Small-scale discharges observed near the top of a thunderstorm

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Abstract

We have used the LOw-Frequency ARray (LOFAR) to image a few lightning flashes during a particularly severe thunderstorm. The images show an exceptional amount of VHF activity at altitudes above 10 km. Much of this is in the form of small-scale discharges occurring seemingly randomly around the centers of active storm cells. Because of their small and incidental structure we refer to these as 'speckles'. A detailed investigation shows strong evidence that these speckles are indicative of positive leader channels and that they are equivalent to the needle activity seen around positive leader tracks at lower altitudes.

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Key Points:

- In the tops of severe thunderstorms many seemingly isolated sources for VHF radiation are observed
- The VHF sources in these tops are small negative discharges, conjectured to be related to an extensive positive leader structure
- The charge-layer structure in these tops is mixed

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Abstract

We have used the LOw-Frequency ARray (LOFAR) to image a few lightning flashes during a particularly severe thunderstorm. The images show an exceptional amount of VHF activity at altitudes above 10 km. Much of this is in the form of small-scale discharges occurring seemingly randomly around the centers of active storm cells. Because of their small and incidental structure we refer to these as 'speckles'. A detailed investigation shows strong evidence that these speckles are indicative of positive leader channels and that they are equivalent to the needle activity seen around positive leader tracks at lower altitudes.

1 Introduction

Almost all flashes we imaged with the LOw-Frequency ARray (LOFAR) (van Haarlem et al., 2013) show a large amount of VHF-activity below an altitude of approximately 8 km. Most of this is in the form of of negative leaders (Hare et al., 2020; Scholten, Hare, Dwyer, Liu, et al., 2021b; Machado et al., 2021), needles (Hare et al., 2019; Pu & Cummer, 2019; Saba et al., 2020; Hare et al., 2021; Wu et al., 2022), and recoil leaders. Rarely we observe VHF activity at higher altitudes up to 10 km, which is usually in the form of high-altitude negative leaders, HANLs (Scholten, Hare, Dwyer, Liu, et al., 2021a). For an exceptional storm that occurred on June 18, 2021 we detected VHF activity up to altitudes of 14 km which is most unusual for the Netherlands. This storm, remnants of storm 'Bill', caused such severe weather conditions in the Netherlands that it attracted media attention, see (*YouTube movie of June 18, 2021 storm*, 2021). Most of this activity at the highest altitudes was of a form we had never seen before, showing as seemingly random and isolated spots, small-regions of VHF-emission that do not grow into a full lightning channel, occurring over long time periods in an area not exceeding 10 by 10 km at altitudes between 9 and 14 km. Because of their spotty nature we refer to them as 'Speckles'. In this letter we give a first report on these speckles as imaged by LOFAR. A very similar phenomena has been reported by (Emersic et al., 2011; Calhoun et al., 2013; MacGorman et al., 2017) in overshooting tops of strong subtropical thunderstorms in the south of the USA at even greater altitude. Our LOFAR observation are the first to see this phenomenon for thunderstorms in the moderate climate zone and, in addition, to image these structures in unprecedented resolution.

In (Emersic et al., 2011; Calhoun et al., 2013; MacGorman et al., 2017) it is noted that at extreme heights in thunder clouds, heights where the updraft pushes the cloud to heights where it overshoots buoyancy, VHF sources are detected continually over long periods at relatively low rates. These flashes have a small spatial extent and duration without discernable channel structure and occur independently of flashes at lower altitudes. From the works of (Ushio et al., 2003) and (Bruning et al., 2010) we know that the large thunderstorm cells proceed as a sequence of lightning bubbles raising above buoyancy, one in front of the other, with lightning activity at increasing heights. Large scale turbulence in the overshoot region causes a mixing of the different charge layers. Our LOFAR observations largely confirm this picture for the tops of thunderstorm cell for a particularly severe storm.

In this work we investigate the discharges associated with the speckle activity and conclude that it is related to (VHF-quiet) positive leader activity much in the same way as needles are seen around positive leader tracks at lower altitudes. In most cases the track-structure is difficult to reconstruct due to the lower density of these speckles as well as a probably more complicated leader structure in the turbulent top region in these clouds that have a rather complex charge structure. In the few cases where recoil leaders show the track structure it is seen that they indeed connect many speckles.

LOFAR (van Haarlem et al., 2013) is a radio telescope consisting of several thousands antennas. These antennas are spread over much of Europe. For the observations presented here we use the antennas in Dutch stations only operating in the 30 – 80 MHz VHF-band where the observations are imaged using the procedure described in ref. (Scholten, Hare, Dwyer, Sterpka, et al., 2021) that employs a time-of-arrival-difference method.

2 data

Speckles have been seen for all flashes of the June 18, 2021 storm that was exceptionally strong as shown in a YouTube movie (*YouTube movie of June 18, 2021 storm*, 2021). For this storm a total of nine were recorded by LOFAR, for technical reasons one approximately every 20 minutes, where for each flash about 1.5 seconds of data is available. All lightning flashes have a very similar structure where each flash shows several active lightning cells with several negative leaders at altitudes below 7 km altitude, many positive leaders between 7 and 10 km altitude showing the typical needle activity (Hare et al., 2019, 2021), and high-altitude negative leaders (Scholten, Hare, Dwyer, Liu, et al., 2021a) as well as speckles (the main subject of this work) at higher altitude. For this work we focus on two (out of four) lightning cells in the seventh flash in this series, 21C7 (at 2021-06-18, 19:37:28 UTC).

Figure 1: An overview of two active cells in flash 21C7 (@2021-06-18, 19:37:28 UTC), one centered around (N,E)=(30,-5) km and another one at (20,3) km from the LOFAR core. We only show the structure of the flash at altitudes above 7 km in order to emphasize the regions showing speckle activity between 9 and 13 km. The black circles in the ground-plane projection mark the regions where the speckles are not masked by other lightning structures but speckles can be saan all around the centers of the two storm cells.

In Fig. 1 we show the observations for the two lightning cells obtained with the impulsive imager (Scholten, Hare, Dwyer, Sterpka, et al., 2021), using a time-of-arrival-difference method for VHF-pulses measured in about 200 LOFAR antennas. We have restricted the figure to altitudes exceeding 7 km to focus on what we call speckles, relatively short (in time and space) clusters of VHF sources that seem not connected to lightning channels and show at seemingly random spots over comparatively long time periods (more than 1 second). The speckles can be seen in the top panel of Fig. 1 as a diffuse background of VHF sources at altitudes between 9 and 13 km. These speckles show as two multi-colored ‘clouds’ in the lower panels around the cores of the two lightning cells centered at (N,E)=(30,-5) km and at (20,3) km, each with a horizontal diameter of the order of 10 km and with main density at 12 km altitude and parts of these are marked by black circles. Since the color coding marks time, the multi-colored aspect of the clouds expresses that these speckles occur at random times. The spottiness (at this scale) expresses that they are isolated and well separated. This in great contrast to negative leaders (HANLs at these altitudes) and recoil leaders that show as thick and thin single-colored lines. By limiting to altitudes above 7 km we have eliminated the negative leaders at lower altitudes.

Analyses of radio soundings launched at De Bilt (approximately 140 km to the south-west of the storm location) at 2021-06-18 12:00 UTC and 2021-06-19 00:00 UTC show that the height of the tropopause is around 12.5 km. The tropopause height indicates the height at which the vertical temperature gradient changes sign and hence air naturally stops rising at this level. Only storms with large internal dynamics are able to significantly rise above the tropopause. Hence any storm that shows activity above the tropopause will exhibit large updrafts, which cause significant charge separation. We have also analyzed cloud top heights derived from the SEVIRI instrument on board Meteosat Second Generation (MSG). In the storm we discuss here we find cloud tops exceeding 13 km, indicating that this storm indeed has large updrafts. Note that the speckles that we observe do not exclusively occur at levels above the tropopause but are also abundant below this level.

To obtain a better insight in the nature of the speckles we have investigated several of them in detail. Most of these speckles can be resolved with our impulsive imager as a few individual VHF sources occurring at the the same spot (typically within meters) over a time-span of milliseconds. Some of the larger ones may span a few hundred meters and contain many tens of sources. This excludes them as imaging artifacts. Some of the smallest speckles show as single sources even when using our more sensitive TRI-D imager (Scholten, Hare, Dwyer, Liu, et al., 2021b; Scholten et al., 2022). The fact that the TRI-D imager does not show more structure is probably due to the very large amount of VHF emission all over the flash making it impossible to image the weaker sources due to the high background level.

Figure 2: A small section of the flash shown in Fig. 1 showing the two different kind of speckles as indicated by the orange and blue circles as well as the early part of a HANL (at t=180 till 260 ms, dark blue colors) and a recoil leader (at t=360 ms, bright green).

One of the most telling examples of the wide variety of speckles is shown in Fig. 2 where we have zoomed-in on a tiny (in space and time) part of Fig. 1. An example of a larger speckle is indicated by the orange circles in Fig. 2 at t=70 ms. It resembles a single corona-flash step of a HANL. It covers a vertical distance of only 200 m (including the very first source, 300 m) and has a horizontal extent of only 100 m. It is able to effectively discharge its volume as the subsequent HANL, starting at t=175 ms, passes over and around the volume covered by the t=70 ms discharge. This indicates that speckles are negative discharges where the necessary positive end is invisible in VHF. The general propagation direction is upward for the structure at t=70 ms as well as the HANL at t=175 ms. An example of the smaller kind is indicated by the blue circle in Fig. 2 at t=275 ms. Due only to the later recoil leader at t=360 ms it becomes clear that these sources are situated on a, hitherto unseen, positive leader track. The recoil leader propagates upward, the same direction as the HANL.

Figure 3: A small section of the flash shown in Fig. 1 showing several recoil leaders as well as some HANLs. In part b only a limited time period is shown to indicate that many of the observed speckles are lying on a track (indicated in grey) that conducts a recoil leader at later times (t=1140 and 1160 ms). The region where speckles are seen is labeled by the 'S' in the figure, while the part with showing more recoils is labeled with the 'R'. The striped area indicates the relatively vague boundary between the two. The structure of the two negative discharges, marked as H_1 and H_2 are shown in more detail in part c.

Another example given in Fig. 3 emphasizes the close relation between the speckles and positive leaders and additionally indicates the intricate charge structure at these heights. Fig. 3a is an enlargement of a section of Fig. 1 showing several downward going recoils, between t=700 and 1200 ms, passing through a speckle cloud and feeding the negative leaders at lower altitudes (not shown). The figure also shows two larger speckles that are indicated by the black circles marked H_1 and H_2 and lie close (at a distance of less than 1 km) to the track taken by the recoil leaders. These are qualified as speckles as they occur well before (400 ms) the development of the recoils leaders in this area, and are small (a length of less than 500 m) as compared to, for example, the recoil leaders that cover many kilometers.

In Fig. 3b we focus on on some speckles and recoil leaders at times between t=800 and 960 ms. In this figure we've indicated two regions 'S' and 'R'. The region labeled 'S' shows flickering and seemingly isolated VHF activity, while the region labeled 'R' contains multiple downward recoil leaders. The grey-line indicates a later recoil leader (t=1140 and 1160 ms), which shows that most of the activity in the 'S' region is not truly isolated but is actually on a VHF-invisible positive leader. For example, just north of the 'S' label is a long-thin negative discharge that, with LOFAR's resolution, is clearly some kind of discharge similar to needles. While related, these speckle discharges are somewhat different from needles in that they emit VHF far less frequently (as needles twinkle at a regular rate).

There is also speckle activity around 12 km altitude in Fig. 3b that is seemingly isolated, as we have no solid evidence of a positive leader connecting this activity to the main flash. A more detailed zoom-in on the longer speckles among them showed that these propagate downward at an acute angle with the curve one would draw to connect them. Thus, even though the activity around 12 km altitude could be truly isolated from the main flash, we believe it is highly likely that the positive leader has actually propagated to 12 km altitude and simply has not been imaged due to the difficulty of locating positive leaders in VHF. We should stress here the similarity of the features seen in Fig. 3b with those shown in Figure 19 in (Hare et al., 2021).

The recoil leaders in region 'R' of Fig. 3b are not perfectly imaged by our impulsive imager, and show spots of VHF emission and empty holes. Thus, it is difficult to tell without the TRI-D imager precisely which VHF emission is actually part of a recoil leader and which is due to speckles. Therefore, the boundary between the speckle region 'S' and recoil region 'R' is ambiguous and highly depends on how the lightning is imaged. In an extreme case, we know that LMAs have a difficult time locating dart/recoil leaders, and thus may present this region of VHF activity as completely isolated from the lightning flash.

Fig. 3c is a zoom-in on H_1 and H_2, showing that both are some kind of highly-branched negative leader. The first one, H_1, started at an altitude of 10.3 km and propagated downward over a distance of almost 1 km covering a horizontal distance of a little less than 300 m in about 10 ms, resulting in an average speed around 10^5 m/s. H_1 resembles a single corona flash of a HANL. The later one, H_2, starts at an altitude of about 11.1 km moving upward over a distance of less than 300 m and horizontal over about 400 m, thus had an average speed of only 10^4 m/s. Therefore, despite both being highly-branched negative leaders, H_1 and H_2 propagate at very different speeds. These two occur 500 ms before and less than 1 km eastward from where the recoil leader passes at an altitude in between them. They therefore, like needles, probably initiate in the corona sheath of an un-imaged positive leader. However, their propagation structure implies that this region has a very complex charge structure. Obviously a positive leader with its corona sheath propagating through a negative charge region already results in complicated electric field. However, H_1 and H_2 are more complex than needles in that they are heavily branched and they change direction (H_1 starts horizontal and turns vertical, H_2 curves heavily at the end). It is known that negative discharges turn horizontal and branch when entering positive charge regions. Thus, there must be a complex mix of positive and negative charge in this region. Possibly a thin negative charge layer bordered by two thin positive charge layers.

3 Summary

We have used LOFAR to image a, for Dutch standards, particularly severe thunderstorm where we observed many VHF emitting sources at altitudes above 10 km. Particularly intriguing is that much activity seems isolated from the main flash, which we refer to as speckles, in the form of seemingly uncorrelated sources of small spatial extent, that are very similar to what has been seen before in LMA observations (Emersic et al., 2011; Calhoun et al., 2013; MacGorman et al., 2017) in the overshooting tops of strong subtropical thunderstorms. With LOFAR we can resolve the structure most of these speckles and find that they are reminiscent of the needle activity seen around positive leaders at lower altitudes (Hare et al., 2019). Sometimes these speckles develop into larger negative discharges very much like what is seen at lower altitudes. The main difference with needles is the speckles re-activate much less frequently. This is most likely due to differences in the atmosphere at these altitudes (density and/or humidity) that also cause negative leaders to show as HANLs rather than normal negative leaders as observed at lower altitudes. Our conjecture is thus that the speckles are relatively small-scale negative discharges around an extensive positive leader complex where the formation of the positive leader itself is a very VHF-quiet process and thus escapes detection with LMA's or LOFAR.

The speckles are seen very prominently in the present particularly violent thunderstorm in the top region of each thunderstorm cell. It is very likely that these cells have overshooting tops, but, as the height of the tropopause in Dutch summers may exceed 12 km, the speckles are not confined to the overshooting tops as was observed in (Emersic et al., 2011; Calhoun et al., 2013; MacGorman et al., 2017) for more tropical storms.

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This paper is based on data obtained with the International LOFAR Telescope (ILT). LOFAR (van Haarlem et al., 2013) is the Low Frequency Array designed and constructed by ASTRON. It has observing, data processing, and data storage facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the ILT foundation under a joint scientific policy. The ILT resources have benefitted from the following recent major funding sources: CNRS-INSU, Observatoire de Paris and Université d'Orléans, France; BMBF, MIWF-NRW, MPG, Germany; Science Foundation Ireland (SFI), Department of Business, Enterprise and Innovation (DBEI), Ireland; NWO, The Netherlands; The Science and Technology Facilities Council, UK.

The data are available from the LOFAR Long Term Archive (for access see (ASTRON, 2020)), under the following locations:
`L821104_D20210618T193728.637Z_stat_R000_tbb.h5`
all of them with the same prefix
`srm://srm.grid.sara.nl/pnfs/grid.sara.nl/data/lofar/ops/TBB/lightning/`
and where "stat" should be replaced by the name of the station, CS001, CS002, CS003, CS004, CS005, CS006, CS007, CS011, CS013, CS017, CS021, CS024, CS026, CS030, CS031, CS032, CS101, CS103, RS106, CS201, RS205, RS208, RS210, CS301, CS302, RS305, RS306, RS307, RS310, CS401, RS406, RS407, RS409, CS501, RS503, or RS508.

To access this data, please create an account following instructions at (ASTRON, 2020) and follow the instructions for "Staging Transient Buffer Board data". In particular the utility "wget" should be used as in

```
wget https://lofar-download.grid.surfsara.nl/lofigrid/SRMFifoGet.py?surl=location
```

where "location" is the location specified in the above.

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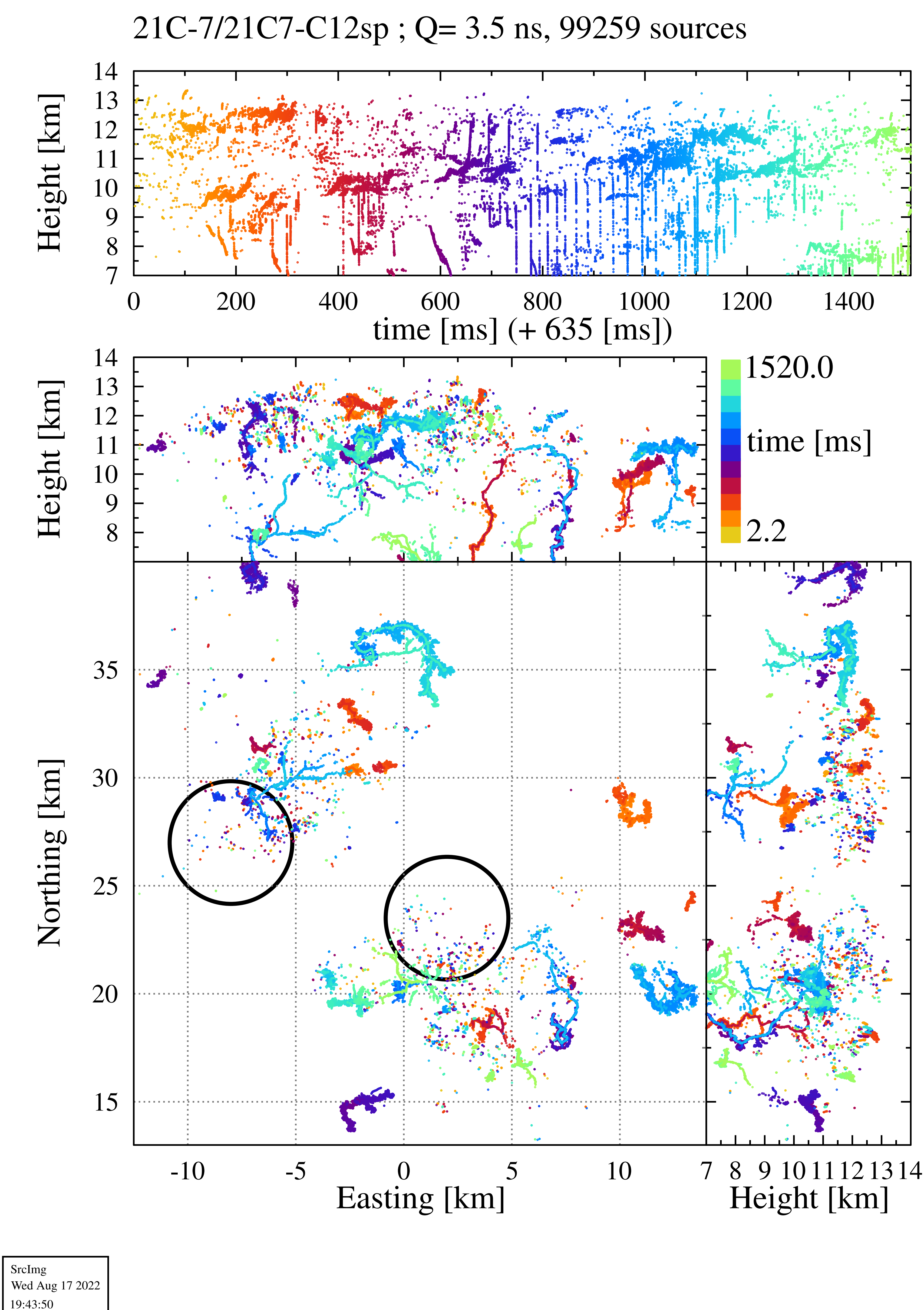
Figure 1.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time [ms] (+ 635 [ms])
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2.2
Northing [km]
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Height [km]
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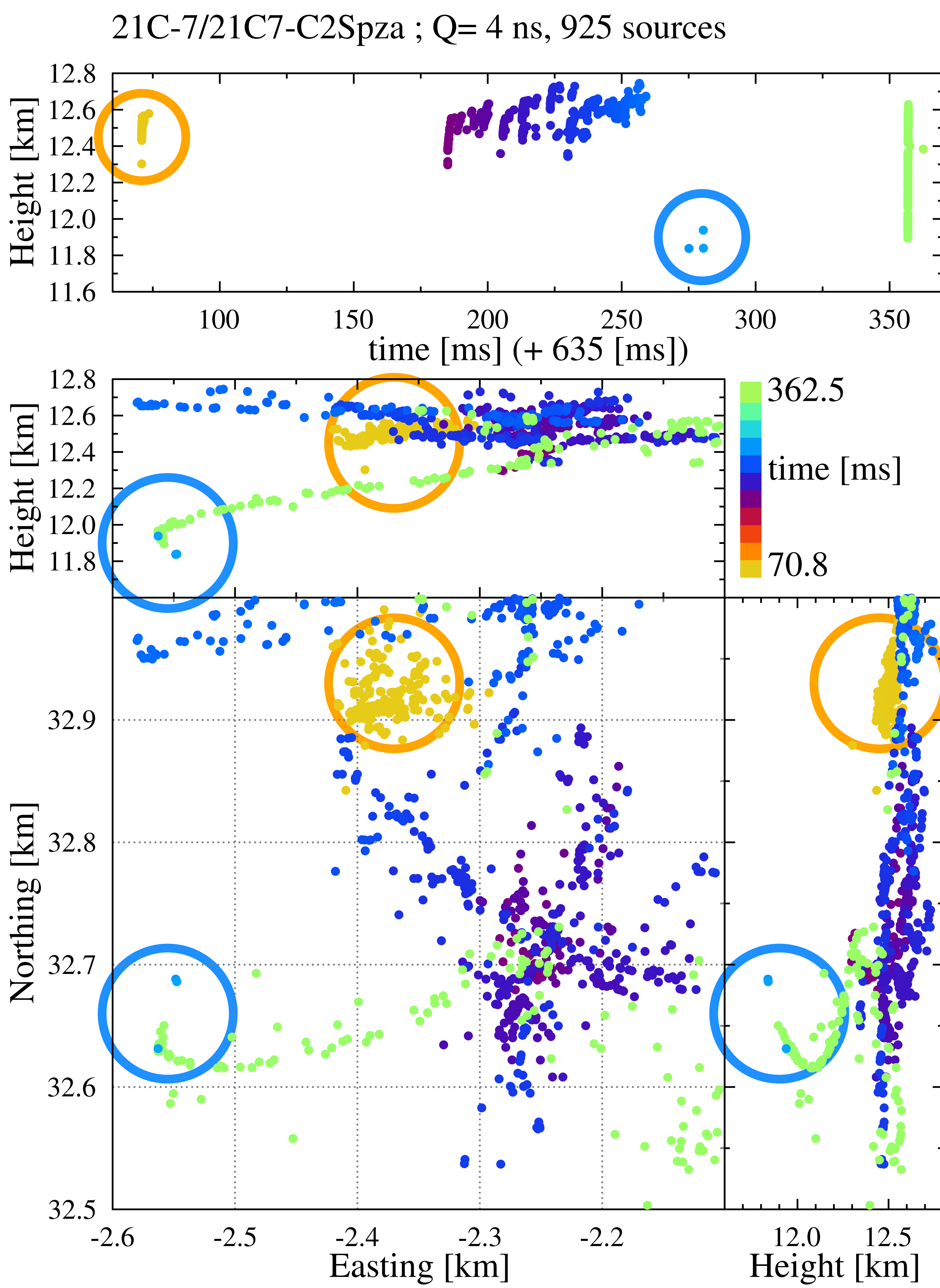
19:43:50

Figure 2.



SrcImg
Wed Aug 17 2022
19:28:37

Figure 3a.

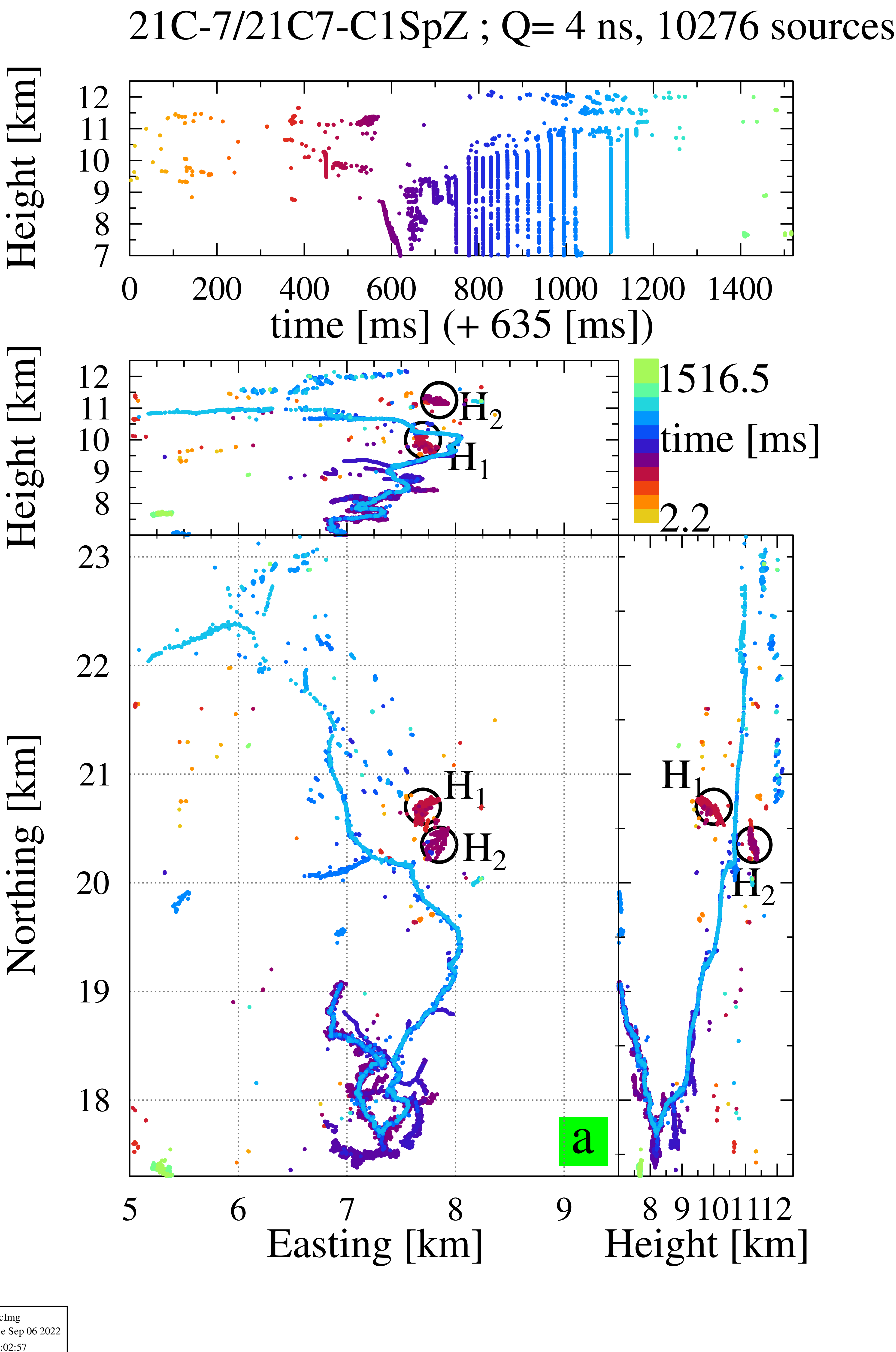
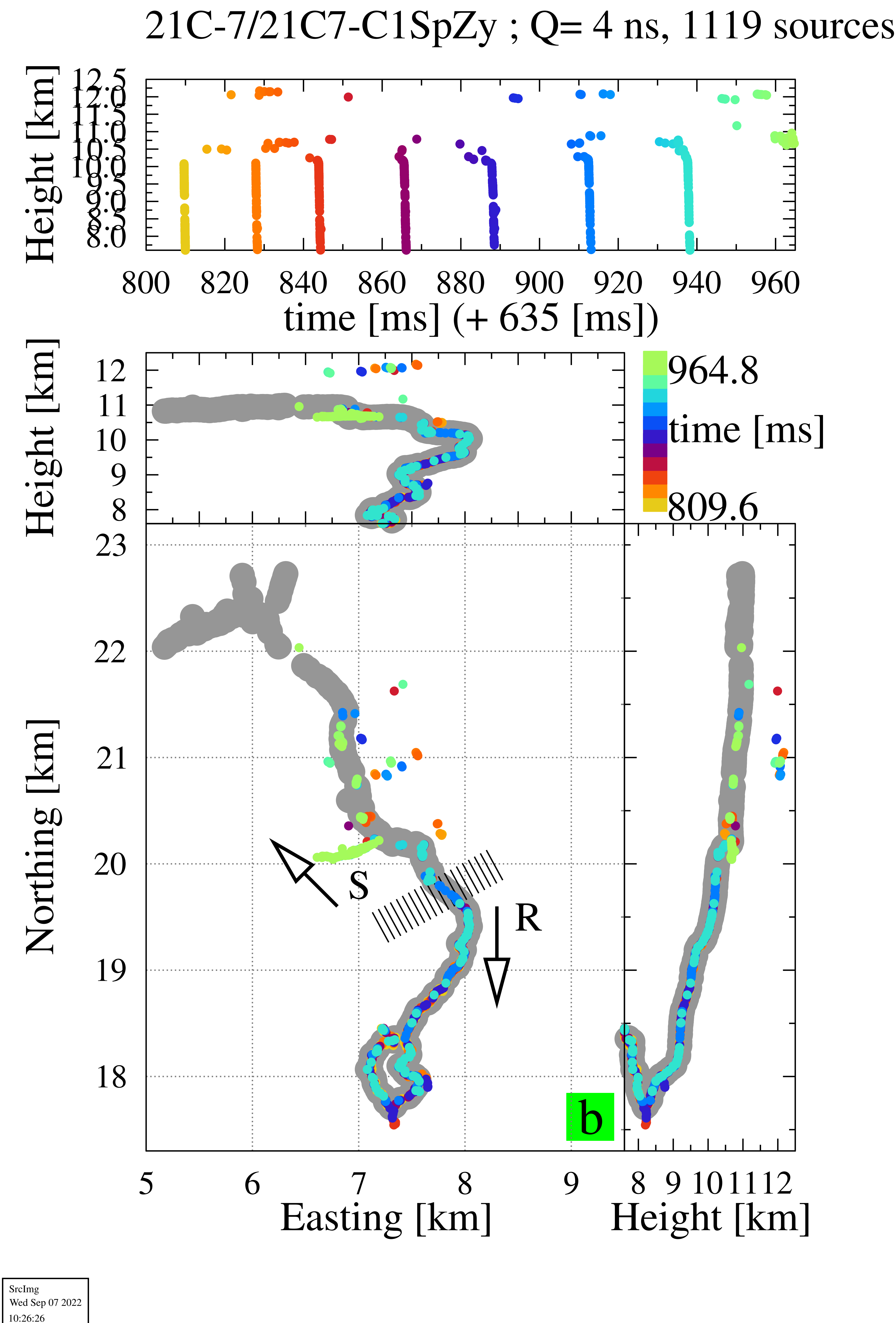
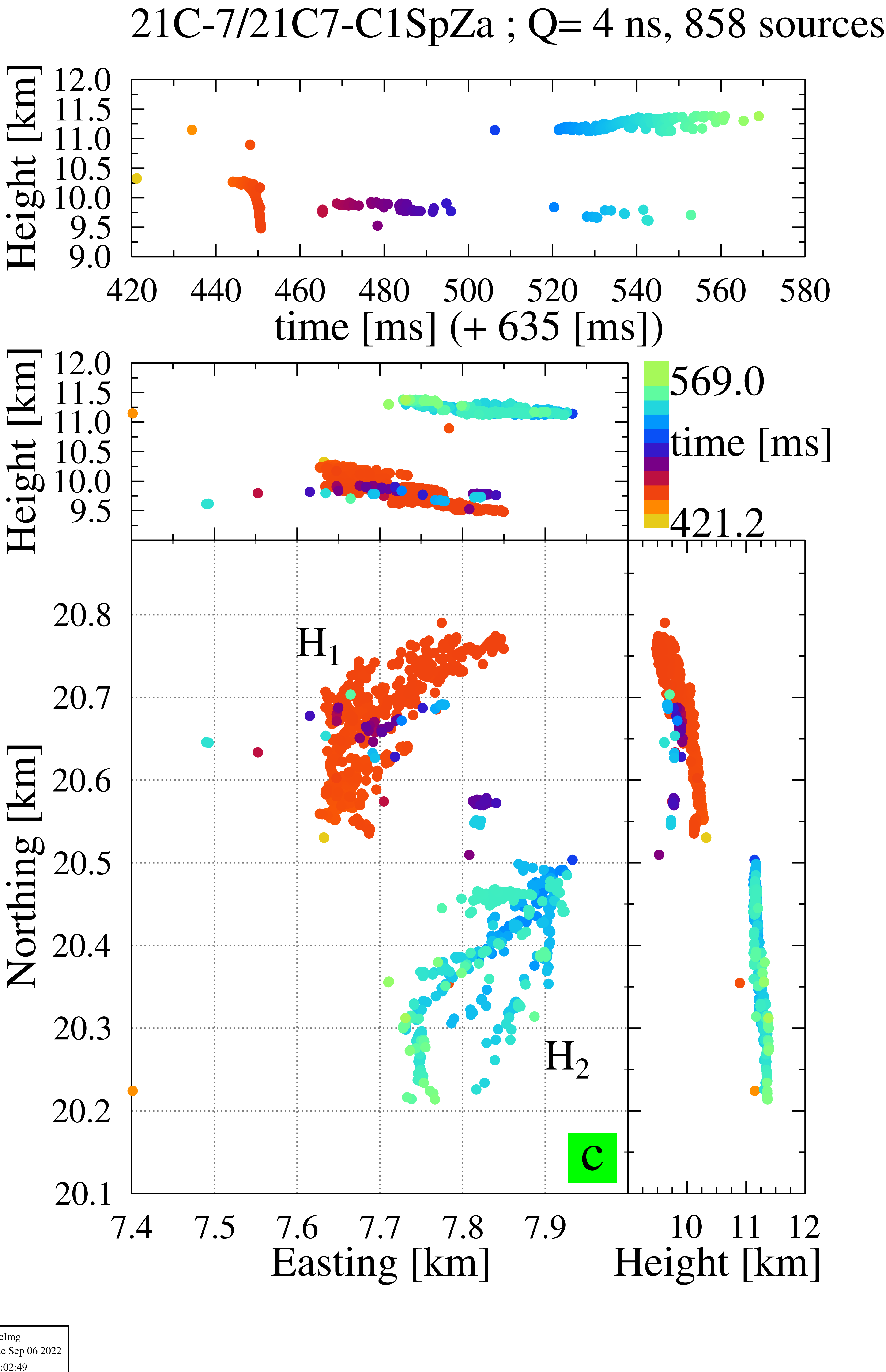

21C-7/21C7-C1SpZ ; Q= 4 ns, 10276 sources
Height [km]
time [ms] (+ 635 [ms])
1516.5
time [ms]
2.2
H_1
H_2
Northing [km]
Easting [km]
Height [km]
a
SrcImg
Tue Sep 06 2022
20:02:57

Figure 3b.



21C-7/21C7-C1SpZy ; Q= 4 ns, 1119 sources
Height [km]
time [ms] (+ 635 [ms])
964.8
time [ms]
809.6
Northing [km]
Easting [km]
Height [km]
S
R
b
SrcImg
Wed Sep 07 2022
10:26:26

Figure 3c.


21C-7/21C7-C1SpZa ; Q= 4 ns, 858 sources
Height [km]
time [ms] (+ 635 [ms])
569.0
time [ms]
421.2
Northing [km]
Easting [km]
Height [km]
H1
H2
c
SrcImg
Tue Sep 06 2022
20:02:49