

Comparison of electrostatic, radio and human observation techniques for thunderstorm warning at the WMO field intercomparison site in Vigna di Valle – Italy

A J Bennett^{1,2}

S Vergari³

¹ Bristol Industrial and Research Associates Limited (Biral), P O Box 2, Portishead, Bristol, BS20 7JB, United Kingdom

² Department of Electronic and Electrical Engineering, University of Bath, Bath, BA2 7AY, United Kingdom

³ Technical Centre for Meteorology of Italian Air Force, Vigna di Valle, 00062 - Bracciano (RM), Italy

E-mail: alec.bennett@biral.com

Abstract

Details of a comparison between different types of local thunderstorm detection techniques deployed at the WMO field intercomparison test bed in Vigna di Valle (Italy) are presented. Measurements made by a stand-alone electrostatic thunderstorm detector, VLF/LF radio network and human observer were compared during several thunderstorms between November 2017 and April 2018, where winter convection is aided by the relatively warm Mediterranean Sea. This WMO site is owned and operated by the Italian Air Force who led the comparison, assisted by the UK meteorological sensor company Biral, which provided expertise on their electrostatic detector deployed at the site. The stand-alone electrostatic sensor (BTD-300) was developed to detect and range all forms of lightning within approximately 80 km (50 miles) using the resultant electrostatic field change, with lightning bearing from the site provided by an integrated low frequency radio receiver, allowing the 2D location of the flash to be found. In addition to lightning location, the instrument detects strong electric field variability and charged precipitation at the site, both of which are used to warn of potential overhead lightning activity before the first flash occurs. The performance of the electrostatic method is compared to that of Italy's established national lightning detection network (Lampinet) comprised of 15 VLF/LF receivers installed around Italy, capable of detecting cloud-to-ground flashes and larger-amplitude intracloud flashes, as well as human observations made by Italian Air Force observers operating continuously at this WMO test site.

Due to the different operating methods between the Lampinet network and the single BTD-300 sensor, the results that will be presented have to be considered as a preliminary study and further investigations are needed in order to compare single position sensors.

1 Introduction

Thunderstorms produce hazardous weather conditions for aviation, both for aircraft in flight and ground-based activities such as boarding and refuelling. As a consequence, early warning and real-time monitoring of thunderstorm activity surrounding an aerodrome is of great importance to ensure the safety of personnel and equipment. Aerodrome thunderstorm detection is traditionally the responsibility of meteorological observers based at the site, listening for thunder and estimating the distance and direction of any lightning

activity. Trained meteorological observers are well placed to differentiate genuine thunder and lightning from other sources of low frequency sound or bright flashes, although the audible limit of thunder tends to limit detection to within 20 km during the day in quiet, outdoor environments. Lightning is of course more easily observed during the night and unbiased reporting requires an unobstructed view at all bearings. This may be achievable in the air traffic control tower, for example. Audible thunder range is further constrained by the building housing the observer and background noise levels, reducing the realistic range to approximately 10 km.

Improving technology and a decline in the number of meteorological observers over recent decades means that lightning is more often detected automatically, with near real-time information of lightning location available to the aerodrome from remote sensing instrumentation. Lightning is a strong source of broadband radio signals, so automatic lightning location is commonly achieved using a national (or international) network of radio receivers combined with precise timing of signal arrival. The differences in arrival time of the signal at each receiver allows the location of the lightning stroke to be estimated, with modern VLF/LF networks achieving location accuracies of less than 1 km. Recent and near-future launches of geostationary satellites containing lightning optical detectors also enables continuous monitoring of lightning from space over large regions of the world.

Satellite and ground-based radio detection networks are designed to enable lightning monitoring over large geographical regions. If local thunderstorm activity surrounding a fixed site such as an aerodrome is required, other technologies are available which only require one sensor installed at the site. An example of a standalone thunderstorm detector with a range of order 100 km is the Biral BTD-300. This instrument monitors changes to the atmospheric electric field below 50 Hz associated with both lightning activity and overhead thunderstorm development (Bennett 2013; 2016; 2018). The BTD-300 detects all forms of lightning activity within approximately 80 km, and stronger flashes up to 120 km. The detection and ranging of lightning uses the electrostatic field change, with corresponding flash bearing derived using an integrated LF radio direction finder (Bennett, 2016).

Given the range of thunderstorm detection techniques available to an aerodrome, it is useful to assess their relative performance. With this aim, a BTD-300 sensor was installed in November 2017 at the WMO field intercomparison test bed in Vigna di Valle, approximately 30 km NW of Rome, Italy. The site is at an altitude of approximately 250m AMSL, near the southern shore of Lake Bracciano. This WMO site (ID 16224 - Vigna di Valle) is owned and operated by the Italian Air Force - Technical Centre for Meteorology, so hourly weather observations, including thunderstorm reports, were available from trained meteorological observers between 0600-1800 UTC nearly every day of the year. The third thunderstorm detection technique to be compared was data from Italy's established national lightning detection network (Lampinet). This network uses 15 Vaisala IMPACT ESP receivers (VLF/LF) installed around Italy and, like the BTD-300, is capable of detecting both cloud-to-ground and intracloud flashes (Biron et al., 2006).

Maps showing the location of the WMO field intercomparison site and BTD-300 reporting sectors are shown in Figure 1. The outer grey circle indicates the maximum reporting range of the BTD-300 (83 km), yellow defines distant lightning (56 km), orange is vicinity lightning

(19 km) and red is overhead lightning (9 km). These distances correspond to 45, 30, 10 and 5 nautical miles respectively. A picture of the sensor installed at the site is shown in Figure 2.

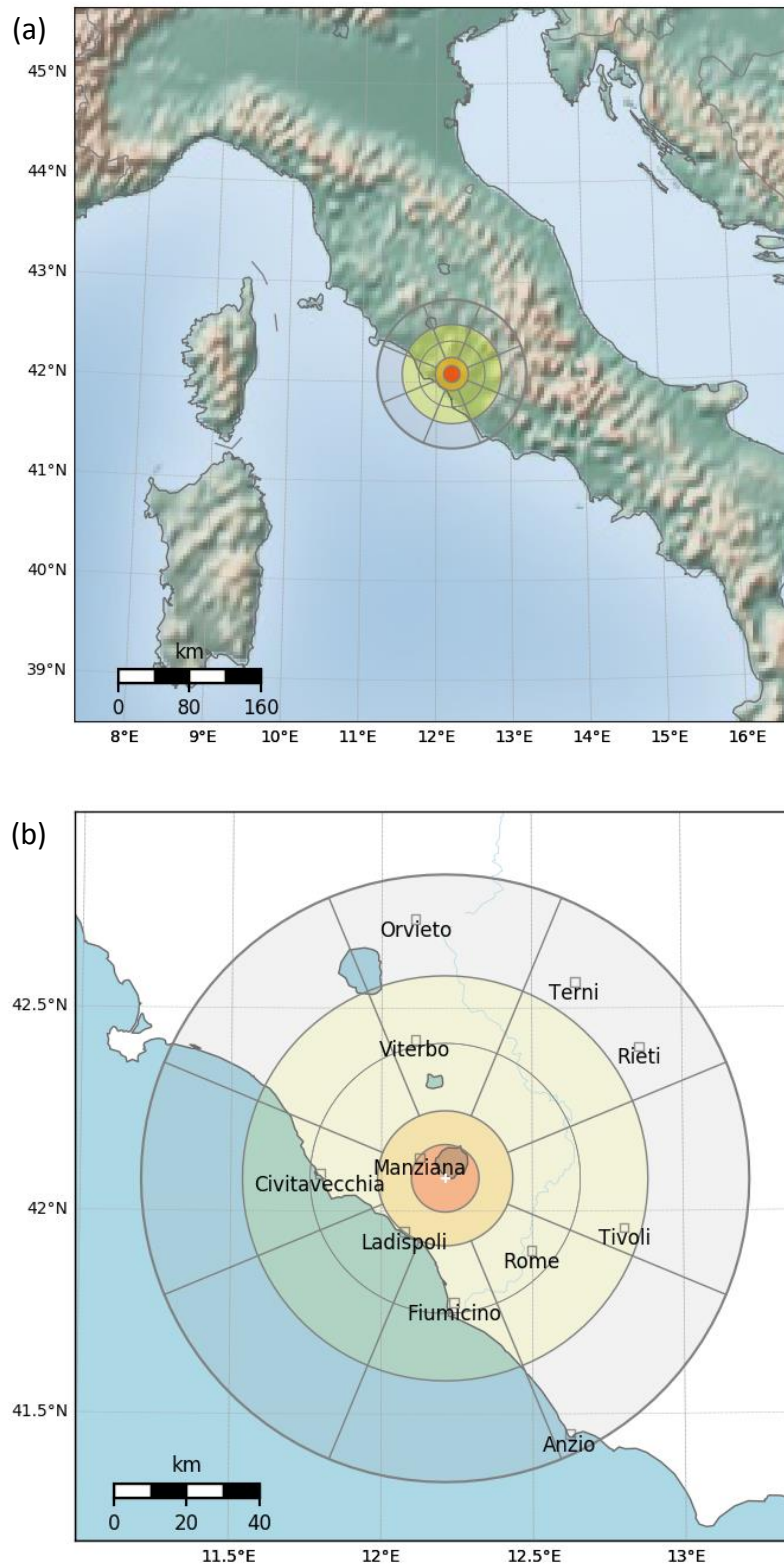


Figure 1: Map showing the location of the WMO field intercomparison site at Vigna di Valle, Italy in (a) regional and (b) local context. The concentric circles indicate BTD-300 reporting sectors.



Figure 2: Biral BTM-300 thunderstorm detector installed at the WMO field intercomparison test bed in Vigna di Valle, Italy.

2 Data selection and analysis method

The occurrence of local thunderstorm activity during the trial period between November 2017 and April 2018 was found by inspection of human observer records and events detected by the BTM-300. From these records, which were continuous, it was found that this time period had 16 days where at least one lightning flash in the vicinity (<19 km) was recorded. A subset of these days was chosen for detailed analysis, with days experiencing 10 or more flashes within 19 km being of particular interest. Thunderstorms where the first flash was nearby were also considered for more detailed review, with seven case studies selected for detailed assessment. The dates and BTM-300 flash totals for the seven case studies are shown in Table 1:

Date	Time (UTC)	BTM-300 flashes <20 km	BTM-300 flashes <83 km	Met Station Main event
29/11/2017	0600-1400	12	21	Thunderstorm
11/01/2018	0000-2359	0	53	Light Rain
2-3/02/2018	0000 (2 nd)-2359 (3 rd)	299	2035	Moderate Rain
19/03/2018	0100-1300	30	102	Thunderstorm
20/03/2018	1500-2300	13	74	Rain
01/04/2018	0300-1500	6	99	No obs
12/04/2018	1000-1300	17	242	Moderate Rain

TOTAL	377	2626	
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Table 1: Case studies during the trial period, with total number of flashes detected and the main event recorded by the Met observers.

The lightning detection network used for this comparison, Lampinet, fundamentally reports the time and location of lightning *strokes*, not *flashes* like the BTD-300, so a stroke grouping algorithm was used. The algorithm defines strokes of all types within 0.5s and 30 km as being of the same flash. Due to the relatively imprecise timing (order 1s) of the BTD-300 flashes compared to those detected by Lampinet, a flash was considered coincident if the time difference was less than 2s. This coincident detection technique was found to be reliable for low to moderate flash rates, although occasional misallocation of flashes as coincident was apparent when the network detected frequent lightning activity. Distant but active thunderstorms meant that lightning was occasionally misallocated to flashes from closer storms detected by the BTD-300. This misallocation was suspected for less than 5% of coincident flashes, although it was considered a contributing factor to the deviation of distances reported by the two systems, especially for instances of apparent BTD-300 distance underestimation.

3 Comparison results

3.1 First warning of local thunderstorm activity

A vital function of any thunderstorm detection technique is to provide warning when the first thunderstorm activity occurs in the local area. With this in consideration, the three techniques were assessed for their ability to provide a timely warning of the onset of lightning activity for the seven case study days. Graphs of the time and warning level for each technique have been plotted with time for ease of comparison. The colour code for flash proximity is blue, orange and red, corresponding to distant, vicinity and overhead lightning respectively. Times when the BTD-300 detected charged precipitation and strong electric field variability are coloured blue and orange respectively. Colour coding for the hourly human observations are grey for towering cumulus, black for cumulonimbus and black with a red cross for thunderstorm. The duration of the case study day where human observations were available is highlighted with a green background.

3.1.1 Case study 29/11/2017

The first indication of local thunderstorm activity was charged precipitation detected by BTD-300 at 08:03:48 UTC. This was shortly followed by a flash 9 km from the site at 08:11:03, detected by both the BTD-300 and Lampinet. The human observer in the hourly messages, reported light rain and overcast conditions from 0600, with Cumulonimbus (Cb) reported in the 0900-1800 observations and thunderstorms reported from 1000-1500. Neither the BTD-300 or Lampinet reported lightning within half an hour of the 1100, 1200 and 1400 and 1500 human observations stating thunderstorm with rain at the site. This discrepancy may be explained with the general rule for observers to wait a reasonable period of time before closing the thunderstorm event, in order to prevent the main risks for aviation from being missed when meteorological conditions are in transition. A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 3. Both the BTD-300 and Lampinet were in good agreement with flash occurrence and proximity.

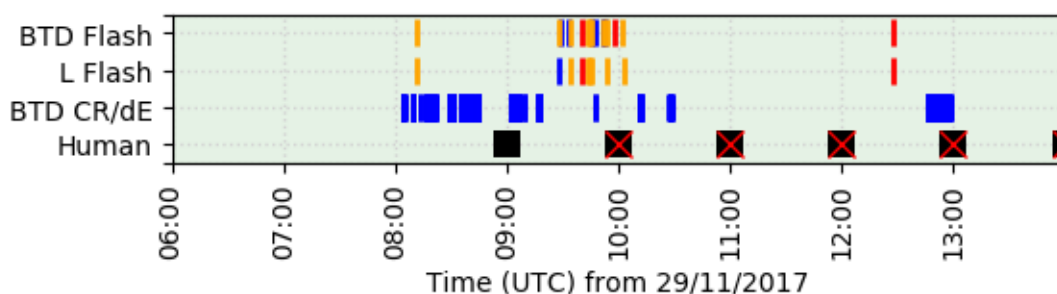


Figure 3: Detection overview for the 29/11/2017 case study period. Time of BTD-300 (“BTD Flash”) and Lampinet (“L- Flash”) flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.2 Case study 11/01/2018

No reported flashes in the vicinity, although both BTD-300 and Lampinet detected distant lightning in the afternoon. No thunderstorms or Cumulonimbus clouds were reported by the human observer. Lampinet closest flash was 54 km (14:23:38), which was also reported by the BTD-300, at 52 km. BTD-300 tended to underestimate flash distance during this time, with closest flash reported as 31 km at 15:08:40.

A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 4. The underreporting of flash distance with time by the BTD-300 during the afternoon can be seen as the longer duration of distant flashes. Whilst these were genuine flashes, their range from the site was actually just beyond the 56 km threshold. Many of the flash distances underestimated by the BTD-300 were of considerable peak current (>100 kA) according to Lampinet. Flashes with large peak currents may also have charge moments significantly greater than that assumed by the BTD-300, hence the tendency for their distance to be underestimated. Charged precipitation detected by the BTD-300 during the early morning suggests that Cumulonimbus cloud was overhead, but did not produce lightning. In the messages of early morning, the observer reported light continuous rain, while in the afternoon non-continuous light rain. These observations are consistent with the end of stormy event and with a distant one, respectively.

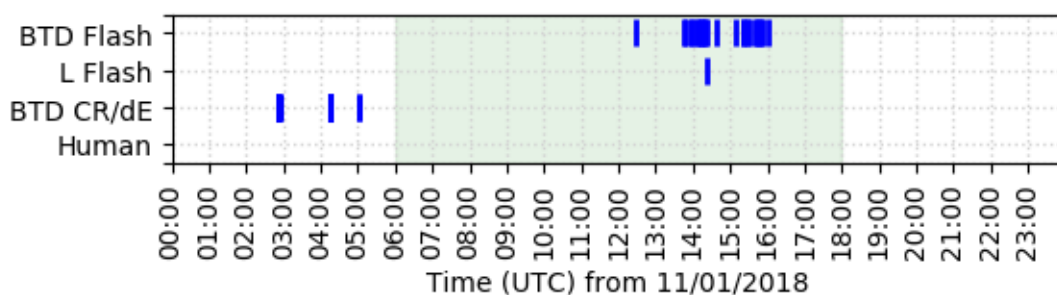


Figure 4: Detection overview for the 11/01/2018 case study period. Time of BTD-300 (“BTD Flash”) and Lampinet (“L- Flash”) flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human

observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.3 Case study 2-3/02/2018

The day began with charged precipitation reported by the BTD-300 at 01:10:24, followed by lightning in the vicinity first detected by the BTD-300 at 01:47:50. This flash was missed by Lampinet, which detected its first flash 87s later at 01:49:17, also in the vicinity. Human observations reported TCu (Towering Cumulus) and light rain at 0800 and 0900 but no Cb or thunderstorm. This is consistent with lightning reported only beyond the vicinity of the site. Both the BTD-300 and Lampinet detected lightning within the vicinity of the site just before 11:00, which was the time the first human observation of Cb was recorded. A graph of lightning flash detected by the BTD-300 and Lampinet between 0700-1300 is shown in Figure 5.

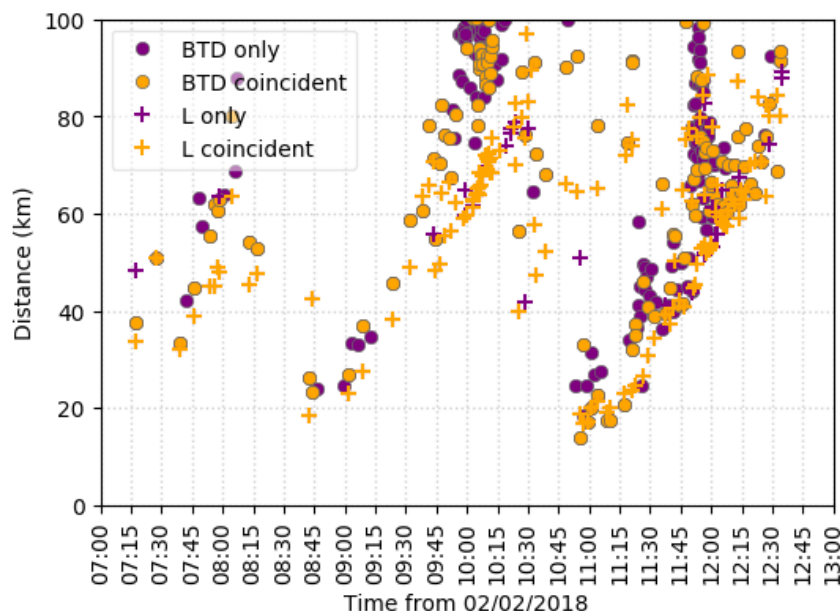


Figure 5: Time and distance of flashes detected by the BTD-300 (circles) and Lampinet (crosses) between 0700-1300 UTC on 02/02/2018. Coincident flashes detected within 2 seconds of both detection systems are coloured orange, with those detected by only one of the systems coloured purple.

Later this day, both BTD-300 and Lampinet detected distant lightning from approximately 23:30. This was the first indication of an active, high flash rate thunderstorm directly approaching the site from the SW. The time and distance of flashes detected by the BTD-300 and Lampinet as this storm approached are shown in Figure 6. This event was the main contributor to flash data during the whole field trial period.

A strong electric field variability warning was issued by the BTD-300 at 00:14:50 on 3rd, when the closest flashes were 12 km away. Flashes became overhead 4 minutes later. This storm occurred outside of office hours, so no human observer data were available.

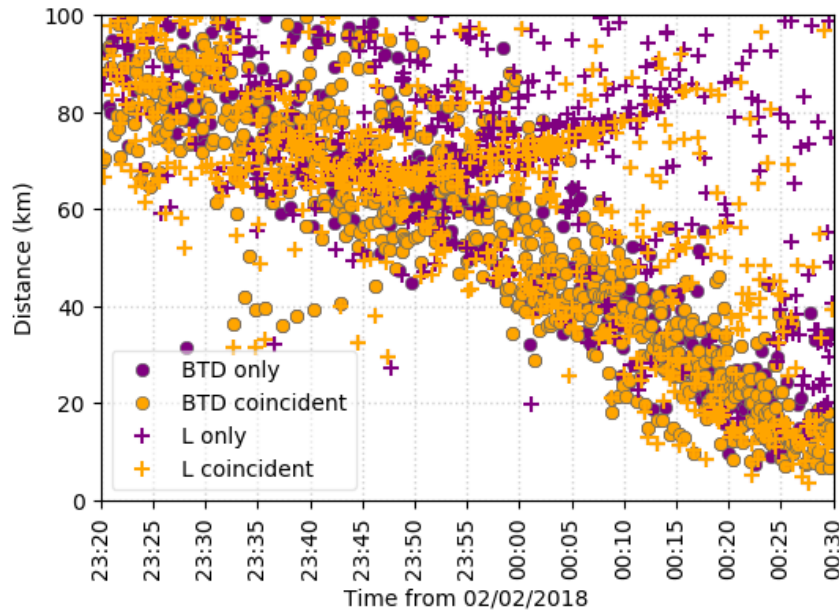


Figure 6: Time and distance of flashes detected by the BTD-300 (circles) and Lampinet (crosses) between 2320 on 02/02/2018 and 0030 UTC on 03/02/2018. Coincident flashes detected within 2 seconds of both detection systems are coloured orange, with those detected by only one of the systems coloured purple.

Human observations reported Towering Cumulus cloud at 1600 on 3rd, which was close to the time where distant lightning was reported by both the BTD-300 and Lampinet. A summary of the time and type of thunderstorm warning data during this two-day case study period is shown in Figure 7.

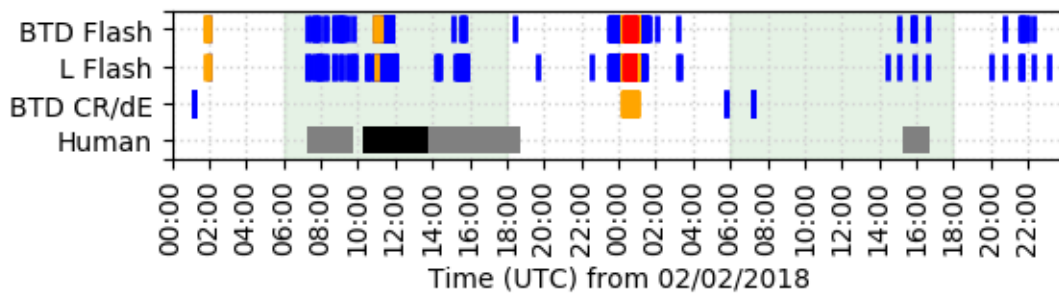


Figure 7: Detection overview for the 02-03/02/2018 case study period. Time of BTD-300 (“BTD Flash”) and Lampinet (“L- Flash”) flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.4 Case study 19/03/2018

A single distant flash at 01:09:57 was detected by both the BTD-300 (61 km) and Lampinet (55 km), although only Lampinet's range fell within the 56 km threshold for distant lightning definition. Charged precipitation was detected by the BTD-300 at 02:49:46, followed approximately 10 minutes later by a 22 km flash occurring at 03:00:11. This flash was detected by both BTD-300 and Lampinet.

The first vicinity flash was recorded by the BTD-300 at 05:22:45, which was not seen by Lampinet. Charged rain was also detected at 05:46:48 and closest flash (4 km) occurred approximately 6 minutes afterwards, at 05:52:11. Human observations recorded thunderstorm and rain from the start of their shift at 0600 and at 1100, approximately the same time as the lightning detectors recorded their last distant flash. Lightning was in the vicinity of the site at the 0900 and 1000 observations. The observer reported at 0900 rain just finished and thunderstorm during the previous hour, at 1000 only rain and again, at 1100, thunderstorm during the previous hour.

A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 8.

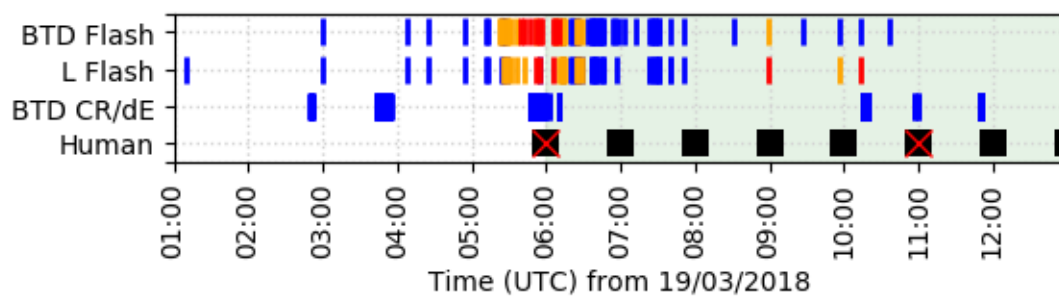


Figure 8: Detection overview for the 19/03/2018 case study period. Time of BTD-300 ("BTD Flash") and Lampinet ("L-Flash") flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.5 Case study 20/03/2018

Distant lightning was detected between approximately 1640 and 1740, with closest approach of ~35 km. Nothing reported by human observers except for the presence of Towering Cumulus cloud.

Charged precipitation was detected by the BTD-300 from 18:15:19, shortly after the end of the human observation period. This was followed nearly 4 minutes later by an isolated, but very close, flash 4 km away at 18:19:43. This flash was a powerful 121 kA positive cloud-to-ground event and was detected by both the BTD-300 and Lampinet, approximately 40 minutes since the last recorded flash. In this instance, the only warning of this potentially dangerous event was provided by the detection of charged rainfall falling at the site, indicative of an overhead Cumulonimbus.

More overhead lightning occurred later in the evening. Warnings triggered by distant lightning detection were already active for the overhead lightning just after 2000, but not

for the ~10 km flash at 20:50:40. Like the powerful flash of 1819, the only warning for this isolated nearby flash came from charged precipitation, detected by the BTD-300 between 20:28:54-20:33:56. According to Lampinet, this flash had a very high peak current of 256 kA, so also a potentially dangerous positive event.

A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 9.

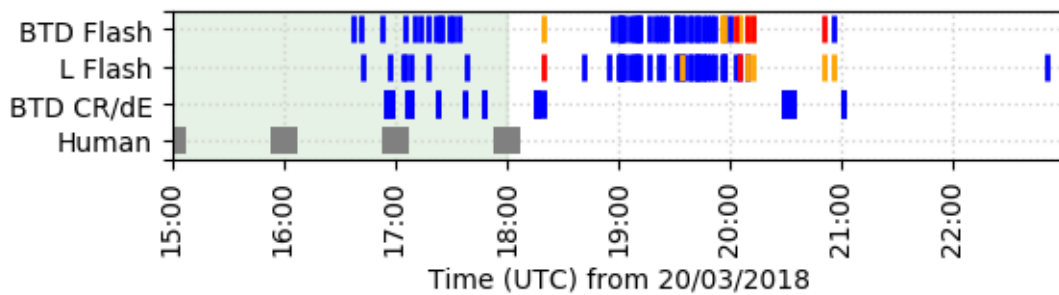


Figure 9: Detection overview for the 20/03/2018 case study period. Time of BTD-300 (“BTD Flash”) and Lampinet (“L- Flash”) flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.6 Case study 01/04/2018

The first warning came from charged precipitation at 03:19:25, followed approximately 9 minutes later by the first flash at 03:28:11 (19 km), detected by the BTD-300 and Lampinet. The last flash of this storm was detected by the BTD-300 at 03:52:42, 10 km from the site. The BTD-300 detected 7 flashes, with the last (and closest) three not detected by Lampinet. No lightning was detected in the vicinity through the rest of the day, but distant lightning was detected by both systems before 0500 and around 0600 as well as between approximately 1300-1400. Since this day was the Easter Sunday holiday, no human observations were available.

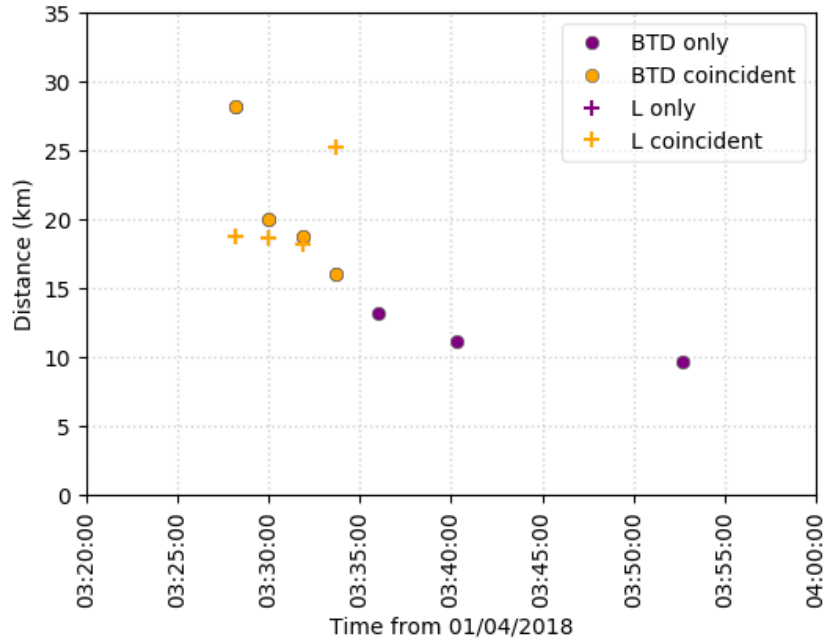


Figure 10: Time and distance of flashes detected by the BTD-300 (circles) and Lampinet (crosses) between 0320-0400 UTC on 01/04/2018. Coincident flashes detected within 2 seconds of both detection systems are coloured orange, with those detected by only one of the systems coloured purple.

A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 11.

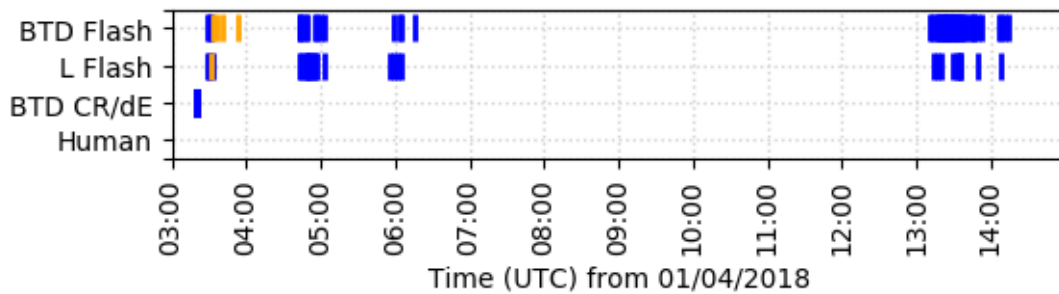


Figure 11: Detection overview for the 01/04/2018 case study period. Time of BTD-300 ("BTD Flash") and Lampinet ("L- Flash") flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.1.7 Case study 12/04/2018

The first distant lightning was reported at 10:38:08 (52 km) by the BTD-300 only. The BTD-300 also detected charged rain from 10:45:18, followed 22s after by the first flash detected by Lampinet at 10:45:40 (20 km). Both systems detected the first vicinity flash shortly after at 10:48:13 (13 km). The closest flash was at 10:54:19 with a range reported by Lampinet as 5 km. This flash range was overestimated by the BTD-300, which reported it to be 26 km. However, an overhead lightning alert was still active for the BTD-300 since it detected an 8

km flash 6 minutes beforehand, at 10:48:13. The time and distance of flashes detected during this time are shown in Figure 12.

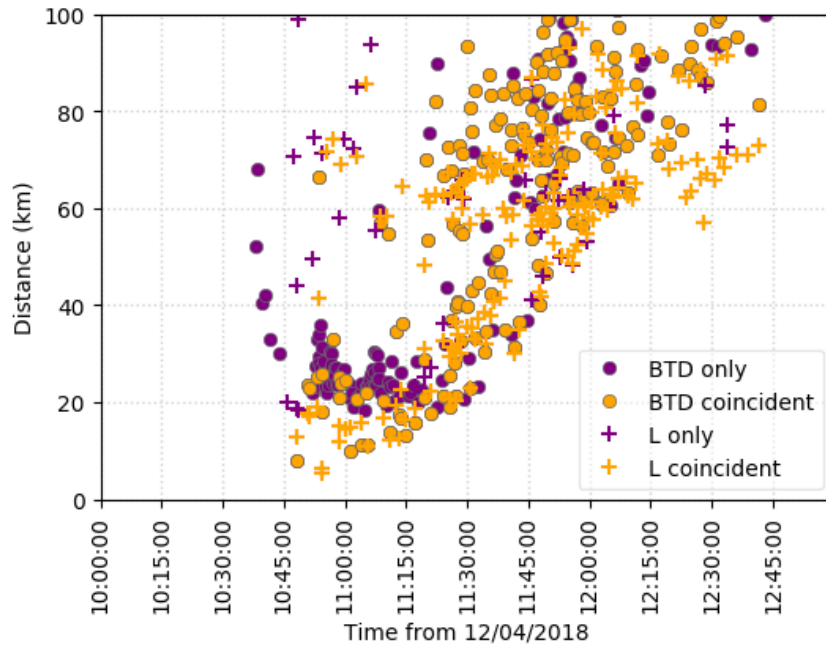


Figure 12: Time and distance of flashes detected by the BTD-300 (circles) and Lampinet (crosses) between 1000-1300 UTC on 12/04/2018. Coincident flashes detected within 2 seconds of both detection systems are coloured orange, with those detected by only one of the systems coloured purple.

No thunderstorms were reported by the human observers during this day, despite overhead lightning. However, Cumulonimbus cloud was reported at 11:00 along with intermittent rain and quite low visibility of 6 km. It is suggested that the combination of poor visibility, overcast, infrequent nearby lightning and bright conditions near local solar noon may have contributed to hide the flash of light and sound of thunder produced by the lightning.

A summary of the time and type of thunderstorm warning data during this case study period is shown in Figure 13.

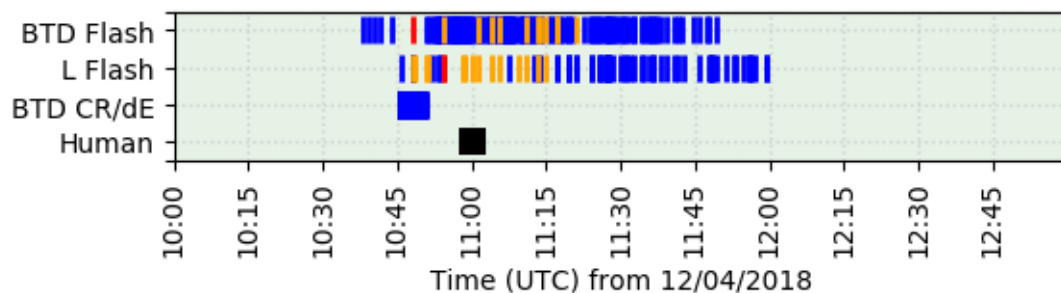


Figure 13: Detection overview for the 12/04/2018 case study period. Time of BTD-300 (“BTD Flash”) and Lampinet (“L- Flash”) flash detection, with colour-coded proximity. The time of charged precipitation and/or strong electric field variability detected by the BTD-300 (BTD CR/dE) and human observations of deep convection and thunderstorms are also indicated. See section 3.1 for an explanation of the colour codes.

3.2 *BTD-300 compared to Lampinet*

Whilst the individual case studies identified some occasions where a difference existed between the timing and ranging of lightning by Lampinet and the BTD-300, it is useful to combine all these data from the seven case studies to produce a more generalised, quantitative analysis. The combined dataset contained 2772 coincident flashes.

3.2.1 *Flash relative detection efficiency*

The flash relative detection efficiency is the number of flashes detected by the BTD-300 compared to Lampinet, expressed as a percentage. This performance metric was determined by grouping the flash distances into 10 km bins and counting the total number of flashes detected by each system. The flash totals and relative detection efficiency is shown in Figure 14. From this figure, it is evident that the BTD-300 detected more than twice as many flashes within 10 km of the site compared to Lampinet, with the relative detection efficiency falling with distance to reach equal totals (100%) by 50-60 km. Lampinet detected more flashes than the BTD-300 beyond 60 km, with the BTD-300 relative detection efficiency dropping below 80%.

The significantly greater sensitivity of the BTD-300 at shorter range is likely to be the result of the larger signal to noise ratio from the larger electric field changes associated with nearby lightning, compared to distant flashes. The inverse cube relationship of electrostatic field with distance (Bennett, 2013) means that sensors such as the BTD-300 which measure electrostatic field changes are characterised by high sensitivity performance at short range around the site, but with a pronounced reduction with distance. Thunderstorm detection techniques using radio-receiver based networks like Lampinet have a more spatially uniform performance at these 100 km length scales, although there is an inevitable compromise between receiver baseline and sensitivity, given the requirement for the signal to be received simultaneously at multiple locations.

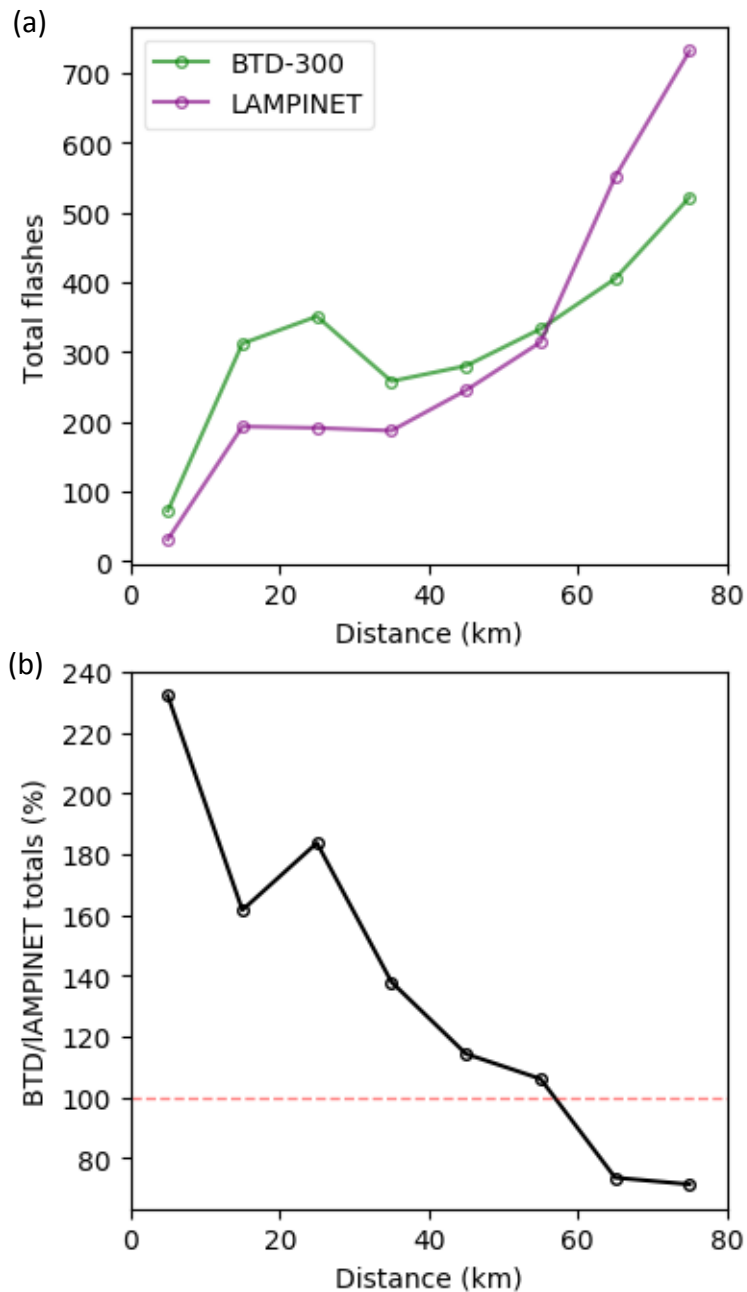


Figure 14: Total number of flashes detected by the BTD-300 and Lampinet, with proximity to the site (a) and corresponding relative flash detection efficiency of the BTD-300 compared to Lampinet (b). Both graphs use 10 km bins and data from all the case study days.

3.2.2 Flash distance

A comparison between the distance to flashes detected by both the BTD-300 and Lampinet was made, with the summary statistics for different lightning proximities given in Table 2. The difference for each coincident flash was calculated by subtracting the Lampinet range from the BTD-300 range.

The median difference for both overhead/vicinity (<19 km) and distant (19-56 km) flashes was relatively small, at 0.6 km. For flashes within 19 km, half of the differences were between -2.1 and 6.4 km. This increased to -7.0 km to 8.0 km for the 19-56 km flashes,

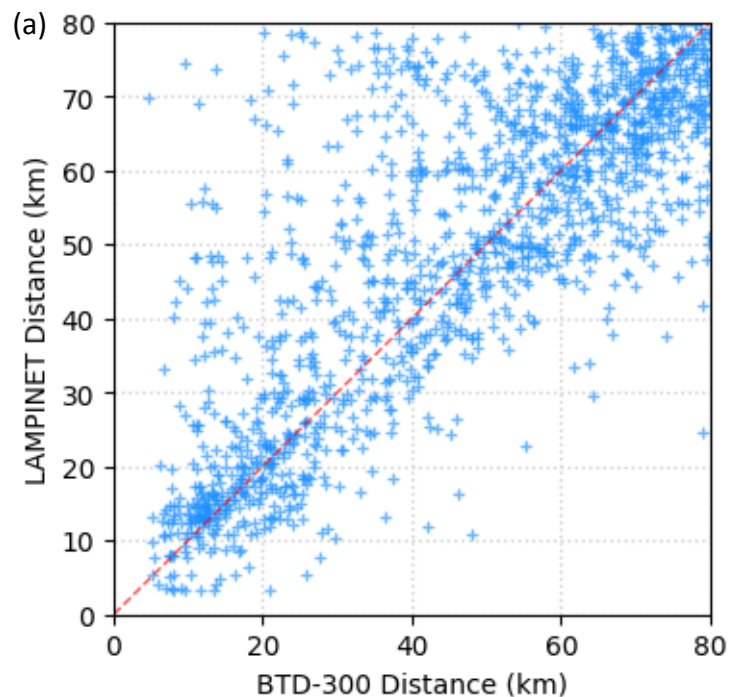
probably on account of the smaller signal to noise ratio of the BTD-300 with increased distance from the source.

	Median (km)	25 th percentile (km)	75 th percentile (km)
Overhead/Vicinity (<19 km)	0.6	-2.1	6.4
Distant (19-56 km)	0.6	-7.0	8.0

Table 2: Median, 25th and 75th percentile of difference between coincident flashes detected by the BTD-300 and Lampinet. Coincident flash distance defined by Lampinet.

Graphical representations of the differences are shown in Figure 15. The scatter plot of Figure 15(a) identifies the overall linear correspondence between the two systems, but also the relatively small proportion of coincident flashes with large differences in estimated range. At least some of these outliers are thought to be related to coincident flash misallocation during high flash rate storms of large spatial extent, given that the timing accuracy of the BTD-300 was $\sim 2s$.

The histogram of Figure 15(b) shows that whilst the modal bins were adjacent to the zero difference line and with a relatively symmetrical distribution, there appears to be a slight tendency for the BTD-300 to underestimate flash distance compared to Lampinet, for differences within 30 km.



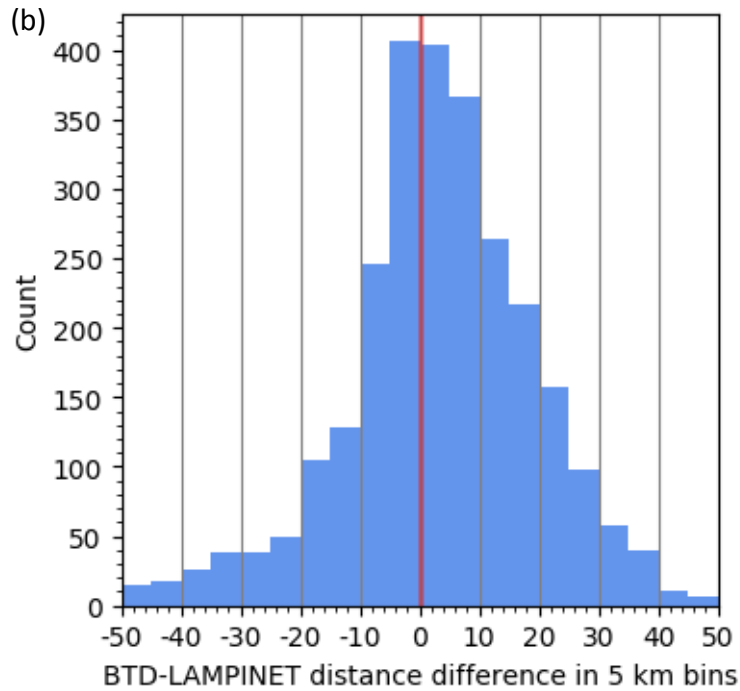


Figure 15: Scatter plot of BTD-300 and Lampinet distance estimation for coincident flashes (a) and histogram of their differences (b), using data from all case study days. The red lines correspond to zero difference.

3.2.3 Flash direction

In addition to flash ranging, the BTD-300 also provides a direction to the flash, enabling the location to be determined. An example of the flash locations produced by the BTD-300 and Lampinet are shown in Figure 16. If the received radio signal strength is below a quality control threshold, the BTD-300 returns “999” and no flash is plotted on the map. Of the 2772 coincident flashes, 1909 (69%) were given a bearing by the BTD-300.

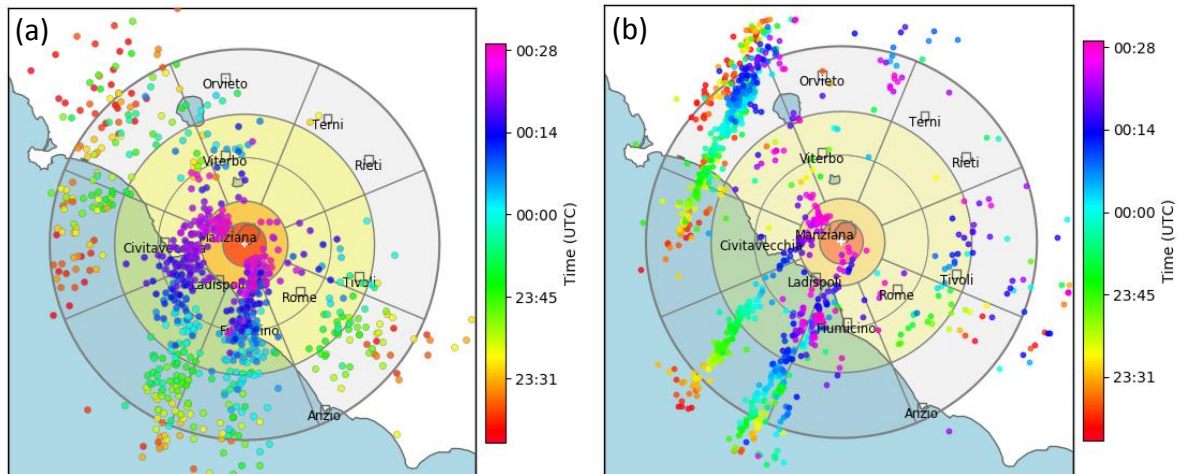


Figure 16: Flash locations between 2320 UTC on 02/02/18 and 0030 UTC on 03/02/2018 for (a) BTD-300 and (b) Lampinet.

Examination of Figure 16 indicates that whilst there is overall good agreement between the systems, a $\sim 20^\circ$ difference in flash direction between the BTD-300 compared to Lampinet is evident, especially for more distant flashes. This is realised more easily by the bearing

difference scatterplot (Figure 17) and histogram (Figure 18). Overall, 65% of BTD-Lampinet bearing differences were within an octant ($\pm 22.5^\circ$). At this site an offset of ~ 12 degrees is evident. Such offsets can be due to uncertainty of the direction of magnetic north when installing the sensor, or non-perpendicular antennas to the direction finder electronics enclosure side during manufacture. Once determined, systematic offsets are removed using the BTD-300 software. The histogram of offset-corrected bearing difference is shown in Figure 19, which increases the percentage of differences with an octant to 73% and within 5 degrees to 24%.

From Figure 17 it can also be seen that in addition to the systematic (bearing independent) offset, there is also a bearing-dependent offset, forming an oscillating pattern on the direction difference plot. This characteristic pattern is due to artefacts of the surrounding site such as nearby ferrous material or long conductors which can re-radiate the lightning signal and distort the arrival angle (e.g. Maier et al., 1983). Once determined, a site-dependent correction can be applied, which will take the form of a skewed double frequency sinusoidal, as described by equation (1).

$$\text{Correction} = A \sin \left(2B + \frac{\sin(2B+P)}{2} + P \right) \quad (1)$$

Where A is the amplitude of the bearing deviation, B is the uncorrected bearing and P is the phase shift. Both A and P will be site specific. A correction was modelled for this site and shown in Figure 20. The combined systematic and site-dependent offset corrections reduced the flash direction difference so that 46% of the differences were within 5 degrees. The histogram of corrected differences is shown in Figure 21. Note that whilst systematic offsets can be automatically corrected for by the BTD-300, bearing-dependent ones cannot currently be automatically compensated for by the software.

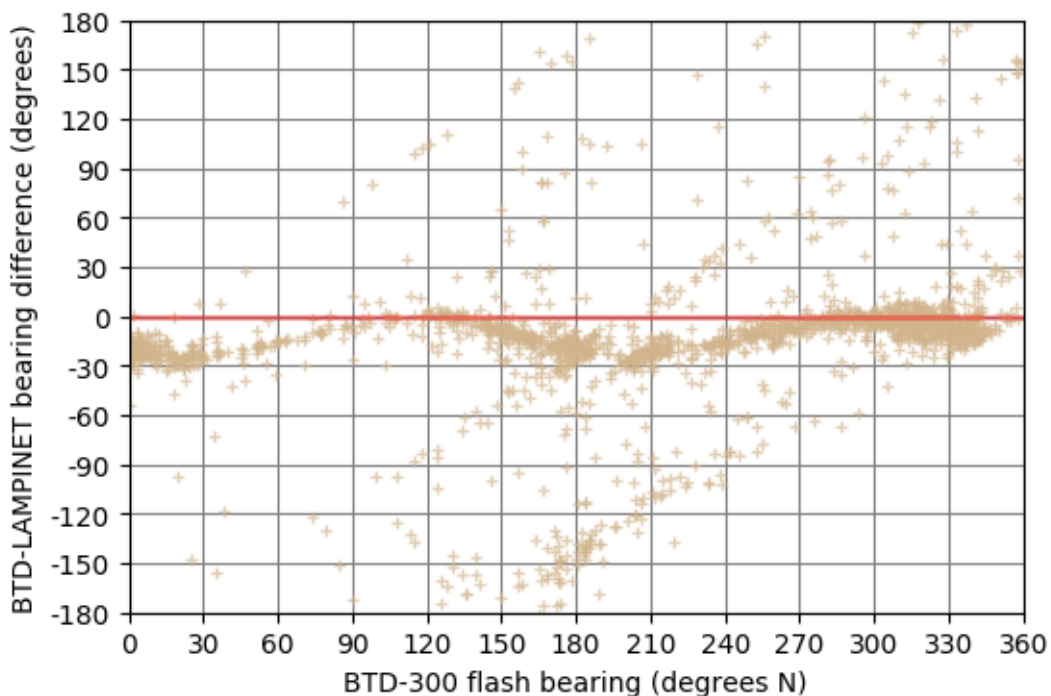


Figure 17: BTD-Lampinet flash bearing difference for the combined dataset

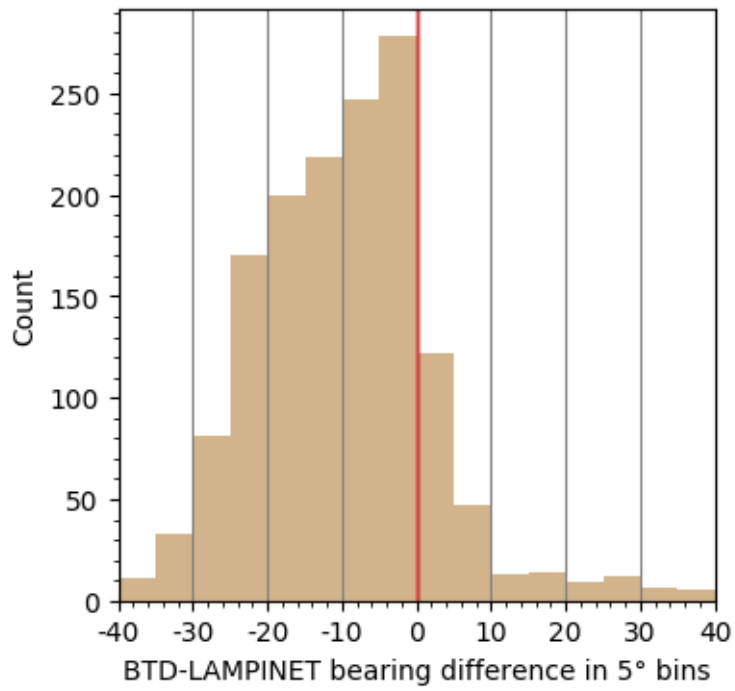


Figure 18: BTD-Lampinet bearing difference

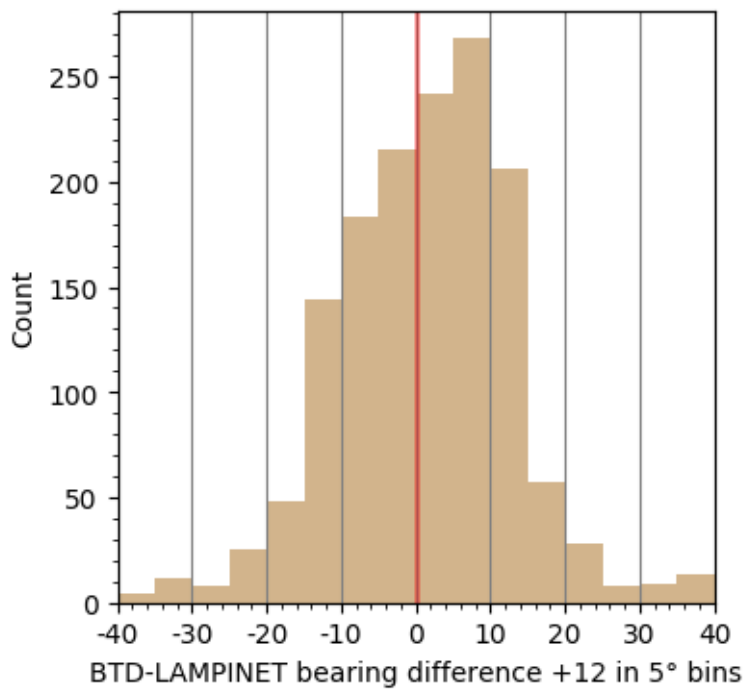


Figure 19: BTD-Lampinet bearing difference with 12° offset correction

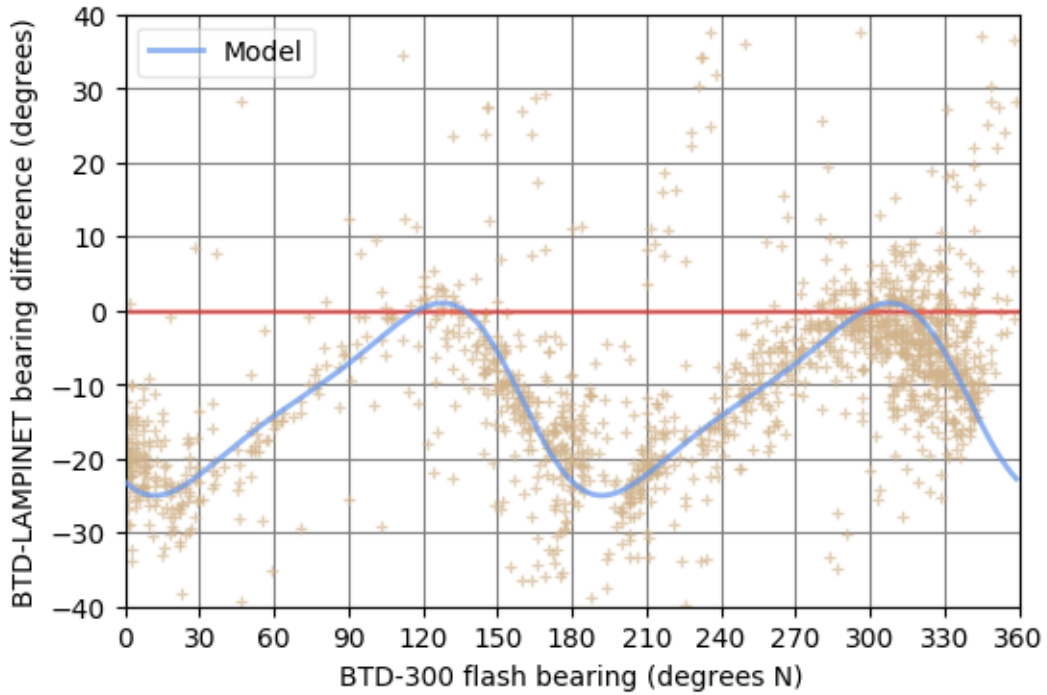


Figure 20: BTD-Lampinet flash bearing difference, with the addition of a double sinusoidal model

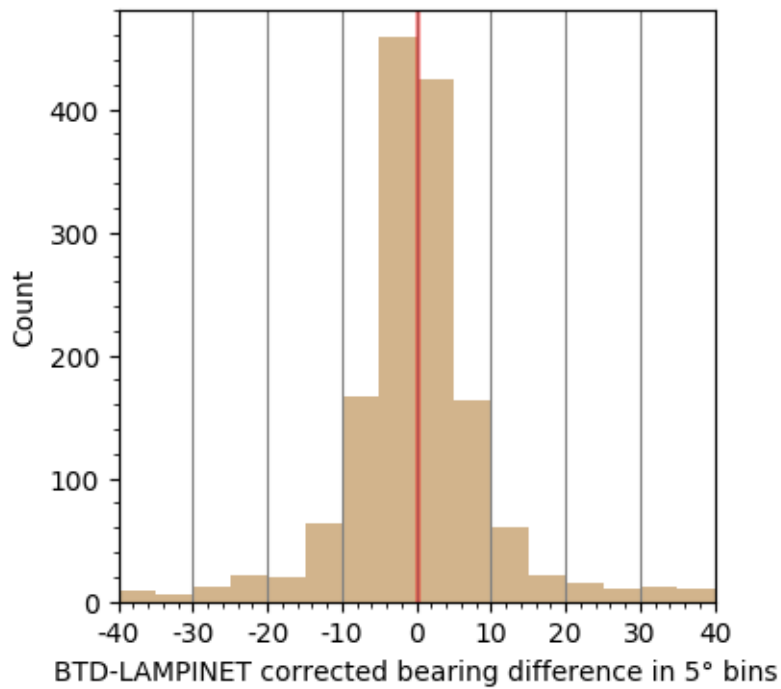


Figure 21: BTD-Lampinet bearing difference, with BTD values corrected for systematic and site-dependent offsets

3.3 Comparison with human observations

During the 6 month trial period, including case studies, 16 days presented at least one lightning flash recorded by the BTD-300 in the vicinity (<19 km), 8 of which had activity

overhead (<9 km). Not all of them have been reported or appreciated by the observer, mainly because they occurred outside of observer working shift (0600-1800 for 6 days a week). Based on long term (4 year) trials by Biral, customer feedback and comparison with other lightning location networks, it is considered very unlikely that the BTD-300 would report false flashes within 19 km, due to the large and unambiguous electrostatic signal required.

The observers of Vigna di Valle Met Station reported that the ability of the BTD-300 to show storm activity approaching the site in real time is useful to safeguard some observing systems particularly sensitive to electrical discharge (e.g. Brewer spectrophotometer) that are operating in Vigna di Valle. On the other hand, observer noted some screen freezing events, which needed the reboot of the operating software.

The dates where either the BTD-300 reported lightning <19 within observer reporting hours and/or observations of thunderstorm, CB or TCU were reported by the human observer are shown in Table 3:

Date	BTB300 (>=1 flash between 0600 and 1800)	Observer's report
29/11/2017	Vicinity	thunderstorm 1000-1700
15/12/2018	BTB not logging at this time	thunderstorm at 1700
27/12/2017	BTB not logging at this time	thunderstorm at 0900
02/02/2018	Vicinity	CB-TCU and rain
03/02/2018	Distant (vicinity outside hours)	CB-TCU and rain
06/02/2018	Vicinity	CB-TCU and rain
07/02/2018	Vicinity	thunderstorm 1000-1200
07/03/2018	BTB not logging at this time	thunderstorm 1300-1800
11/03/2018	Vicinity	no obs available
12/03/2018	Vicinity	TCU and rain
17/03/2018	Vicinity	TCU -CU
18/03/2018	Vicinity	no obs available
19/03/2018	Overhead	thunderstorm 0600-1300
20/03/2018	Vicinity	TCU -CU and rain
31/03/2018	Overhead	thunderstorm 1600-1800
01/04/2018	Vicinity	no obs available
04/04/2018	Vicinity outside hours only	TCU -CU and rain
05/04/2018	Vicinity	CB-TCU and rain
12/04/2018	Overhead	CB-TCU and rain

Table 3: Dates where the BTB-300 reported at least one flash within 19 km and/or human observations of a thunderstorm at the site.

3.4 Non-lightning warning flags of the BTB-300

An assessment of the performance of the non-lightning warning flags provided by the BTB-300 gave the following results, where CR is charged precipitation (rain in most instances), dE is strong electric field variability (corona) and DL is distant lightning (Table 4):

	CR	dE	DL
Probability of Detection (POD)	0.64	0.66	0.94
False Alarm Ratio (FAR)	0.19	0.01	0.26

Table 4: POD and FAR relating to early warning of flashes <19 km using charged precipitation, strong electric field variability and distant lightning. All measurements made using the BTD-300.

These findings indicate that distant lightning gives the highest probability of detection of nearby (overhead or vicinity) lightning within the next 30 minutes, at 94%. Approximately 65% of nearby lightning was preceded by CR or dE triggers. However, when CR or dE triggers were activated, they had a lower false alarm ratio than distant lightning, with dE having a false alarm ratio of only 1%.

4 Conclusions

All human observed thunderstorms were detected by the BTD-300 but this is not true to the contrary. The days where human observation reported deep convective cloud but no thunderstorm, despite lightning being in the vicinity (or even overhead), demonstrates that whilst deep convective cloud can be readily identified within the vicinity of a site during daylight, lightning is more challenging to observe reliably without appropriate instrumentation.

When comparing the BTD-300 to the Lampinet lightning location network, this single-site sensor detected more than twice the number of flashes as the network within 10 km, with totals exceeding that of Lampinet until 50-60 km from the site, beyond which Lampinet had the higher detection efficiency. Considering that the nearest Lampinet sensor was far from the BTD-300 at about 60 km, and the "Net Conception" of Lampinet, with 15 receivers for the whole national territory, requires a compromise between receiver baseline and sensitivity, further investigation at the same site of a Lampinet sensor should be done to test the performance in depth.

Differences in flash distance estimation were apparent between the two methods which increased with distance from the site, but the differences typically were within 10 km. The BTD-300 exhibited both systematic and bearing-dependent differences in flash direction compared to Lampinet, which were likely to be due to site-specific sources. Approximately three quarters of the offset-corrected flash directions agreed to within an octant ($\pm 22.5^\circ$).

With regards to non-flash warning triggers from the BTD-300, charged precipitation and strong electric field variability provided additional lead time of local thunderstorm activity in some instances, which would not have been possible using lightning detection alone. The relatively low probability of detection of these triggers means that they cannot be relied upon without the addition of lightning detection, although when activated they are a useful indicator of imminent nearby lightning activity.

Acknowledgements

The authors thank Antonio Spalletta from S3Consulting for his assistance in arranging the trial, Marco Taliani from gm-servizi for installing the BTD-300 and the meteorological

observation team at Vigna di Valle for their observation records with particular reference to thunderstorm activity. The Lampinet data were supplied by the Italian Air Force.

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