Colloque PNST Marseille
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Caractéristiques et variabilités des champs électriques et magnétiques des éclairs typiques et extrêmes (superbolts) mesurés depuis l'espace par les sondes Van Allen

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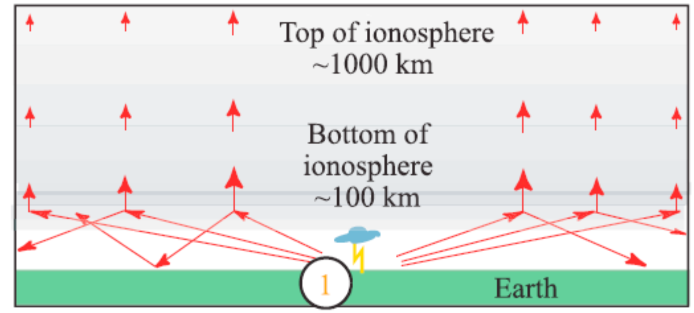
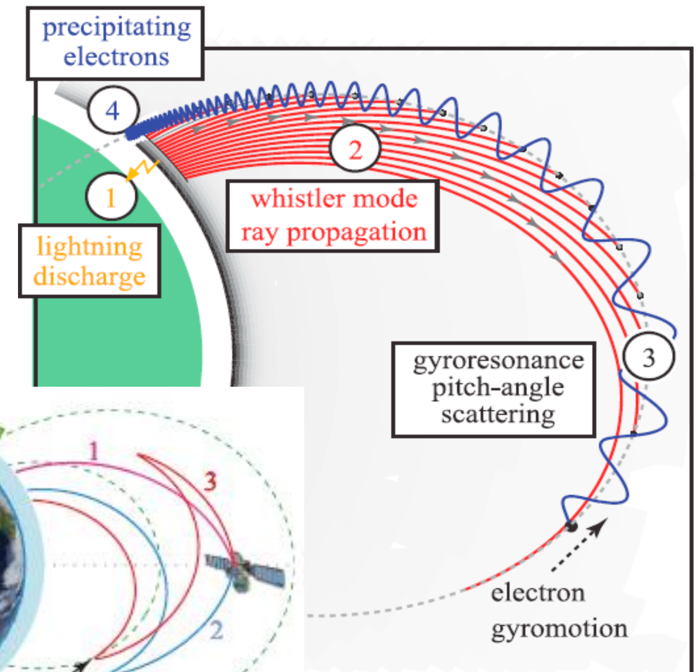
Cloud-to-ground lightning flashes strongly emit electromagnetic radiation in the very low frequency (VLF) band.

This radiation propagates with low attenuation inside the Earth-ionosphere waveguide for thousands of kilometers (up to 18 000 km).

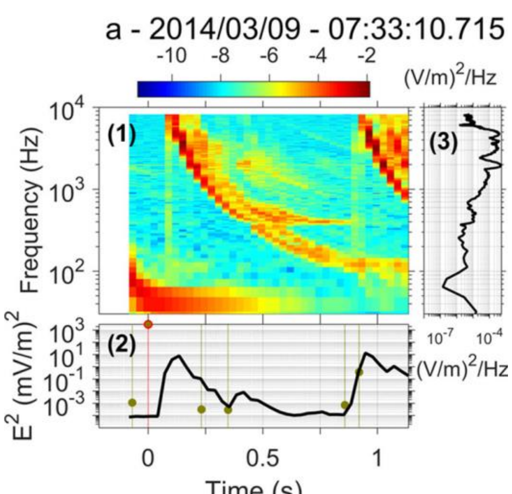
These lightning-generated waves (**LGW**) can escape from the waveguide to the magnetosphere in ducted modes along magnetic field lines or in unducted modes.

We study LGW for their effects on Earth's radiation belt electrons

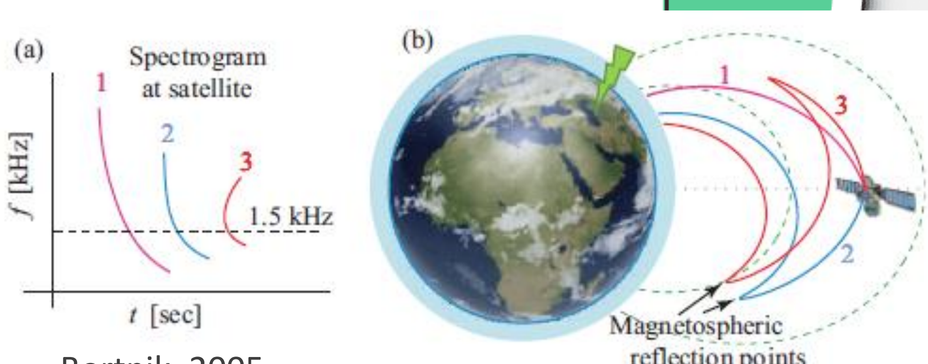




Inan, Cummer, and Marshall (JGR, 2010)



Ripoll, Farges et al., 2021.



Bortnik, 2005

Carpenter,1968; Clilverd et al., 2008; Crombie,1964; Helliwell, 1969; Inan & Bell, 1977

Description of the data used in the study

Instrument of interest in this study:

- Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) (Kletzing et al. 2013)

Acquisition mode:

- Survey (automatic spectra on 0.5s data acquired every 6 s).
- Burst (high frequency): triggered (6s of data at full resolution)

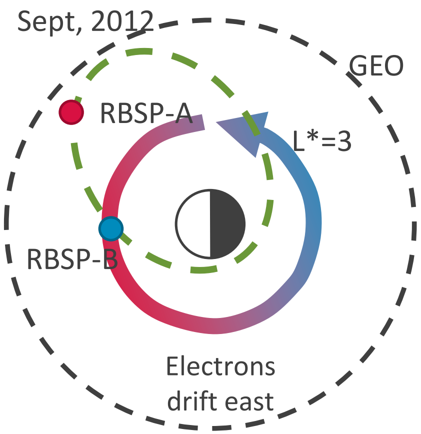
RBSP database:

- Survey spectra for L in [1.1, 3] from 2012 to 2019 and both RBSP:
  - 12.8M for magnetic field from 10/1/2012 to 05/31/2018 (RBSP-B) and 06/30/2018 (RBSP-A)
  - 11.8M for electric field from 10/1/2012 to 06/30/2019 (RBSP-B) and 06/30/2016 (RBSP-A)

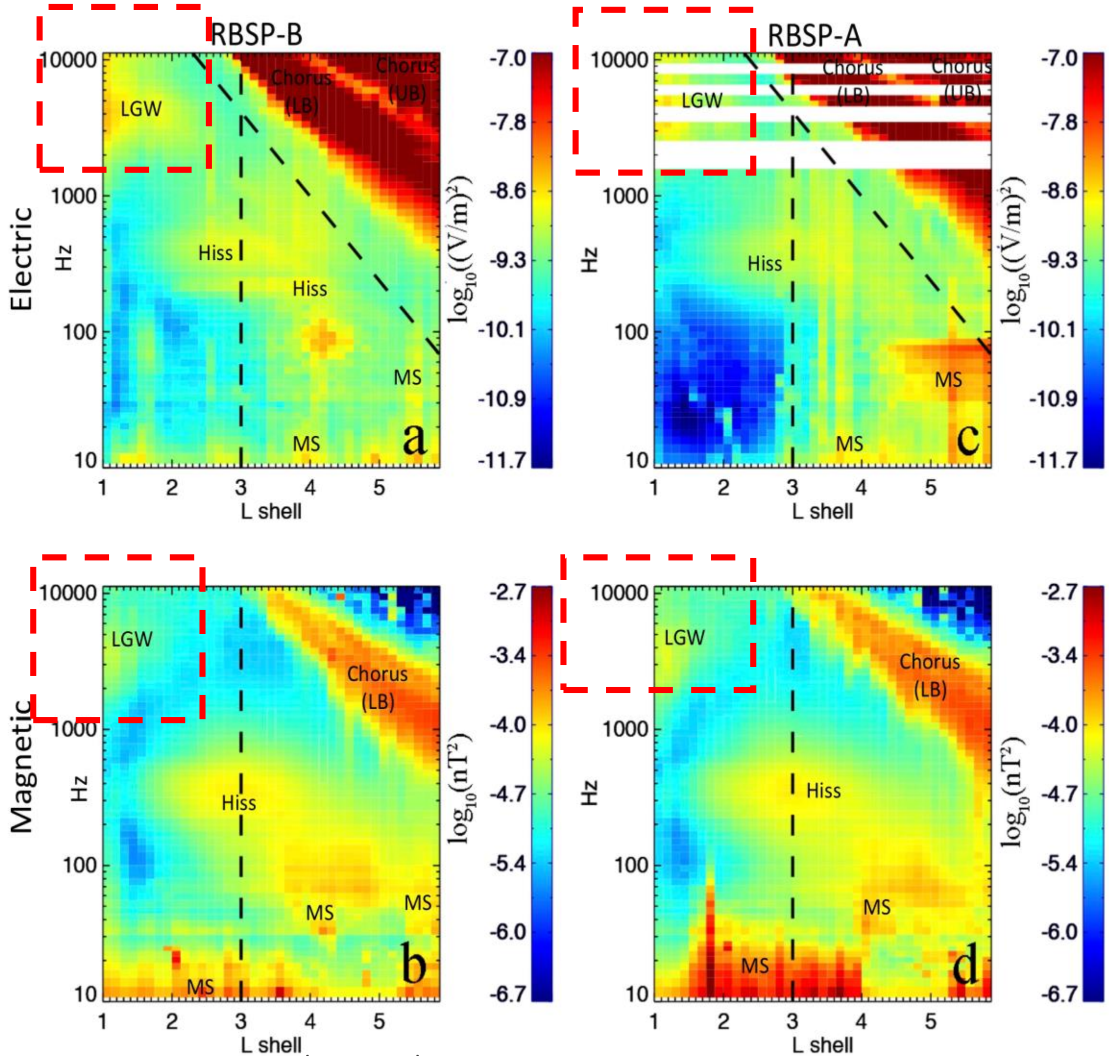
24.6 millions of B or E values

Van Allen Probes (RBSP) mission

Two identical spacecraft
Start of the mission: 08/30/2012
End of mission: 07/19/2019 (Probe B)
10/18/2019 (Probe A)
Perigee altitude: 618 km (L=1,09)
Apogee altitude: 30,414 km (L=5,77)
Inclination: 10.2° (equatorial orbit)
Period: 537.1 minutes (2,7 orbits / day)



Survey data and LGW selection criteria



Dawn MLT sector (3-9 MLT)

From Malaspina et al. GRL 2017

Average power spectral density integrated over each of the 65 pseudo-logarithmically-spaced frequency B2(L) and E2(L) for RBSP A and B

LGW selection criteria:

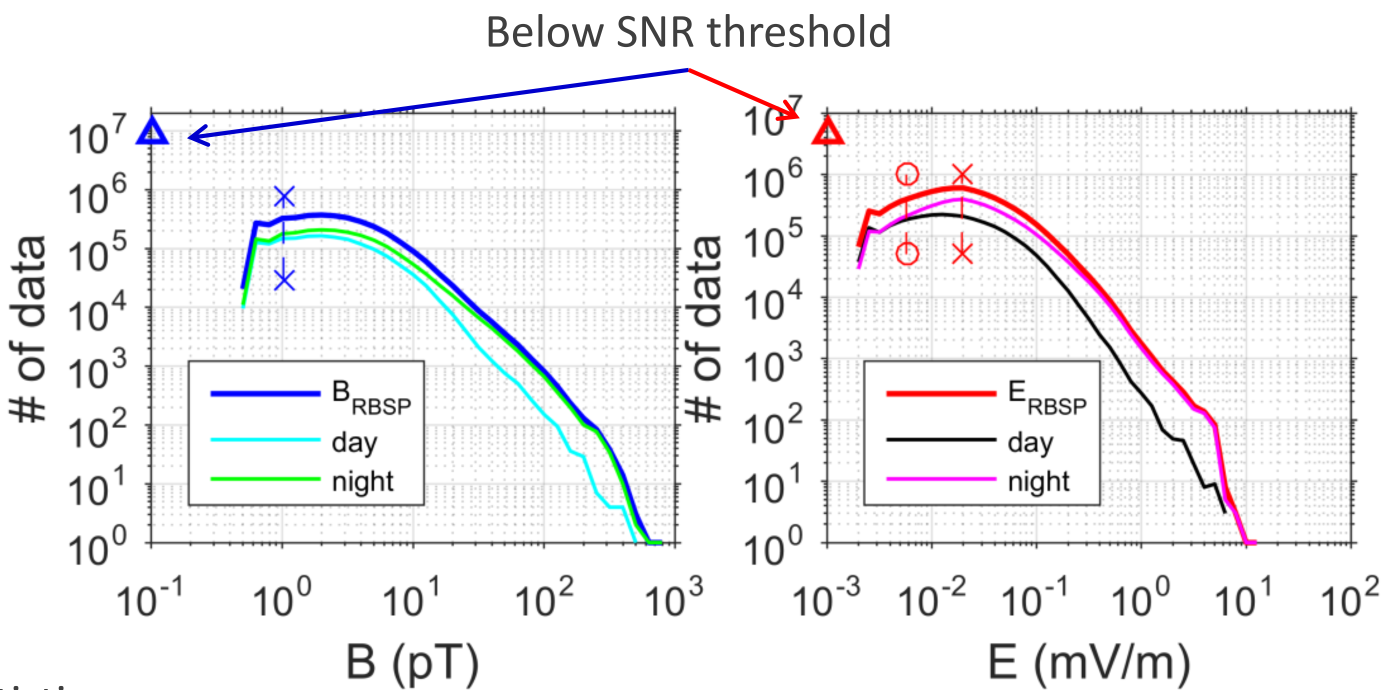
- L-shell ≤ 3
- frequency ≥ 2 kHz

E-field and B-field statistics

Global statistics analysis of LGW E- and B-fields measured by RBSP

Data considered:

- 24.6 millions of Survey measurements including those with low SNRs :
    - B-field values are set to 0 if its SNR < 5
    - E-field values are set to 0 if its SNR < 13 (Malaspina et al., 2017)



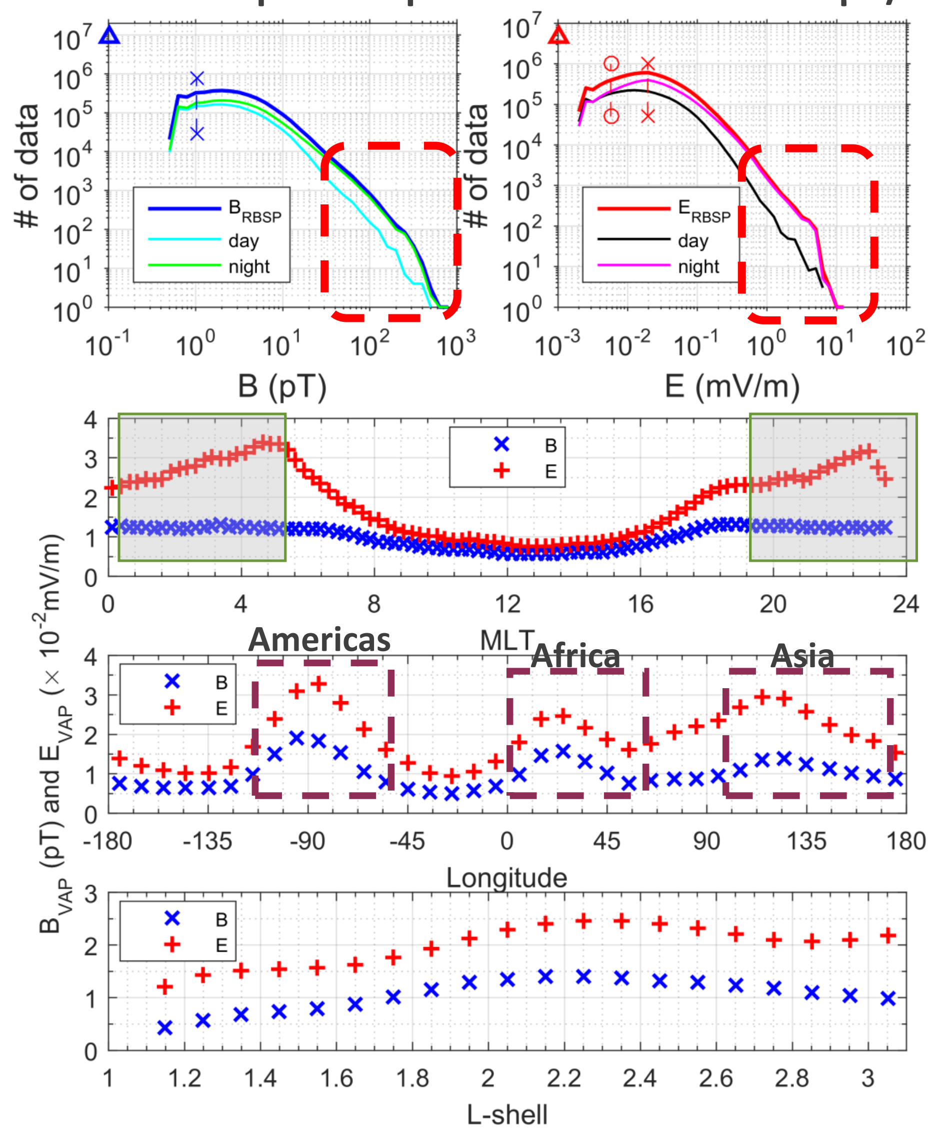
Main statistics

- 10 times more powerful B-field events (> 100 pT) during nighttime than daytime.
- Mean B = 1.0 pT ± 1.6 pT (mainly between 0.5 and 2 pT)
- Mean E = 19.4 ± 58.6 µV/m, and the median is 5.7 µV/m (mainly between 10 and 40 µV/m)

➢ LGWs are less powerful than whistler mode hiss waves by a factor 1/10 to 1/100

Statistics analysis of LGW E- and B-fields measured by RBSP

- **10 times more powerful** events (B > 100 pT or E > 1 mV/m) **during nighttime** than daytime.
- the **day/night difference** is more pronounced for electric field (with a factor ~3 than for the magnetic field (a factor ~2), indicating a stronger attenuation of the electrical field signal during daytimes
- **Influence of land** on the wave amplitudes, with peaks over the United States, Africa, and Asia/Australia that are 2 to 3 times larger than amplitudes over oceans.
- **Clear decay** of both the E- and B-field LGW mean amplitudes **with L < 2** (by a factor ~2–3 between L = 2.15 and L = 1.15)



Ripoll, Farges, et al. GRL 2020

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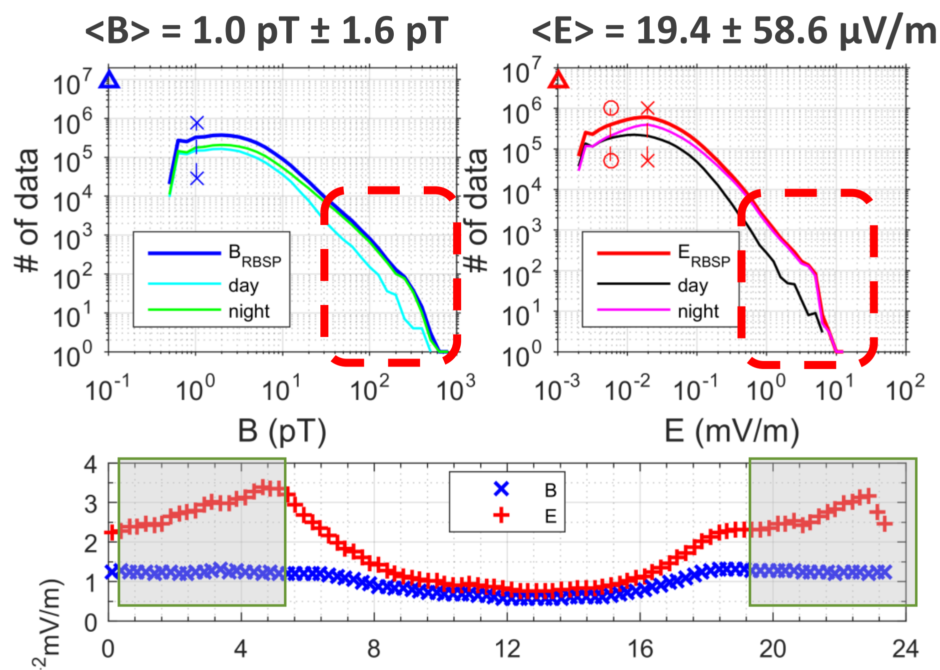
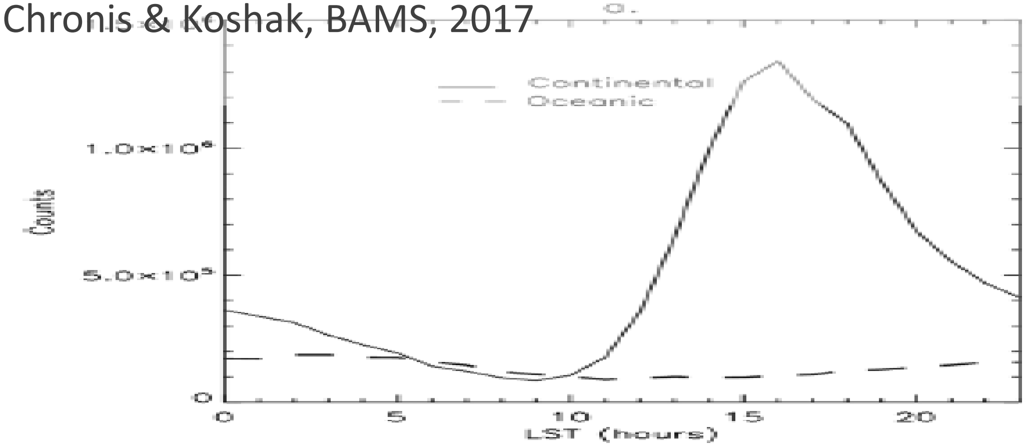


Chronis & Koshak, BAMS, 2017



L-shell

Ripoll, Farges, et al. GRL 2020

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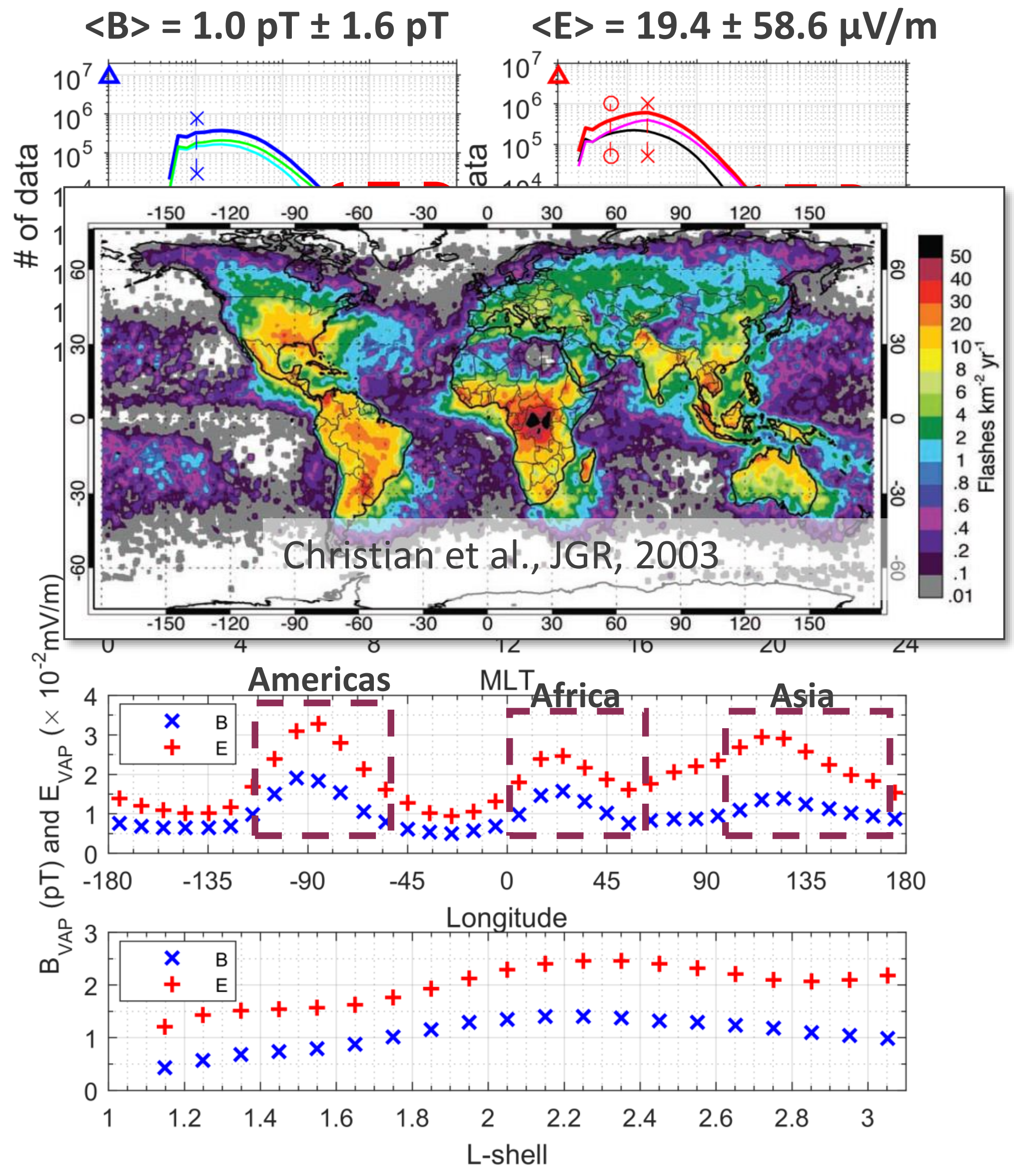
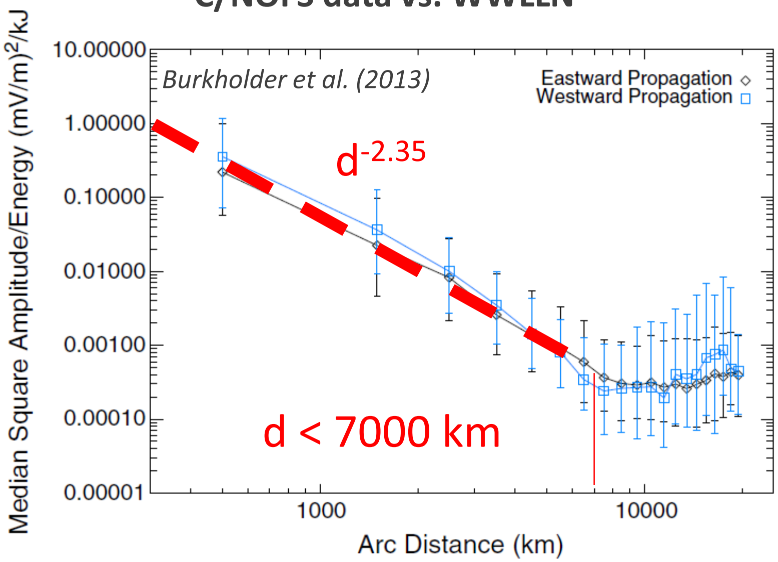


Ripoll, Farges, et al. GRL 2020

Variation of E- and B-field with distance, MLT and L-shell

Variation of E-field power with distance

C/NOFS data vs. WWLLN



Nighttime measurements

$$\frac{E^2}{W}(d) = \beta_{sat}{}^{day/night} \times d^{\alpha_{sat}}$$

(Ripoll et al., GRL, 2019)

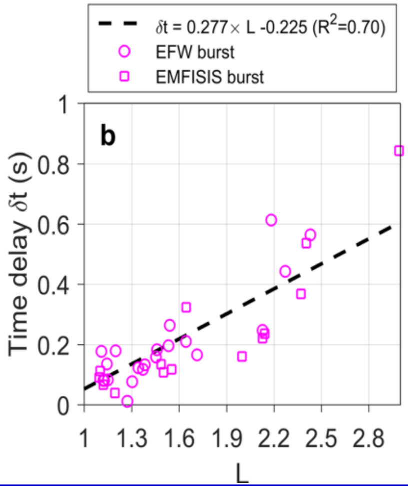
- W is the WWLLN (World Wide Lightning Location Network) flash energy
- d is the distance to the nearest magnetic footprint (MFP)
- α_{sat}**=-2.35** from *Burkholder et al. (2013)* and d_j < 7000 km (alternative: α_{SAT}=-1.76 from Fiser et al. 2010 & Zahlava et al. 2019)
- β_{sat} **is a constant** that is representative of the day/night difference

With RBSP Survey data, it is possible to deduce the variability of this power law in L and MLT

Variation of power with distance using RBSP Survey data

Association with WWLLN using superbolt VAP burst measurements

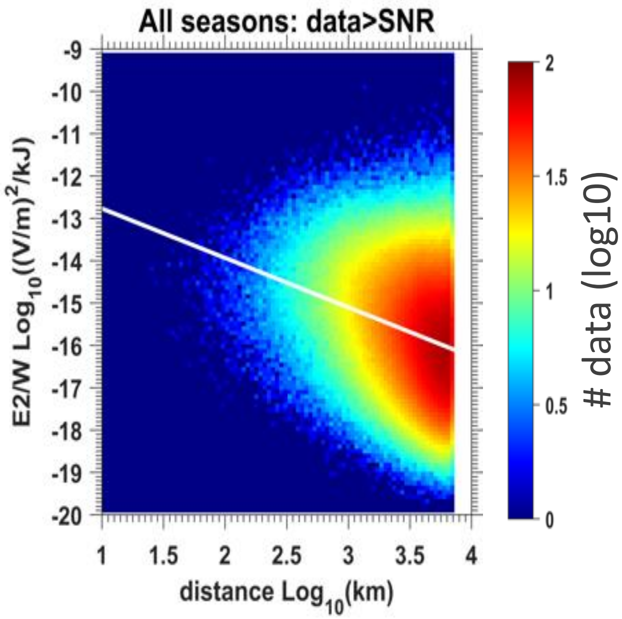
$$|t_{WWLLN} - t_{RBSP}\{i\} + \boldsymbol{\delta t}\,| < 0.25\ s$$



Ripoll, Farges, et al., Nat. Comm., 2021

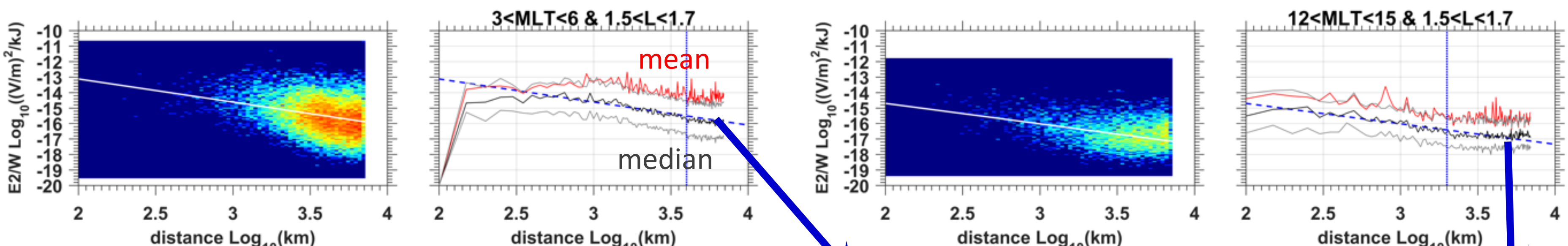
Need to associate one Survey data to an unique specific WWLLN flash using an association method.

➔ 2 millions events used (i.e. 20% of the full database)



Ripoll, Farges et al., Frontiers, 2021

NIGHT **DAY**



Power law regression fits with median of the distribution

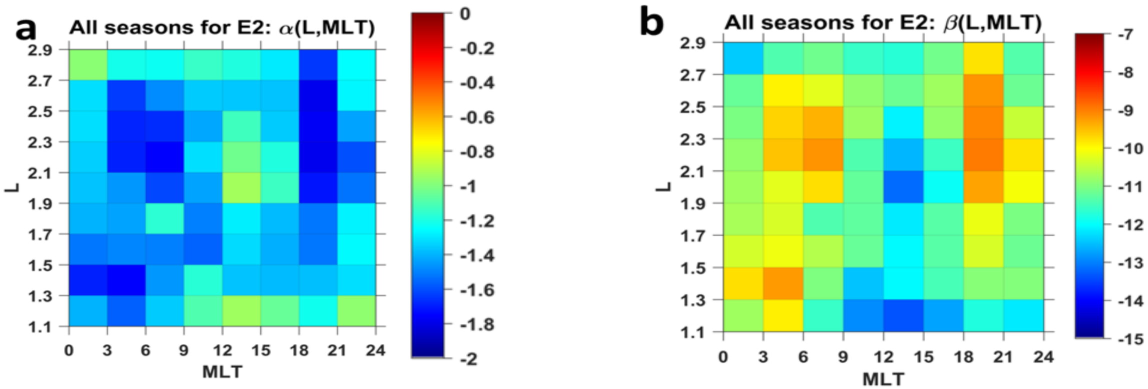
Power decay law with distance in L and MLT

$$\frac{X^2(L, MLT)}{W} = 10^{Log_{10}\beta(L,MLT)} \times d^{\alpha(L,MLT)}$$

(Ripoll, Farges, et al., Frontiers, 2021)

Where X = E-field or B-field

α(L,MLT) β(L,MLT)



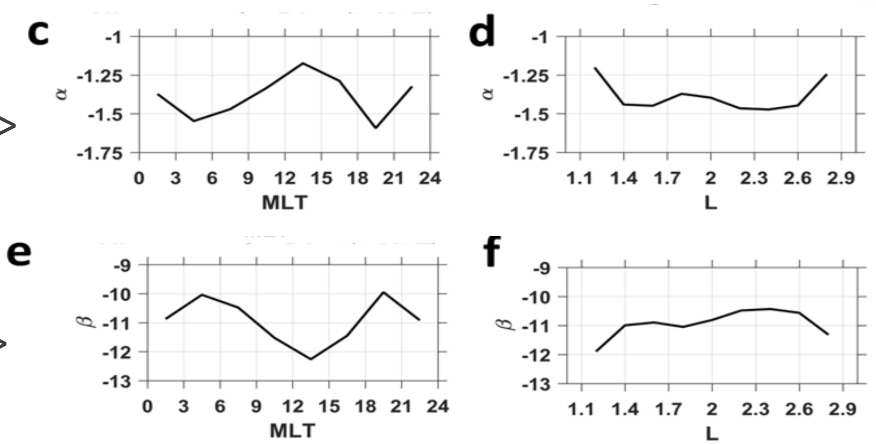
E-field

-1.5 ≤ α ≤ -1.25

-12 ≤ β ≤ -10

<α(L,MLT)>

<β(L,MLT)>



- α is max at noon
- β varies on 2 orders of magnitude and depends on MLT

➔ **Electric power decreases nearly quadratically with distance**

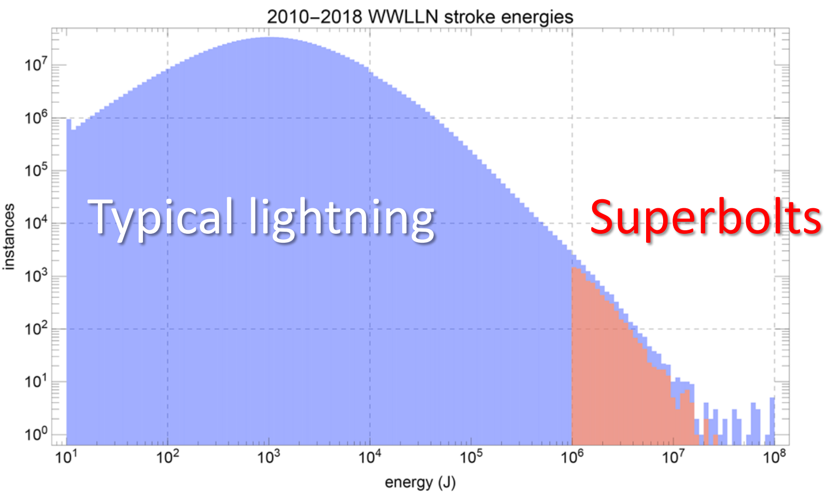
➔ **Similar result for magnetic power which decreases linearly with distance (not shown)**

Superbolts

Superbolts: strongest lightning flashes

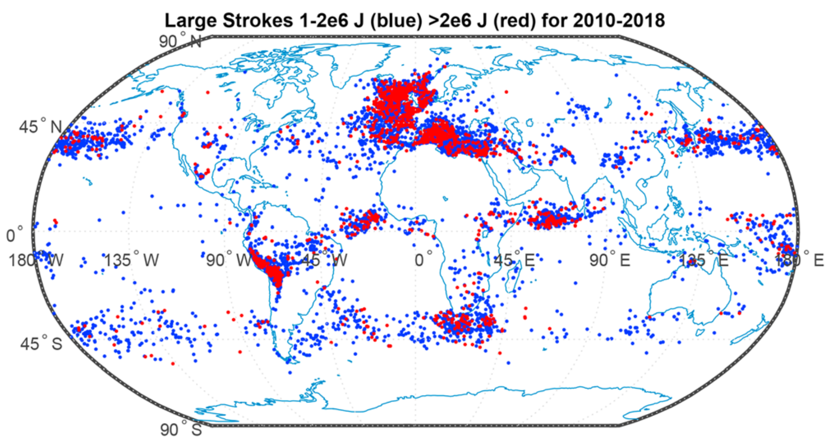
Superbolt?

- **Initialy, optically: 100 times more intense than the typical lightning (Turman, 1977)**
- **Here, VLF electric power: 1000 times the median power (Holzworth et al., 2019)**



E > 1000 kJ (median = 1,3 kJ)

➔ 1 flash / 2500



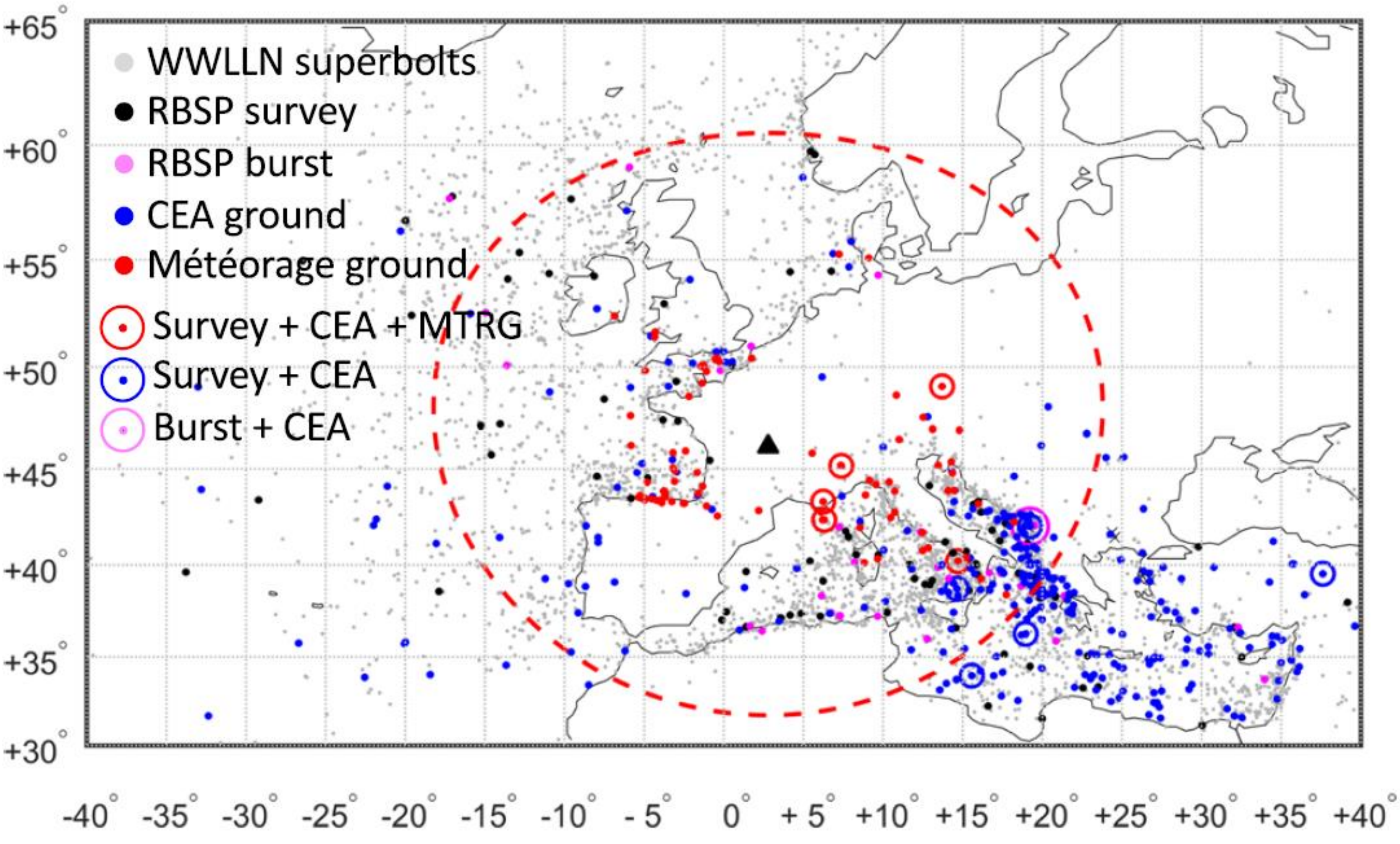
Superbolt: over ocean, in winter and in Western Europe

$\neq$

Typical flashes: over continent, in summer and over tropical zone

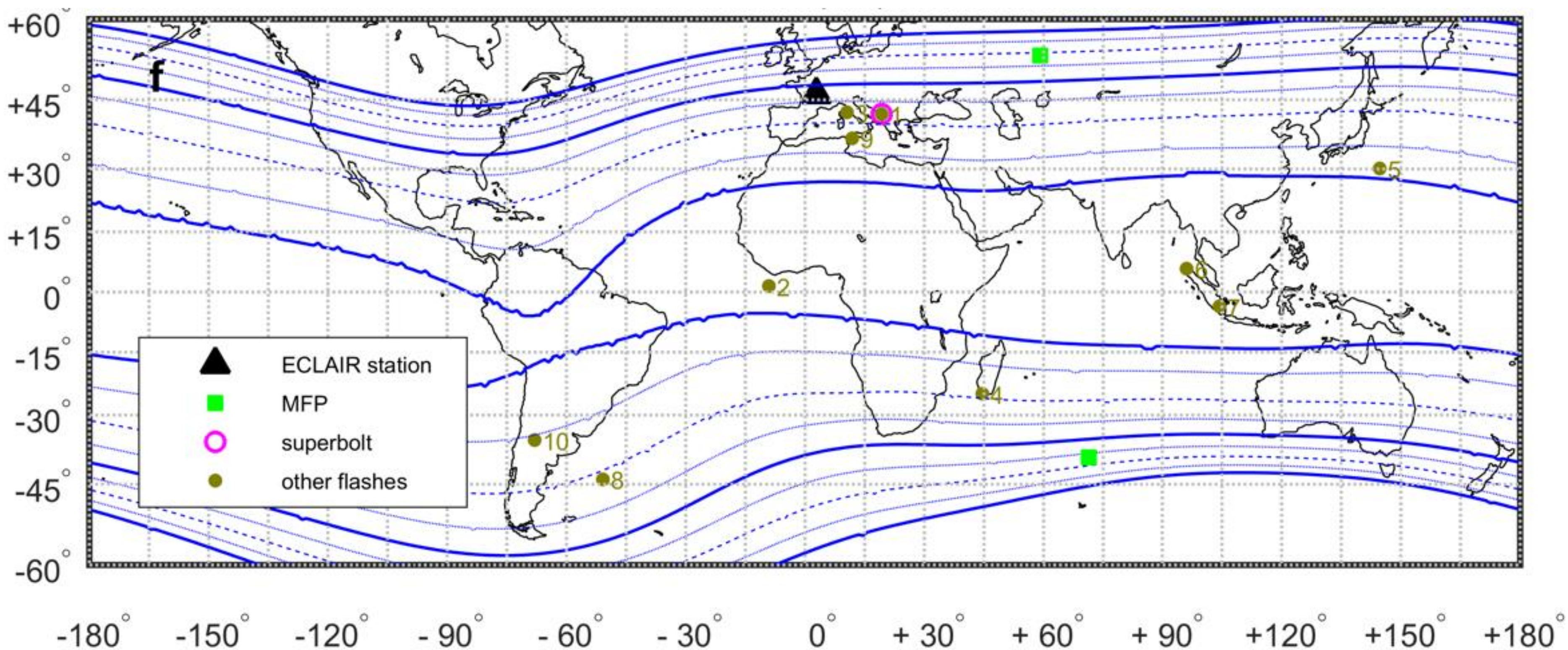
Holzworth et al., GRL, 2019

Superbolt from ground and from Space (Van Allen Probes)



Ripoll, Farges, et al., Nat. Comm., 2021

Simultaneous observation from ground and space



Ripoll, Farges, et al., Nat. Comm., 2021

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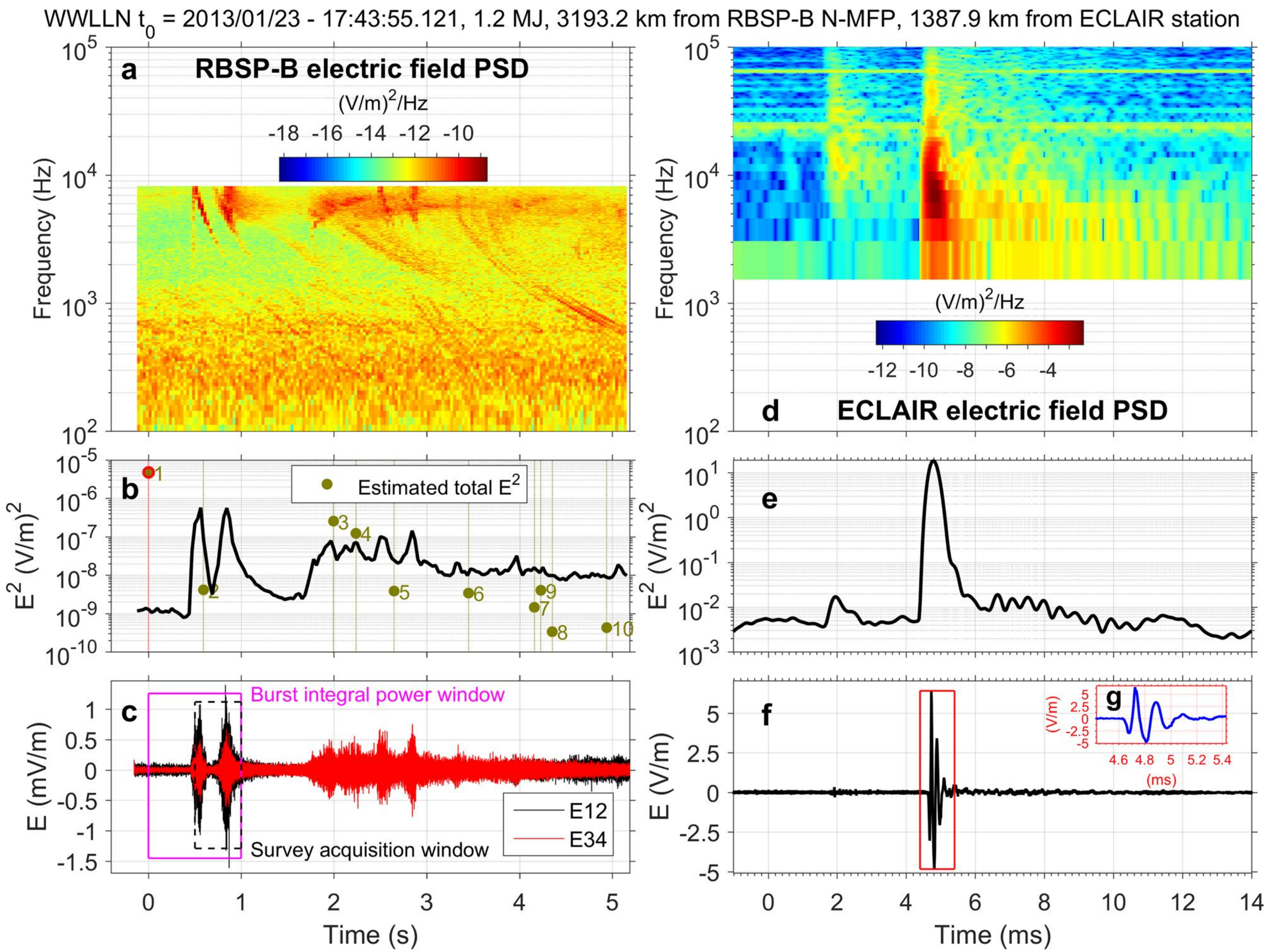
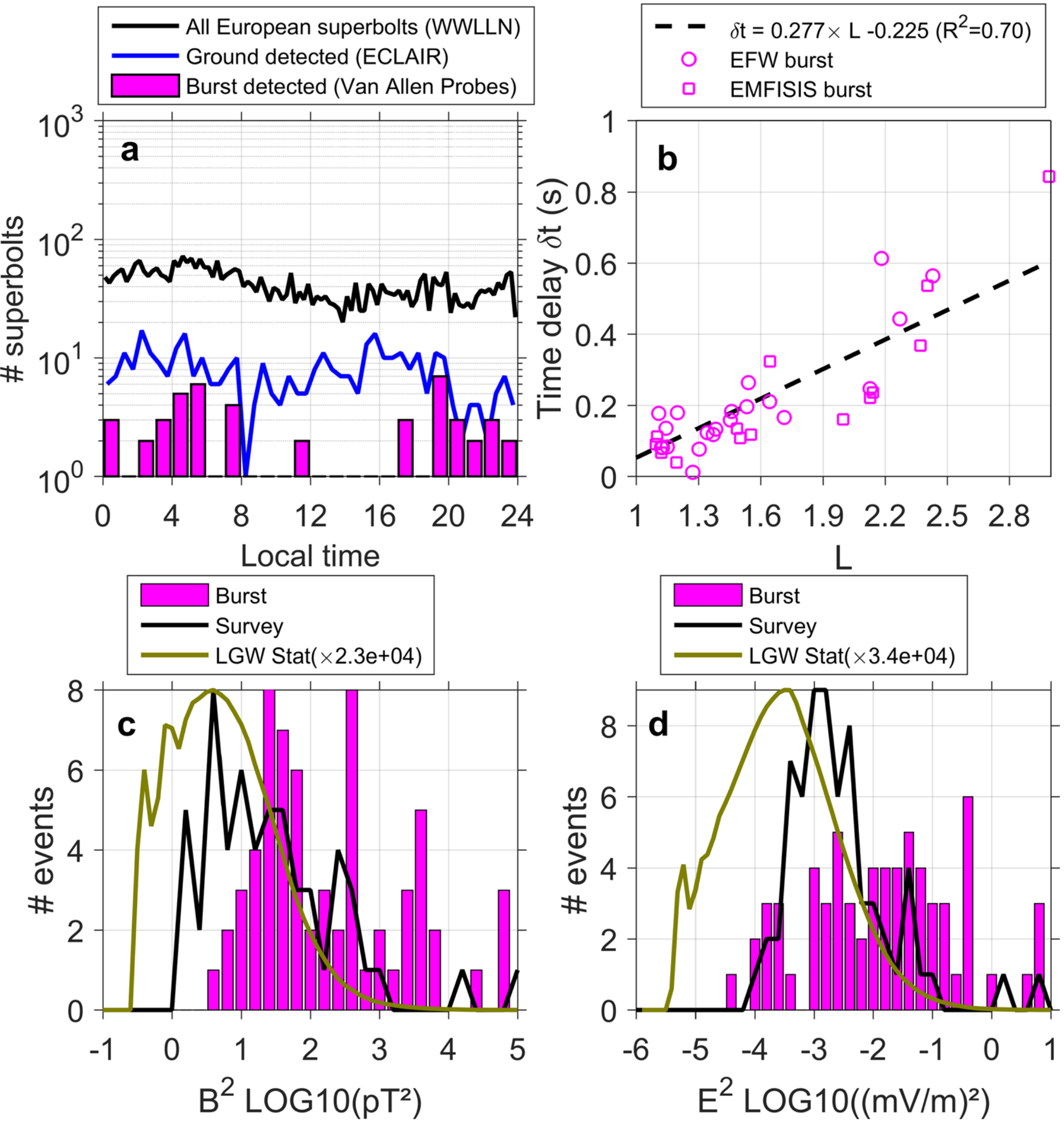


Ripoll, Farges, et al., Nat. Comm., 2021

Superbolt properties in space



- **rare during day time in space while there is a factor 2 between day and night at ground**
- **10–1000 times more powerful than normal lightning:**
  - 83 pT
  - 873 µV/m
- **Strongly contributing to the LGW rms amplitude for L<2 (e.g. 44% at L=1.1)**

Ripoll, Farges, et al., Nat. Comm., 2021

Conclusions

- High quality of Van Allen Probes wave measurements, showing excellent correlations with a WWLLN proxy (except below L = 2), cf. Ripoll, Farges, et al . (2019).
- ~24.6 millions of LGW electric and magnetic amplitudes were measured in survey mode by the EMFISIS instrument of the Van Allen Probes (80% of the entire mission).
- Take away message:
  - Even though extreme LGW can be very powerful, particularly at low L and during night, the mean electric/magnetic power remains low compared with other whistler waves
  - There is a region in space of low lightning wave amplitude (9–15 hr MLT and L < 2) due to the denser dayside ionosphere. In addition, we find weaker wave amplitudes below L = 1.5 at all MLT, where the ground-level lightning activity is maximal.
    - **Thus, there is difficulty of lightning VLF waves to penetrate, or/and to propagate, or/and to remain at low L-shells, certainly due to the denser ionosphere during daytime (in agreement with transmission theory).**
  - Empirical laws of the attenuation of the power with distance derived with (L,MLT) dependence. E2 varies with distance quasi quadratically while B2 varies more linearly.
- Study of the high-power tail of the distribution: superbolts are a good candidate of extreme waves to study nonlinear wave-particle interactions