DE LA RECHERCHE À L'INDUSTRIE

Acoustics of lightning

LETMA
MODELLING INFRASONIC PROPAGATION

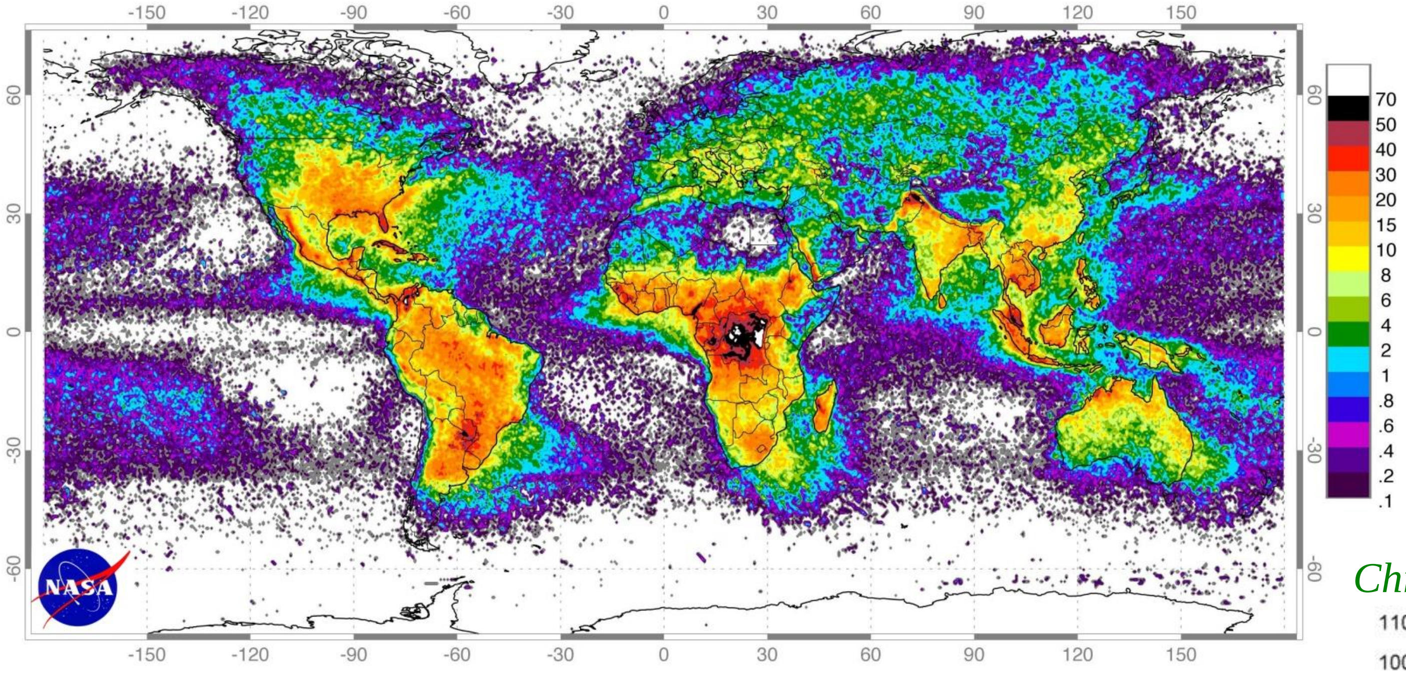
« Waves and Geosciences: infrasound and beyond » - Lyon (France) - March 2022

T. Farges (CEA) and F. Coulouvrat (CNRS & Sorbonne Université)

First worldwide distribution of IntraCloud (IC) and Cloud to Ground (CG) flashes

(space optical observation)

44 ± 5 flashes /s

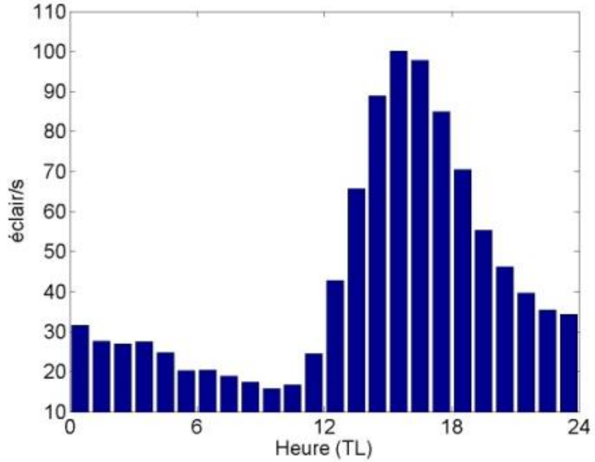


Fl/km²/an

High Resolution Full Climatology Annual Flash Rate

Global distribution of lightning April 1995-February 2003 from the combined observations of the NASA OTD (4/95-3/00) and LIS (1/98-2/03) instruments

Christian et al., 2003



Temporal variabilities

- seasonal : max in summer and fall
- daily : max between 14h and 17h (local time)

« Typical » thunder recording

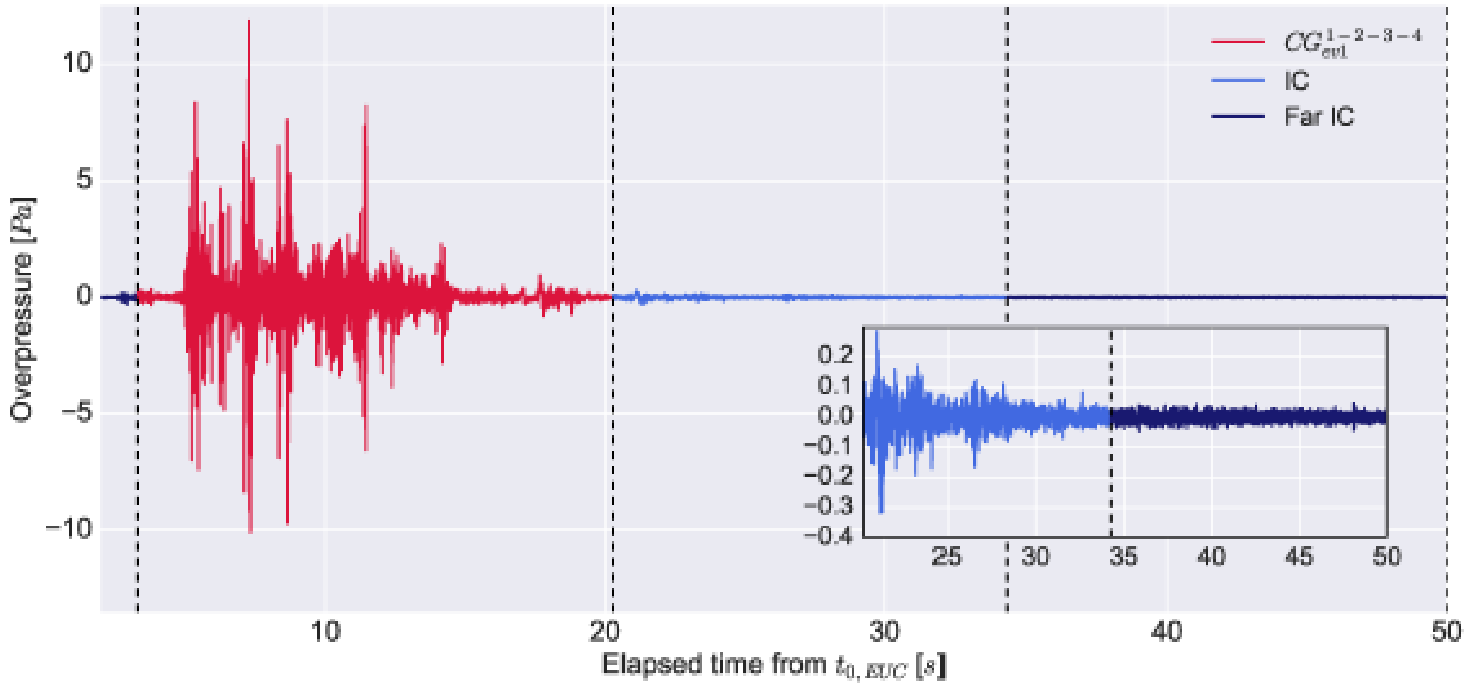
Lacroix et al., JGR, 2018

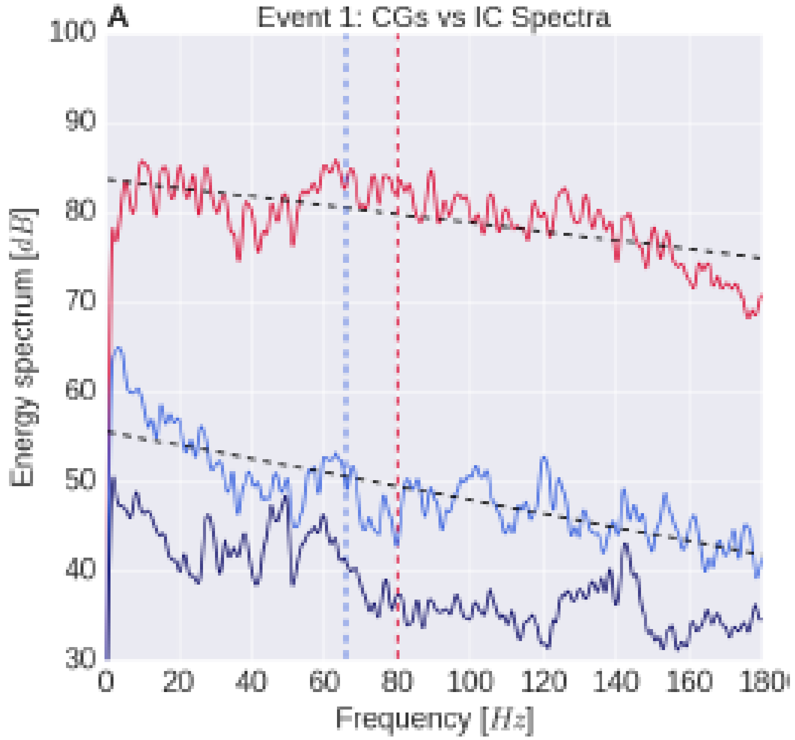
Time domain

- long duration (from a few s to 1 mn)
- large amplitude (up to 50 Pa)
- several peaks (of a few 0.1 s)

Frequency domain

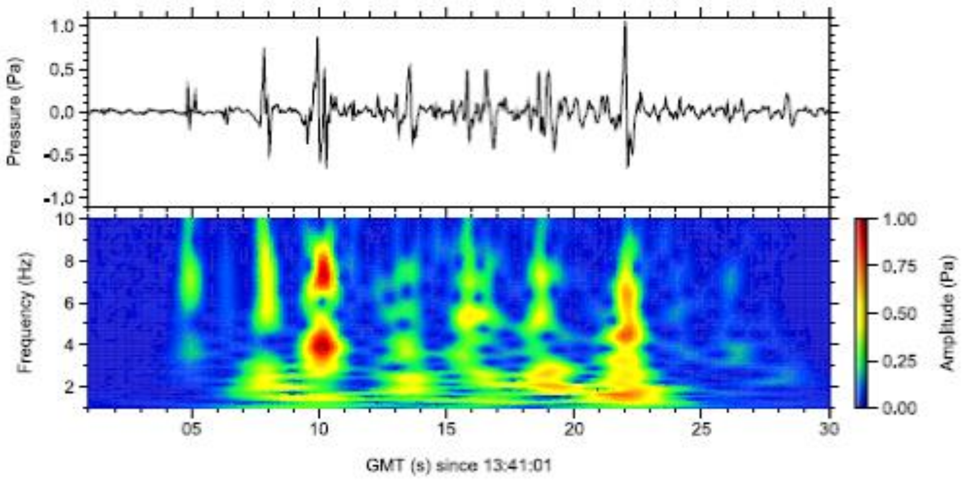
- broadband signal
- slow decay with frequency
- large infrasound content



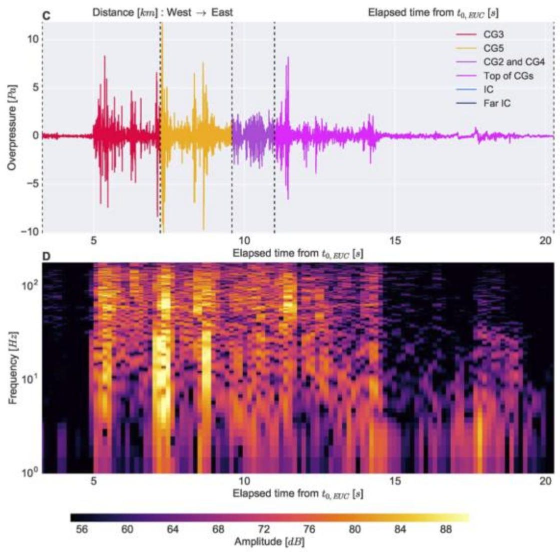


(26/10/2012 - 20:38:12 near Uzès aérodrome - Gard - Southern France)

1 - 10 Hz band (r < 5 km) *Assink et al., GRL, 2008*

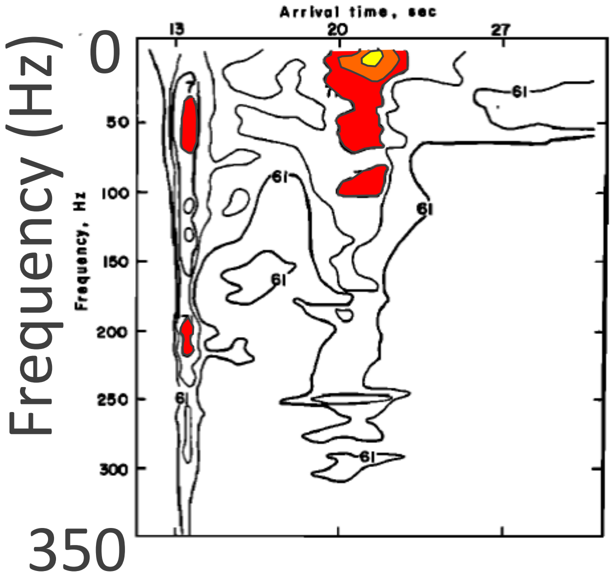


0.5 - 180 Hz band (r = 3 km) *Lacroix et al., GRL, 2018*

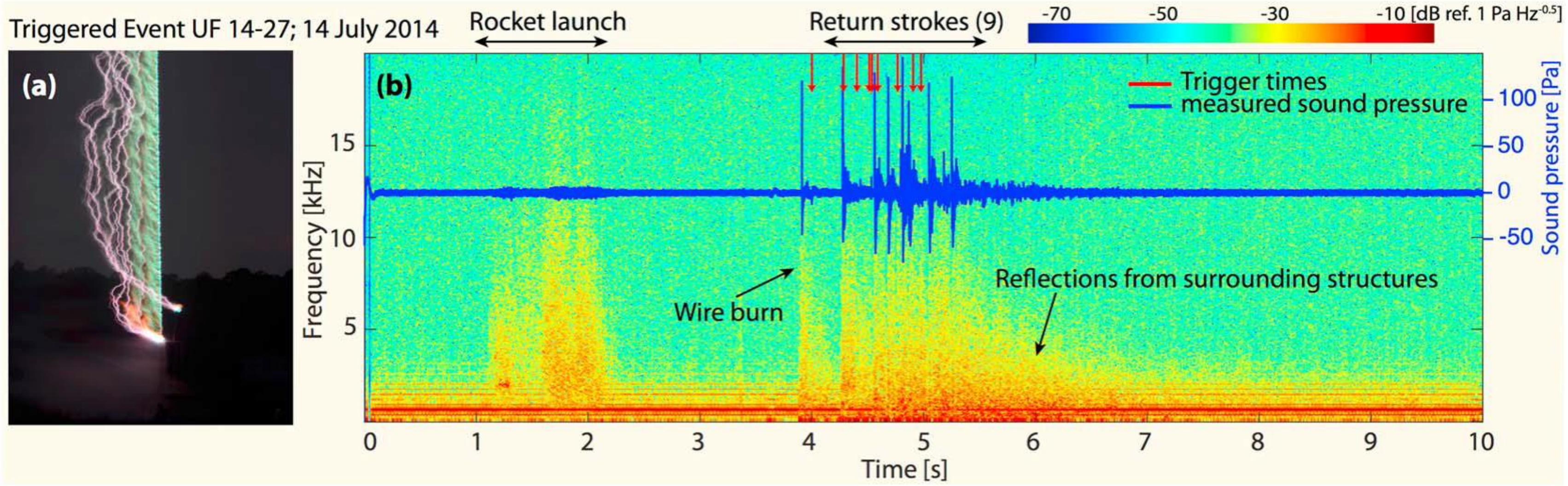


Holmes et al., JGR, 1971

0.3 Hz–20 kHz band



20 Hz–20 kHz band (r = 100 m) *Dayeh et al., GRL, 2015*



Wide-band signal : several types of captors can be used

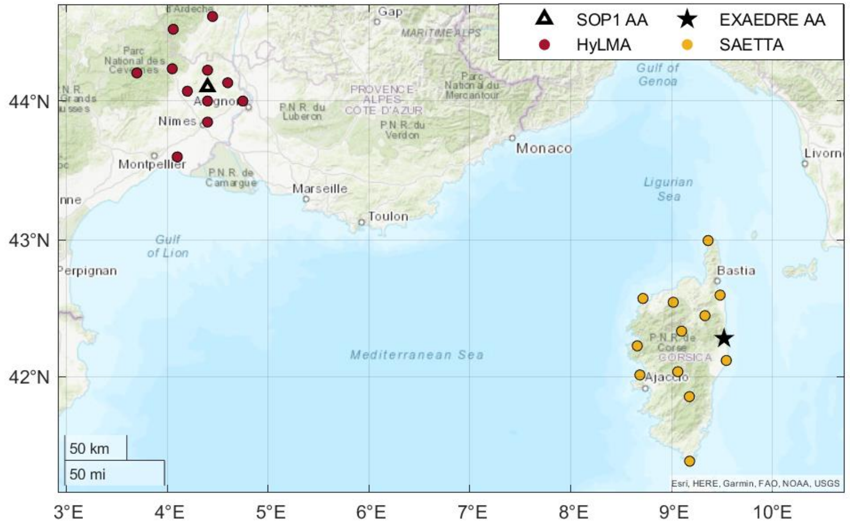
- permanent IMS stations, microbarometers : only the LF part of thunder
- microphones : (bandwidth 0.1 Hz–20 kHz)
- 2 dedicated campaigns

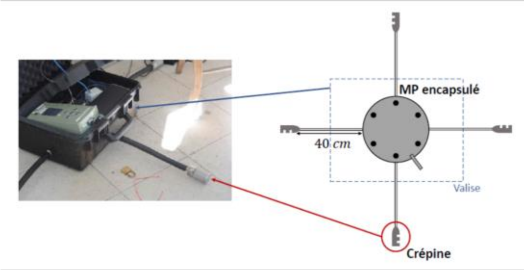
HyMeX SOP1- Southern France - September to November 2012

Array of 4 μbaros (500m) and 4 μphones (50 m - sampling 500 Hz)

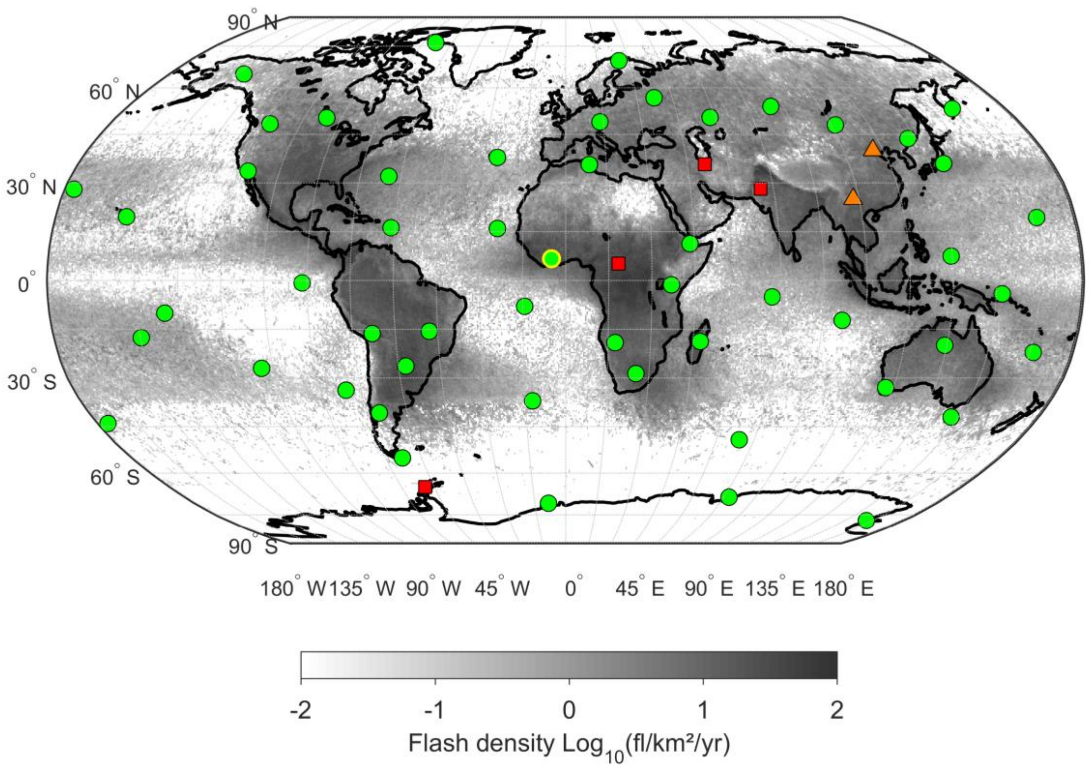
Exaedre - Corsica - September to October 2018

ies





Infrasound Monitoring of CTBT



Farges et al., Atmosphere, 2021

Global Climate Observation

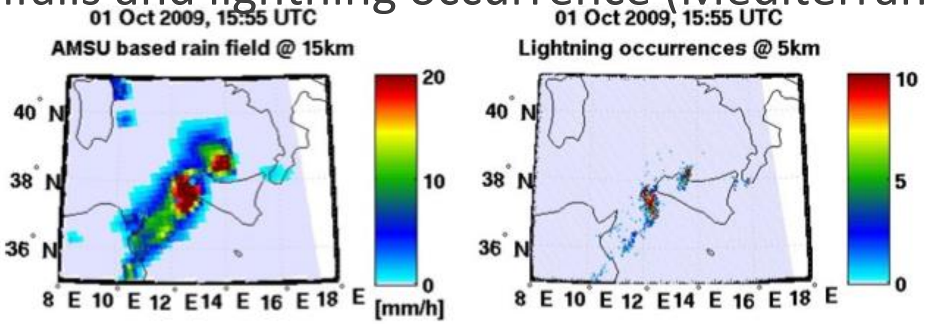
- since 2016, lightning is one of the Essential Climate Variables (ECV) of the Global Climate Observing System (GCOS)
- includes Thunder Day Database (1st historical data)
- acoustics, through thunder recording, is an observational way to detect, reconstruct and characterize lightning, in complement to optical and electromagnetic ones
- **this is the objective of this lecture !**

Zemp, et al. GCOS 240 (2021).

Lightning is a good proxy for delineating high impact convective storms and their intensity (rainfall, cloud cover, cloud top heights, strong convection, severe storms, NOx chemistry, and dynamics including major storms systems) *(Zemp, et al. GCOS 240, 2021)*

Examples of strong correlation between

- intense rainfalls and lightning occurrence (Mediterranean rim)



(Dietrich et al., Nat. Hazards Earth Syst. Sci., 2011)

- increase of lightning occurrence and global warming (Arctic area)

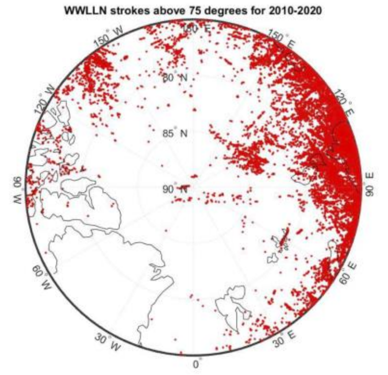


Figure 3. Global distribution of WWLLN strokes in June July and August for 2010–2020 above 75°N. WWLLN, World Wide Lightning Location Network.

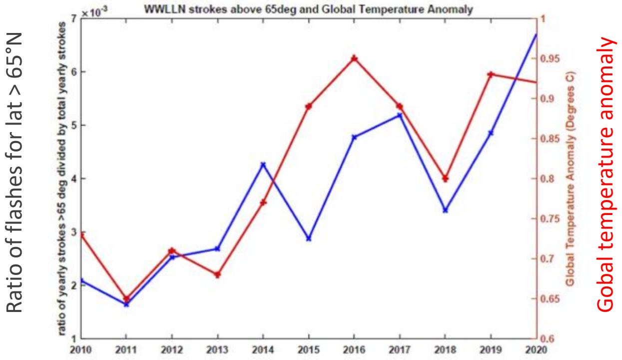


Figure 5. Ratio of the number of WWLLN strokes above 65°N to the Total global WWLLN strokes (blue) and the Global Temperature. Anomaly in degrees C, for June, July, and August each year. WWLLN, World Wide Lightning Location Network.

(Holzworth et al., GRL, 2020)

Roadmap

1. A brief history (FC)
2. Some physics of lightning (TF)
3. Thunder models (FC)
4. Lightning detection by thunder (TF)
5. Lightning reconstruction and characterisation by thunder (FC)
6. Sprites (TF)

A brief history


https://collections.louvre.fr/ark:/53355/cl010270094 https://commons.wikimedia.org/w/index.php?curid=3363148

Zeus holding the Thunderbolt
480/470 b.p., Louvre museum, Paris

ancient Greeks : Zeus

Romans : Jupiter

ancient Germans : Thor (Donner, Thunder)

Gallics : Taranis

ancient Egyptians : Seth

Mesopotamia : Hadad, Ada, Iskur

Hindu mythology : Indra

…

https://collections.louvre.fr/ark:/53355/cl010066113

N. Poussin,
The Flood or the Winter (1660-1664),
Louvre museum, Paris

A. Goscinny & R. Uderzo,
Asterix and the Soothsayer,
Dargaud (1972)

Par Christian Hornemann — fi.wikipedia.org, Domaine public
https://commons.wikimedia.org/w/index.php?curid=3014987

L. van Beethoven
Pastoral Symphony n°6, op.68
4th movement (1808)
A. Vivaldi
Concerto n°2 , op.8, RV315, « Summer »
3rd movement

Until 18th century, electric nature of lightning is completely ignored, and both lightning and thunder remain difficult to explain

(Anaxagore, Anaximandre, Aristote, Asclépiodote, Diogène d'Apollonie, Sénèque, Descartes…)

- lightning : some « fire », or « exhalation » or « vapor » and inflamed for instance by sunlight or by the friction of clouds against one another;
- thunder : noise from air blowing out when a cloud is bursted, or from cloud collisions (analogy with avalanches)

« L'Encyclopédie » (Diderot and d'Alembert)

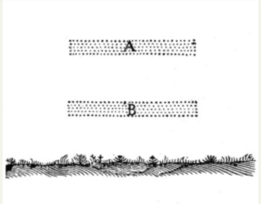
1751 - Tome 5, p.268

- lightning : mixture of sulfurous and oleaginous « vapors » which inflame (analogy with gun powder)
- **distance of lightning can be estimated by time separating lightning from thunder propagating much slower (173 toises / seconde)**

A: hot cloud
> condensation (!)
> heavier
> falls on B

B: cold cloud

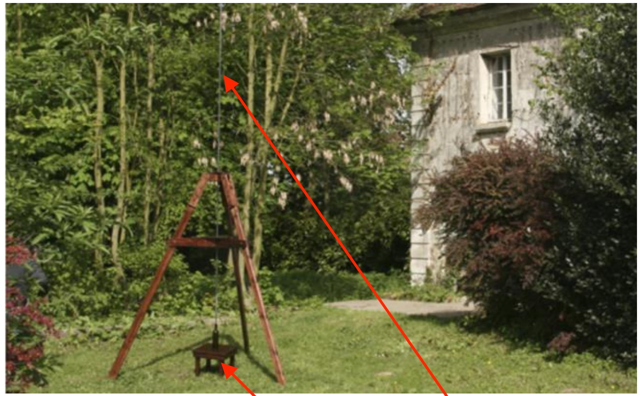
Mais pour les orages qui sont accompaignés de tonnerre, d'esclairs, de tourbillons, et de foudre, desquels iay pû voir quelques exemples sur terre, ie ne doute point qu'ils ne soient causés de ce qu'y ayant plusieurs nues l'vne sur l'autre, il arriue quelquefois que les plus hautes descendent fort à coup sur les plus basses. Comme si les deux nues A et B n'estant composées que de neige fort rare et fort estendue, il se trouue vn air plus chaud autour de la superieure A, qu'autour de l'inferieure B, il est euident que la chaleur de cet air la peut condenser et appesantir peu à peu, en telle sorte que les plus hautes de ses parties, commenceant les premieres à descendre, en abbatront ou entraisneront auec soy quantité d'autres, qui tomberont aussy tost toutes ensemble auec vn grand bruit sur l'inferieure. En mesme façon que ie me souuien d'auoir vû autrefois dans les Alpes, enuiron le mois de May, que les neiges estant eschauffées et appesanties par le soleil, la moindre esmotion d'air estoit suffisante pour en faire tomber subitement de gros tas, qu'on nommoit ce me semble des aualanches, et qui retentissant dans les valées imitoient assés bien le bruit du tonnerre. En suite de quoy on peut entendre pourquoy il tonne plus rarement en ces quartiers l'hyuer que l'esté. car il ne paruient pas alors si aysement



R. Descartes, Les Météores, 1637, Discours septiesme, Des tempestes, de la foudre, et de tous les autres feux qui s'allument en l'air.

- mid 18th century : abbé J.A. Nollet (and others) suggest electrical nature of lightning
- July 29, 1750: 1st public suggestion by Benjamin Franklin of an experiment proving this nature (printed in April 1751)
- May 10th 1752: inspired by Franklin, 1st experiment by Thomas-François Dalibard, in Marly-la-Ville, reported three days later at French Academy of Sciences
- June 15th, 1752 : Franklin and his son may (?) perform privately the famous kite experiment (reported only on 19th October)

replica of Dalibard experiment in Marly-la-Ville



Benjamin West (circa 1816)

Benjamin Franklin drawing Electricity from the Sky

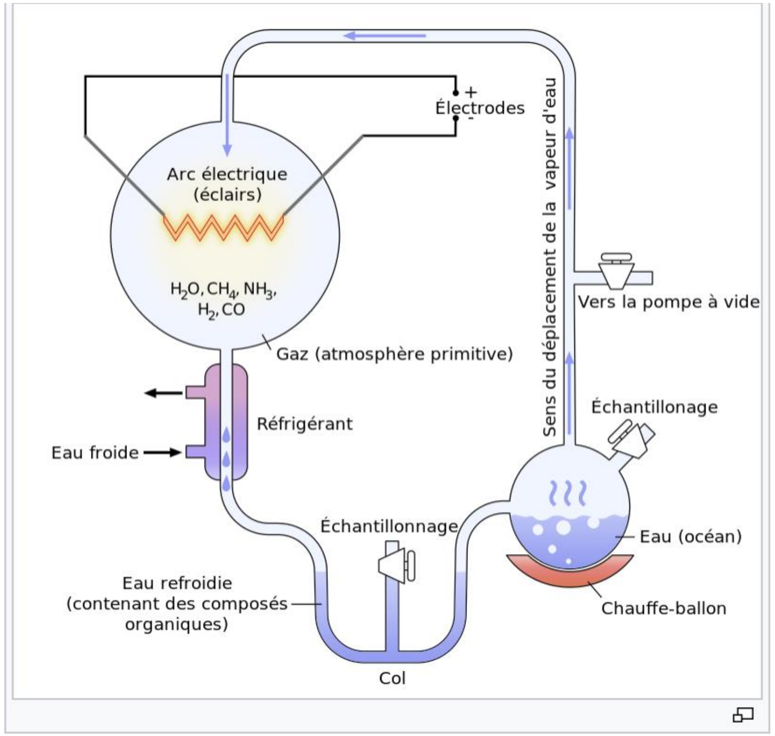
Philadelphia Museum of Arts

1953 famous Miller's experiment

Miller, Science, 117, 1953

putative Earth early atmosphere
water (H_2O)
methane (CH_4)
ammonia (NH_3)
hydrogen (H_2)
+ electric spark (for ligthning)

output
5 (now 11) prebiotic amino-acids



https://fr.wikipedia.org/wiki/Exp%C3%A9rience_de_Miller-Urey

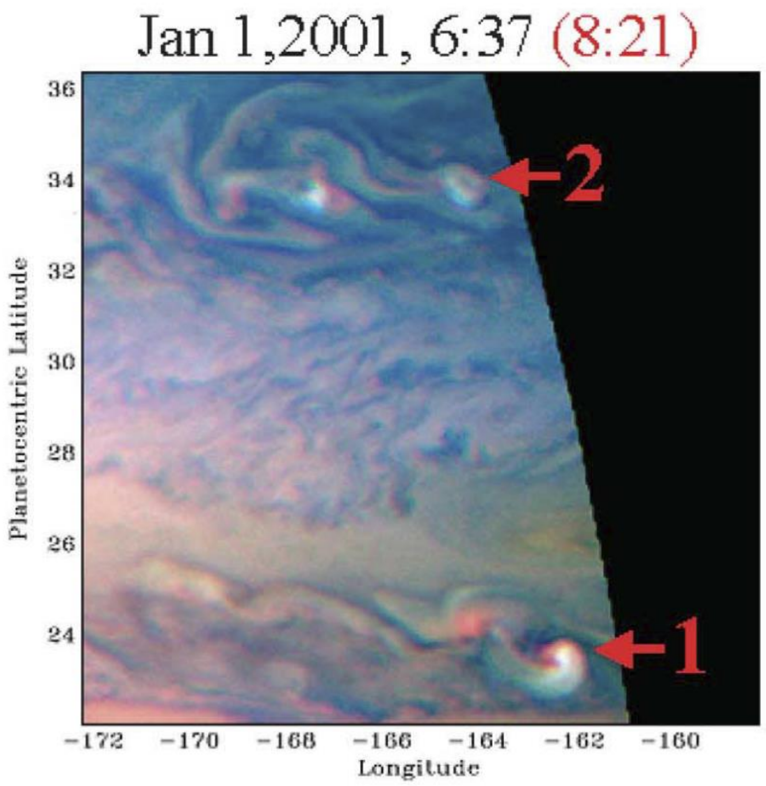
Lightning, one ingredient of life's origin ?

Optically observed (Voyager, Galileo, Cassini)
- Earth (ice-water clouds)
- Jupiter (ice and/or ammonia clouds) *Gurnett et al. GRL, 1979*
- Saturn (ice and/or ammonia clouds)

Likely (indirect observations : EM bursts, chemistry…)
- Uranus, Neptune

Debatable
- Venus (aerosols, sulphuric acid)

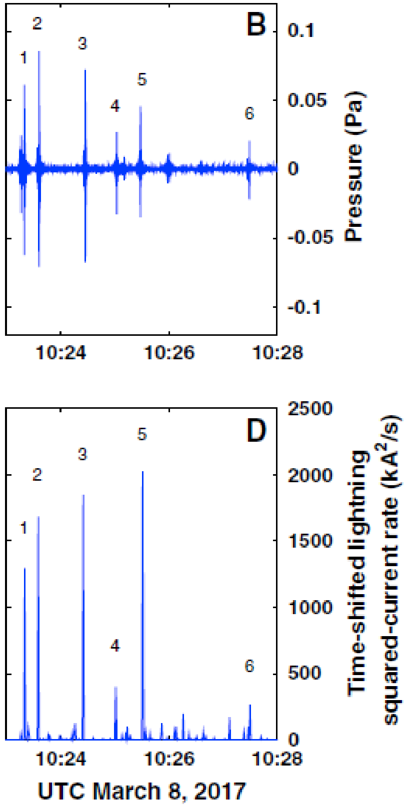
Theoretically possible
- Mars (dust), Titan (methane)



Cassini: correlation between lightning on the night-side (red arrows) with dayside Jovian clouds. False colors

Dyudina et al., Icarus, 2004

Thunder measurement during Bogoslof eruption (Alaska, March, 2017)



Haney et al., GRL, 2018

Hunga Tonga-Hunga Ha'apai
15 janvier 2022

Sakurajima, Japan

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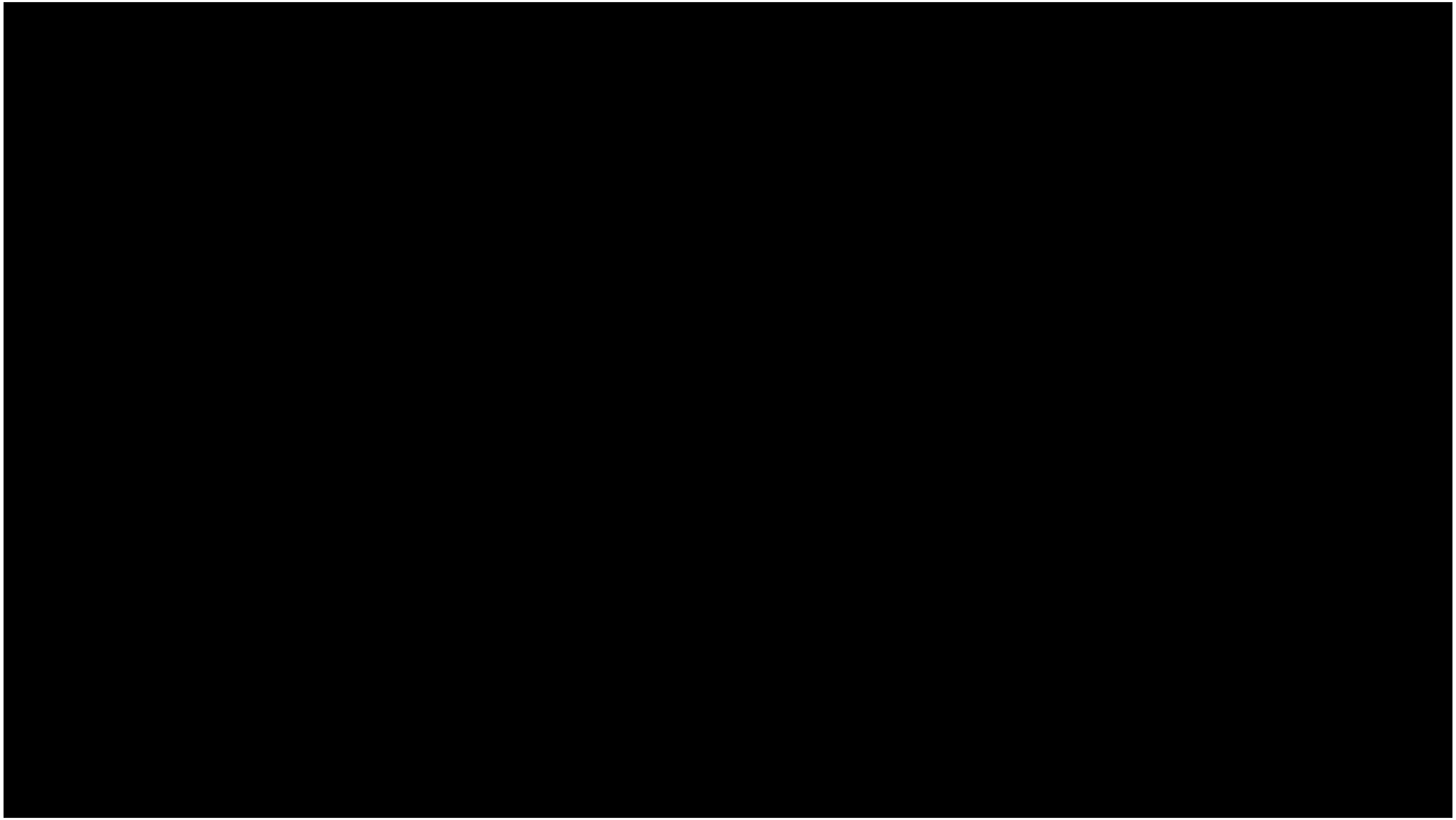
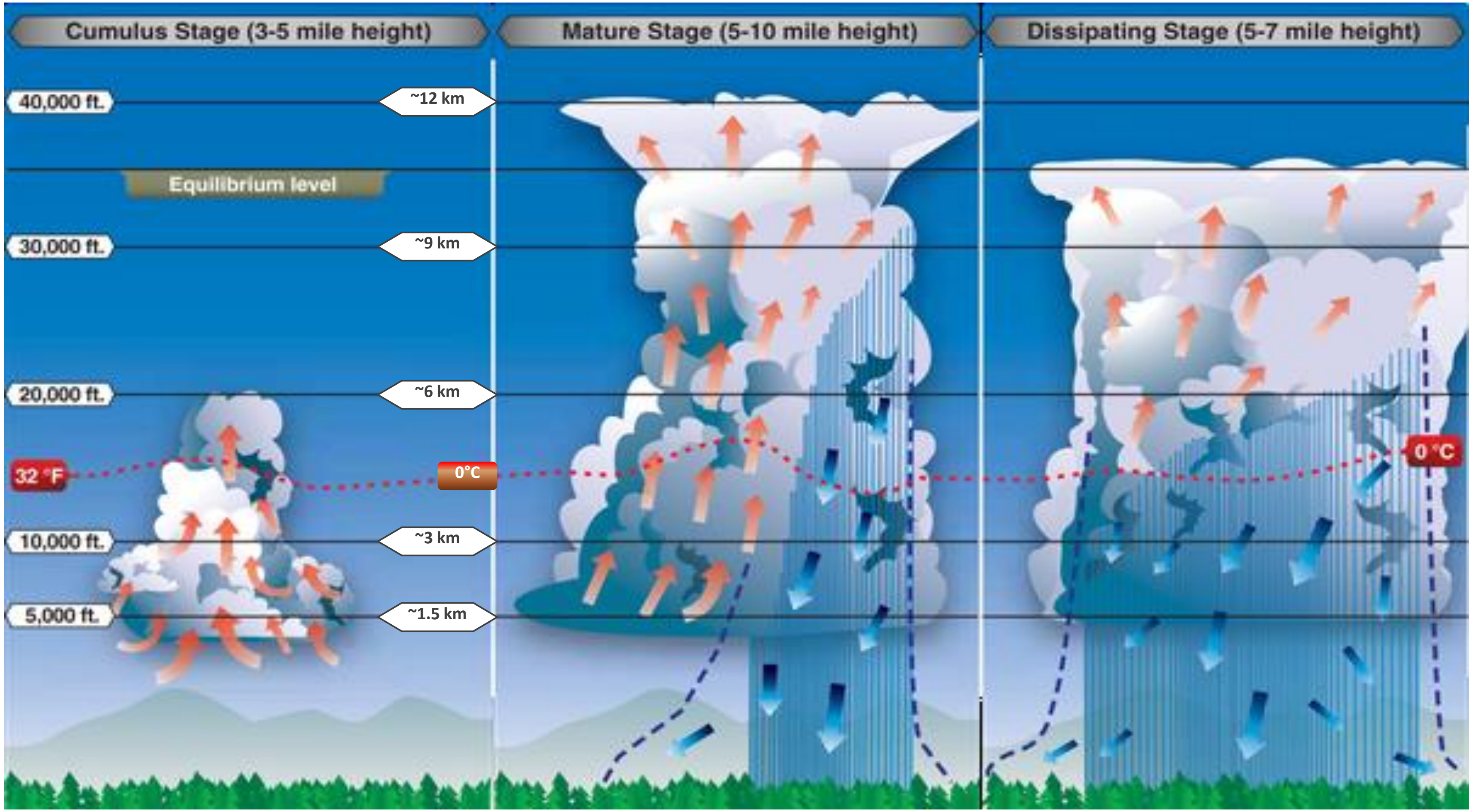
Some physics of lightning

Developing stage of a cumulonimbus

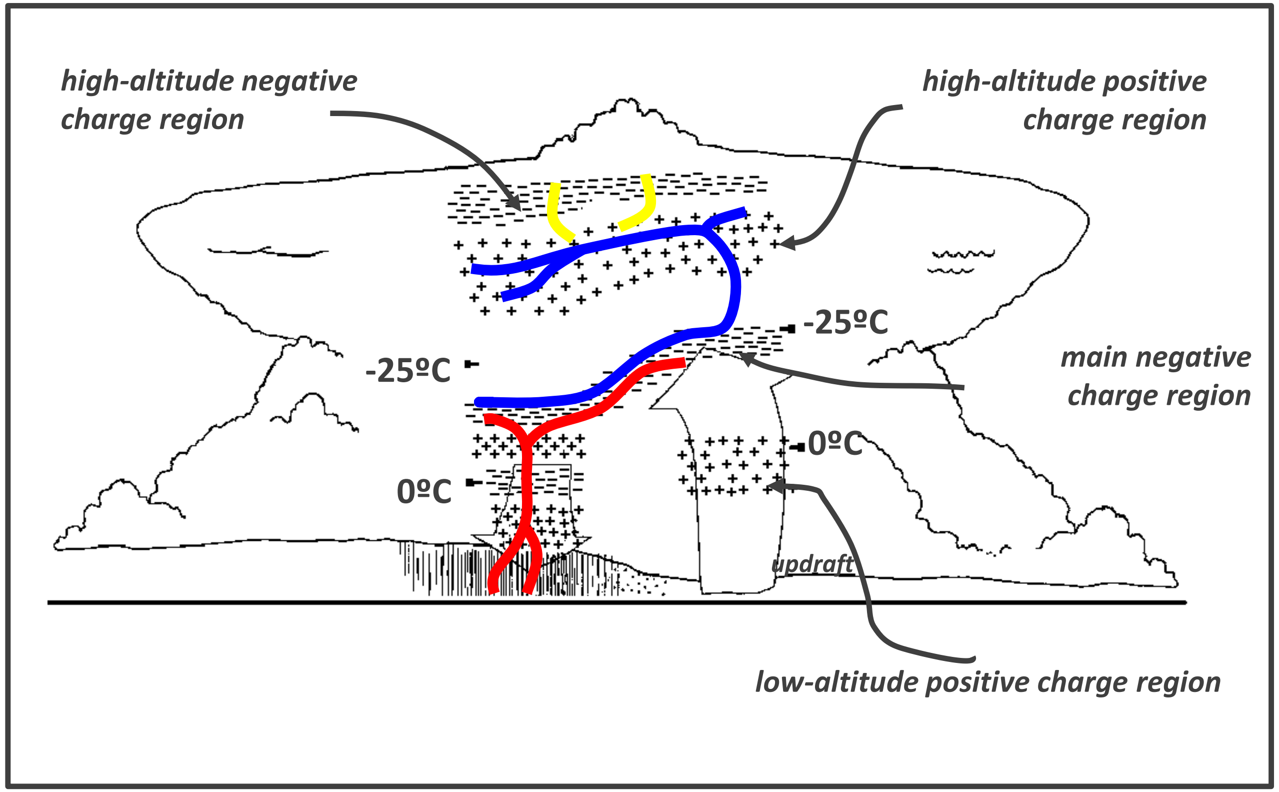


Developing stage of a cumulonimbus



Source: FAA Handbooks and Manuals

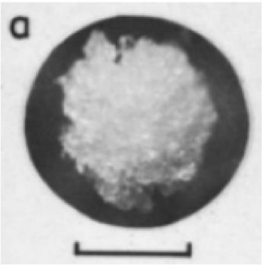
convective cells = cumulonimbus



From *Stolzenburg and Marshall, 2008*

The cloud electrification arises from the interaction between hydrometeors: ice crystals (a few micrometers), graupel (a few millimeters) and supercooled liquid water droplets.

Above the isotherm -10°C, **ice crystals** are charged **positively** and **graupel negatively**. It is the opposite below the isotherm -10°C.



graupel photo

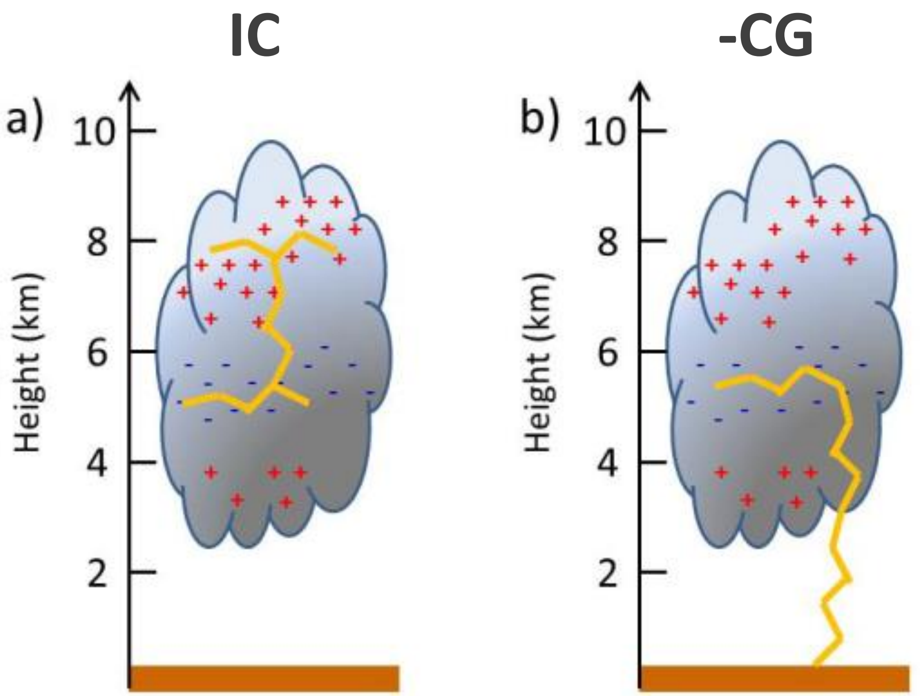
Locatelli and Hobbs, JGR, 1974

Two main categories of discharges

- **intra-clouds** or inter-clouds (**IC**) - 75% of all discharges
- **cloud-to-ground** (**CG**) - 25% of all discharges, and among them

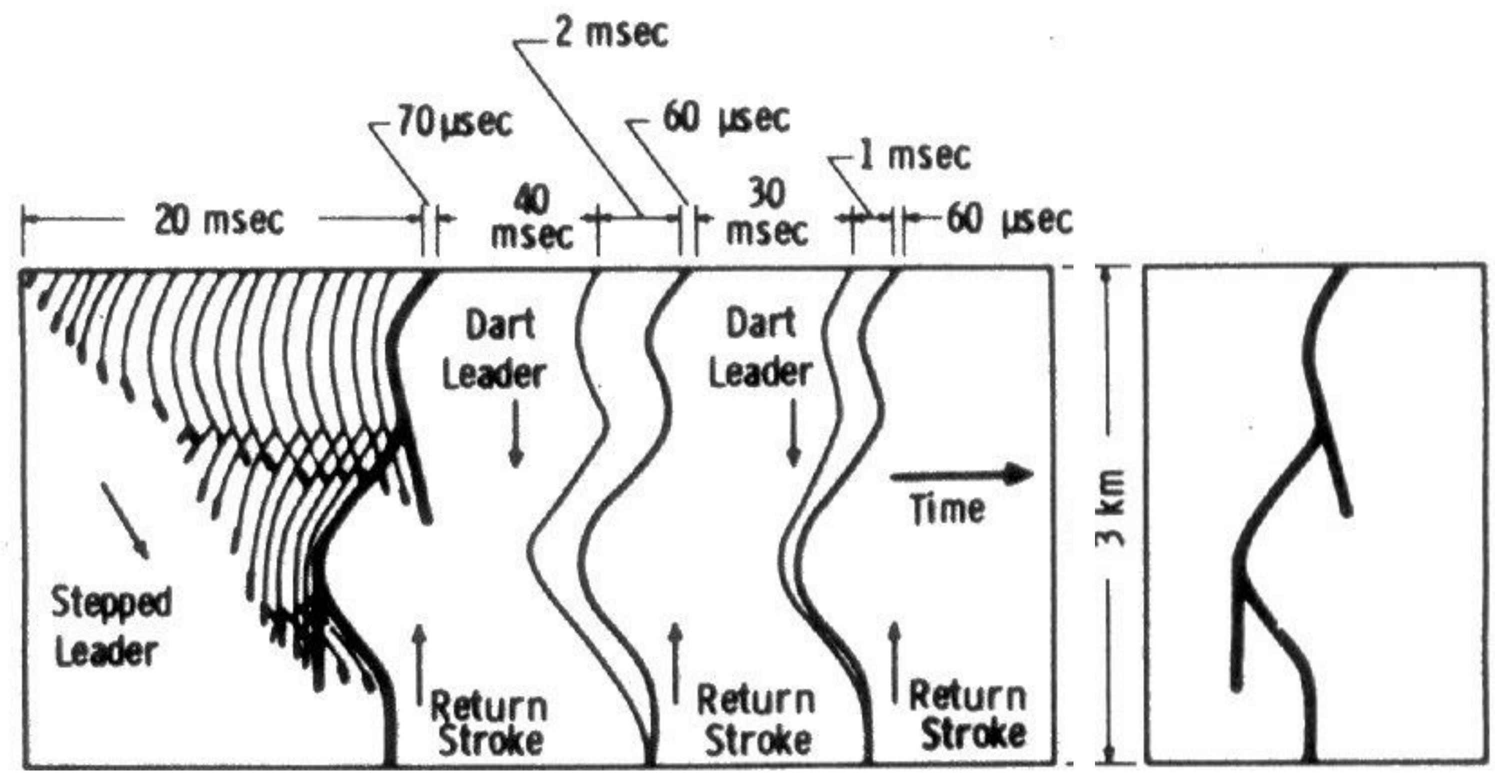
  - 90% of **negative** discharges
    (**-CG**, negative charges going down from the cloud)

  - 10% of **positive** discharges
    (**+CG**, positive charges going down from the cloud)



Farges et al., Springer, 2019

Flash occurring inside a cloud seen from the side



Rakov and Uman, 2005

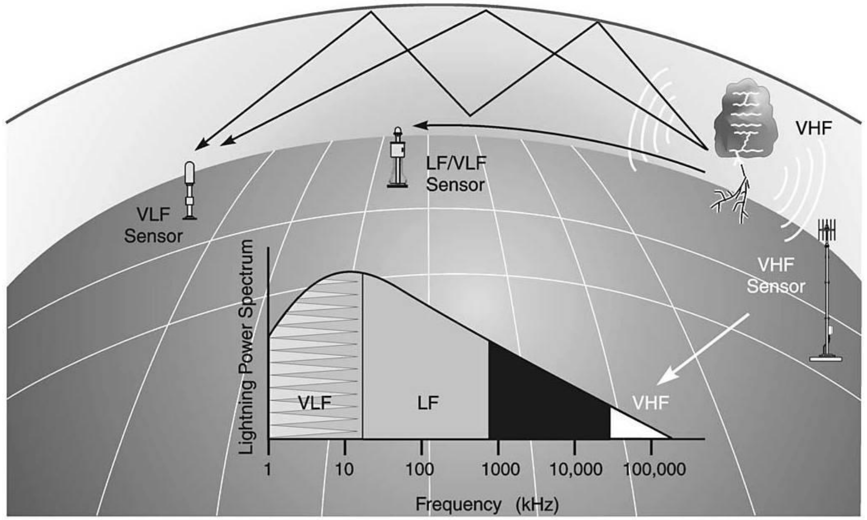
stepped leader	<	return stroke	<	interval between return strokes	<	total flash
1-5 µs		50-100 µs		20-50 ms		0.2 - 1 s

touchdown

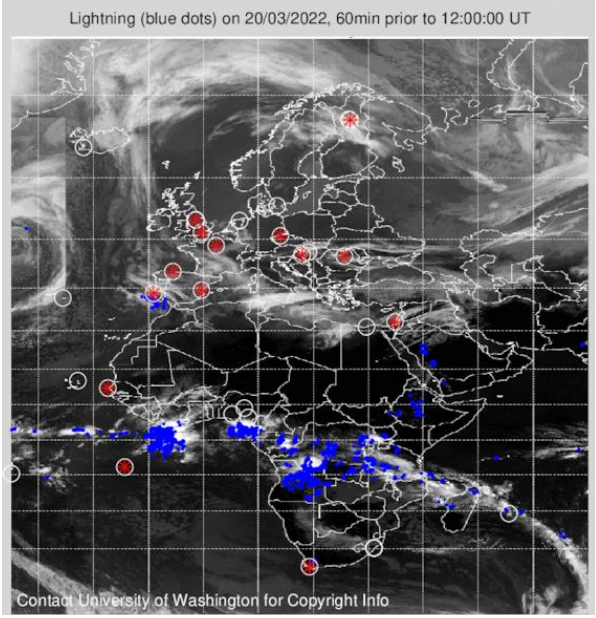
High-speed camera, 7 000 images / s
© Tom A. Warner

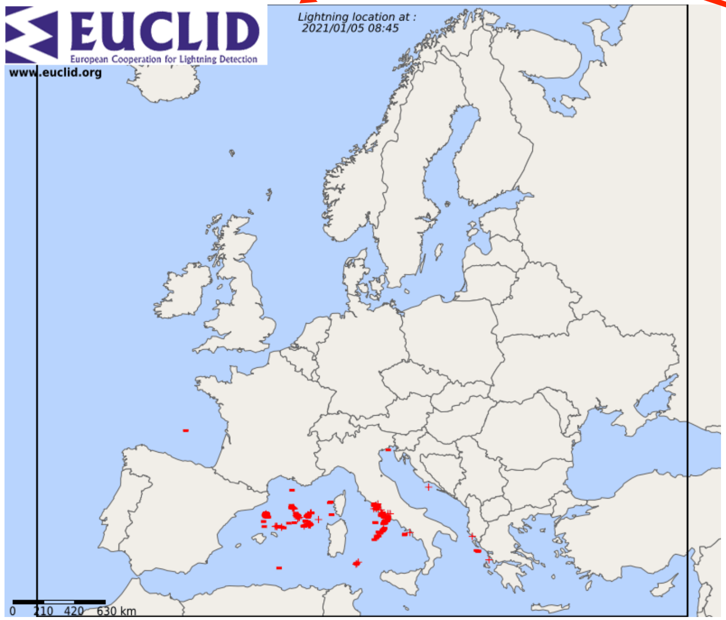
Lightning location networks using electromagnetic waves

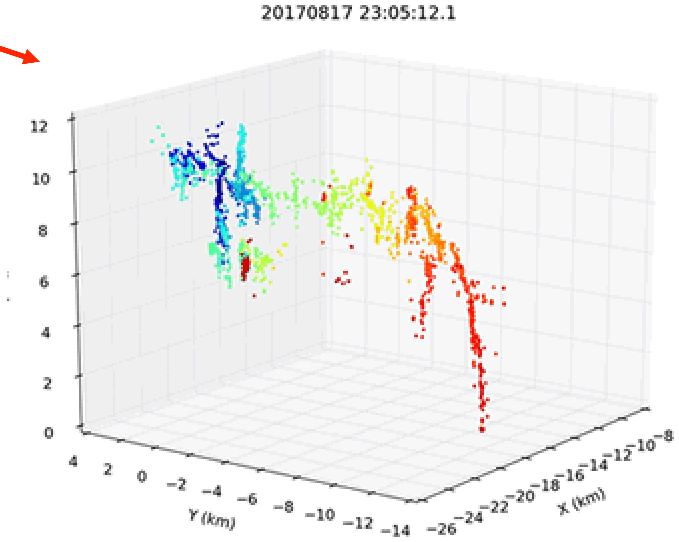
	Global	Continental	Regional (300 km)
Spectrum	VLF	VLF-LF	VHF
# sensors	60	150 - 200	10 - 30
Efficiency	20-70% CGs	>90% CG < 10 % IC	Mainly IC and leaders



Cummins et Murphy, 2009

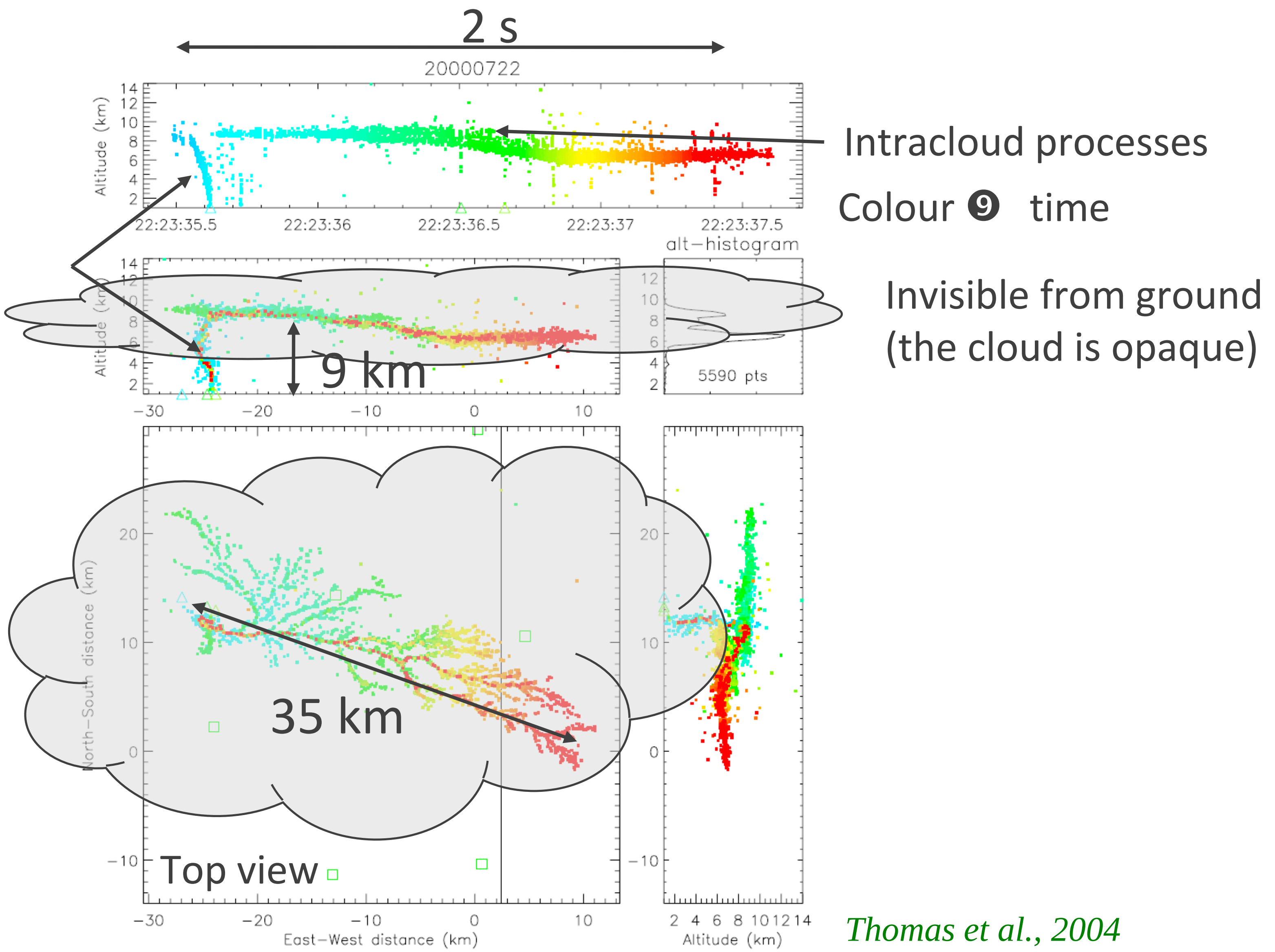






Takagi･Wang･Wu Lab-FALMA (gifu-u.ac.jp)

Example of VHF detection
(Lightning Mapping Array)



Thomas et al., 2004

Thunder models

Thunder: two main models in the literature

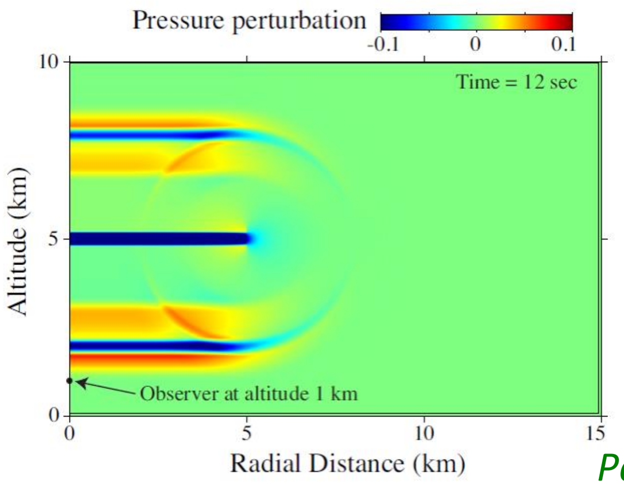
The **electrostatic** model (pressure release following the discharge)

The **hydrodynamical** model (shock wave from the lightning channel)

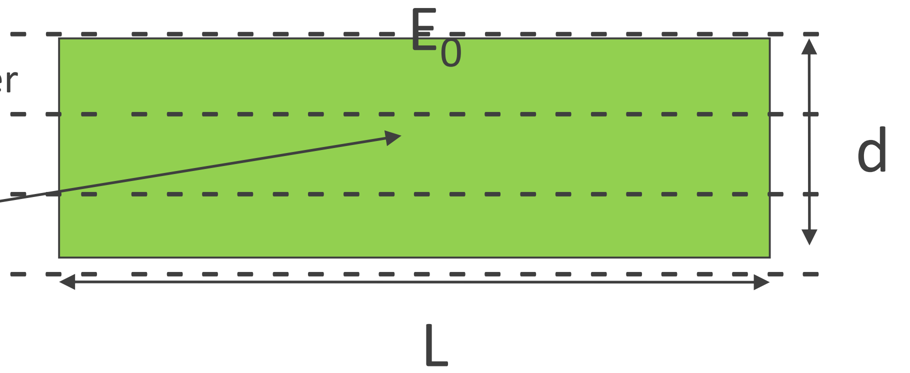
The electrostatic model

Layers of charged particles in the cloud : lower pressure because of electrostatic repulsion
Electrical flash > charge annihilation > cloud contraction > low frequency acoustic wave
Electrostatic model : conversion into acoustic energy of part of the electrostatic energy contained in the cloud before the discharge (*Wilson, 1920; Dessler, 1970; Few, 1985; Pasko, 2009*).

"The pressure within a charged cloud - like that within a charged soap bubble – must be less than the pressure outside" … " It is evident however that the sudden contraction of a large volume of air must furnish a by no means negligible contribution to the thunder which follows the discharge." (Wilson, 1920 - Nobel Prize in 1927).

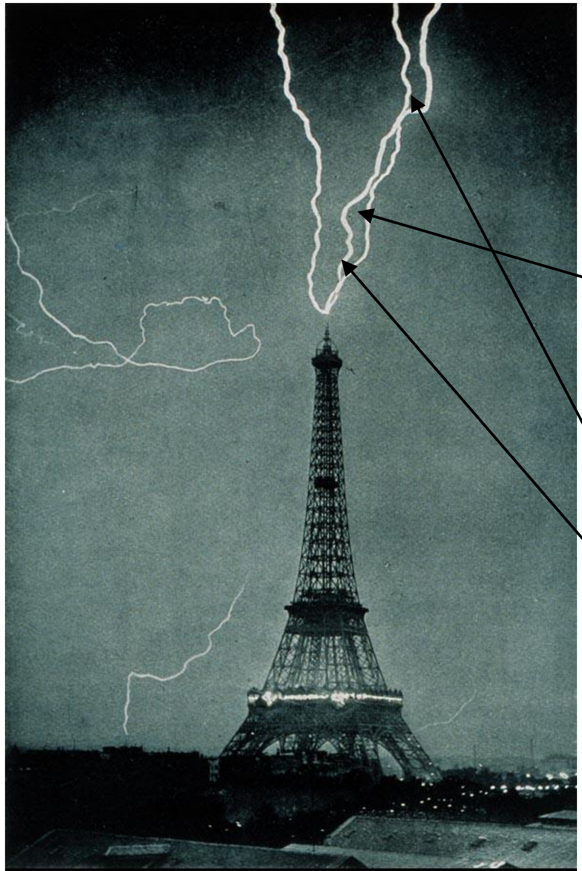


Pasko, ICTCA, 2009



$$\Delta P = -\varepsilon_0 E_0^2/2$$

The calculated amplitude (**few Pa**) and frequency (**0.1 - 10 Hz**) are in agreement with the observations. But the emission pattern is very vertical. The detection of infrasound from flashes located several kilometers away (>> 10 km) cannot be explained by this mechanism.



Photograph of lightning striking the Eiffel Tower, June 3, 1902, taken by M.G. Loppé.

Lightning: local ionization at high temperature (~ 30,000 K)

High temperature

> high pressure

> strong shock around the ionized channel

> decays away from the source

Tortuous geometry ⇨ +/- interferences

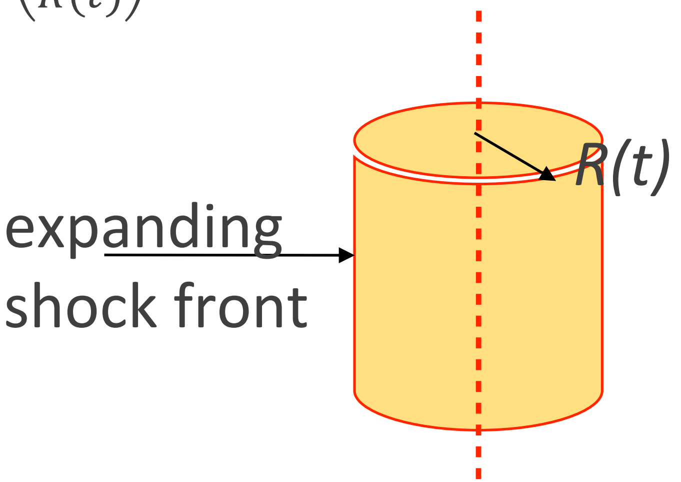
Mass	Momentum	Perfect gas
$\frac{\partial\rho}{\partial t}+\frac{\rho v}{r}+\frac{\partial(\rho v)}{\partial r}=0$	$\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}\right)+\frac{\partial p}{\partial r}=0$	$p/\rho^{\gamma}=Cte$

$r < R(t)$ Self-similar solution

$$p(r,t)=p_0\left(\frac{R_0}{R(t)}\right)^2 f\left(\frac{r}{R(t)}\right)$$

$$v(r,t)=c_0\left(\frac{R_0}{R(t)}\right)\phi\left(\frac{r}{R(t)}\right)$$

$$\rho(r,t)=\rho_0\psi\left(\frac{r}{R(t)}\right)$$



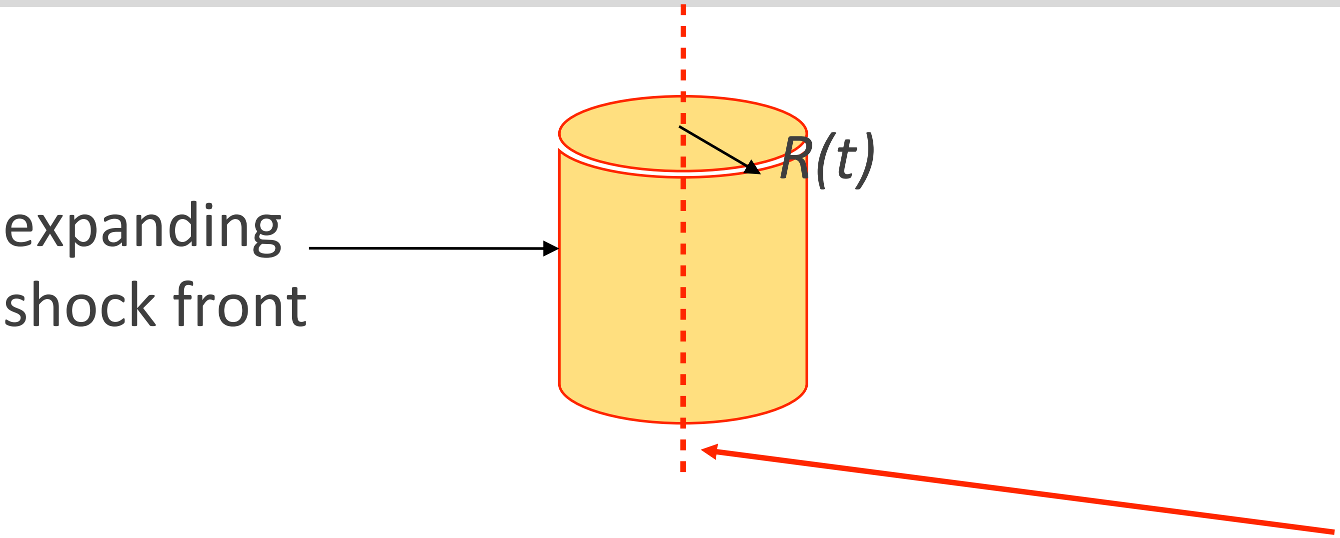
$r > R(t)$ Strong shock approximation

$$p \approx 0$$
$$\rho \approx 0$$
$$v \approx 0$$

$r = R(t)$ Rankine-Hugoniot relations

Lin, J. Appl. Phys., 1953

Deposited energy and intrinsic radius



Single driving parameter : **deposited energy / unit length** [J/m] E_0

Time variation $$R(t) = Cte\left(\frac{E_0}{\rho_0}\right)^{1/4} t^{1/2}$$

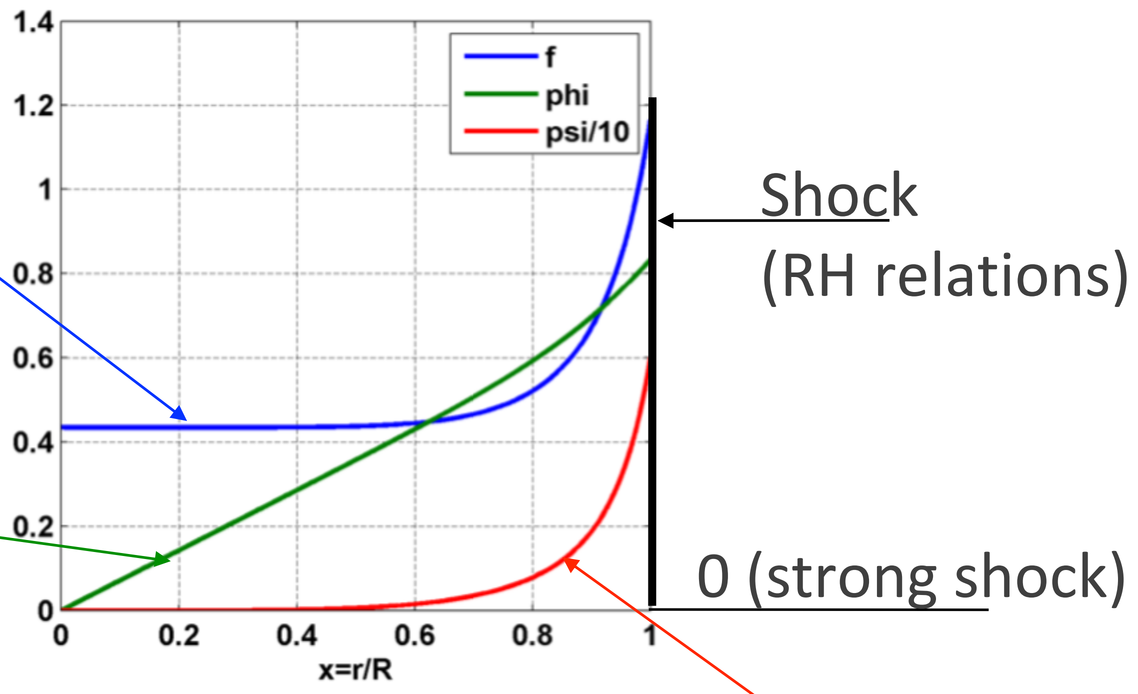
Shock intrinsic radius R_0 $$R_0 = Cte\left(\frac{E_0}{p_0}\right)^{1/2}$$

Lin, J. Appl. Phys., 1953

Self-similar solution

$$p(r,t) = p_0\left(\frac{R_0}{R(t)}\right)^2 f\left(\frac{r}{R(t)}\right)$$

$$\rho(r,t) = \rho_0\psi\left(\frac{r}{R(t)}\right)$$



$$v(r,t) = c_0\left(\frac{R_0}{R(t)}\right)\phi\left(\frac{r}{R(t)}\right)$$

$$R_0 = Cte\left(\frac{E_0}{p_0}\right)^{1/2}$$

$E_0 \in [1 - 100] J/cm$ ➡ $R_0 = 1 - 10cm$

Lin, J. Appl. Phys., 1953

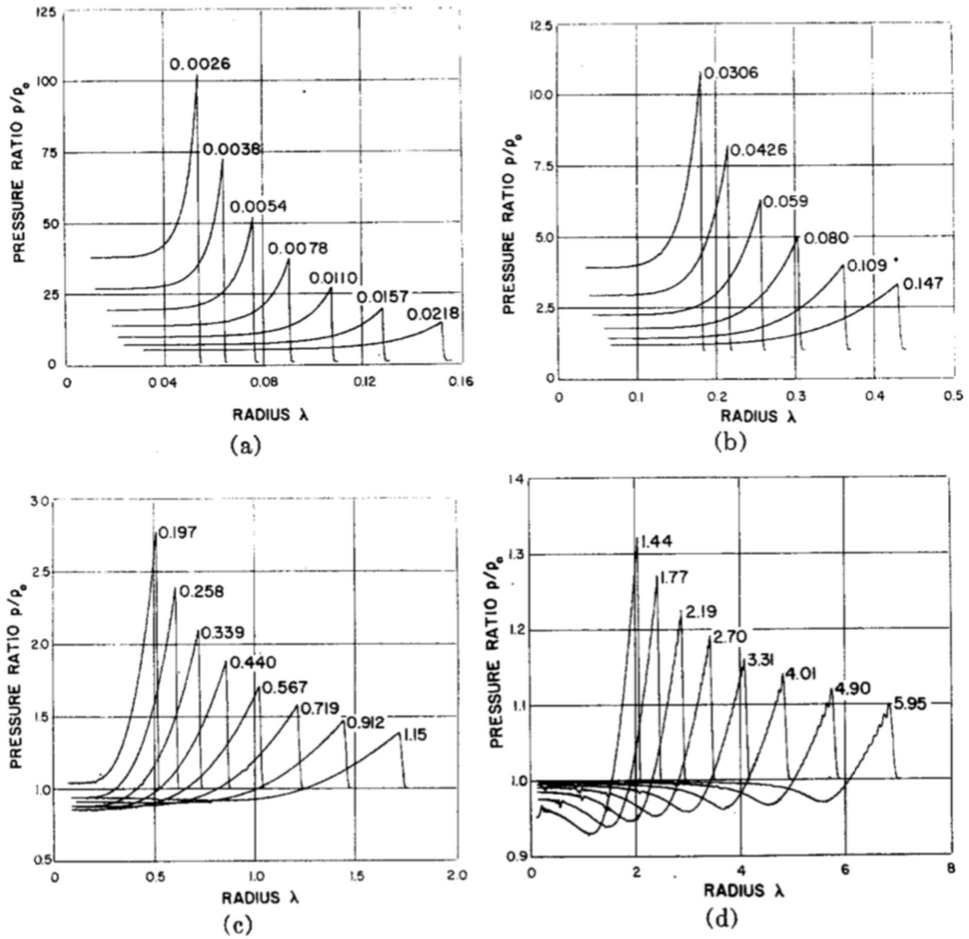
For $R(t) >> R_0$: strong shock approximation invalid

No more analytical solution

Numerical simulation

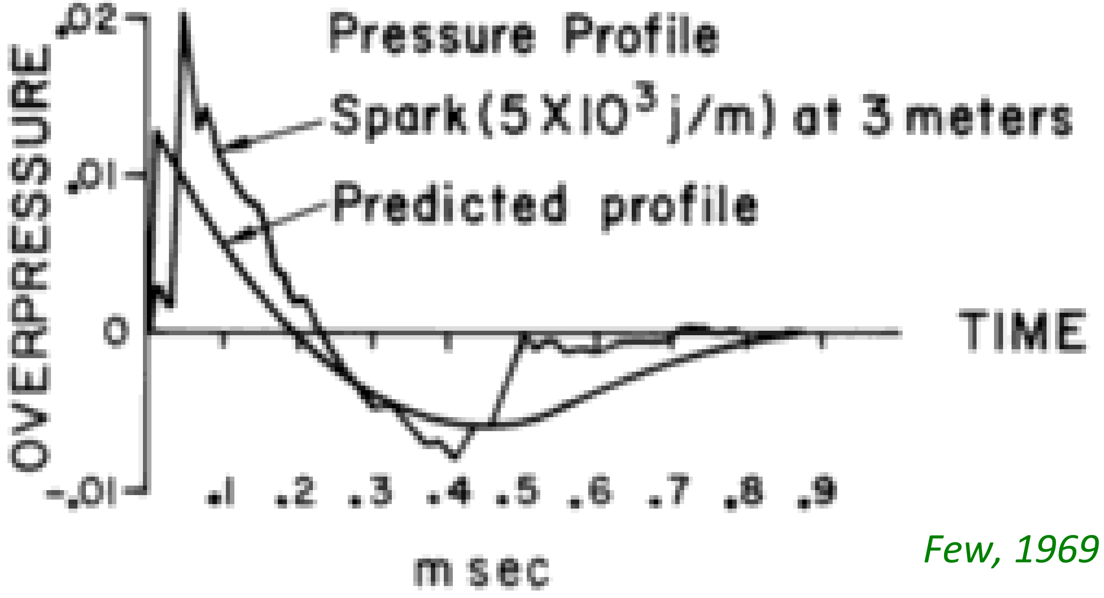
Transition from strong to weak shock

Expansion phase progressively appears behind the shock

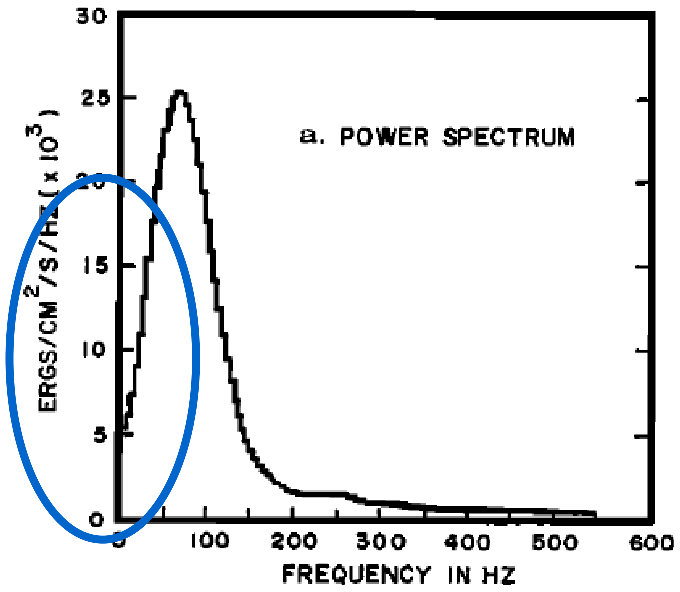


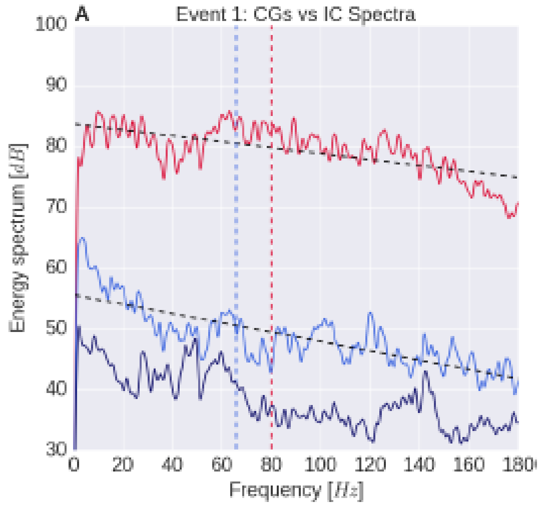
Plooster, Phys. of Fluids, 1970

Experimental validation (spark)



Few, 1969





The hydrodynamic model
1) explains the audible part (thunder)
but
2) underestimates infrasound amplitude
(needed energy would be too high).
3) observed spectra are not so sharply peaked

Optical observations for -CG (90 % of cases)

- lightning strokes in **steps** about **8 m** long

  LeVine & Gilson, NASA, 1984

- mean deviation between steps **16.3°**

  Hill, JGR, 1968

Random model for generating a tortuous source

Ribner & Roy, J. Acoust. Soc. Am., 1982

> Constructive and destructive interferences between various steps **(frequency dependent)**

> At sufficient distances, each step can be viewed as a point source

> « Chain of pearls » model *Few, JGR, 1969*

regime	Strong shock	Weak shock	Acoustic nearfield	Acoustic farfield
decay	r^{-2}	$r^{-3/4}$	$r^{-1/2}$	r^{-1}

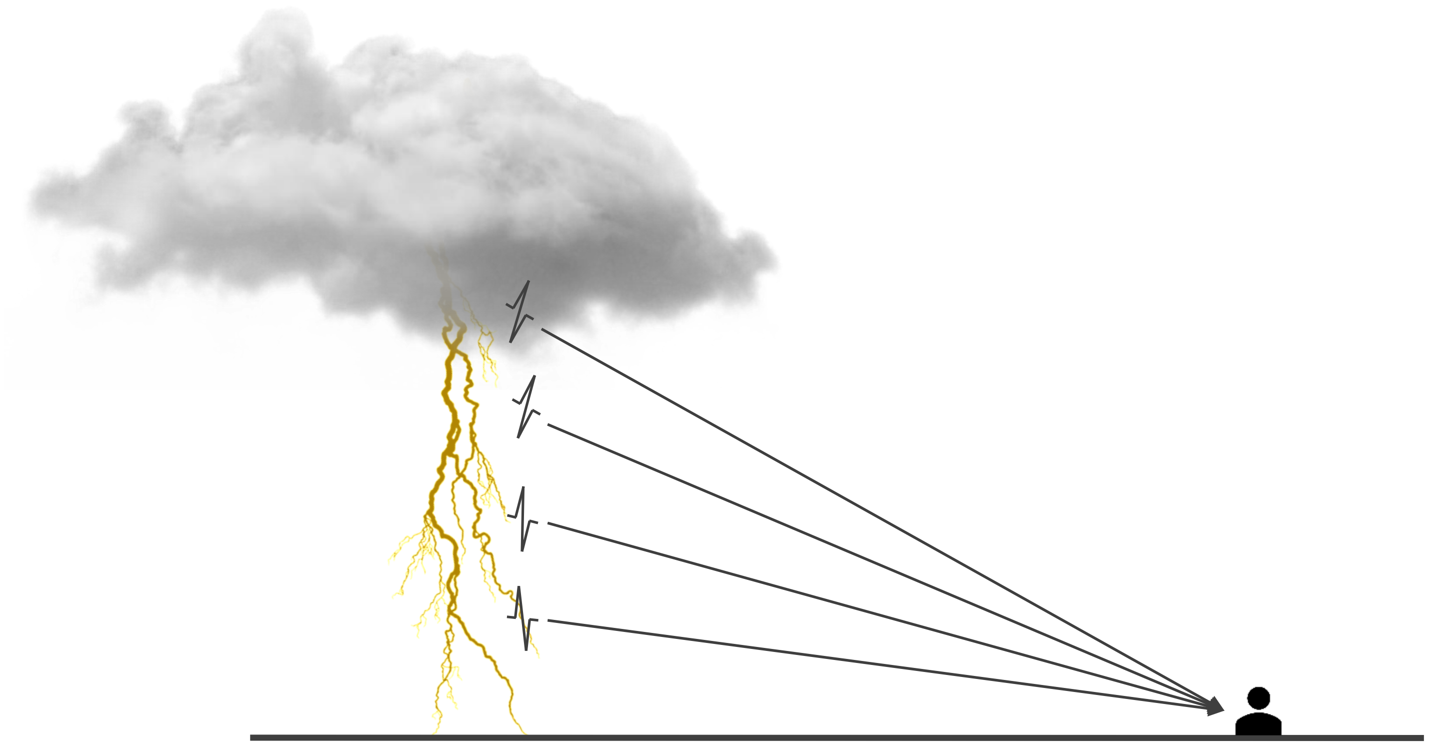
acoustical observations

size	$\approx 1cm$	$\approx 8m$	$\approx 3 - 5km$
scale	Intrinsic radius	Step length	Near- to far-field transition Return stroke height

A new hydrodynamic model

We developed *(Lacroix et al. GRL, 2019)* a new model based on *Few (1969, 1995)* model to explain the full acoustic spectrum and its variability with distance. It takes into account three components:

1. a radiation-hydrodynamics source model,
2. a random lightning geometry using –CG characteristics (tortuosity),
3. a propagation model including absorption

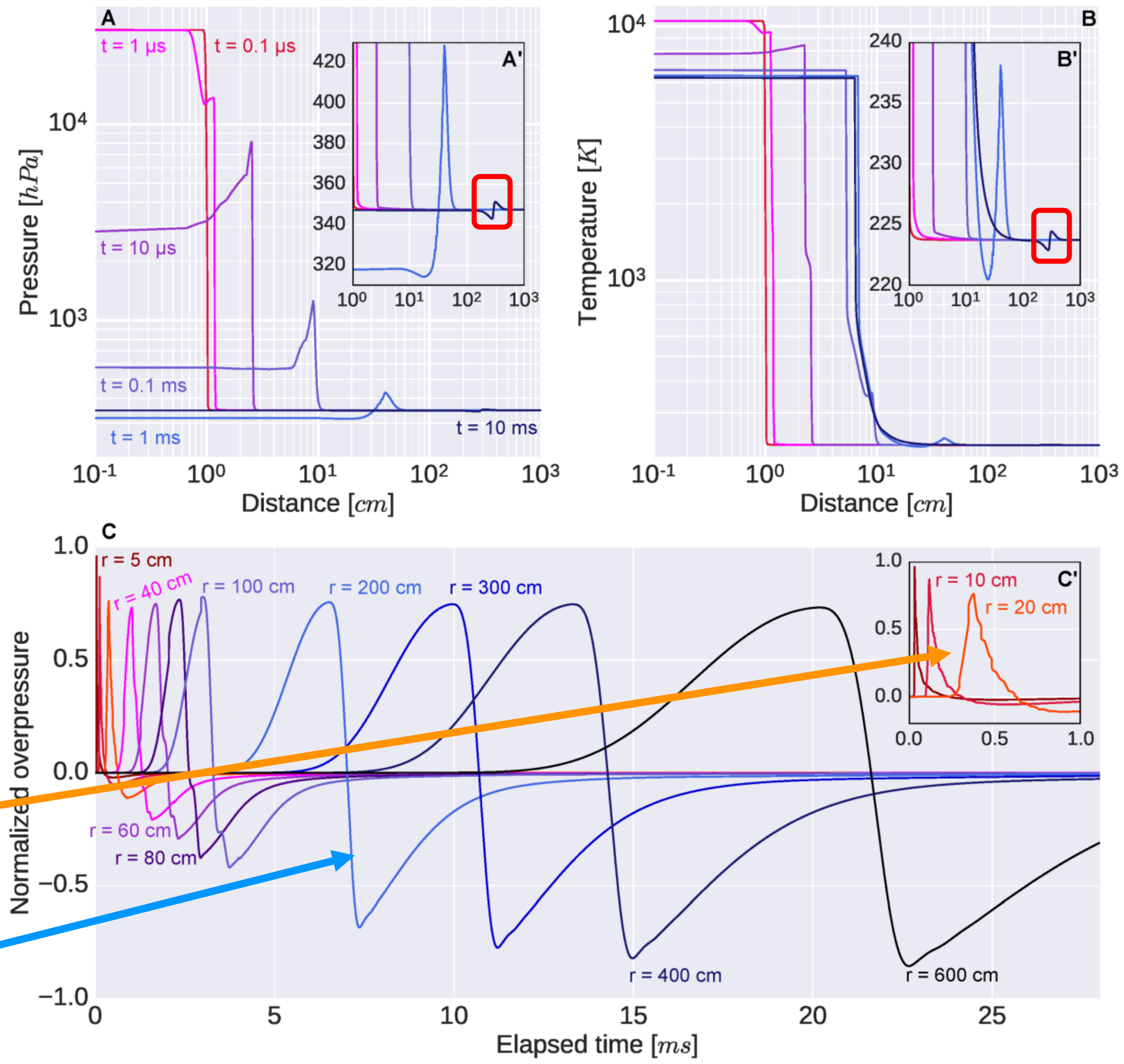


New model: the strong shock

Source model
- coupling between hydrodynamics **AND** radiative transfer
- cylindrical geometry

Ripoll et al. (2014)

3 values of deposited energy, consistent with usual return stroke values (*Borovsky (1998); Cooray (2003)*)
4 J/cm - 28 J/cm - 60 J/cm



- Kinney-like shock wave close to the channel (20 cm)
- Smooth wave far from the channel (200 cm)

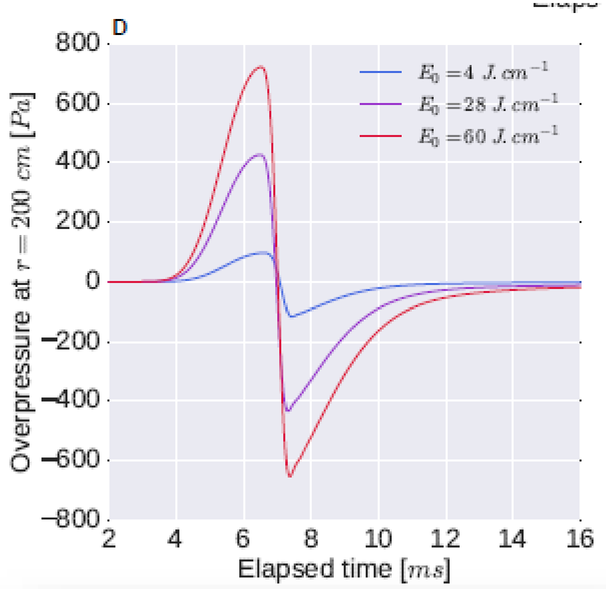
Lacroix et al., 2019

New model : the acoustic source

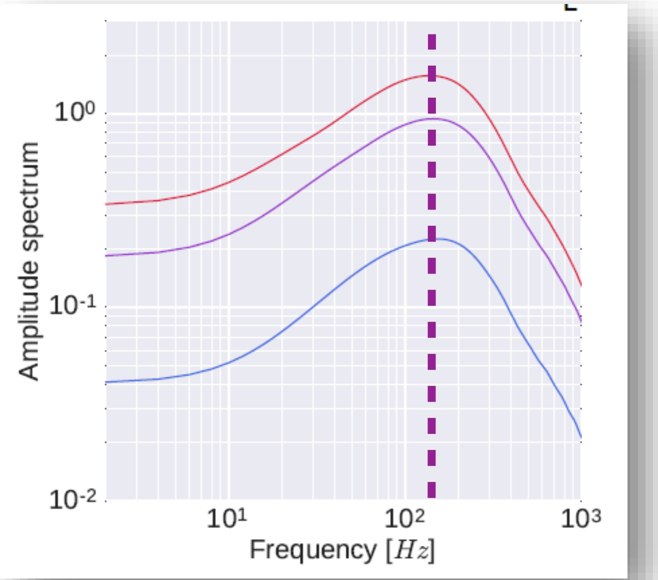
Source model
- coupling between hydrodynamics AND radiative transfer
- cylindrical geometry

Ripoll et al. (2014)

3 values of deposited energy, consistent with usual return stroke values (*Borovsky (1998); Cooray (2003)*)
4 J/cm - 28 J/cm - 60 J/cm



Time waveform

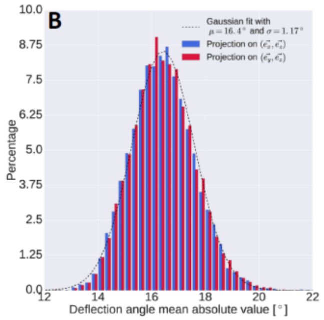


Frequency spectrum
(peaks at **150 Hz** as for Few's model)

Lacroix et al., 2019

-CG geometry statistics:

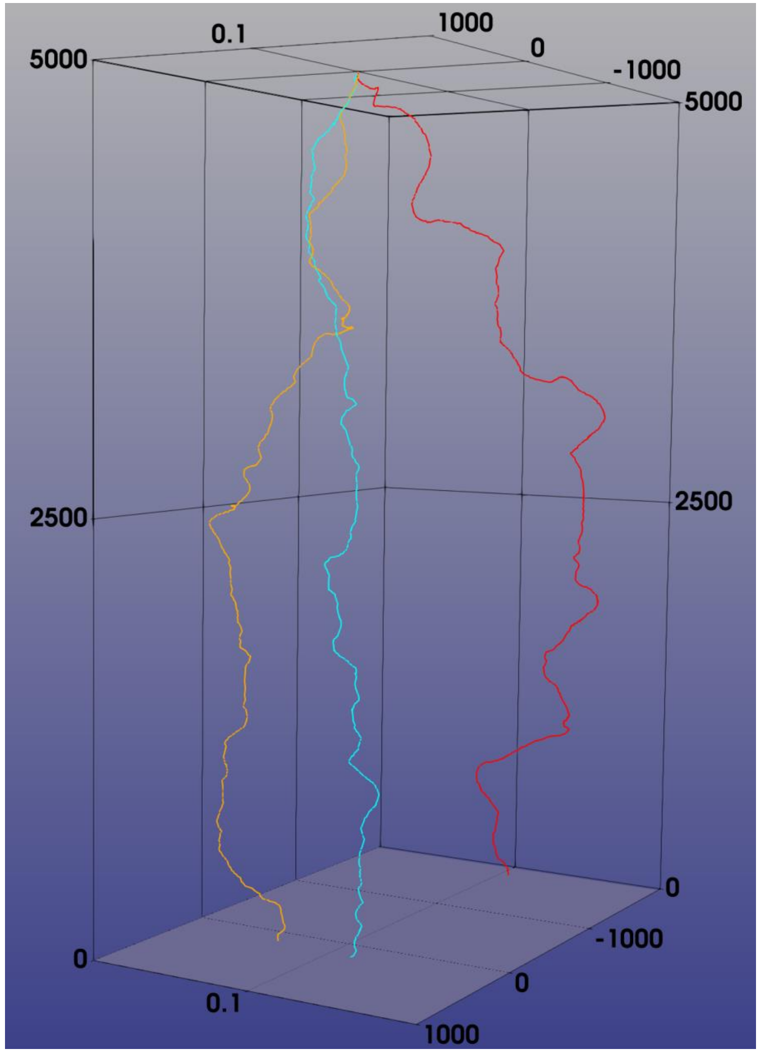
- Typical deflection angle between two steps of $\sim 16{,}3°$ (*Hill, 1968*)
- Typical step length of 8 m (*Levine and Gilson, 1984*)
- Typical inception height of 5 km



Construction method based on *Ribner and Roy (1982)*

10,000 flash geometries calculated, with realistic outputs

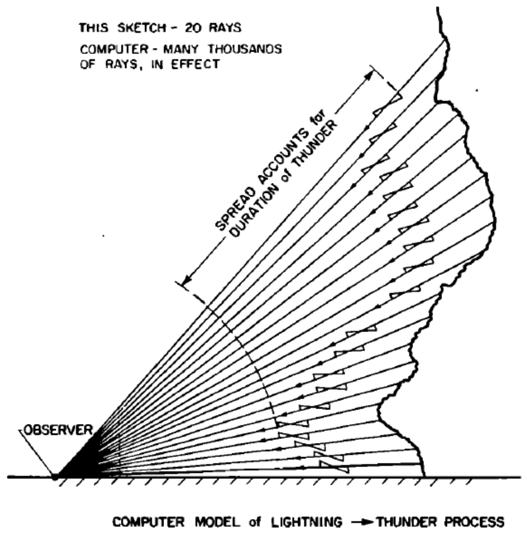
72 flashes finally selected (isotropic distribution)



Lacroix et al., 2019

New model : propagation

- Flash is discretized as N point sources
- Sources are identical and all emit the same signal *s(t)* at the same time
- The receiver gets the sum of the contributions of each source
- Homogeneous atmosphere but with absorption (*Bass, 1980*)



Ribner and Roy (1982)

Pressure wave (in frequency domain)

$$\tilde{P}(f) = \tilde{G}_{tot}(f) \times \tilde{s}(f)$$

G_{tot} = impulsive response of the overall lightning stroke (**geometry and distance**)

s = source signal (**physics**)

New model : impulsive response

Pressure wave (in frequency domain) $\tilde{P}(f) = \tilde{G}_{tot}(f) \times \tilde{s}(f)$

G_{tot} impulsive response of the overall lightning stroke

Geometrical attenuation — Spectrum modulator (overlooked by *Few (1969)*)

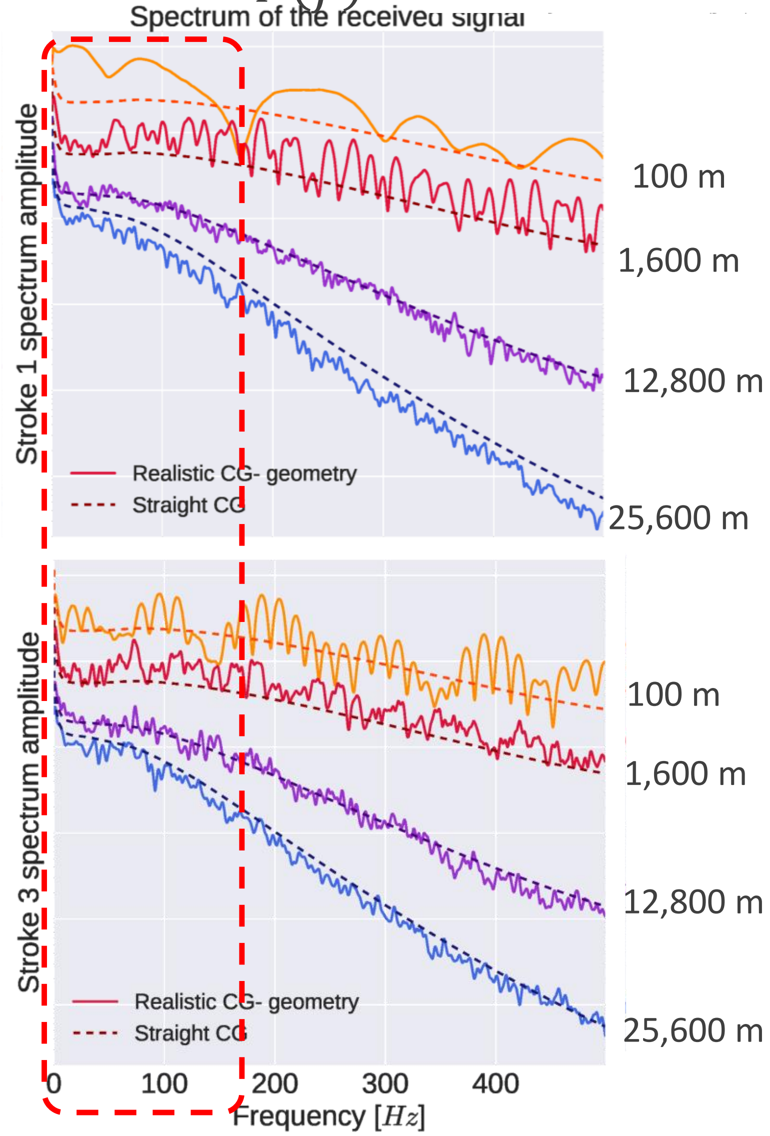
$$\left|\tilde{G}_{tot}(f)\right|^2 = \sum_{n=0}^{N} \frac{e^{-4\pi f \alpha(f) \tau_n}}{16\pi^2 R_n^2} + \sum_{\substack{n,m \\ n\neq m}}^{N} \frac{e^{-2\pi f \alpha(f)(\tau_n - \tau_m)}}{16\pi^2 R_n R_m} \cos(2\pi f[\tau_n - \tau_m][1-\nu(f)])$$

- $\tau_n = R_n/c_0$: time of flight from the n[th] source
- $\alpha(f)$ and $\nu(f)$ stands for absorption and dispersion

Interferences : <0> at high frequencies, 1 at low frequencies

New model: signal spectrum

$$\tilde{P}(f) = \tilde{G}_{tot}(f) \times \tilde{s}(f)$$



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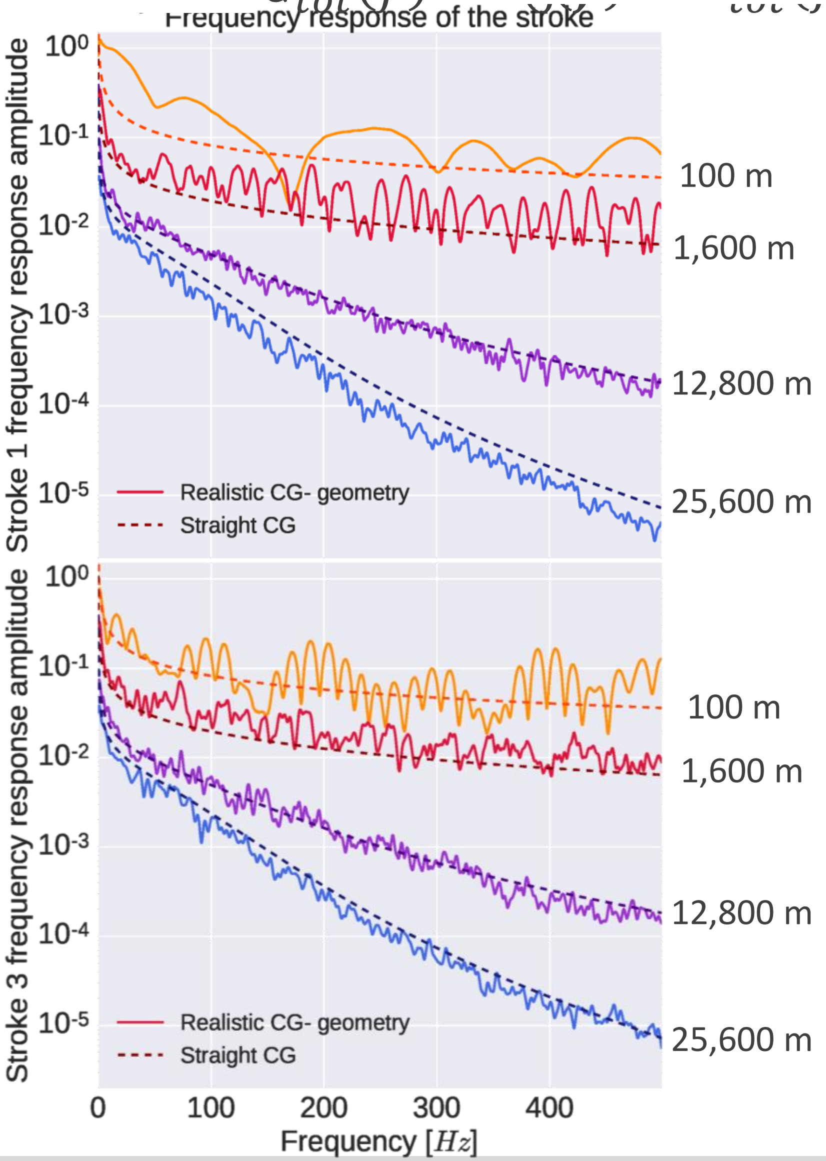
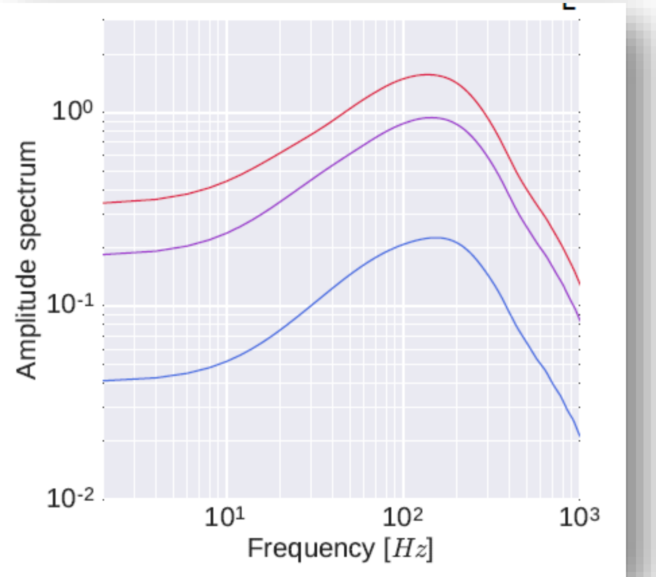


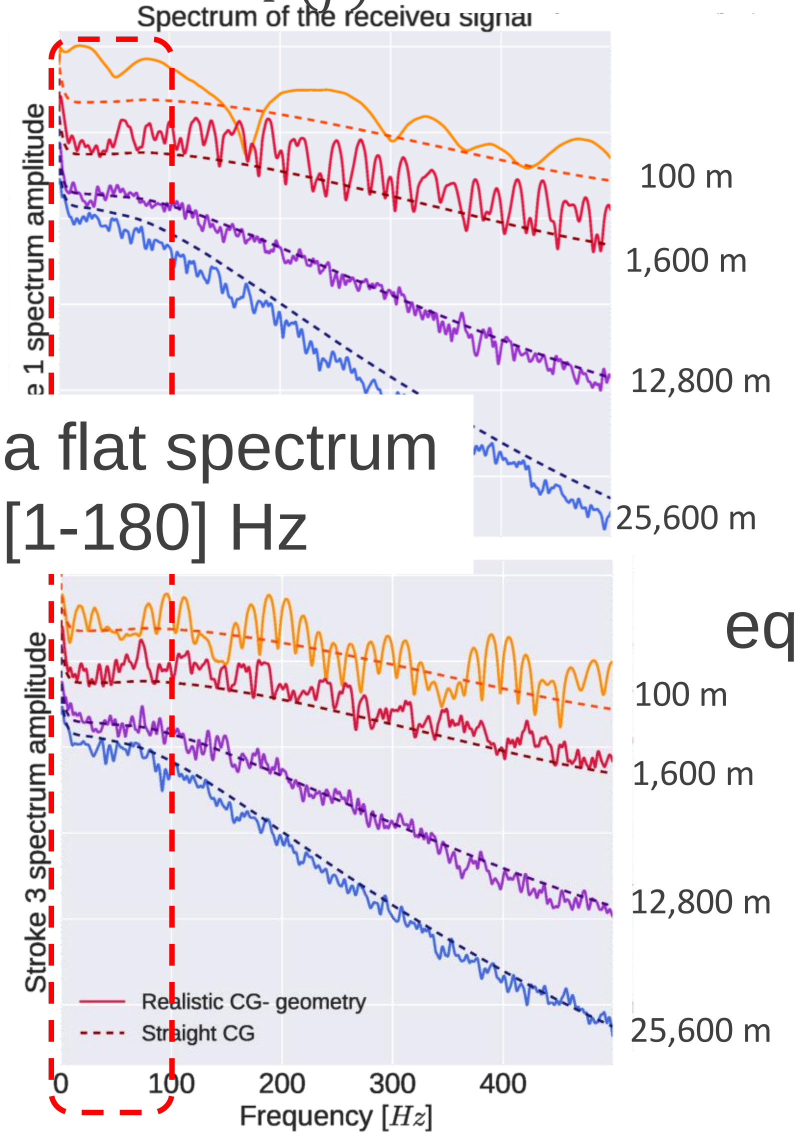
X



Lacroix et al., GRL, 2019

New model: signal spectrum

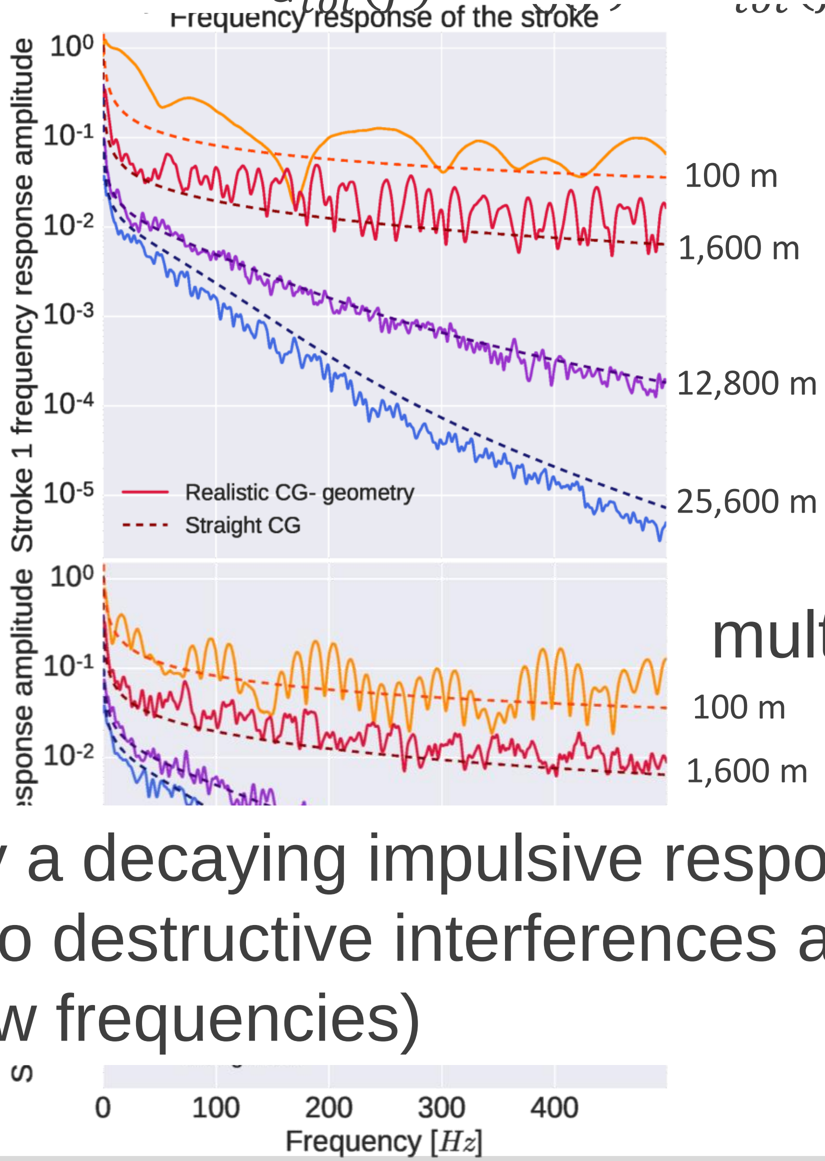
$$\tilde{P}(f) = \tilde{G}_{tot}(f) \times \tilde{s}(f)$$



a flat spectrum [1-180] Hz

=

equal

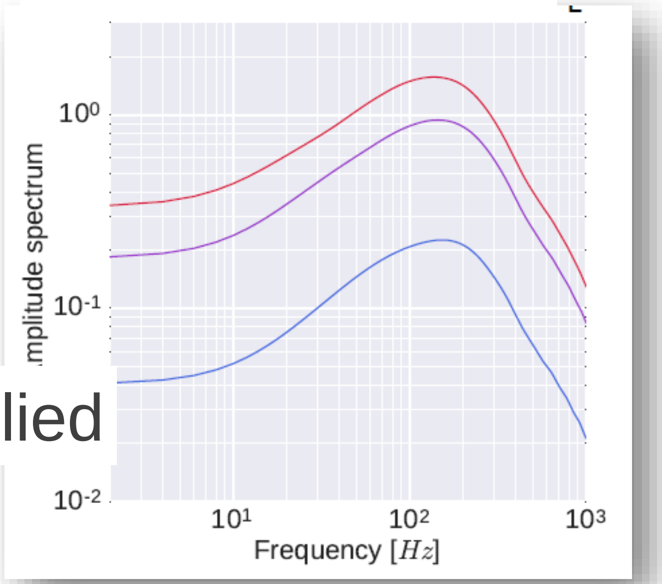


by a decaying impulsive response (no destructive interferences at low frequencies)

x

multiplied

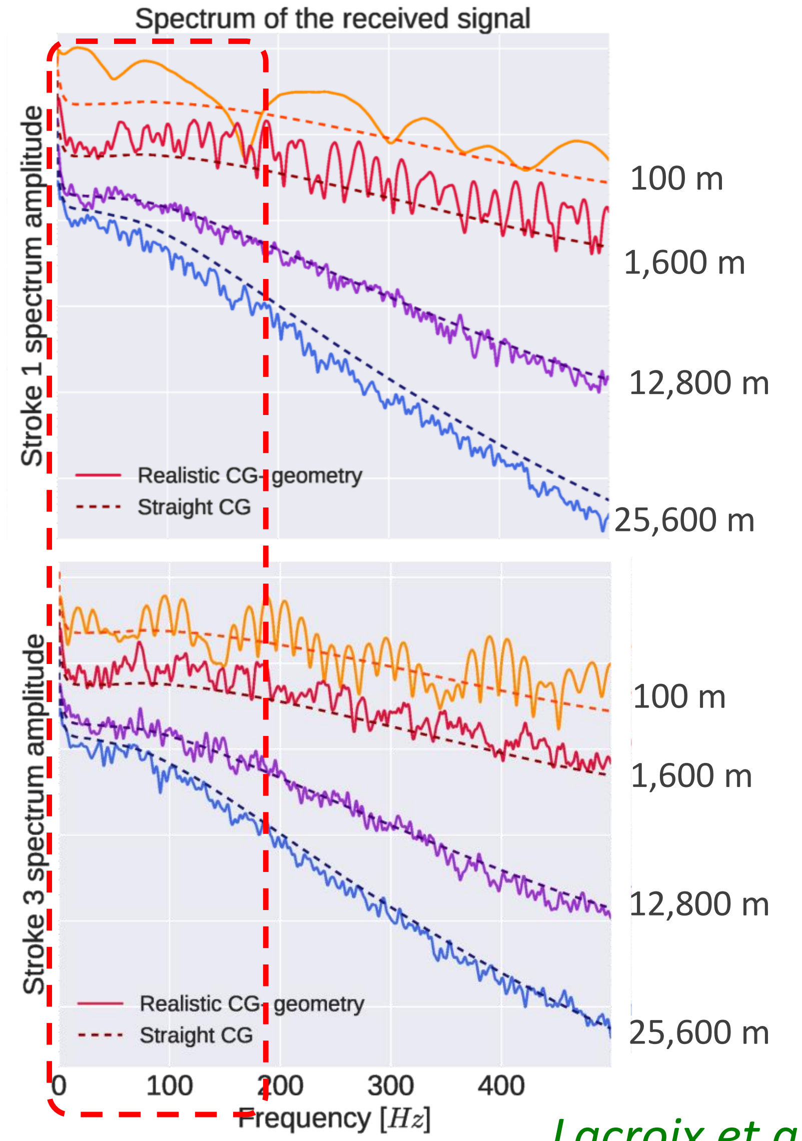
A peaked source (physics)



Lacroix et al., GRL, 2019

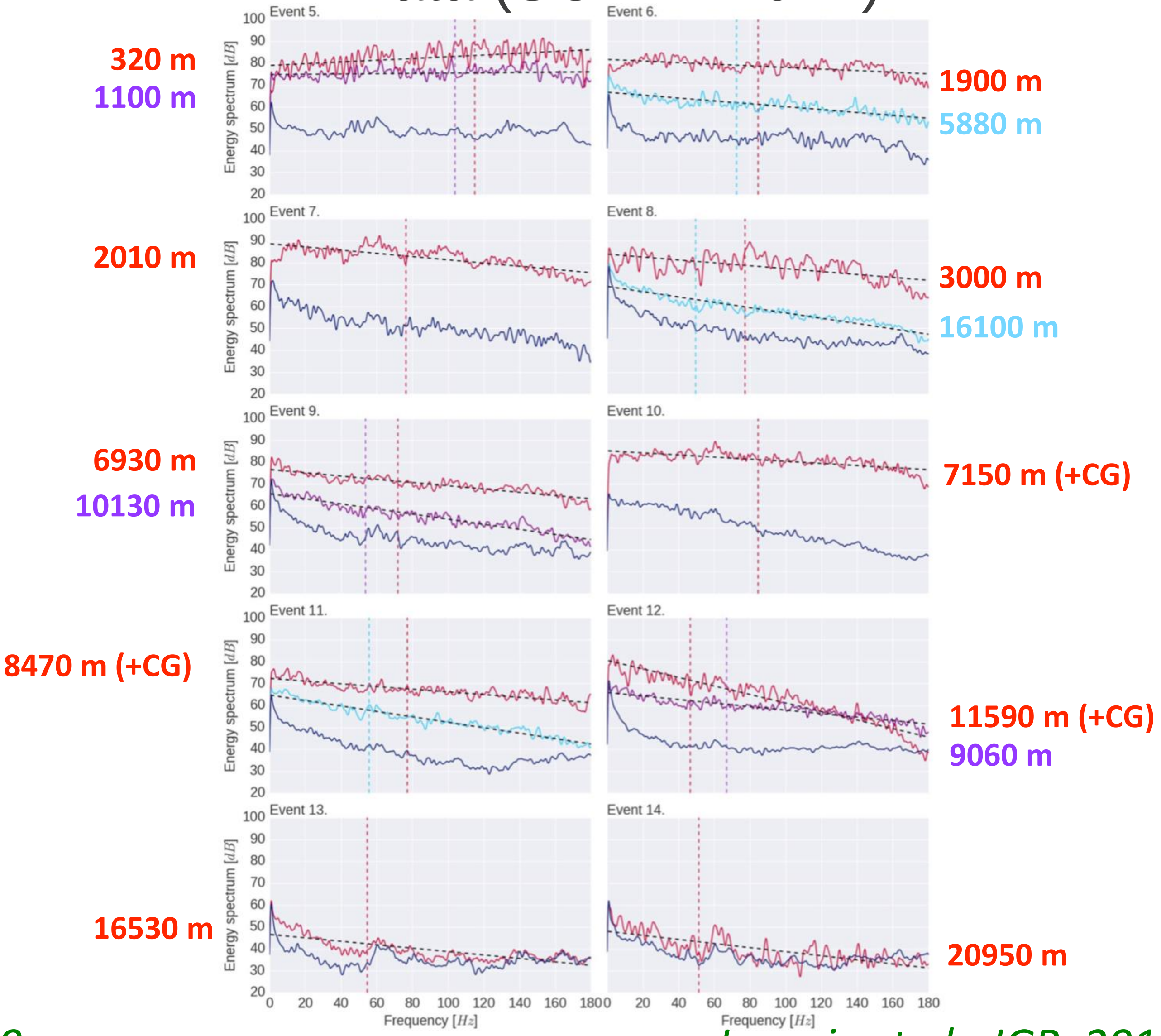
Flat spectrum: model vs data

Model



Lacroix et al., GRL, 2019

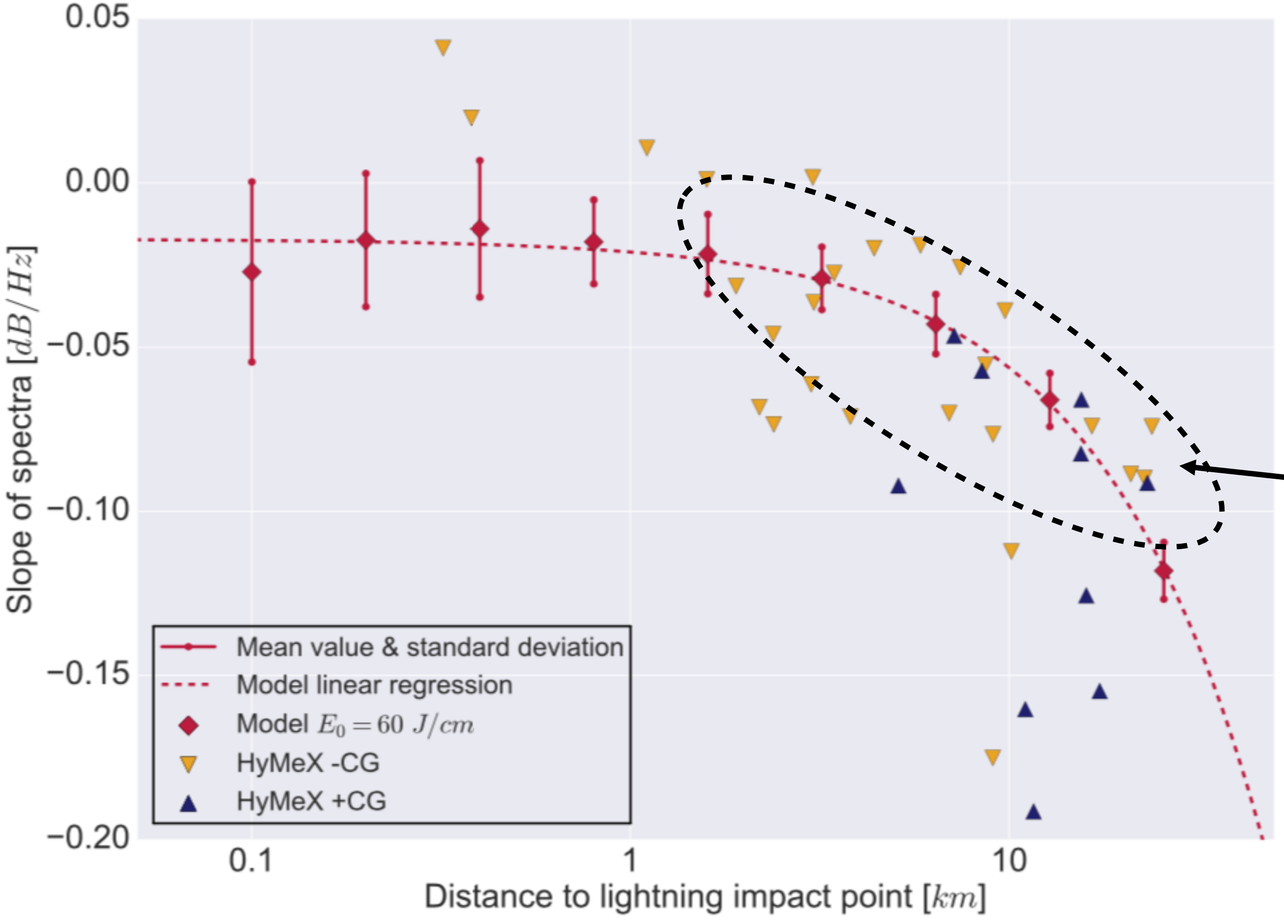
Data (SOP1 - 2012)



Lacroix et al., JGR, 2018

Model

- 72 tortuous flash realizations
- 9 microphones



Measurement

(SOP1 - Cévennes - 2012)

26 CG-

10 CG+

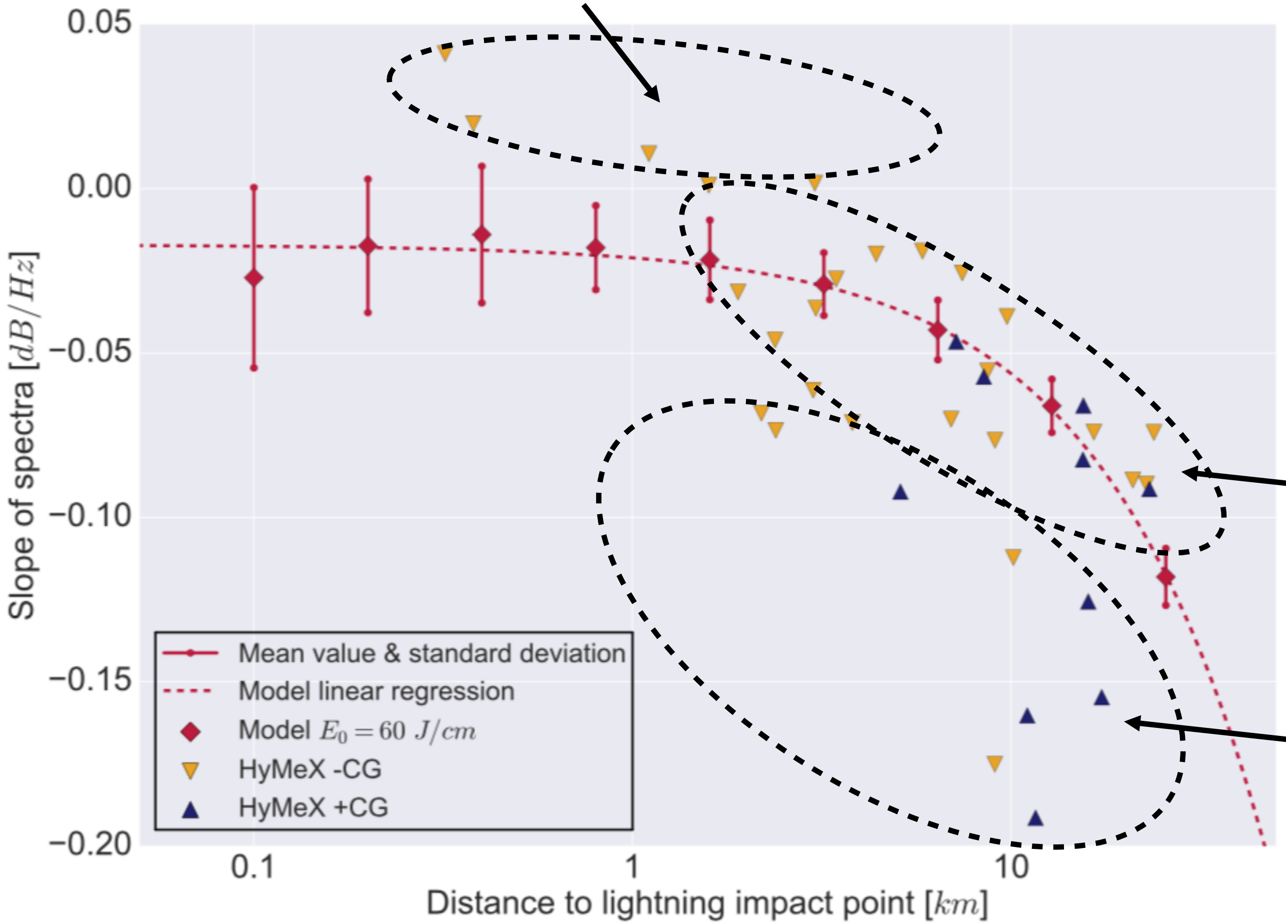
Good agreement

Lacroix et al., GRL, 2019

Model ? Statistics ?

Model

- 72 tortuous flash realizations
- 9 microphones



Measurement

(SOP1 - Cévennes - 2012)

26 CG-
10 CG+

Good agreement

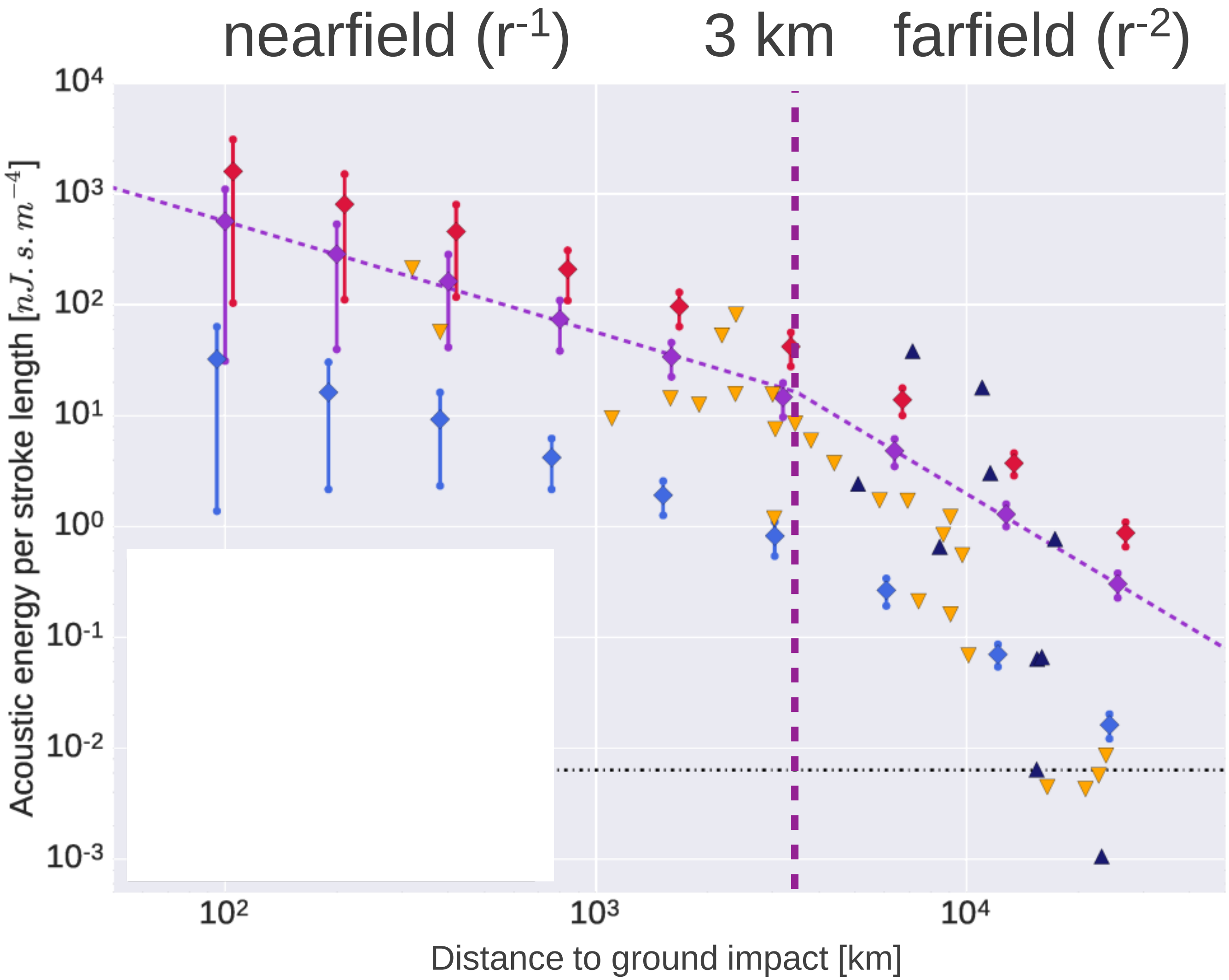
Meteorology ?

Lacroix et al., GRL, 2019

Model

- 72 tortuous flash realizations

- 3 input energies
  - 4 J/cm
  - 28 J/cm
  - 60 J/cm



Measurement

(SOP1 - Cévennes - 2012)

26 CG-

10 CG+

Lacroix et al., GRL, 2019

Model

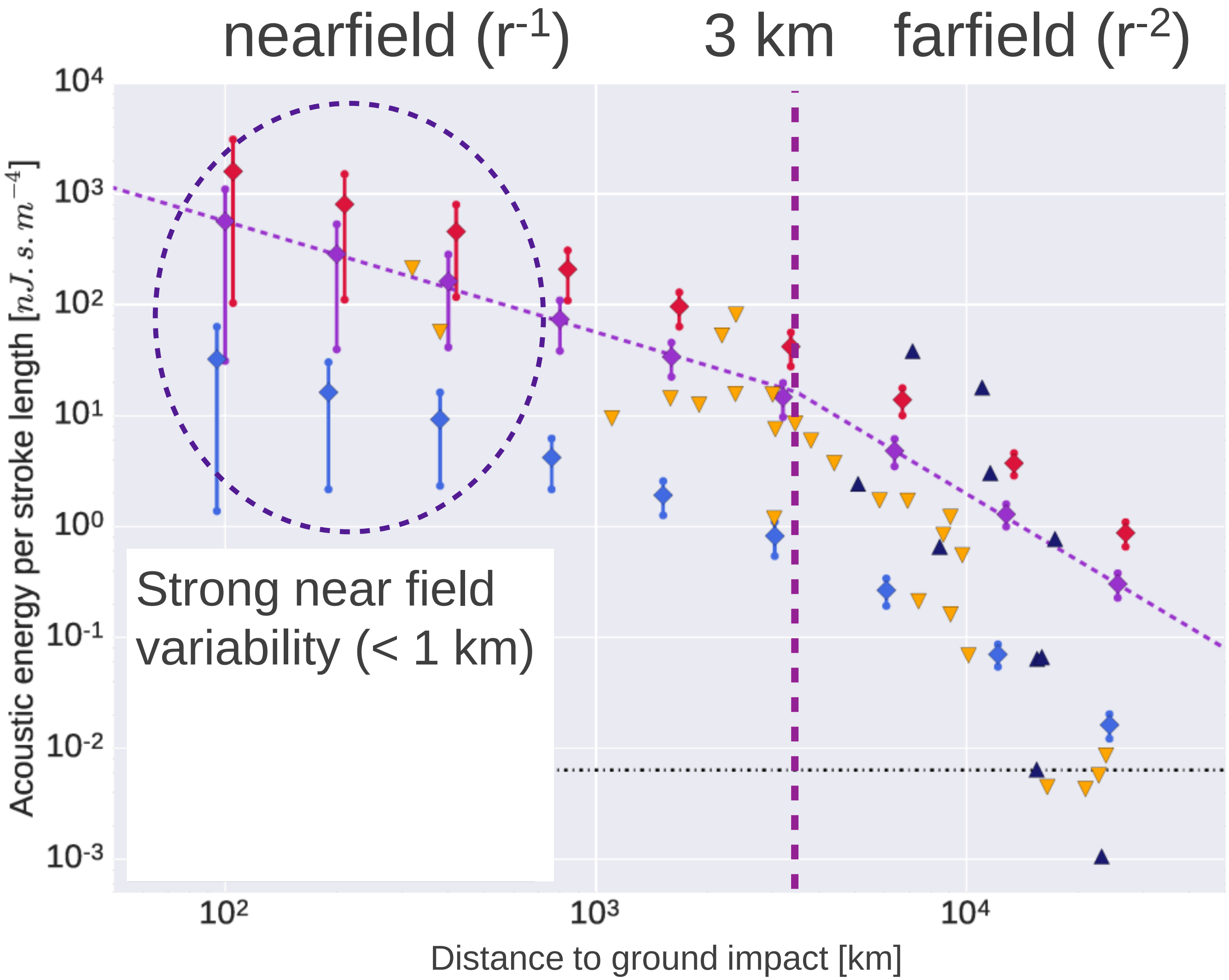
- 72 tortuous flash realizations

- 3 input energies

4 J/cm

28 J/cm

60 J/cm



Measurement

(SOP1 - Cévennes - 2012)

26 CG-

10 CG+

Lacroix et al., GRL, 2019

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  - 4 J/cm
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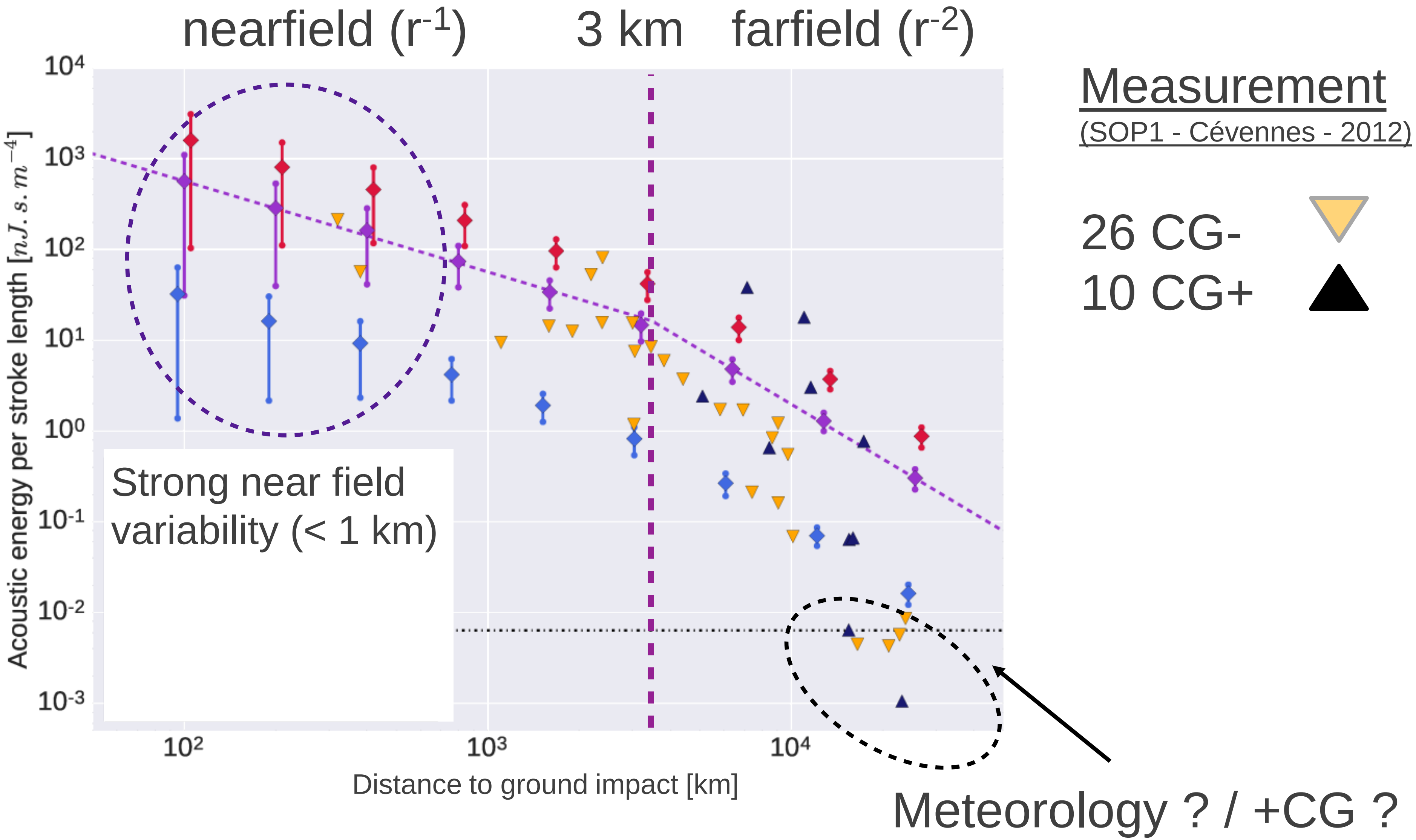


Measurement
(SOP1 - Cévennes - 2012)

26 CG-
10 CG+

Lacroix et al., GRL, 2019

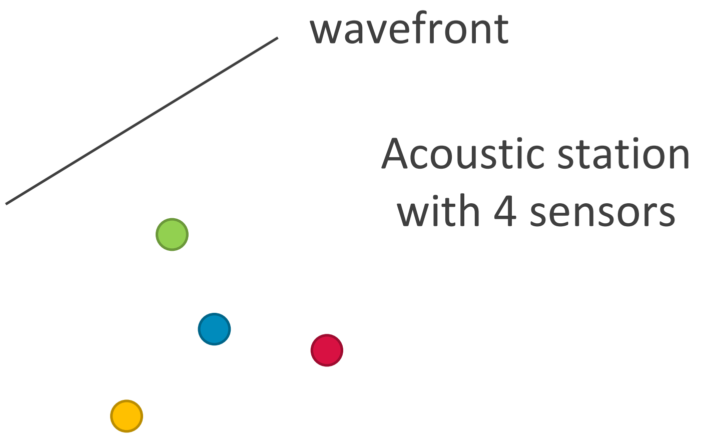
Hydrodynamical model explains main observations

- Takes into account flash tortuosity, atmospheric absorption, a realistic source waveform
- Tortuosity induces a high nearfield variability (< 1km, few data in this region)
- Near- to far-field transition around 3 km
- « Flat » spectra ([1-100] Hz, opposite effects of source and geometry)
- Estimates energy deposited in the ionized channel (typically 30 to 60 J/cm)

… but

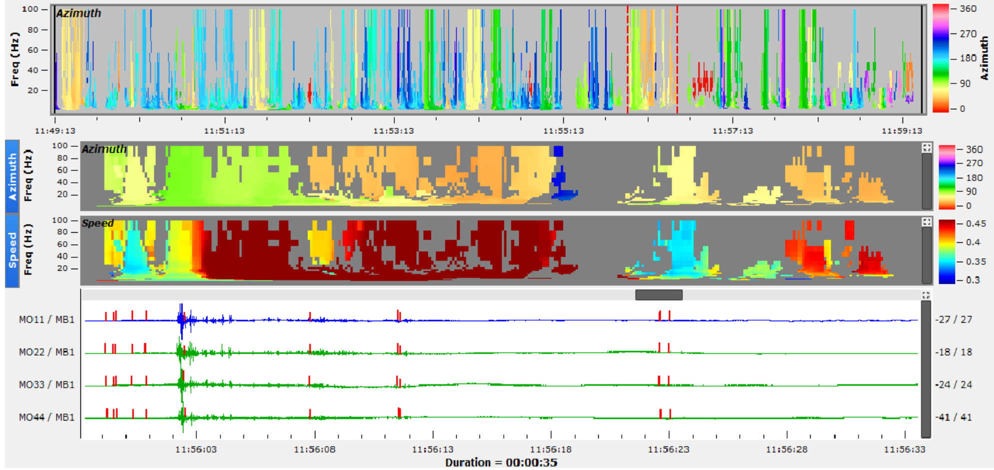
- Larger variability in measurement and poorer agreement in the farfield : meteorology ?
- Variability of deposited energy ? ***(see Damien Bestard's poster !)***
- Assumption of homogeneous deposited energy questionable ***(see Damien Bestard's poster !)***
- Model valid for -CG only
- Too few data in the near field (< 1 km)

Lightning detection by thunder



Considering that the source is far enough to have a plane wavefront, the PMCC algorithm - Progressive Multi-Channel Correlation (*Cansi, 1995; Cansi and Le Pichon, 2008*) - can give the azimuth and apparent ground speed (projection of the wave speed in the plane of the sensors).

For this we calculate the cross-correlation between the signals of 3 sensors to find the wave propagation time between them. As soon as the signal is sufficiently coherent, we have a detection.
➔ Method described in Le Pichon and Charbit lecture and tutorials by Vergoz.



For each one, PMCC provides:

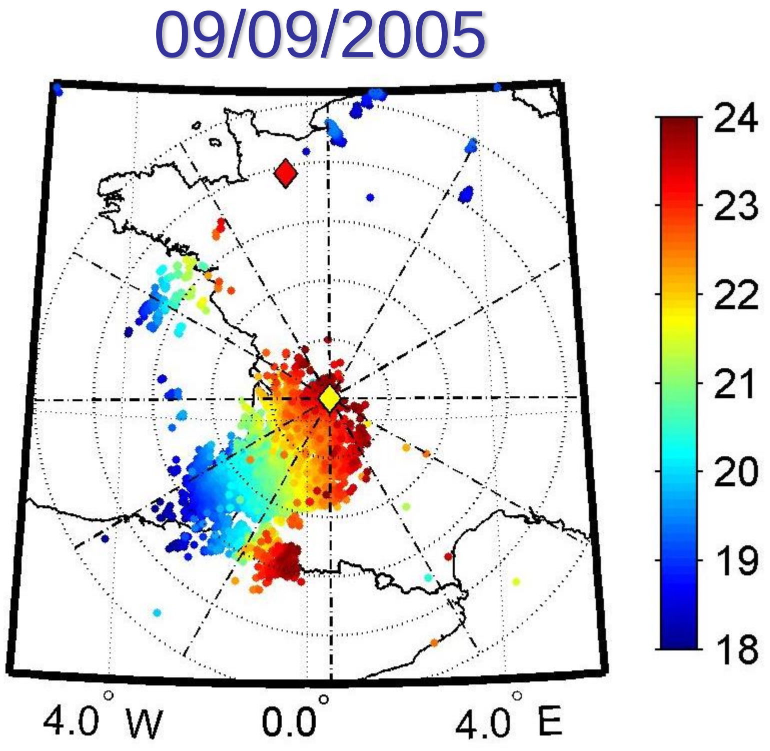
- Time of the detected event,
- Azimuth,
- Apparent ground speed,
- RMS amplitude,
- Frequency range of the signal.

❾ Detection performances, limits, and contribution of thunder measurements

from three measurement campaigns

Campaign	Location	Triangle size	Sampling frequency (type of sensors)
EuroSprite (summer 2005)	**Dordogne (South-Western France)**	**1 km**	**20 Hz (microbarometers)**
HyMeX-SOP1 (fall 2012)	**Cévennes (Southern France)**	**500 m**	**50 Hz (microbarometers)**
		50 m	**500 Hz (microphones)**
Permanent station/IMS (2005-2019)	**Ivory Coast**	**3 km**	**20 Hz (microbarometers)**

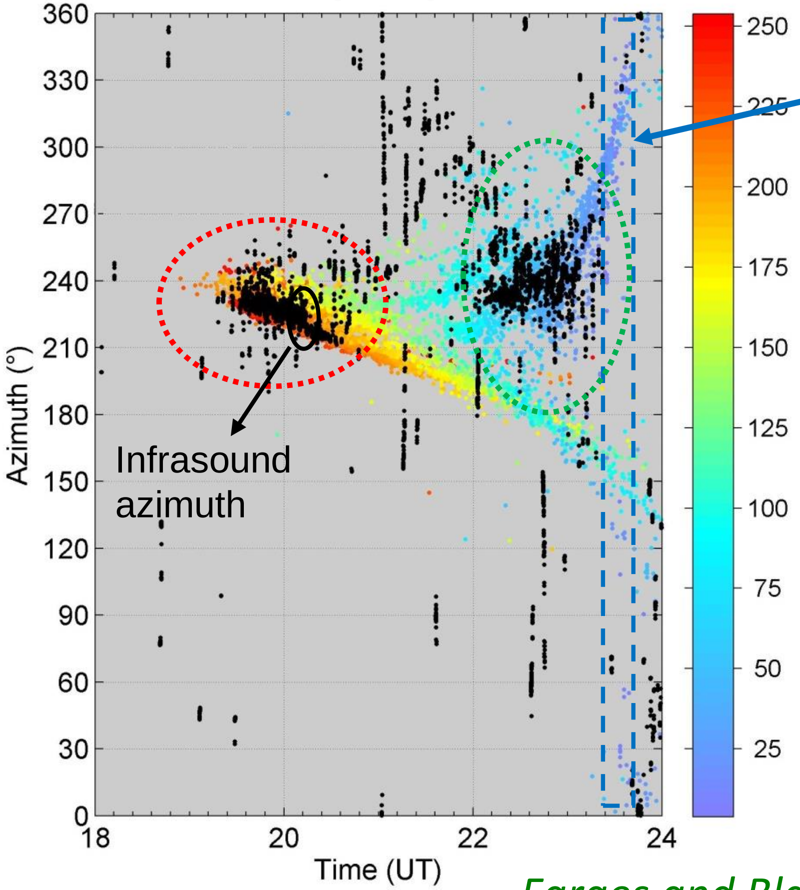
Flash location with Météorage data



Farges and Blanc, 2010

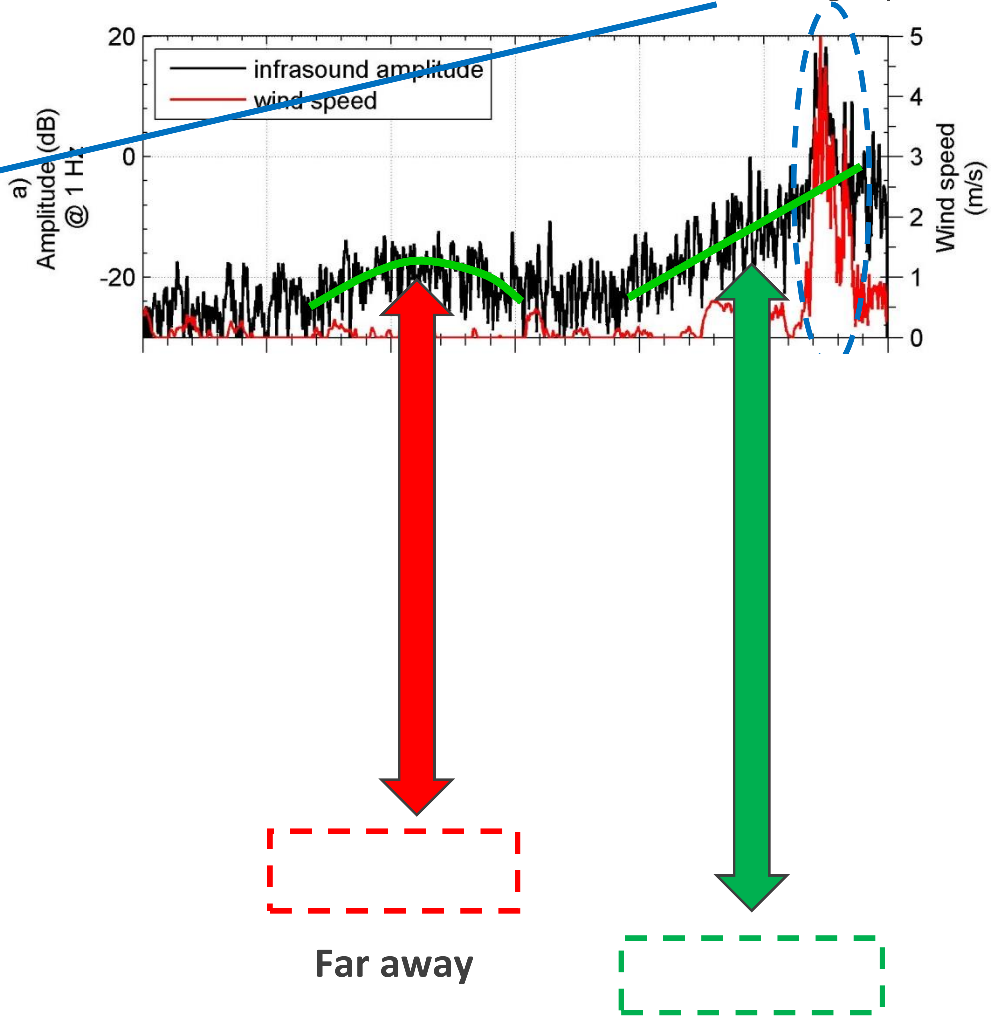
lightning azimuth variation with time
relatively to the position of the station

09/09/2005



Farges and Blanc, 2010

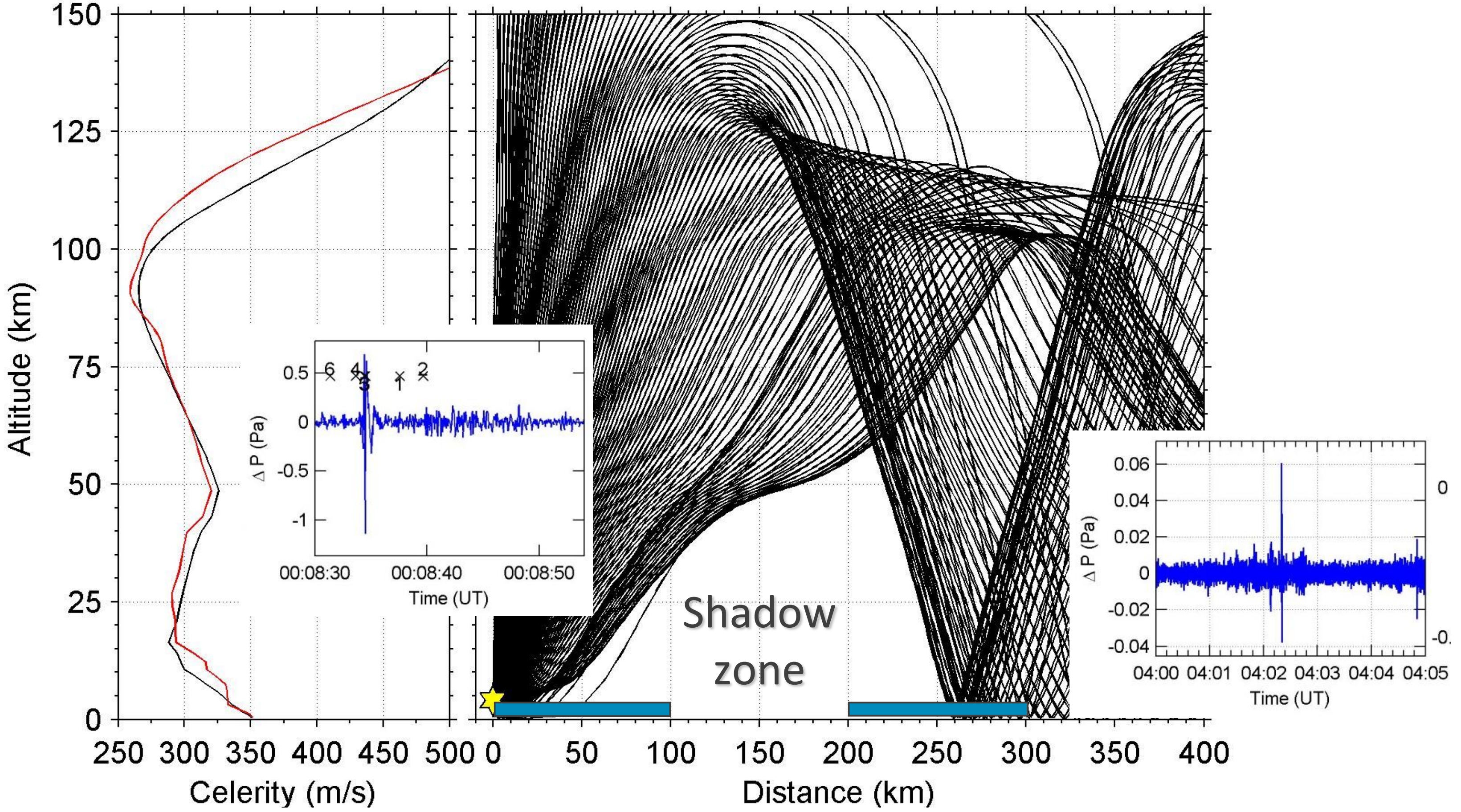
Wind gusp



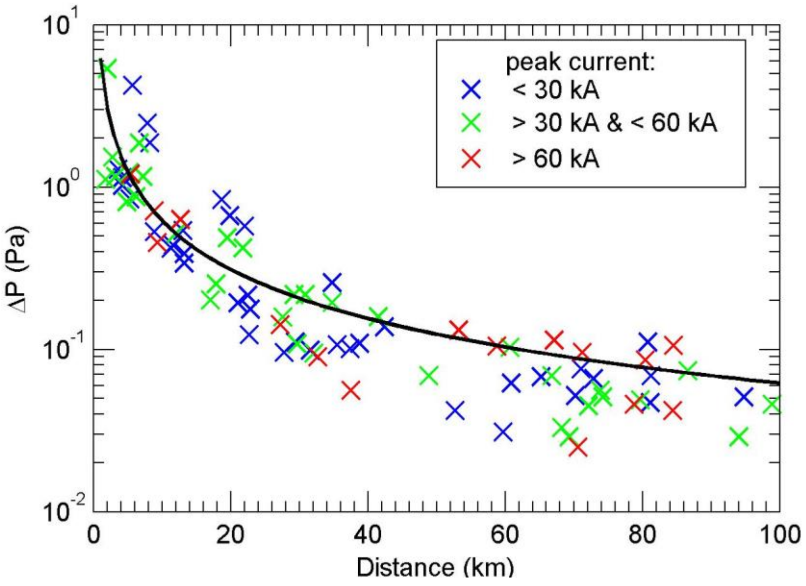
Far away

Close

AGAP ray-tracing propagation (*Gainville, 2006*) using early-September typical atmosphere conditions and a point source at 4 km height.



1/r amplitude decay

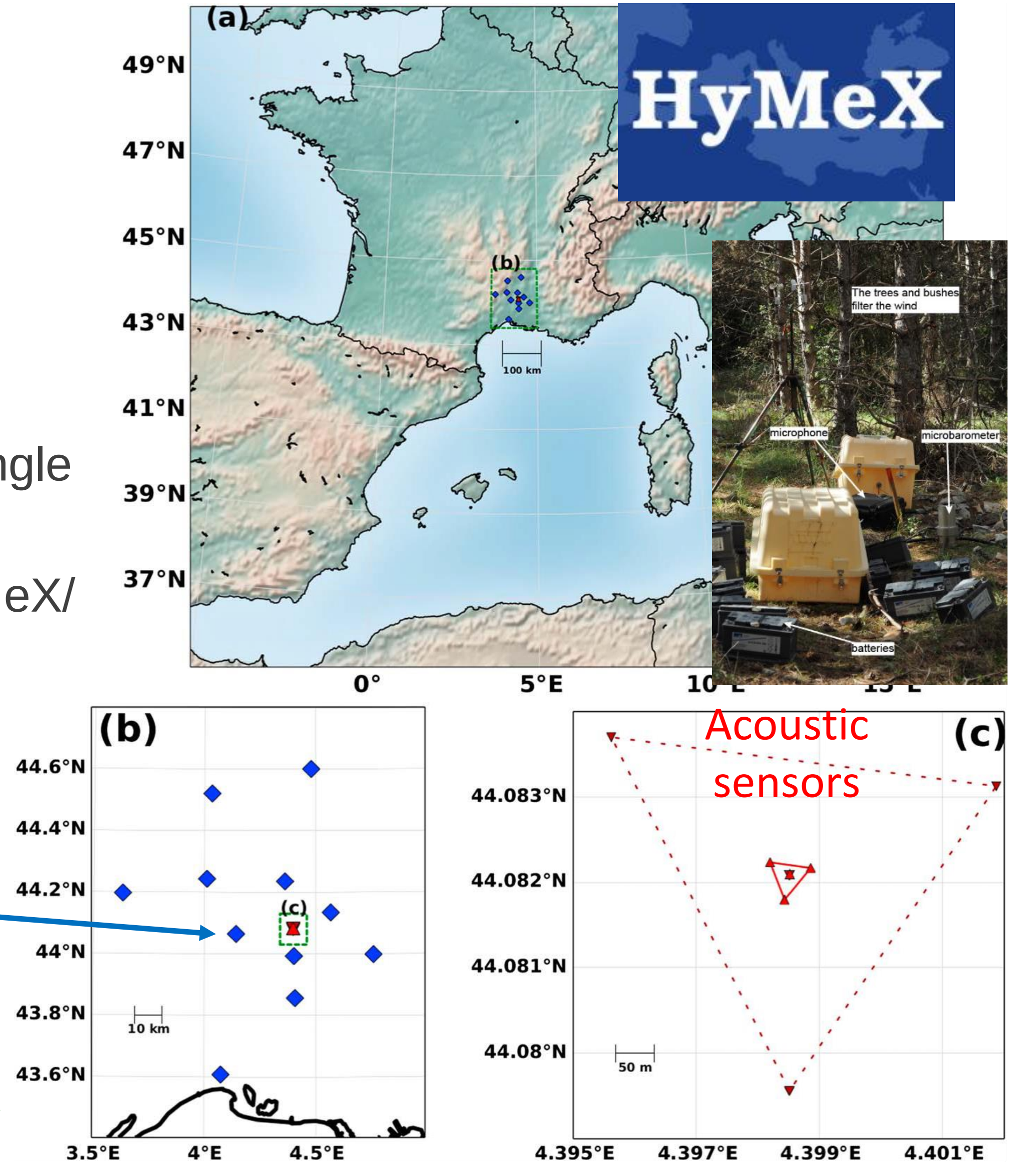


Farges and Blanc, 2010

Observations in South of France (Cévennes-Vivarais)

September - November 2012

- **3D lightning structure with an LMA (EM-VHF)**
- **2D lightning location system (EUCLID, EM-LF)**
- **Acoustic station:**
  - 4 MB2005 (10^{-5}–30 Hz, 50 samples/s): 500-m side triangle
  - 4 microphones (0.1 Hz–20 kHz, 500 samples/s): 50-m side triangle
  - GPS dating
- (*Defer et al., 2015*): all data available @ http://mistrals.sedoo.fr/HyMeX/



LMA sensors

Gallin et al., JGR, 2016

Detection areas and conditions: meteo impact

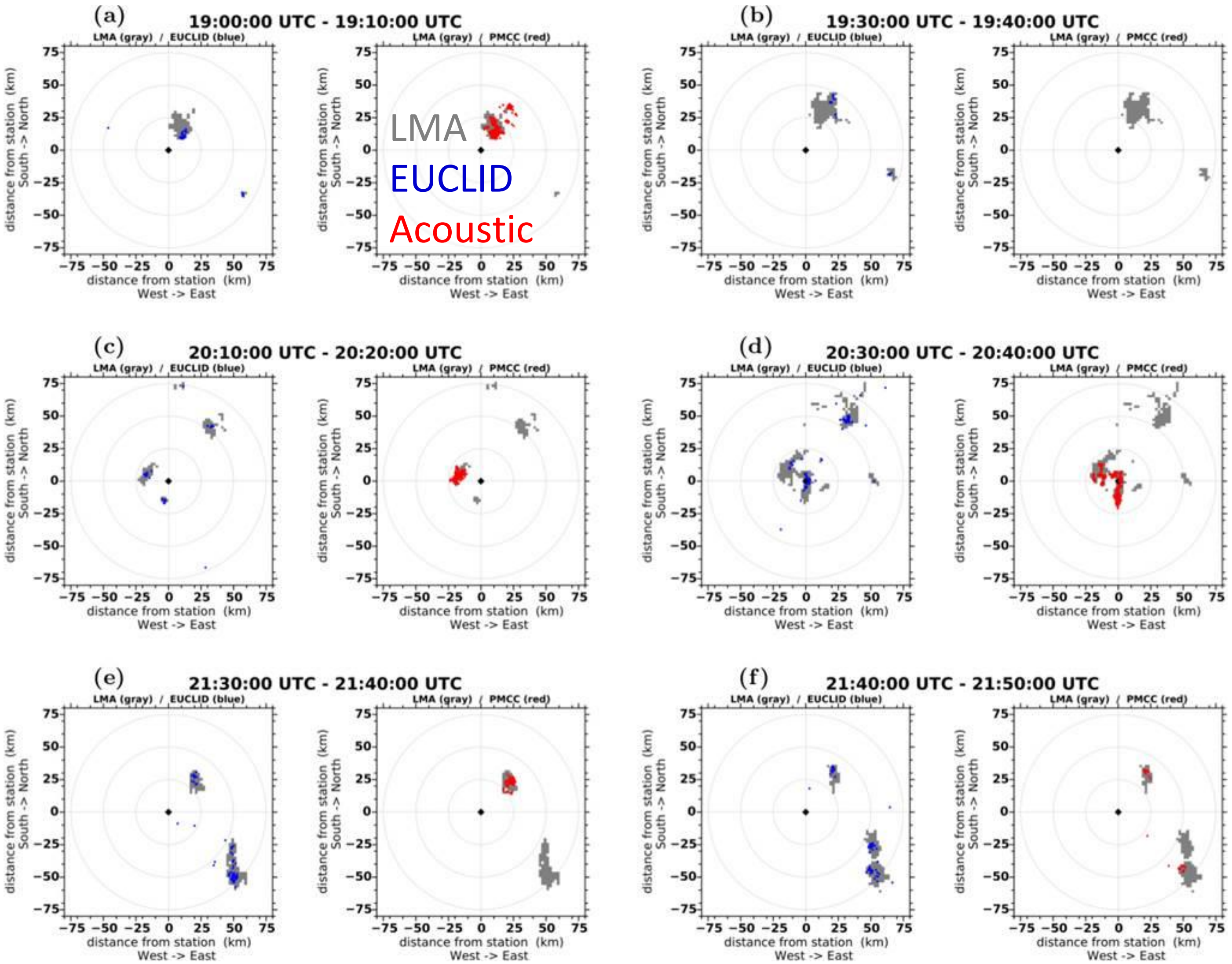
26 Oct. 2012

Gallin, 2014

- Confirmation: good follow-up of the thunderstorm activity up to 75 km from the station

- but between 19:30 and 20:00 loss of detectability: may be due to unfavorable local weather conditions (wind gradient, wind gust?)

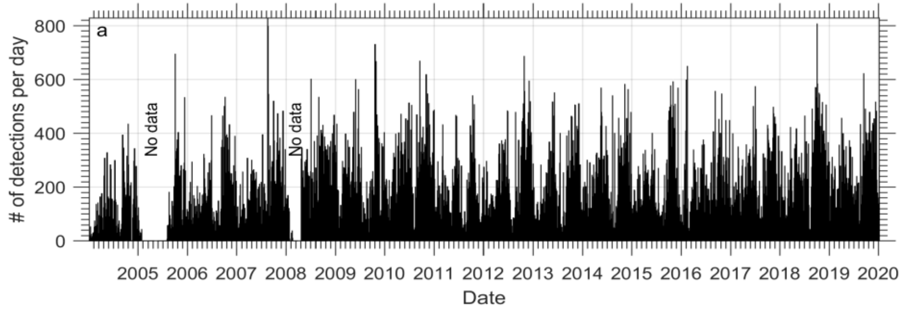
- Masking effect: 21:30-21:40 ❾ flashes from the closest convective cell mask those from farther ones



2005-2019

Acoustics

IS17 data

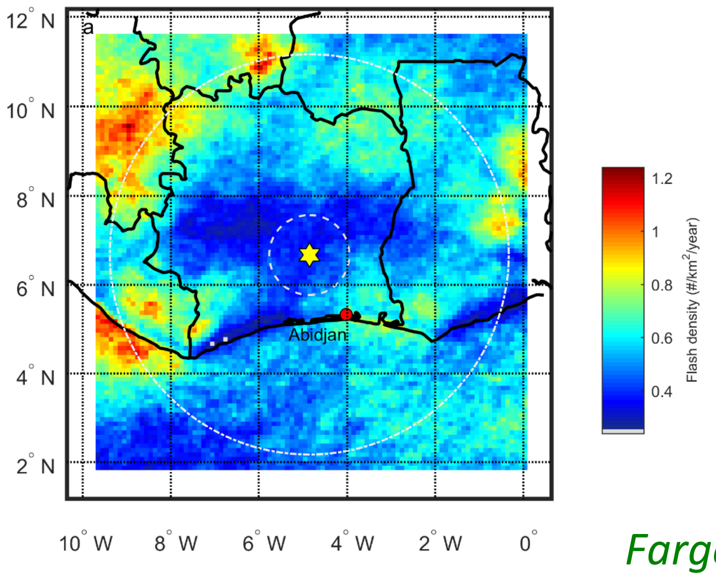


742,105 (1-5 Hz) infrasound detections

Ivory coast IMS IS17 station

VLF-EM

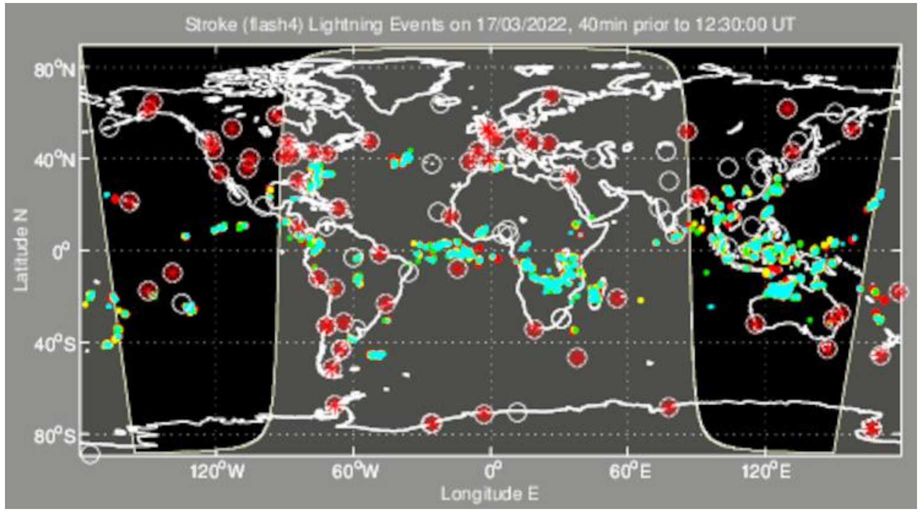
WWLLN data



~15 million flashes

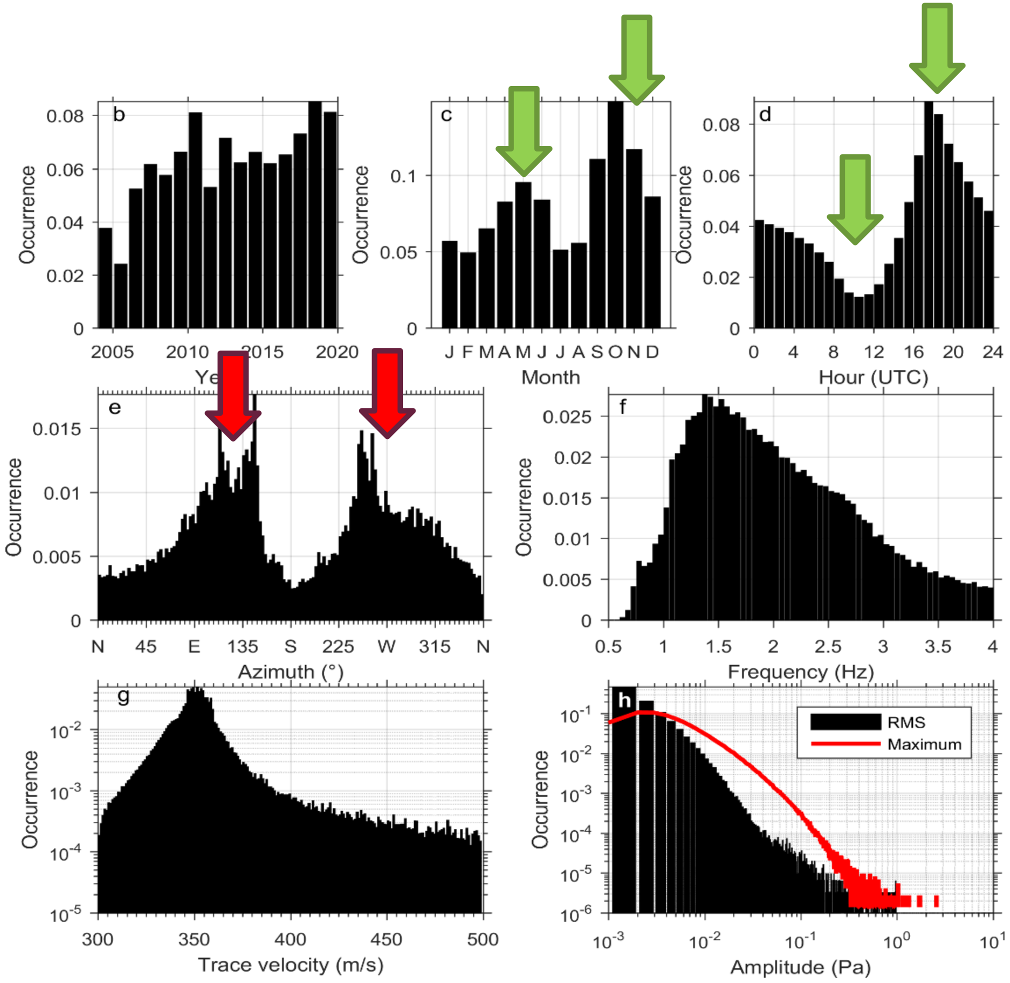
Farges et al., Atmosphere, 2021

WWLLN (wwlln.net)



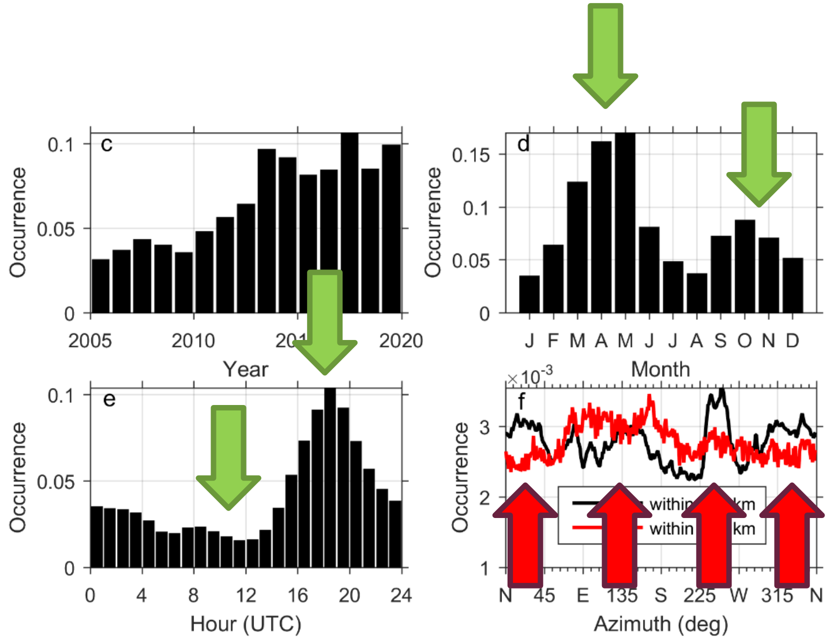
Comparison of time and azimuthal distribution

IS17 data (infrasound)



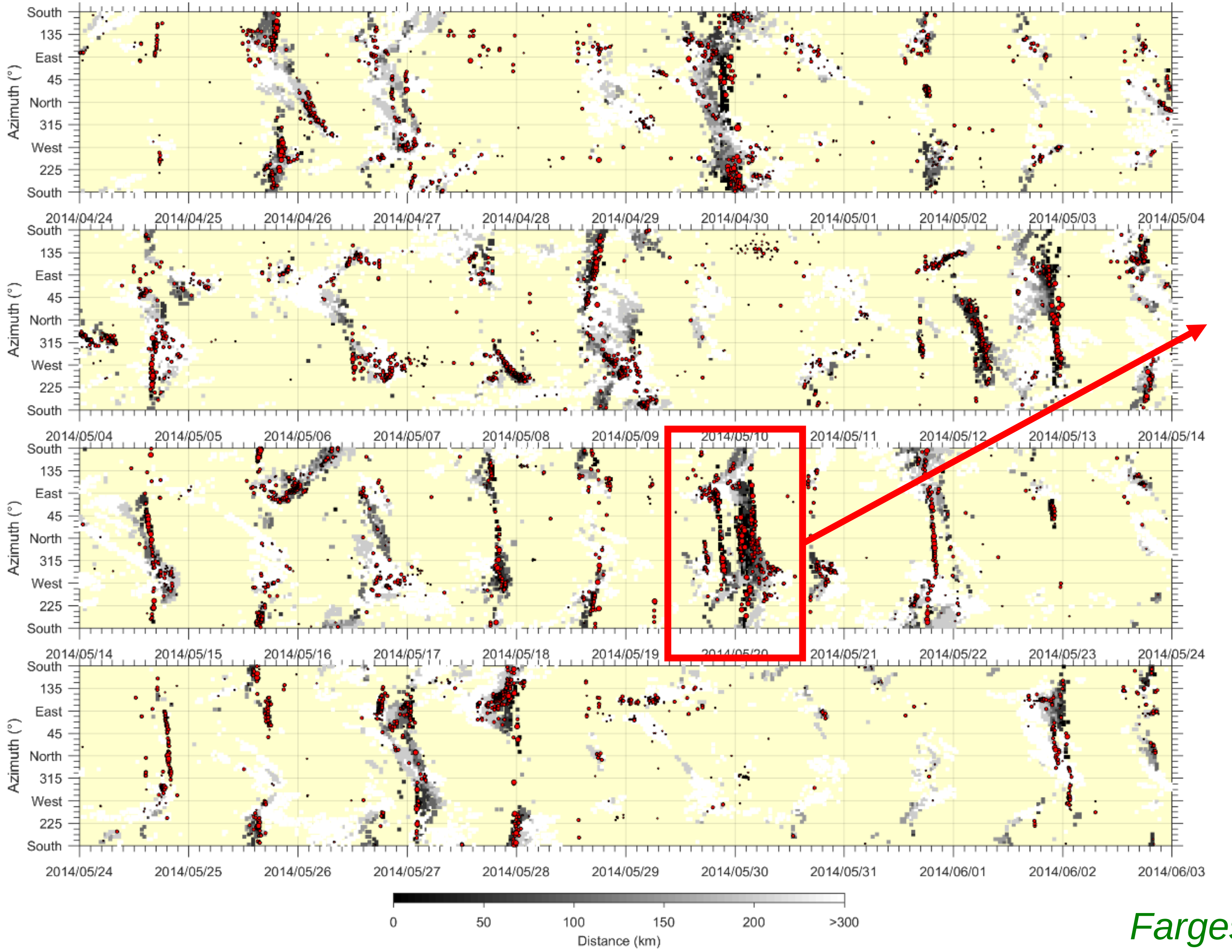
Farges et al., 2021

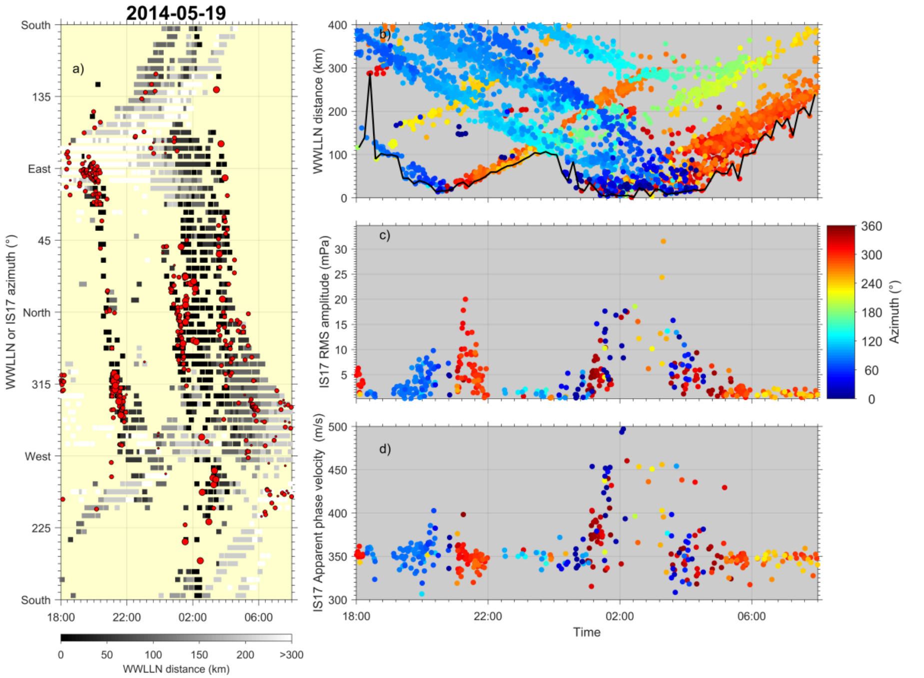
WWLLN data (EM)



- Similar temporal distribution: 2 main seasons (Spring/Fall), daiy variation with a maximum at 18UT and a minimum at 10UT
- Discrepancy on azimuth distribution: 2 peaks (SE & SW) in infrasound data while 4 peaks are found in WWLLN data

Azimuth vs. time comparison





Similar behavior to that observed in France but repeated for hundreds of thunderstorms !

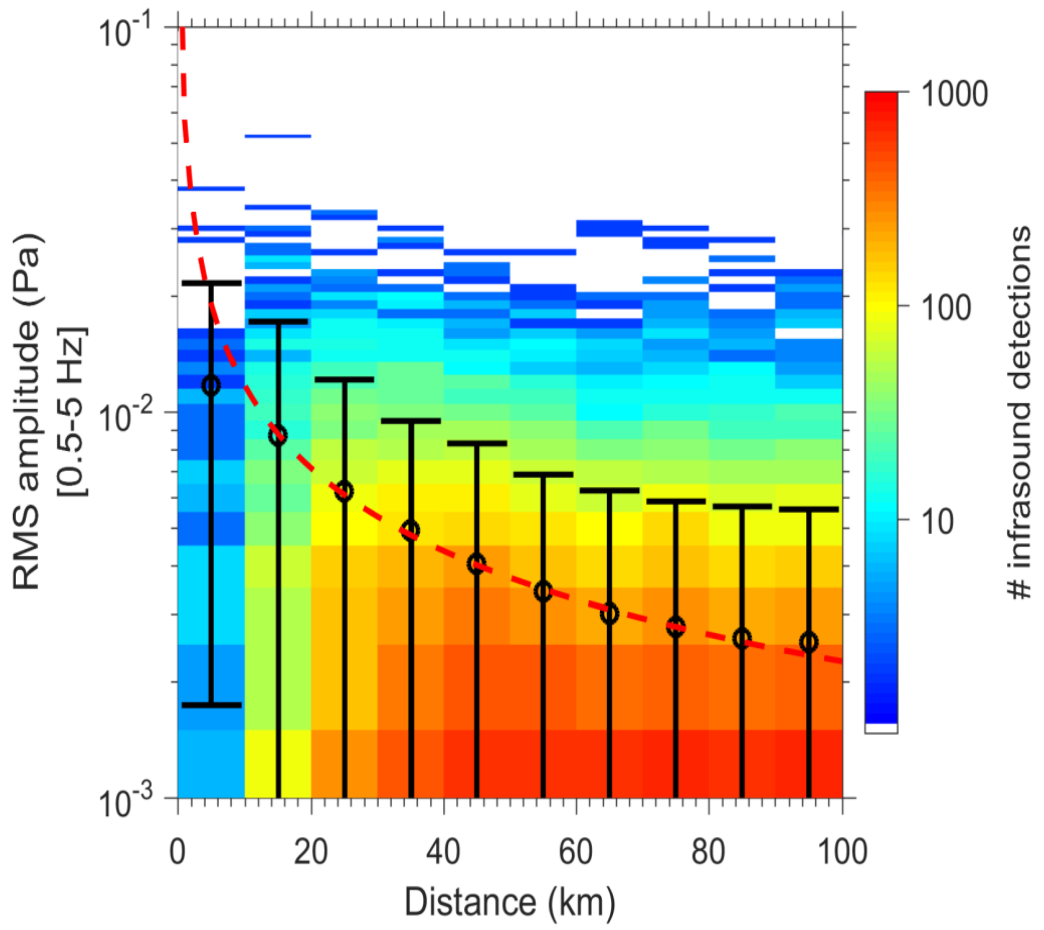
Farges et al., 2021

Thunder Amplitude Decay with Distance for Tropospheric Propagation

With **32,777** infrasound detections automatically associated one-to-one to a WWLLN flash within 100 km from IS17, *Farges et al. (2021)* found:

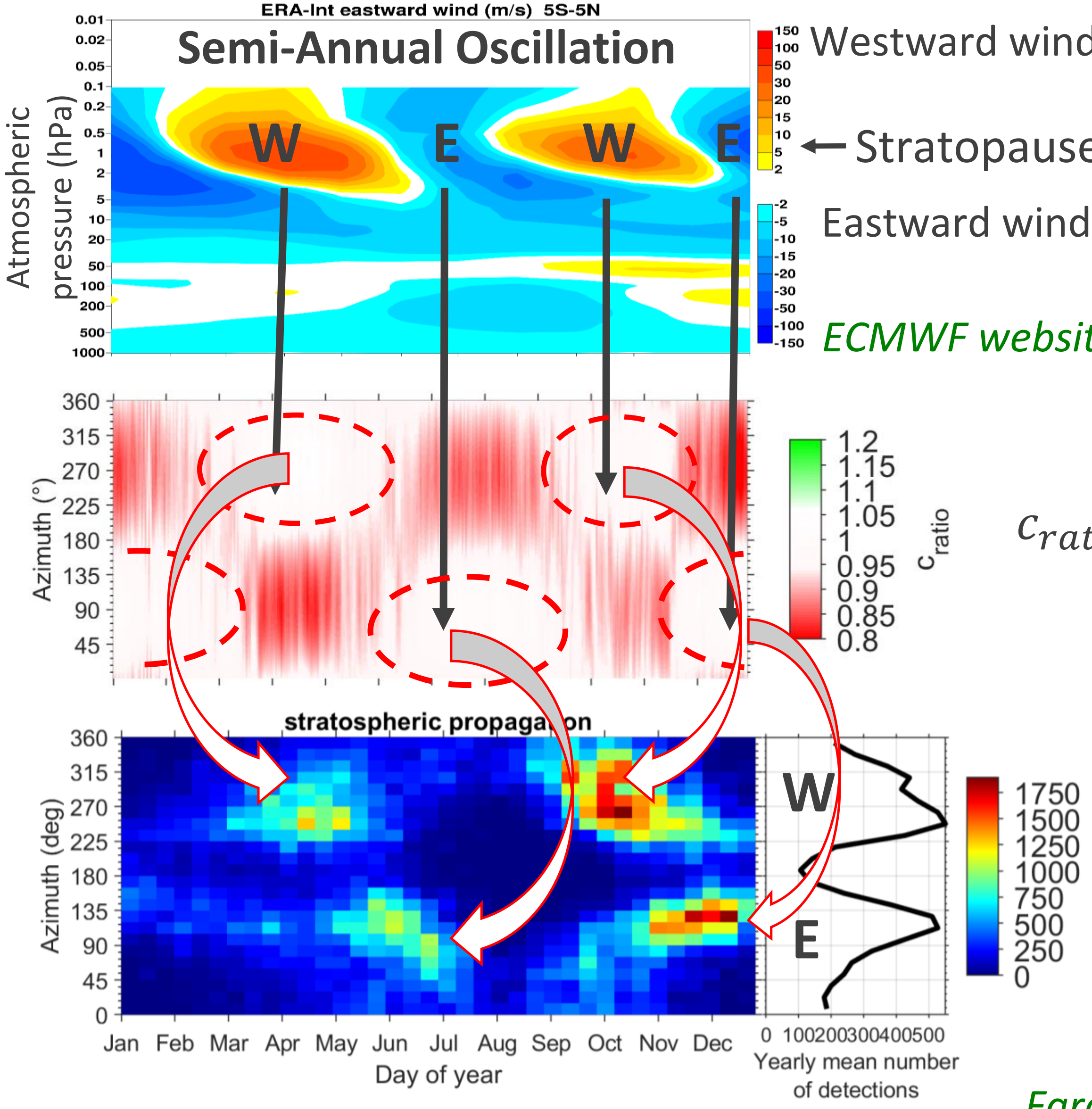
$$P_{RMS} = \frac{0.0615}{r^{0.717}}$$

Attenuation is slower than a 1/r decay law (point source in the linear regime)
>
Likely due to tropospheric guided waves



Farges et al., 2021

Stratospheric propagated thunder to sound middle atmosphere



ECMWF website on QBO and SAO

$$c_{ratio} = \frac{c_{stratopause}}{c_{ground-level}}$$

Farges et al., 2021

Comparison of the monthly distribution of azimuths of detections associated with thunder for stratospheric propagations (up to 500 km away from IS17) with the direction of the stratospheric winds.

When $c_{ratio} \geq 1$, infrasound emitted near the ground can be reflected near the stratopause and propagates back to the ground.

Distribution reflects the **Semi-Annual Oscillation** of winds in the stratosphere at tropical latitudes.

This explains the discrepancy between the azimuth distributions of infrasound detections and of lightning flashes.

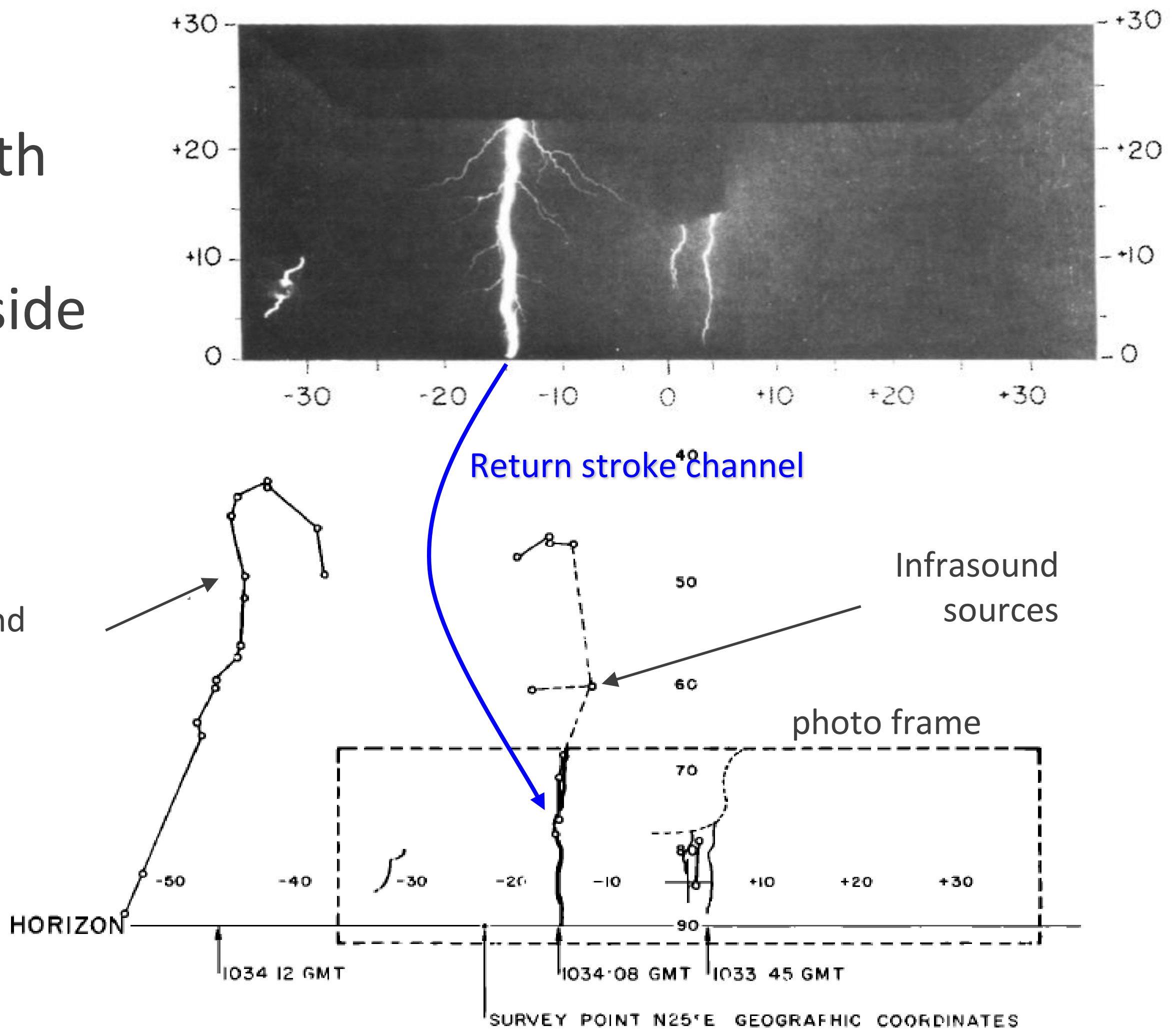
- The measurement and detection of thunder by networks of acoustic sensors allow to follow the evolution of thunderstorm cells in time.

- Thunder can be detected at less than 75 km with waveforms that can be used for analysis.
  - Wind conditions can mask thunder by the noise it generates, hence the need to place the sensors under vegetation cover and to use filtering systems.
  - One flash of lightning can mask another! A nearby thunderstorm cell will prevent the detection of a more distant thunderstorm cell.
  - Infrasound amplitude decreases in $1/r^{0.7}$, likely due to tropospheric propagation.

- The measurements of thunder by the great multiplicity of sources allow:
  - To delimit the shadow zone, in which few detections are possible.
  - To image the wind fluctuations in the stratosphere, using the stratospheric phases

Lightning reconstruction and characterisation by thunder

Few (1970) suggested the use of the cross-correlation method (as PMCC) to find the azimuth and elevation angle of thunder measured by an array of 4 microphones [0.1 - 450 Hz] in a 30 m side triangle.

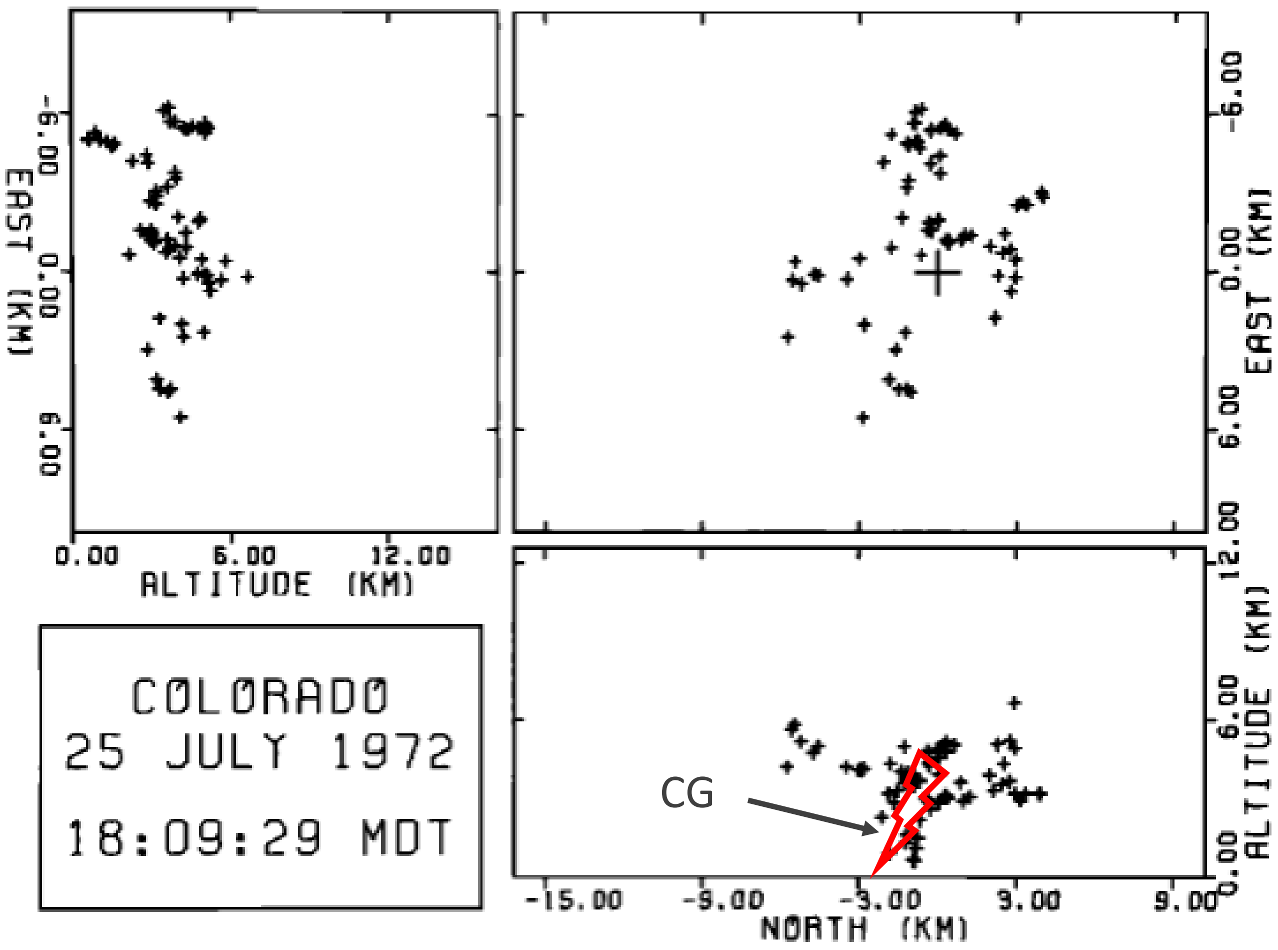


Comparison of the ionized channel of a photographed return arc and the location (azimuth, elevation) of acoustic sources.

Few and Teer, JGR, 1974

MacGorman et al (1981): first 3D reconstruction of a lightning flash using acoustic measurements.

Method based on the determination of:
- azimuth and elevation angles: cross-correlation method [Few (1970); Few and Teer (1974)]
- distance: from the propagation time of the thunder
  (Acoustical arrival time - EM arrival time)



❾ First 3D view of the discharges **inside** the cloud (EM methods under development at that time) so no external validation of these results.

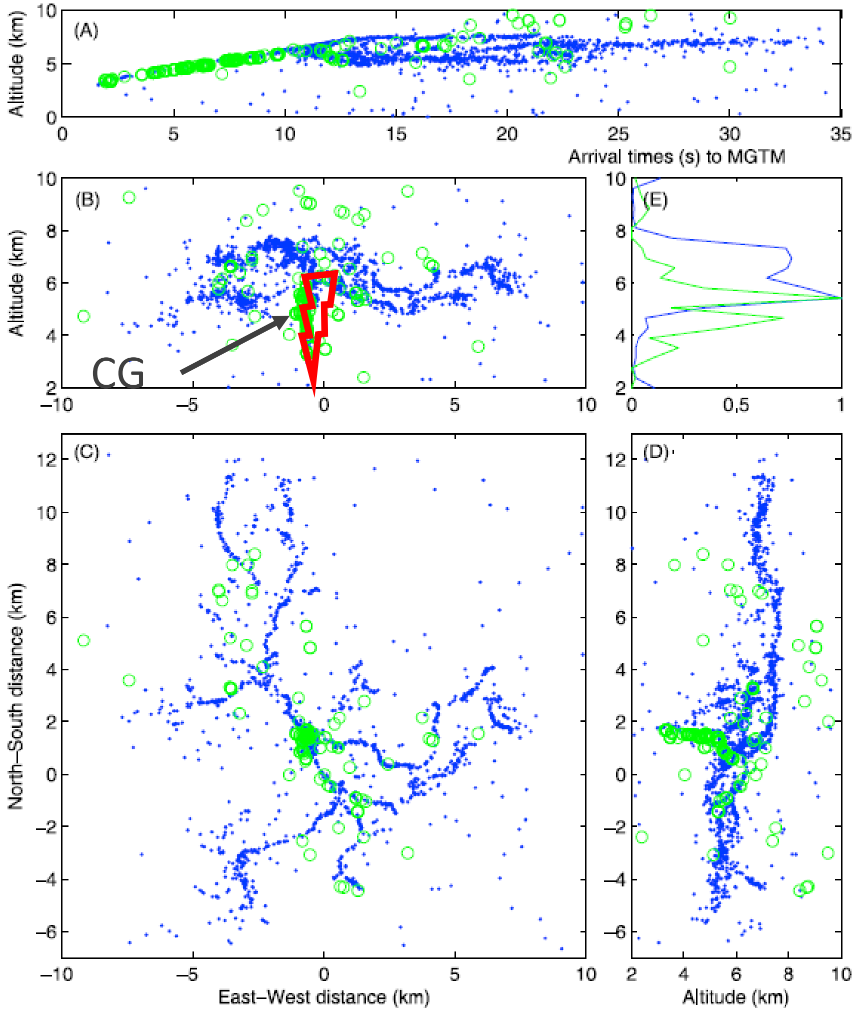


Figure 7. Overlays of locations of acoustical (circles) and LMA radiation sources (dots) for the second triggered lightning flash over the triggering site (Kiva) on the Magdalena Mountains of New Mexico at 2322:48 UTC on 6 August 2009. See Figure 6.

- Acoustics : 4 microphones array (25-m side triangle)
- EM : Lightning Mapping Array (VHF)
- Triggered lightning (rocket)

- Using MacGorman et al. (1981) methodology

- Very good superposition of **EM-VHF** and **acoustic** sources
- Mainly around the CG discharge

Arechiga et al., JGR, 2011

Reconstruction method adapted from MacGorman et al. (1981):

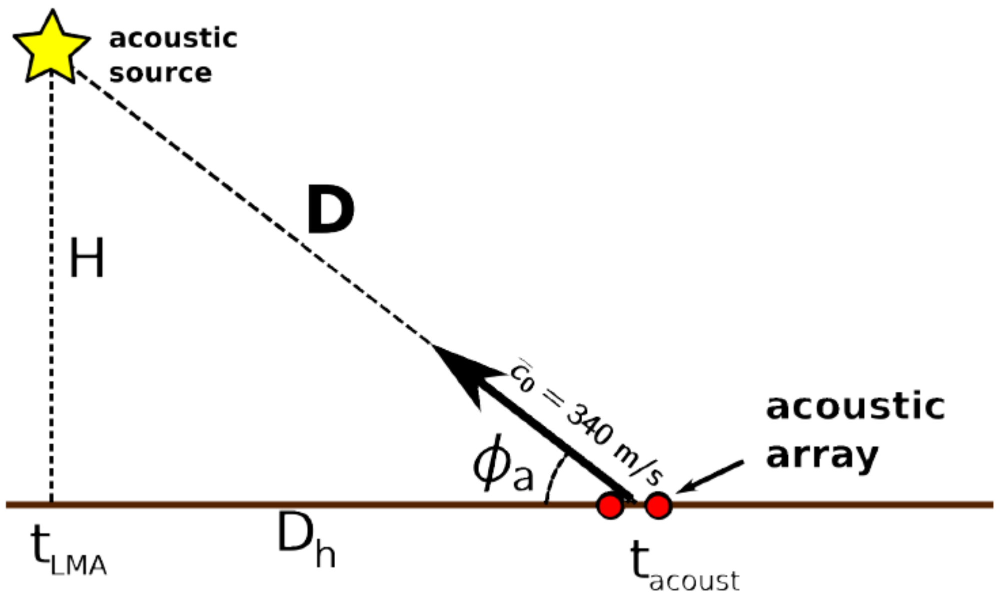
We assume a straight propagation from the acoustic station to the source:

- constant sound speed c_0 all along the propagation,
- azimuth and elevation angle calculated by PMCC,
- distance $D = c_0\ (t_{acoust} \_ t_{LMA})$

The elevation angle ϕ_a is calculated:

$$\cos(\phi_a) = \frac{c_0}{V_h}$$

with the horizontal velocity V_h calculated by PMCC.



Gallin et al., JGR, 2016

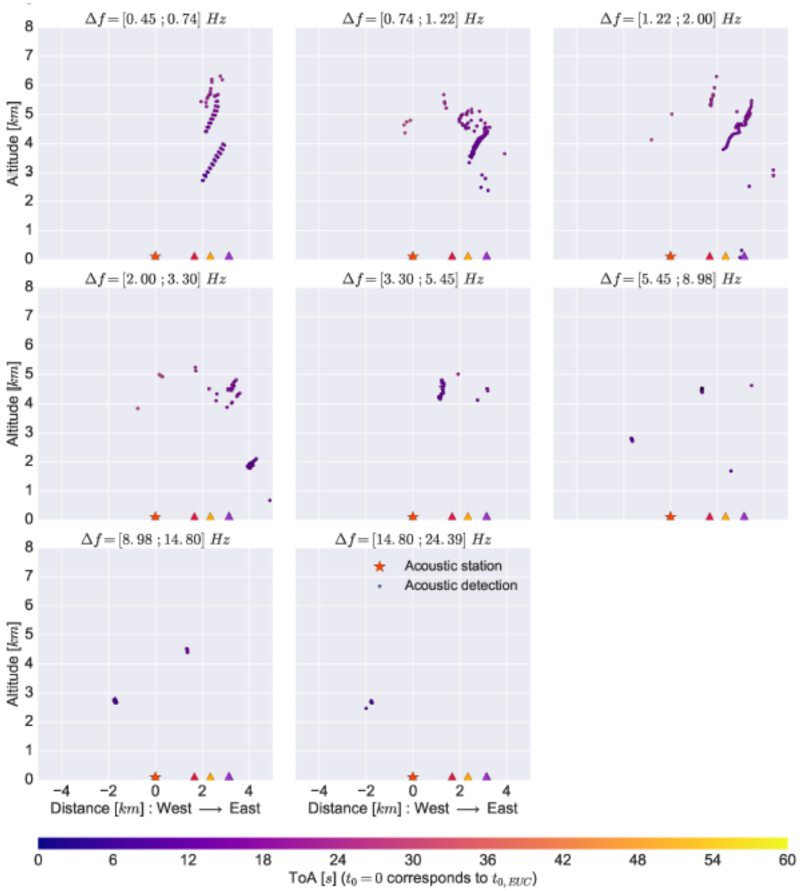
Comparison of 2 networks (50-m and 500-m triangles)

Reconstruction for a lightning **2 km** from the arrays,
by frequency bands for the
- microbarometer (MB) array
- microphone (MP) array.

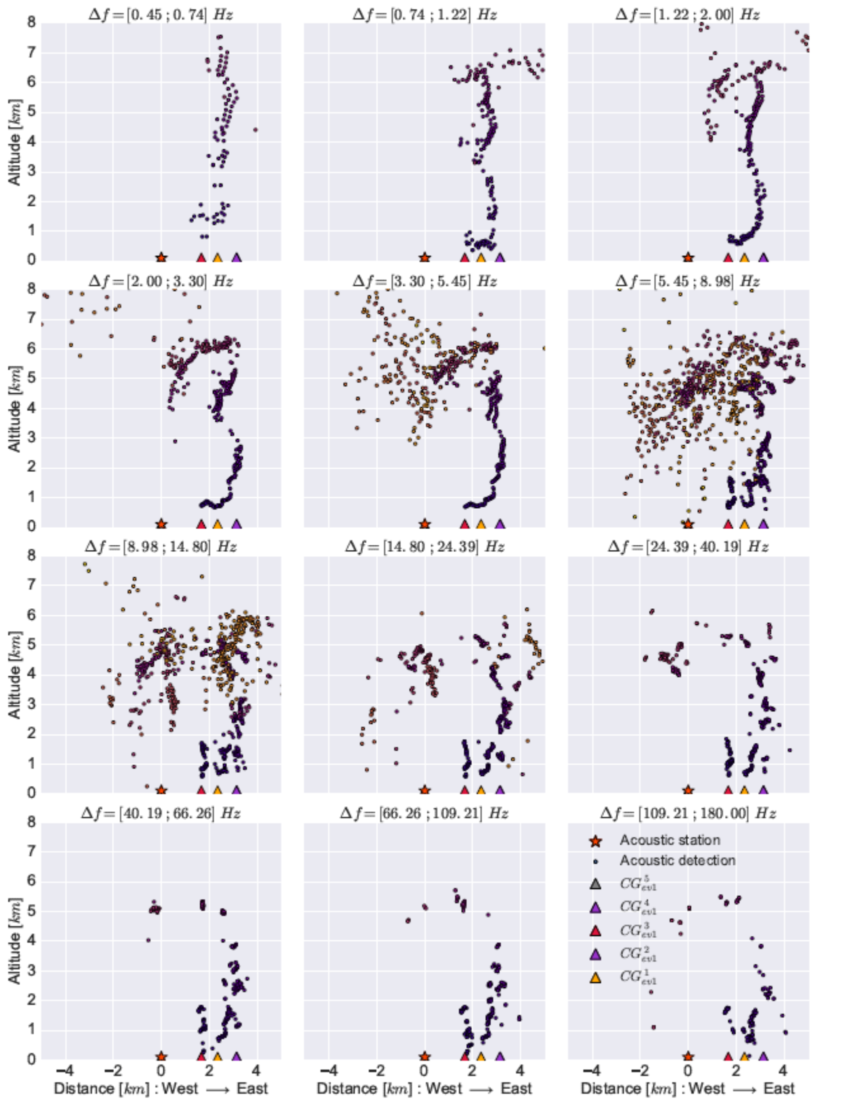
(MP data decimated to be at the same sampling frequency than MB ones)

❾ Many more detections with MP than MB.

MB network - 500 M



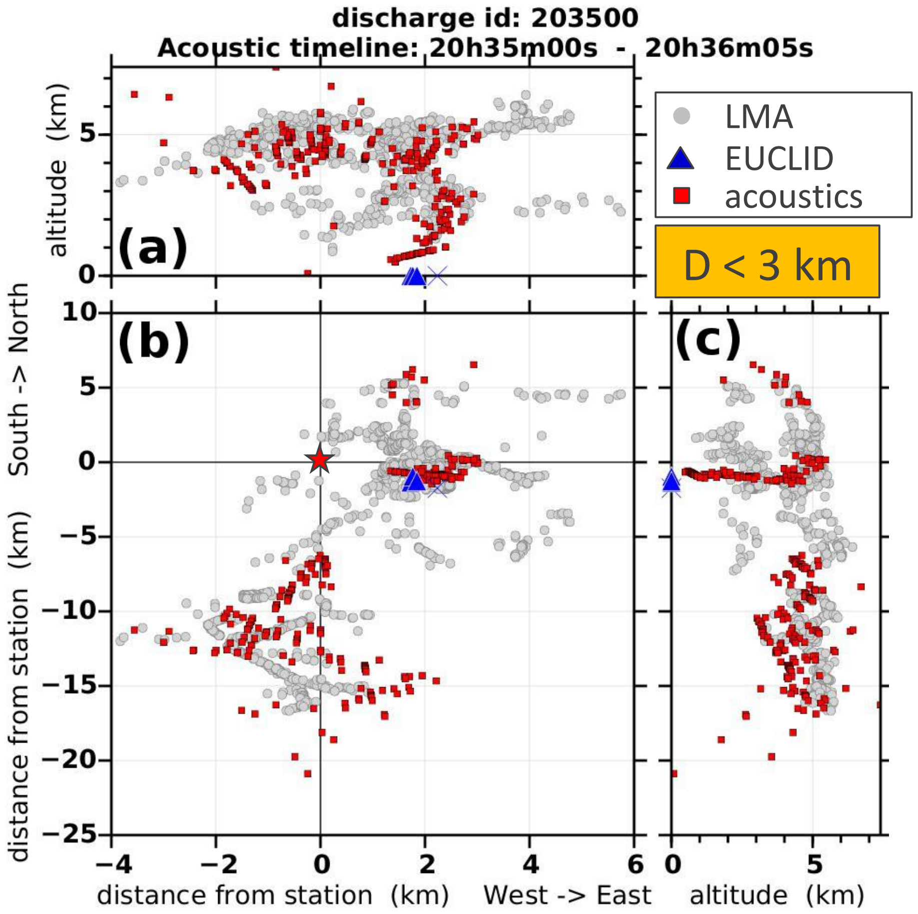
MP network - 50 m

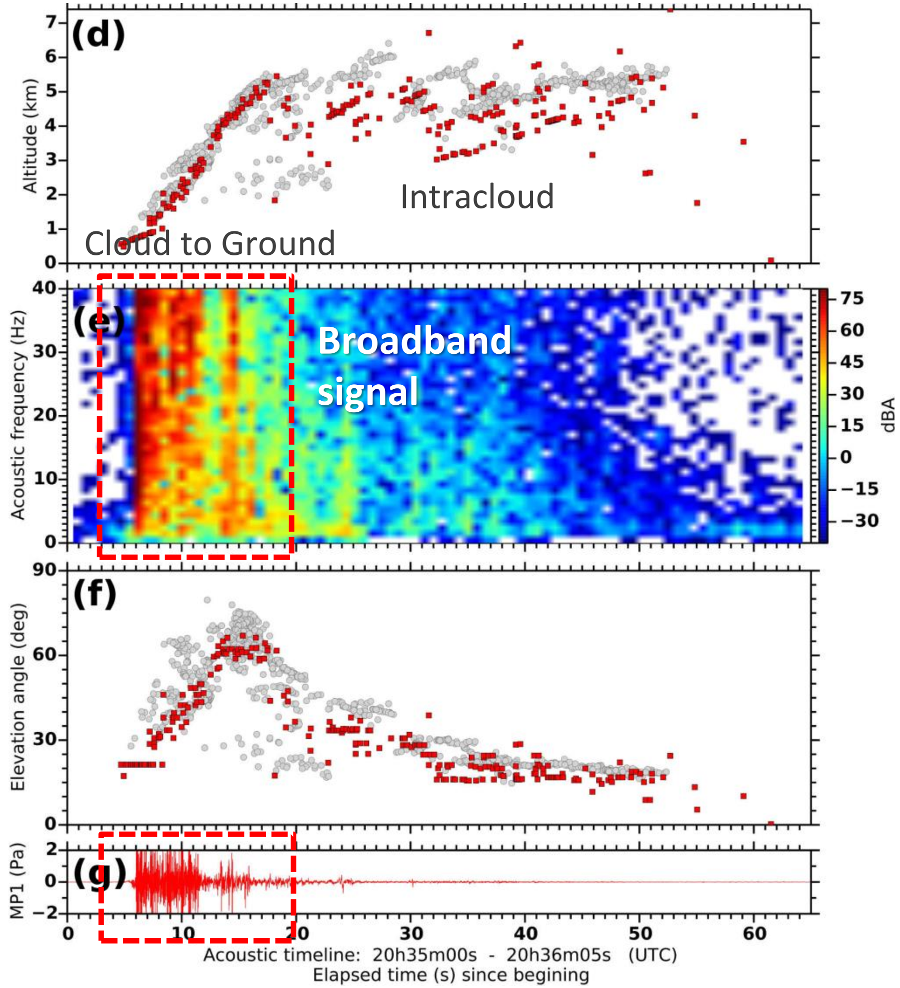


❾ It is the size of the network that is important to correctly reconstruct in 3D

Lacroix et al., JGR, 2018

Reconstructed acoustics sources are co-localized with EM-VHF (LMA) discharges

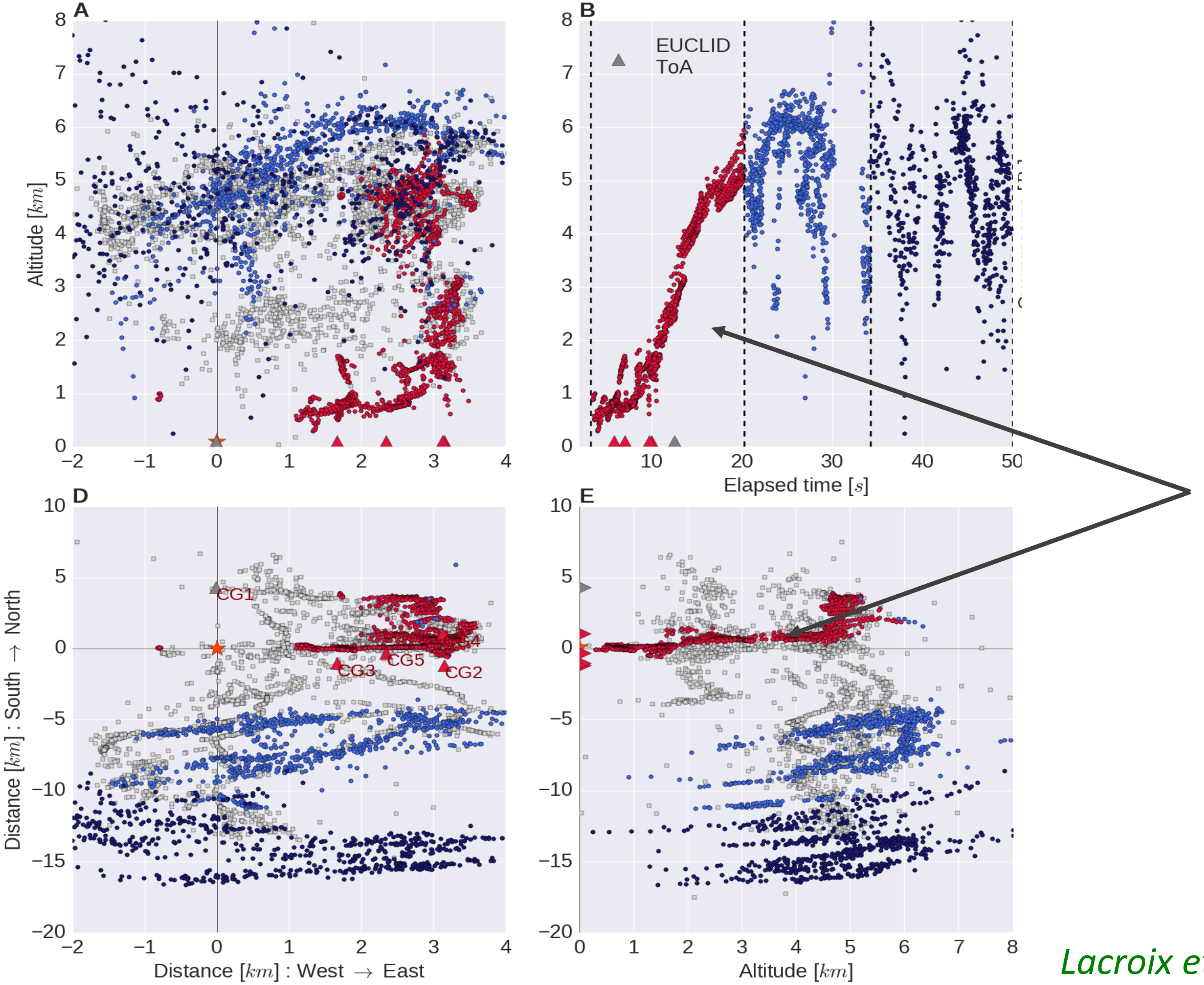




Gallin et al., JGR, 2016

❾ Better description of the return stroke channel than LMA at low altitude (<1 km)

Acoustical separation of cloud-to-ground and intra-cloud discharges

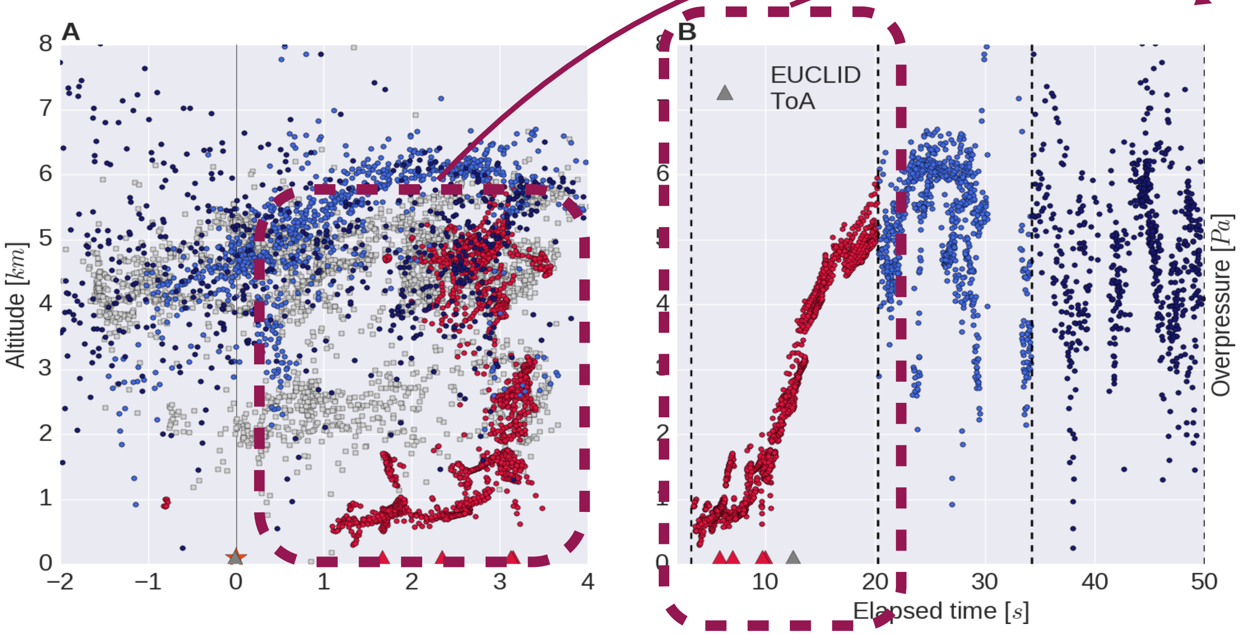


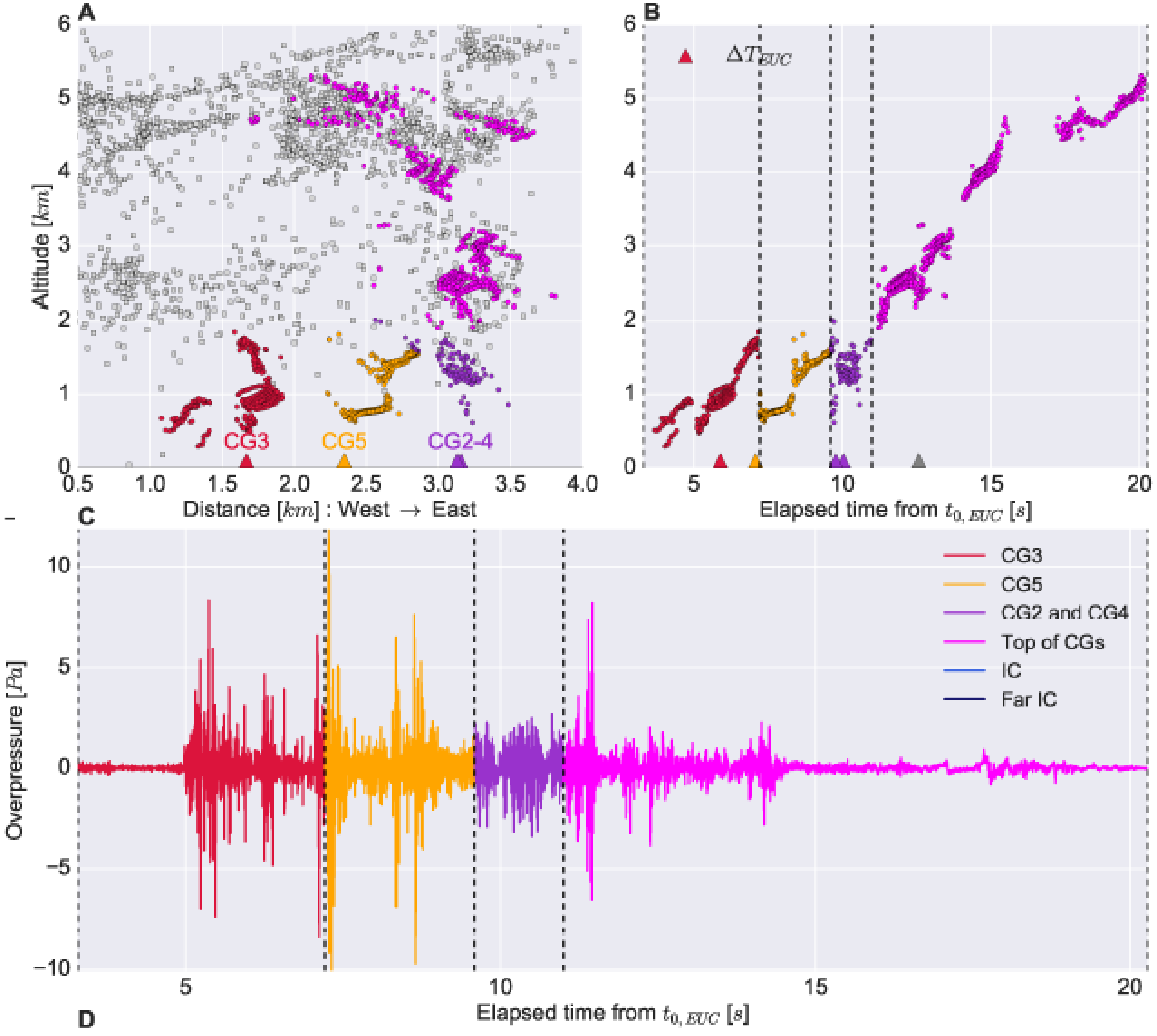
Using the CG/IC EUCLID time and the localization of the sources, we can define time windows for each phase of the flash.

Lacroix et al., 2018

Identification of different return strokes of the same flash

26/10/2012-20:38:12, 2 km away from station
5 return strokes

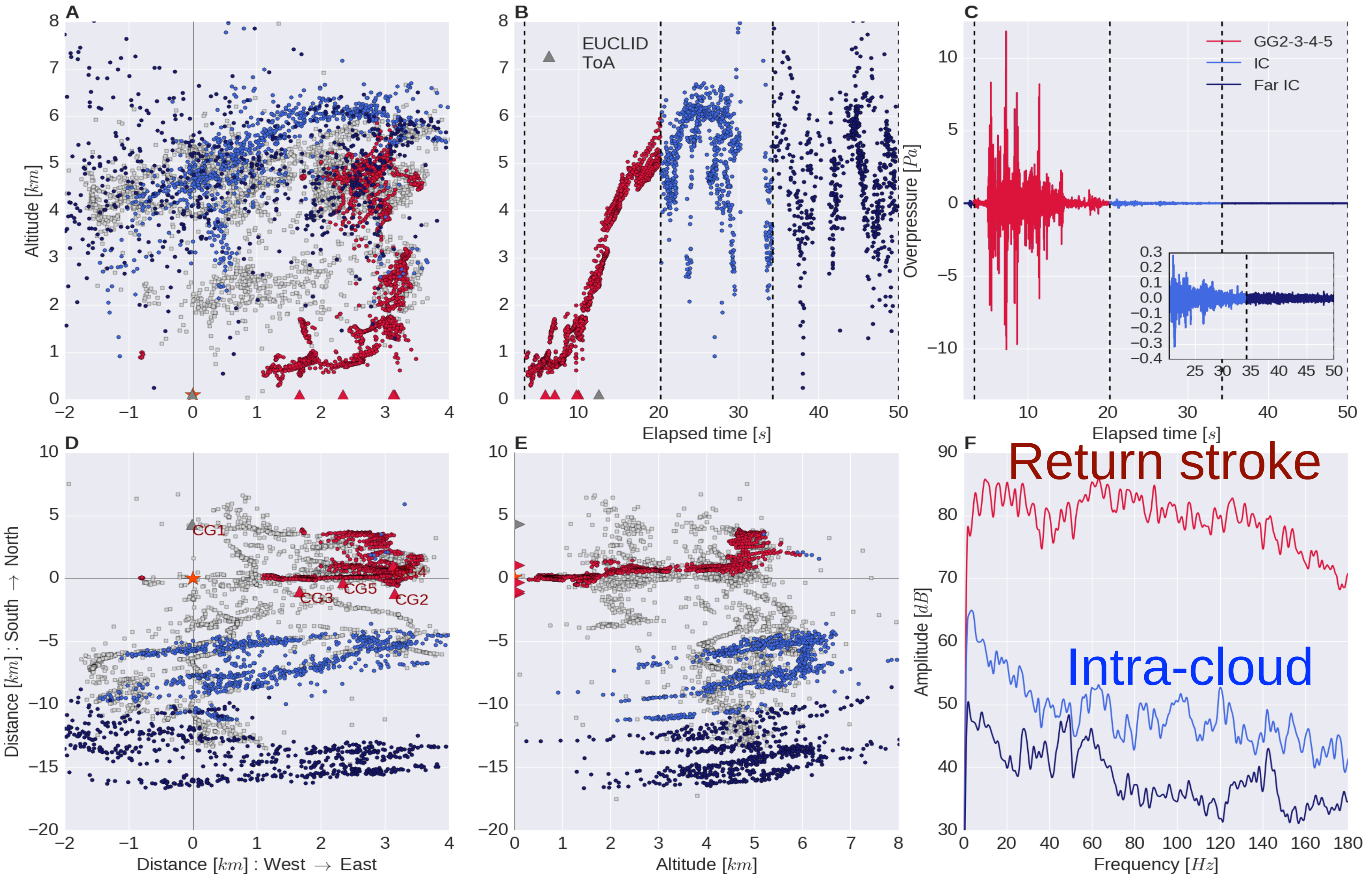




Reconstruction of 3 return strokes, few hundred meters apart, within a time interval of 300 ms

Lacroix et al., JGR, 2018

Frequency spectra of cloud to ground vs intra-cloud flashes



- **Strong infrasonic content from the return stroke** (cloud to ground) channel

➔ Wilson's electrostatic model cannot explain this (because the source would be in the cloud).

- **Flat spectra**, no clear peak around 150 Hz as expected with Few (1969) model

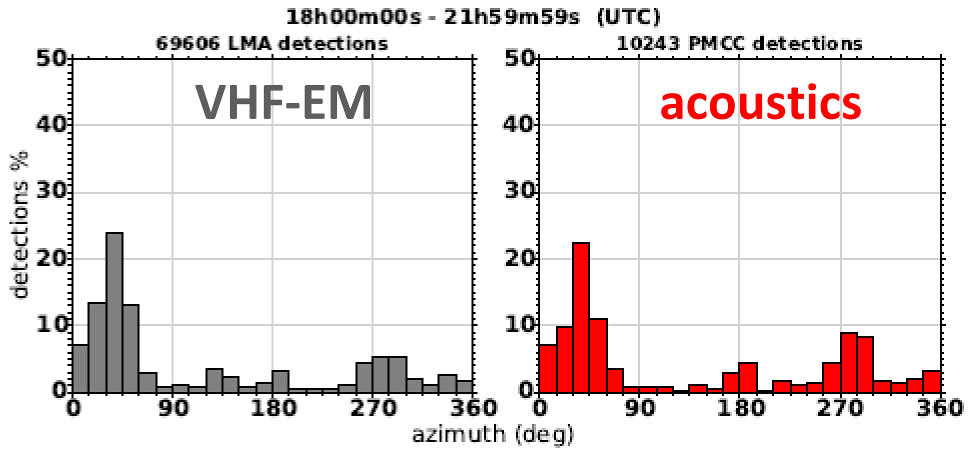
➔ in agreement with our model.

Lacroix et al., 2018

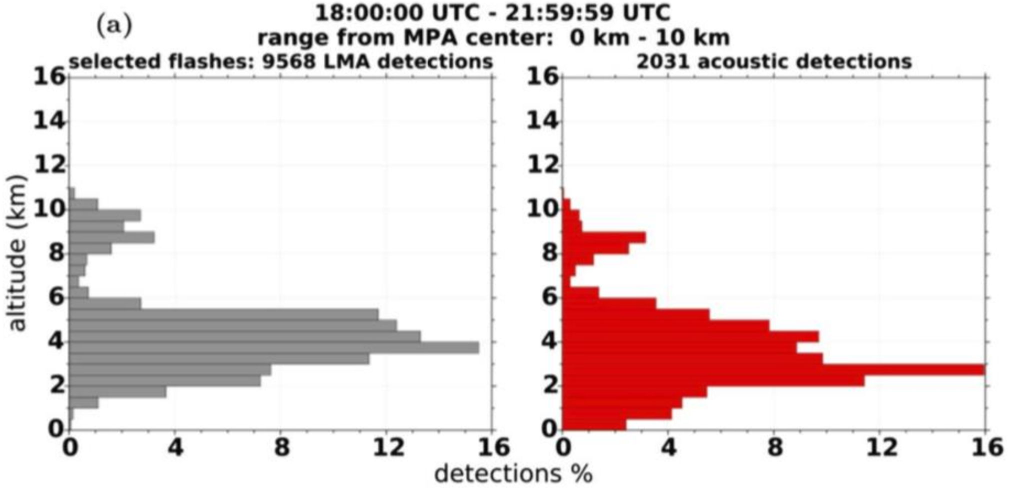
Performance of the acoustical reconstruction

Analysis of 56 lightning flashes within 75 km of acoustic station from 18:00 to 22:00 UTC.

- Azimuth distribution: discharges are detected in all directions with good proportion.
- Altitude/distance distribution: good up to at least 10-15 km from the acoustic station !



Gallin et al., 2016

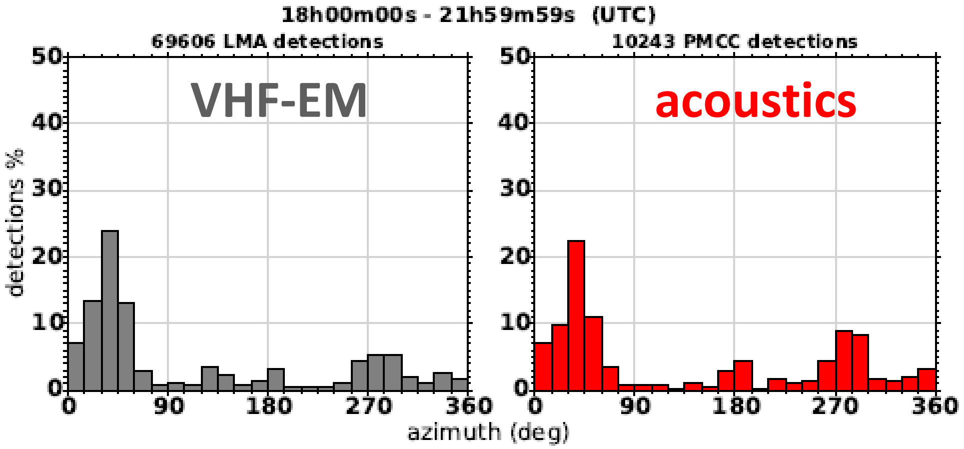


Performance of the acoustical reconstruction

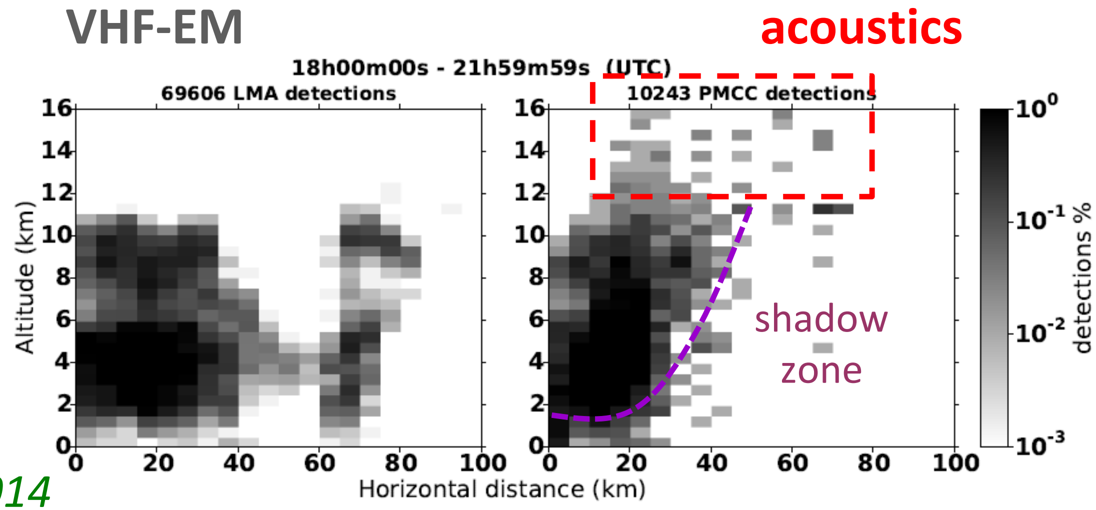
Analysis of 56 lightning flashes within 75 km of acoustic station from 18:00 to 22:00 UTC.

- Azimuth distribution: discharges are detected in all directions with good proportion.
- Altitude/distance distribution: good up to at least 10-15 km from the acoustic station !
- but altitude bias for flash distance > 15 km: some sources are too high
- shadow zone appearance (20-40 km)

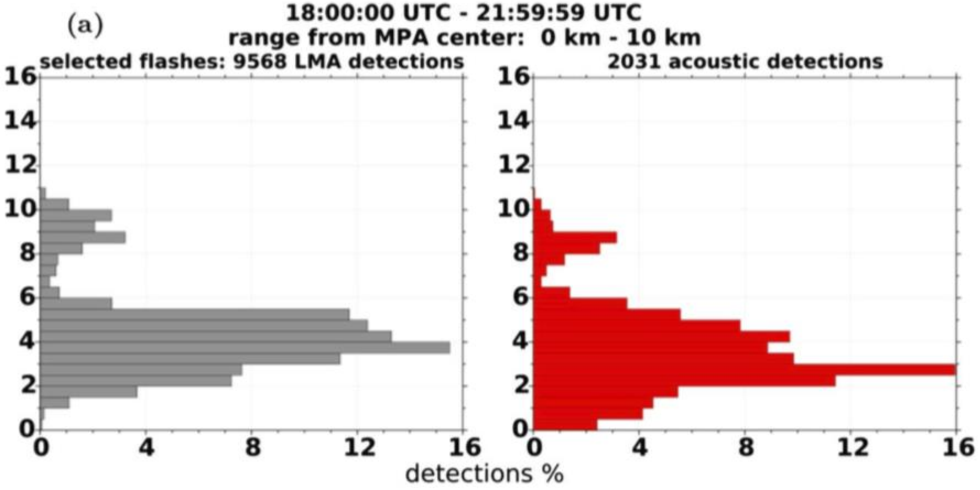
Likely effect of atmosphere inhomogeneity



Gallin et al., 2016



Gallin, 2014



Analysis of **7** flashes over **3** thunderstorms (Cévennes 2012)

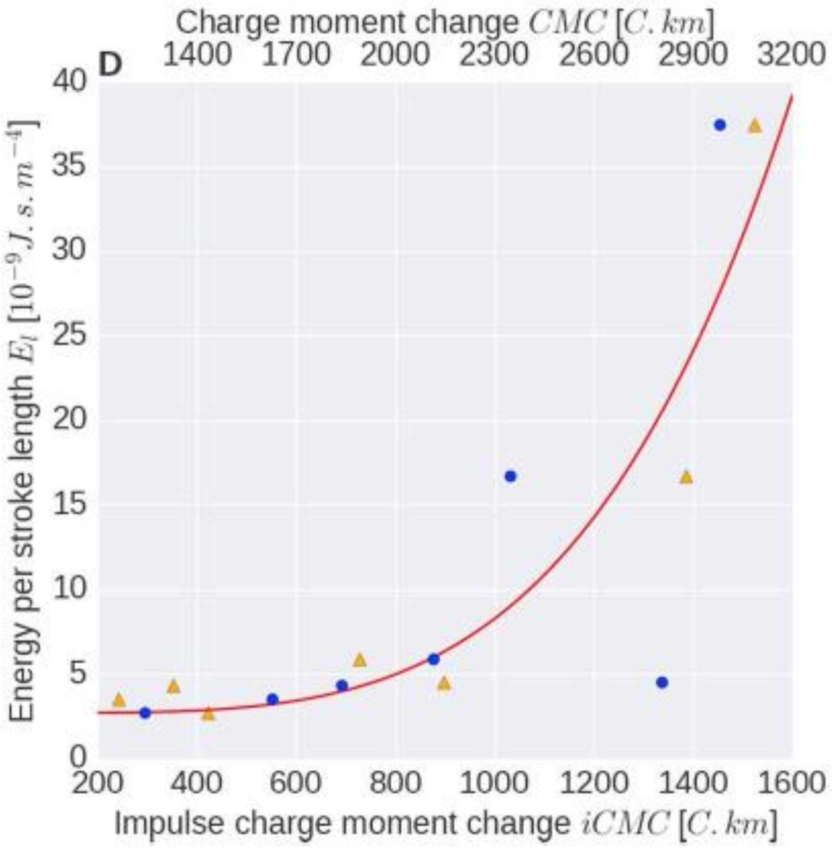
Correlation of
acoustical energy E_l per stroke length
with
(impulse) charge moment charge *CMC /iCMC*

$$E_l = Cte \times iCMC^4$$

➒It is a **first** positive link between acoustical (thunder) energy and one of the electrical lightning parameters
(*Farges and Blanc (2010)* showed that peak current does not correlate well acoustic amplitude)

… but measured only for seven, most energetic +CG flashes, associated with sprite occurrence *(Soula et al. , 2015)*

More data are needed to confirm this result…

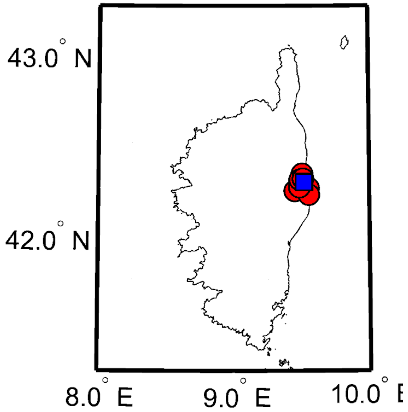


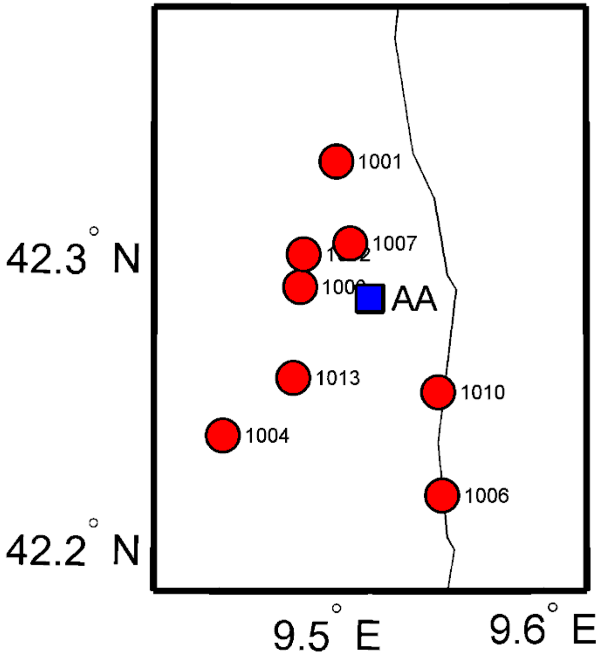
Lacroix et al., JGR, 2018

Spatial distribution of the acoustic energy of thunder

New measurement campaign in September/October 2018 in Corsica (EXAEDRE):

- 1 acoustic array (AA) of 4 microphones in a 30-m triangle
- 8 isolated microphones located between 2.2 to 8.0 km from AA
- Sampling frequency: 250 Hz, GPS dating

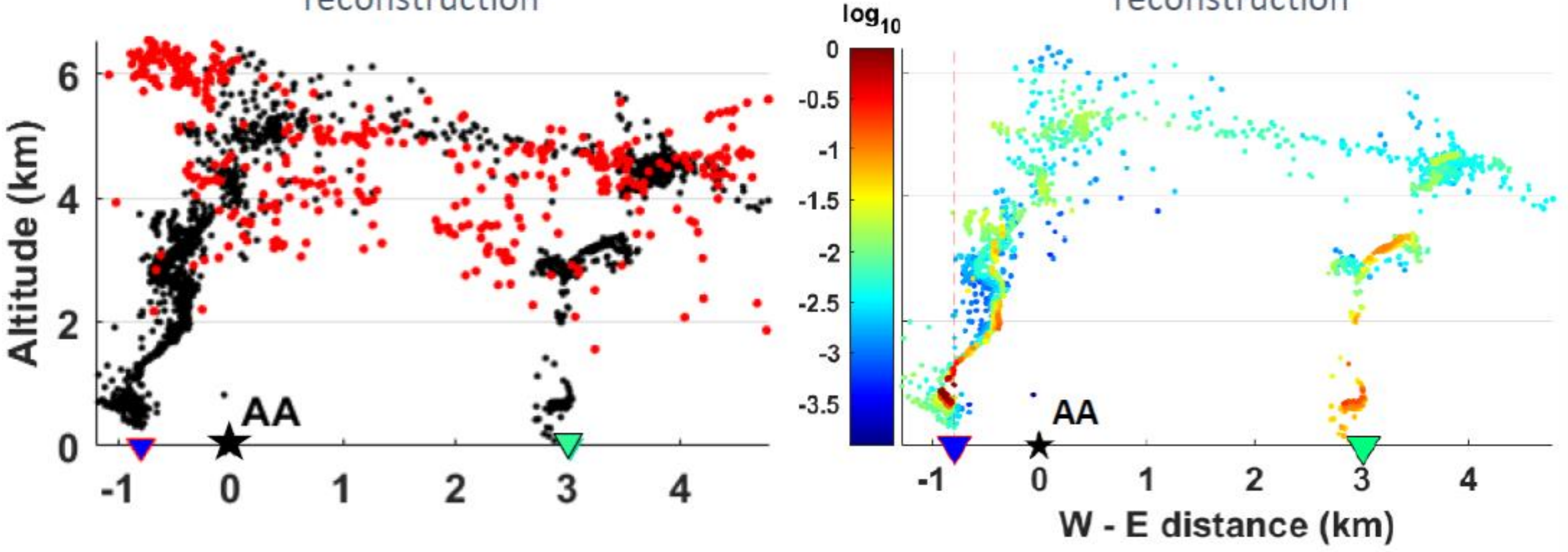




Three days of interest (thunderstorm within 25 km of AA): Sept. 6 & 17, Oct 2

Spatial reconstruction

Energy reconstruction



Acoustical energy along the channel

see Damien Bestard's poster !

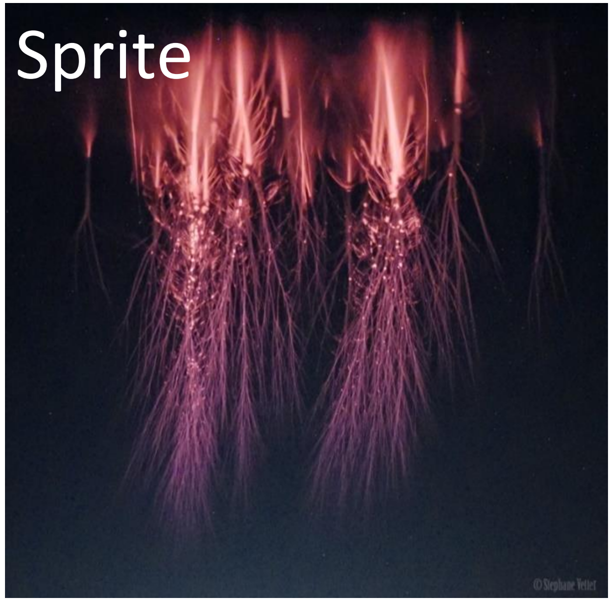
- A method anterior to EM observations: acoustics, first observation of IC discharges
- Individual lightning flashes can be reconstructed by arrays of microphones (30-50 m) up to 10-15 km
- Acoustics complements EM methods
- Most efficient for cloud to ground return strokes (most energetic part of the flashes)
- Infrasound originates mostly from return stroke : dominant source of infrasound is lightning return stroke ionisation

and in the future

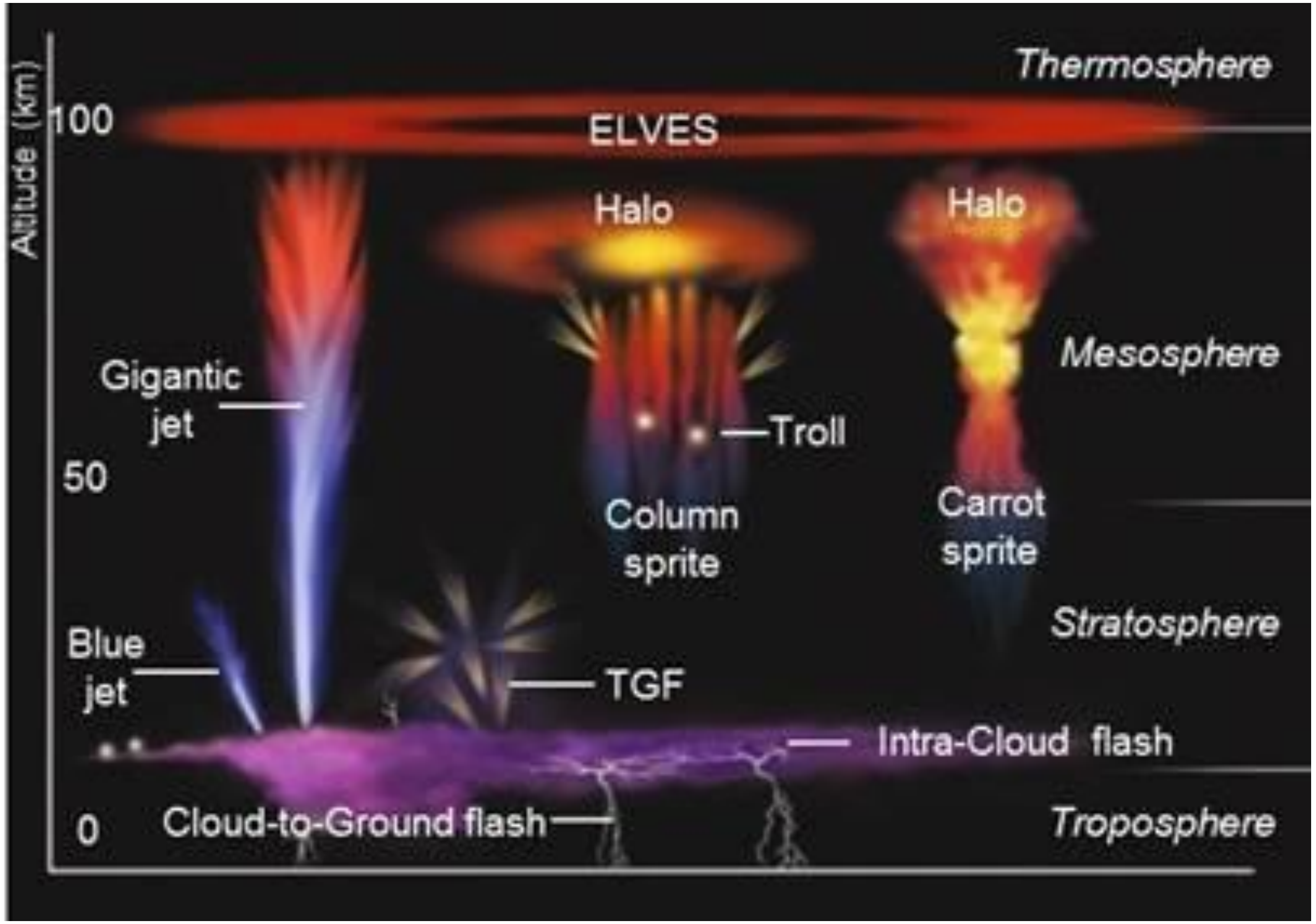
- Evaluate the benefit of MCML (Multi-Channel Maximum Likelihood) method for lightning
- Confirm the correlation with iCMC or other electrical / energetic parameters
- New data (campaign in Paris region during Olympic Games ?)
- Confirm/explain the strong heterogeneities and power variability (3 to 4 orders of magnitude)
- Quantify influence of local, instantaneous meteorology (extension of reconstruction range ?)

Infrasound from sprites

Welcome in the fantasy world of the middle atmosphere of the Earth!



Duration: from 0.5 ms to hundreds of ms
Global occurrence: from 0.5/minute (sprite) to 3/minute (ELVES) # 44/s (lightning)



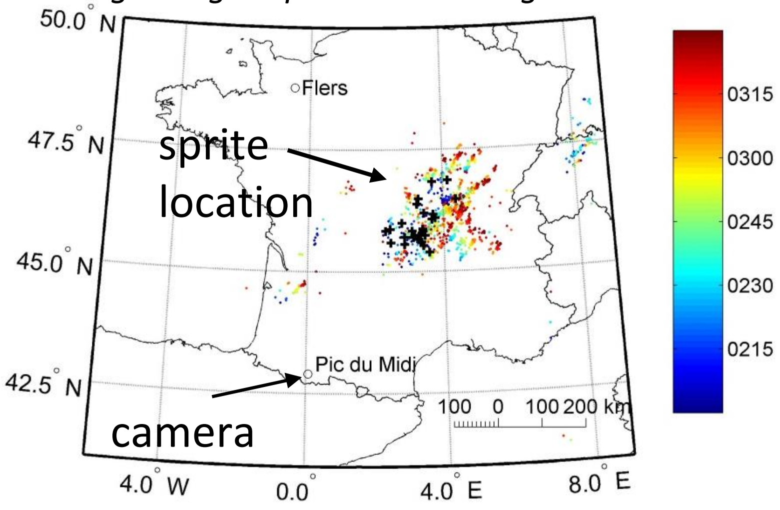
Adapted from Blanc and Farges, Pour la Science, 2012

Different phenomena due to different mechanisms are involved:

- **Sprites** are streamers induced by the quasi-electrostatic field of very strong +CGs
- **ELVES** are the results of the flash EMP interaction with the lower ionosphere
- **Blue jets** are « typical » IC going upward which rarely evolve as **gigantic jet** connecting to the ionosphere

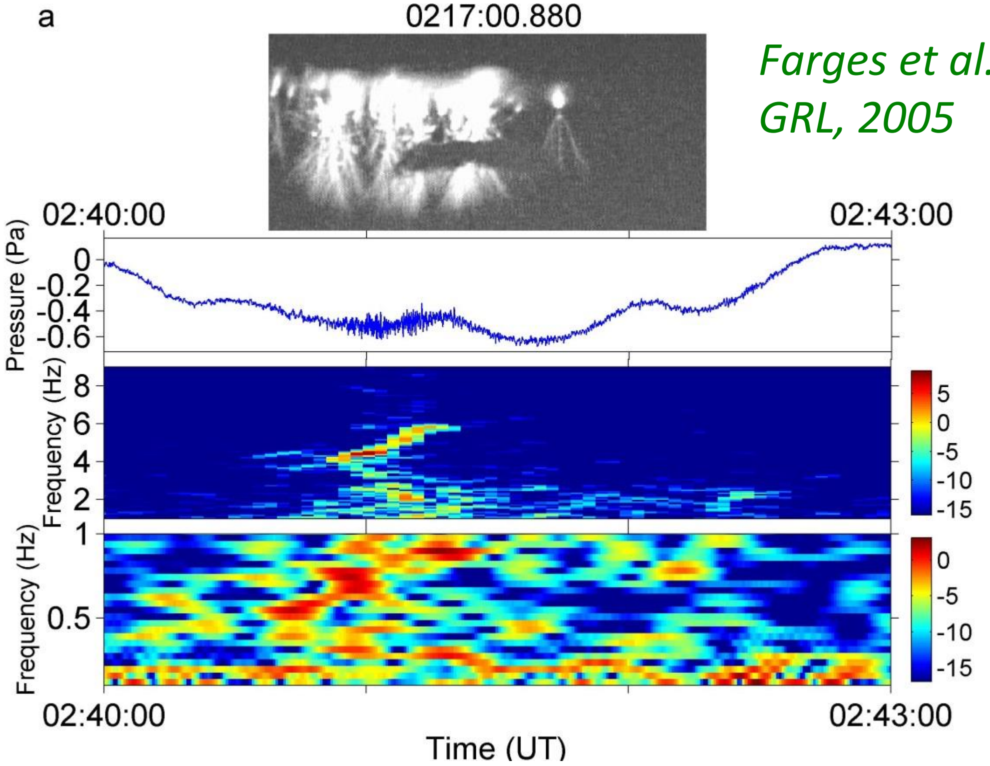
First identification: during the EuroSprite campaign in 2003

Lightning map with Météorage data



July 21, 2003 thunderstorm:

- 28 observed sprites
- from 02:00 to 03:15 UT
- from 350 et 500 km to Flers acoustic station



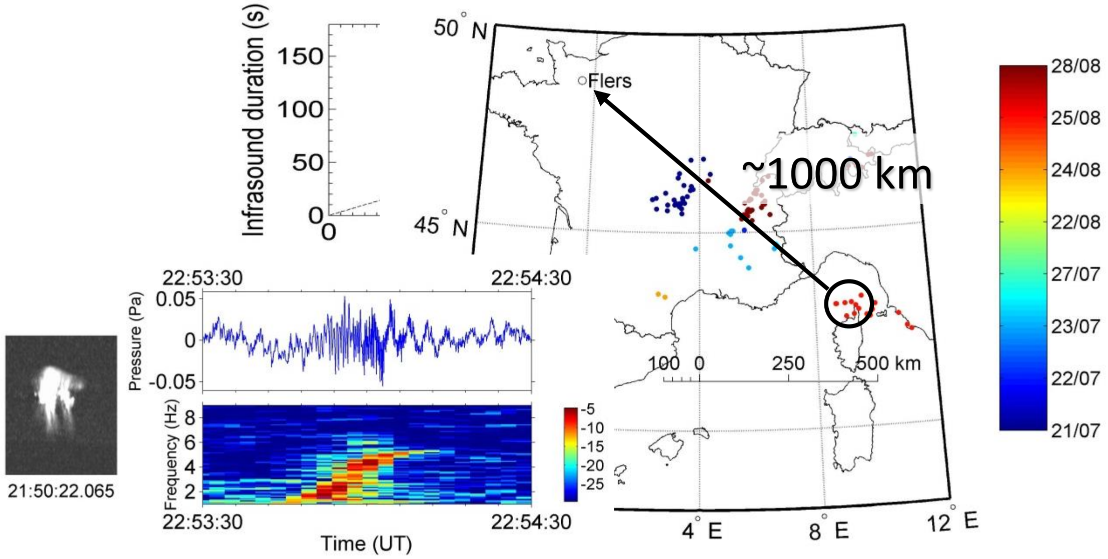
Farges et al., GRL, 2005

• detection of several infrasounds with a particular signature: chirp (*Liszka, 2004*)

• **delay** between the time of occurrence of the sprite and the time of arrival of the infrasound is compatible with that calculated for a source at 60 km altitude

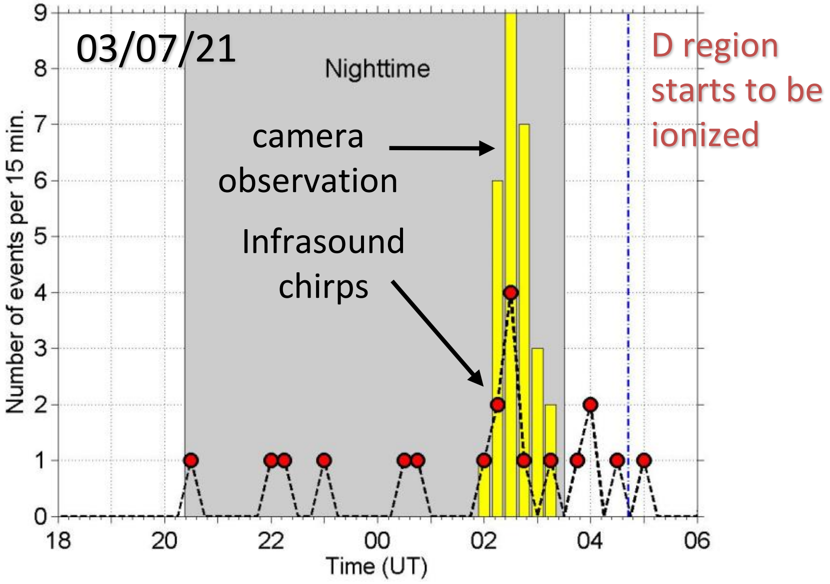
Sprite infrasound main behaviour

- The infrasound duration is directly related to the horizontal extension of the sprite in the observation direction (*Farges et al., GRL, 2005*)



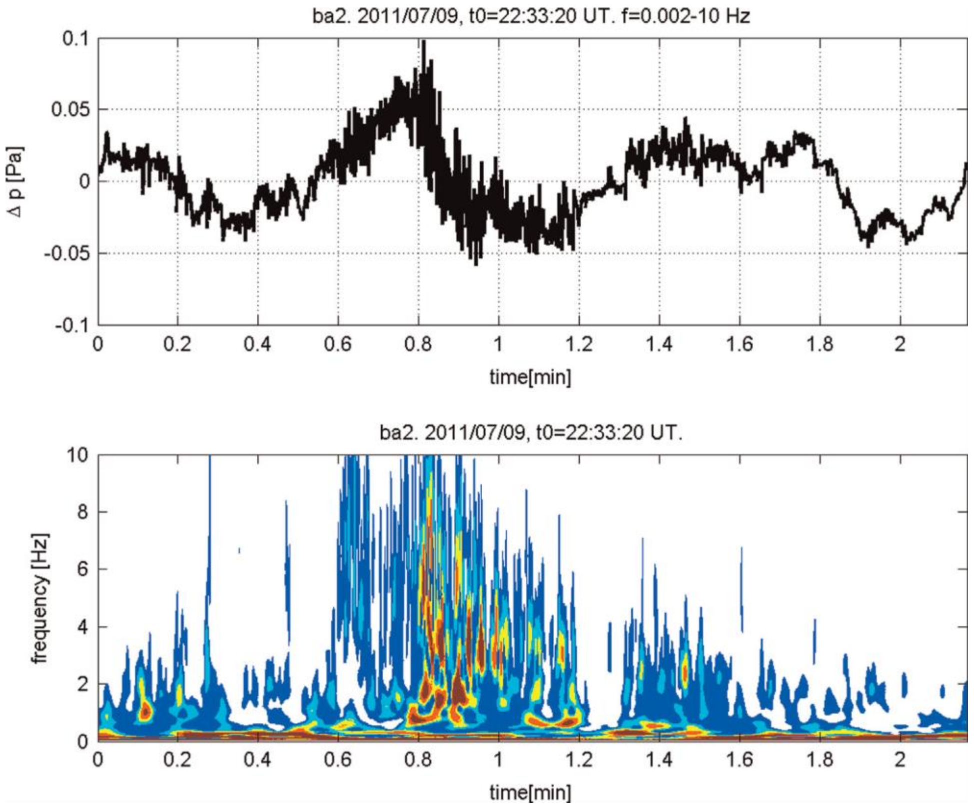
- Detection limit : ~ 1000 km (*Neubert et al., JASTP, 2005*)

- Several chirp signals have been detected at dawn: allows to show that the conditions of sprite formation is still possible even if it is not possible to see them anymore (sky too bright) (*Farges et al., GRL, 2005; Neubert et al., Surv. Geophys., 2008*)



Other observations of infrasound sprite signature over:

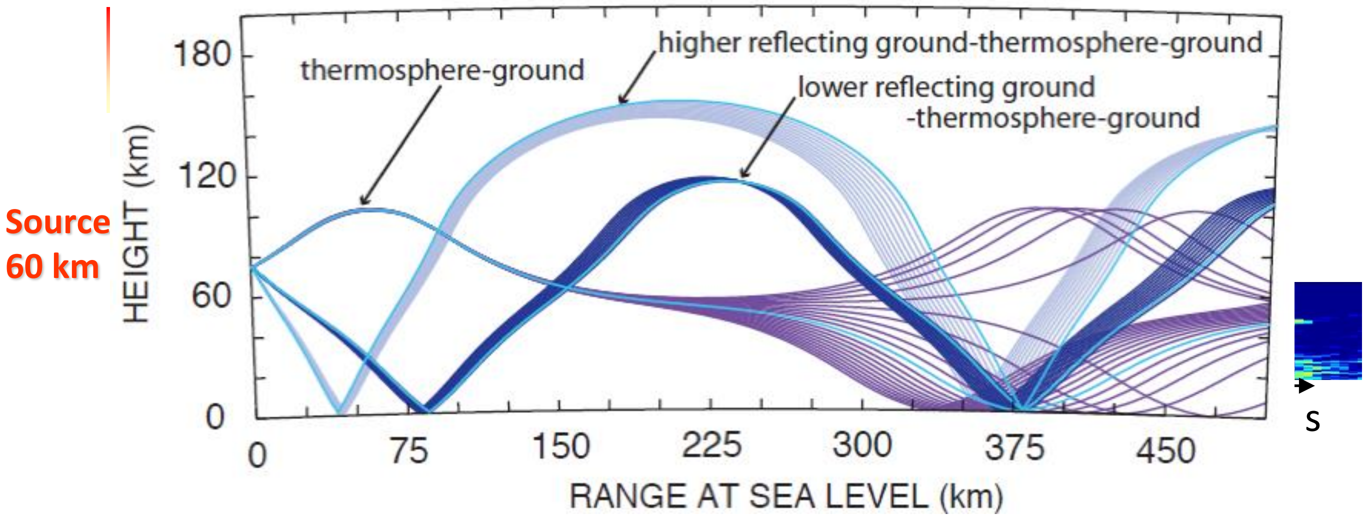
- Sweden from 1994 to 2004 (*Liszka and Hobara, JASTP, 2006)*
- Czech Republic on July 10, 2011 (*Sindelarova et al., JASTP, 2015*)
- Israel, 2011-2012 (*Applebaum et al., Atmos. Res, 2020*)



Sindelarova et al., JASTP, 2015

Explanation of the chirp signature

The chirp signature is assumed to be due to horizontal extension (duration) and a low-pass filter effect when reflecting signals in the lower thermosphere (100 - 150 km)



Farges et al., GRL, 2005

de Larquier, 2010

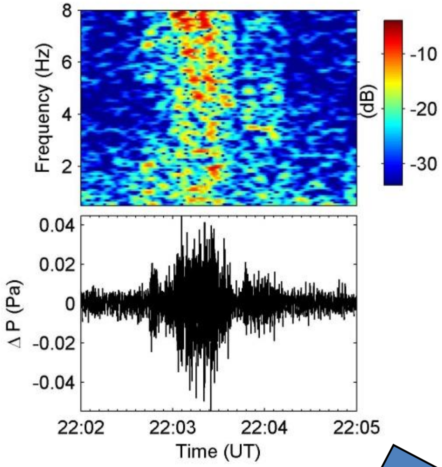
• Hypothesis confirmed by numerical simulations (*de Larquier, Master thesis, 2010*): 3 calculated phases, only one observed.

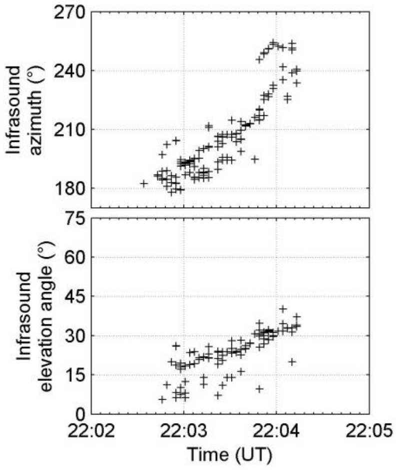
2005 Eurosprite campaign

Inverted chirp signature

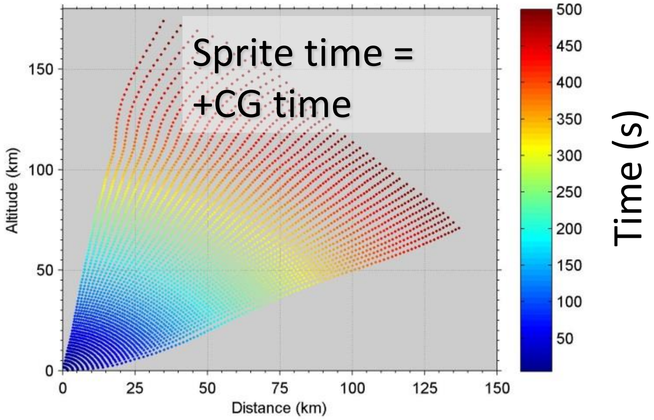
PMCC

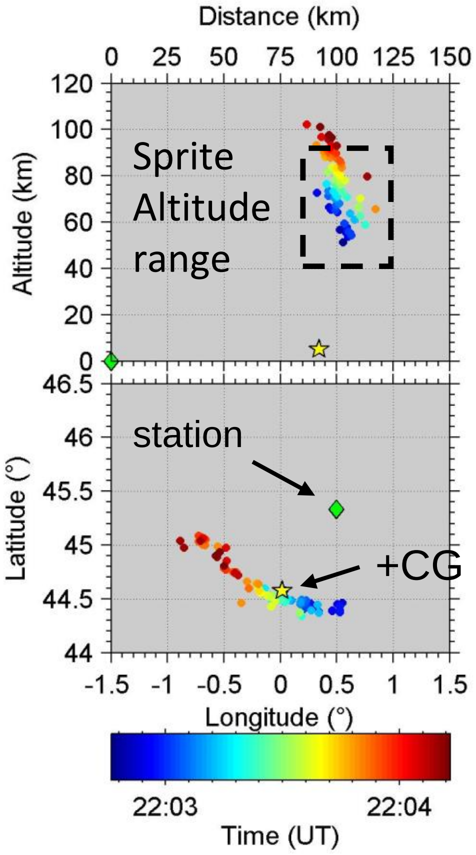
05/09/05



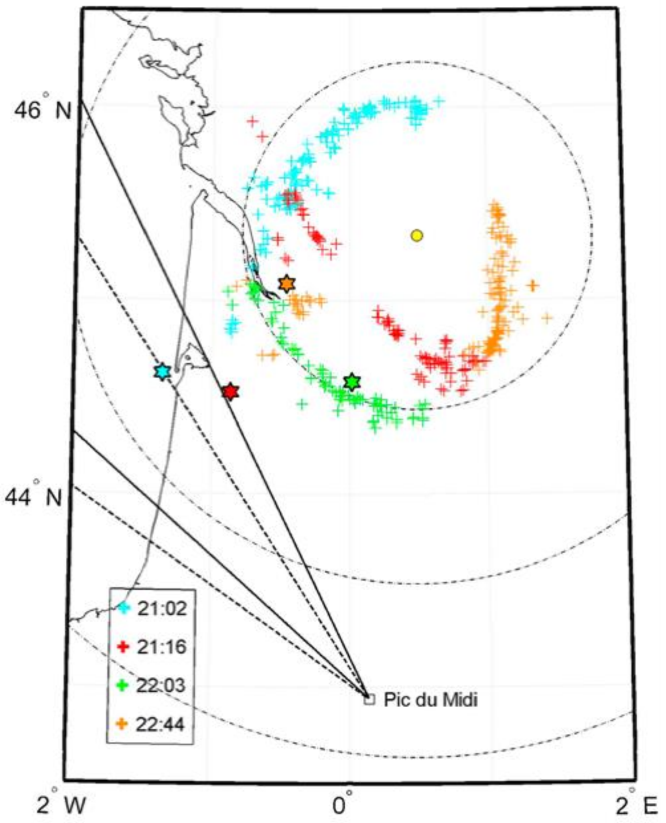


Ray tracing
Propagation





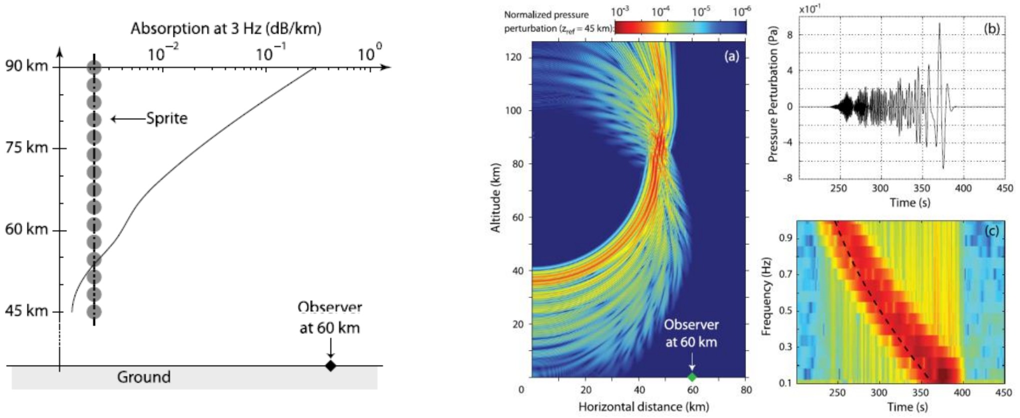
4 sprites reconstructed but no optical confirmation (outside the field of view)



Farges and Blanc, JGR, 2010

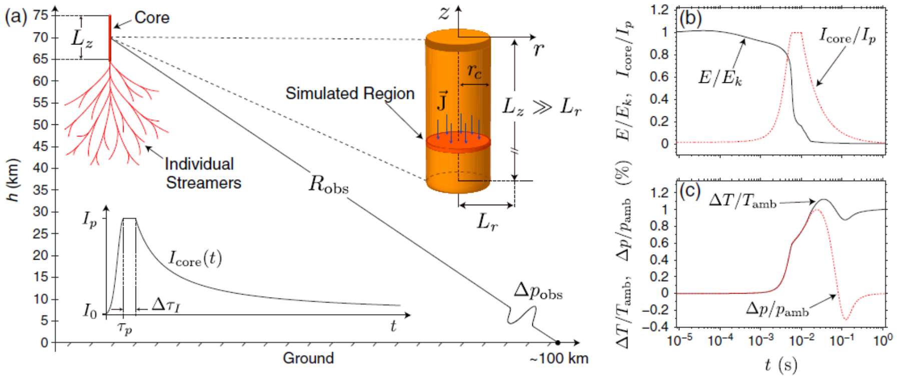
Simulations show:

- Inverted chirp shape (observed in direct propagation) is explained by the dimension of the streamers according to the altitude: **the finer structures (at low altitude) radiate at higher frequency**.



de Larquier and Pasko, GRL, 2010

- The heating in the streamer heads (~1 K) leads to the formation of an acoustic wave: **only the most intense sprites would produce infrasound**



da Silva and Pasko, GRL, 2014

- Sprites are detected in infrasound measurements thanks to a particular signature in the time/frequency plane (chirp) that can be explained theoretically.
  - They can be detected up to 1000 km away.
  - Their duration is directly related to the horizontal extension of the sprites.
  - In direct propagation (< 200 km), we can reconstruct the geometry of the source.

- Sprite acoustic detection can complement optical observations when they are not possible (day, cloud cover, ...).

- Only the most intense and the largest sprites allow a detection.

DE LA RECHERCHE À L'INDUSTRIE

Thank you for your attention

LETMA
MODELLING INFRASONIC PROPAGATION

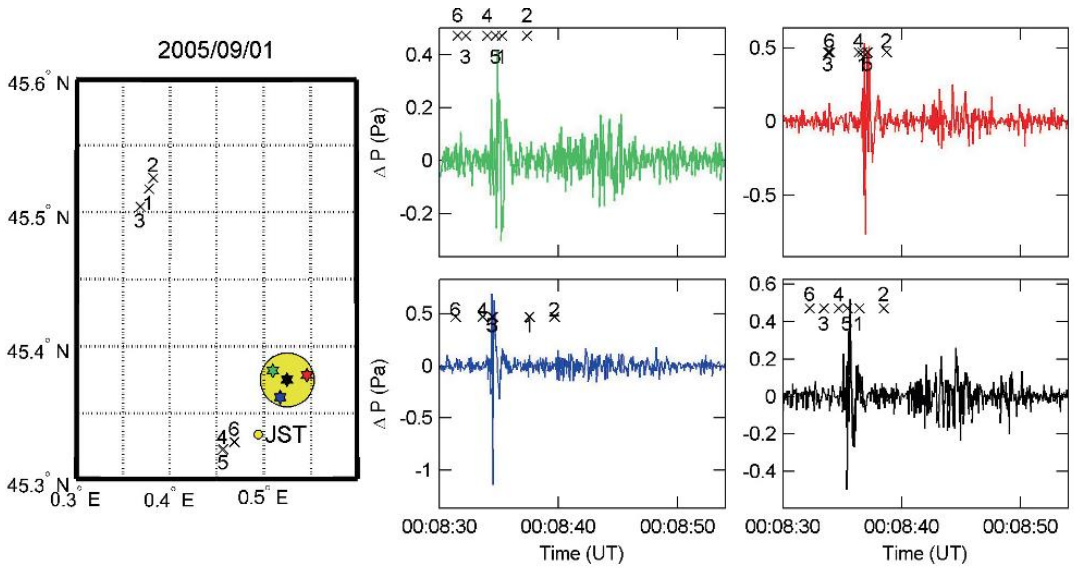
« Waves and Geosciences: infrasound and beyond » - Lyon (France) - March 2022

T. Farges (CEA) and F. Coulouvrat (CNRS & Sorbonne Université)

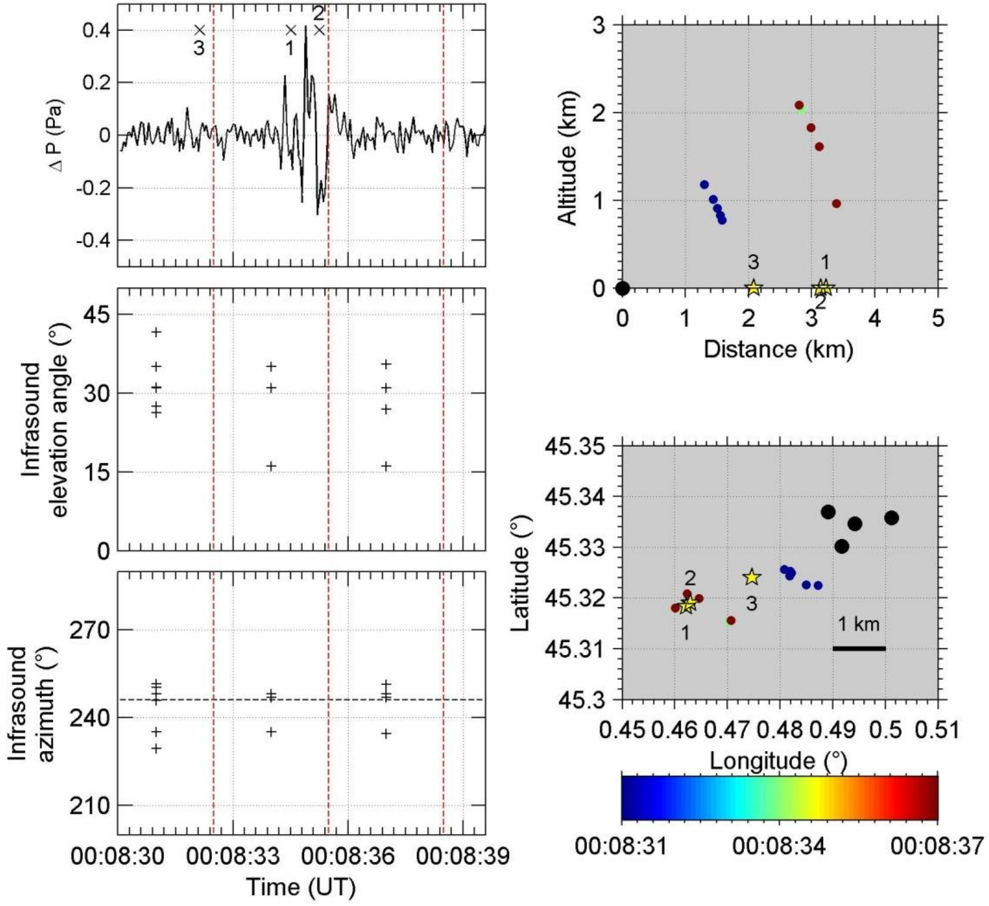
EuroSprite 2005

1-km triangle / F_s=20 Hz

Farges et Blanc, 2010



Farges, Springer, 2008



- Good 2D localization but not as good as MacGorman et al.: very few sources reconstructed!
- Is this due to the size of the network (30 m / 1 km) or to the frequency range of the signals used ([0.1-450 Hz] / [< 10 Hz])?