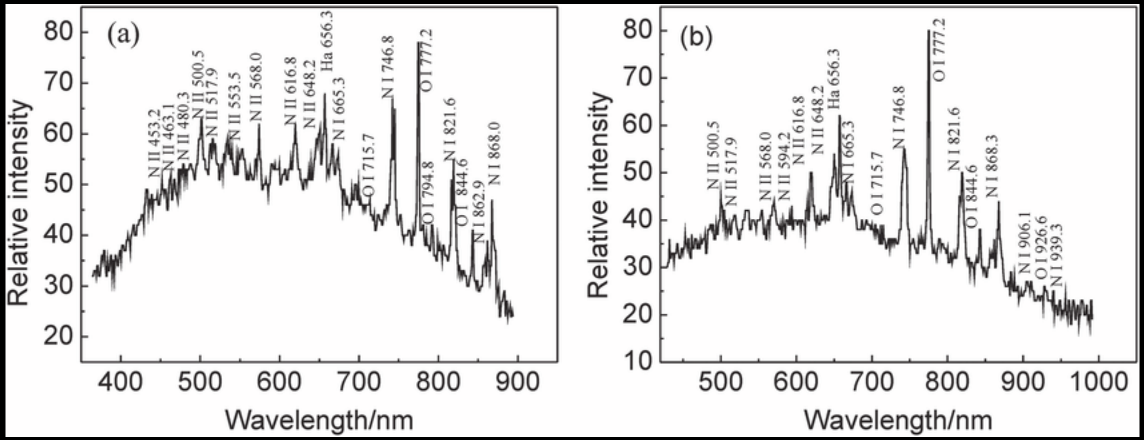
1.1 Historical overview: lightning research from late 19th to mid 20th century

Diagnostic tools

photography

Helping in determining how many strokes lightning flashed often contain (strike camera)

spectroscopy



Dong et al., 2017

Herschel (1868), N line as the brightest in visible .

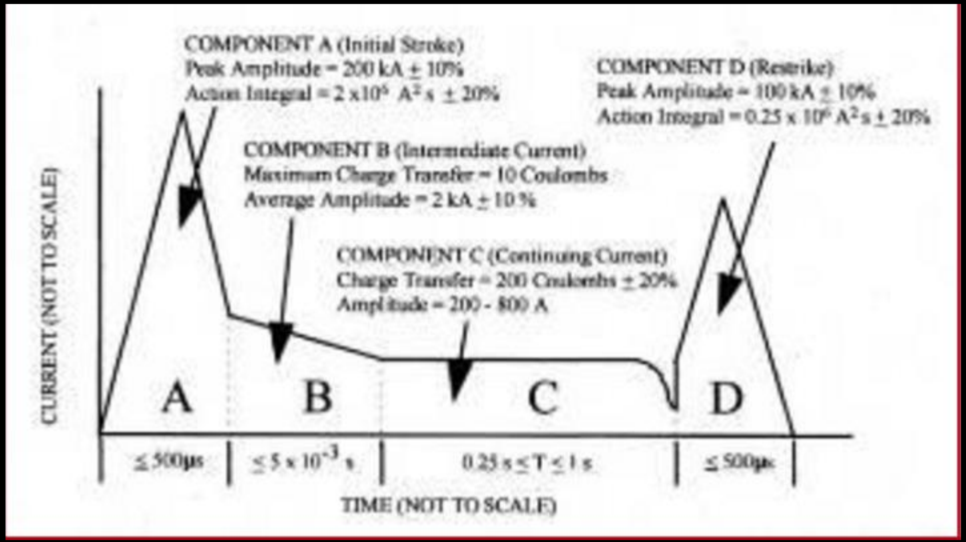
Lines relative intensity particular for each spectrum.

Dufay (1949), Information about the physical conditions in and around the lightning channel by using the lightning spectrum.

Slipher (1917), line and continuum emissions.

1.1 Historical overview: lightning research from late 19th to mid 20th century

Pockels (1900), 1st estimates of lightning peak current, inferred from the residual magnetization of pieces of basalt placed near the strike object.



Evans et al., 2015

Standard electrical **current waveform** for simulated lightning strike testing on aerospace materials.

Chapter 4

C.T.R. Wilson - Electrostatic field measurements to infer the thunderclouds **charge structure**.

Simpson and Scrase (1937), measurement of electric field inside thunderstorms.

Chapter 3

Workman et al. (1942), EM fields from close lightning.

Austin (1926), atmospheric

Modern era since 1970s

First field records

Chapter 4 ^ 9

1.2 Types of lightning discharges and lightning terminology

Lightning = Lightning discharge = lightning flash = flash
Also, lightning bolt (non-technical)

- Whether it strikes the ground or not

Lightning strike
When involving an object on ground or in the atmosphere

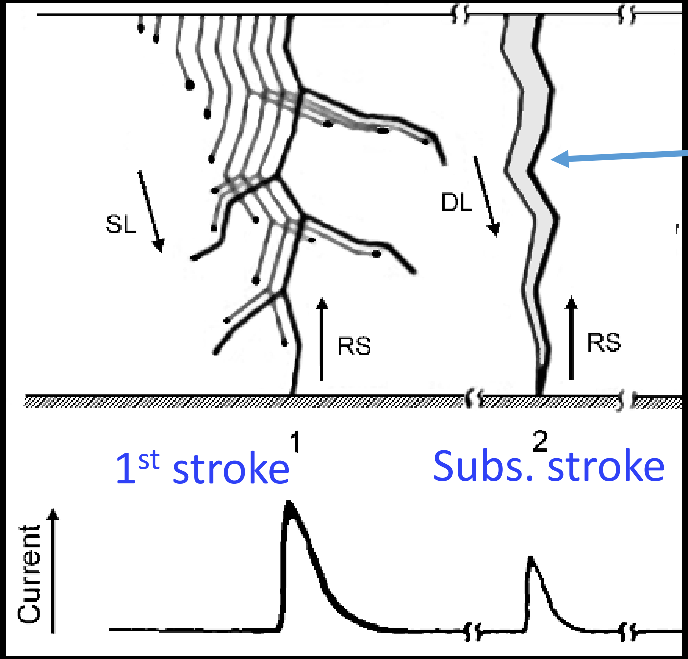
Stroke = component stroke
Components of cloud-to-ground discharges

Each stroke { Downward leader / Upward return stroke / Low level continuing current*

Much of the presently used lightning terminology was introduced by South African researchers

SoAf researchers:
Lightning stroke are composed:

- Downward leader and upward return stroke.
- First-stroke leader is stepped.



Formed channel

Subsequent strokes are initiated by **Dart = dart-stepped**

Charge transfer to ground

Three possible modes

(a) dart-leader–return-stroke sequences
(b) Continuing currents
(c) M-components

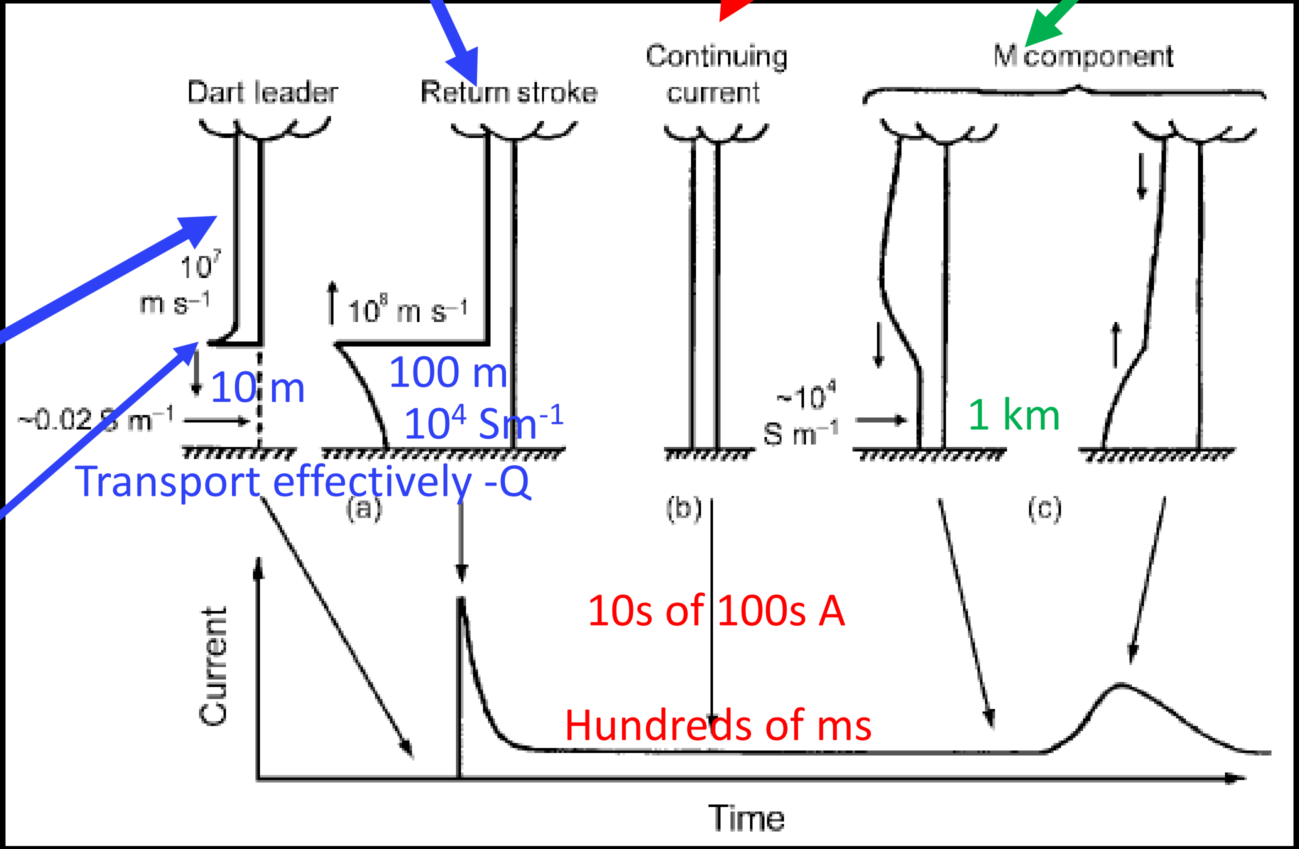
Viewed as a quasi-stationary arc C-G

Neutralizes negative leader charge

- Transient process
- Existence of a channel
- With continue current
- Act as a waveguide

Deposits negative charge

Create a conductive path



Perturbation

Superposition of 2 waves with opposite directions

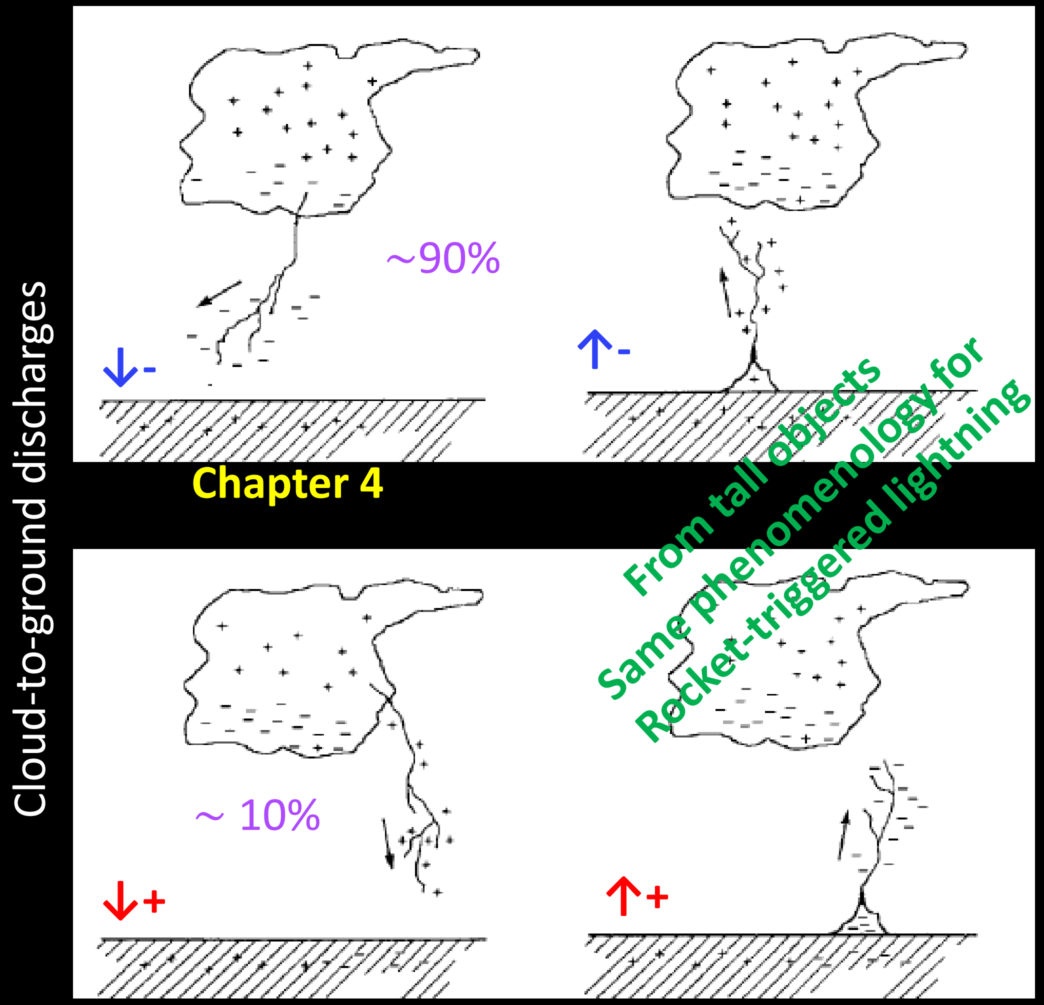
Perturbation

If σ<, downward M-component → dart leader

Non-conducting path

Conducting path

1.2 Types of lightning discharges and lightning terminology



Polarity of the charge effectively lowered
Direction of propagation initial leader

<u>Effectively:</u> individual charges are not transported all the way from the cloud to ground. Rather, the flow of electrons in one part of the lightning channel results in the flow of other electrons in other parts of the channel

Individual electrons in the lightning channel move only a few meters during a return stroke that transfers a coulomb or more of charge to ground

<u>Initial continuous current</u>
relative low-level current flowing during the initial stage of:
- upward lightning
- rocket-triggering lightning

1.2 Types of lightning discharges: ICs

~75% of lightning discharges
Cloud discharges (ICs)
- Intracloud
- Intercloud
- Cloud-to-air

Chapter 9

1.2 Lightning terminology: Leader and streamer

Leader
- Self-propagating discharge creating a channel
- Conductivity $\sim 10^4$ Sm^{-1}

Streamer = Low luminosity leader
- Self-propagating discharge creating a channel
- Conductivity << 10^4 Sm^{-1}
- The air behind a streamer tip remains an insulator

In literature
Sometimes used interchangeably

Chapter 4

Corona = point discharge
- Numerous individual streamers
- Confined to vicinity of “electrodes” such:
  1. Grounded object
  2. Leader tip
  3. Lateral surface of leader channel
  4. hydrometeor

1.3 Salient lightning properties

Table 1.1. *Characterization of negative cloud-to-ground lightning*

Parameter	Typical value[a]
Stepped leader	
Step length, m	50
Time interval between steps, μs	20–50
Step current, kA	> 1
Step charge, mC	> 1
Average propagation speed, m s^{-1}	2×10^5
Overall duration, ms	35
Average current, A	100–200
Total charge, C	5
Electric potential, MV	~ 50
Channel temperature, K	~ 10 000
First return stroke[b]	
Peak current, kA	30
Maximum current rate of rise, kA μs^{-1}	≥10–20
Current risetime (10–90 percent), μs	5
Current duration to half-peak value, μs	70–80
Charge transfer, C	5
Propagation speed, m s^{-1}	$(1–2) \times 10^8$
Channel radius, cm	~ 1–2
Channel temperature, K	~ 30 000

Table 1.1. (*cont.*)

Parameter	Typical value[a]
Dart leader	
Speed, m s^{-1}	$(1–2) \times 10^7$
Duration, ms	1–2
Charge, C	1
Current, kA	1
Electric potential, MV	~ 15
Channel temperature, K	~ 20 000
Dart-stepped leader	
Step length, m	10
Time interval between steps, μs	5–10
Average propagation speed, m s^{-1}	$(1–2) \times 10^6$
Subsequent return stroke[b]	
Peak current, kA	10–15
Maximum current rate of rise, kA μs^{-1}	100
10–90 percent current rate of rise, kA μs^{-1}	30–50
Current risetime (10–90 percent), μs	0.3–0.6
Current duration to half-peak value, μs	30–40
Charge transfer, C	1
Propagation speed, m s^{-1}	$(1–2) \times 10^8$
Channel radius, cm	~ 1–2
Channel temperature, K	~ 30 000
Continuing current (longer than ~ 40 ms)[c]	
Magnitude, A	100–200
Duration, ms	~ 100
Charge transfer, C	10–20

Table 1.1. (*cont.*)

Parameter	Typical value[a]
M-component[b]	
Peak current, A	100–200
Current risetime (10–90 percent), μs	300–500
Charge transfer, C	0.1–0.2
Overall flash	
Duration, ms	200–300
Number of strokes per flash[d]	3–5
Interstroke interval, ms	60
Charge transfer, C	20
Energy, J	$10^9 – 10^{10}$

[a] Typical values are based on a comprehensive literature search and unpublished experimental data acquired by the University of Florida Lightning Research Group.
[b] All current characteristics for return strokes and M-components are based on measurements at the lightning channel base.
[c] About 30 to 50 percent of lightning flashes contain continuing currents having durations longer than ~ 40 ms.
[d] About 15 to 20 percent of lightning flashes are composed of a single stroke.

1.3 Salient lightning properties

Table 1.2. *Characterization of microsecond-scale electric field pulses associated with various lightning processes. Adapted from Rakov et al. (1996)*

Type of pulses	Dominant polarity[a] Atmospheric electricity sign convention	Physics sign convention	Typical[b] total pulse duration, μs	Typical[b] time interval between pulses, μs	Comments
Return stroke in negative ground flashes	positive	negative	30–90 (zero-crossing time)	60×10^3	3–5 pulses per flash
Stepped leader in negative ground flashes	positive	negative	1–2	15–25	Within 200 μs just prior to a return stroke
Dart-stepped leader in negative ground flashes	positive	negative	1–2	6–8	Within 200 μs just prior to a return stroke
Initial breakdown in negative ground flashes	positive	negative	20–40	70–130	Some milliseconds to some tens of milliseconds before the first return stroke
Initial breakdown in cloud flashes	negative	positive	50–80	600–800	The largest pulses in a flash
Regular pulse burst in both cloud and negative ground flashes	Both polarities are about equally probable		1–2	5–7	Occur later in a flash; 20–40 pulses per burst
Narrow bipolar pulses	negative	positive	10–20	-	Probably associated with the initial breakdown in cloud flashes

[a] The polarity of the initial half cycle in the case of bipolar pulses.
[b] Typical values are based on a comprehensive literature search and unpublished experimental data acquired by the University of Florida Lightning Research Group.

Various lightning processes emit RW
Spectral peak 5 to 10 kHz (> ~50 km).

At f > spectrum peak up to ~10 MHz,

Spectral A = 1/f

At 10 MHz - 10 GHz

Spectral A = 1/sqrt(f)

The mechanisms of radiation 3–30 MHz (HF), and above are not fully understood.

It is thought that HF emissions are caused by numerous small sparks occurring during the formation of new channels.

1.4 The Global Electric Circuit

1.4.1 Conductivity of the atmosphere

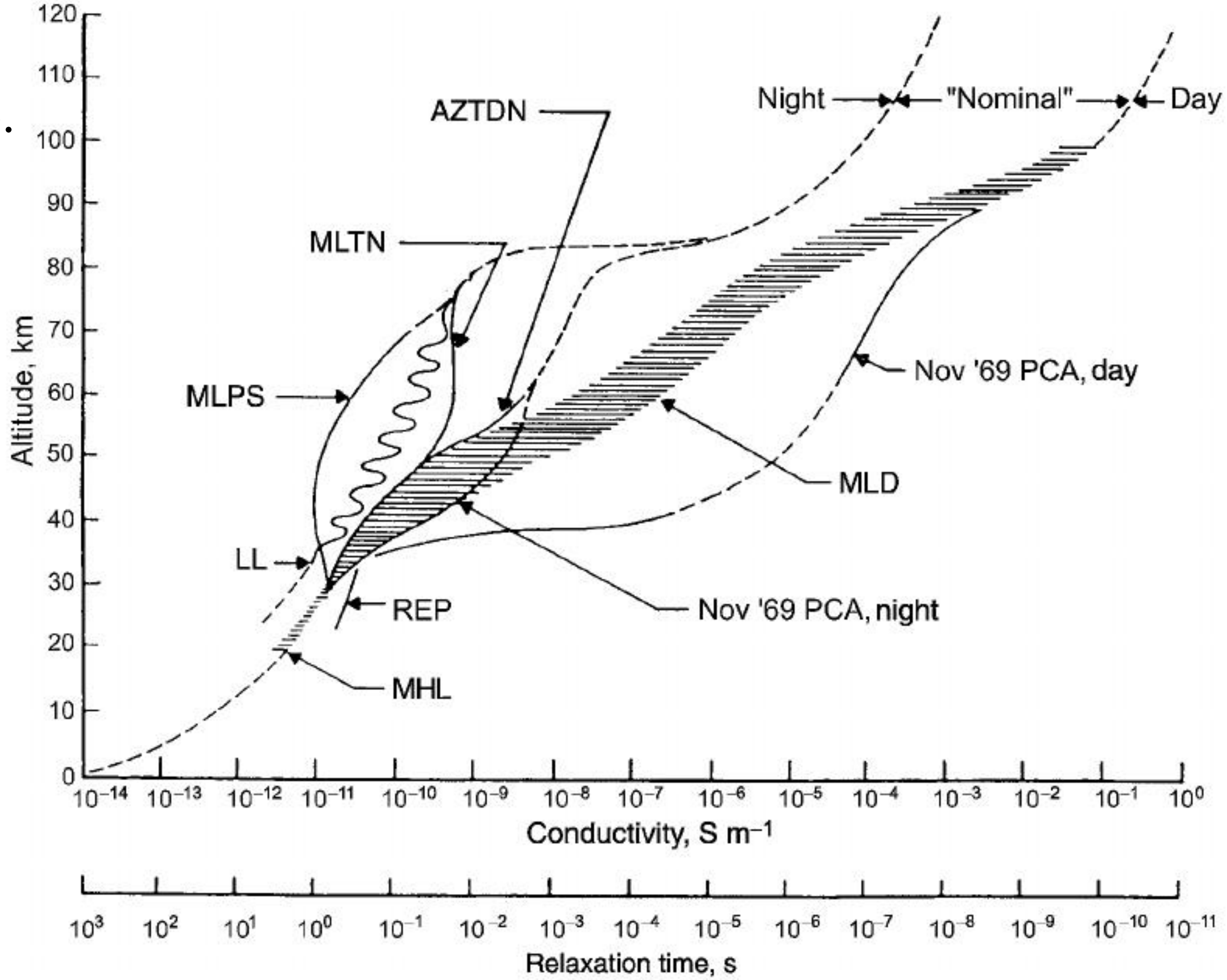
- The electrical conductivity of the air at sea level is about $10^{-14} Sm^{-1}$, and it increases rapidly with altitude.

- ⬇ 50 km (cosmic rays; natural radioactivity).
  Small ions.
  Free electrons can be neglected.

- ⬆ 60 km (free electrons).
  Equipotential region
  Electrosphere or "equalizing" layer

- At 100 km
  ~ conductivity of the Earth (land or sea)

- Thunderstorm may significantly perturb the σ ~ factor 2.



1.4 The Global Electric Circuit

1.4.2 Fair-weather electric field

- $\vec{E}$ ~ 100-200 V/m. The electric field vector is directed downward.
  Downward-directed field (**positive** / "atmospheric electricity" sign convention)
  Downward-directed field (**negative** / "**physics**" sign convention)

- $|\vec{E}|$ decreases with increasing altitude. For example, according to Volland (1984):

$$E(z) = -[9.38e^{-4.527z} + 44.4e^{-0.375z} + 11.8e^{-0.121z}]$$

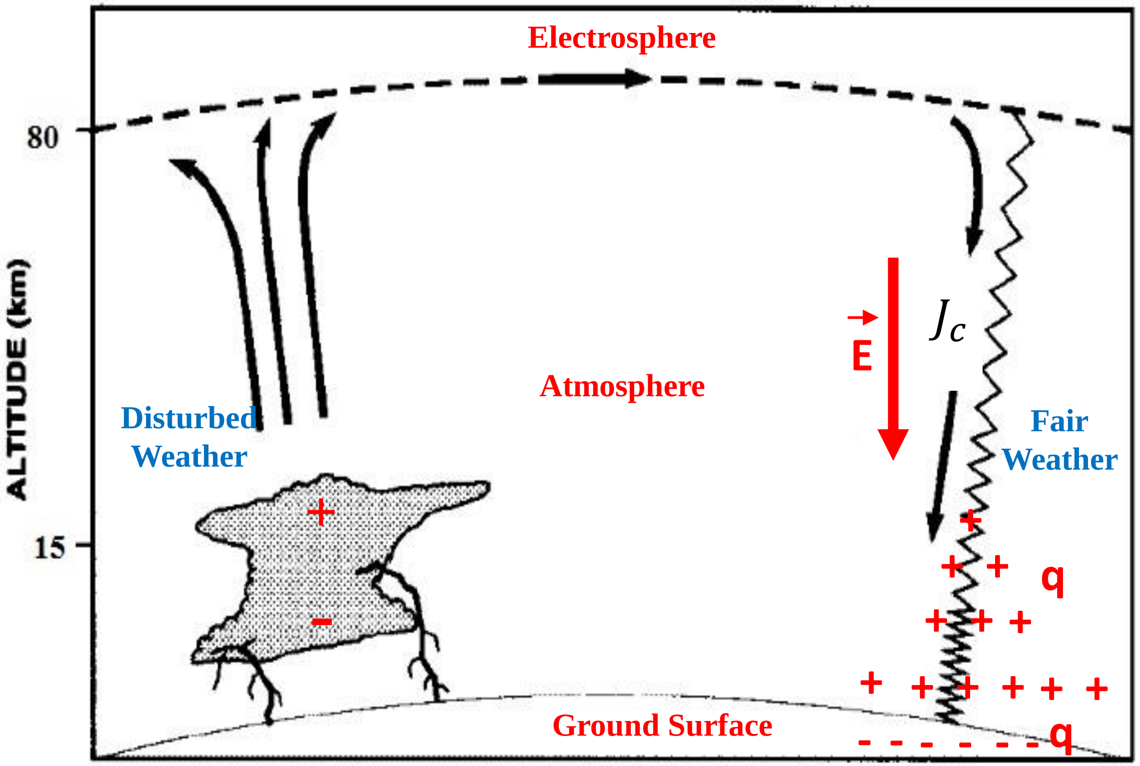
- $|\vec{E}|$ ~ 150 V/m (at the ground)
  $|\vec{E}|$ ~ 300 mV/m (at 30 km)
  $|\vec{E}|$ ~ 1 μV/m (at 85 km)

1.4 The Global Electric Circuit

1.4.3 "Classical" view of atmospheric electricity

- V ~ 300 kV
- Q ~ 5 x $10^5 C$ (Earth's surface is negatively charged, 90 % within 5 km.
- Fair-weather leakage current of the order of 1 kA ($2pAm^{-2}$)

  Must be a mechanism or mechanisms acting to resupply that charge.
- Wilson (1920) suggested that the negative charge on the Earth is maintained by the action of thunderstorms.



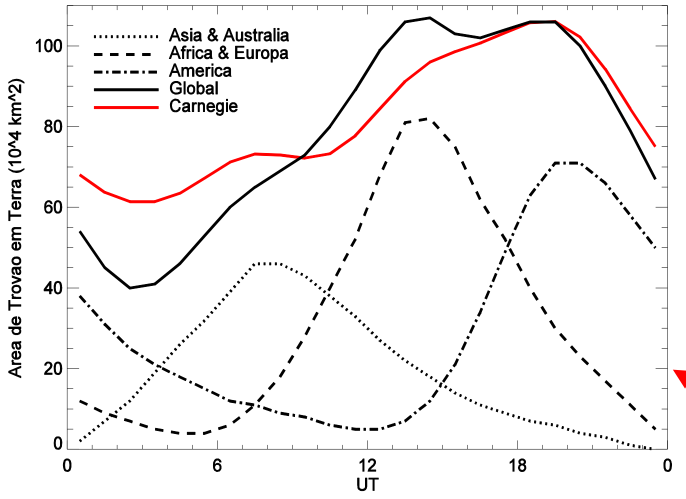
MacGorman and Rust (1998)

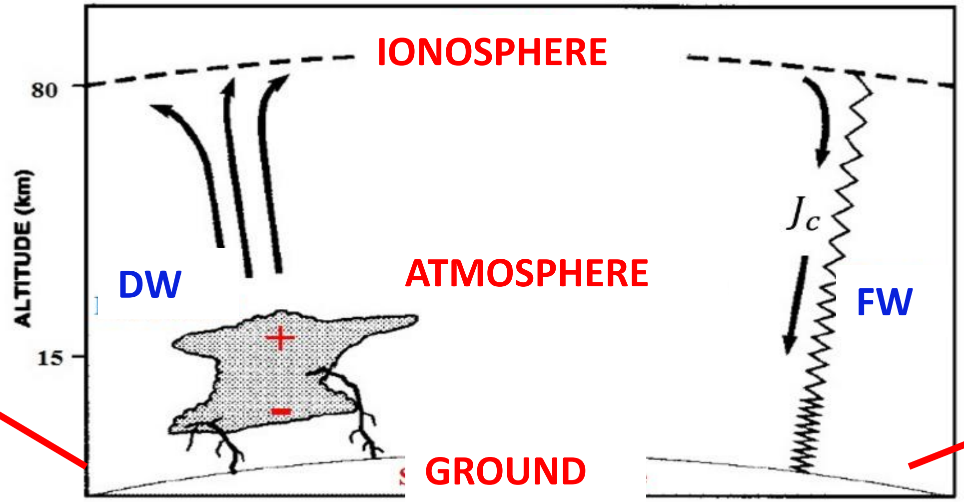
1.4 The Global Electric Circuit

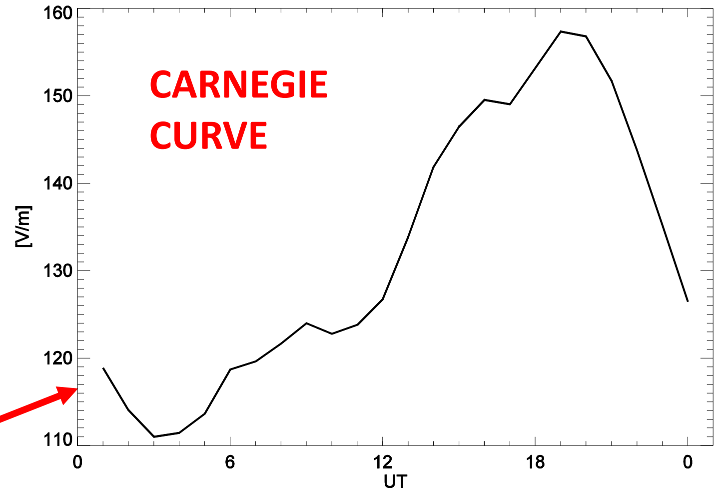
1.4.3 “Classical” view of atmospheric electricity

- The diurnal variation of the fair-weather field as a function of universal time over the oceans (Carnegie curve) appears to follow the diurnal variation of the total worldwide thunderstorm area. Both characteristics exhibit maximum values near 1900 UT and minimum values near 0400 UT.

- However, the annual variation of the fair-weather electric field is not in phase with the annual variation of thunderstorm activity throughout the world.







1.4 The Global Electric Circuit

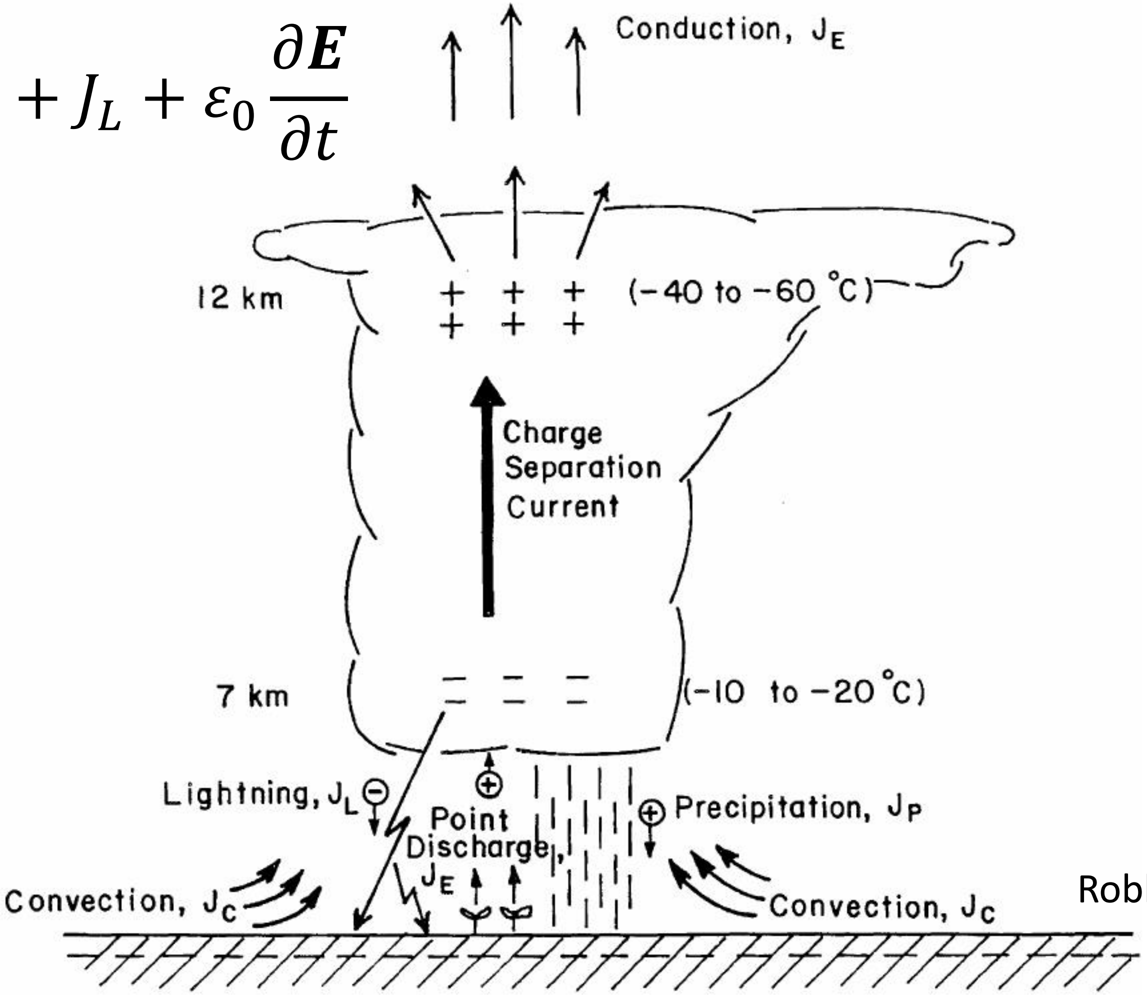
1.4.4 Maxwell current density

- The Maxwell current density J_M associated with a thunderstorm is defined as the sum of four terms:

$$J_M = J_E + J_C + J_L + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

- J_M:
  Under thunderstorms:
  $J_M = 10nAm^{-2}$ (Krider and Blakeslee, 1985)
  $J_M = 1nAm^{-2}$ or less (Deaver and Krider, 1991)
  Above thunderstorms:
  $$J_M = J_E + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

- At altitudes of 16–20 km $\longrightarrow$ $J_E = \sigma E$
  At the ground $\longrightarrow$ $\varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$
  during active storm periods.



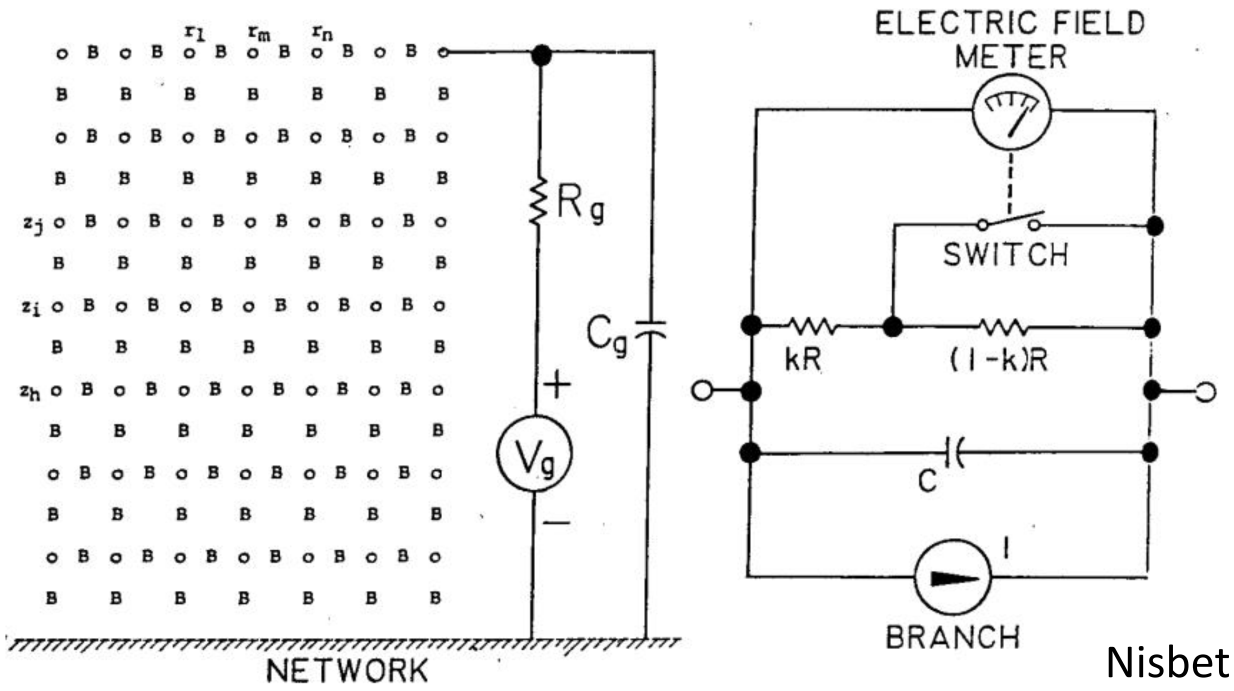
Roble (1991)

1.4 The Global Electric Circuit

1.4.5 Modeling of the global circuit

- Models have been developed by several authors (analytical and numerical models)
  Quasi-static approximation
  Time-varying problem (lightning).
- These models provide a convenient means of examining the various processes operating in the global circuit.

Nisbet (1983) modeled the atmosphere by a network of **resistors**, capacitors, and switches, where the current through these circuit elements represents **conduction**, displacement, and lightning currents, respectively.



Nisbet (1983)

1.4 The Global Electric Circuit

1.4.6 Alternative views of the global circuit

- Kasemir (1994, 1996): only equipotential layer is the Earth.
  Two types of generator: Convection, acting in both stormy and fair-weather regions
  Precipitation

- Kundt and Thuma (1999): Relatively low cloud top voltage (1 MV relative to the Earth).
  However, Marshall and Stolzenburg (2001), found +25 MV.
  Additionally, +32 MV (electrified stratiform clouds), substantial contribution to the global electric circuit.

Outline 1.5 and 1.6

- Regarding the utilization of lightning energy
- Problems with the utilization of lightning energy.
- Summary

Regarding the utilization of lightning energy

- Lightning energy ⇨ 10^9 to 10^{10} J

- One light bulb ⇨ 100W

If we use a light bulb for 1 month

The equivalent energy would be:

100 W x 3600 s x 24h x 30 days = 0.3×10^9 J

Regarding the utilization of lightning energy

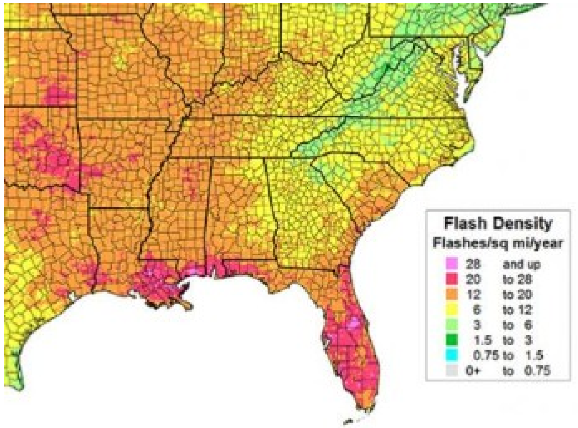
- This means that

Energy of 1  = 3 

During 1 month!!!!

Difficulties to use lightning energy

- Lightning density



Florida:

1 m^2 – 1 flash – 100 000 years!

100 000 m^2 – 1 flash each year!

60m

Attractive radius, $R = \alpha H^{\beta}$, $\alpha = 2$, $\beta = 1$ ⇨ R =120m

$\pi \times R^2 = 50{,}000$ m^2

50 000 m^2 ⇨ 0.5 flash/year.

Difficulties to use lightning energy

- Florida:

  24 towers to capture 12 flashes each year

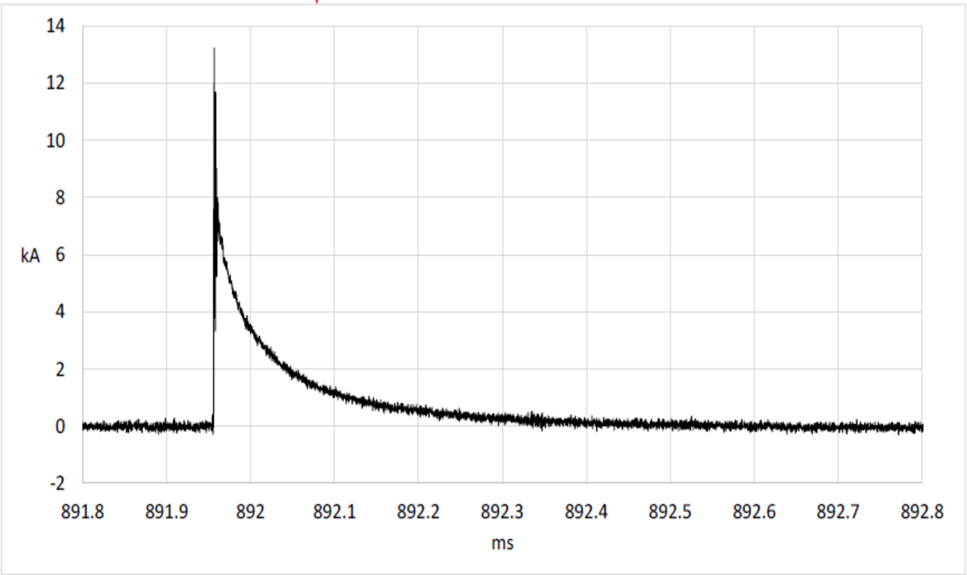
  To give enough energy for only 3 light bulbs!!!

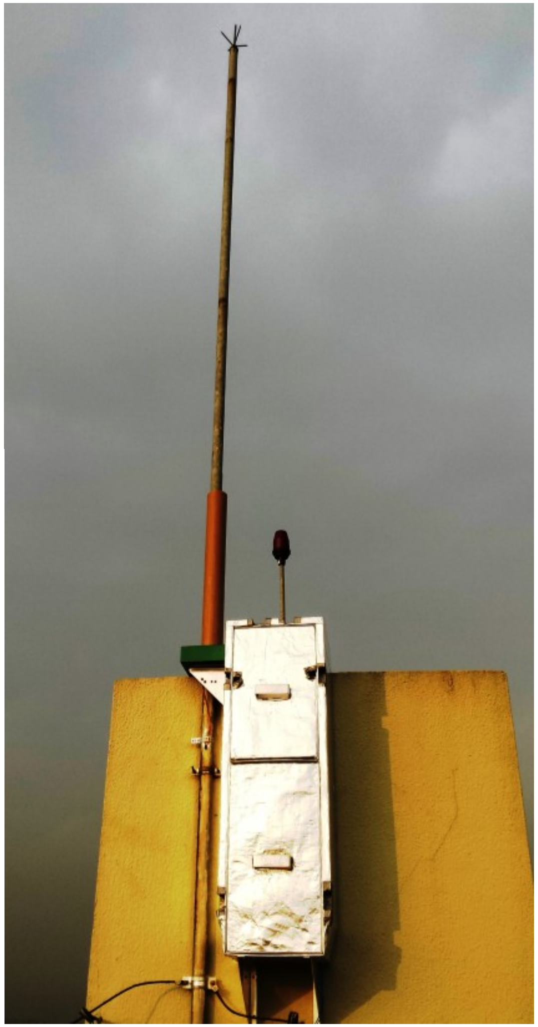
Difficulties to use lightning energy

- All towers should store the energy, it would be a good source of energy
- How to store the energy of a lightning flash???
- There is no practical way to do it!!!

Difficulties to use lightning energy

- But the transferred energy per unit resistance to ground is about 10^5 A^2s
- In the Figure below we show the profile of the current in instrumented towers (Brazil)





Difficulties to use lightning energy

- But the transferred energy per unit resistance to ground is about 10^5 A^2s.

  $Et = R.i^2.t = 10\ \Omega\ .10^5\ A^2s = 10^6\ J$

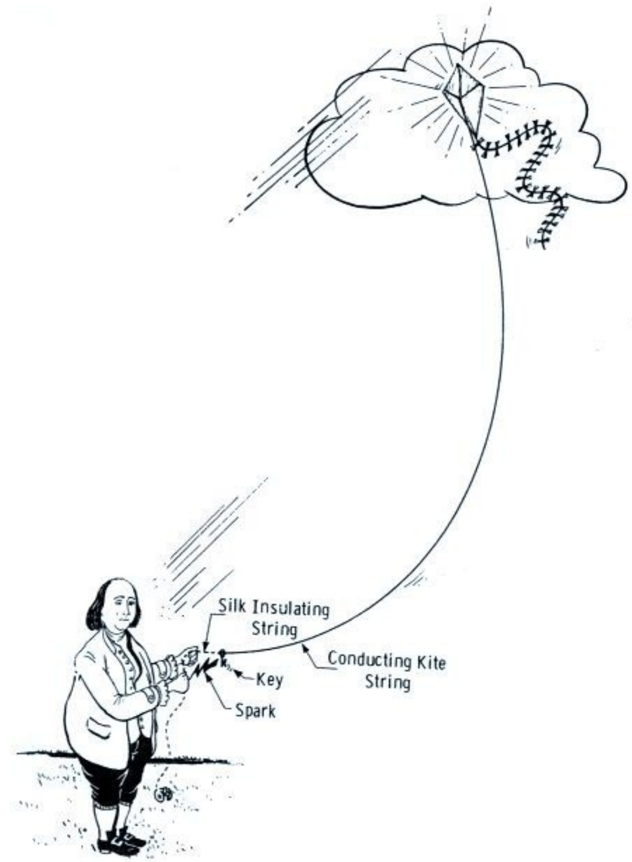
  $Et = 10^{-3}\ Etotal$

- Therefore we would need not 24 towers but

  24 000 towers to feed 3 bulbs during 1 year.

Summary

- Studies of thunderstorm electricity began in 1752 when an experiment proposed by B. Franklin was conducted in France.
- The global electric circuit
- It appears to be impractical to utilize lightning energy.



Thank you very much…!!!