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Needle-like structures discovered on positively charged lightning branches

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1 Needle-like structures discovered on positively
2 charged lightning branches: Supplementary
3 Information
4

5 **1 Method**

6 The lightning flashes used in this work were mapped using data from the LO-
7 FAR (LOw Frequency ARray) radio telescope. Due to its effective lightning
8 protection system, LOFAR is able to continue to operate during thunderstorm
9 activity[1]. The Dutch LOFAR stations consist of 38 (24 core + 14 remote)
10 stations spread over 3200 km² in the northern Netherlands. The largest base-
11 line between core stations is about 3 km, the largest baseline between remote
12 stations is about 100 km. From each station we use 6 dual-polarized low band
13 dipole antennas (LBA), sampled at 200 MHz, to observe the 30 – 80 MHz band.
14 The raw time series data were saved to the transient buffer boards, which contin-
15 uously buffer the last 5 s of data from a maximum of 48 dual-polarized antennas
16 per station. The resulting relative timing accuracy is better than 1 ns. See [2]
17 for more details on LOFAR. When a lightning flash occurs within the area en-
18 closed by the Dutch LOFAR stations, as observed by www.lightningmaps.org,
19 the transient buffer boards are stopped and the data is read to disk.

20 The method we used to map each lightning flash has three major steps. In
21 the first step we fitted plane-waves to the time of pulses received by individual
22 LOFAR stations. Note that the LOFAR stations are less than 100 m in diameter
23 and the lightning is many kilometers from the closest LOFAR station, so that a
24 plane-wave approximation is very good for individual LOFAR stations. These
25 plane-waves were used to identify non-functional antennas, and the intersec-
26 tion of their arrival directions gave a rough first estimate of the flash location,
27 accurate to a few kilometers. Since each station has its own clock and cable de-
28 lays, in the second step we found the clock offsets between the different LOFAR
29 stations by simultaneously fitting the locations of multiple events and station
30 clock offsets to the measured times of radio pulses, with a Levenberg-Marquardt
31 minimizer. In order to achieve the highest precision, we chose to fit locations of
32 5 events that created pulses that were strong but not saturating, had a simple
33 structure, and did not change shape significantly across different stations. Af-
34 ter fitting, the root-mean-square difference between the modeled and measured
35 arrival times of the radio pulses was around 1 ns. The resulting station clock
36 offsets are consistent with LOFAR station clock calibrations, which are known

37 for the core stations but not the remote stations.

38 After finding the station clock offsets, in the third step we mapped the
 39 lightning flash using a new interferometric imaging algorithm inspired by those
 40 used in astronomy. The goal of this algorithm is to find for each source the
 41 3D location, \vec{X} , that corresponds to the maximum value of the image intensity,
 42 $I(\vec{X})$, defined by

$$I(\vec{X}) = \frac{1}{N} \sum_{\substack{i,j \\ i \neq j}} \frac{|C_{i,j}(\Delta T_{i,j}(\vec{X}))|}{\max(|C_{i,j}|)}, \quad (\text{S1})$$

43 where $C_{i,j}(t)$ is the complex-valued cross-correlation between the signals recorded
 44 on antennas i and j , $\Delta T_{i,j}(\vec{X})$ is the time difference between a signal on an-
 45 tenna i and a signal on antenna j if those signals were both emitted by a point
 46 source at \vec{X} , and $\max(|C_{i,j}|)$ is the maximum value of the absolute value of
 47 the cross-correlation between antenna i and j . In different mapping stages the
 48 sum is performed differently as described in more detail below. N is the length
 49 of the sum. The cross correlation is built from the complex valued voltages
 50 as discussed later, it is also up-sampled by a factor of 8 and interpolated with
 51 a periodic cubic spline in order to achieve sub-sample timing accuracy. The
 52 cross-correlation is normalized so that if \vec{X} is exactly equal to the location of
 53 the source region, and the source region is a point source, then $\Delta T_{i,j}(\vec{X})$ will
 54 correspond to the maximum of the cross-correlation, and the value of the image
 55 intensity will be exactly 1. Therefore, if we find the correct source location,
 56 then the intensity of the image should be close to 1 with lower values indicat-
 57 ing poorer fits. Because of noise and the fact that our sources are not perfect
 58 point sources, we never expect the peak of the image intensity to actually be
 59 precisely 1. Note that if the signal in an antenna is dominated by noise, then
 60 the cross-correlation of that signal with any other signal will be fairly flat, and
 61 so will not affect the location of the peak of the image.

62 The two difficulties are finding the image intensity maximum without form-
 63 ing the entire image, and in choosing the correct signal length to use in the
 64 cross-correlation. Our algorithm was specifically designed to solve these prob-
 65 lems for imaging lightning. Before imaging, a 3D rectangular bounding box is
 66 defined around the lightning flash using the approximate location from the first
 67 step and assuming the lightning flash is 5 km wide and 6 km tall [3]. If, after
 68 imaging, the flash is less than 500 m from the edge of the bounding box, the
 69 box is expanded by 500 m and the flash re-imaged. The imaging is run on data
 70 blocks that are 2^{16} samples long (327 μs). The data block for each antenna has
 71 a timing offset so that a point source in the middle of our bounding box will
 72 produce a pulse in the middle of the data block for every antenna. Since the
 73 pulses near the edge of the data block cannot be imaged, as discussed further
 74 below, each block has a slight overlap so that every received pulse can be imaged
 75 without repetition.

76 Radio signals from the lightning will sometimes saturate the LOFAR digitiz-
 77 ers, therefore, first, saturated data are removed by setting the saturated areas
 78 and the following 50 samples to zero. We also include a half-Hann window

79 (length of 50 samples) around these windows that are set to zero. Furthermore,
80 since man-made artificial radio frequency interference (RFI) corrupts parts of
81 the measured spectrum, the data blocks are band-pass filtered between 30 –
82 80 MHz and RFI lines are removed according the method described in [4]. This
83 filtering also removes the negative frequency components so that the resulting
84 signal is complex valued and analytic. After filtering the raw data, the lightning
85 is imaged in two stages. The goal of the first stage is to find an approximate
86 location for the source inside our bounding box. However, since this stage is
87 designed to search the entire bounding box it is not as precise as possible. There-
88 fore, we follow with a second stage that assumes that the result of the first stage
89 is close to the real source location and attempts to refine the location.

90 For each block of data we image each pulse in order of strength, with stronger
91 pulses imaged first. Once we know the time of the pulse that we want to image
92 on a central antenna, t_p , we calculate a window, $L_i + t_p$ and $H_i + t_p$, for every
93 other antenna, i , such that we know that the corresponding pulse will arrive
94 between times $L_i + t_p$ and $H_i + t_p$ on antenna i , under the assumption that the
95 source location is within the boundary box. This central antenna is referred
96 to as the reference antenna, and is chosen so that the difference between the
97 minimum L_i and maximum H_i is as small as possible. This leads us to the
98 algorithm of the first stage:

99 1) Form a window centered on the largest source on the reference antenna.
100 This window is 50 data points long (250 ns) in order to accommodate the typ-
101 ical width of the radio pulse. Note that we ignore pulses that are within the
102 maximum L_i of the beginning of the block and within the maximum H_i of the
103 end of the block in order to avoid imaging sources that may not be seen on all
104 antennas within this data block.

105 2) On every other antenna i form a window between times $L_i + t_p$ and $H_i + t_p$.

106 3) Calculate the cross-correlations, $C_{i,p}(t)$, between the windowed data on
107 the reference antenna and the windowed data on every other antenna. Since the
108 windows are different lengths on every antenna, every window is zero-padded to
109 a length that is the next power of two larger than the largest $H_i - L_i$.

110 4) Find the location \vec{X} that maximizes equation S1, where j is the reference
111 antenna, and the sum over i is over all other antennas. This maximization
112 is done with the Nelder-Mead algorithm [5] with the starting point chosen to
113 be a random point within the bounding box. This procedure is repeated until
114 the same maximum (within 1 m) is found 100 times, with a maximum of 1500
115 iterations.

116 The location of the maximum of the image intensity in stage 1 is now \vec{X}_{guess} ,
117 an approximate location for stage 2. It is assumed that this location is very close
118 to the actual source location, and stage 2 is used to refine the source location.
119 The steps in stage 2 are:

120 1) For every antenna create a window centered at t_i , where t_i is the time
121 that this antenna would receive the radio pulse if that pulse was emitted from
122 the approximate location, \vec{X}_{guess} from the previous stage, and received at the
123 reference antenna at time t_p . The windows are chosen to be 50 samples long for
124 all antennas.

125 2) Calculate the cross-correlations, $C_{i,j}(t)$, between the windowed data on
126 every pair of antennas.

127 3) Find the maximum of equation S1, where the sum is now over every pair
128 of antennas, excluding the antennas in the LOFAR core (except station CS002,
129 so that we still have one station in the area of the core). The LOFAR core
130 is excluded because it is small (about 3 km diameter) and so only provides
131 information on large scales. This large scale information is important in stage
132 1, but is not only not useful in stage 2 but also significantly increases the time
133 needed in stage 2. The maximization in this step is similar to that in stage 1,
134 except the Nelder-Mead guesses are all within a box of 100 m width centered on
135 \vec{X}_{guess} , only 5 iterations are required for convergence, and there are a maximum
136 of 50 iterations.

137 4) If the new maximum is more than 1 m away from \vec{X}_{guess} , then our new
138 location becomes \vec{X}_{guess} and we repeat from step 1 of stage 2. Most sources
139 converge within 2 or 3 iterations, however if we have already had 8 repetitions
140 of stage 2, then we quit looping with the status that stage 2 has not converged.

141 If stage 2 converges, we then “remove” this source from the data. This is
142 done on every antenna by first calculating t_i , which is the time that radio pulse
143 would arrive if the location from stage 2 is correct and the reference antenna
144 received a pulse from the source at time t_p . Then a window of data centered
145 on t_p is set to zero. As in stage 2, this window is 50 samples long. This is done
146 so that the stronger sources do not interfere with the imaging of the weaker
147 sources.

148 There are three primary differences between stage 1 and stage 2. First, stage
149 1 has much longer signal lengths than stage 2. This is because stage 2 assumes
150 that the source location is roughly known and stage 1 only assumes that the
151 source is inside the bounding box. Secondly, the sum (in equation S1) in stage
152 2 is over all pairs of antennas, while the sum in stage 1 is only over pairs of
153 antennas where one antenna is the reference antenna. This is done because
154 almost all antennas in stage 1, except the reference antenna, have windows that
155 are very large. If the cross-correlation were formed between these large windows
156 it would be dominated by pulses that do not come from the source we wish to
157 image. This is different from the reference antenna, which has a very small
158 window that only includes the pulse we want to image, and stage 2 which has
159 small windows on all antennas. Finally, as explained above, stage 2 excludes all
160 antennas from the LOFAR core (except station CS002) and stage 1 includes all
161 antennas.

162 We repeat stage 1 and stage 2 on the next strongest source in the data block
163 until 100 sources have been found or the amplitude of the pulse on the reference
164 antenna is the same as our noise level. We stop at 100 sources to minimize the
165 possibility of imaging a weaker source whose reconstructed location is artificially
166 influenced by a stronger source. Most of the time there are more than 100 radio
167 sources in a block of data. This algorithm relies heavily on finding the correct
168 global maximum in stage 1, and this maximum is easily missed. We perform
169 three cuts in order to separate the miss-located sources from well-located ones.

170 We require that stage 2 converges, that the result of stage 2 is within 50 m of
171 the result of stage 1, and that the image intensity in stage two at the location
172 of the source is greater than 0.85. The requirement that the distance between
173 the stage 1 and stage 2 results are within 50 m is to help guarantee that the
174 assumption in stage 2 is met. Out of 17,290 sources from the 2017 flash with an
175 image intensity larger than 0.85, only 473 have a stage 1-stage 2 distance larger
176 than 50 m. The intensity cut at 0.85 was chosen to best balance image quality
177 and number of sources; a histogram of intensity of the radio sources for the
178 2017 flash is shown in Fig. S36. As this cut is increased or decreased, the image
179 quality smoothly improves or worsens; no image features completely appear or
180 disappear at different cut levels. About 30% of the pulses we attempted to image
181 pass all three cuts. The time of the source is easily found from the location, \bar{X} ,
182 and the time the pulse was received on the reference antenna, t_p .

183 1.1 Artifact Checks

184 We have performed a number of tests of our imaging technique in an attempt
185 to search for potential artifacts. First, we checked if the needles could be due to
186 some dependence between the reconstructed locations of different sources. I.E.
187 it is possible that finding the location of one source (perhaps the wrong location)
188 could affect the imaged location of a different source. We have found that this
189 is unlikely to be the case because different twinkles of the needles are always
190 on different $327 \mu\text{s}$ long (2^{16} samples) blocks of data, and each data block is
191 processed independently. This implies that the spatial and temporal structure
192 between needle twinkles cannot be due to any imaging dependence between the
193 needle twinkles. Furthermore, there are many individual needle twinkles which
194 are spread across two blocks of data, strongly implying that the structure of
195 individual needle twinkles cannot be due to imaged source location affecting each
196 other. Finally, we have also imaged the 2017 flash without removing the pulses
197 of imaged sources, and found that while our source location efficiency decreases
198 to 20%, the properties of the needles, and the lightning flash in general, remains
199 the same.

200 As discussed above, we remove pulses from the data that saturate the LO-
201 FAR antennas. We have checked if this process introduces artifacts by imaging
202 the 2017 flash without removing saturated pulses. The resulting image contains
203 all the same features as our image from the standard approach.

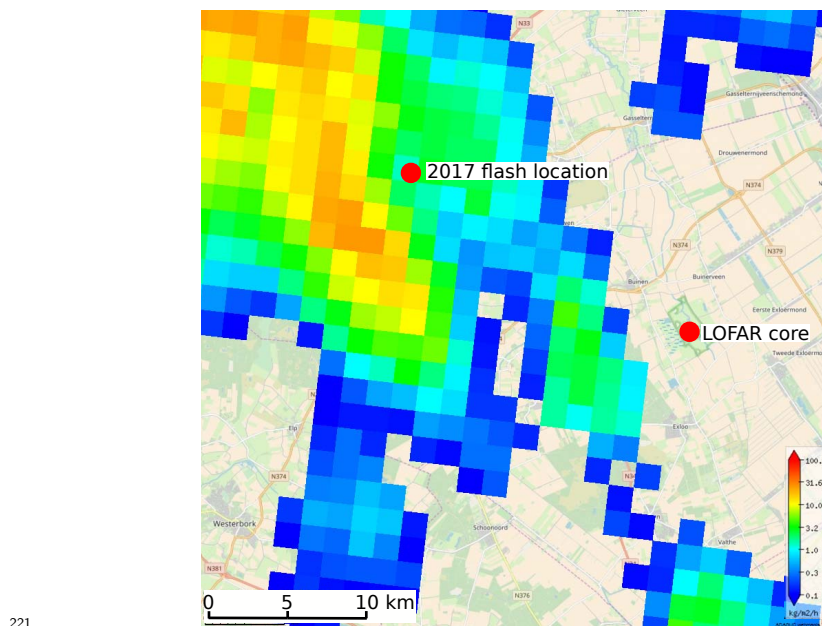
204 In our imaging algorithm we pick a reference antenna in order to determine
205 which pulse to image. We have checked that the final image does not depend
206 upon the choice of reference antenna by re-imaging the 2017 flash using a differ-
207 ent reference antenna that is 20 km from the typically reference antenna. The
208 resulting image is indistinguishable from the normal image.

209 Finally, it is conceivable that if the overlap between blocks is not handled
210 correctly, then pulses could be double counted, leading to artifacts. In order
211 to check this, we have created a histogram of times, modulus block size, of
212 imaged sources that belong to needles. This histogram is flat, within statistical
213 deviation, indicating that imaged sources on needles do not come from any

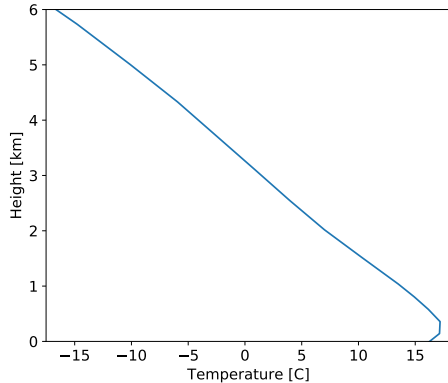
214 preferred time in a block.

215 2 Additional data on 2017 flash

216 Fig. S1 shows the radar reflectivity around the 2017 lightning flash, provided
217 by KNMI. The radar shows that the 2017 flash occurred just to the east of the
218 main core of a storm. figref2017-temp shows the altitude versus temperature for
219 the time and location of the 2017, extracted from the Global Data Assimilation
220 System (see <https://ready.arl.noaa.gov/gdas1.php>).



222 Figure S1: Radar reflectivity during the time of the 2017 flash, provided by
KNMI (available from <http://geoservices.knmi.nl/viewer2.0/>).



223

224 Figure S2: Altitude versus temperature profile during the 2017 lightning flash,
 225 derived from the Global Data Assimilation System.

226 Three animations are also included in the supplementary information.

227 `Lightning_complete_rotating.mov` is an animation of the whole 2017 flash.

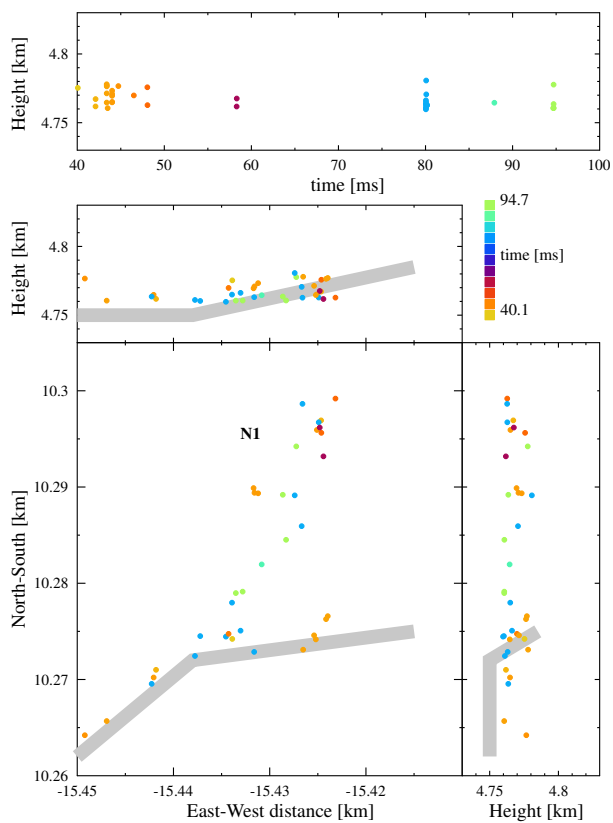
228 `Lightning_detail_needle.mov` details a section of positive leader, with
 229 sources from N4 shown in red.

230 `Lightning_detail_negative_leader.mov` details a section of negative leader,
 in order to illustrate the difference between negative and positive leaders.

231 3 2017 Additional Imaged Needles

232 Below are a number of figures detailing more needles along the length of the
 233 positive channel shown in Fig. 2 left. We have chosen this particular section of
 234 the positive leader at random, other sections show similar features. Each figure
 235 shows a grey line that illustrates the approximate location of the positive leader
 236 channel, the same location as shown in Fig. 2 left. The location of the positive
 237 leader channel is found by drawing lines by eye through the source locations
 238 shown in Fig. 2 left, keeping in mind that the needles tend to extend out from
 239 the positive leader channel.

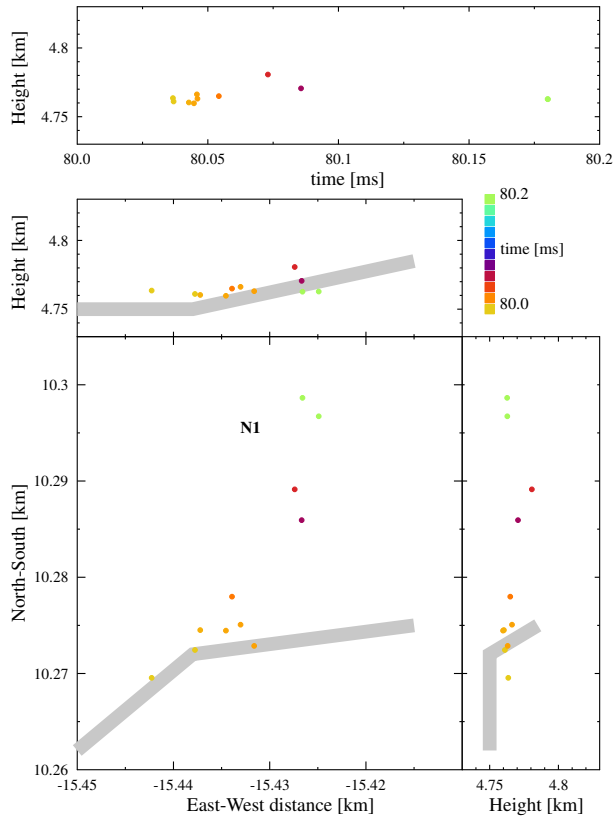
240 Fig. S3 shows a zoom-in on a region around N1 in Fig. 2 left. The “N1” label
 241 shows the location of the needle that is about 45 degrees off the positive leader
 242 channel. The sources along the positive channel could be due to the needle N1,
 243 smaller needles that we could not image, or some other phenomenon that we
 244 could not image. This needle clearly twinkles at least four times: at $t=44$ ms,
 245 58 ms, 80 ms, and 95 ms. The two sources at $T=48$ ms and the one source
 246 at $T=88$ ms could also be twinkles, but it is difficult to be certain. With so
 247 few sources in each twinkle, it is entirely reasonable that some twinkles were
 248 not imaged. Fig. S4 details one twinkle at 80 ms of N1. This twinkle has few
 249 located points, but it is clear that the VHF sources farther from the positive
 250 channel occurred later.



251

Figure S3: Region around N1 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel. The label “N1” indicates the needle N1.

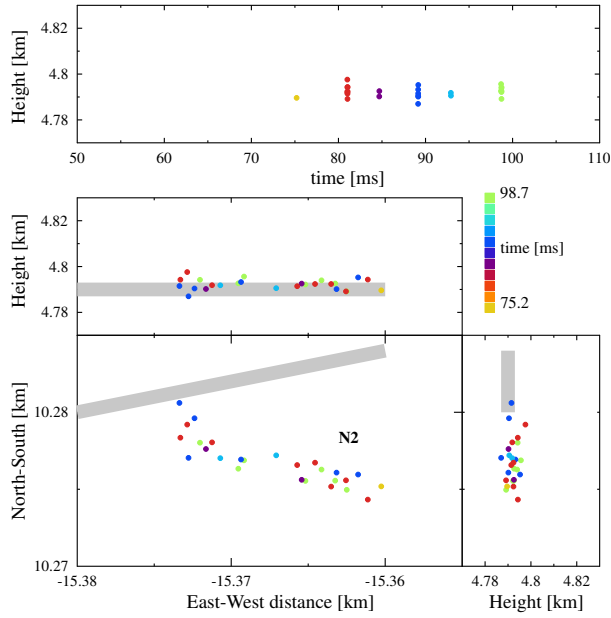
252



253

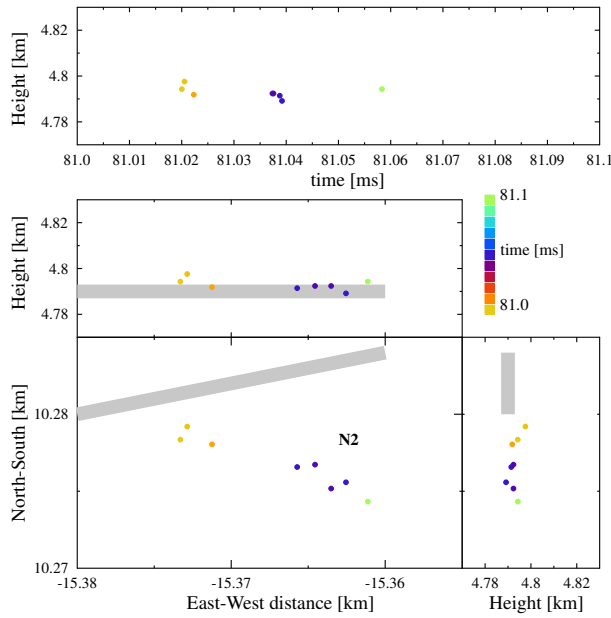
254 Figure S4: Region around one twinkle at $T=80$ ms of needle N1.

255 Fig. S5 shows a zoom-in on a region around N2 in Fig. 2 left. There do not
 256 appear to be any sources along the leader channel in this region, all the sources
 257 seem to come from needle N2. This needle has at least 5 twinkles at $T=81$ ms,
 258 85 ms, 89 ms, 83 ms, and 98 ms. Each of which are about 3–5 ms apart. There
 259 is one source at $T=76$ ms that could be another needle twinkle, but it is difficult
 260 to tell with only one located source. Fig. S6 shows one twinkle of N2, at $T=81$
 261 ms.



262

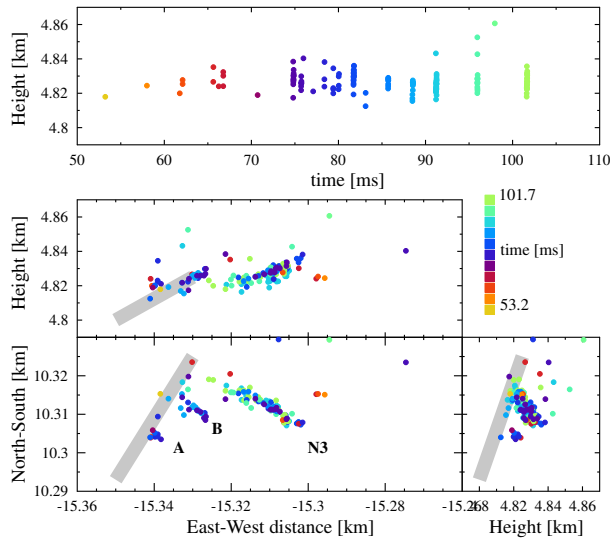
Figure S5: Region around N2 of the 2017 flash (see Fig. 2 left). The grey line
 263 shows the approximate location of the positive leader channel.



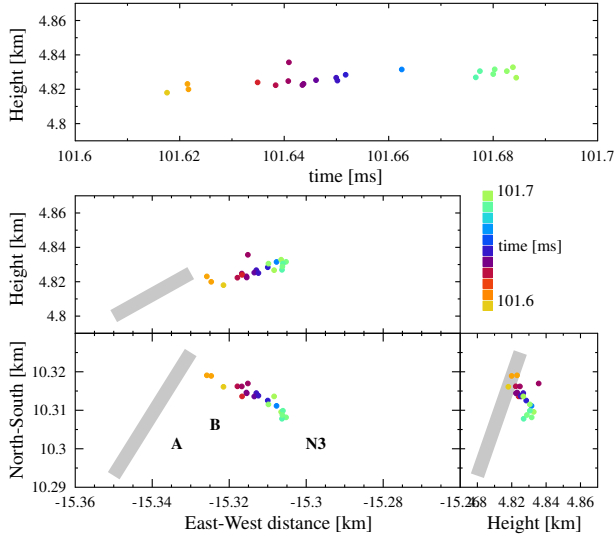
264

Figure S6: One twinkle, at $T=81$ ms, of needle N2.
 265

266 Fig. S7 shows a zoom-in on a region around N3 in Fig. 2 left. This region has
 267 three separate needles in close proximity, labeled “A”, “B”, and “N3”, where
 268 needle N3 is the one most clearly seen in Fig. 2. Height vs Altitude shows a
 269 number of twinkles from these three needles, and it is difficult to distinguish
 270 which twinkle goes with which needle from this figure. It is clear that the last
 271 two twinkles at $T=96$ ms and 103 ms both come from needle N3. These two
 272 twinkles are about 7 ms apart. Fig. S8 shows one relatively well imaged twinkle
 273 of needle N3. While there is some scatter, in general the later VHF sources tend
 274 to occur farther from the positive leader channel.



275 Figure S7: Region around N3 of the 2017 flash (see Fig. 2 left). The grey line
 276 shows the approximate location of the positive leader channel. The three labels,
 “A”, “B”, and “N3” distinguish between three separate needles.



277

278

Figure S8: One twinkle, at $T=101$ ms, of needle N3.

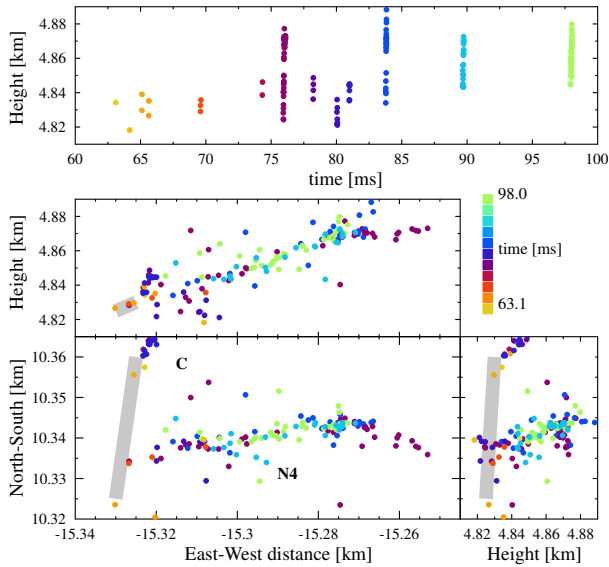
279

280

281

282

Fig. S9 shows a zoom-in on a region around N4 in Fig. 2 left, the same region as shown in Fig. 3. As discussed in the main body this needle has 5 well-imaged twinkles. Fig. S9 also shows a few sources from a separate structure, labeled “C”, which could be another needle.



283

Figure S9: Region around N4 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel.

Fig. S10 shows a zoom-in on a region around N5 in Fig. 2 left. This region has three separate groups, labeled “D”, “E”, and “N5”. Despite being imaged with very few sources, Groups E and N5 are clearly needles, as they clearly have multiple twinkles, with each twinkle having multiple sources. Group D only has three sources from different times. It is possible that Group D is a small needle with at least three twinkles, but there are too few sources to be certain.

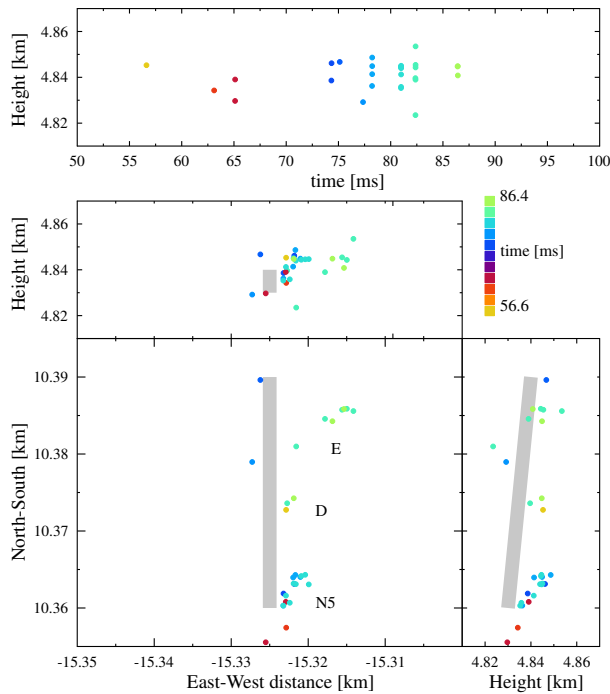
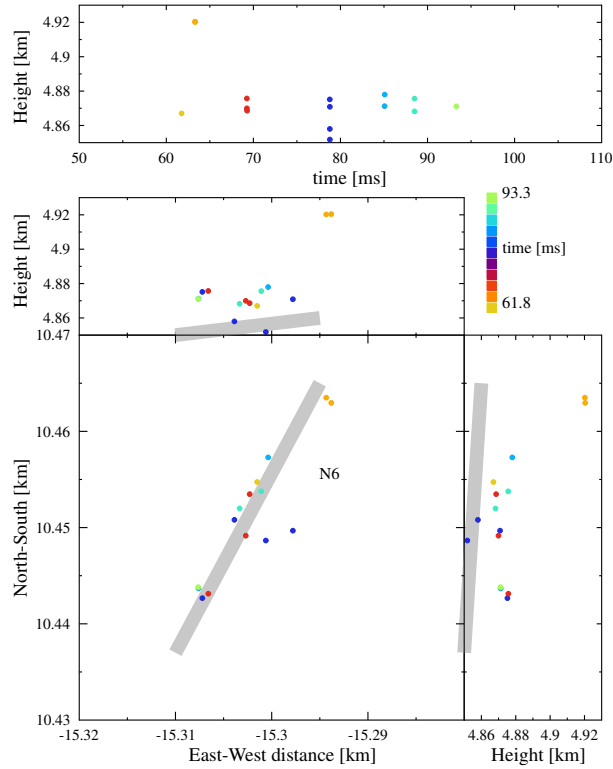


Figure S10: Region around N5 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel. The three labels, “D”, “E”, and “N3” distinguish between three separate groups of sources. Groups E and N5 are clearly needles.

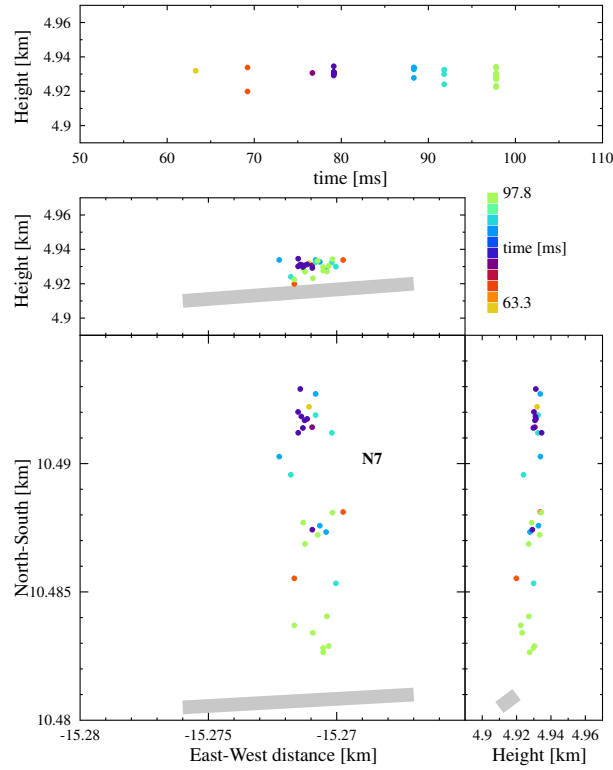
Fig. S11 shows a zoom-in on a region around N6 in Fig. 2 left. This needle has at least four activations at $T=69$ ms, 78 ms, 85 ms, and 88 ms. There are single sources at $T=63$ ms and 94 ms that could also be twinkles. There are also two sources at 4.92 km altitude, $T=65$ ms, that seem to be from a higher altitude than the rest of the needle. It is not clear how these two sources are related to needle N6. This needle only has a few sources in each twinkle, as so is not a well-imaged needle. It appears to be parallel to the positive leader channel; however, the fact that this needle is poorly imaged and that the path

301 of the positive leader is difficult to discern makes it difficult to tell if N6 is truly
 302 parallel to the positive leader channel or not.



303
 304 Figure S11: Region around N6 of the 2017 flash (see Fig. 2 left). The grey line
 shows the approximate location of the positive leader channel.

305 Fig. S12 shows a zoom-in on a region around N7 in Fig. 2 left. This needle
 306 has at least 5 activations at $T = 68$ ms, 80 ms, 88 ms, 92 ms, and 98 ms.
 307 There are also two sources at $T=63$ ms and 77 ms that could be poorly imaged
 308 twinkles. The shortest time between imaged activations is about 4 ms and the
 309 longest is about 10 ms. However, given that there are multiple twinkles with
 310 few, or perhaps only one, sources, it is entirely possible that some twinkles were
 311 not imaged at all.



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Figure S12: Region around N7 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel.

313 Fig. S13 shows a zoom-in on a region around N8 in Fig. 2 left. This needle
 314 has at least 6 activations at $T=70$ ms, 76 ms, 85 ms, 87 ms, and 90 ms, as well
 315 as a single source at $T=81$ ms. It is interesting to note that the activation at
 316 $T=87$ ms, altitude of 4.94 km, is only about 2 ms after the previous activation.
 317 Furthermore, this twinkle has three sources that appear on the opposite side
 318 of the leader channel (between $Y=10.475$ km and 10.48 km). It is not clear
 319 why this is the case, especially given that the location of the leader channel in
 320 Fig. S13 is highly approximate.

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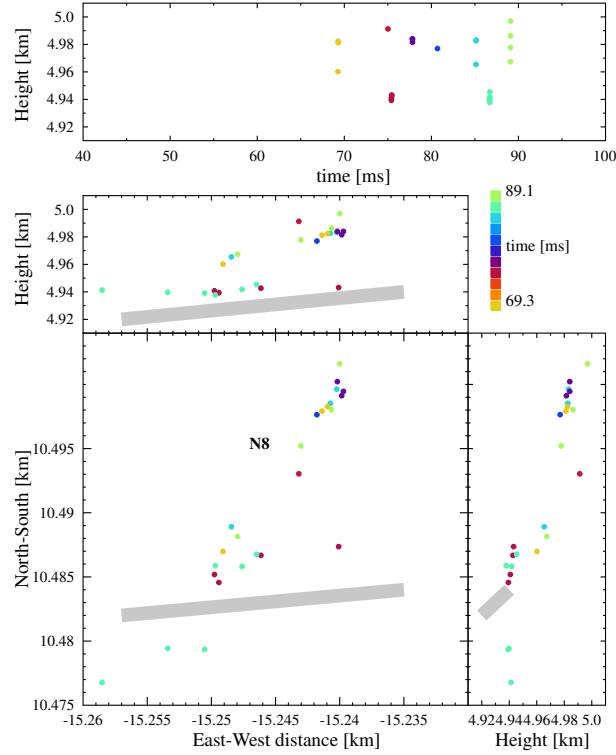


Figure S13: Region around N8 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel.

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Fig. S14 shows a zoom-in on a region around N9 in Fig. 2 left. This region has two needles labeled “F” and “N9”. Needle N9 has four clear twinkles at $T=77$ ms, 83 ms, 87 ms, and 93 ms. There is about 4–6 ms between each twinkle. Needle E clearly twinkles twice at $T=78$ ms and 85 ms. These two needles can be clearly distinguished, as the 6 clear twinkles shown in Height vs Time fall into two groups. The first group, containing the twinkles from N9, are above an altitude of 5 km. The other group, the activations corresponding to Needle F, clearly come from a lower altitude with a slight time offset relative to needle N9. Furthermore, needle N9 and needle F come from two distinct separate regions in the plan projection. The minimal distance between needle N9 and needle F is about 5 m. The fact that we can distinguish two needles that have a minimal distance around 5 m is one piece of evidence that our location error is better than 5 m. Fig. S14 shows one twinkle of needle N9, at $T=87$ ms.

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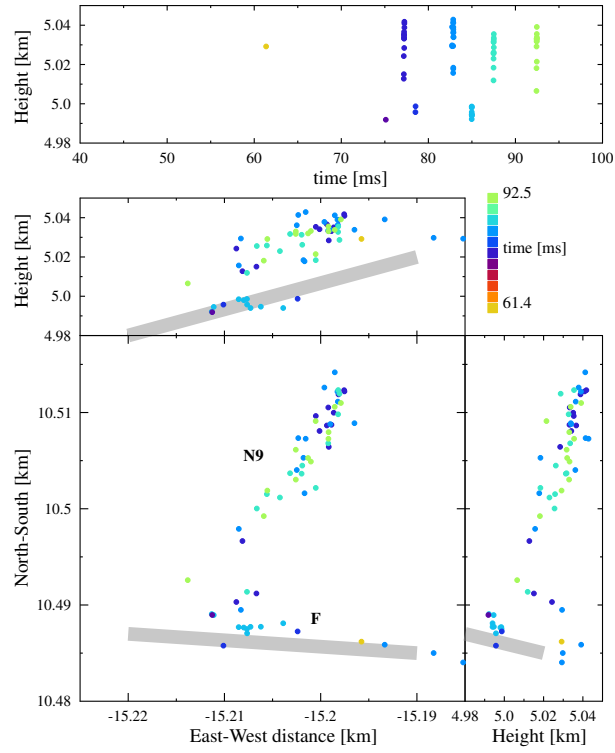
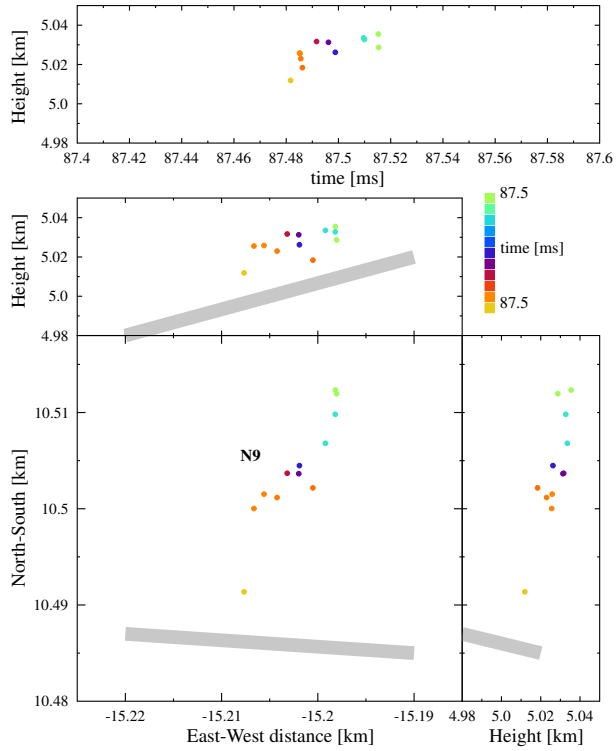


Figure S14: Region around N9 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel. Labels “F” and “N9” distinguish between the two needles.



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Figure S15: One twinkle of needle N9, at $T=87$ ms.

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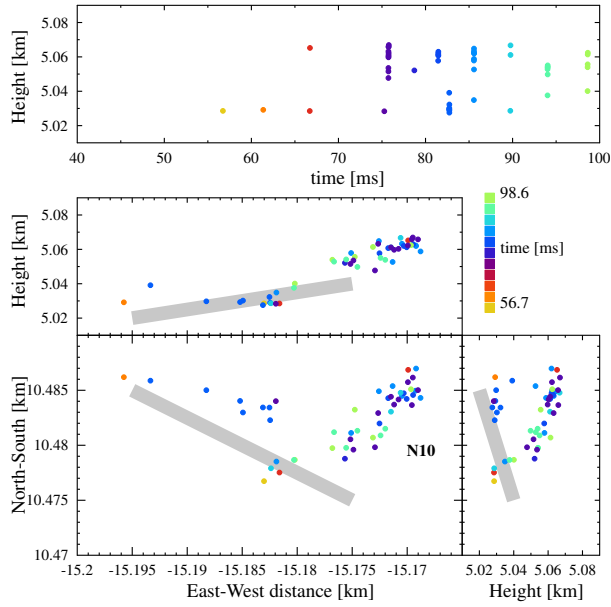
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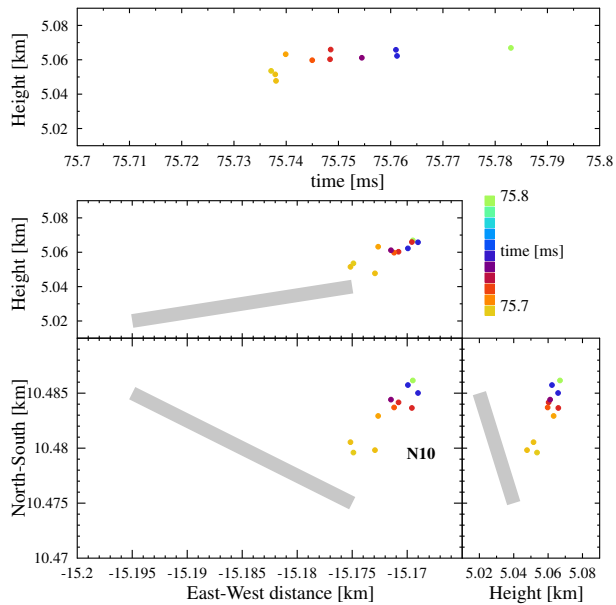
Fig. S16 shows a zoom-in on a region around N10 in Fig. 2 left. Apart from needle N10, this region also contains multiple sources along the positive leader channel. These sources are grouped together in time at $T=83$ ms, similar to a needle twinkle. These sources could be due to a small needle that is poorly imaged and close to parallel with the positive leader channel. Needle N10 has 6 clear activations at $T=76$ ms, 81 ms, 85 ms, 90 ms, 94 ms, and 99 ms. Needle N10 appears to have sources on both sides of the positive leader channel. However, the sources south of the channel are most likely a smaller, poorly imaged needle. Fig. S17 details the twinkle at $T=75$ ms.



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Figure S16: Region around N10 of the 2017 flash (see Fig. 2 left). The grey line shows the approximate location of the positive leader channel. The “N10” shows the sources related to needle N10.

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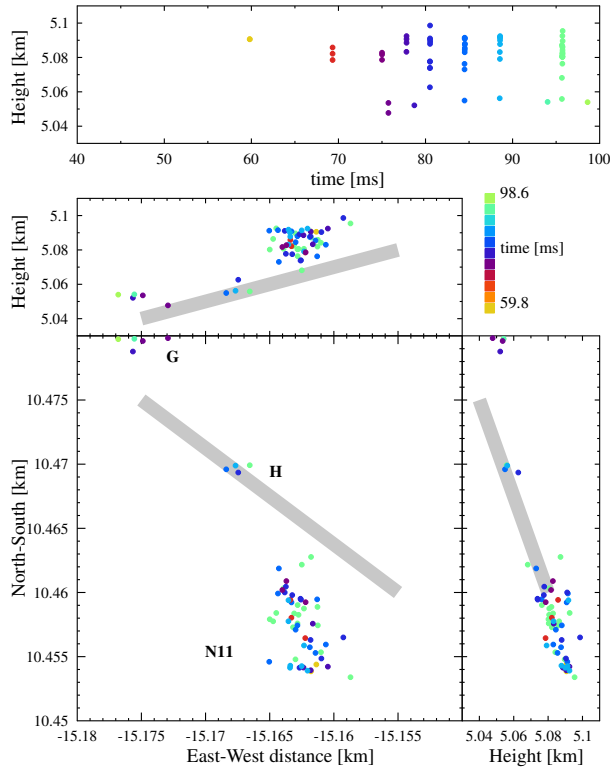


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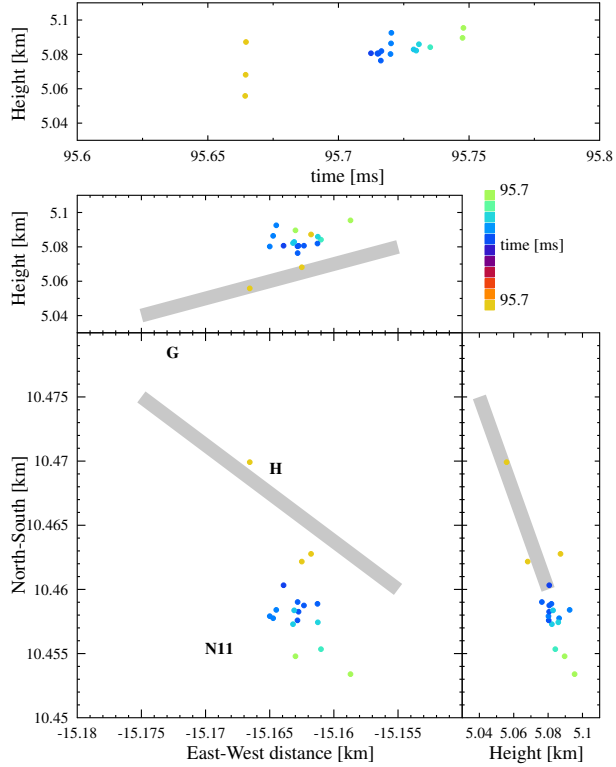
Figure S17: One twinkle of needle N10, at $T=75$ ms.

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351 Fig. S18 shows a zoom-in on a region around N11 in Fig. 2 left. This needle
 352 is very short in length but still contains a larger number of sources. N11 has
 353 7 clear twinkles at $T=70$ ms, 75 ms, 77 ms, 81 ms, 85 ms, 88 ms, and 96 ms.
 354 There are also two smaller groups of sources, labeled “G” and “H” separate
 355 from needle N11. These smaller groups could be smaller poorly imaged needles,
 356 but they do not have enough sources to say for certain. Fig. S19 shows a twinkle
 357 of N11 at $T=95$ ms.



358 Figure S18: Region around N11 of the 2017 flash (see Fig. 2 left). The grey line
 shows the approximate location of the positive leader channel. The labels “G”,
 “H”, and “N11” distinguish between the three groups of sources, where N11 is
 359 clearly a needle.



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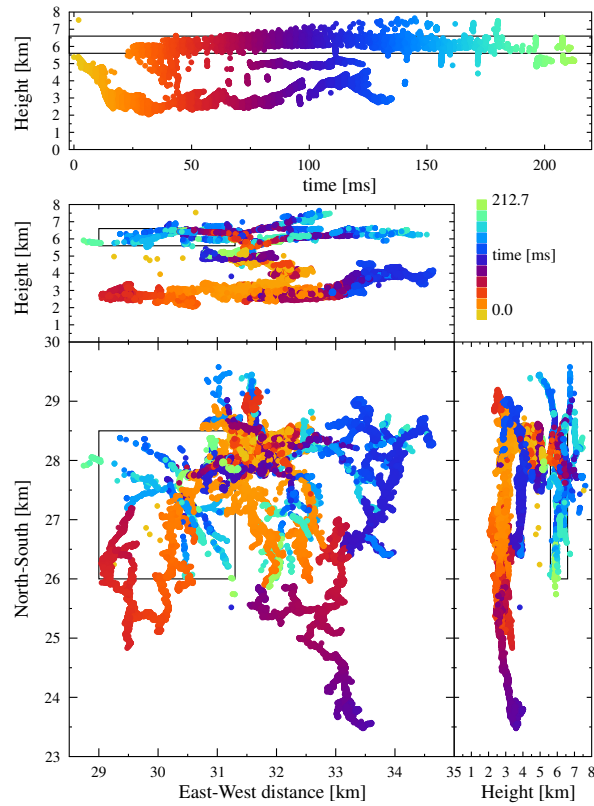
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Figure S19: One twinkle of N11 at T=95 ms.

362 4 2016 Additional Imaged Needles

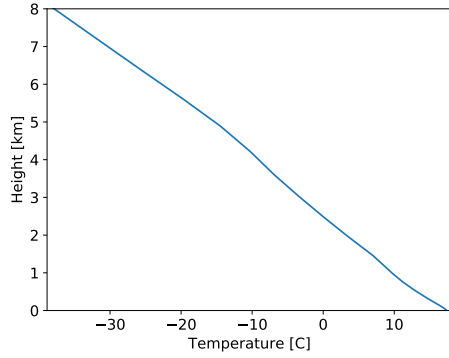
363 Fig. S20 shows an overview of the flash from 12, July, 2016. This was an
 364 inverted intra-cloud flash, 40 km from the core of LOFAR and outside the area
 365 enclosed by LOFAR, and so was not imaged with as high of a quality as the
 366 2017 flash. The negative leader started around 5.5 km altitude, propagated
 367 down to 2.5 km altitude by $t=25$ ms, and then propagated horizontally into
 368 a positive charge region. The positive leader was not seen until 25 ms after
 369 the start of the negative leader, and its first located sources were about 300
 370 m above the start of the negative leader. The positive leader then propagated
 371 into a negative charge region at 6 km altitude. Later, at $t=75$ ms, a branch
 372 of the negative leader propagated into a small positive charge region at about
 373 4.5 km altitude. Fig. S21 shows the altitude versus temperature for the time
 374 and location of the 2016, extracted from the Global Data Assimilation System
 375 (see <https://ready.arl.noaa.gov/gdas1.php>). Fig. S22 shows a section of positive
 376 leader. Most of the sources are scattered along the leader channel, not at the

377 tip of the leader, and so are consistent with needles, however the leader is too
378 poorly imaged for many of the needles to be visible.



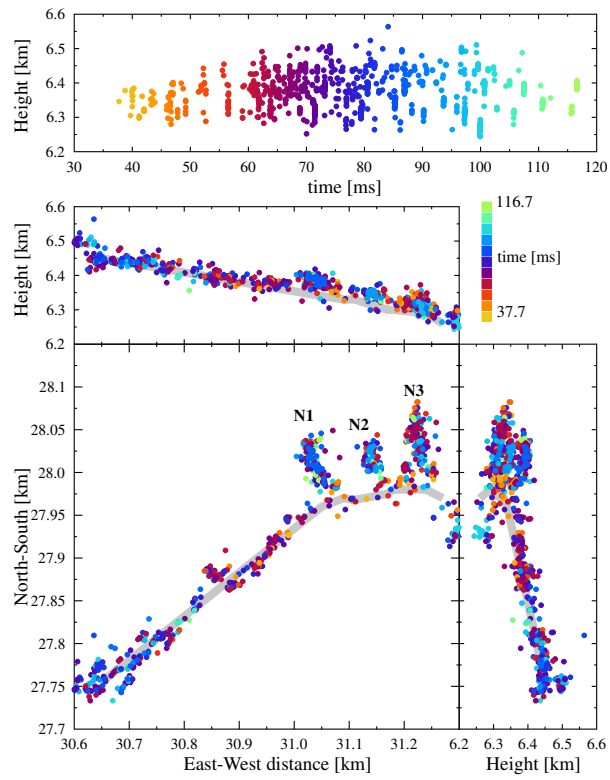
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Figure S20: Image of a lightning flash that occurred on 12, July, 2016. Each dot is the location of a VHF source. The sources below 5.5 km altitude are from the negative leader, and the sources above 5.5 km altitude are from the positive leader. This was an inverted intra-cloud flash, and did not connect to ground.
380 The box shows the region expanded in Fig. S22.



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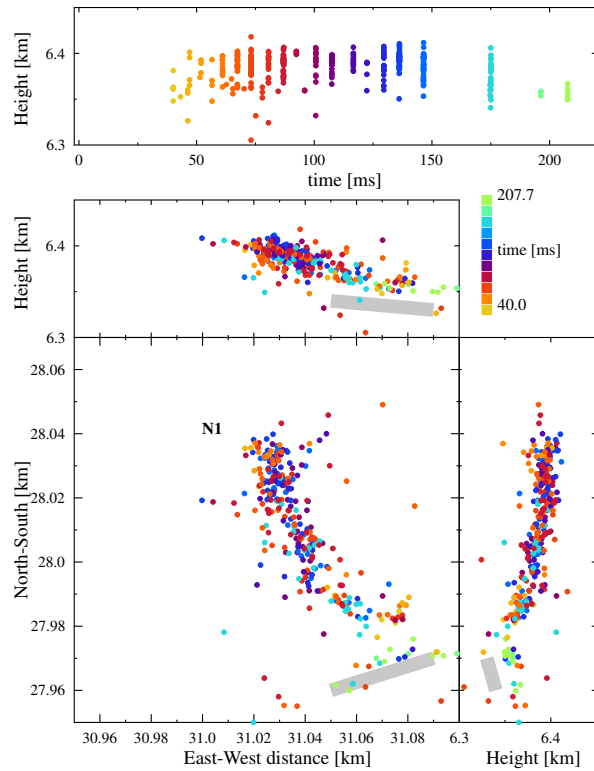
Figure S21: Altitude versus temperature profile during the 2016 lightning flash,
 382 derived from the Global Data Assimilation System.



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Figure S22: Image of a section of positive leader during the 2016 flash shown in Fig. S20. This section shows three clear needle-like structures, in addition to many sources that are scattered along the body of the leader that are consistent with being due to needles, but the image is not clear enough to be certain. The grey lines show the approximate location of the positive leader channel.

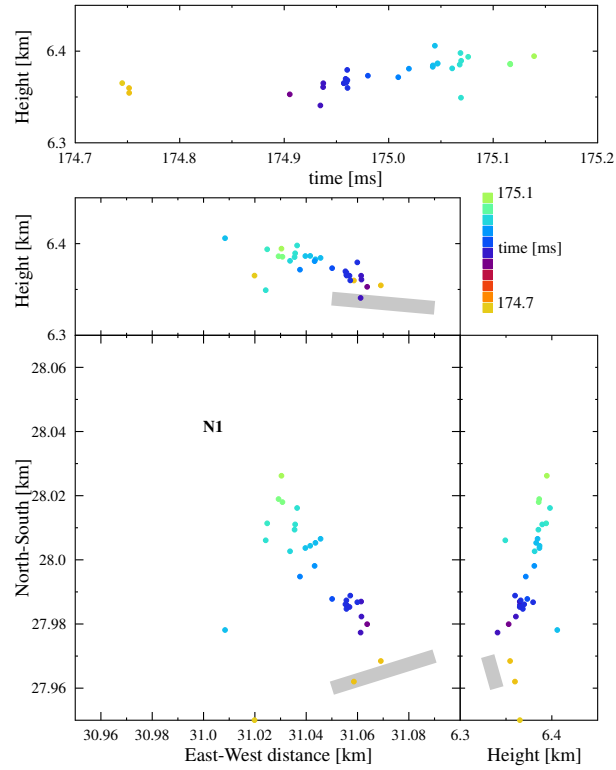
Fig. S23 details needle 2016-N1 shown in Fig. S22. This needle is about 60 m long, and twinkles over 18 times. Most of the twinkles occur 5–10 ms after the previous one, but the last well-imaged twinkle seems to occur over 50 ms from its previous twinkle. It is not obvious if this is physical, or due to twinkles not being imaged. Fig. S24 shows one twinkle of needle 2016-N1 at T=175 ms.



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Figure S23: Region around 2016-N1 shown in Fig. S22.



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Figure S24: One twinkle of 2016-N1 at T=175 ms

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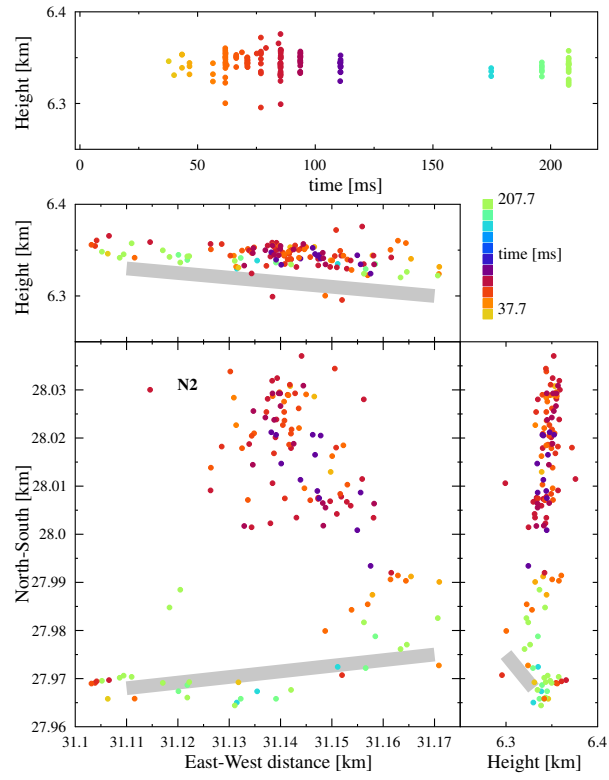
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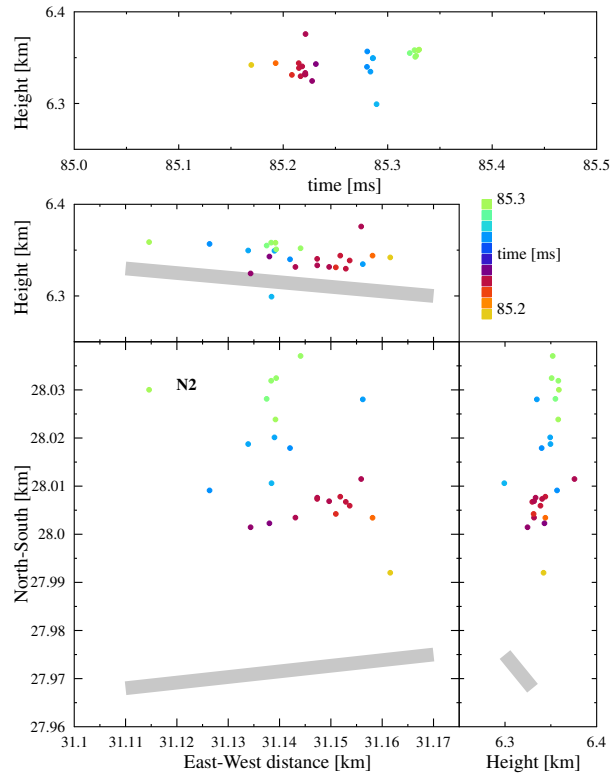
Fig. S25 details needle 2016-N2 shown in Fig. S22. This needle is about 40 m long, and twinkles about 9 times. There are also three groups of sources that occur $t=150$ ms, but these seem to occur along the positive leader channel and not 2016-N3, and so may be part of a poorly imaged needle. Fig. S26 shows one twinkle at T=85 ms.



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Figure S25: Region around 2016-N2 shown in Fig. S22.



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Figure S26: One twinkle of needle 2016-N2 at T=85 ms.

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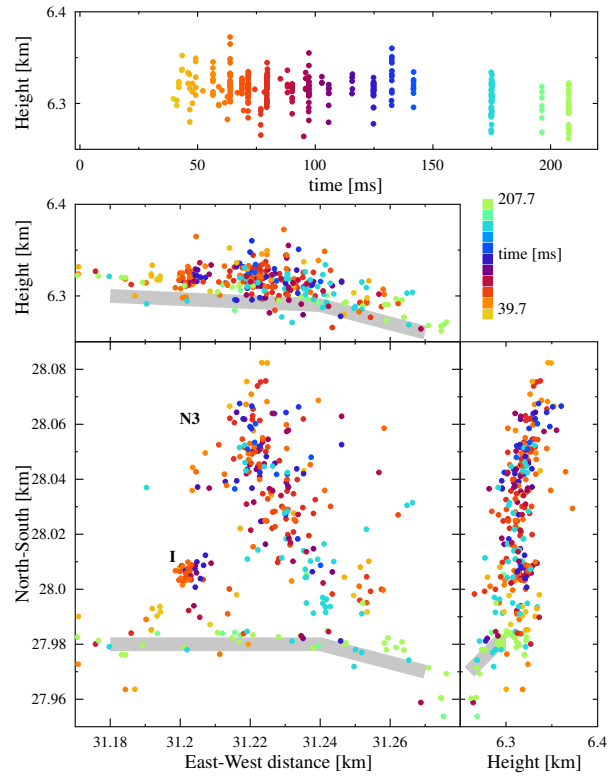
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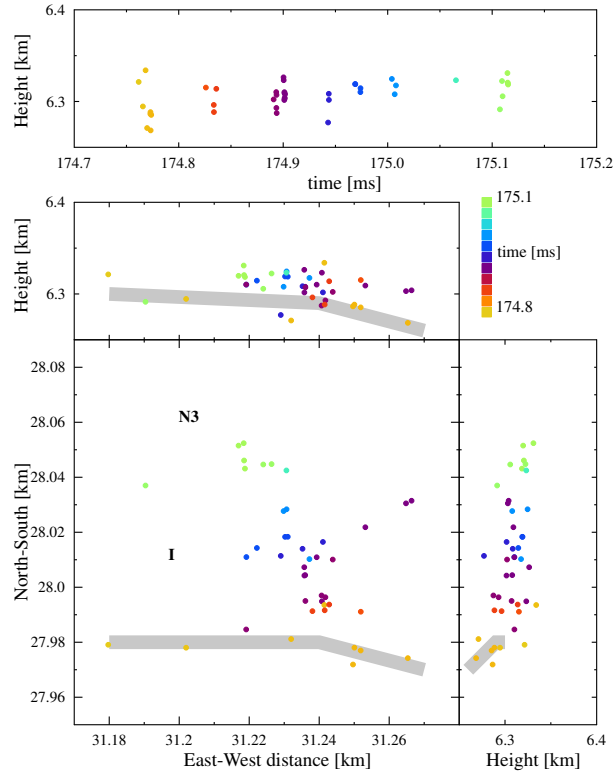
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Fig. S27 details needle 2016-N3 shown in Fig. S22. This needle is about 100 m long, one of the longest needles we have found. This needle twinkles over 14 times. Most of the twinkles are 5 – 10 ms apart, but like 2016-N1, there is a later twinkle that occurs over 50 ms since the previous twinkle. There is also a small needle, labeled “I”, that is about 10 m long, and twinkles 4 times. Fig. S28 shows one twinkle of needle 2016-N3 at T=175 ms. This twinkle seems to be clustered in time. It is not clear if this clustering is an imaging artifact or is physical.



411

412 Figure S27: Region around 2016-N3 shown in Fig. S22. The labels “2016-N3”
 and “I” show two different needles.



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Figure S28: One twinkle of needle 2016-N3 at T=175 ms

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5 Additional Hypothesis

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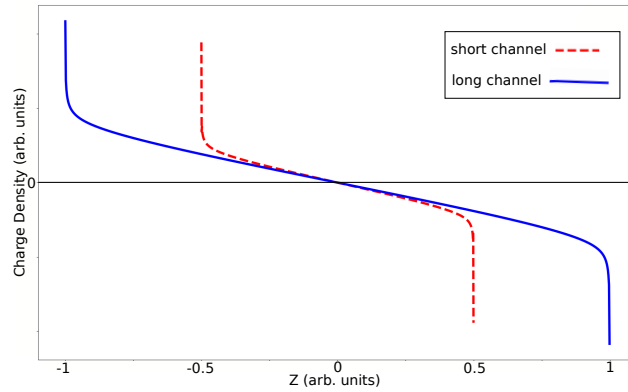
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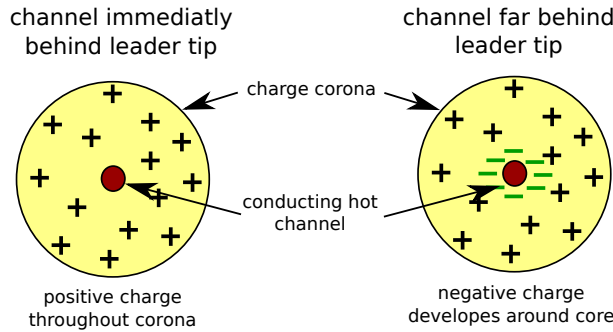
429

Apart from the hypothesis listed in the main body, there are two other ways that the electric field perpendicular to the leader channel could flip direction. The first effect is due to the fact that the highest charge densities around a lightning leader are found at the tip of the leader. This is illustrated by Fig. S29, which shows the line charge density along a short and long cylinder in a uniform electric field, calculated using a method-of-moments simulation [6]. This figure shows a large spike in the line-charge density at the tips of the cylinders. This implies that as a leader grows, the charge density at one point on the leader starts high but then must decrease as the leader grows. For an infinitely conducting cylinder this is no problem, but lightning is a different story. The corona around the lightning channel that holds the positive charge must, by definition, be very poorly conducting. If it was not, then any significant charge density would flow away quickly. As a result, the positive charges cannot be removed easily, therefore negative charge must be added to the inside of the corona as the

430 leader gets longer. Fig. S30 shows a diagram of the charge corona around
 431 the lightning leader according to this hypothesis. The corona of a section of
 432 positive leader that is immediately behind the leader tip is mostly dominated
 433 by positive charges, but the corona on a section of leader far behind the leader
 434 tip will have a layer of negative charge in order to lower the total line charge
 435 density. Eventually the negative charge will cause dielectric breakdown, which
 436 we map as a needle twinkle. However, the charge-density difference between a
 437 short and long channel is only large near the tip of the leader, so it is not clear
 438 if this effect is strong enough to produce needles over hundreds of meters, this
 439 is compounded by the fact that the leader channel is generally curved, and not
 440 straight as used in Fig. S29.



441
 442 Figure S29: Line charge density along a short and long perfectly conducting
 cylinder in a uniform electric field.



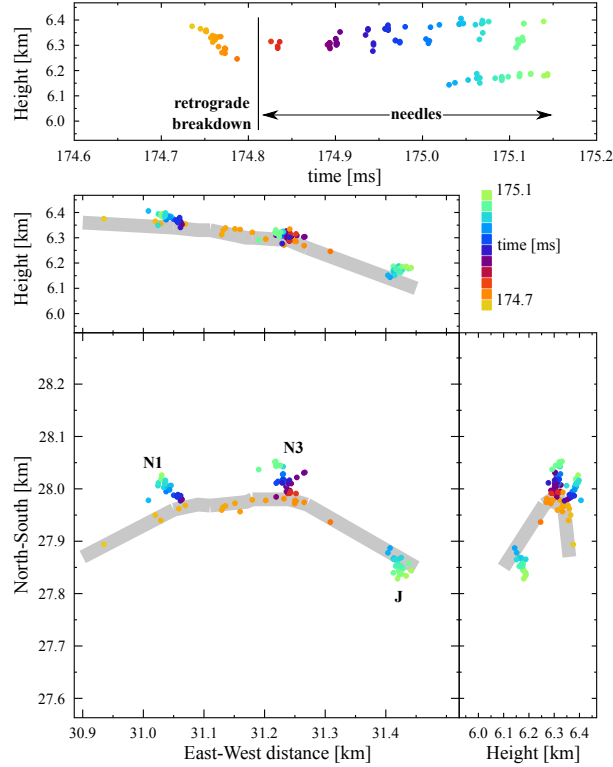
443
 444 Figure S30: Diagram showing the corona immediately behind the positive leader
 tip which is mostly positive charge, and the corona far behind the leader tip
 which contains a layer of negative charge.

445 The third mechanism is comparatively simple. It is known that there are
 446 current pulses that start on the positive leader and propagate along the leader

447 channel towards the negative leader. They are typically called retrograde neg-
448 ative breakdown, also known K-changes or recoil leaders [7, 8, 9, 10, 11, 12].
449 Since these current pulses are a form of negative breakdown, they move nega-
450 tive charge along the channel as they propagate. So it is possible that as they
451 propagate by a needle they could deposit enough negative charge to initiate
452 breakdown that we then see as a needle twinkle. In our data see many instances
453 of negative retrograde breakdown, however only a single one is associated with
454 needle activity.

455 Fig. S31 shows this retrograde breakdown seen in the 2016 flash, and three
456 needles that twinkled shortly afterwards. The retrograde breakdown is poorly
457 imaged, and only has an imaged length of about 400 m. The three needles
458 include N1 and N3 shown in Fig. S22, and a third needle that is labeled “J”.
459 It is interesting to note that needle N2, which is between N1 and N3, does not
460 twinkle. Needle J is after the imaged length of the the retrograde breakdown.
461 However, given how soon needle J happens after the retrograde breakdown, it
462 is most likely that the retrograde breakdown continued down the channel, past
463 needle J, and simply was not imaged.

464 Most of the retrograde negative breakdown imaged by LOFAR is similar
465 to that reported in previous literature. Future work will be needed to see if
466 LOFAR sees any new properties that have not been previously reported.



467

468 Figure S31: An instance of negative retrograde breakdown that is shortly fol-
 469 lowed by the twinkles of three needles.

470 Unfortunately, for all three hypothesis given, too little is known about light-
 471 ning leaders, such as their capacitance, how much charge they collect as they
 472 propagate, the distribution of that charge along the lightning channel, and the
 473 structure of the leader corona, to produce a numerical model to compare against
 474 our observations. Similarly, we are presently unable to estimate the current on
 475 the leader channel or how needles affect that current more precisely than the
 hypothesis given main text.

476 6 Potential for Optical Observations

477 One possibility to gain more insight into the physics behind needles is to image
 478 them with a high-speed camera. However, it is not clear if needles can be de-
 479 tected through optical observations. The primary difficulties being that needles
 480 are small and positive leaders are often hidden from view inside thunderclouds.
 481 This uncertainty is compounded by the fact that we don't know if needles are
 482 highly conductive, similar to negative leaders, and thus very luminous or needles

483 only consist of clusters of streamers and do not form a conducting channel, and
484 so are not very luminous.

485 Upward positive leaders near ground have been studied extensively (see [13]
486 and citations therein) without detection of needles, but it is possible that up-
487 ward positive leaders behave differently than positive leaders in intra-cloud or
488 negative cloud-to-ground lightning. One obvious possibility is that upward posi-
489 tive leaders may have a higher current, and therefore do not form disconnections
490 that can lead to needles.

491 It should be noted that the structure of needles have three primary charac-
492 teristics: 1) They are relatively small, around 100 m long or less. 2) They are
493 roughly perpendicular to the positive leader channel. 3) They flicker multiple
494 times, with about 2-10 ms between flickers.

495 7 Location Error Analysis

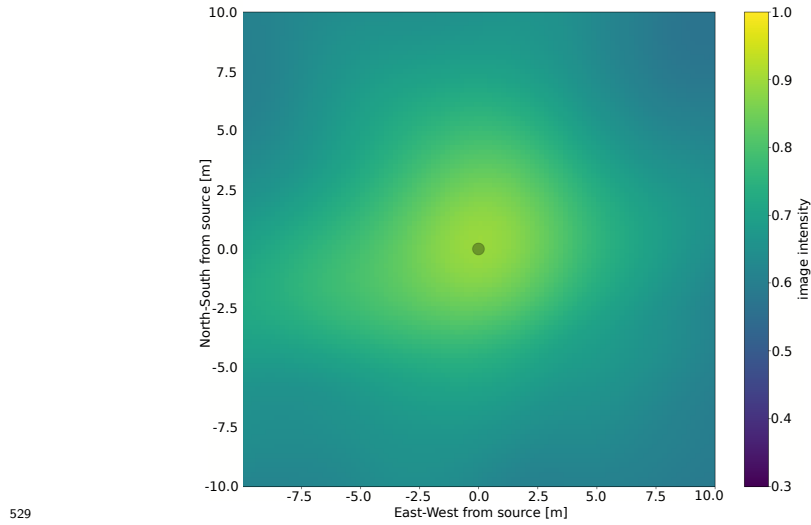
496 The dominant source of location error in our analysis comes from our assumption
497 that our sources are point sources. In reality, lightning VHF source regions are
498 extended sources. The visible effect is that our measured waveforms have a
499 different shape and a different polarization depending on the antenna. Antennas
500 that are relatively close, as are all antennas in the LOFAR core (diameter 2 km)
501 for example, have very similar waveforms, however antennas that are far apart
502 can have very different waveforms, as they view the radio source region from
503 completely different angles. The resulting effect in our analysis is that the
504 waveforms do not interfere with each other in the same way that one would
505 expect for short-baseline interferometry. This is the primary reason that we
506 take the absolute value of the cross-correlation before summing over pairs of
507 antennas in equation S1, as it makes our analysis less sensitive to this problem.

508 We have estimated the location error of our sources by looking at the size
509 of the smallest structures that we can image, which must be larger than twice
510 our location error. Such structures would be the width of the needles and the
511 negative leader and the distance between needles. The width of the needles and
512 the negative leaders all tend to be 5 m, and we have not found any well-imaged
513 structure with a size smaller than 5 m. Furthermore, Fig. S14 shows two needles
514 that we have imaged that are about 5 m apart. Therefore, since our location
515 error cannot be much larger than the diameter of our image size (5 m diameter),
516 and we can image structures as small as 5 m in size, then we conclude that our
517 location accuracy must be better than 2 m in X and Y. Our location accuracy
518 in Z is much worse, but better than 15 m.

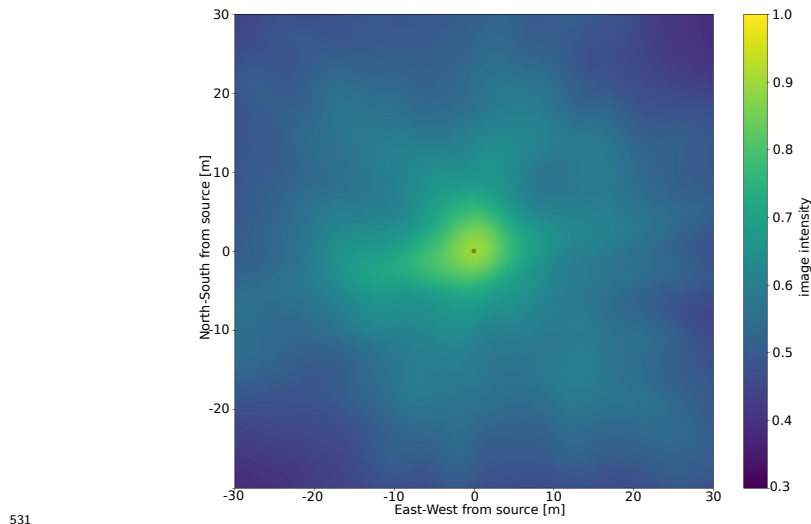
519 Fig. S32, Fig. S33, Fig. S34, and Fig. S35 show the image intensity around
520 a typical source, defined by equation S1, sliced at constant height and constant
521 North-South distance at the location of the source. These four figures show
522 the main beam around the found source location. These figures show that the
523 image is smooth, with minor side beams

524 Not all sources are equally well-imaged. As discussed previously, about 30%
525 of the sources we attempt to image pass our final cuts. Our primary cut is that

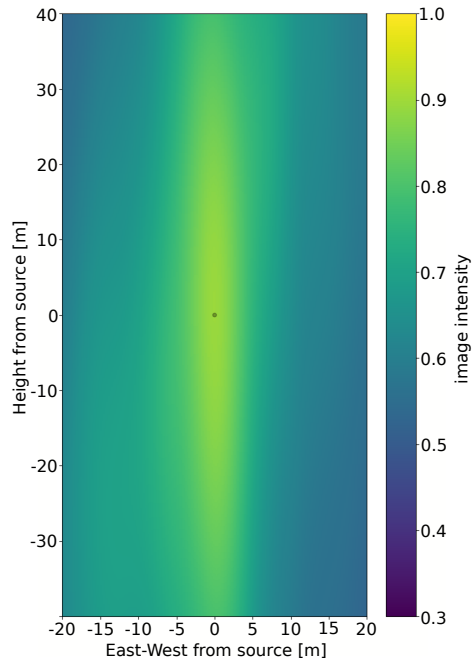
526 the image intensity must be larger than 0.85 (maximum of 1). Fig. S36 shows
527 the distribution of image intensities. The source used to produces the images
528 in Fig. S32, Fig. S33, Fig. S34, and Fig. S35 had an intensity of 0.91.



529
530 Figure S32: Image of a source sliced at a constant height. The found location
of the source is at the grey circle.



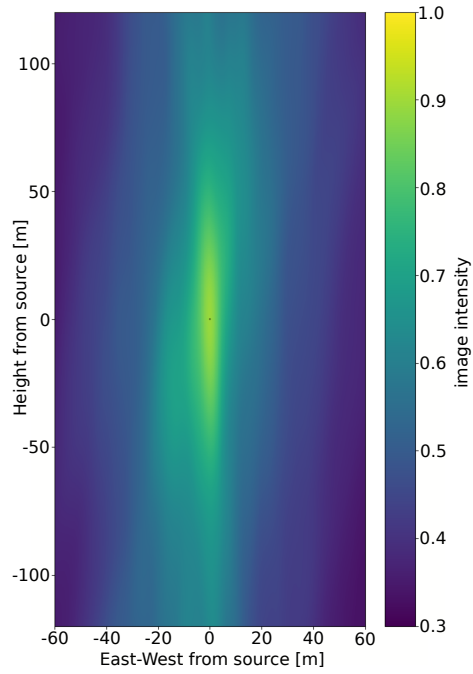
531
532 Figure S33: Image of a source sliced at a constant height. The found location
of the source is at the grey circle.



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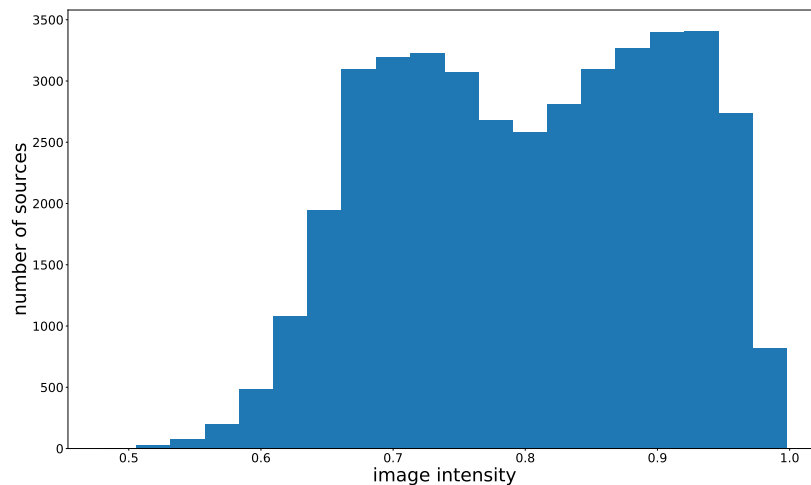
Figure S34: Image of a source sliced at a North-South distance. The found location of the source is at the grey circle.

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Figure S35: Image of a source sliced at a North-South distance. The found
536 location of the source is at the grey circle.



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538 Figure S36: Histogram of image intensities for the 2017 flash.

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