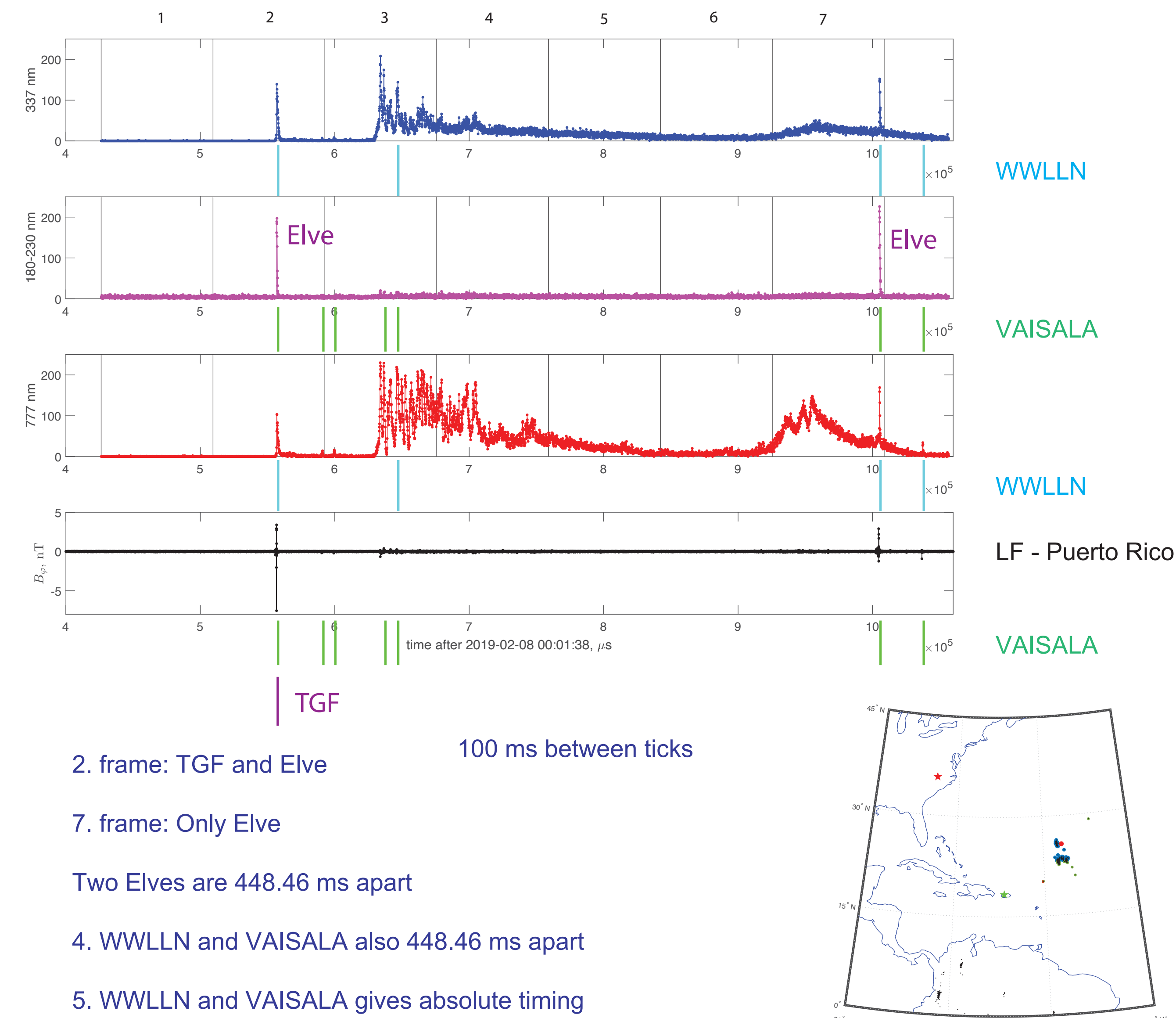


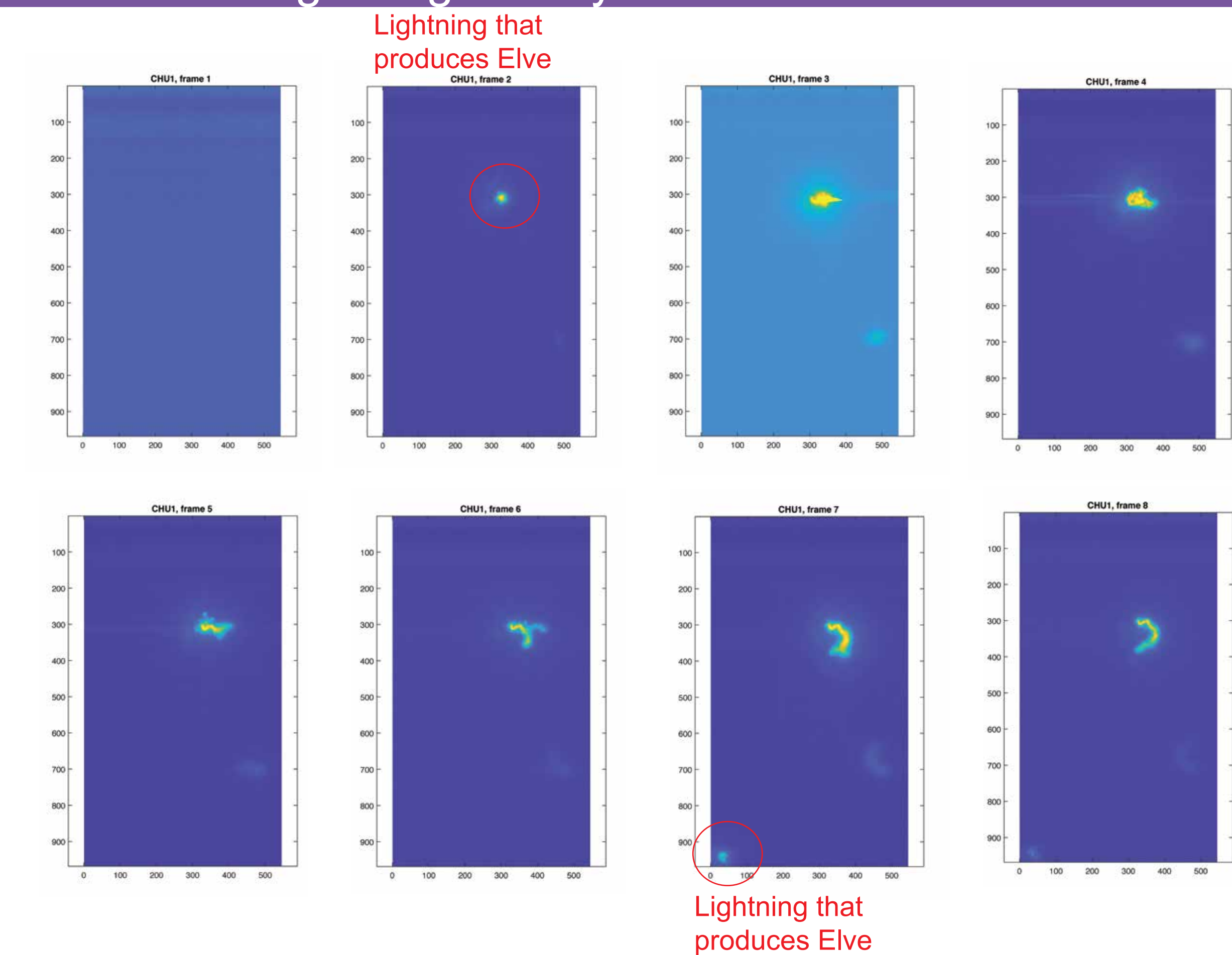
Abstract

On February 8, 2019 the Atmosphere-Space Interaction Monitor (ASIM) passed a thunderstorm system north east of Puerto Rico and observed a TGF and an Elve from the same lightning stroke at the very beginning of a lightning flash. A second Elve was observed 456 ms later but without any signature of a TGF about 300 km south-east of the first Elve. The strokes associated with the two Elve events were detected by WWLLN and Vaisala, which allows for an absolute timing accuracy of the ASIM measurements of at least 100 μ s. Images of the lighting strokes support the source locations for the Elves and TGF. Low Frequency radio measurements from Puerto Rico indicate that the first stroke was an intracloud positive while the latter was a cloud-to-ground stroke. The UV emissions from the Elves preceded the optical emissions in 777 nm by 50 μ s and 90 μ s, respectively. Modelling of the scatter and absorption of the 777 nm emissions within the cloud can explain these delays as well as the duration of the emissions. Current moments derived from radio measurements at Puerto Rico and Duke University indicate a fast (30 μ s) and large (200 kA) current pulse in the IC+ stroke emitting an electromagnetic wave that produces the Elve and a slow (1-2 ms) current that also could have contributed to the optical signals.

Overview of the lightning activity

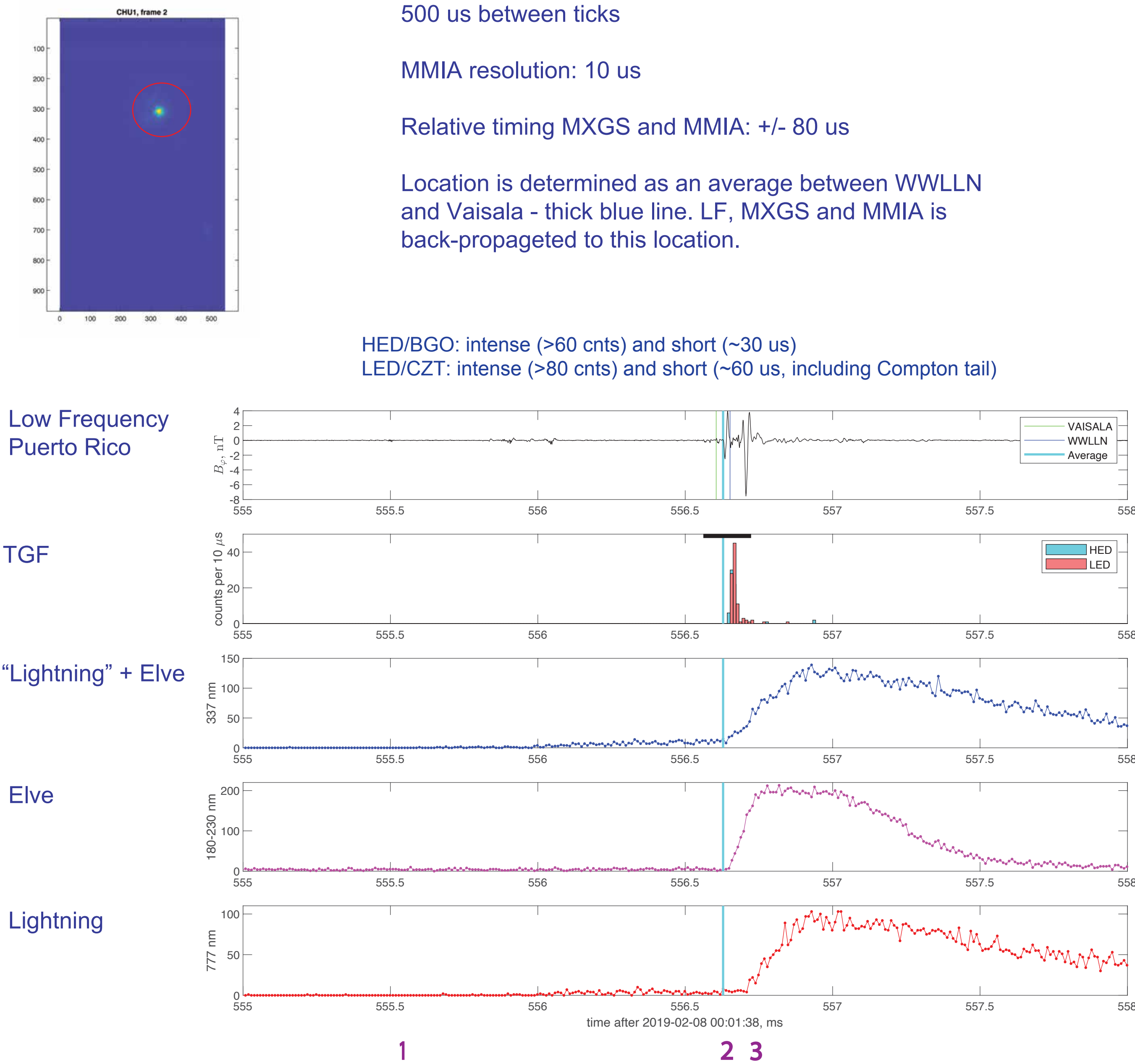


Location of lightning activity



The simultaneous WWLLN and VAISALA data locate the two Elves about 300 km apart

First Elve and TGF from IC+



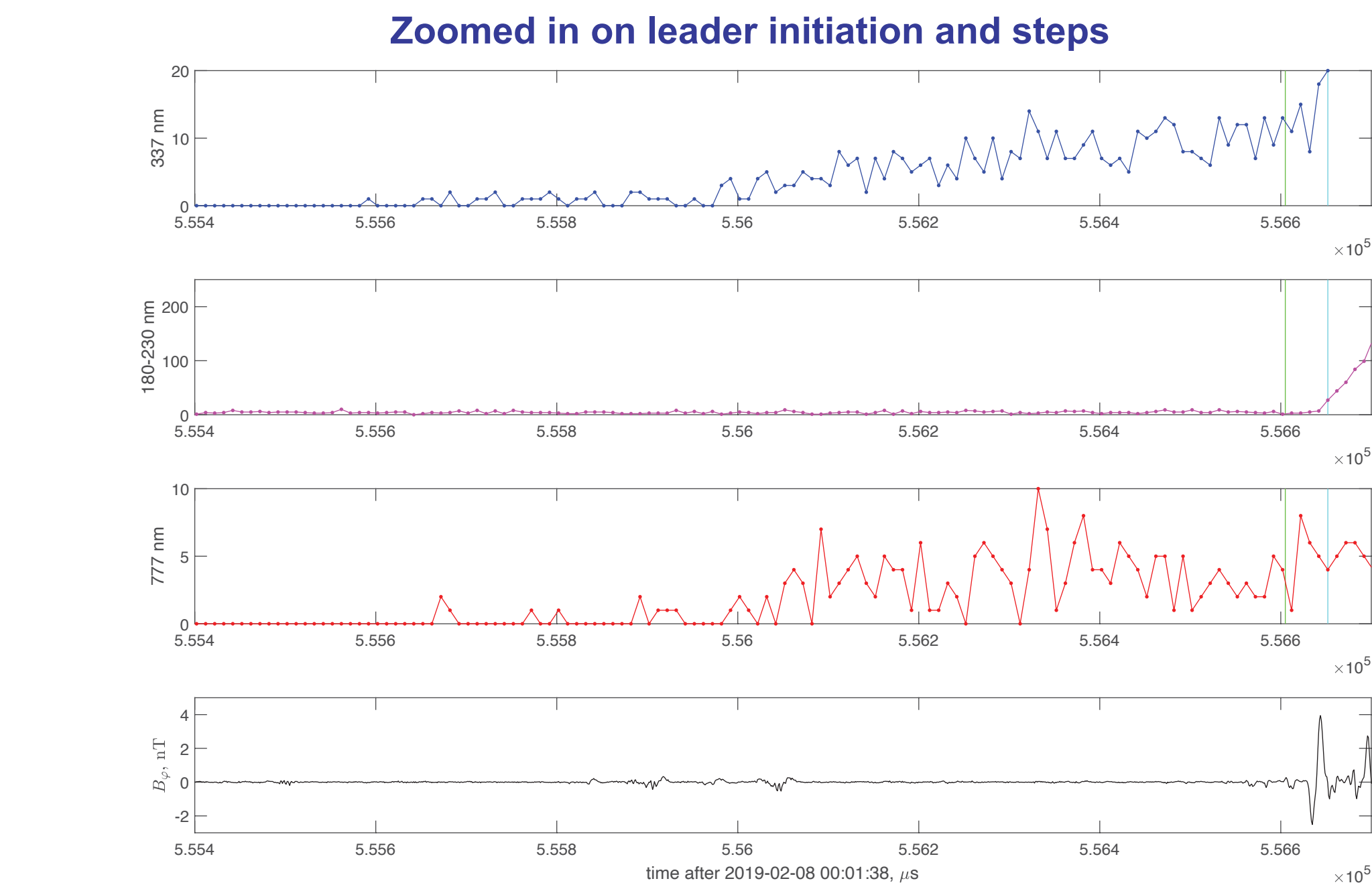
The sequence of events (see numbers under the Figure):

- Weak signals in 337 nm and 777 nm 1 ms before the TGF. Leader steps are seen in the radio (LF) - starting ~1 ms before the TGF. Interpretation: Leader initiation, development and stepping (see zoomed version below):
- Fast and large current pulse is seen in radio (LF) Elve is seen in the UV emission (20 μ s delayed to LF, due to geometry and lifetime of excited states of N₂ molecules that emits in the LHB. Rise time is ~100 μ s and duration ~1ms. TGF starts same time (+/- 80 μ s) Interpretation: Fast and large current pulse simultaneous with the onset of TGF and the EM wave that produced the Elve, which was observed 20 μ s later.
- Optical pulse in 777 nm starts ~90 μ s later than LF onset with rise time of ~200 μ s, lasts for 2 ms. Interpretation: The delay can be explained by scattering of 777 nm emission within the cloud (see modeling). The long duration can be explained by scattering from the cloud below the stroke (IC+)

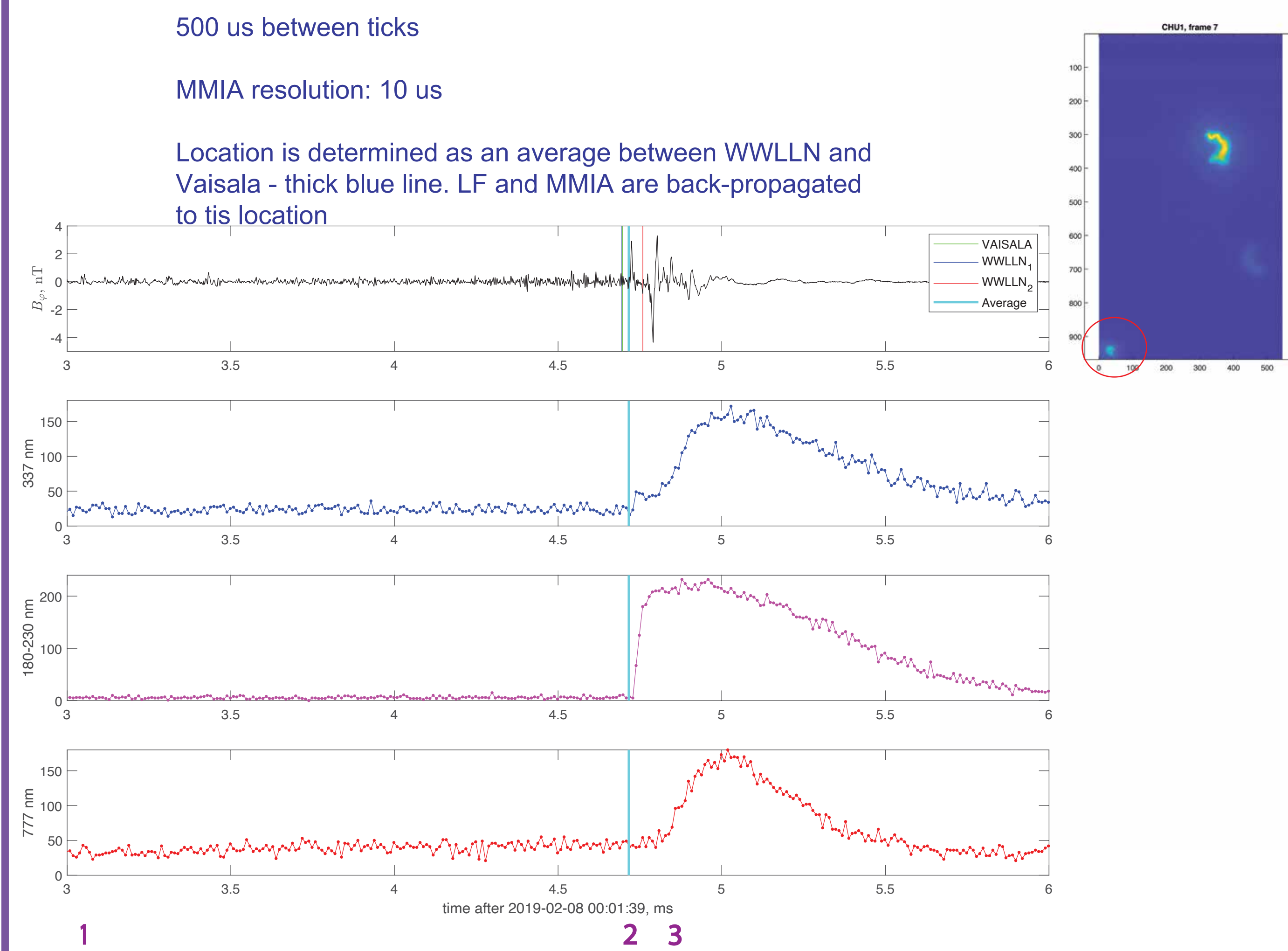
Signal in the 337 nm starts with a small jump simultaneous with the UV and then a slower pulse similar to the large pulse as in 777 nm.

Fast and large current pulse gives the electromagnetic pulse (dj/dt).

The radio indicates an IC+



Second Elve from CG-



The sequence of events:

- Continuous activity seen in radio (LF) 2 ms before the Elve Interpretation: Leader initiation and propagation
- Fast and large amplitude current is seen in radio Elve is seen in the UV emission (delayed 12 μ s to LF onset) with rise time: ~70 μ s and lasts for ~1ms.
- Optical pulse in 777 nm ~100 μ s delayed to LF. Rise time: ~190 μ s, and a duration of 800 μ s. Interpretation: The delay and duration of the 777 nm emission can be explained by scattering through the cloud, but without any scattering from cloud below (CG-lightning) - see modeling results

Signal in the 337 nm starts simultaneous with the UV and then similar to the large pulse as in 777 nm

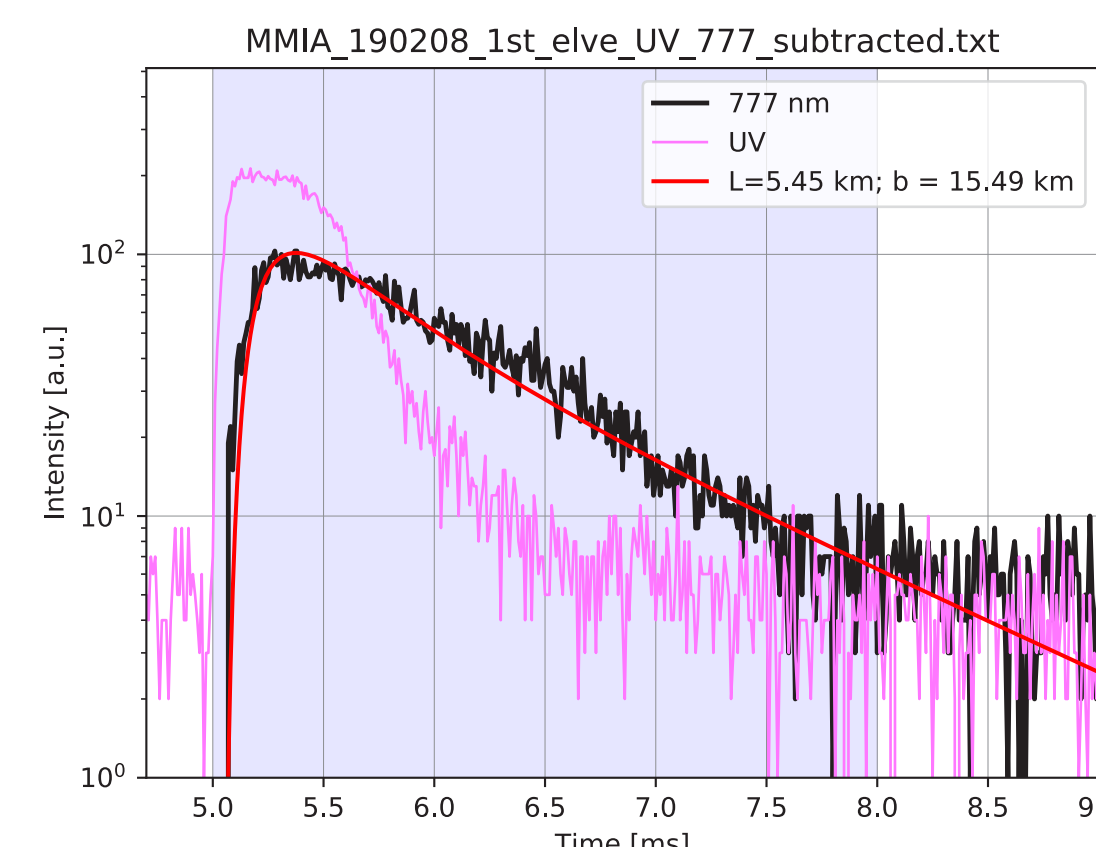
Fast and large current pulse gives the electromagnetic pulse (dj/dt).

The LF radio from Puerto Rico indicates a CG- Opposite polarity than the first one

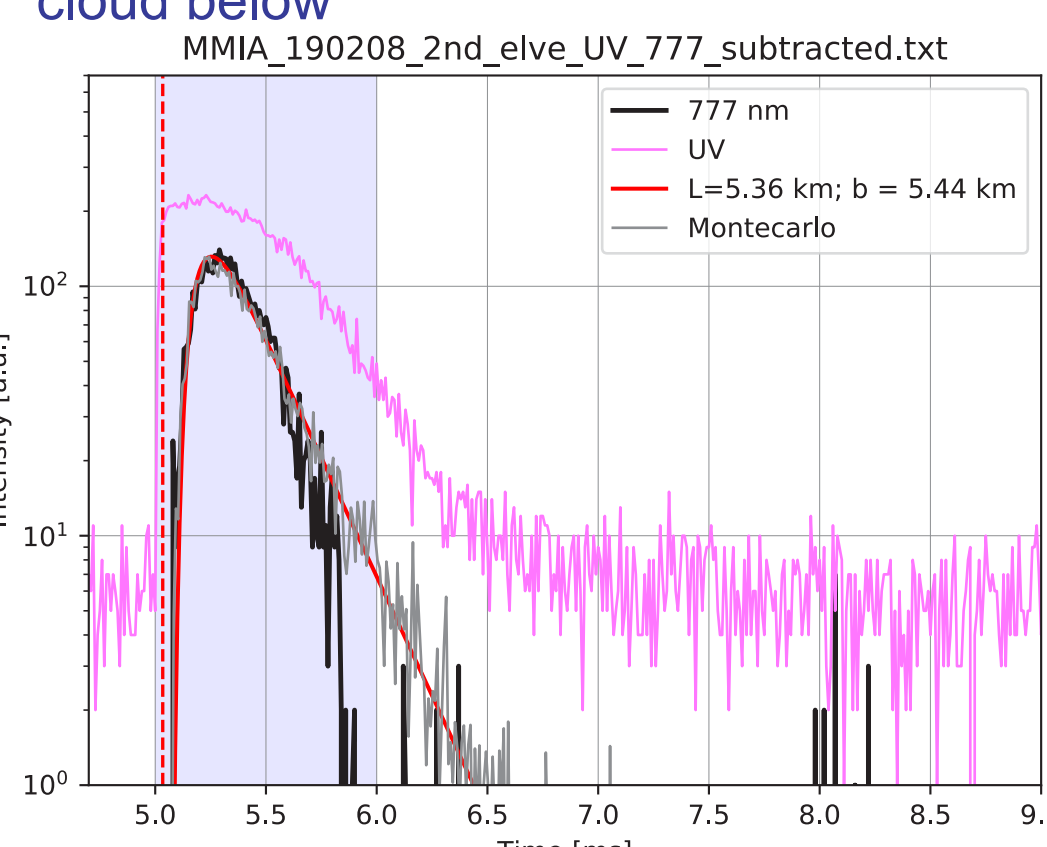
The scattering of 777 nm emissions within the cloud

Homogeneous cloud bounded by two parallel planes, droplets of 10 μ m, and density of 100/cm³
L: distance from cloud top to source
b: is the thickness of cloud

1st Elve: If cloud top at 15-16 km, the IC+ is at ~10 km, reasonable for IC+. Long duration is due to scattering from below



2nd Elve: If cloud top at 10 km, the CG- is at ~5 km, but more important: It is from the bottom of the cloud, consistent with CG-. Short duration is due to no scattering from cloud below



Acknowledgement

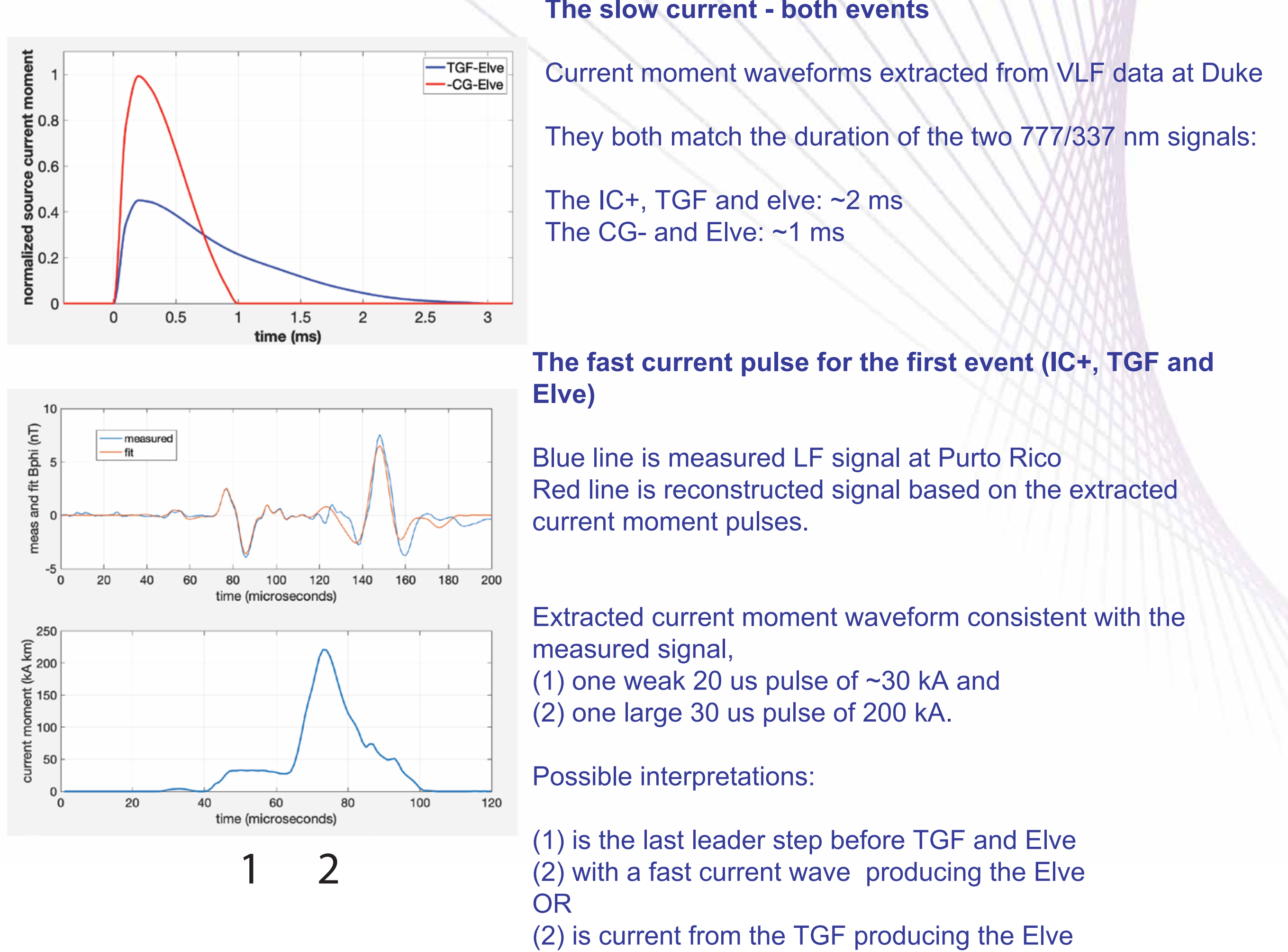
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We thank WWLLN and Vaisala for the use of their data.

Current moments

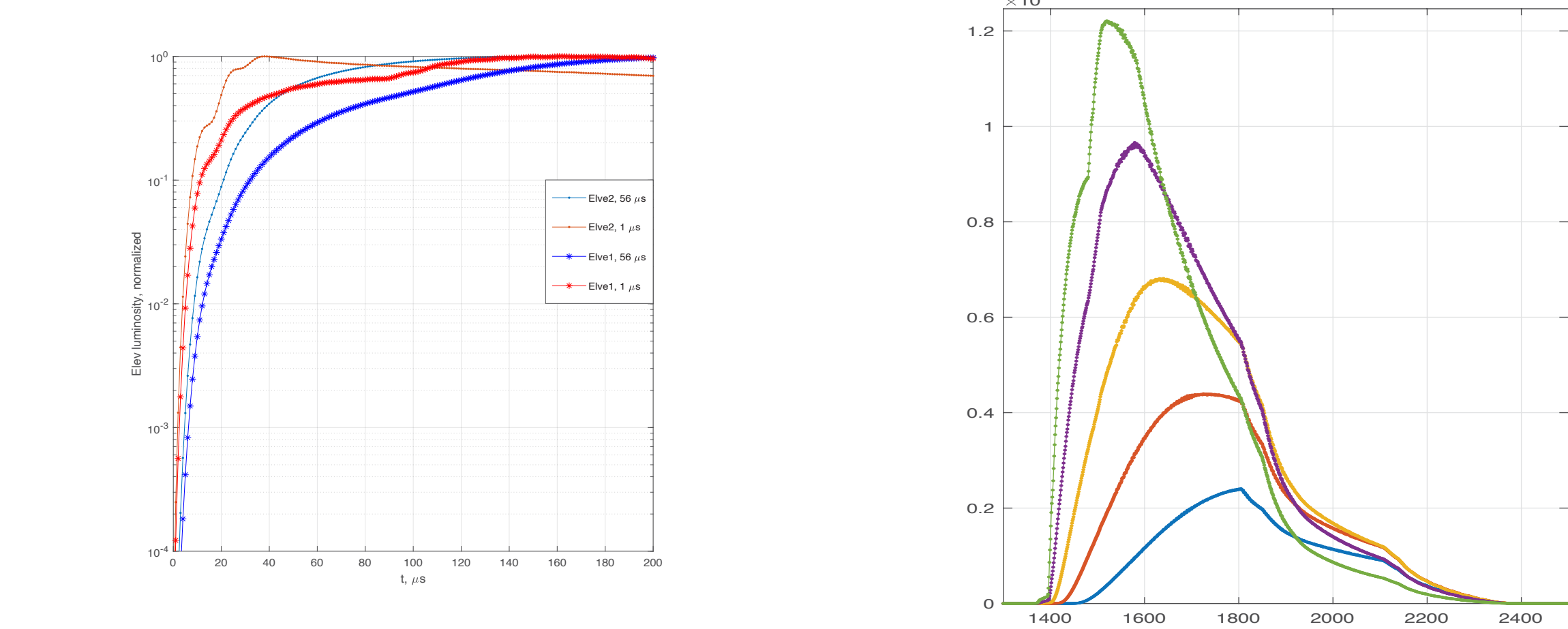


Modeling Elve signal in UV for the IC+

Input for modeling: The extracted 30 μ s current pulse from LF Puerto Rico data

The lifetime of excited states of N₂ molecules of 56 μ s which gives a delay relative to direct EM wave of 20 μ s and 12 μ s for 1st and 2nd Elve, respectively (1.5 order of magnitude down from peak)

The different colors are for different directional diagrams meaning different angles of the main lobe
Green curve has rise time (100 μ s) consistent with measured UV. All have compatible duration of ~1 ms



Summary

- Two Elves were observed ~456 ms and 300 km apart.
- IC+ produced an Elve and a TGF
- 456 ms later a CG- produced an Elve but no TGF was observed from space
- LF radio measurements of the IC+ show that the weak optical signals (337 nm and 777 nm) before the Elve/TGF are associated with upward negative leader steps.
- LF measurements for 2nd Elve show it is an CG-, preceded by continuous downward leader propagation
- The UV signal is delayed 20 μ s and 12 μ s to the onset of the LF pulse, due to geometry and lifetime of excited states of N₂ molecules.
- The optical emissions in 777 nm are delayed to the onset of the LF pulse by 90 μ s and 100 μ s, respectively. Both the delays and duration of 777 nm emissions can be explained by scattering within the cloud.
- Reconstructed current moments give:
a) one fast (30 μ s) and large (200 kA) pulse emitting an electromagnetic wave that produces an Elve.
b) one slow (1-2 ms) current pulse, that may contribute to the optical signal.
- Open questions:

For the IC+: Is the fast and large current a fast current wave from a leader step that produces both electromagnetic wave and a TGF, OR: is the current from the TGF itself?