Meter-scale Measurements of VHF structure of natural leader streamers

or

The largest streamers can be individually imaged in VHF

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and the LOFAR Cosmic Ray KSP

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kvi - center for advanced radiation technology

NWO Netherlands Organisation for Scientific Research

Outline

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.

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 2×10^{-6} J
  - Consistent with a total streamer charge with order-of-magnitude of 8 μC

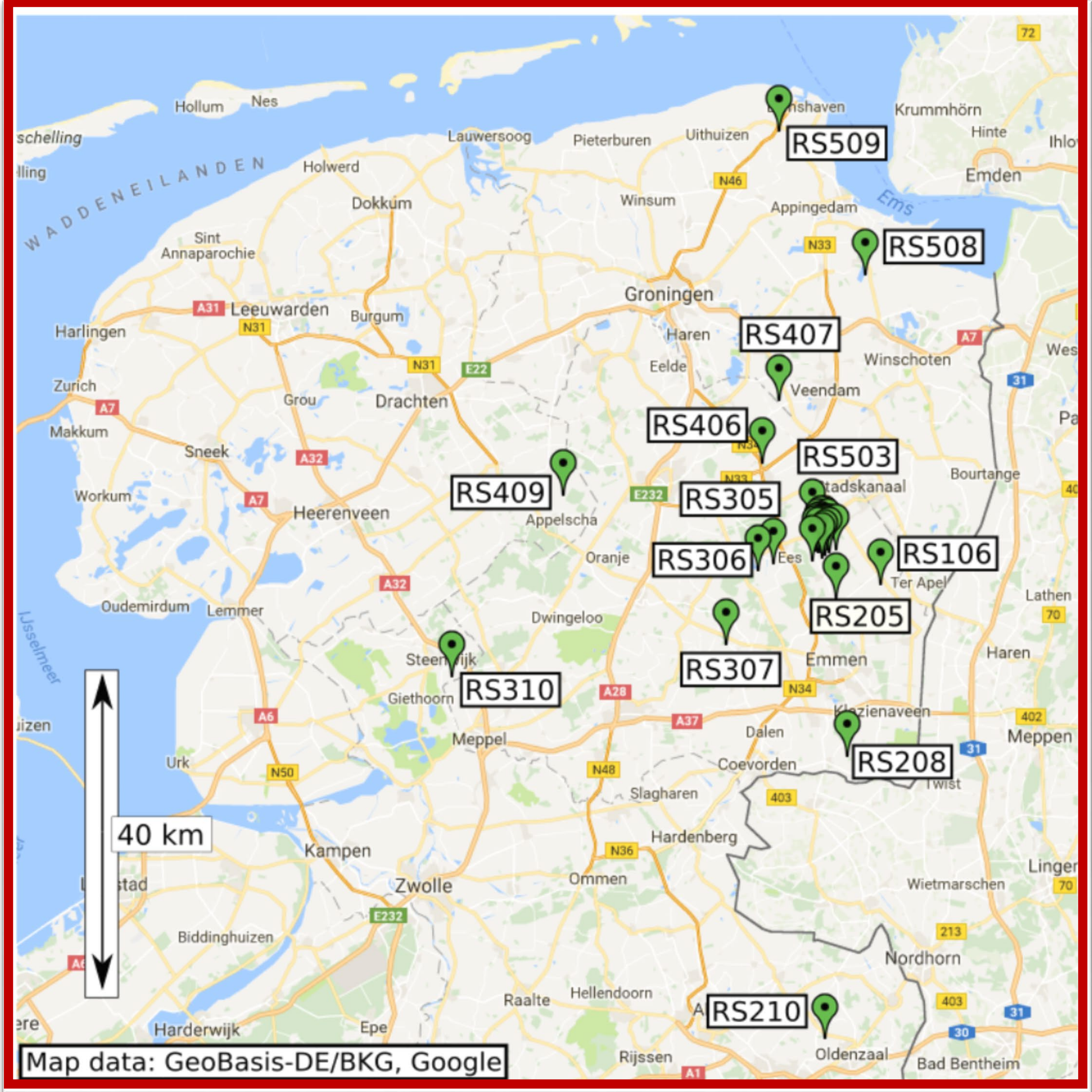
Dutch LOFAR

- 24 “core” stations
- 14 “remote” stations
- 3200 km^2 enclosed area

Per Station:

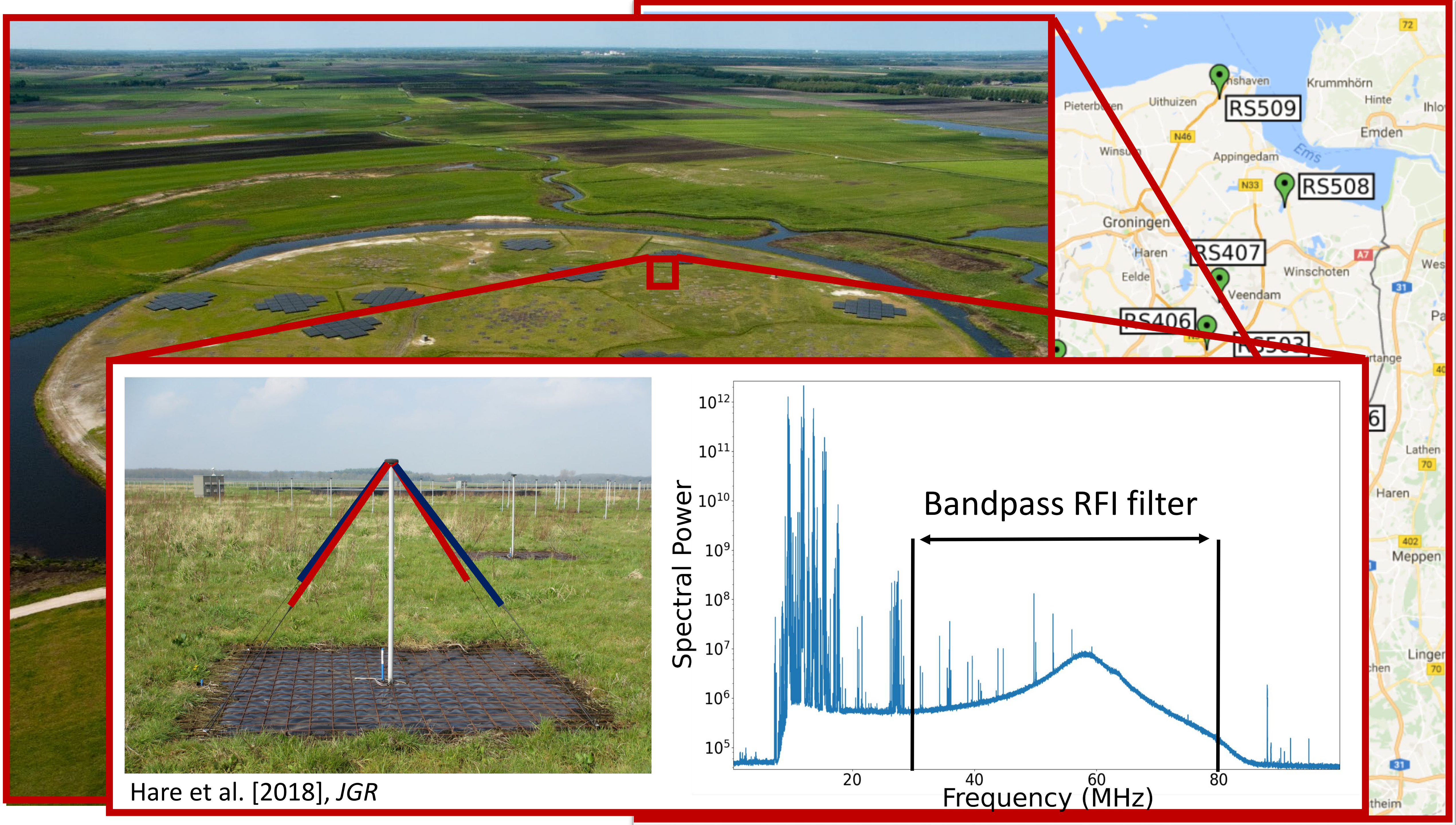
- 96 low-band antennas
  - 10 – 90 MHz
  - 48 dual-polarized pairs
  - We use 6 dual-polarized pairs out of the 48 pairs

- 20 high-band antennas
  - 110-250 MHz
  - presently not utilized

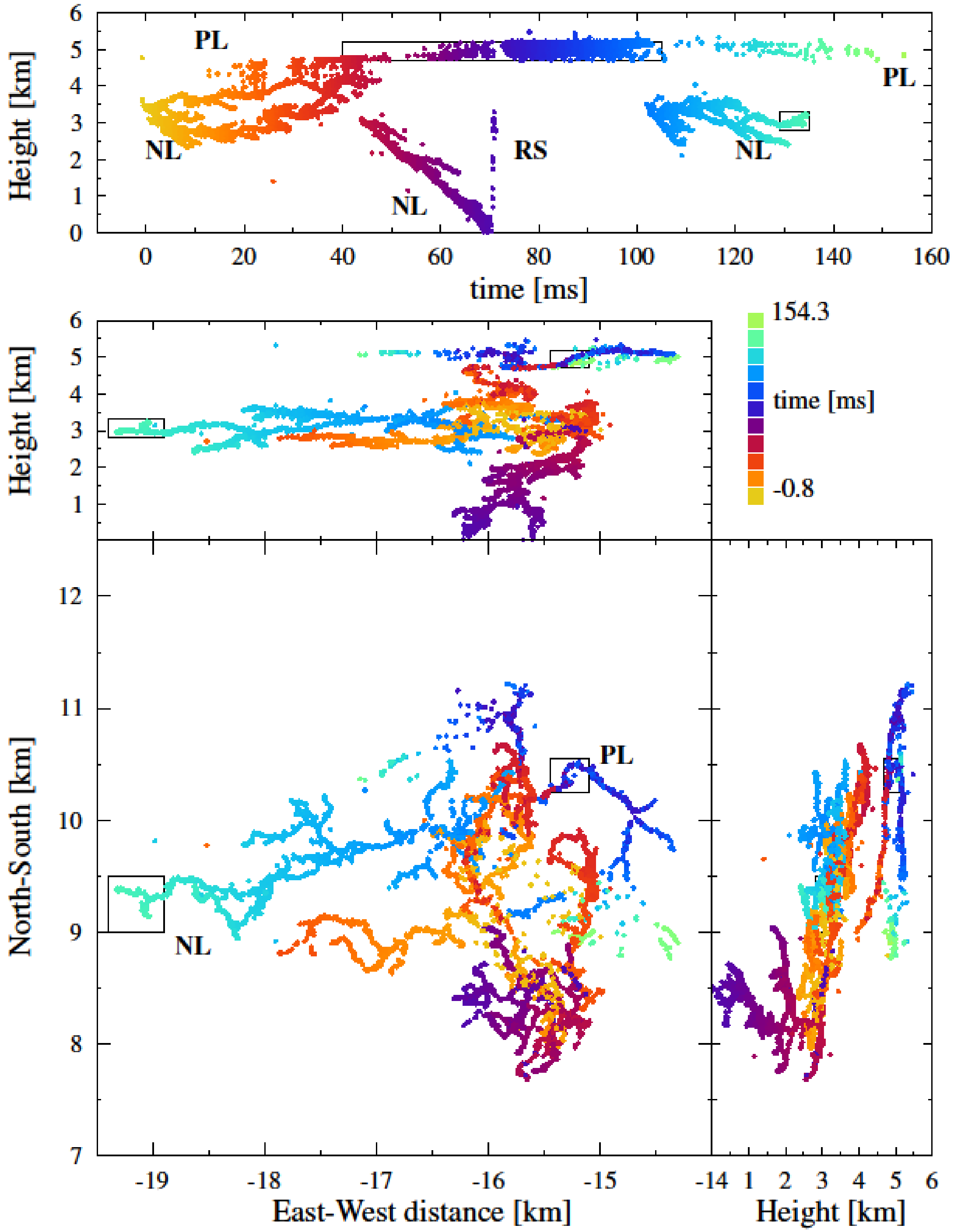


Also shown in Hare et al. [2018], *JGR*

RS509
RS508
RS407
RS406
RS305
RS306
RS106
RS205
RS307
RS208
RS210
Uithuizen
Krummhörn
Hinte
Emden
Appingedam
Ems
Groningen
Haren
Eelde
Winschoten
Veendam
Bourtange
Oranje
Ter Apel
Lathen
Emmen
Haren
Meppen
Slagharen
Twist
Ommen
Wietmarschen
Nordhorn
Oldenzaal
Rijssen
Bad Bentheim
N46
N33
A7
E232
N34
A28
A37
N48
N36



RS509
RS508
RS407
RS406
Groningen
Uithuizen
Krummhörn
Hinte
Emden
Appingedam
Winschoten
Veendam
Haren
Eelde
Lathen
Meppen
Bandpass RFI filter
Spectral Power
Frequency (MHz)
Hare et al. [2018], *JGR*



PL- positive leader
NL- negative leader
RS- return stroke

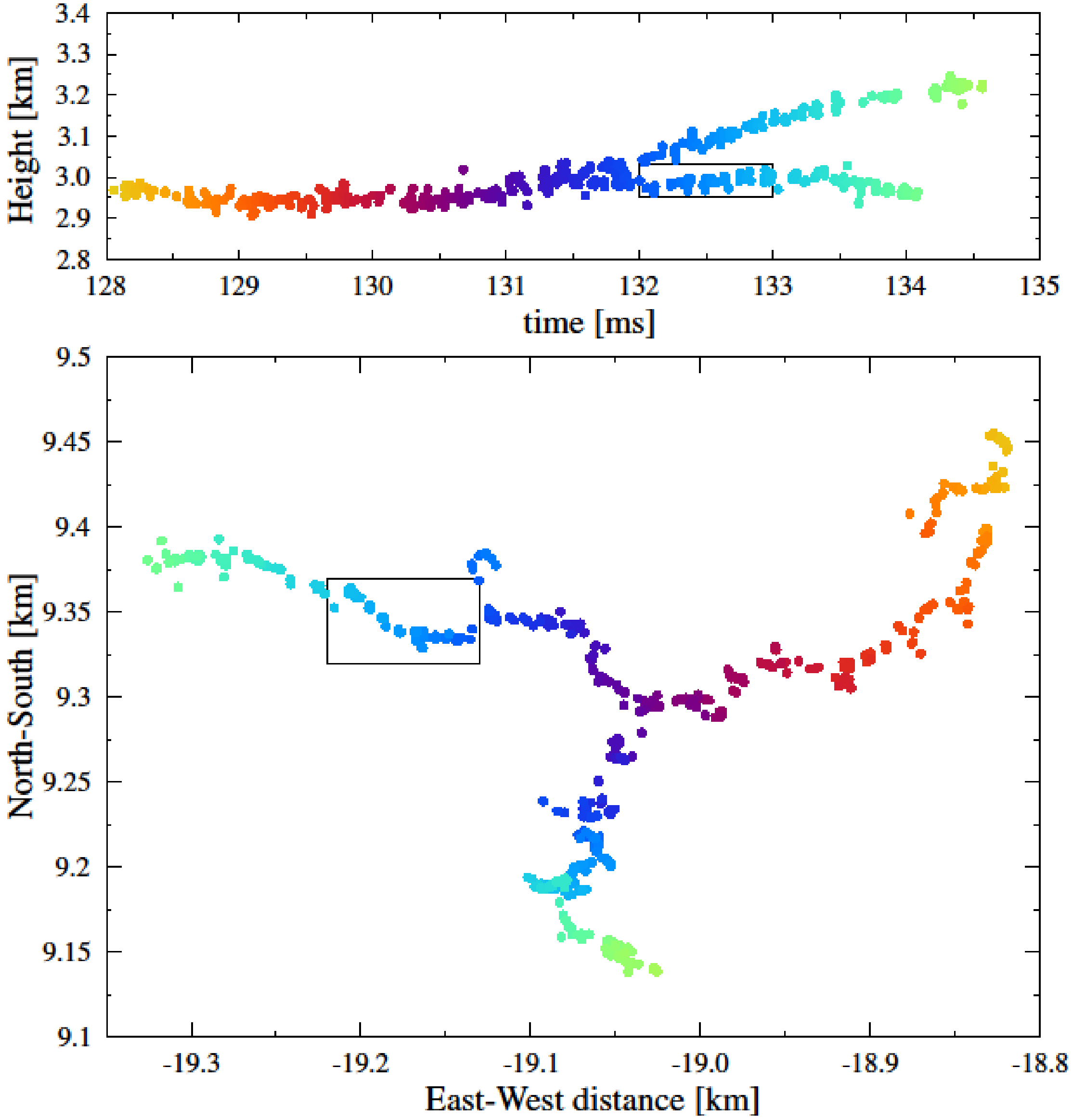
15,000 sources after cuts
≈ 100 sources per ms

120 ns minimum between sources

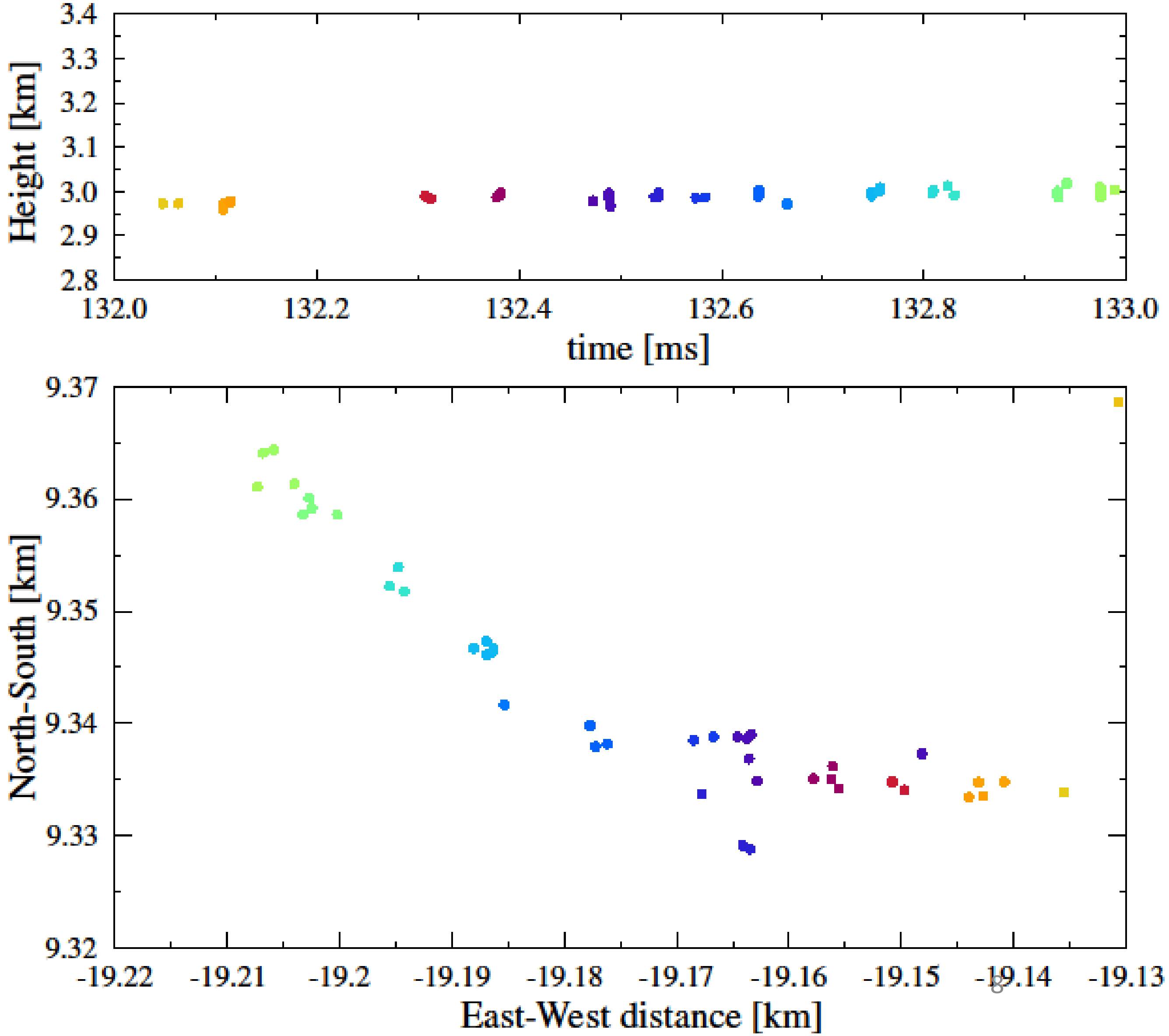
Horizontal accuracy around 1 m

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

Negative Leaders



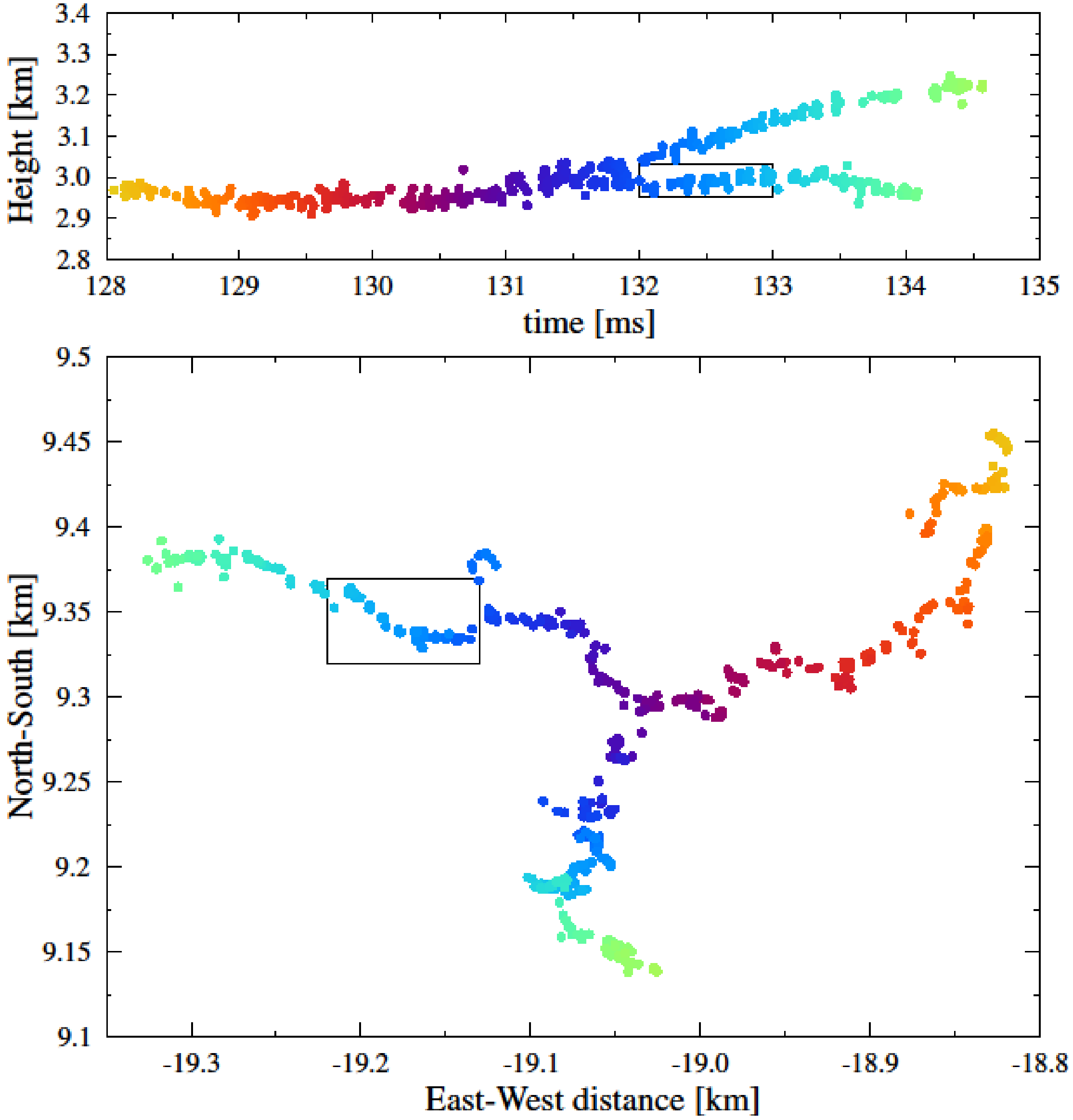
Zoom - In

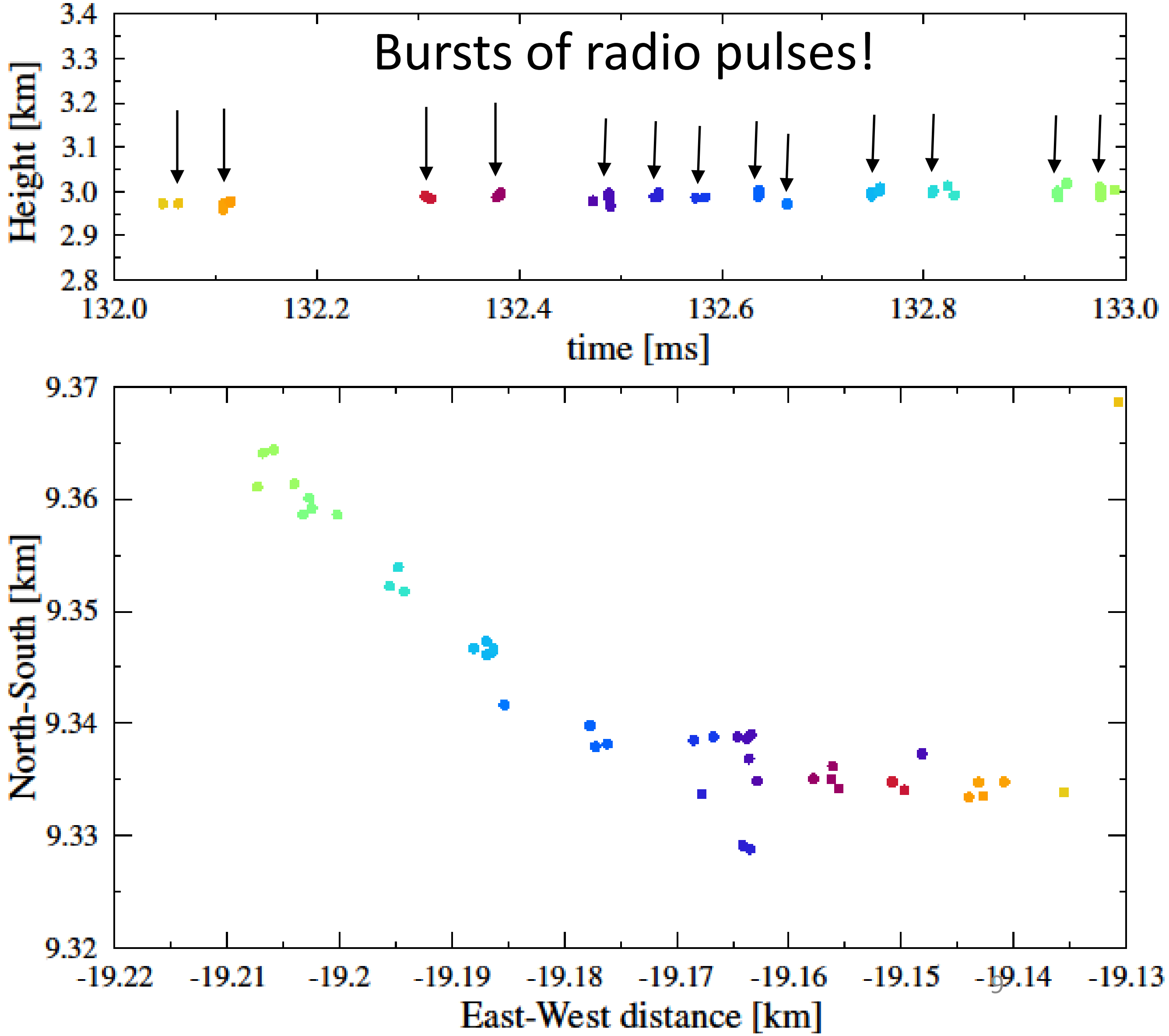


Also shown in Hare et al. [2019], *Nature*

Negative Leaders

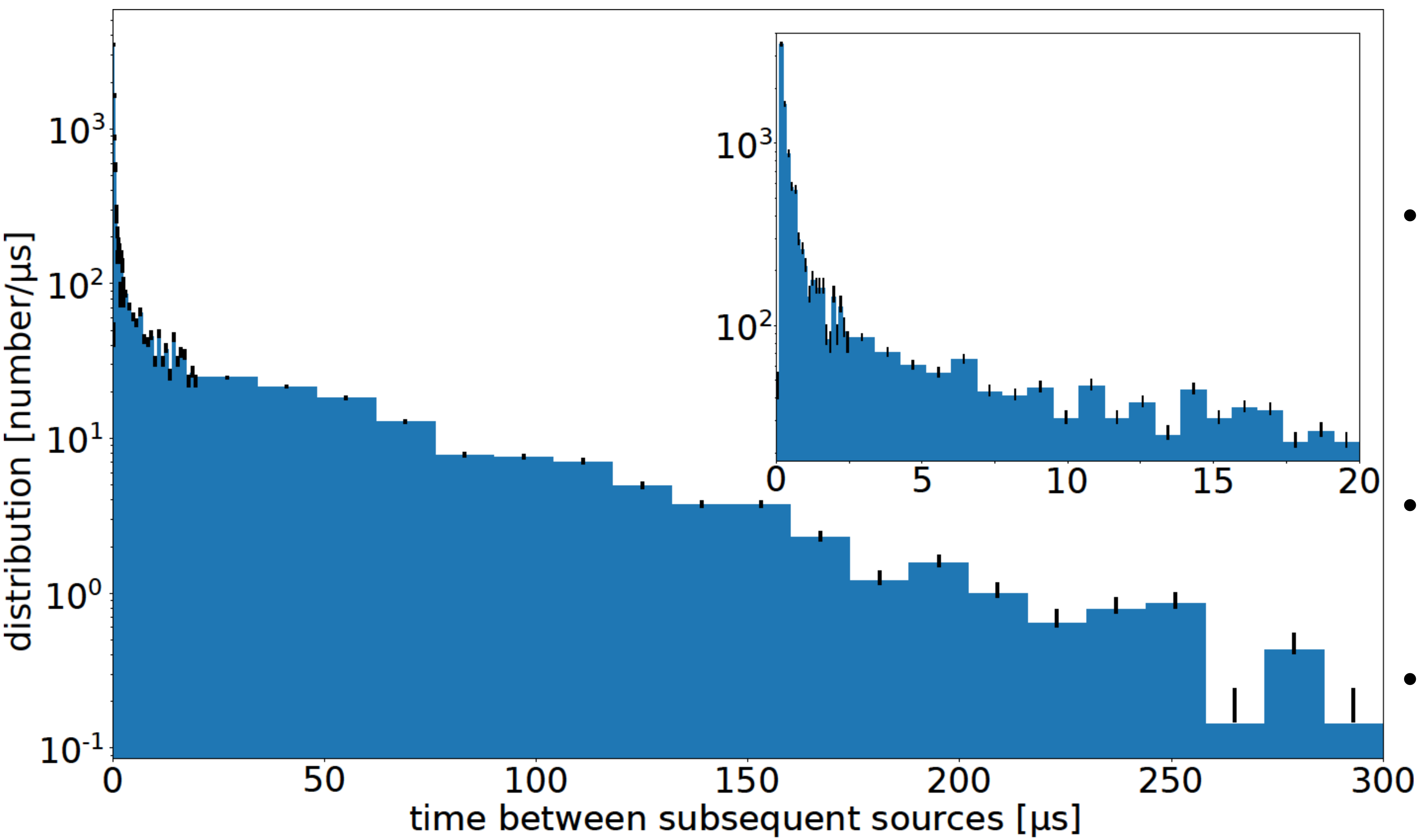
Zoom - In





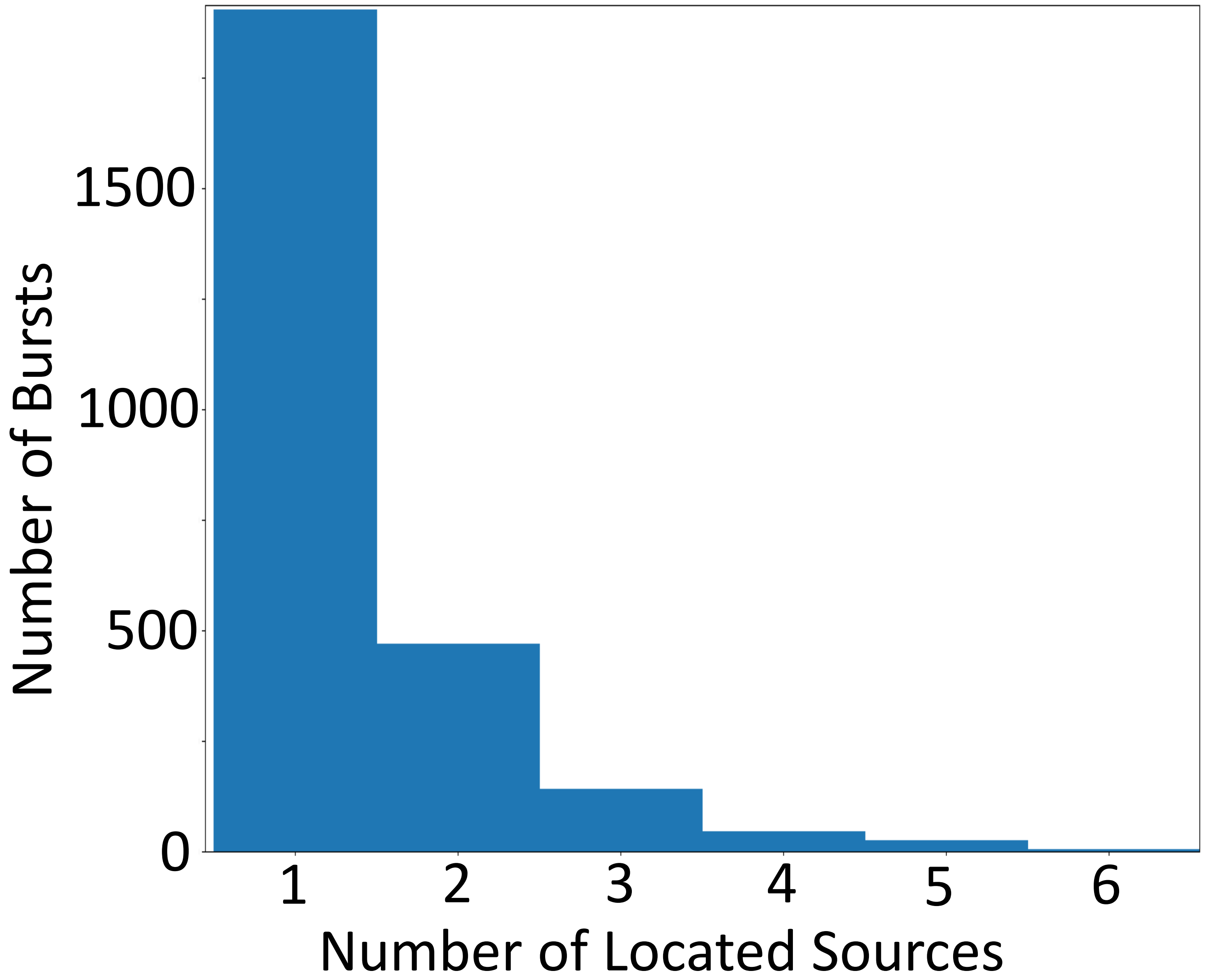
Also shown in Hare et al. [2019], *Nature*

Distribution of time between located sources

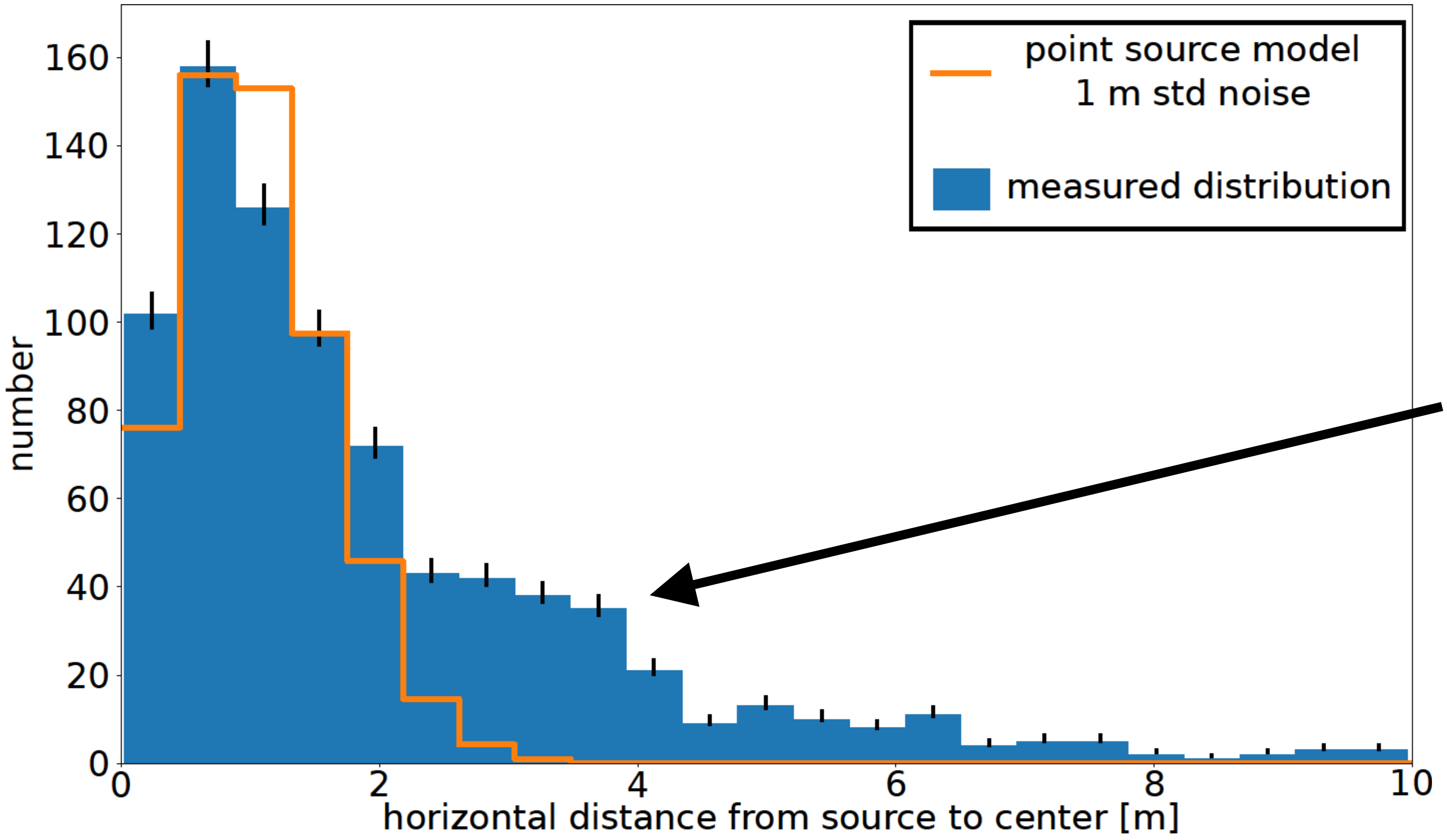


- Mostly horizontal leaders
  - 3-4 km altitude
- Uniformly distributed sources should be flat in log-space
- Strong spike below 2 μs
- Thus bursts are real, not statistical artifact

Number of Sources per Burst

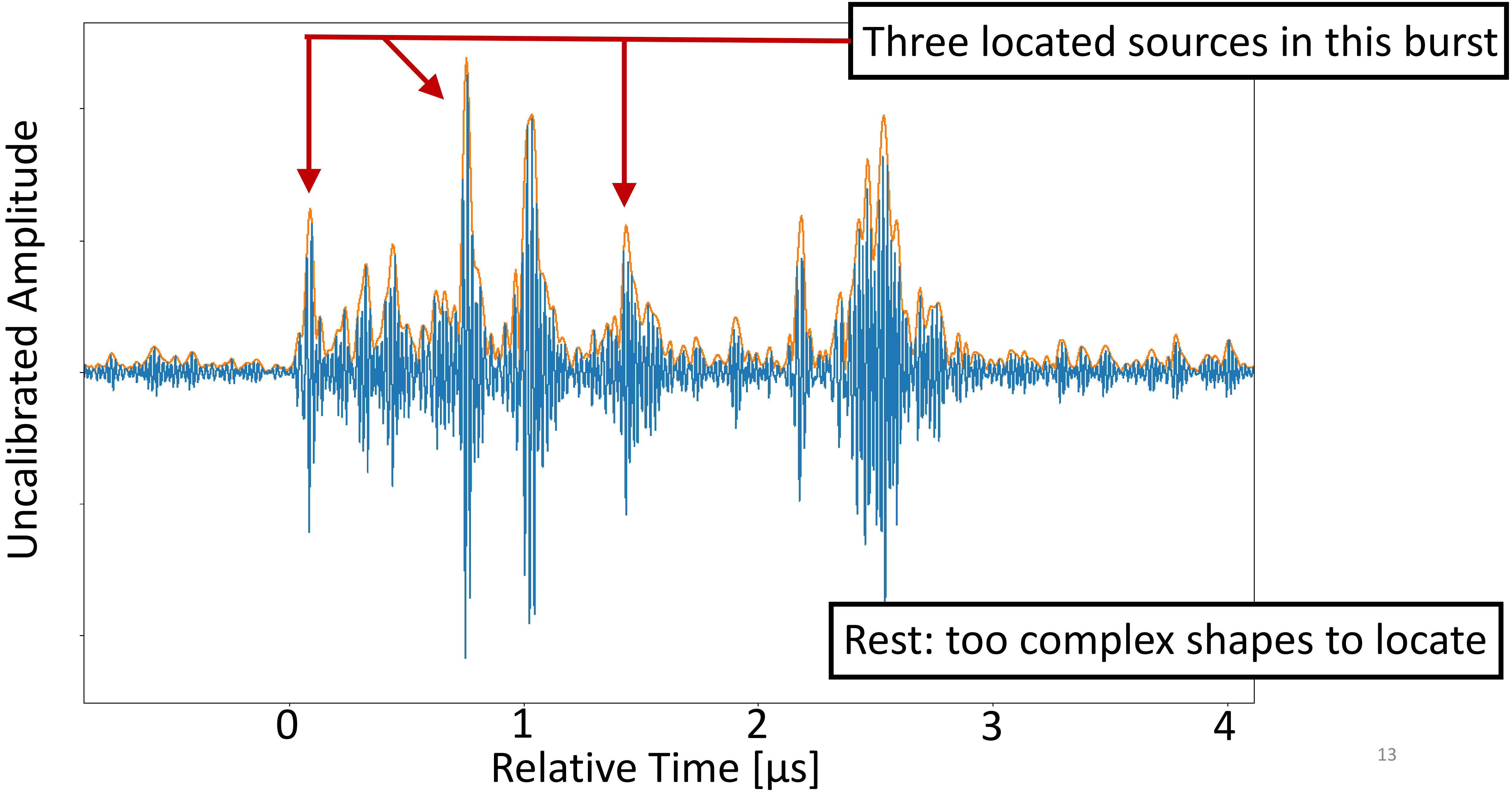


Spatial Distribution of Sources in a Burst

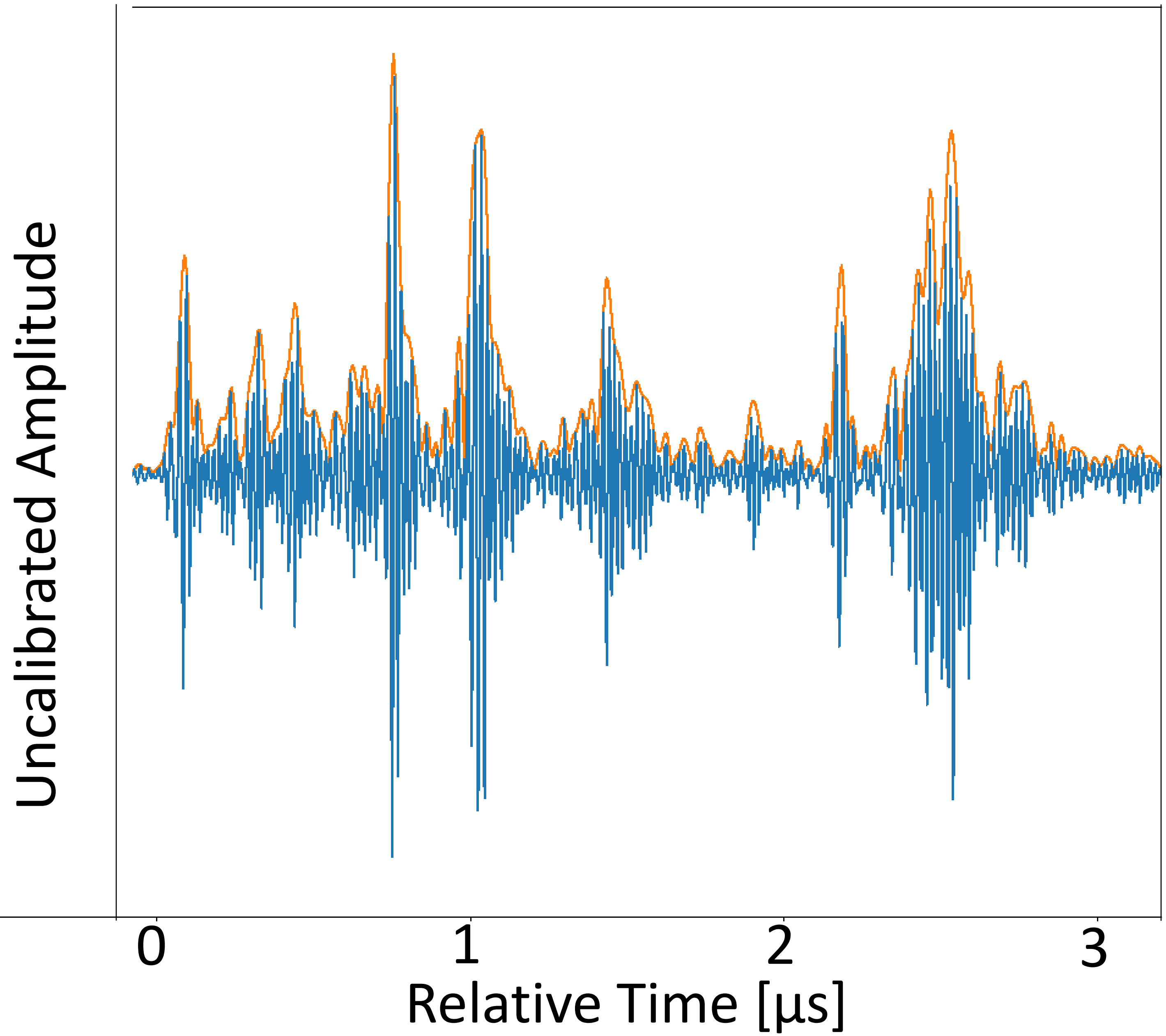


- 2/3 come from one location
- 1/3 from further away

Typical Raw Trace of Burst : we still miss a lot



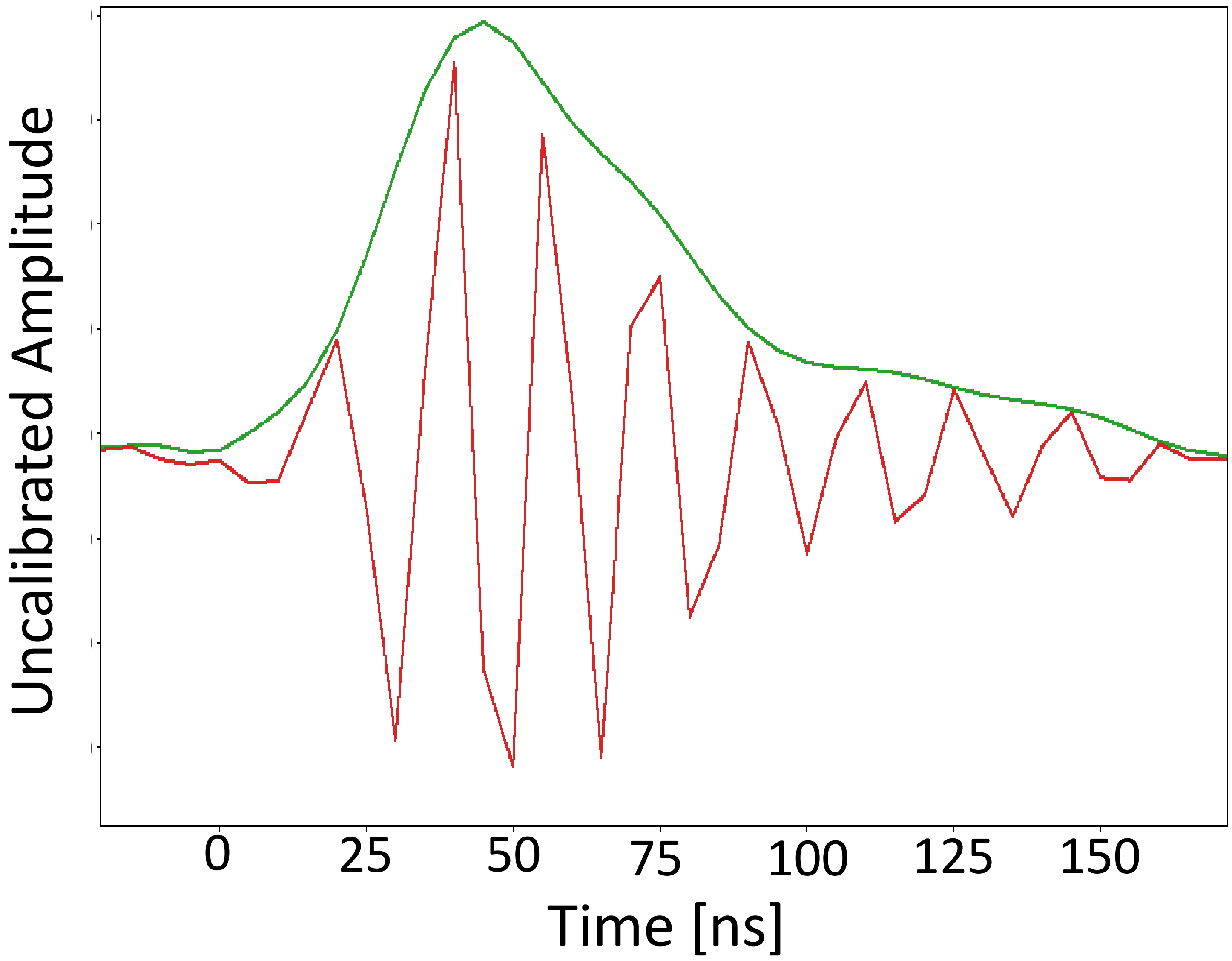
Typical Raw Trace of Burst : key observations



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

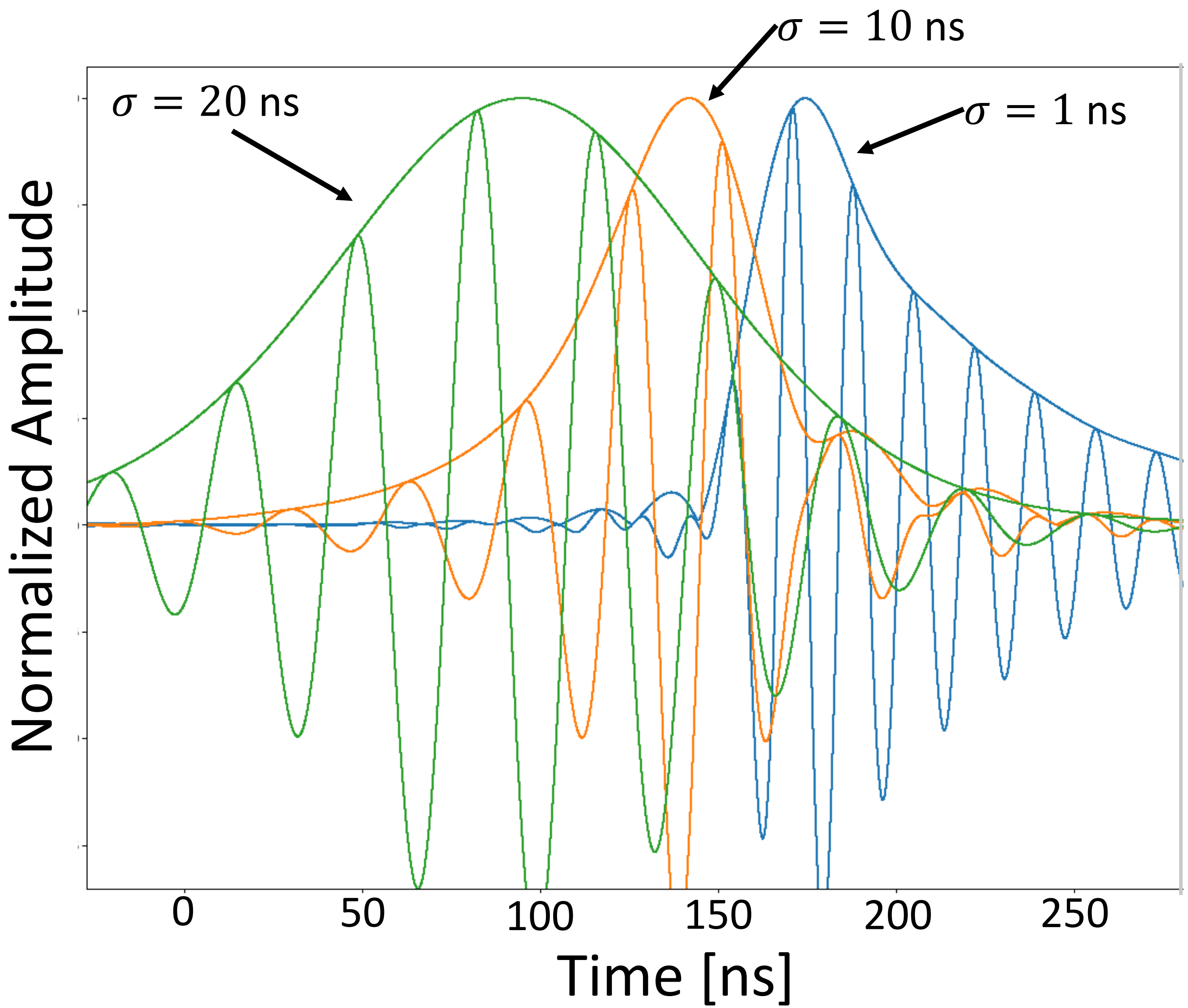
Zoom-in on one pulse



- 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



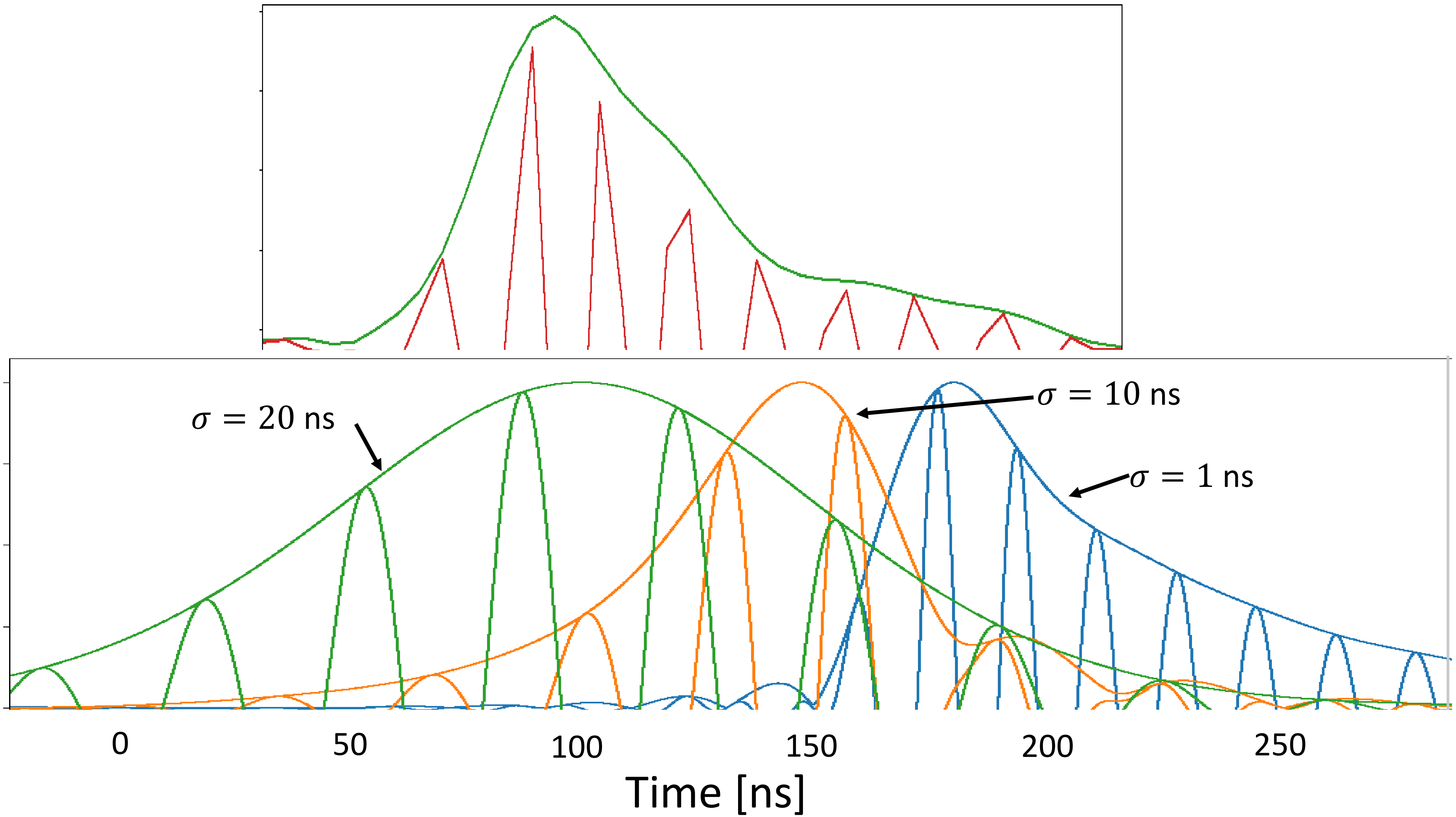
Gaussian σ	**Resulting FWHM**
1 ns	≈ 50 ns
10 ns	≈ 50 ns
20 ns	≈ 100 ns

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



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?

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

A = sensitivity reduction due to high-zenithal angle ($\approx$ 1/20)
Pn = known power density due to galactic background
$\approx 2 \times 10^{-12}$ W/m^2

eq 1) $$Ps \times A = Pn \times S^2$$

S = signal amplitude relative to noise background ($\approx$ 200)
Ps = signal power density in 30-80 MHz band

S^2 is received power relative to noise background power

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Relate power density to energy

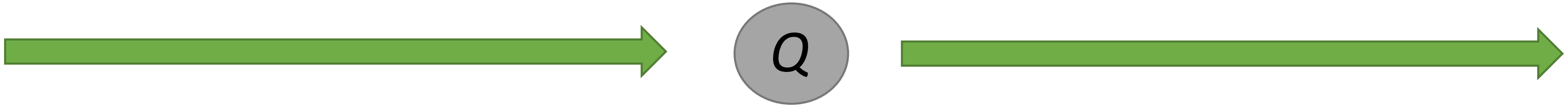
eq 2) $E = \tau \, Ps \, 4\pi D^2$

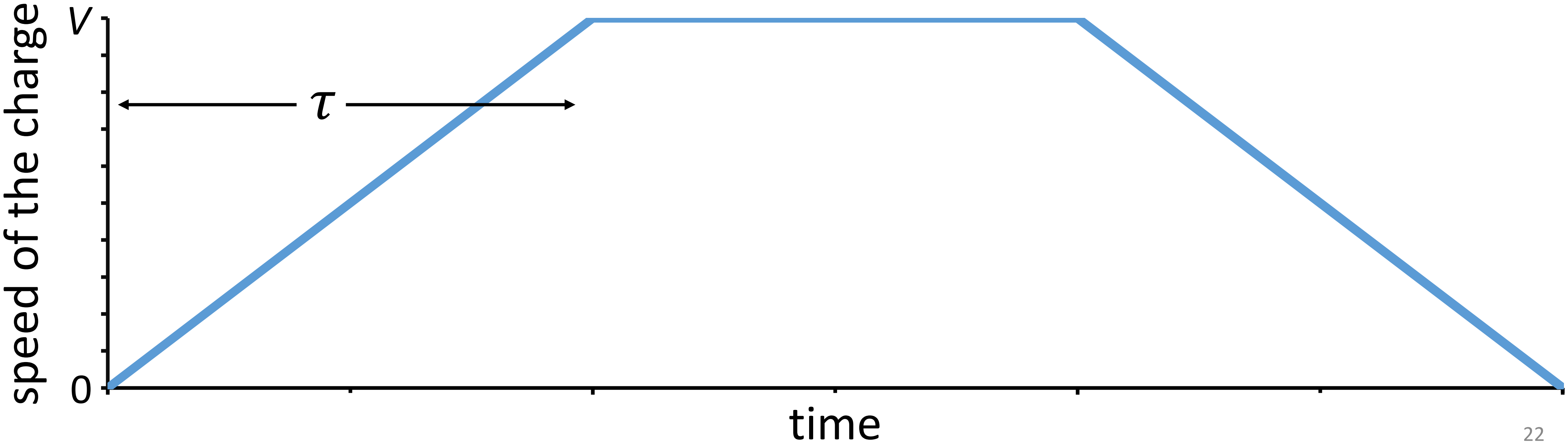
τ : pulse width (≈ 1 ns)
D : distance between antenna and source (≈ 10 km)
E : estimated energy emitted in band

eq 3) $E = \dfrac{\tau \, Ps \, 4\pi D^2 \, S^2}{A} = 2 \times 10^{-6}$ J

Charge Estimate : simple charge model

Assume streamer can be approximated by a charge, *Q*, that accelerates, moves forward, then deacelerates





Charge Estimate

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

D = distance from source (≈ 10 km)
V = maximum velocity (≈ 1 mm/ns)
τ = acceleration time (≈ 1 ns)

Charge Estimate

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Account for frequency band

eq 5) $$Pq \times F = Ps$$

F = fraction power in our band (30 – 80 MHz)
≈ 0.1 for pulse width between 1 – 10 ns (order of magnitude)

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$\approx$ 0.1 for pulse width between 1 – 10 ns (order of magnitude)

Combine equations 1, 4, and 5, and solve for *Q*

eq 6) $$Q = 4\pi S\sqrt{\frac{Pn\ \varepsilon_0 c^3}{A\ F}\frac{\tau D}{v}} = 8\ \mu C = 5 \times 10^{13}$$ electrons