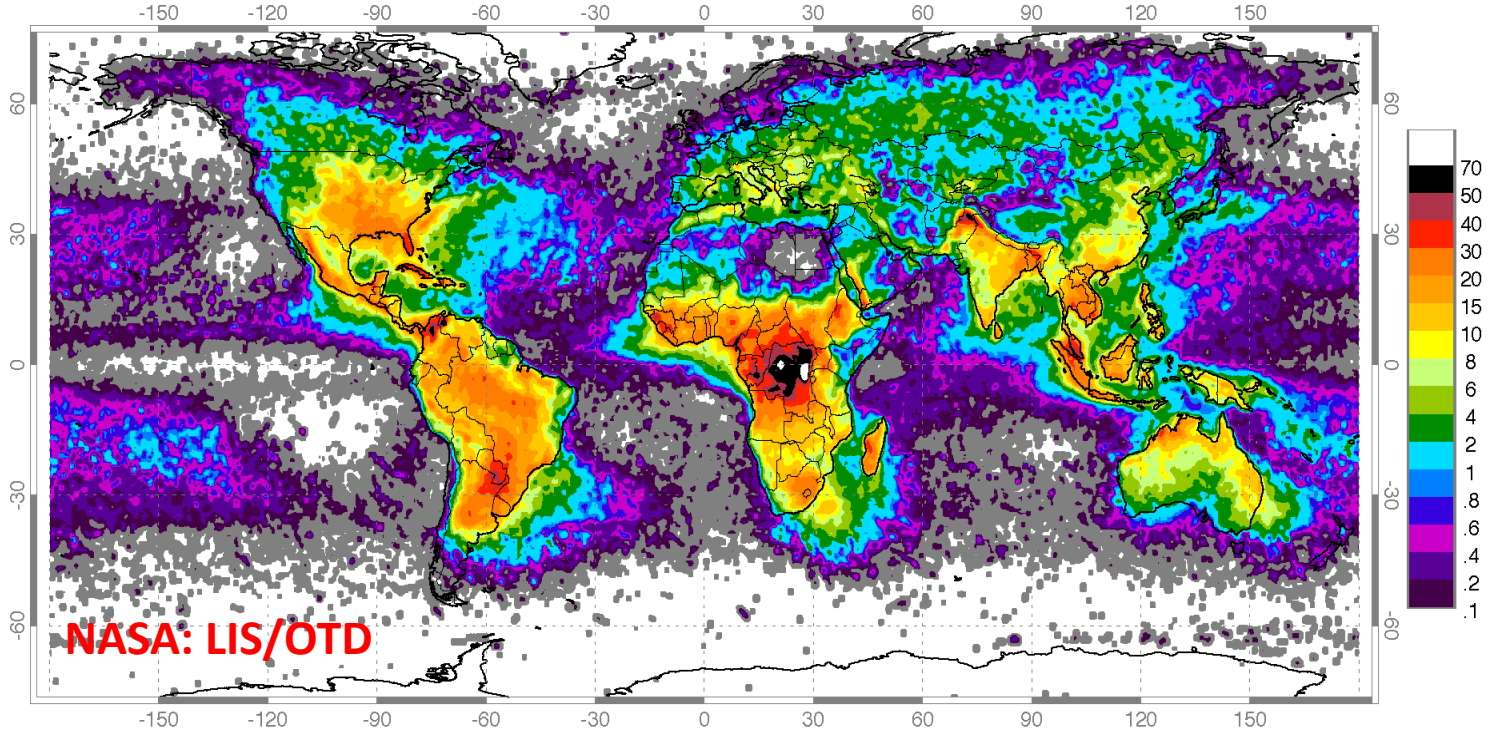
KNOW | Krajowy Naukowy Ośrodek Wiodący

Studying Global Lighting Activity Using Schumann Resonance Measurements



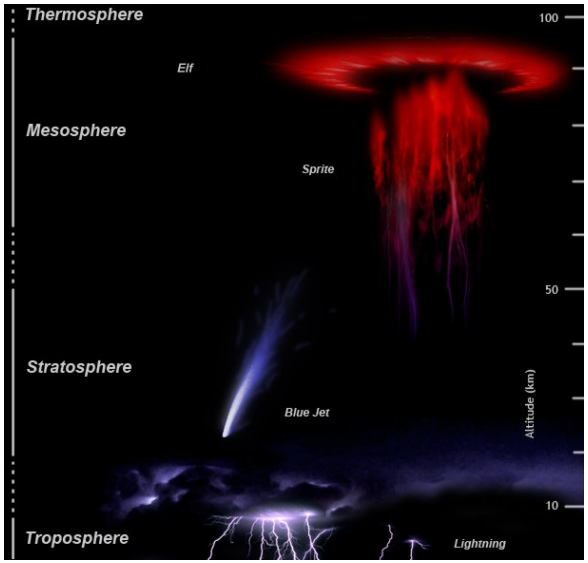
Michał Dyrda (IFJ PAN), Andrzej Kułak (AGH & OA UJ), Janusz Młynarczyk (AGH) for the Krakow ELF Research Team

Krakow ELF Research Team

- **Astronomical Observatory UJ**: Andrzej Kułak, Michał Ostrowski, Volodia Marchenko, Jerzy Kubisz (engineer) and Adam Michalec (emeritus)
- **Institute of Physics UJ**: Zenon Nieckarz
- **University of Science and Technology AGH**: Janusz Młynarczyk
- **Institute of Nuclear Physics PAS**: Michał Dyrda
- **International collaborators**:
  - Earle Williams (Massachusetts Institute of Technology)
  - Gabriella Satori (Hungarian Academy of Sciences)

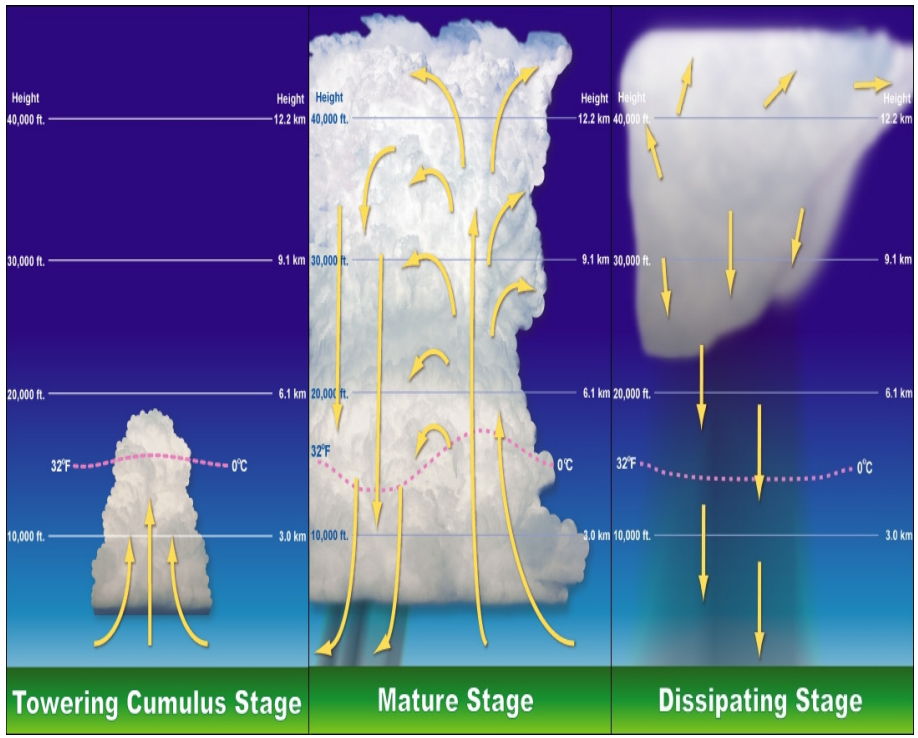
Storms in Nature

Typically – 1800 thunderstorms all over the World and 50-100/sek lightning discharges



Conditions to form thunderstorm:

1. Moisture
2. An unstable air mass
3. A lifting force (heat)



Lightning discharges:

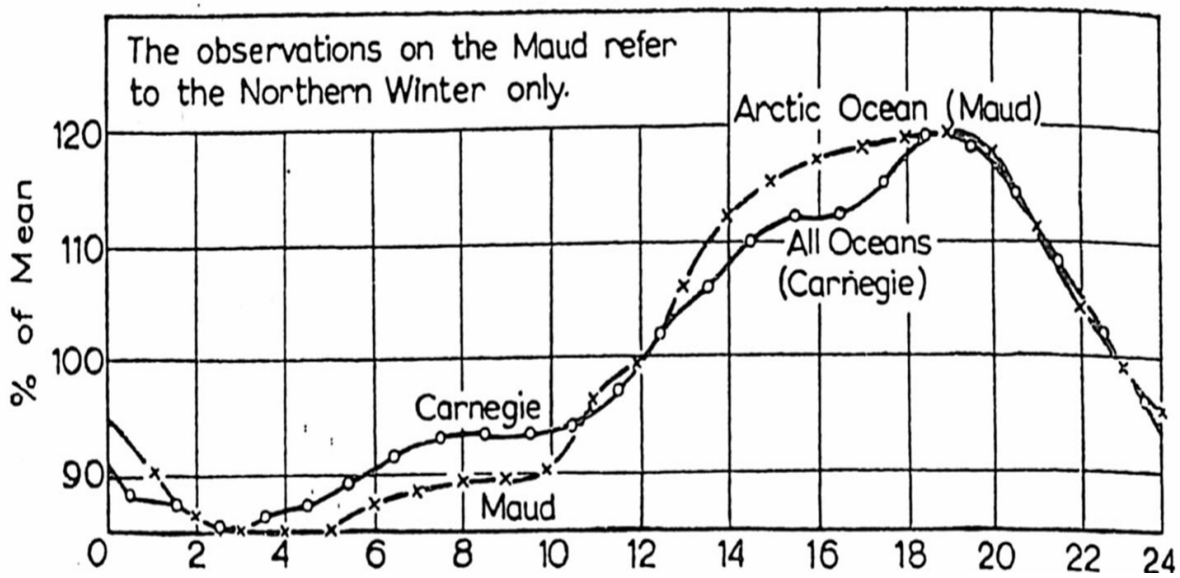
- Cloud-to-ground (CG)
  - 90 of all discharges CG^-
  - typical current I_{CG-} = 22 kA but I_{CG+} = 300 kA
- Intra-cloud (IC)
- Cloud-to-cloud (CC)

Also **transient luminous event (TLE) :**

- Sprites
- Jets
- Elves
- Terrestrial Gamma Ray flashes (TGF)

Carnegie Curve

1752 Lemonnier: in fair weather regions there is a persistent E-field of 100 V/m pointing downwards



1920s: diurnal variation of the atmospheric electric field, independent of location and local time, but dependent only on **universal time !**

Global Electric Circuit:

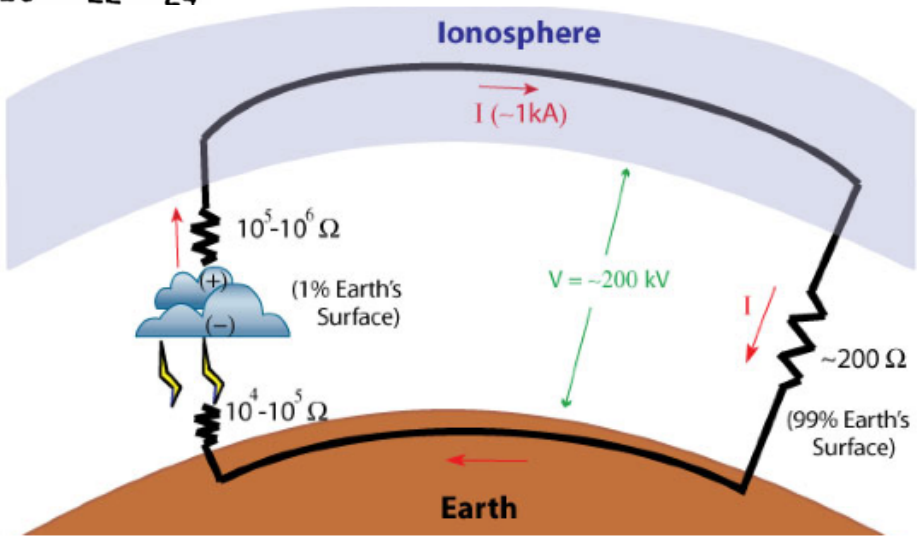
Earth's charge $Q = 4\pi R^2 \varepsilon_0 E \approx 4.5 \times 10^5$ Coulomb

capacitance of the Earth $C = Q/V \approx 1$ Farad

time scale for the discharging of the capacitor:

$\tau = R \bullet C = 300$ sec!

Where are the batteries !?



Where are the batteries ?

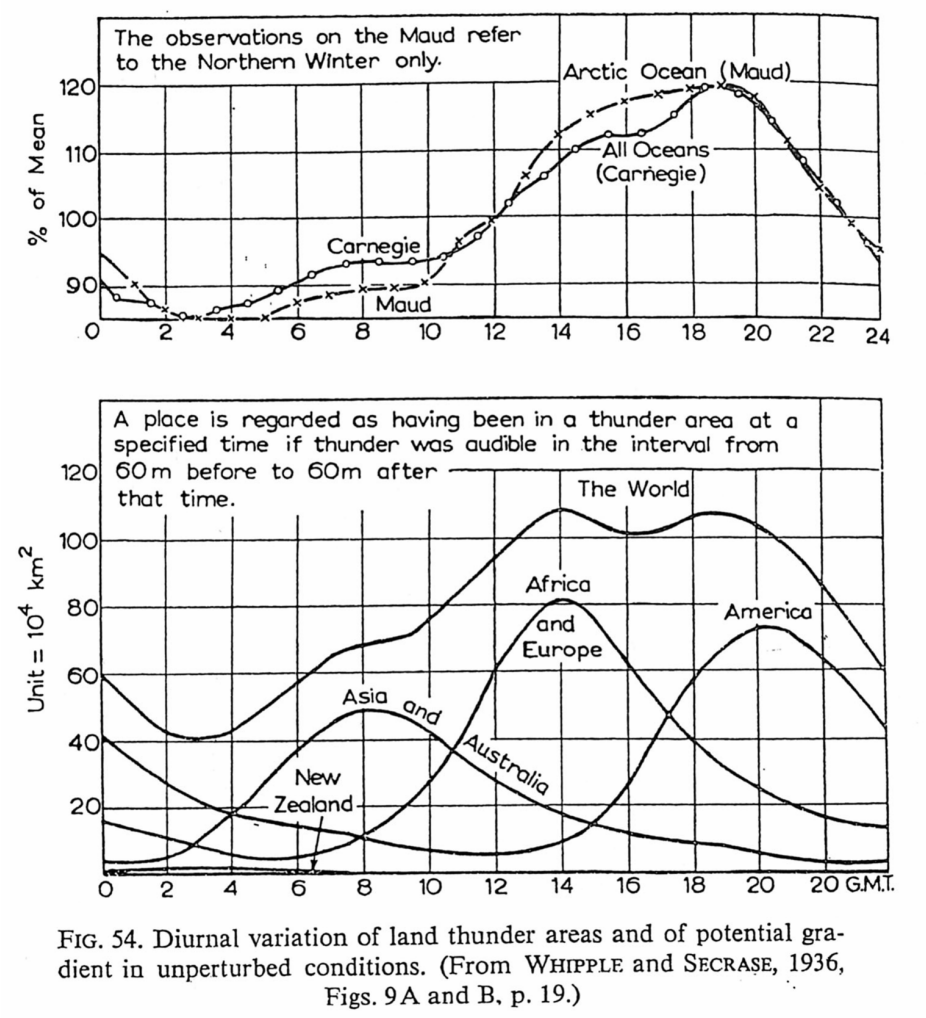
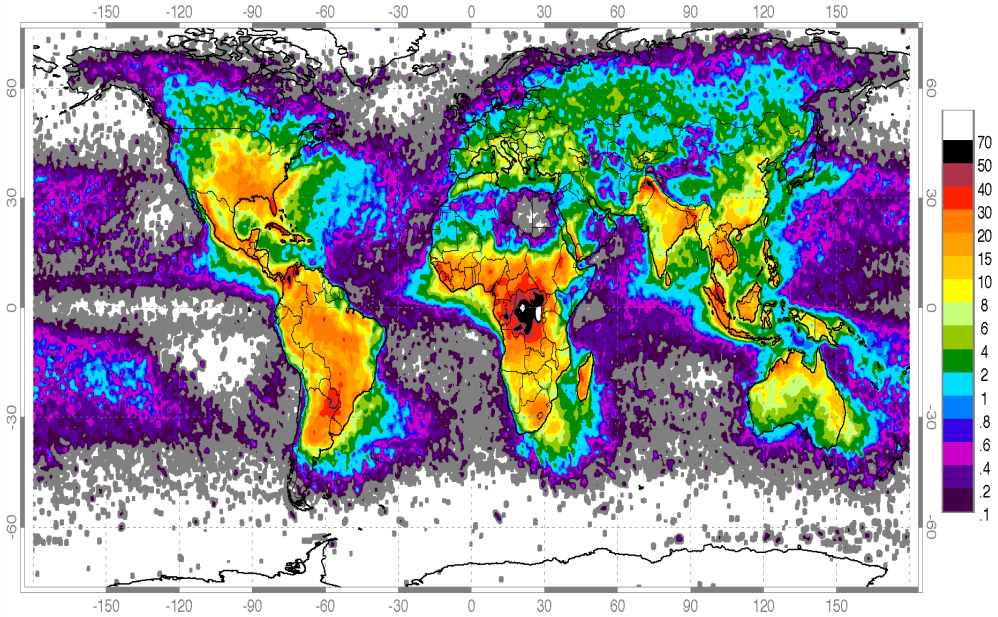


FIG. 54. Diurnal variation of land thunder areas and of potential gradient in unperturbed conditions. (From WHIPPLE and SCRASE, 1936, Figs. 9A and B, p. 19.)

Batteries = tropical thunderstorms



Lightning detection methods

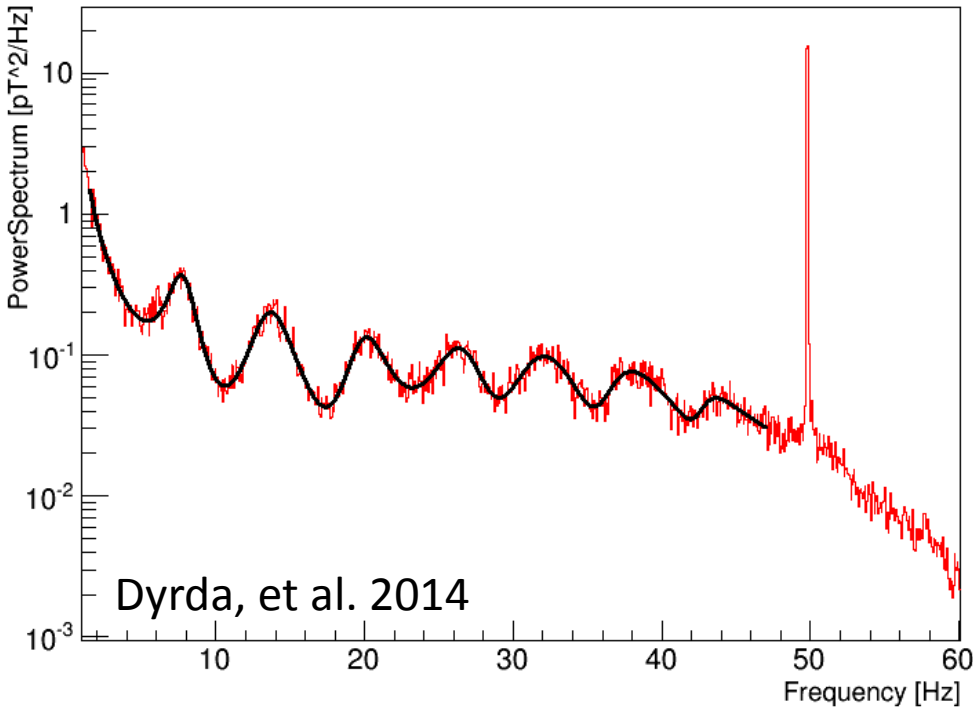
- Optical observation done by satellites:
  - detailed information about observed area (10^5 km^2), (i.e. LIS/OTD NASA)
  - new system of three satellites in 2018
  - but clouds screening – might not be able to measure total storms activity
- Radio observations: VLF (3-30 kHz), HF and VHF:
  - detection range varies form ~100 km up to ~1000 km (VLF) (global – WWLLN; local – i.e. LINET in Europe)
- ELF observation (1Hz-3kHz):
  - single detector can detect signals form all atmospheric lightning's
  - unambiguous map construction of global storms activity up to distances ~ **20 Mm**!
  - with few detectors -> possibility to image global storm activity in geographical coordinates
  - can measure CG lightning's, no screening effect

Extremely Low Frequency Waves -Schumann Resonance

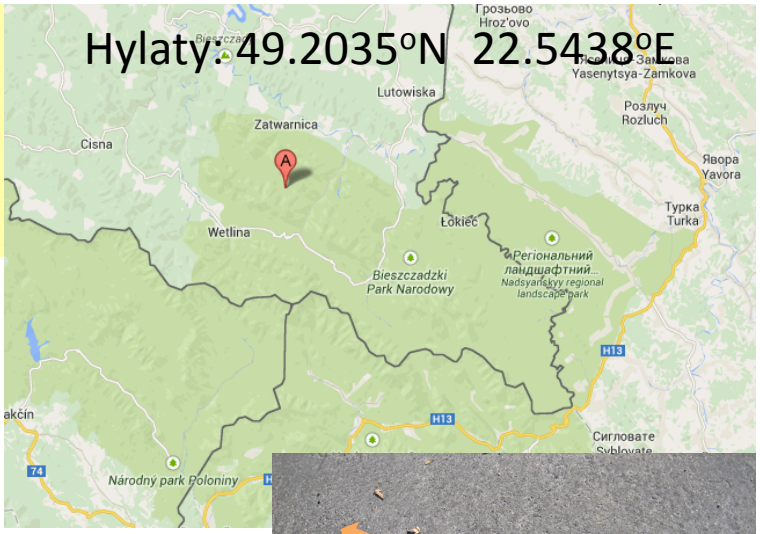
- Global electromagnetic resonance – solutions to the Maxwell equations - Winfried Otto Schumann (1952)
- Earth (limited dimensions) –> resonance cavity -> excited by lightning –> antennas that radiate electromagnetic energy
- Signals very weak at large distances from sources
- Earth-ionosphere waveguide – resonator at ELF frequencies
- Amplifies spectra signals at resonance frequencies (ideal cavity - no damping):

$$f_n = \frac{c}{2\pi a}\sqrt{n(n+1)} = 10.6,\ 19.3,\ \ldots\ [Hz]$$

(Real) Earth-ionosphere cavity:
f_n = 8, 14, 20, 26 ... Hz



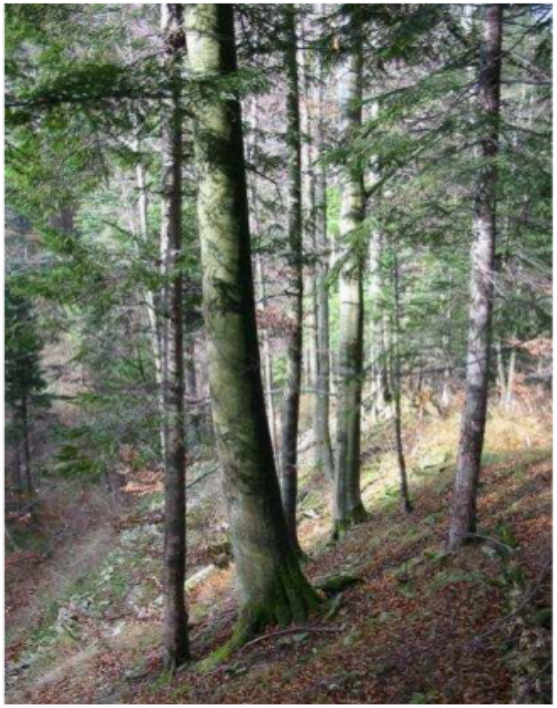
ELF electromagnetic field measurements at the Hylaty station in Poland

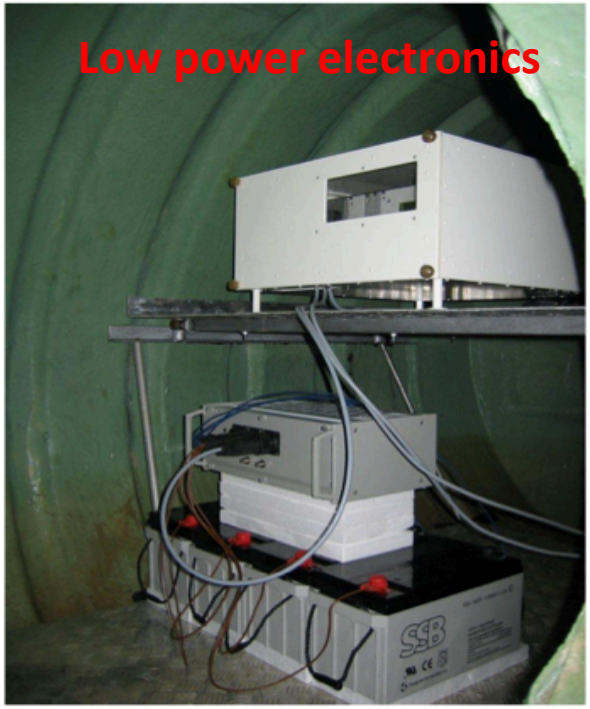


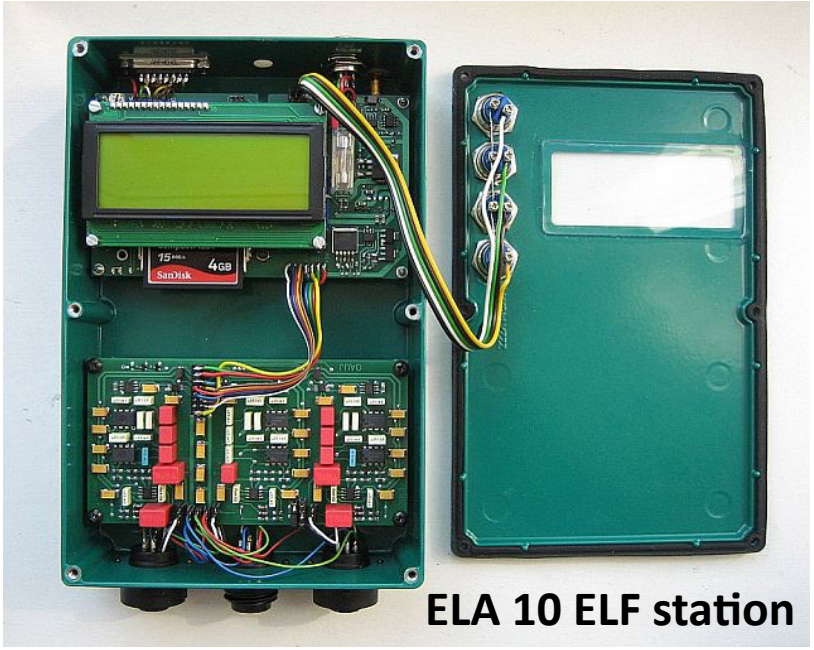
Hylaty ELF station specifications [Kulak et al., 2014]:

- Two ELF receivers: 0.03 - 55 Hz and 0.03 - 300 Hz
- Two signal channels NS and EW for each receiver
- Sampling frequencies: 175 and 900 Hz
- Sensitivity: **0.05 pT/sqrt(Hz)** at 10 Hz
- Data storage – CF card 32Gb

Also special GPS time units







ELF data file format

- Each file - 5 minutes of ELF data
- File name – data/time [UT]
- Sample length 16 bit (older + younger byte)
- Every files begins with a 64 byte ASCII header

Example of file header (the first 64 bytes in ASCII)

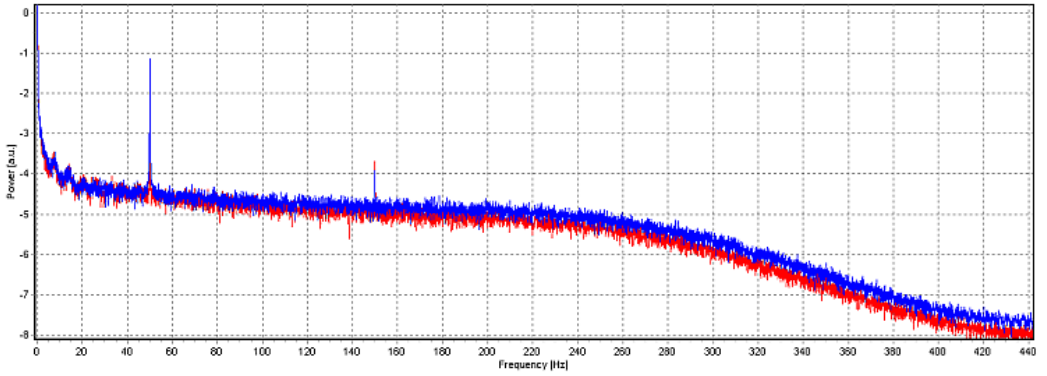
Stacja ELF ELA7b02.07.2008 11:401 3 T: 30.300000000000000000000

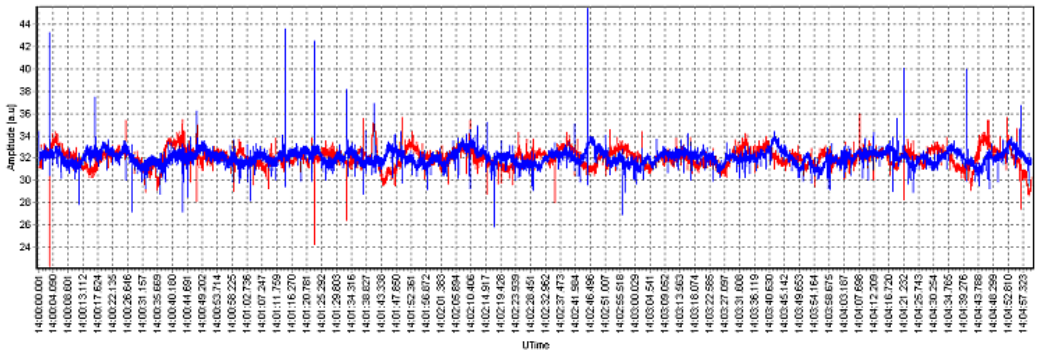
Stacja ELF ELA7b – device name
02.07.2008 11:40 - time (UT)
1 3 - names and numbers channels **(1=NS and 3=EW)**
T: 30.3 – temperature in Celsius

Immediately after the end of the 64 byte ASCII header start sampled data

```
00033800: 7C 12 A3 63 7C 11 A3 4F|7C 11 A3 49 7C 12 A3 3F | |■Łc|■ŁO|■ŁI|■Ł?
00033810: 7C 11 A3 2F 7C 11 A3 29|7C 12 A3 15 7C 12 A3 09 | |■Ł/|■Ł)|■Ł■|■Ł■
00033820: 7C 13 A3 07 7C 12 A2 ED|7C 12 A2 E7 7C 12 A2 EA | |■Ł■|■˝í|■˝ç|■˝ę
00033830: 7C 12 A3 13 7C 12 A3 74|7C 11 A3 B9 7C 12 A3 D1 | |■Ł■|■Łt|■Ląą|■ŁŃ
00033840: 7C 12 A3 AF 7C 11 A3 9D|7C 13 A3 9B 7C 12 A3 7A | |■ŁŻ|■Ł'|■Ł›|■Łz
00033850: 7C 12 A3 75 7C 13 A3 63|7C 11 A3 5B 7C 11 A3 50 | |■Łu|■Łc|■Ł[|■ŁP
00033860: 7C 11 A3 49 7C 12 A3 7B|7C 12 A3 D1 7C 13 A4 11 | |■ŁI|■Ł{|■ŁŃ|■¤■
00033870: 7C 11 A4 21 7C 13 A4 08|7C 11 A3 F5 7C 13 A3 E9 | |■¤!|■¤■|■Łő|■Łé
00033880: 7C 12 A3 E5 7C 12 A3 C7|7C 11 A3 B9 7C 13 A3 AF | |■Łĺ|■ŁÇ|■Łą|■ŁŻ
00033890: 7C 12 A3 97 7C 11 A3 8D|7C 12 A3 73 7C 12 A3 6F | |■Ł-|■ŁŤ|■Łs|■Ło
000338A0: 7C 13 A3 5D 7C 13 A3 4F|7C 11 A3 45 7C 11 A3 2B | |■Ł]|■ŁO|■ŁE|■Ł+
000338B0: 7C 11 A3 24 7C 13 A3 0D|7C 13 A2 F7 7C 13 A2 E9 | |■Ł$|■Ł■|■˝÷|■˝é
000338C0: 7C 12 A2 E5 7C 13 A2 D9|7C 11 A2 C2 7C 12 A2 B3 | |■˝Í|■˝Ů|■˝Â|■˝ł
000338D0: 7C 12 A2 A7 7C 13 A2 99|7C 11 A2 8A 7C 12 A2 7B | |■˝§|■˝™|■˝Š|■˝{
000338E0: 7C 11 A2 69 7C 12 A2 54|7C 11 A2 48 7C 12 A2 3A | |■˝i|■˝T|■˝H|■˝:
000338F0: 7C 12 A2 2F 7C 13 A2 1A|7C 13 A2 09 7C 12 A1 F7 | |■˝/|■˝■|■˝■|■˝÷
00033900: 7C 12 A1 E7 7C 12 A1 D5|7C 12 A1 D1 00 00 00 00 | |■ˇç|■ˇŐ|■ˇŃ■■■■
00033910: 00 00 00 00 00 00 00 00|00 00 00 00 00 00 00 00 | ■■■■■■■■■■■■■■■■
000339E0: 00 00 00 00 00 00 00 00|00 00 00 00 00 00 00 00 | ■■■■■■■■■■■■■■■■
000339F0: 00 00 00 00 00 00 00 00|00 00 76 CA 00 00 CE 33 | ■■■■■■■■■■vę■■Î3
```

The last two bytes 0xCE33 = 52787 is a counter of samples during 300 seconds -> sampling is 52787 / 300 = 175.95 sample/sec





Spectral Decomposition Method (Decomp)

Kulak et al. 2006

$$W(f,\theta) = s + \frac{z}{f^m} + \sum_{k=1}^{N} \frac{p_k(\theta)[1 + e_k(\theta)(f - f_k)]}{(f - f_k)^2 + g_k^2/4}$$

$W(f,\theta)$ – wave power spectrum [T^2/Hz]
s – white noise term [T^2/Hz]
z/f^m – color noise term , z -> [$Hz^{m-1}T^2$]
p_k – power parameter of k^{th} mode [T^2Hz]
e_k – asymmetry parameter [Hz^{-1}]
f_k – resonant (intrinsic) frequency [Hz]
g_k – peak width [Hz]
N = 7 in our case

Lack of asymmetry
$e_k = 0$

Lorentzian Curve
but f_k -> $f_k^*(\theta)$
all parameters – classical meanings

Parameter m:
<m> = 2.06

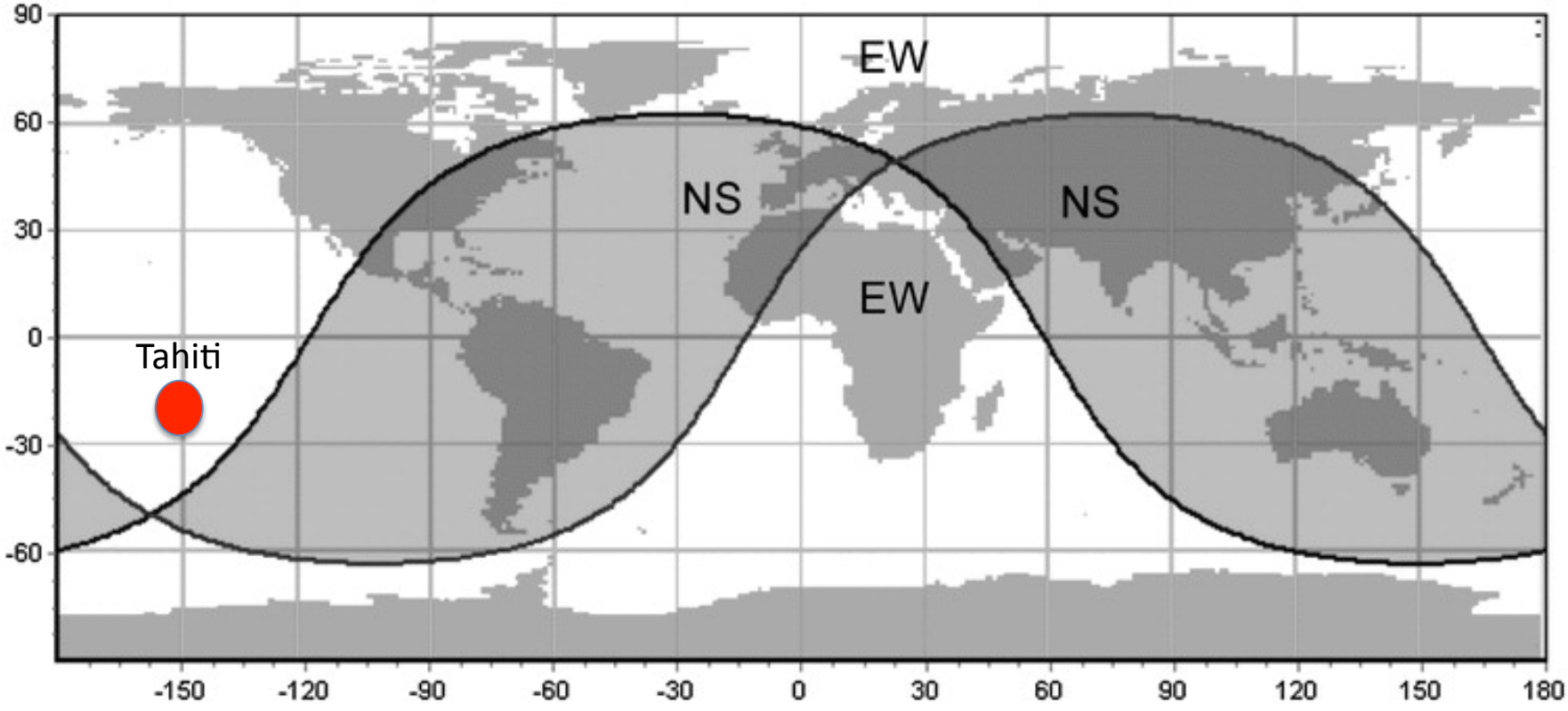
Thunderstorms activity maps - algorithm

- Time bins – 10 min
- FFTW – observational SR power spectrum
- Decomp – in frequency range 1-48 Hz

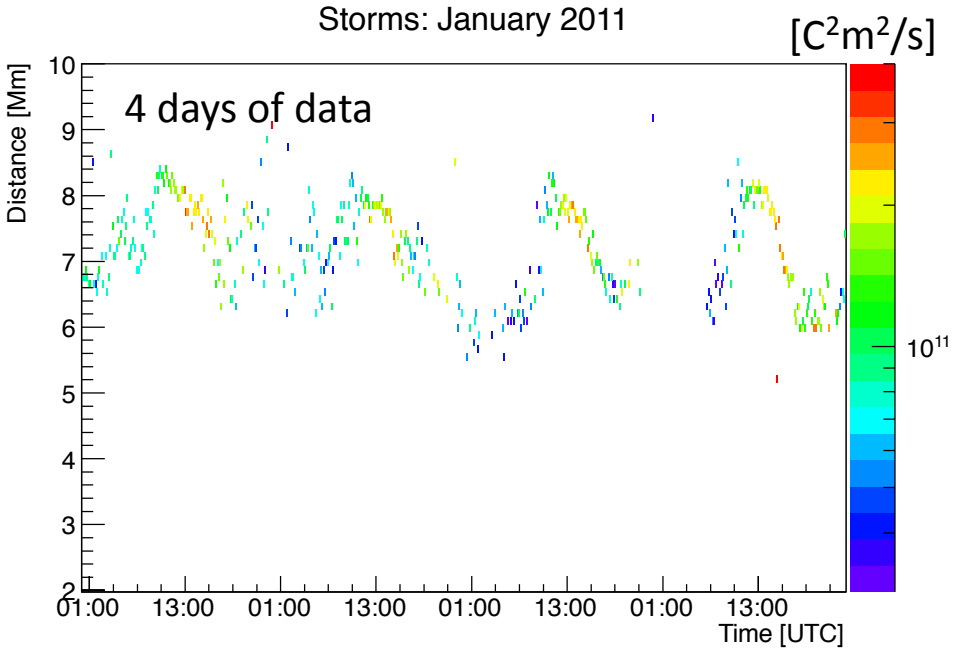
$$W(f,\theta) = s + \frac{z}{f^m} + \sum_{k=1}^{N} \frac{a_k[1 + e_k(f - f_k)]}{(f - f_k)^2 + (\frac{g_k}{2})^2}$$

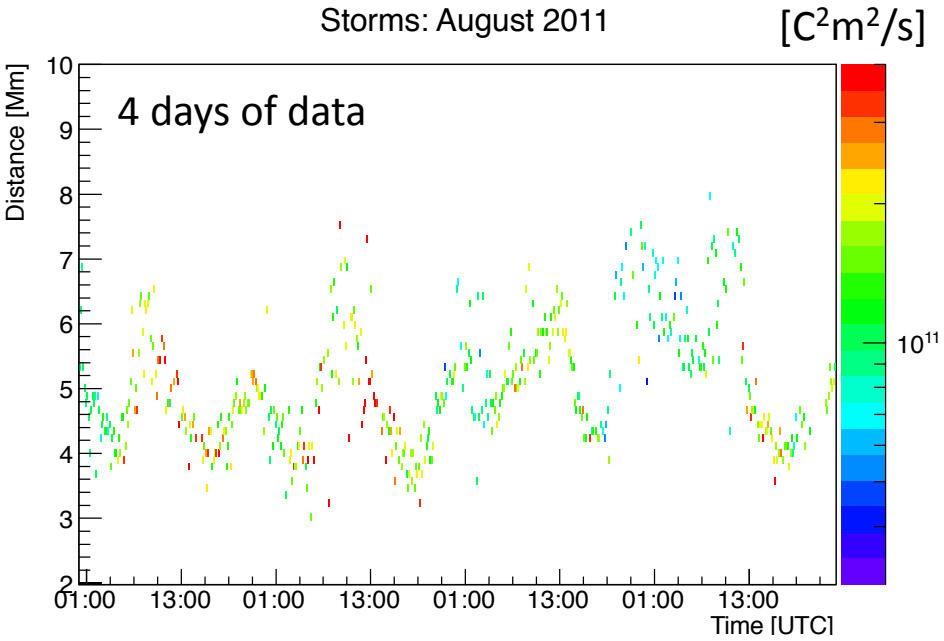
- Model power spectra calculated for known source-observer separations with step ~ 0.1 Mm
- χ^2 test –> distance to the thunderstorm center [Mm]
- Thunderstorm center intensity in absolute units $(C*m)^2/s$
- Data storage – Cyfronet
- Thunderstorms activity maps calculated using PLGrid infrastructure
- Our codes (C++) and ROOT – data analysis framework

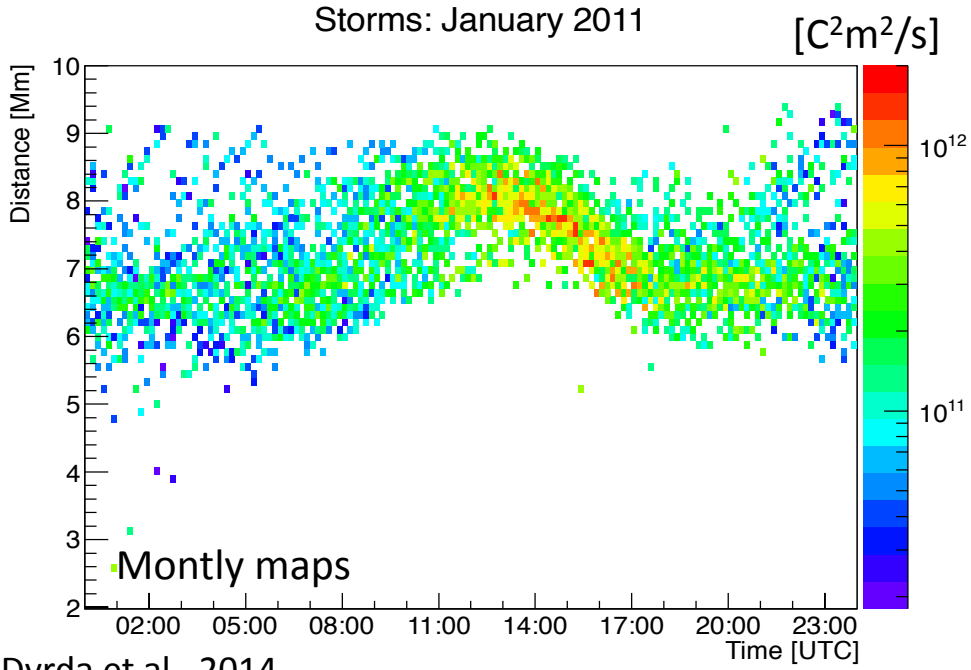
Hylaty – great circles

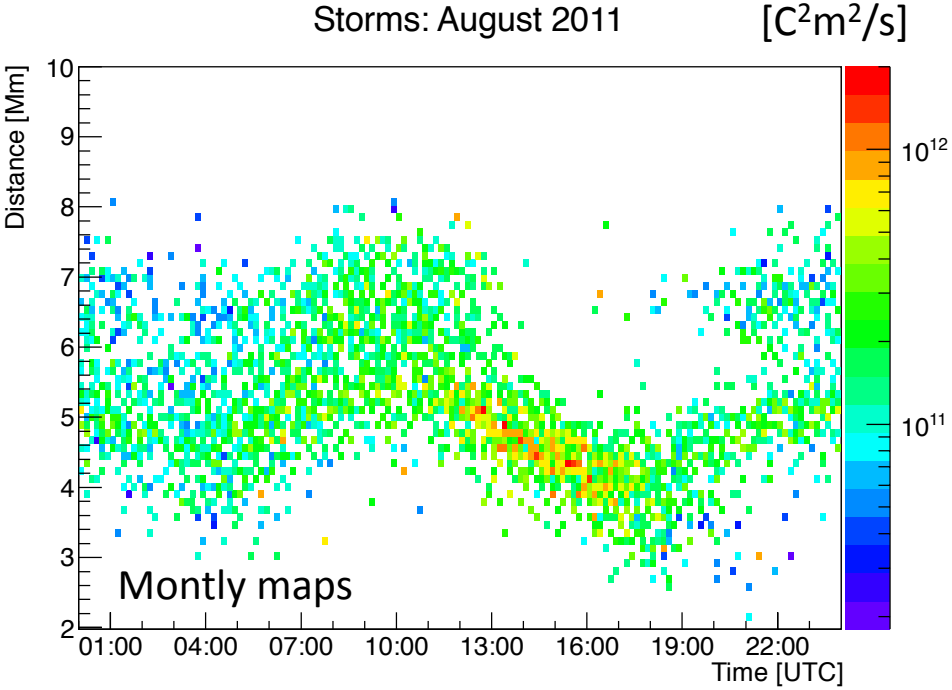


African thunderstorms activity in 2011



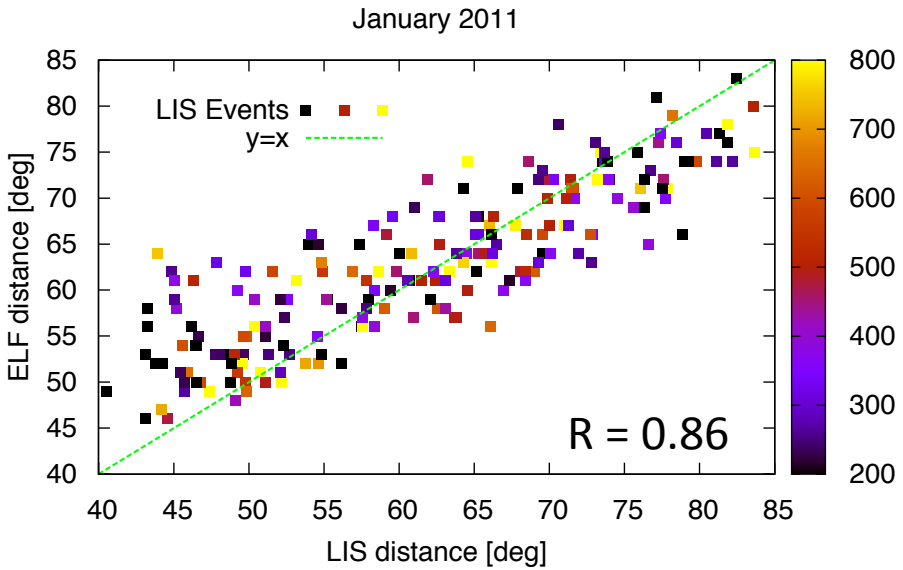


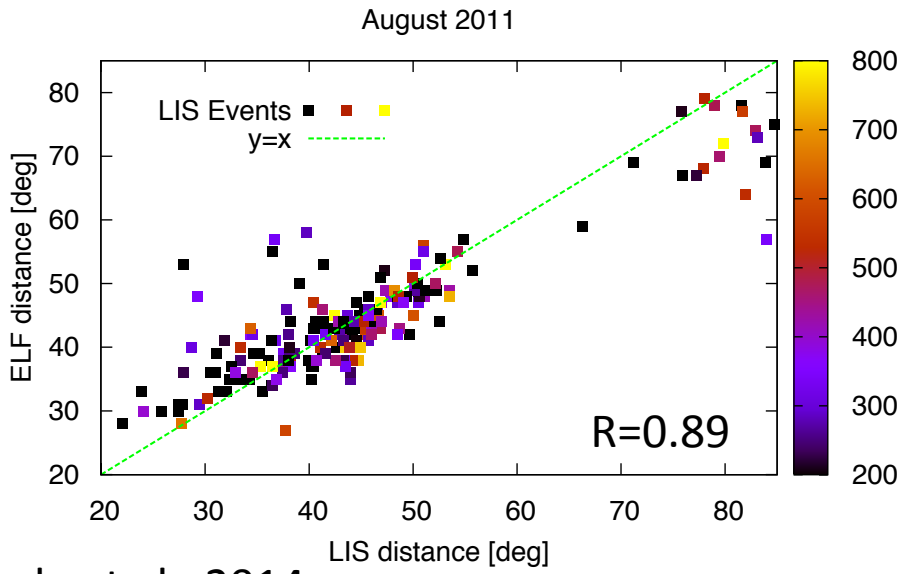




Dyrda et al., 2014

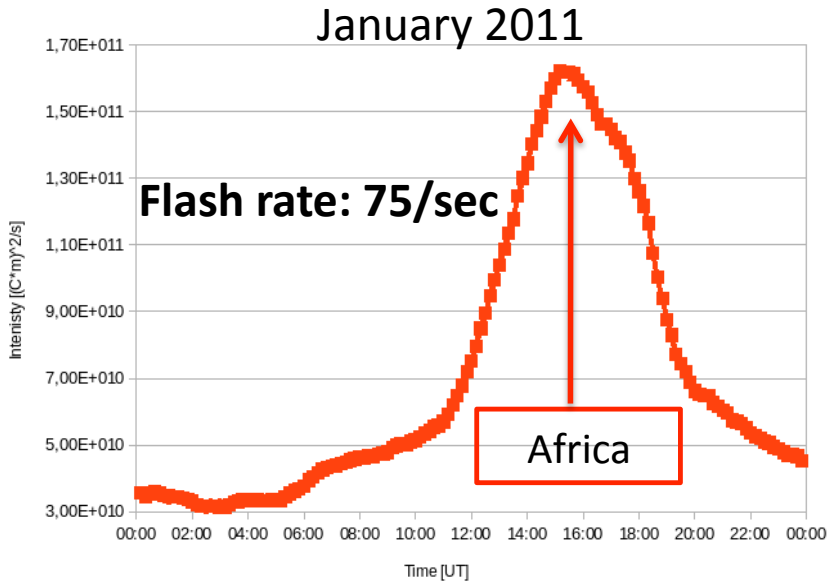
Correlation with optical measurements

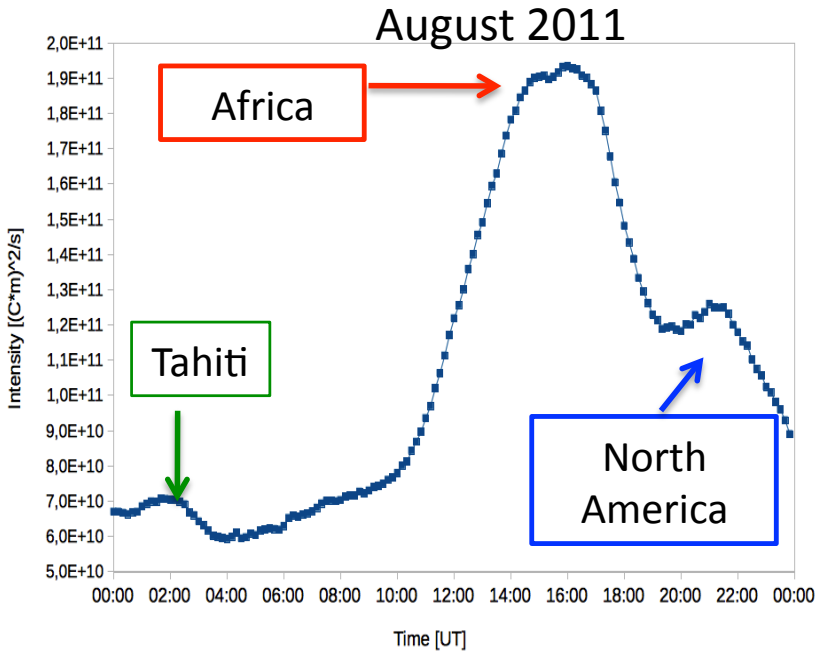


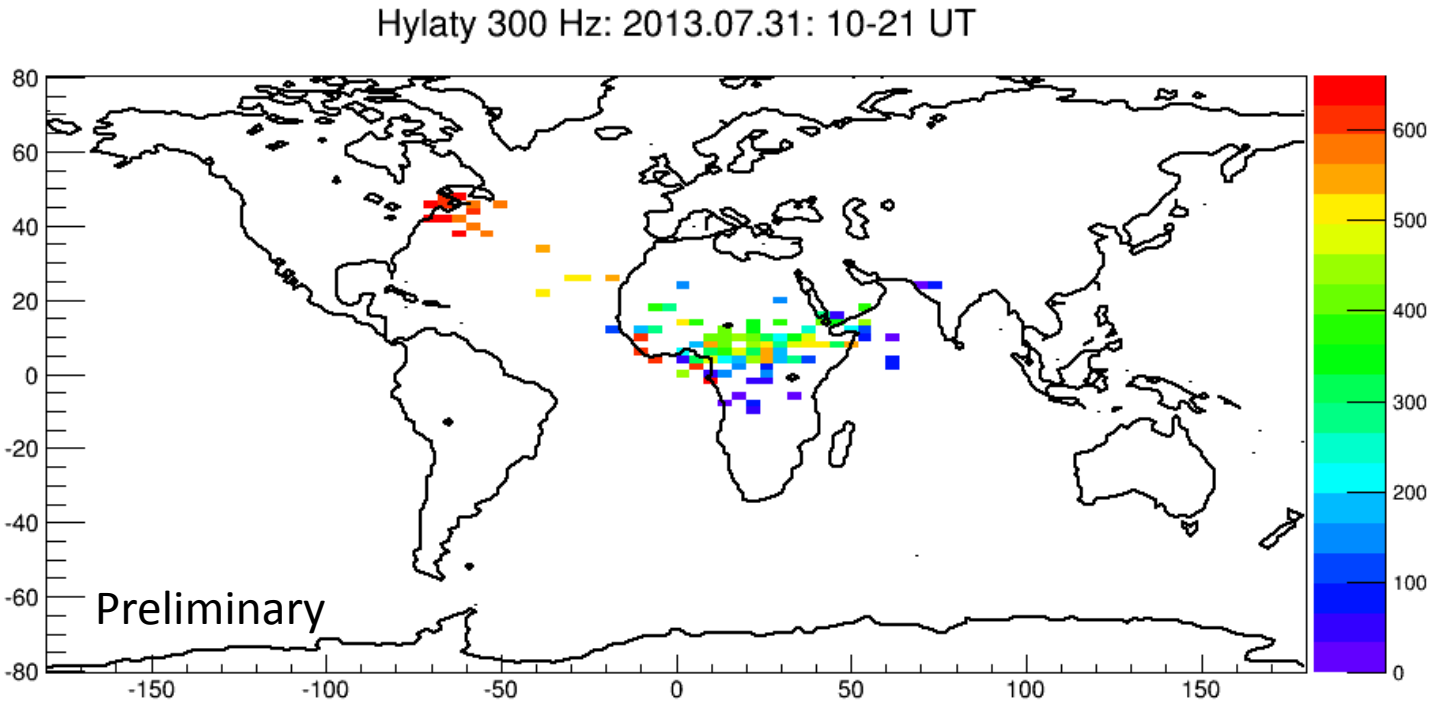


Dyrda et al., 2014

Our carnegie-type curves



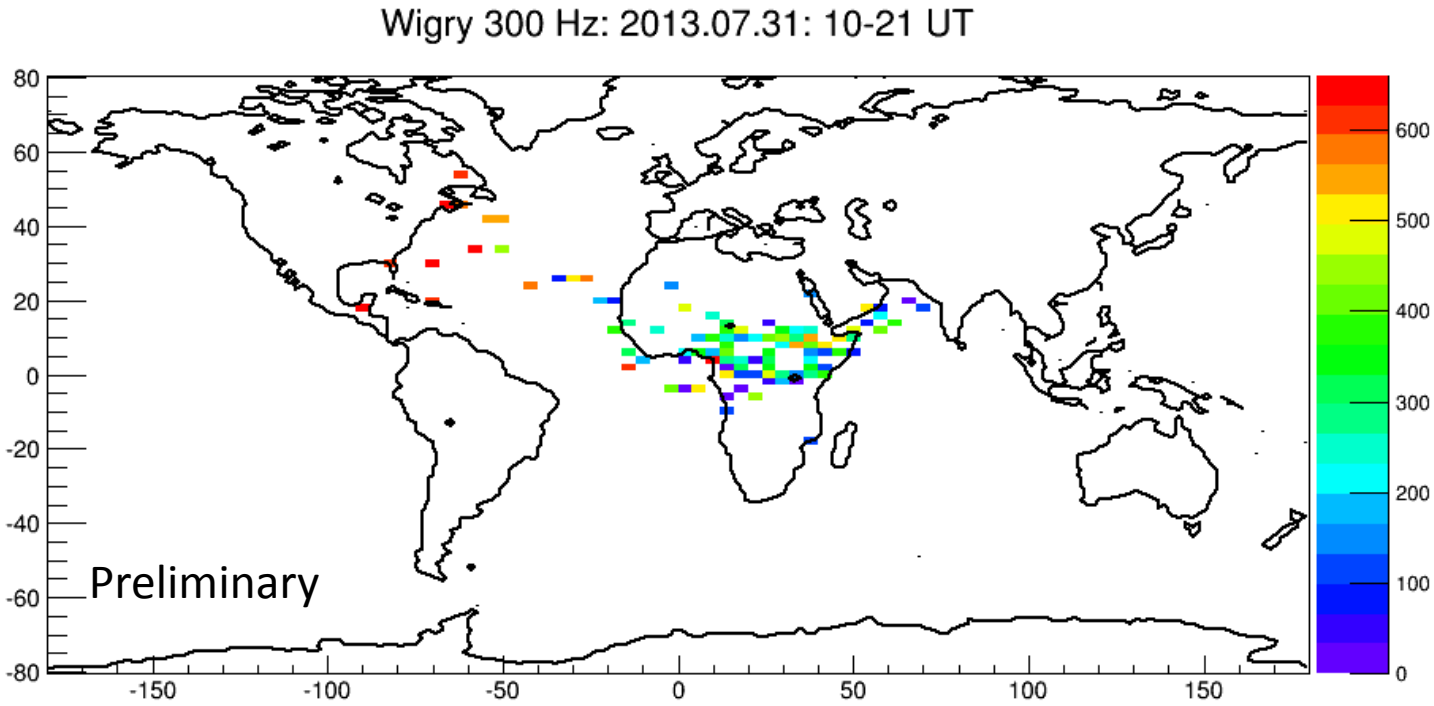




Thunderstorm centers in geographical coordinates

In summer 2013 simultaneous observation with 3 ELF station:

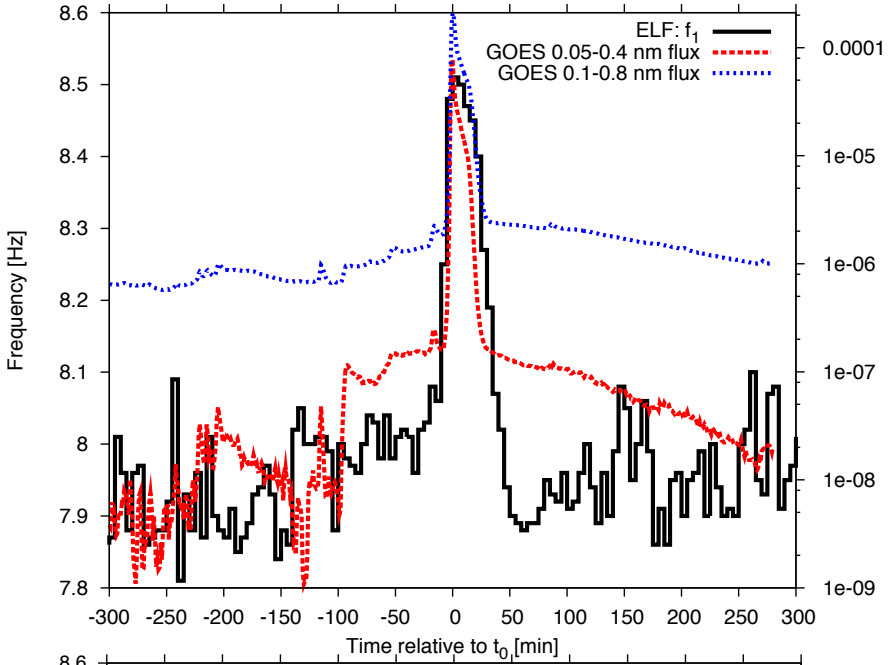
- Hylaty
- Wigry Lake
- Karkonosze

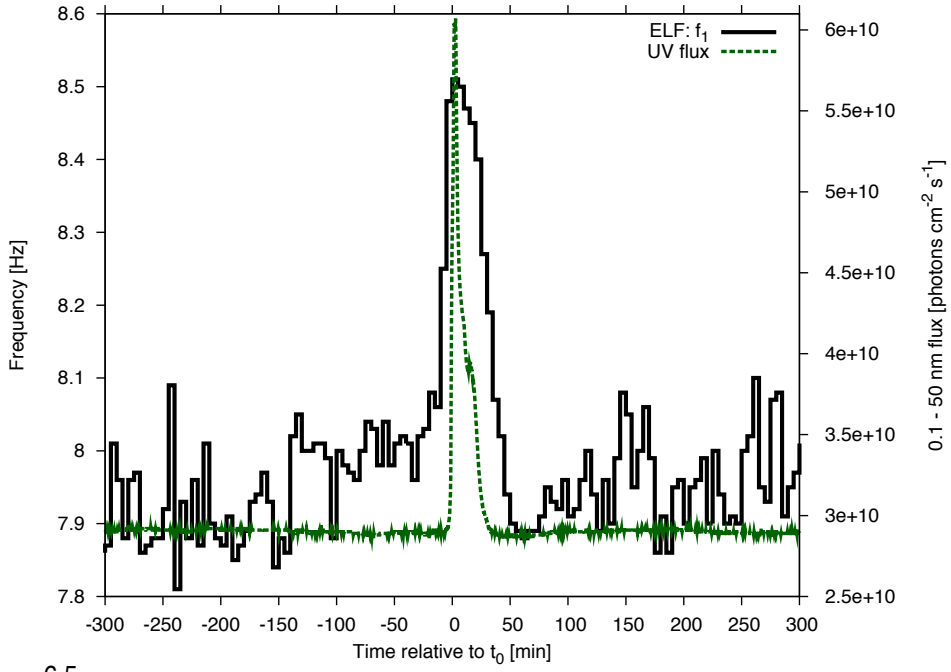


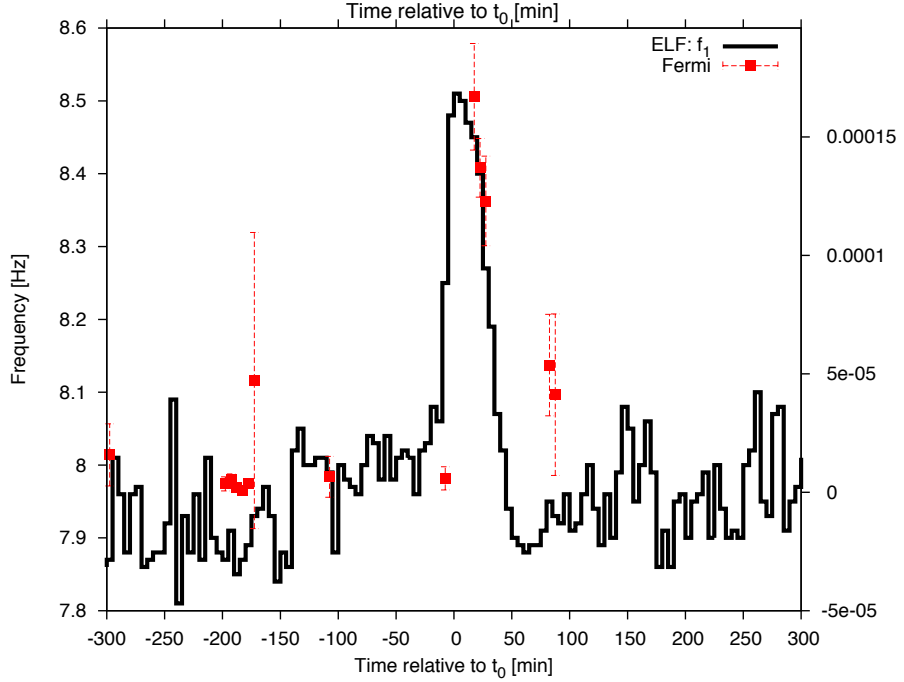
ELF Very Long Baseline Radio Locator

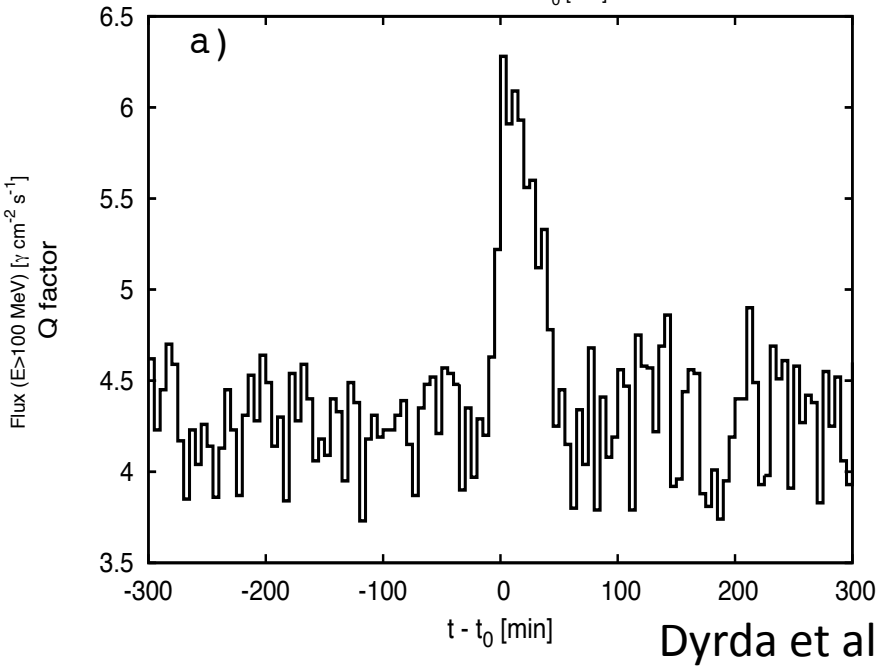
Backup slides

Schumann resonance – solar flares









Dyrda et al., 2015