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# High-Precision Leader Observations by LOFAR

Brian Hare, Olaf Scholten, Joeseph Dwyer, and the LOFAR Cosmic Ray Key Science Project
University of Groningen, KVI-CART, Netherlands (b.h.hare@rug.nl)

We will present detailed 3D maps of a cloud-to-ground and intra-cloud flash that has been imaged using a fully coherent 3D interferometric lightning imaging technique with data collected by the LOFAR (LOw Frequency ARray) radio telescope. Due to baselines of the order of 100 km, combined with broad-band interferometry in the 30 – 80 MHz band, we reach a resolution of the order of 1 m in the horizontal plane, 10 m in the vertical direction, and are able to locate about 25 sources per 50 $\mu$s. This unprecedented resolution allows us to study positive and negative leader propagation, the physics of the return stroke and lightning initiation, in detail.

The positive leaders both of these flashes show a new phenomenon, termed “needles”, that reveal the path of the positive leader through their cumulative formation. These needles extend outwards from the sides of the positive leader, behind the tip of the leader. VHF sources are observed to propagate in a positive charged fashion through the leaves over regions 30-100 m long with speeds from 3x10$^5$ up to 1.5x10$^6$ m/s. In addition, VHF sources are observed to repeatedly propagate through the same needle 4-10 times with a repetition rate around 5 ms. As is common in LMA data, LOFAR observes hardly any VHF sources from the tip of the positive leader.

Negative leaders observed by LOFAR do not contain any structures similar to needles and are seen to propagate in a sequential fashion, as expected from LMA. Negative leader tips contain dense VHF sources, enough that there must be many VHF sources per leader step. While the reconstructed VHF source locations on negative leader tips do sometimes show complex clusters, there is no obvious indication of stepping. As we will show, the absence of clear stepping in the VHF will give a clue as to the nature of the sources responsible for VHF emission.