Meter-scale Measurements of VHF structure of natural leader streamers

or

The largest streamers can be individually imaged in VHF

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Joseph Dwyer, Ute Ebert, S. Nijdam
and the LOFAR Cosmic Ray KSP
Under the idea that these slides will be viewed individually, I’ve organized them like notes. This slide gives the location of different independent sections.

Next slide presents the main arguments I wish to make.

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Many figures and arguments are borrowed from Hare et al. [2020], *PRL*
Conclusion

• Each leader step produces a burst of VHF sources
  • 2/3 of sources from one location (≈ 1 m)
  • 1/3 from about 3 m distance
  • Multiple discrete pulses per burst

• Observed VHF pulses are consistent with antenna impulse response
  • Source of individual pulses must be 10 ns or less in duration
  • Each pulse is most likely due a single streamer
  • Only a few streamers per step are strong enough to make a visible pulse

• Can estimate emitted energy in our frequency band
  • Order-of-magnitude of $2 \times 10^{-6}$ J
  • Consistent with a total streamer charge with order-of-magnitude of 8 µC
Dutch LOFAR

• 24 “core” stations
• 14 “remote” stations
• 3200 km² enclosed area

Per Station:
• 96 low-band antennas
  • 10 – 90 MHz
  • 48 dual-polarized pairs
  • We use 6 dual-polarized pairs out of the 48 pairs
• 20 high-band antennas
  • 110-250 MHz
  • presently not utilized

Also shown in Hare et al. [2018], JGR
Bandpass RFI filter

Hare et al. [2018], *JGR*
PL - positive leader
NL - negative leader
RS - return stroke

15,000 sources after cuts
≈ 100 sources per ms

120 ns minimum between sources

Horizontal accuracy around 1 m

Also shown in Hare et al. [2019], Nature
Negative Leaders

Also shown in Hare et al. [2019], *Nature*
Negative Leaders

Also shown in Hare et al. [2019], Nature
Distribution of time between located sources

- Mostly horizontal leaders
  - 3-4 km altitude
- Uniformly distributed sources should be flat in log-space
- Strong spike below 2 μs
- Thus bursts are real, not statistical artifact
Number of Sources per Burst

Number of Bursts

Number of Located Sources

1
2
3
4
5
6

1000
500
1500
11
Spatial Distribution of Sources in a Burst

- 2/3 come from one location
- 1/3 from further away
Typical Raw Trace of Burst: we still miss a lot

Three located sources in this burst

Rest: too complex shapes to locate
Typical Raw Trace of Burst: key observations

Notes

- VHF signal is very impulsive
  - There are few of the strongest amplitude pulses

- Amplitude distribution is exponential
  - Many more of lower-amplitude pulses

- Very little temporal structure
  - Pulses occurred at a random rate
• Figure shows a relatively clean pulse

• Very similar to impulse response

• FWHM is about 50 ns
Antenna Frequency Response
Impulse response convolved with Gaussian with 1, 10, and 20 ns widths

<table>
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<th>Gaussian $\sigma$</th>
<th>Resulting FWHM</th>
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<tr>
<td>1 ns</td>
<td>$\approx 50$ ns</td>
</tr>
<tr>
<td>10 ns</td>
<td>$\approx 50$ ns</td>
</tr>
<tr>
<td>20 ns</td>
<td>$\approx 100$ ns</td>
</tr>
</tbody>
</table>

Conclusion:
- Signal consistent with impulse response
- Signal must be around 10 ns in duration or shorter

Direct visual comparison on next slide
Antenna Response VS Observed Pulse

\[ \sigma = 1 \text{ ns} \]
\[ \sigma = 10 \text{ ns} \]
\[ \sigma = 20 \text{ ns} \]
What is the source of VHF emission?

Each pulse is due to one streamer

• Only the very strongest streamers visible in VHF

• Vast majority of $2^{16}$ streamers are below noise threshold

• Explains impulsive temporal structure
  • Individual pulses are seen because there are very few of the strongest streamers

Each pulse is many streamers

• Streamers in one pulse would need to occur within 10 ns to explain pulse width

• But there would need to be a waiting time between pulses to explain impulsive nature of the data

• Resulting groups of streamers would then need to occur with a random rate and exponential amplitude spectrum

• No known mechanism for this
Explanation of Spatial Distribution?

Why do pulses seem to come from one location?

• Our hypothesis:
  • Detected VHF pulses aren’t due to typical streamer propagation
  • VHF pulses are made when an ionization wave breaks up into streamers
  • Each new streamer emits a VHF pulse
    • Most pulses are below noise
  • Explains why majority of pulses are from same location

• Other possibilities?
First we can estimate emitted power density, using noise background to calibrate signal.

Noise is dominated by galactic background, which has a well-known power spectra

\[ P_s \times A = P_{n} \times S^2 \]

\( A = \) sensitivity reduction due to high-zenithal angle (\( \approx 1/20 \))

\( P_{n} = \) known power density due to galactic background

\( \approx 2 \times 10^{-12} \) W/m\(^2\)

\( S = \) signal amplitude relative to noise background (\( \approx 200 \))

\( P_s = \) signal power density in 30-80 MHz band

\( S^2 \) is received power relative to noise background power.
Emitted energy estimate

First we can estimate emitted power density, using noise background to calibrate signal. Noise is dominated by galactic background, which has a well-known power spectra.

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\( P_s \) = signal power density in 30-80 MHz band

Relate power density to energy

\[ E = \tau P_s 4\pi D^2 \]

\( \tau \) : pulse width (\( \approx 1 \) ns)

\( D \) : distance between antenna and source (\( \approx 10 \) km)

\( E \) : estimated energy emitted in band

\[ E = \frac{\tau P_s 4\pi D^2 S^2}{A} = 2 \times 10^{-6} \] J
Assume streamer can be approximated by a charge, $Q$, that accelerates, moves forward, then deaccelerates.
Charge Estimate

\[ Pq = \frac{1}{(4\pi)^2 \varepsilon_0 c^3} \left( \frac{Qv}{\tau D} \right)^2 \]

- emitted power density

\( D = \) distance from source (\( \approx 10 \text{ km} \))

\( V = \) maximum velocity (\( \approx 1 \text{ mm/ns} \))

\( \tau = \) acceleration time (\( \approx 1 \text{ ns} \))
Charge Estimate

\[ Pq = \frac{1}{(4\pi)^2 \varepsilon_0 c^3} \left( \frac{Q\nu}{\tau D} \right)^2 \]  : emitted power density

\[ Pq \times F = P_{eq} \]

Account for frequency band

\[ Pq \times F = P_{eq} \]

\( D = \text{distance from source ( \approx 10 \text{ km})} \)
\( V = \text{maximum velocity ( \approx 1 \text{ mm/ns})} \)
\( \tau = \text{acceleration time ( \approx 1 \text{ ns})} \)

\[ F = \text{fraction power in our band ( 30 – 80 MHz)} \]
\[ \approx 0.1 \text{ for pulse width between 1 – 10 ns (order of magnitude)} \]
Charge Estimate

\[ Pq = \frac{1}{(4\pi)^2 \varepsilon_0 c^3} \left( \frac{Qv}{\tau D} \right)^2 \] : emitted power density

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Account for frequency band

\[ Pq \times F = Ps \]
\[ F = \text{fraction power in our band} \ (30 - 80 \text{ MHz}) \]
\[ \approx 0.1 \text{ for pulse width between } 1 - 10 \text{ ns (order of magnitude)} \]

Combine equations 1, 4, and 5, and solve for \( Q \)

\[ Q = 4\pi S \sqrt{ \frac{Pn}{AF} \frac{\varepsilon_0 c^3 \tau D}{v} } = 8 \mu C = 5 \times 10^{13} \text{ electrons} \]