WPD ALARM Phase 2 Further Findings

Project Deliverables 7 and 8 combined

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Introduction

Document purpose

The purpose of this document is to report the NIA WPD ALARM project phase 2 initial findings.

Audience

This document is addressed to Stuart Fowler of Western Power Distribution.

Scope

This report covers the further findings part of the WPD ALARM Project phase 2 distance-to-fault functionality.

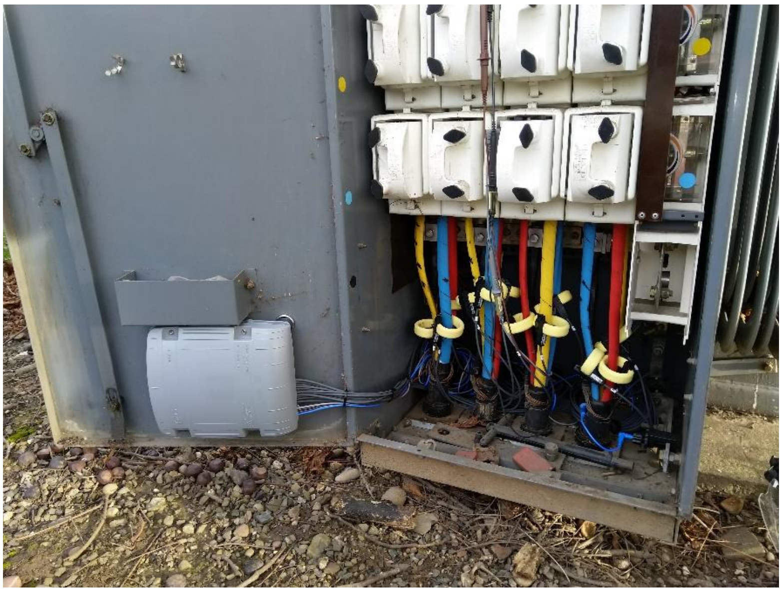
This report does not include the technical implementation of the distance to fault solution.

Background

The WPD ALARM project is an OFGEM NIA Project awarded to GridKey by Western Power Distribution (WPD) Ltd.

The purpose of the project is to test the feasibility of predicting the distance of potential faults in the low voltage electricity network by capturing and measuring transients generated by electrical arcing where cables and/or joints are starting to break down. These transients are commonly known as pecking events.

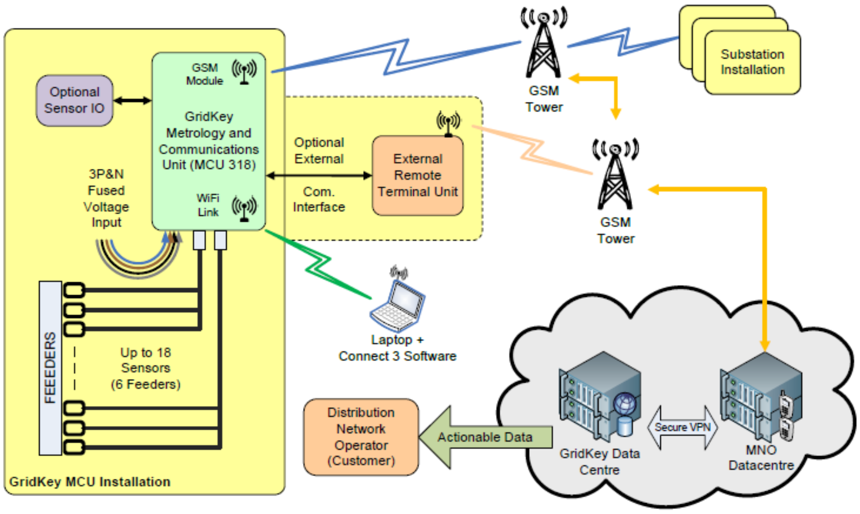
The system utilises GridKey MCU318 units which are fitted to low voltage substations. Each unit measures the bus-bar voltages for each phase with respect to neutral. It also uses Rogowski-coil sensors to monitor the currents in each feeder/phase. The photograph below shows a typical MCU318 installation with yellow sensor coils fitted around the phase conductors.



As it is unrealistic to generate these types of arc events in a laboratory or controlled conditions, WPD nominated various substations that were suspected to be active with pecking events for the distance to fault equipment to be fitted to.

To obtain the relevant data to calculate the distance to fault, the MCU318 was configured to capture voltage and current waveforms triggered by a high current transient detected in the downstream network. The captured waveforms are then uploaded to the GridKey datacentre and sorted into relevant, or non-relevant datasets, based on whether they fit the characteristics expected from an arc transient. The relevant data captures are fitted against an electrical model to estimate the distance that the transient occurred downstream from the substation transformer.

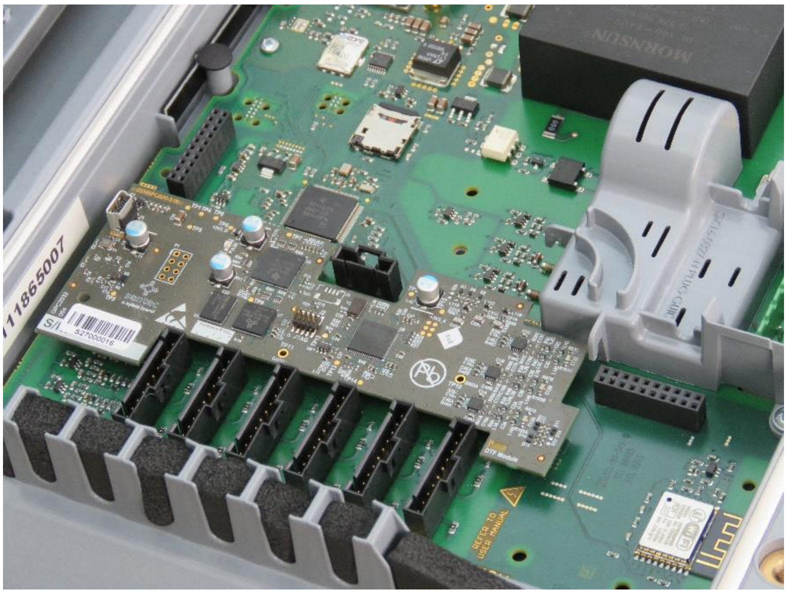
The picture below shows the connectivity of the GridKey system.



Because there is a certain amount of variation between events, the distance from the transformer to a potential fault cannot be determined reliably by a single event. However, as these events are numerous in nature, it is possible to capture many from each feeder so the range of the distances can be determined using statistical analysis of the relevant events recorded.

Phase 1 of this project was to establish how numerous these events actually are and if it is possible to collect the necessary data to determine a distance to fault measurement and build up relevant statistics. This utilised the MCU318's built-in circuits to quickly test the feasibility of the system and test the algorithms used as well as any other variables that need to be taken into account.

Phase 1 successfully demonstrated that it is possible to capture the relevant data from the waveforms. In phase 2 a daughter board was fitted into the MCU318 to measure the voltage and current with a greater resolution in time, higher bandwidth and greater dynamic range, thereby increasing the accuracy of the waveforms captured, with the expectation that this will lead to more accurate calculations. It is worth mentioning that – similarly to Phase 1 – also in Phase 2 the transient current waveforms are not captured on a per-feeder/per-phase basis. In fact, to simplify the architecture of the system, the transient currents measured are summed per phase across all connected feeders. A captured event therefore contains three voltage and three current waveforms, corresponding to the three phases. It is believed that this choice will not affect the accuracy of the distance predictions, since only one feeder is expected to create transients at any one instant. The allocation of a transient to a particular feeder is achieved using the on-board current measurement capability on the base board of the MCU318. The picture below shows the MCU318 with the high resolution capture daughter board fitted.



Project Schedule

The below table shows the status of the overall project. This report is to conclude milestone 7 as highlighted below.

Milestone	Milestone Description	Schedule date / Status
1	Install all PAB hardware	27/02/2020 - Complete
2	Phase 1 (PAB) Initial findings	04/06/2020 - Complete
3	Phase 1 (PAB) Further findings	04/09/2020 - Complete
4	Phase 1 (PAB) Closedown report	01/12/2020 - Complete
5	All active DTF boards installed	15/01/2021 - Complete
6	Phase 2 initial findings	19/02/2021 - Complete
7	Phase 2 further findings	11/06/2021
8	Phase 2 Closedown report	10/08/2021

These milestones were outlined in Western Power ALARM Project Statement of works dated 3rd September 2019.

Report

Further findings Objectives

The objectives for the further findings stage of phase 2 was to increase the confidence in the data the system produces, help increase the accuracy of the system and provide a useful tool to assist in the reduction of CI/CML in business as usual.

To achieve these objectives, the further findings part of phase 2 was separated into 4 focus areas:

1. Site status summary.

   A summary of the activity seen across all of the sites with the distance to fault with the distance to fault installed with a detailed analysis of the most active sites.

2. DTF Data spread analysis.

   This study was to identify any additional factors were contributing the distance uncertainty and/or patterns to the spread of the measurement distribution.

3. Verification of distance measurements.

   This objective was for Western power to independently correlate the pecking event distance calculations to actual and/or potential fault locations using technologies and techniques already in normal use.

4. Business as Usual Concept.

   This objective is to demonstrate how the data can be presented to local teams for WPD to interpret and action as the business requires.

Executive summary

Phase 2 equipment has successfully been deployed at 26 sites. In total, the programme collected and analysed in excess of 6500 pecking events.

Of the 26 sites monitored, 2 have been very active in comparison to the rest, collecting over 50% of the total number of events recorded. A variety of different behaviours were observed, with some sites having regular activity and others with pecking events recorded only in limited time periods with sudden onset and/or cessation. For some of the monitored substations, the analysis of the data is providing statistically reliable distance-to-fault (DTF) readings. Further work is needed to validate these findings. Initial validation using Kehui devices at Fairfield Crescent is consistent with the DTF data.

Six of the monitored sites have had fuse operations. Some of these fuse blows were associated with permanent faults that required on-site work to restore normal operation. In one case, (Nottingham Rd) the DTF indication matched the location of the fault found by the local team. At Gulson Rd, although there were only a few events detected prior to the fuse operation, the DTF data was found to be pointing at the correct location. In other cases, because the equipment has not been installed for an extended period, very few or zero pecking events were available therefore no distance indication could be provided.

When pecking events are recorded by the DTF system on a specific phase and feeder, the distance for each event is calculated and common distances counted. A histogram is then generated showing the frequency of events at each distance recorded. The peak of the histogram shows the most likely distance to the cause of the events with the remaining data spreading either side of the peak.

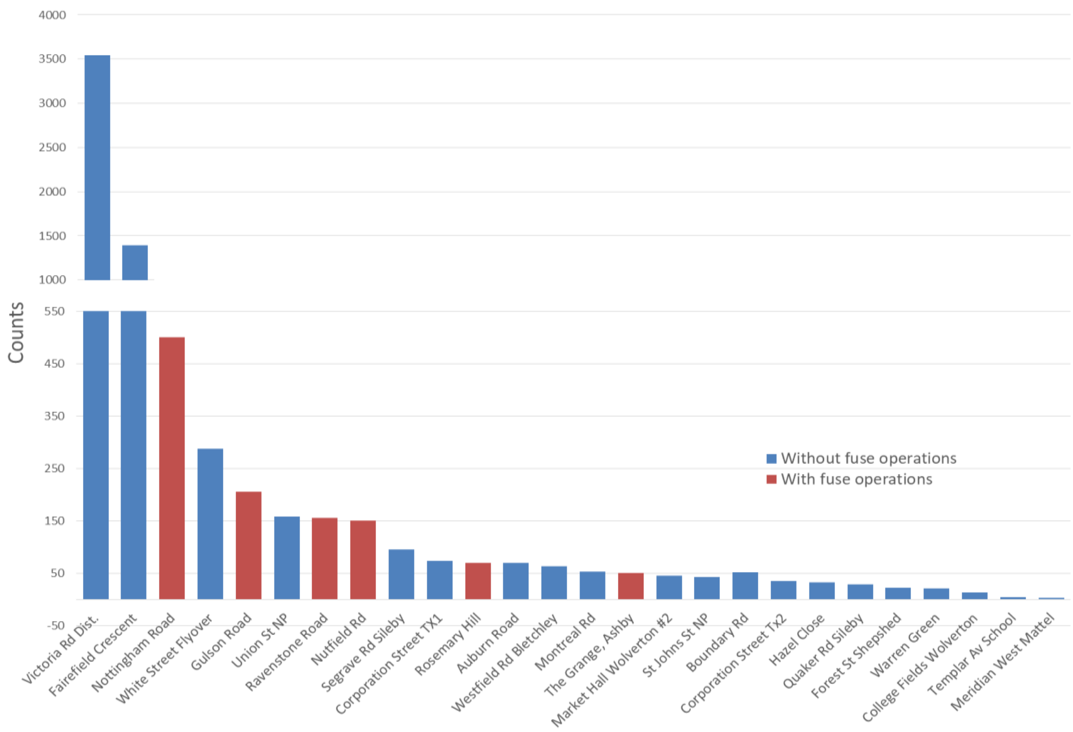
An improvement in the spread of the DTF indications after switching to Phase 2 hardware was observed on Fairefield Crescent, leading to a smaller statistical uncertainty in the location. On Victoria Rd., where a particularly broad distribution was observed, the standard deviation of the data did not improve with Phase 2 hardware, suggesting that for this substation the spread does not depend on the accuracy of the hardware. Even in this case, the ability of the DTF boards to capture more waveforms significantly reduces the statistical uncertainty on the fault location. In the case of Victoria Road, the distance error was reduced from 10m to 5.5m demonstrating a significant benefit using the active DtF board.

Additional investigations are being carried out to understand the variability observed in the DTF estimates.

Verification of the DTF algorithm prediction is being carried out by WPD in collaboration with Gridkey. Site Status Summary

Overall Site Status Overview

There are 26 sites being monitored with over 7150 pecking events collected and analysed. The chart below shows the number of events recorded at each of the sites.



Of the 26 sites monitored, 2 have been very active in comparison to the other 24, collecting over 50% of the total number of events recorded. The vertical axis has been extended for these sites due to the number of events recorded. This shows that there is a very uneven distribution across the monitored network with most of the study focussing on a few of the sites.

As far as the programme is aware, 6 of the monitored sites have had fuse operations, with none of these being the sites demonstrating the highest pecking event activity.

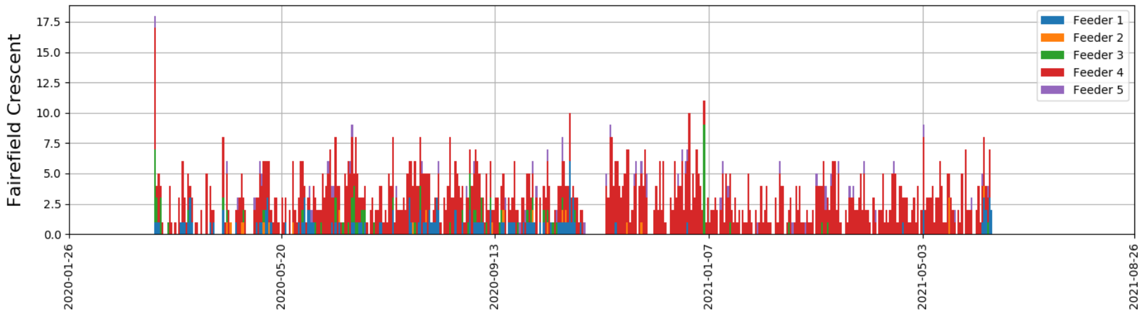
High activity installation status

Pecking event distribution in time

The charts below show the frequency of pecking events for the most active sites over the duration of the monitoring including the events recorded in phase 1 for select substations showing different, representative behaviours. The graph reports the number of pecking events analysed to provide a distance estimate per day since the start of the project. The bars are colour coded depending on the feeder along which the pecking event occurred, as determined by the MCU318 firmware.

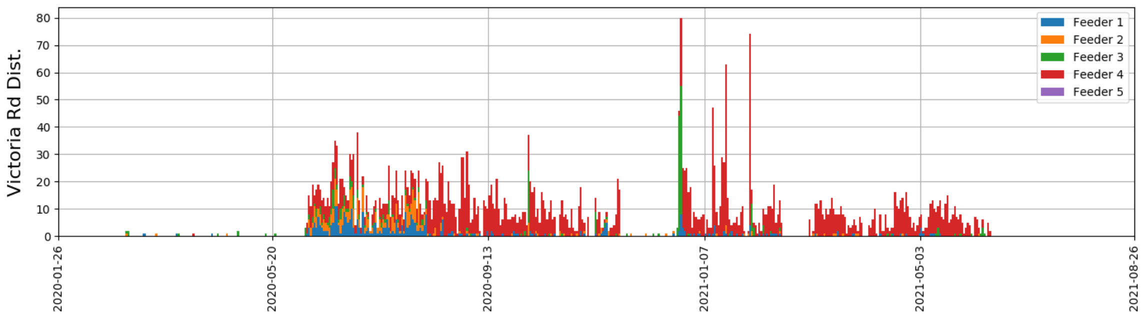
Fairfield Crescent

The chart below is Fairfield Crescent. This site has been regularly producing pecking events throughout the project.



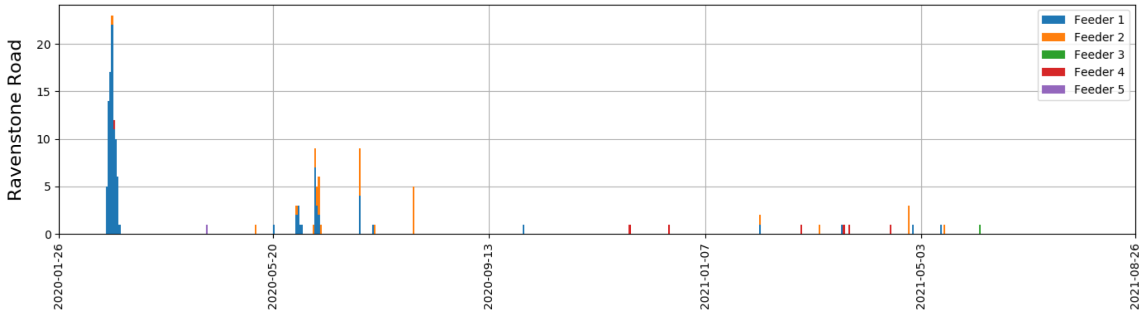
Victoria Road

The site below is Victoria Rd. It was initially very quiet but suddenly started to produce events in high numbers. The reason for the sudden start is not known at present. Though beyond the scope of this project, an analysis to try and correlate the onset of the pecking events with the history of that substation or local events might shed light on the mechanisms triggering these phenomena.



Ravenstone Road

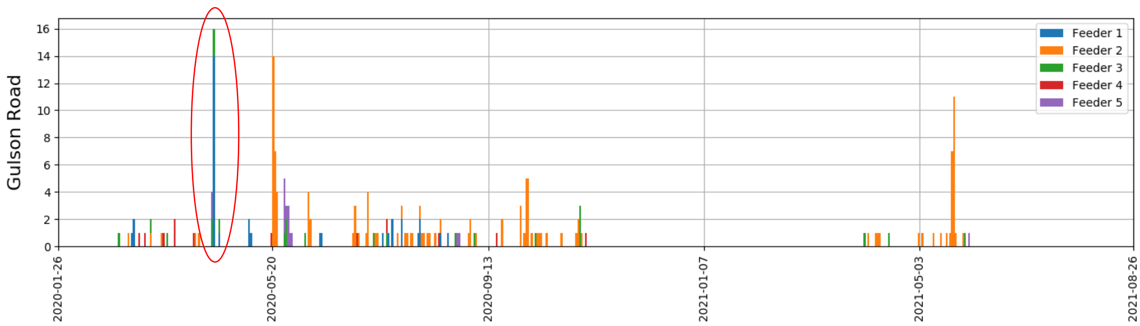
Ravenstone road produced a burst of events for a limited amount of time, but then became relatively quiet. It is not clear if an issue was addressed, or if the events just stopped.



Gulson Road

Gulson Road produced a burst of events just before a fuse operation.

The red circle shows the events preceding the fuse operation.

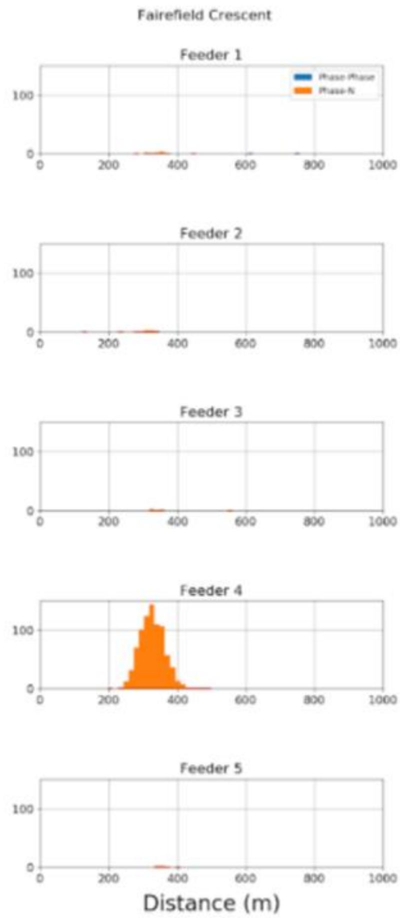


Distance to Fault Calculations

To estimate the distance to fault, the captured waveforms are fitted against an electrical model to determine impedances, which are the converted to distance using a distance calculation equation. The calculated distances are used to generate a histogram, with the peak of the distribution of distances indicating the most probable location of the fault.

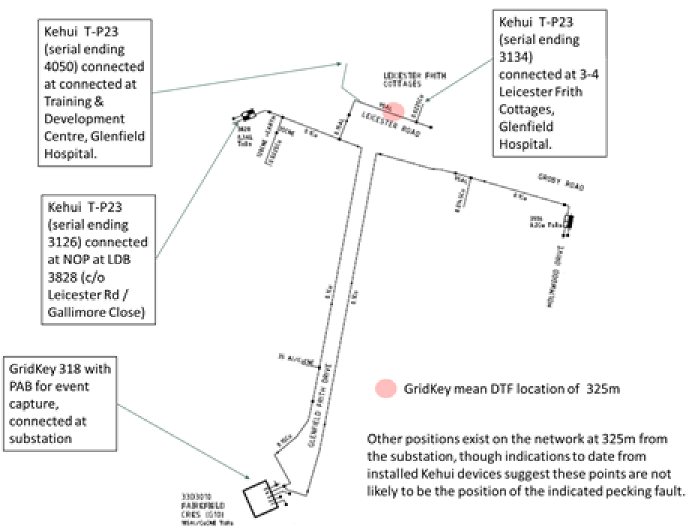
Fairfield Crescent Distance to Fault

Fairfield Crescent produced over 500 fitted events on a single feeder (feeder 4) building up a good statistical sample with a narrow enough range to generate a histogram as shown in the diagram below:



The histogram shows the likely distance to be 325m within +/-5m, with the uncertainty calculated as the error on the mean for a normal distribution.

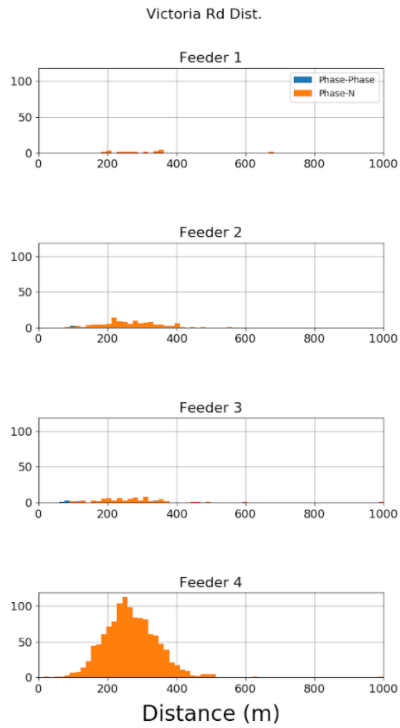
It is worth mentioning that on feeders with multiple branches – the most common case – a given distance might correspond to multiple locations on different branches. In the case of Fairfield Crescent, WPD performed extensive investigations with Kehui devices to determine the branch (Leicester Rd, see map below) and confirm the position of the active site. Analysis of T-P23 acquisitions suggested that the site is on the branch marked with the pink circle, close to the junction with the branche going to the Training & Development Centre. Further investigations with Kehui devices are planned to pinpoint the fault.



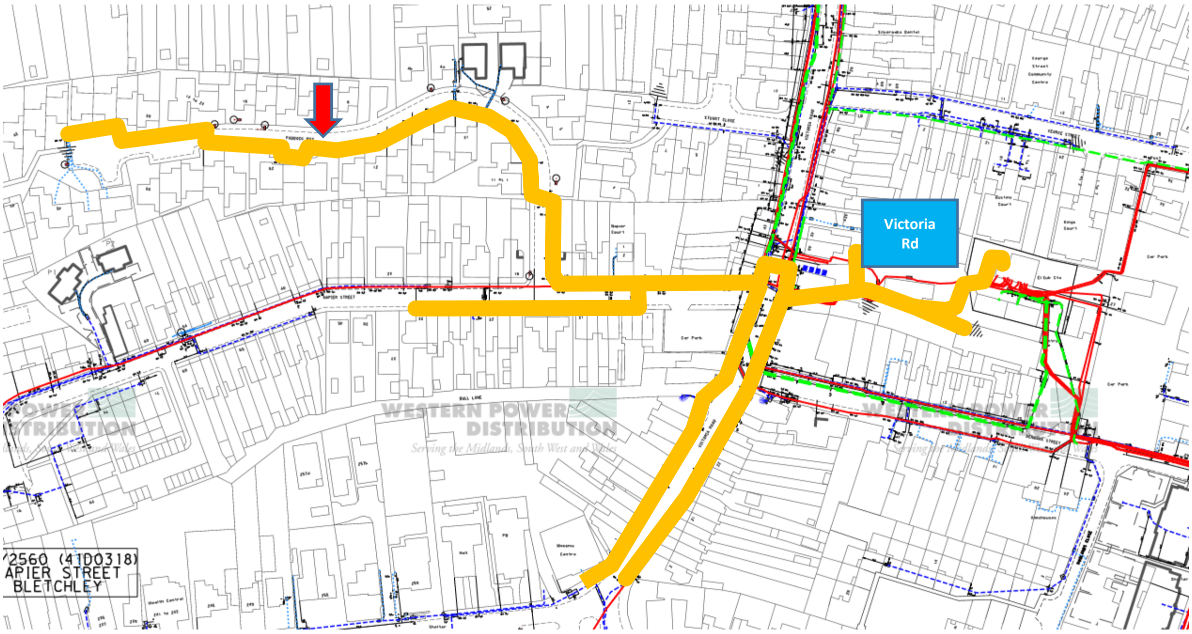
This site is now ready for the next steps to confirm of the active site location and cause.

Victoria Road Distance to Fault

Victoria Road is the other site exhibiting large numbers of pecking events. The distance-to-fault histogram for these events is shown below. Compared to Fairfield Crescent, the present distribution is significantly wider, with a standard deviation of 88 m vs 43 m. The causes of the observed spread in the data could include more than one event location, different load types, and/or cross-talk between feeder currents, and work is underway to determine the contribution of each of these to the uncertainty. Preliminary results of this activity are reported in the next paragraph.



A map for Victoria Road is shown below, with feeder 4 highlighted in orange. The most likely location of the fault is indicated by a red arrow.

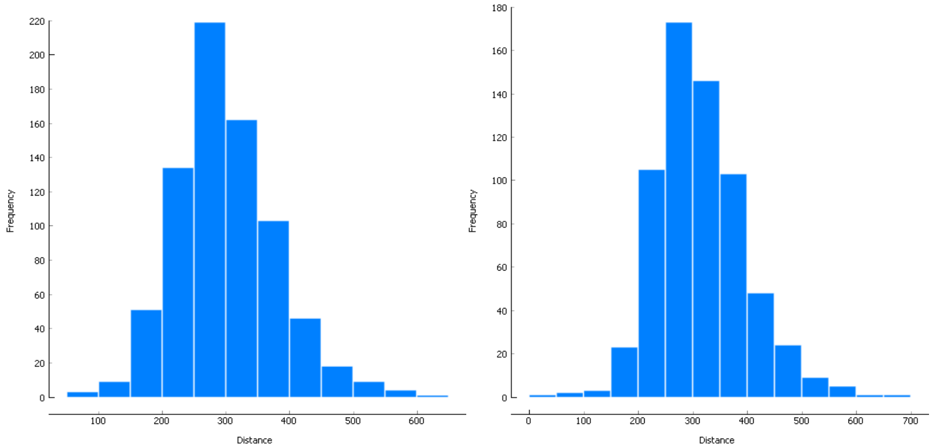


Comparison between Phase 1 and Phase 2 results

Replacing the PABs with active DTF boards was expected to yield several advantages:

1. Improved waveform capture (higher resolution), leading to more accurate distance estimations.
2. Ability to capture multiple events occurring in a short time. The MCU was limited to one waveform per minute. The rearm time on the active DtF board is 200 ms.
3. More flexibility in choosing the trigger level. This allows filtering out small current spikes that are not real pecking events.

To address point 1, the results from two substations were considered, i.e. Victoria Rd. and Fairefield Crescent. The former was equipped with additional Phase 2 HW while also leaving the Phase 1 HW in place. This allows comparing results collected during the same time frame.

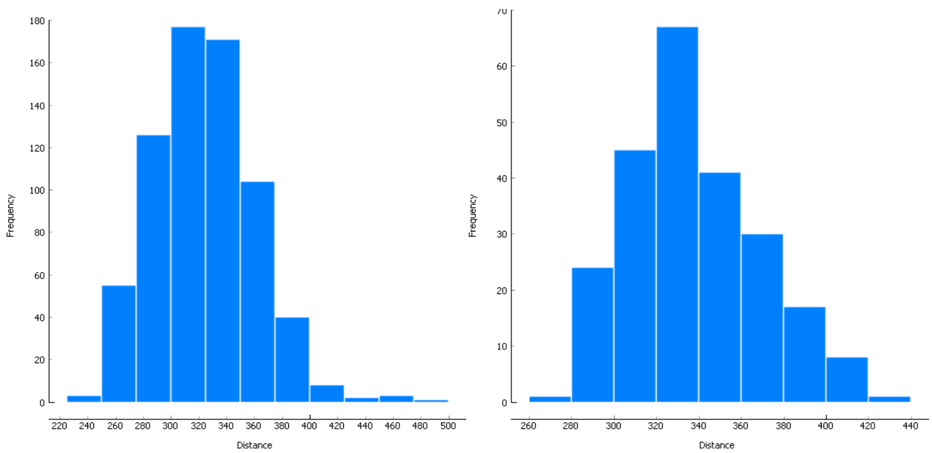


The two graphs above show the DtF distributions for the data collected with PAB (left) and active DtF board (right). The average distances and standard deviations are reported below.

HW	Mean (m)	Standard deviation (m)
PAB	301	80
Active DtF	314	82

The data show remarkably similar standard deviations, with only a small difference in average distance.

A different picture emerges from the analysis of the data from Fairefield Crescent. In this case the PAB was replaced at the beginning of Phase 2 with an active DtF board. Even if it is not possible to compare results acquired during the same time period, a comparison is still possible due to the large number of events recorded on this substation.



The two graphs above show the DtF distributions for the data collected with PAB (left) and active DtF board (right). The mean distances and standard deviations are reported below.

HW	Mean (m)	Standard deviation (m)
PAB	324	36
Active DtF	330	30

In this case, the standard deviation decreased by 16%, yielding a similar increase in location accuracy.

The current interpretation for these results is that the use of an active DtF board can improve the location accuracy compared to using a PAB. The results on Victoria Rd. suggest that the spread in the DtF estimates originates from causes that do not depend on the particular HW used. In the case of Victoria Rd. the external disturbances are large enough to offset the gain coming from the use of an active board.

Additional investigations are being carried out to identify the causes for the spread in the data. Some preliminary results are reported in the next section. Narrowing down the distribution will give greater confidence to teams for where to investigate, which will be important in BaU operation.

Regarding points 2 and 3 above, the 1-minute rearm time of the MCU and the fact that the MCU was more prone to capture waveforms with small current spikes caused the unit to miss a number of real pecking faults. To quantify the gain achieved by switching to the active DtF boards it is worth comparing the number of valid pecking events captured by the two units at Victoria Rd. in the same interval of time. The table below show the number of valid waveforms captured by the two units since the 6th of March.

HW	Mean (m)	Standard deviation (m)	Number of valid waveforms	Error on the mean (m)
PAB	283	73	109	10
Active DtF	294	65	142	5.5

Interestingly, even if the standard deviations differ only by ~10%, the error on the mean, calculated assuming a normal distribution, is almost a factor of 2 smaller when looking at the Active DtF board data thanks to the larger number of captured waveforms.

Key learning points:

- The active DtF board can potentially yield distance distribution with smaller spread, but on some substations this gain is offset by variability in the data that is still under investigation
- Even if the standard deviation of the data in some cases does not improve, the ability of the DtF boards to capture a significantly larger number of events translated to an improved location accuracy.

DTF data spread analysis

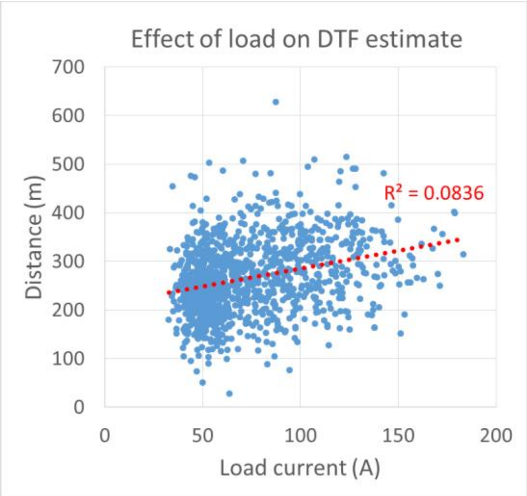
The hypotheses considered for the spread of the distance calculations are as follows:

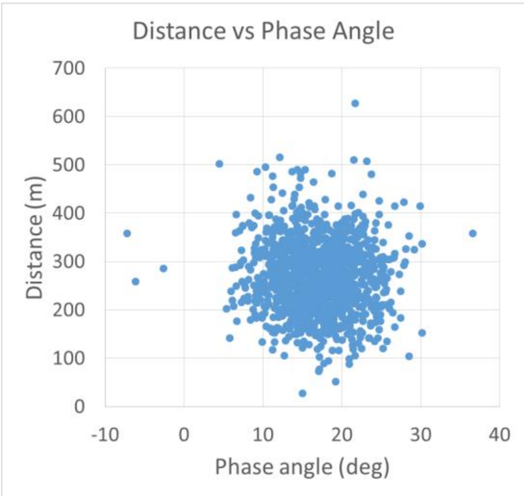
- Effect of feeder load on measured event current.
- Different kind of loads.
- Daily variations in the kind/magnitude of loads.
- Cross-talk between MCU current channels.

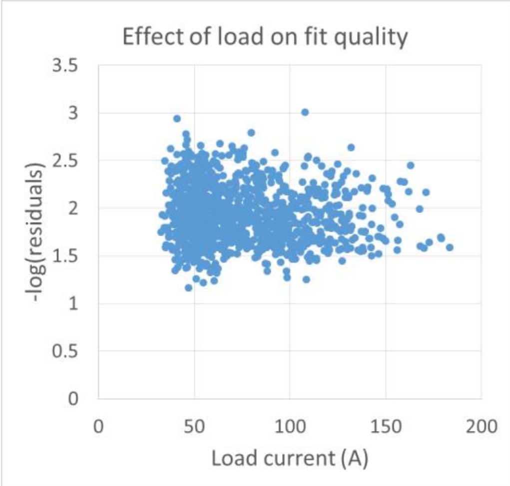
To highlight any correlation existing between the estimated distance and the factors listed above, each event was classified with the feeder load current just before the event, the load phase angle, and the time of day.

No significant correlations between the estimated distances and any of these parameter were found, as shown in the scatter charts below. Additionally the load current before the event does not seem to affect the quality of the fit.

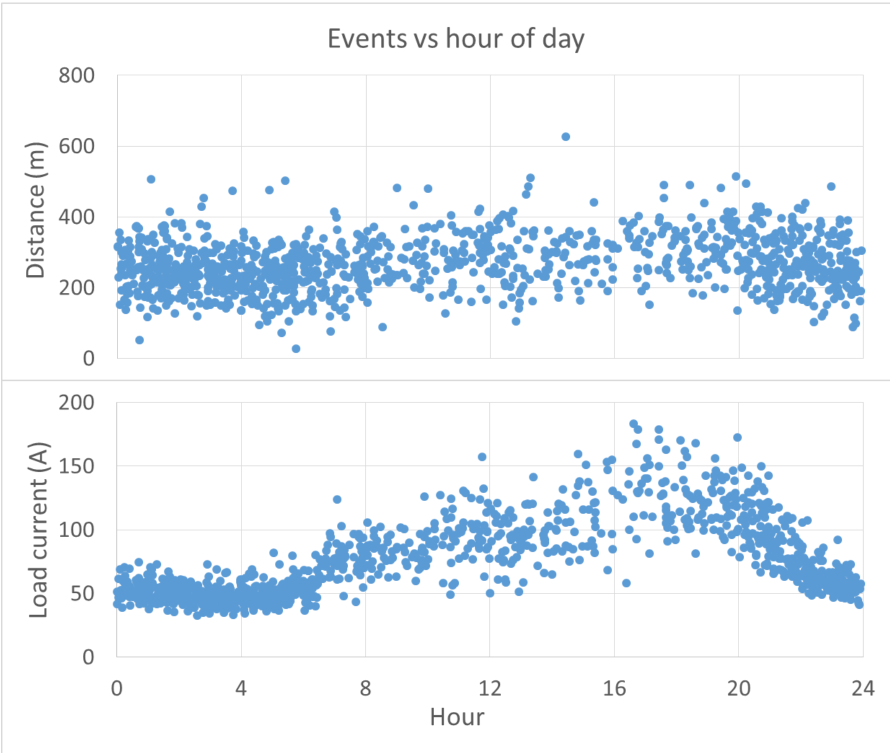
We also observed that there is no systematic increase in fitting error with deviation from the mean distance: some faults which are 2+ standard deviations from the mean have better fitting errors than faults near the mean. Therefore, electronic noise in the Gridkey unit or random disturbances on the measured signal do not seem to be responsible for the observed spread.







An analysis was carried out with the objective of correlating the time of day to the DTF estimate to establish if different characteristics of loads – active at different periods of the day – can affect the analysis outcomes. While the calculated distances do not show any significant correlation with the time of day, our analysis highlighted that the frequency of events is higher overnight:



Victoria Road Analysis

We are analyzing results from Victoria Road, where there are a large number of faults, to narrow down the potential causes:

Sensor cross-coupling: for Victoria Road we tried experiments where only the current from single feeders were measured - as opposed to normal installations where the MCU measures the summed currents from all of the feeders. The results showed that currents in non-fault feeders are caused by the dynamics of the fault, rather than due to coupling between current sensors; allowing us to remove that as a potential cause of distance variation.

Cable capacitance modelling: changing the estimates for the feeder capacitance gives rise to significantly different distance calculations for the same fault. A model which calculate this value with greater consistency can potentially reduce distance variations, work on this is ongoing.

For some substations, there is significant variance in the fault distance calculated from our fitting model, e.g. the distribution of distances for Victoria Road has a standard deviation of ~80m, compared to only ~40m for Fairefield Crescent. There are no systematic increases in fitting error with deviation from the mean distance: some faults which are 2+ standard deviations from the mean have better fitting errors than faults near the mean.

Narrowing down the distribution will give greater confidence to teams for where to investigate, which will be important in BaU operation.

Phase crosstalk: In the current architecture, the MCU receives the signals from the current sensors (up to a maximum of 18: one per phase/per feeder) and measures the bus-bar voltages. The signals from the feeders are summed on a per-phase basis and fed (three signals) to the DTF board. The DTF board also measures independently from the MCU the bus-bar voltages. This solution allows utilising a high-resolution, high-speed ADC to capture current and voltage waveforms. A limitation of this approach is that the DTF does not have access to the individual feeder currents. Therefore, when a pecking event occurs, the DTF board cannot determine the feeder of the event. It has to rely on the MCU to provide the feeder identification.

It became apparent that due to the constraints of the approach to collect summed bus bar data, on some occasions the pecking events were assigned to the wrong feeder, likely due to the feeder-to-feeder currents described below.

While the number of pecking events assigned to the incorrect feeder are not significant on a statistical basis, it was important to understand if this was caused by crosstalk and if it was affecting the accuracy of the calculated distances.

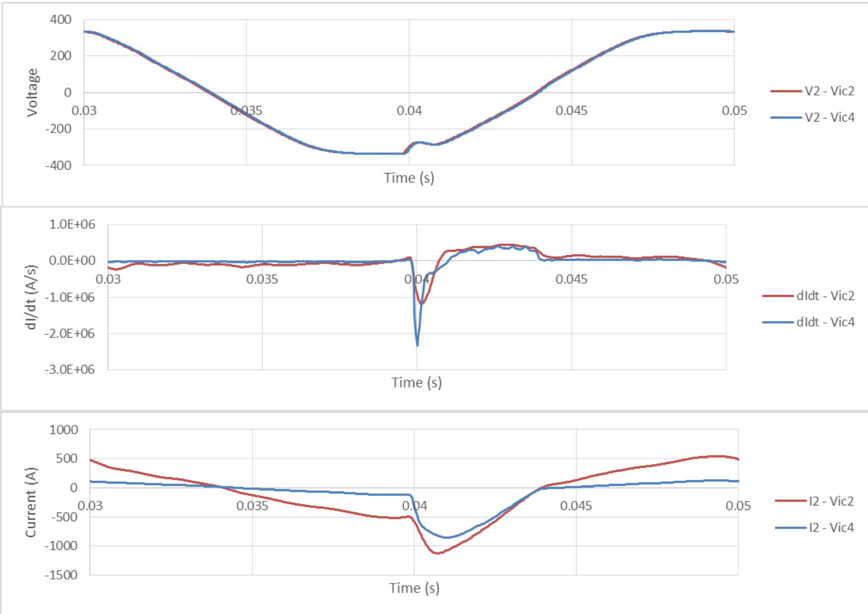
To determine if this was the case, additional investigations were performed to isolate these events to confirm if this is due to crosstalk and if it was affecting the accuracy of the measurements.

In particular, though most of the events at Victoria Rd were observed on feeder 4, some were attributed to feeder 2 by the MCU and labelled as ambiguous by the maximum-current algorithm that is designed to reduce the number of pecking events incorrectly identified. By fitting an additional MCU unit with DTF board at Victoria Rd, with only the current of feeder 2 monitored, the data can be compared with the original fully populated MCU and identify if feeder 2 is being triggered by crosstalk.

With this second unit in place, the results showed that events attributed to feeder 2 were actually occurring on that feeder, confirming that our trigger algorithm is effective in identifying the correct feeder in the vast majority of cases.

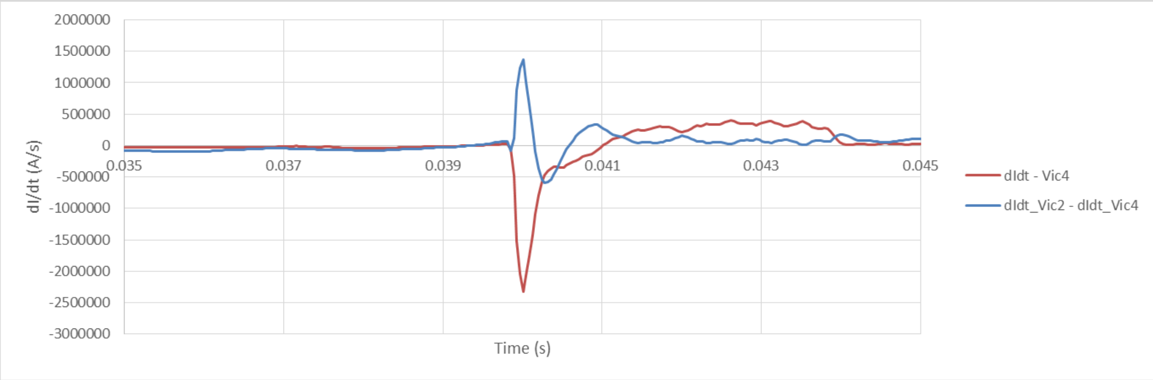
Feeder-to-Feeder currents: the unit installed at Victoria Rd with just one feeder monitored, i.e. current sensors fitted only to feeder 4 (one per phase), highlighted that when a pecking fault strikes on a given feeder, there is a significant current flowing also in the other feeders connected to the same substation. This has interesting implications on the distance-to-fault estimates.

In the graphs below a comparison between the voltage, dI/dt, and current waveforms recorded by two units during the same event is reported. Curves labelled with "Vic2" were recorded by the unit with all the feeders connected. "Vic4" indicates the waveforms recorded by the unit with current sensors fitted only on feeder 4.

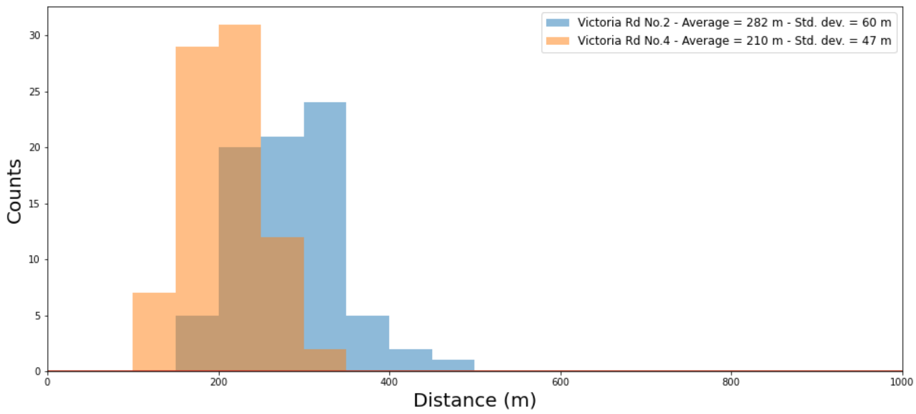


While the voltage waveforms look similar, the difference in the dI/dt waveforms is striking, with a significantly sharper and deeper dip recorded by Vic4 at the onset of the pecking fault. The portions of the current waveforms during the faults show a different shape reflecting the difference in the dI/dt signals. The larger background current in the waveform from Vic2 (bottom panel) is to be expected due to the fact that this trace represents the sum of the currents on all the feeders.

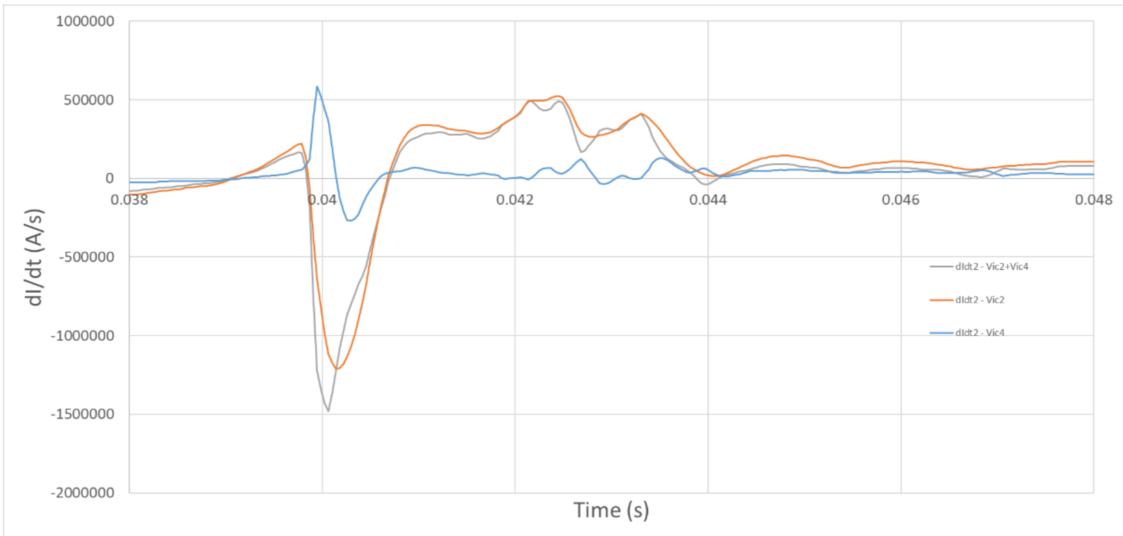
The difference between the dI/dt traces suggests that during the pecking fault there is a significant current flowing in the other feeders. This can be quantified considering that the signal measured by Vic4 is the sum of all the feeders, while Vic2 measures only feeder 4. Therefore, the difference between these two signals corresponds to the total current flowing in the other feeders. The graph below shows a comparison between the dI/dt signal in feeder 4 (Vic4) and the difference dI/dt(Vic2) – dI/dt(Vic4) and demonstrates that – in particular at the onset of the pecking fault – the current flowing in the feeder experiencing the fault is of the same order of magnitude than the currents flowing in the rest of the feeders. The opposite sign of the two traces signifies that the current from all the feeders flows into the fault (or out of the fault for negative line cycles).



It is important to notice that if these additional currents are not handled correctly in the model, DTF estimates can be significantly biased. In fact, running a set of waveforms collected by the two units through our algorithm give significantly different DTF estimates, as shown in the histogram below.



To further verify these observations, we disconnected the current sensors on feeder4, Vic4, and connected those on another feeder, i.e. feeder 2. The following graph show the dI/dt waveforms recorded on the 17/05/2021 for a pecking fault on feeder 4. The sensor connected on feeder 2 (Vic 4) recorded a significant dI/dt signal, as expected from the results discussed above. The gray line represents the dI/dt signal that would be recorded by measuring the current only on feeder 4 (neglecting the currents on feeders 1, 3, 5, 6, which are not individually recorded in this test). Qualitatively, this trace reproduces the features discussed above, with a deeper and sharper dI/dt dip.



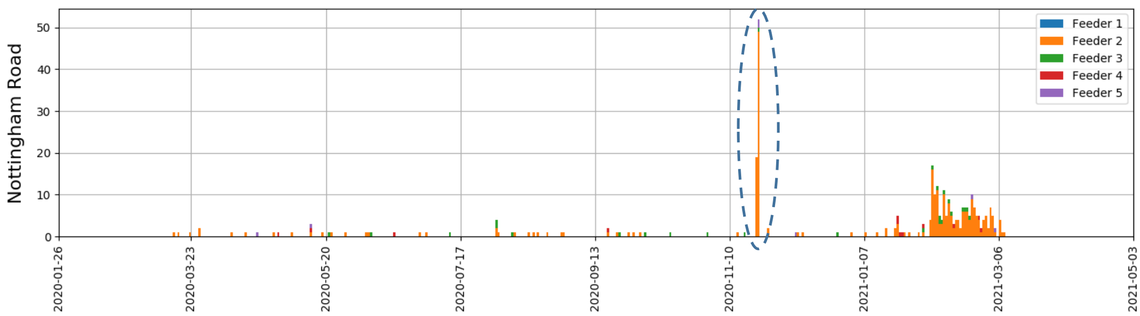
Field Distance Verification

Nottingham Road Fuse Operations

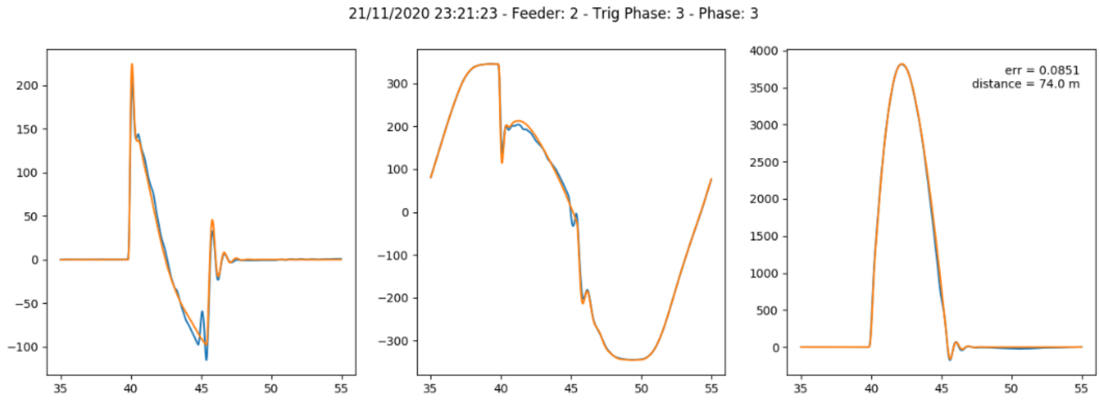
Nottingham Road experienced 3 fuse operations.

22 November 2020

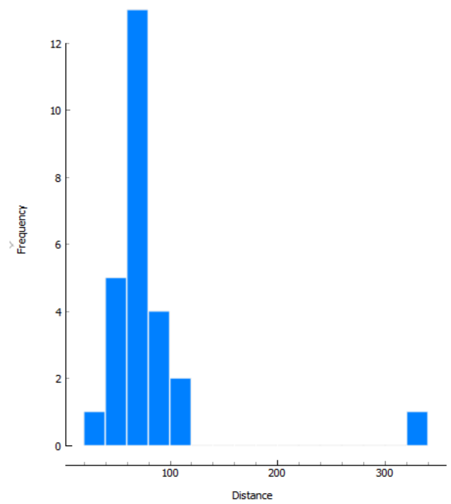
The fuse blew after a few high-current events, with very little previous data. The time distribution of pecking events for this substation is shown in the picture below, where the dashed line encircles the events immediately preceding and following the initial fuse blow event.



A representative waveform recorded during the burst is displayed in the picture below, showing peak currents in excess of 3.5 kA:



The collection of distances from the waveform fitting of the events just before the fuse operations, plotted as a distribution histogram, showed a peak at 73 m ± 5 m, consistent with the position where the local team located the actual fault (~80 m).



This particular event, with a remarkably accurate DTF indication, highlighted some important learning points:

- The ALARM project aims at acquiring pecking-event data over long periods to provide an indication of the location(s) that are most likely to develop a permanent fault. Nevertheless, In this case, the fault was associated with a burst of pecking events captured just before the fuse operation, with limited previous data. The agreement between the DTF data and the actual fault location suggests that even in these cases the ALARM approach can provide useful information help the local teams in locating the fault, provided that the analysis results are available quickly enough. To address this point, the frequency at which the analysis scripts are run was changed from once per day to once every two hours.

- A quick route is needed to provide useful indications to local teams in a timely fashion.

Other fuse operations were observed on the same substations:

- 16/12/2020 – Feeder 5

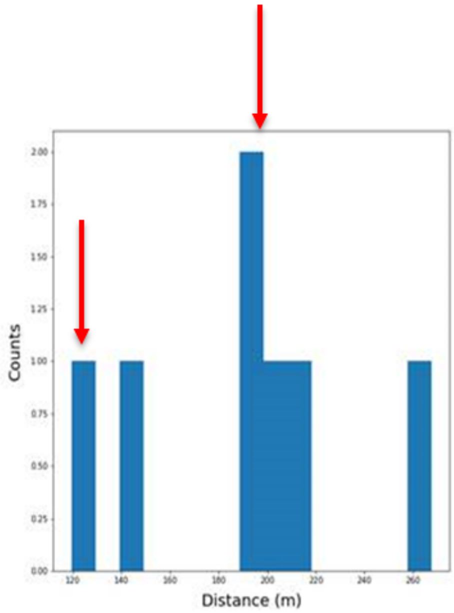
- 21/01/2021 – Feeder 2

Unfortunately these fuse operations were preceded by a very limited number of captured pecking events. For this reason, it was not possible to provide DTF estimates.

Gulson Road

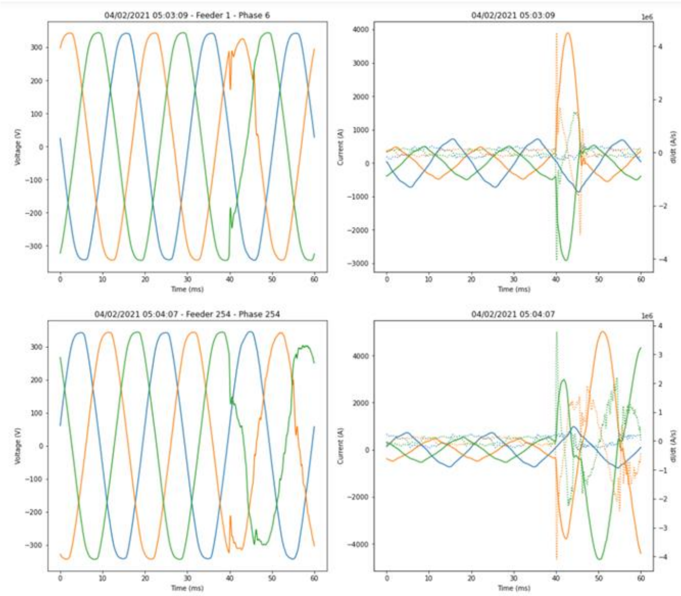
Similarly to Nottingham Rd, Gulson Rd also experienced a fuse operation (during phase I), preceded by an even smaller number of pecking events. The fault that caused that particular fuse operation was located at ~200m. Although this correlates with the histogram, this distance recorded only 4 events so is not conclusive.

The red arrow at 120m could be a secondary issue starting to develop.



St John's Street

The waveforms captured below correspond to two individual fuse operations at St John's Street. The waveforms clearly show that this was a phase-to-phase transient.

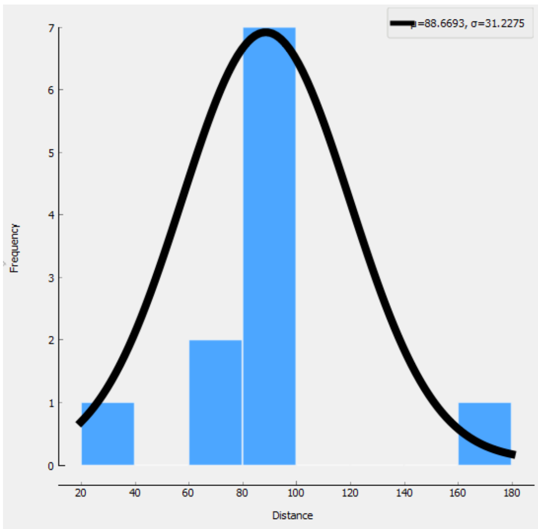


Only 4 pecking events were detected for this site, with an estimated distance of 120m +/-14m. There is no feedback from the local team regarding whether this has been addressed and, if so, the distance of the fault.

Victoria Road Feeder 3 Events

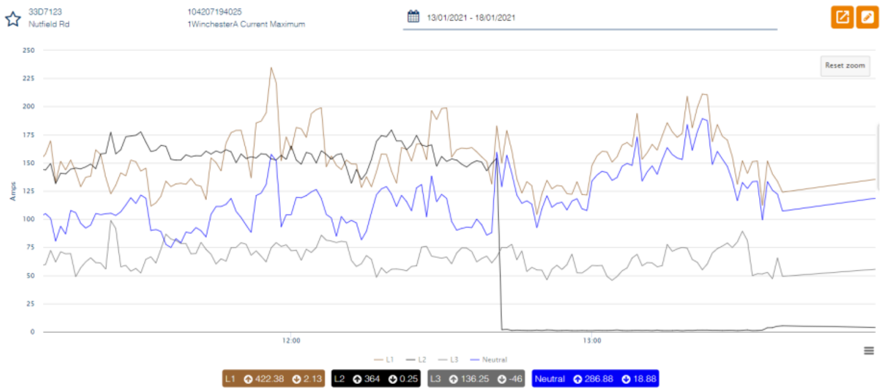
On 10-Nov-2020 a number of phase-to-phase events were captured from Victoria Road feeder 3 with currents up to 8KA without blowing any fuses.

No other events were observed afterwards, but most of the events recorded show a distance between 80 to 100m, potentially providing a useful indication of a likely developing fault.

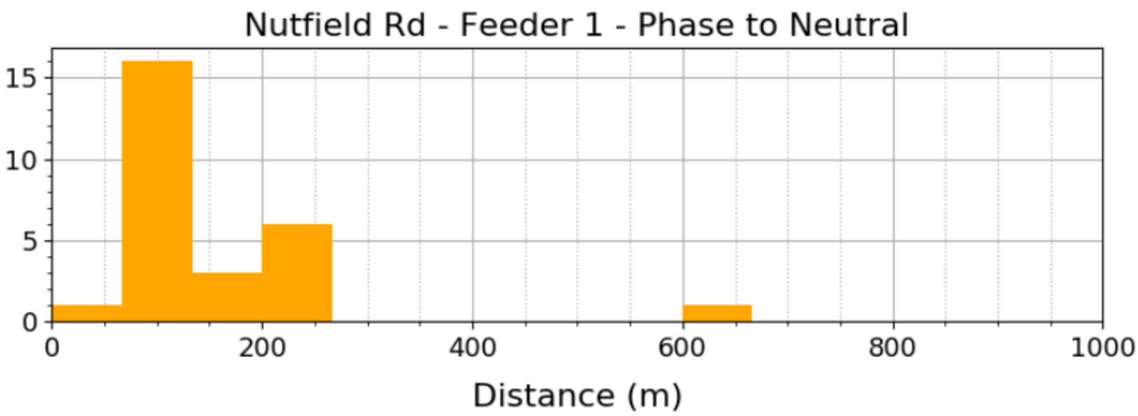


Nutfield Rd

A fault developed on Nutfield Rd on 14-Jan-2021. The maximum-current trace recorded by the GridKey unit, reported below, did not show any significant spike before the fuse operation:



The fault was located by the local team at ~40 m from the substation. The histogram (shown below, distance in meters on the horizontal axis, counts on the vertical axis) does not show any feature corresponding to that location. Instead, a peak at 100 m is clearly visible.



Further investigations are needed to determine if the peak at 100 m is originating from a different fault located around the indicated distance, or is caused by events originating actually at the location of the fault (40 m) that the analysis algorithm failed to characterise properly.

Independent Verification of event data

Verification of event data is still in progress by WPD and will be reported separately.

Business as Usual (BaU) Concept

For the distance to fault to be of use to WPD on an ongoing basis, the data has to be presented in a way that it can be interpreted by the field operations teams.

The initial proposal is to add an additional webpage for each site within the Lucy Electric GridKey web interface that is already in use with a table detailing the DtF data.

The following table is an example of the data a site overview table could contain, where "*n*" is a predetermined and/or selected range:

Substation Location: (for example) New Street				
Feeder ID	**Total N° Events**	**N° of Events last *n* days**	**Estimated distance (m)**	**Deviation (+/-m)**
New St 1	0	0	N/A	N/A
New St 2	30	20	200	60
New St 3	7000	300	150	10
New St 4	100	5	N/A	N/A
New St 5	50	1	N/A	N/A

Using the above data it is easy to see which sites and feeders have recorded high numbers of pecking events that could lead to a fault and justify further inspection for pre-emptive measures.

A second scenario could be where a fault has occurred and could direct the local teams where the fault is likely to be minimising the risk of digging in the wrong place.

Looking at the example numbers, it is easy to see that New St 3 feeder is active and has a fairly good distance calculation. The other feeders are fairly quiet and in the case of New St 2, it is clear from the numbers that there are not enough events to accurately calculate a distance, but the site activity is escalating. The other feeders have not had any activity so will not be of concern.

The frequency charts and histograms shown in the next section could also be made to be visible to help interpret the data. These could also be displayed within a date range so the trend of activity over time can be analysed.

With further data analysis and business operational requirements, alerts could be setup using thresholds of the recorded data above to assign investigations or append to faults that have already occurred.

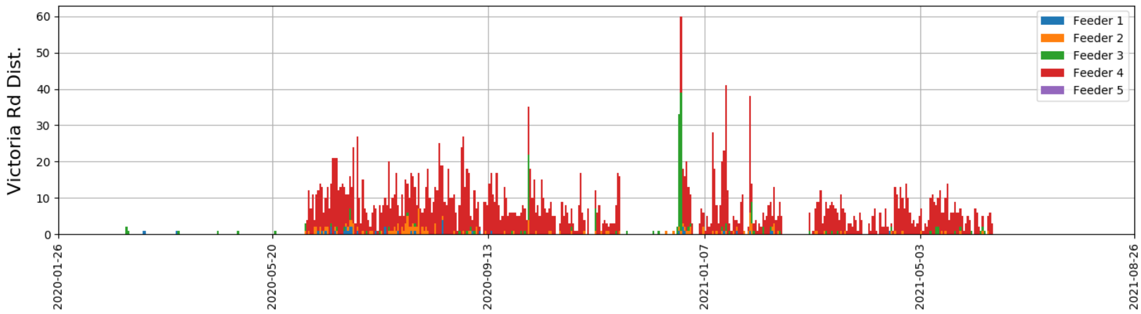
Overall results

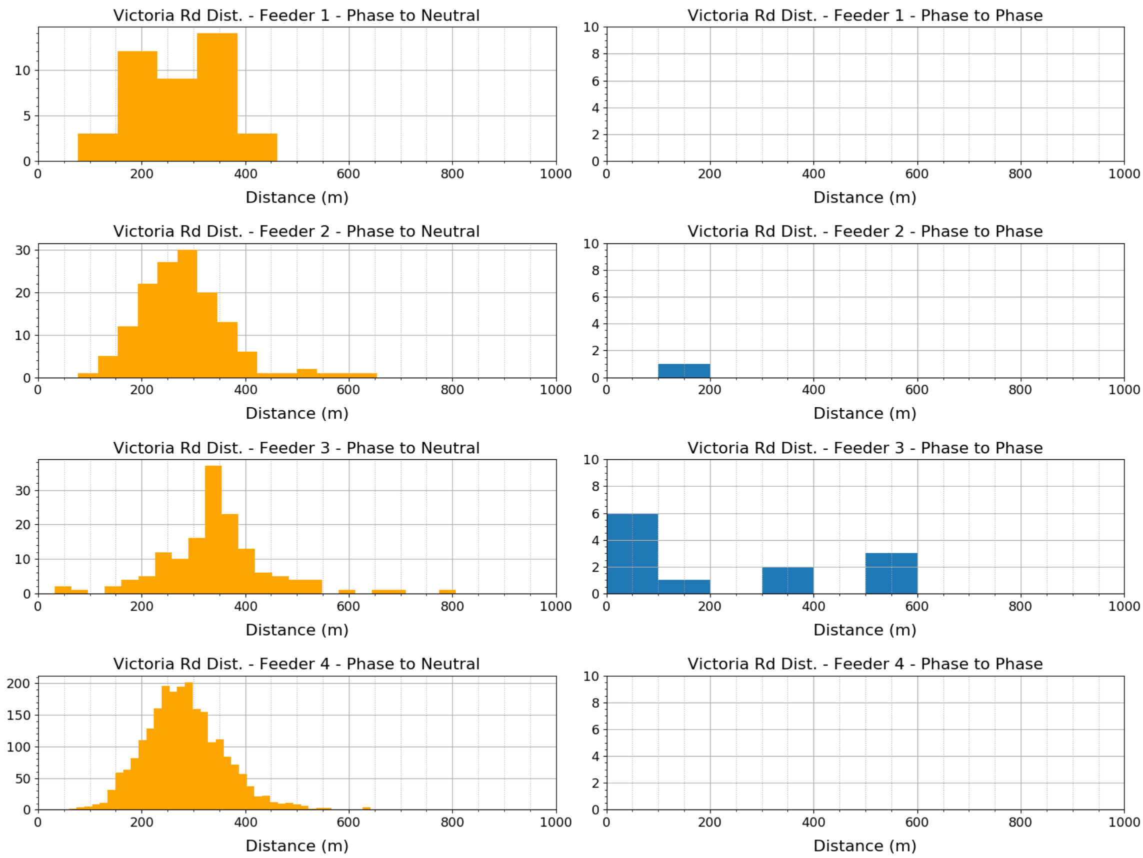
Histograms

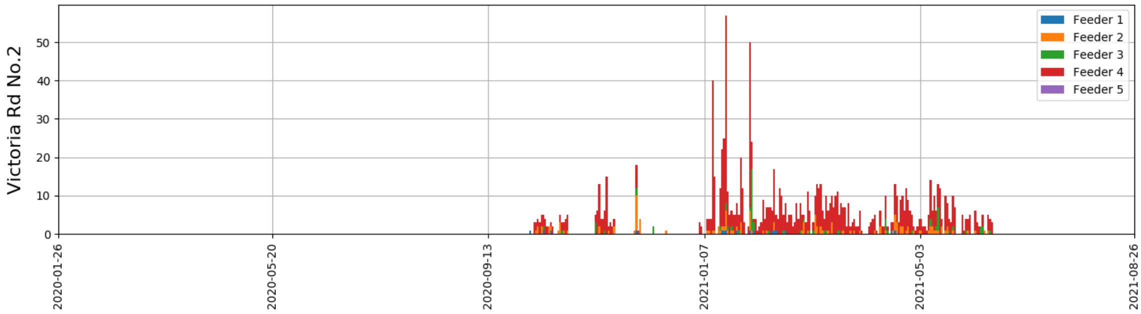
A collection of time-distribution and distance-to-fault histograms recorded since the start of the project is presented below. The feeder IDs in the data presented below are corrected using the maximum-current algorithm.

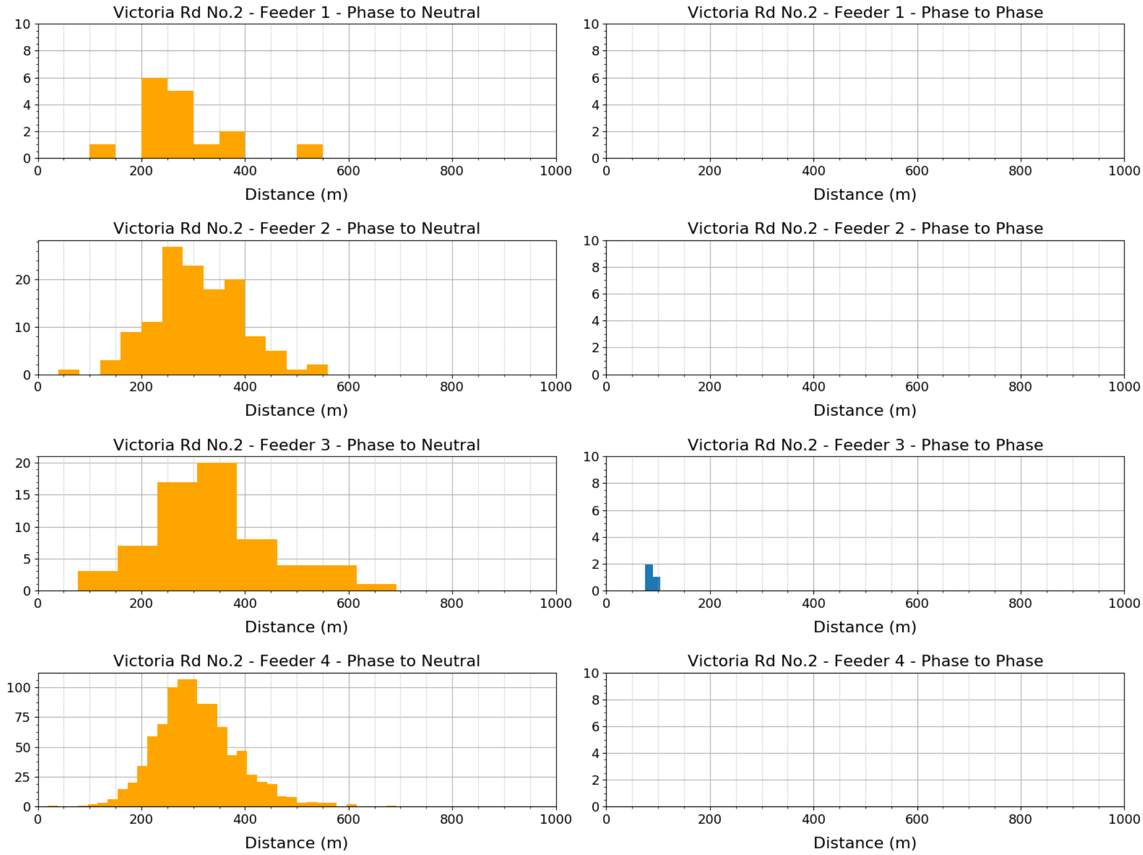
Victoria Rd Dist.

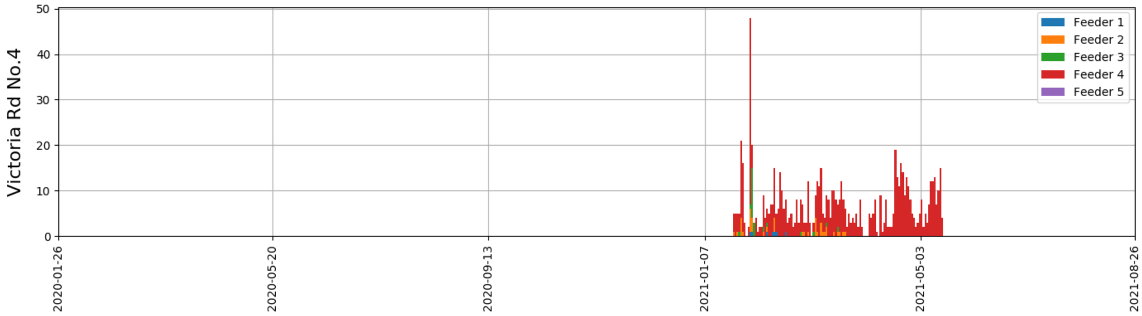
There are currently three units installed on this substation. "Victoria Rd Dist." is a phase I module, without DTF board.

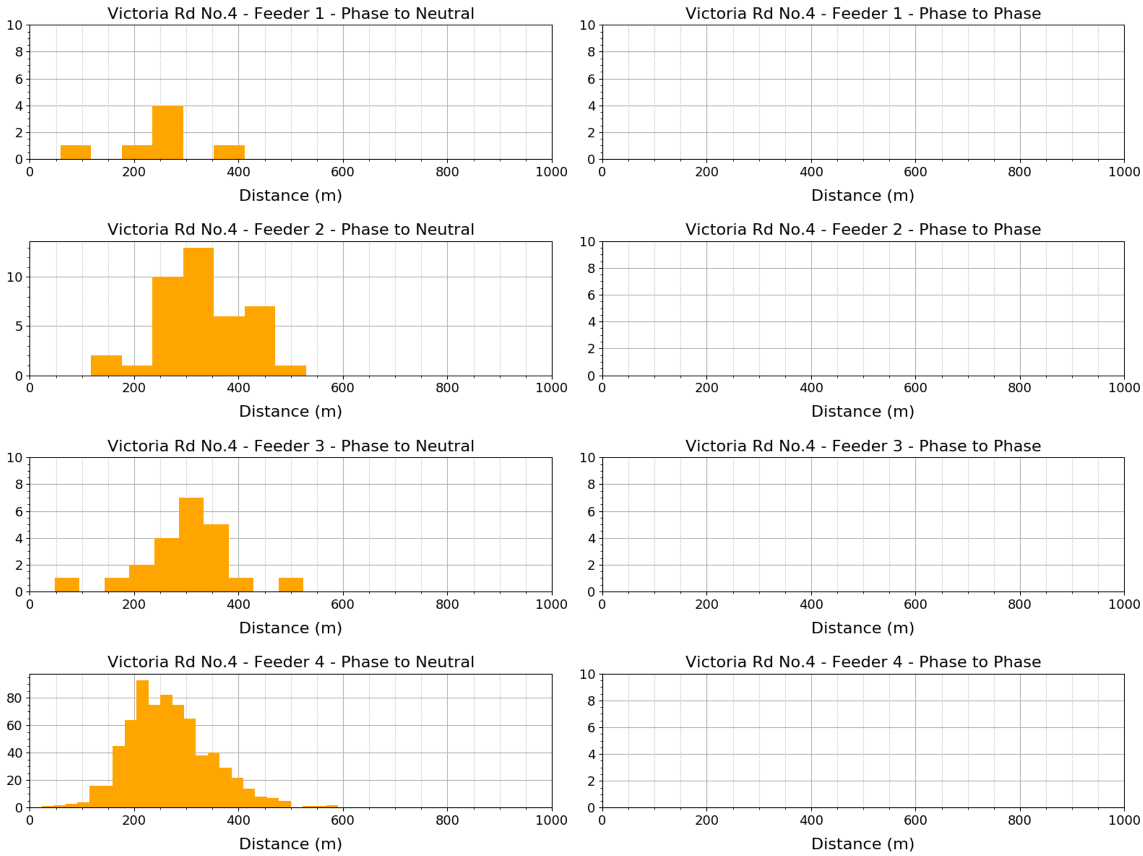




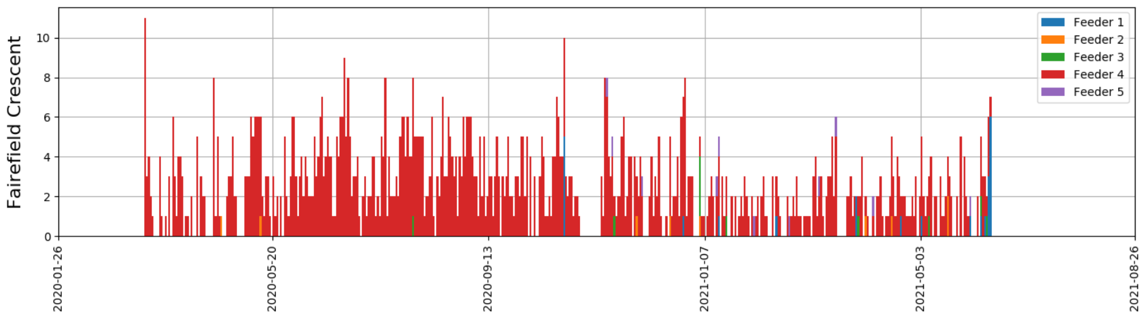

Victoria Rd No.2
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
0
10
20
30
40
50
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

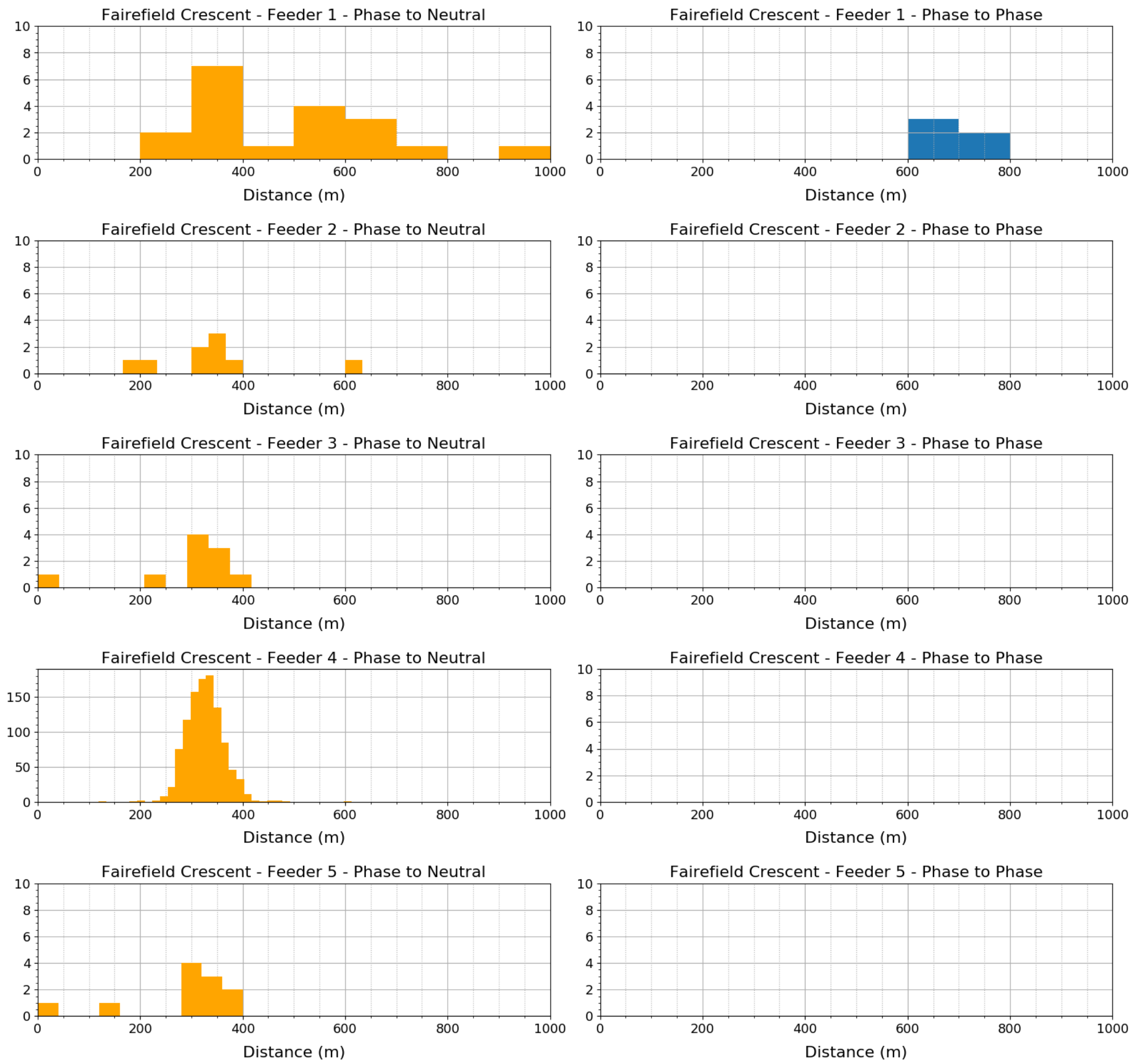

Victoria Rd No.2 - Feeder 1 - Phase to Neutral
Victoria Rd No.2 - Feeder 1 - Phase to Phase
Victoria Rd No.2 - Feeder 2 - Phase to Neutral
Victoria Rd No.2 - Feeder 2 - Phase to Phase
Victoria Rd No.2 - Feeder 3 - Phase to Neutral
Victoria Rd No.2 - Feeder 3 - Phase to Phase
Victoria Rd No.2 - Feeder 4 - Phase to Neutral
Victoria Rd No.2 - Feeder 4 - Phase to Phase
Distance (m)


Victoria Rd No.4
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

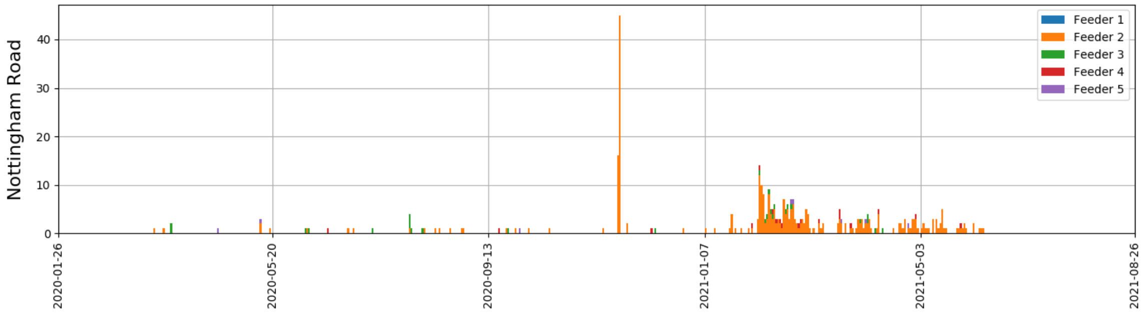

Victoria Rd No.4 - Feeder 1 - Phase to Neutral
Victoria Rd No.4 - Feeder 1 - Phase to Phase
Victoria Rd No.4 - Feeder 2 - Phase to Neutral
Victoria Rd No.4 - Feeder 2 - Phase to Phase
Victoria Rd No.4 - Feeder 3 - Phase to Neutral
Victoria Rd No.4 - Feeder 3 - Phase to Phase
Victoria Rd No.4 - Feeder 4 - Phase to Neutral
Victoria Rd No.4 - Feeder 4 - Phase to Phase
Distance (m)

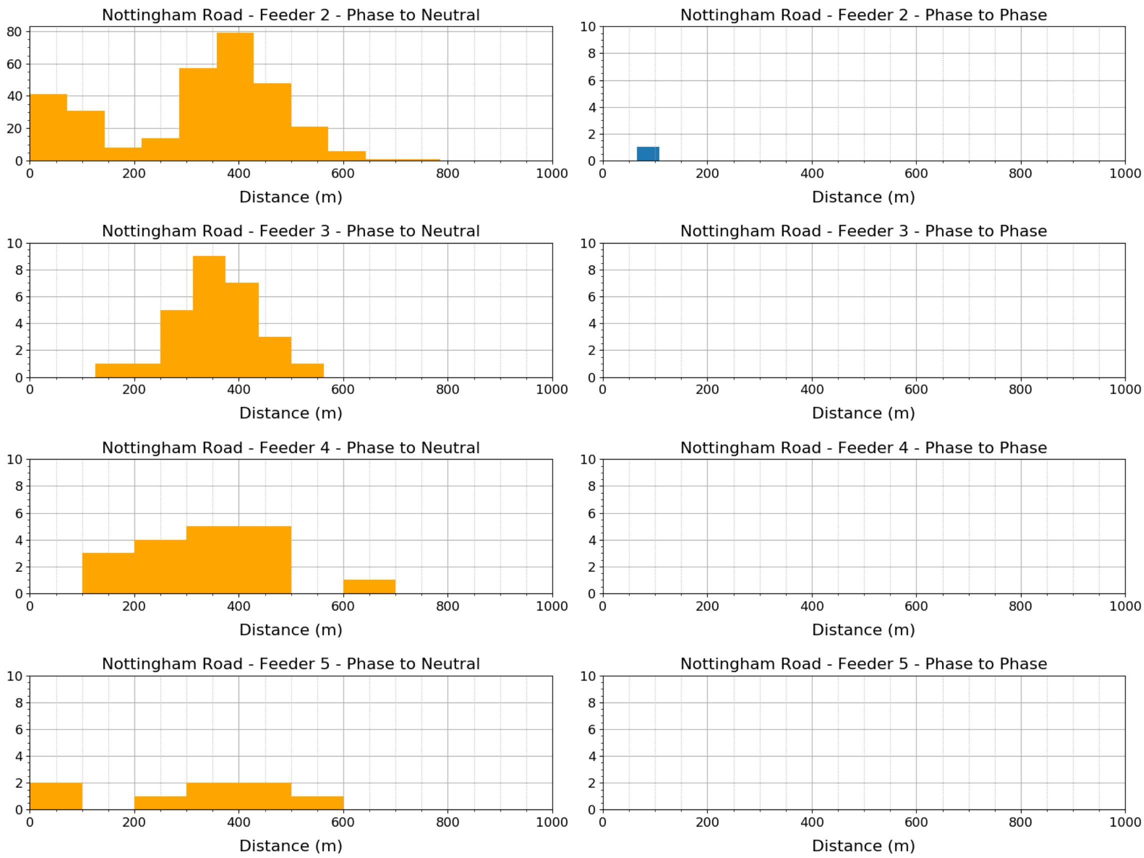
Fairefield Crescent



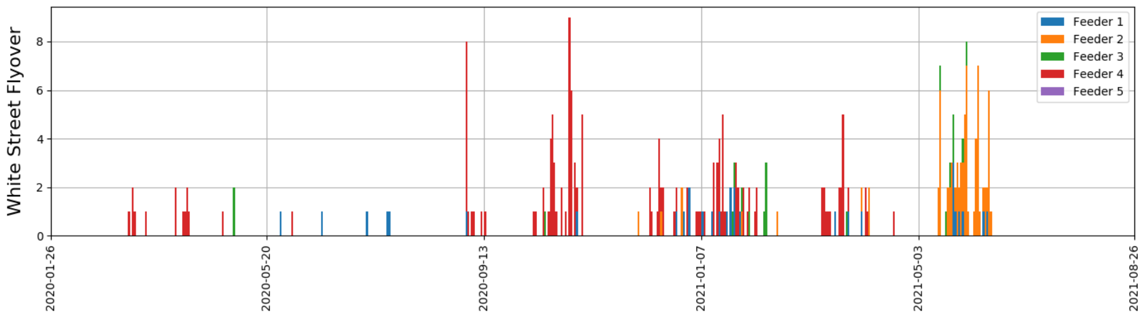


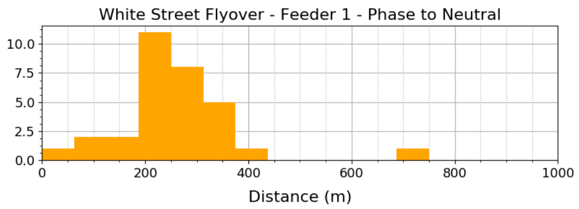
Nottingham Road

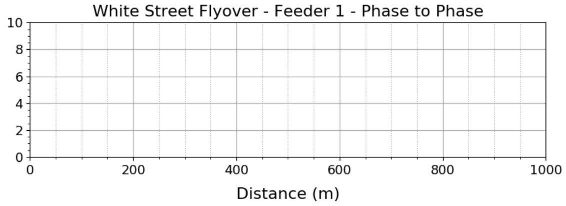


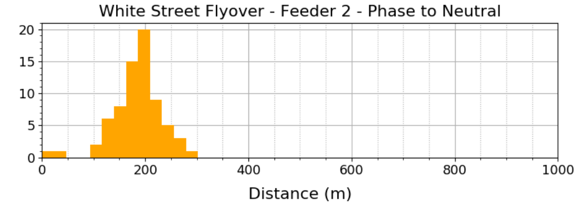


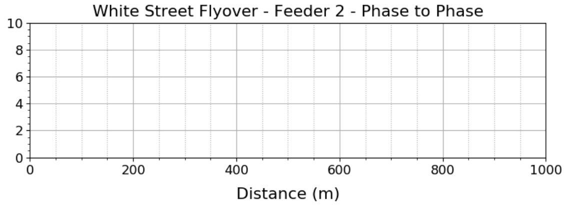
White Street Flyover

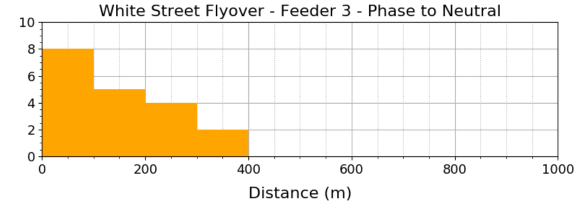


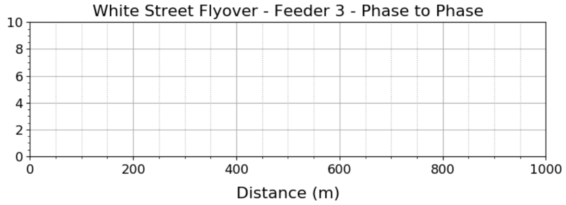


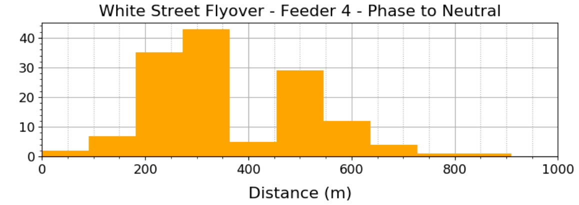


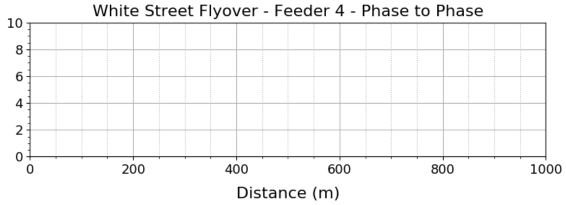




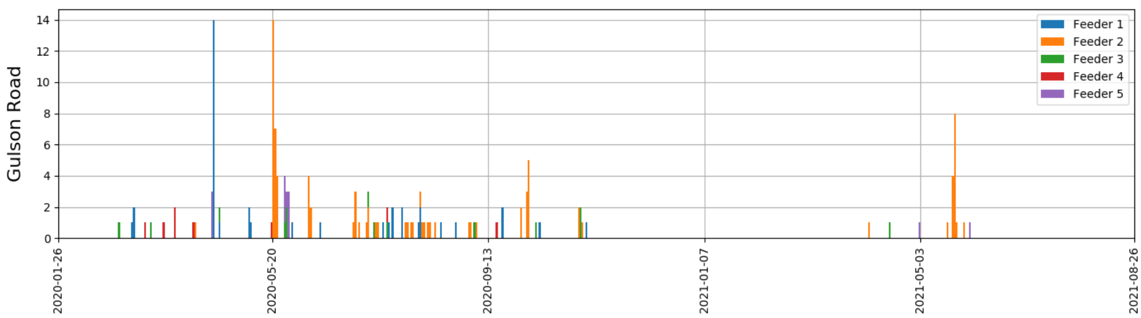


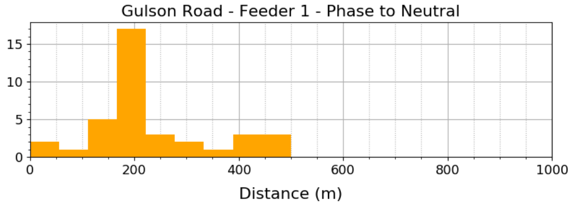


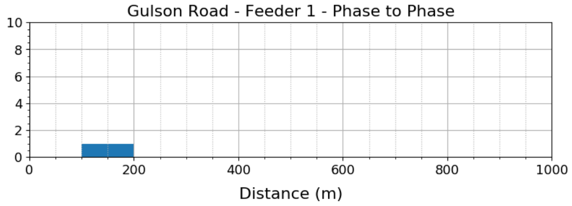


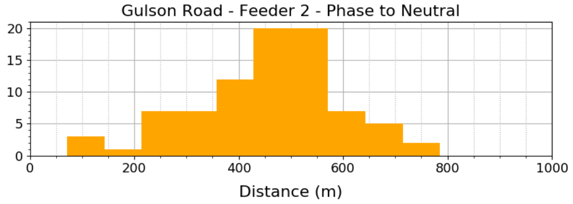


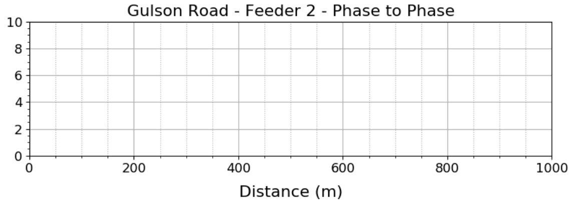
Gulson Road

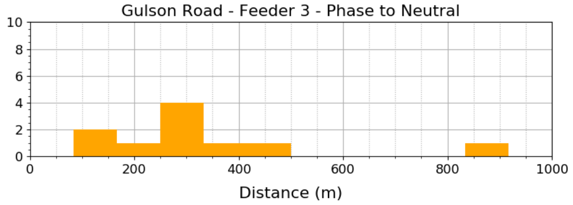


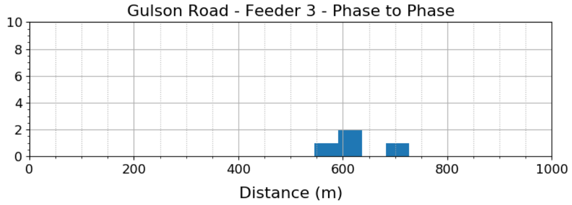

Gulson Road - Feeder 1 - Phase to Neutral
Distance (m)

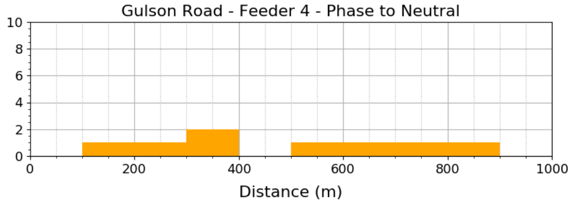

Gulson Road - Feeder 1 - Phase to Phase
Distance (m)

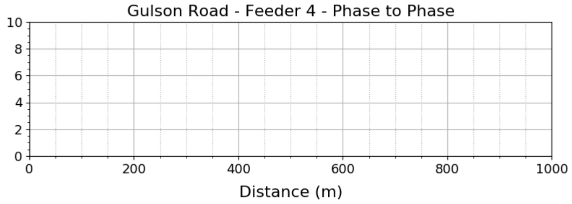

Gulson Road - Feeder 2 - Phase to Neutral
Distance (m)

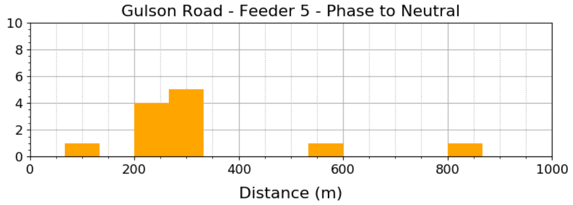

Gulson Road - Feeder 2 - Phase to Phase
Distance (m)

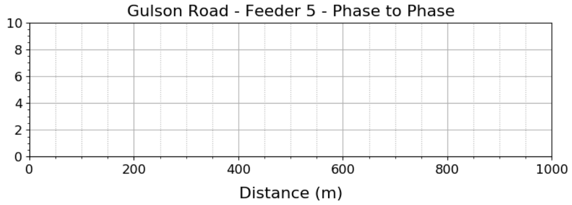

Gulson Road - Feeder 3 - Phase to Neutral
Distance (m)


Gulson Road - Feeder 3 - Phase to Phase
Distance (m)

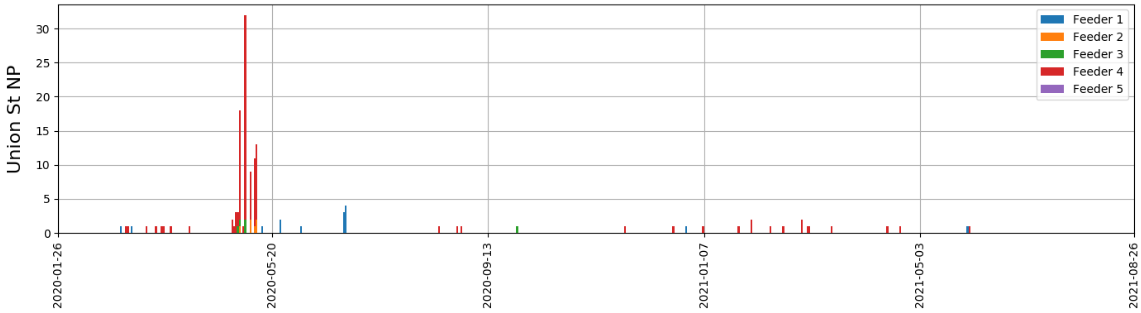

Gulson Road - Feeder 4 - Phase to Neutral
Distance (m)

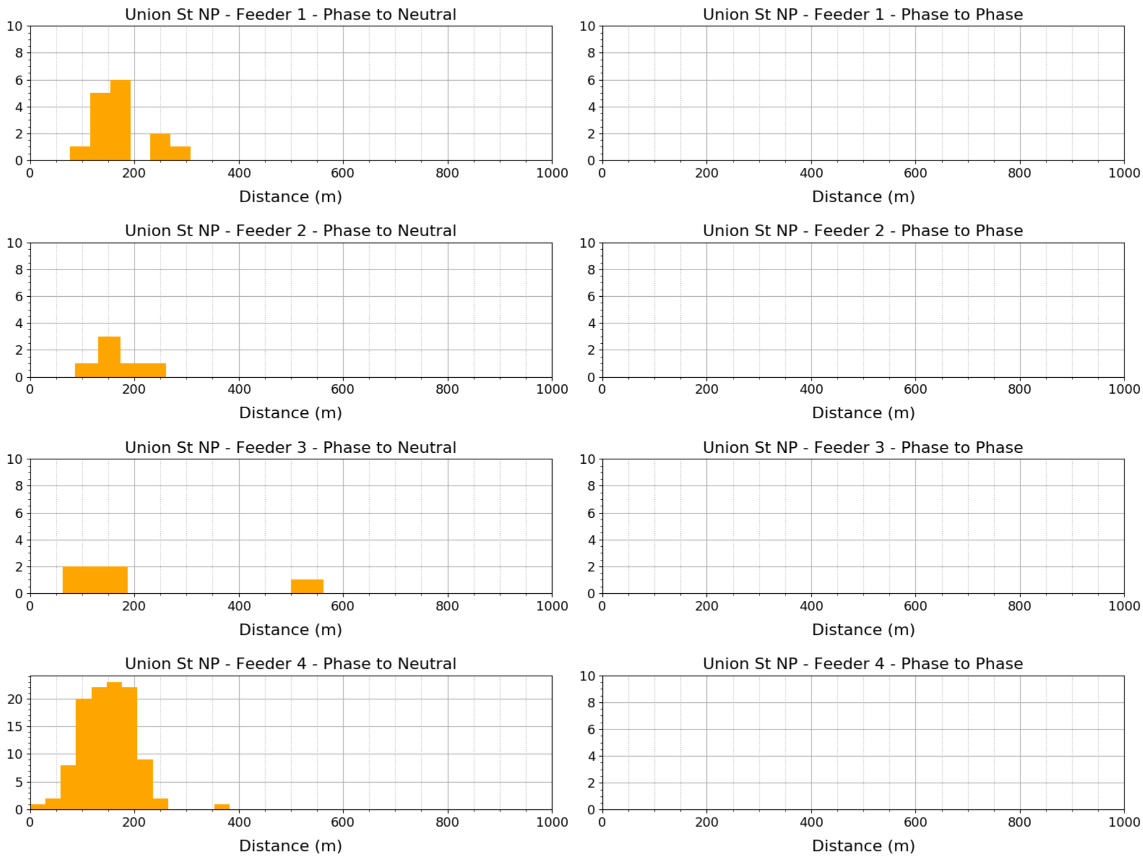

Gulson Road - Feeder 4 - Phase to Phase
Distance (m)


Gulson Road - Feeder 5 - Phase to Neutral
Distance (m)

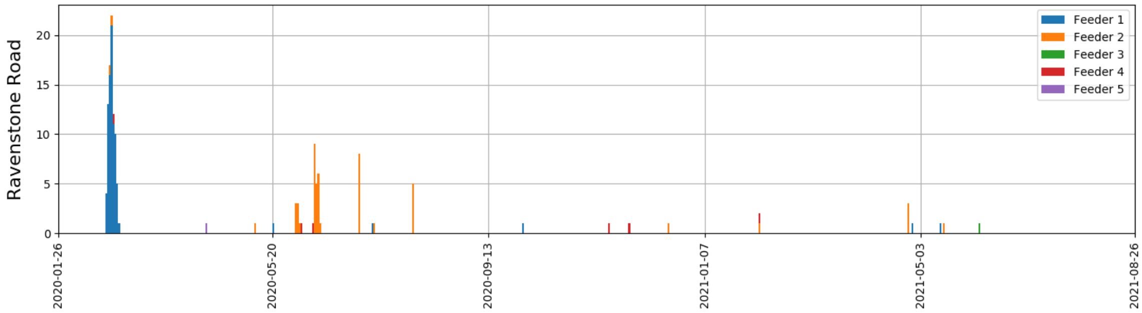

Gulson Road - Feeder 5 - Phase to Phase
Distance (m)

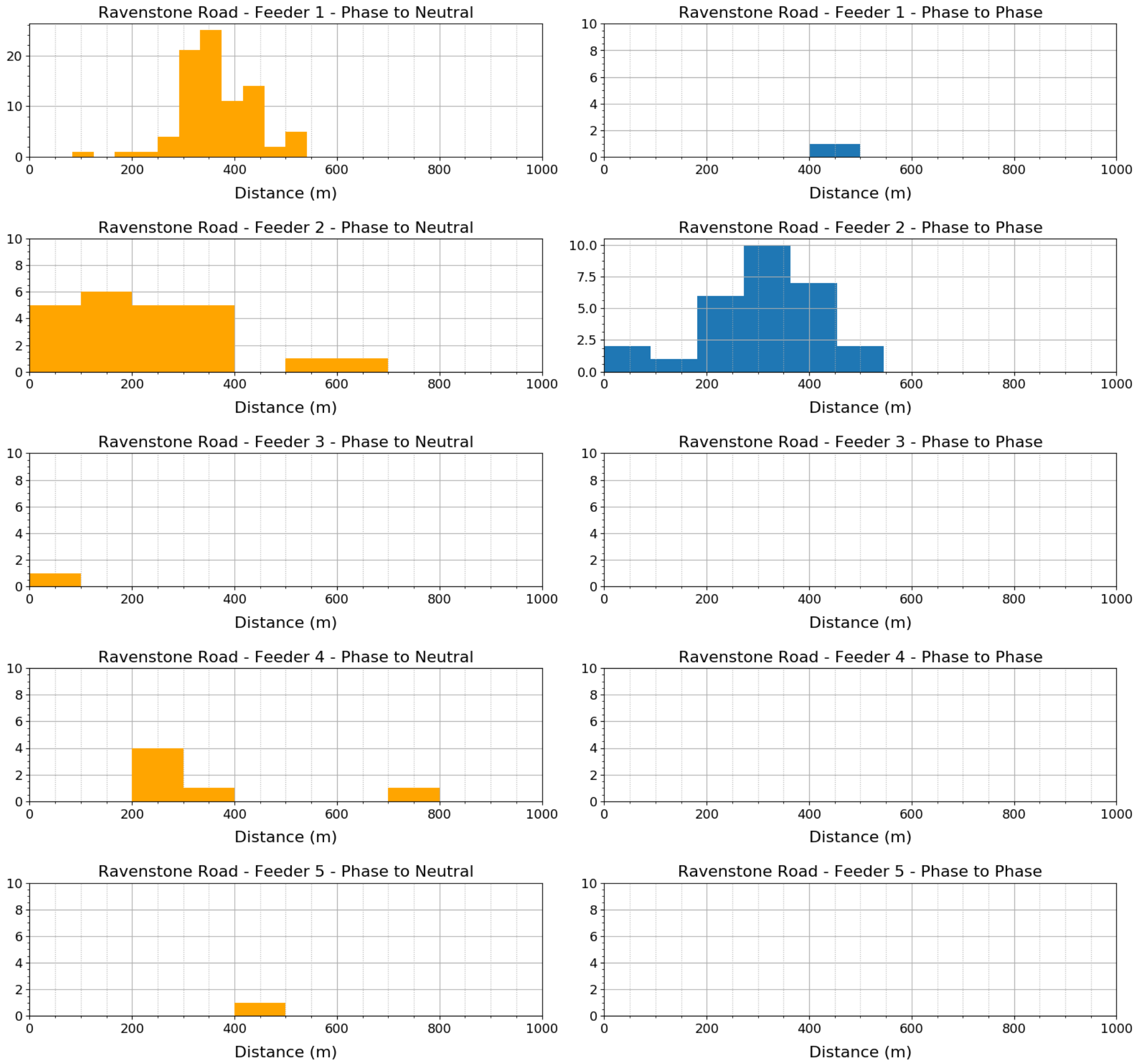
Union St NP


Union St NP
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
0
5
10
15
20
25
30
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

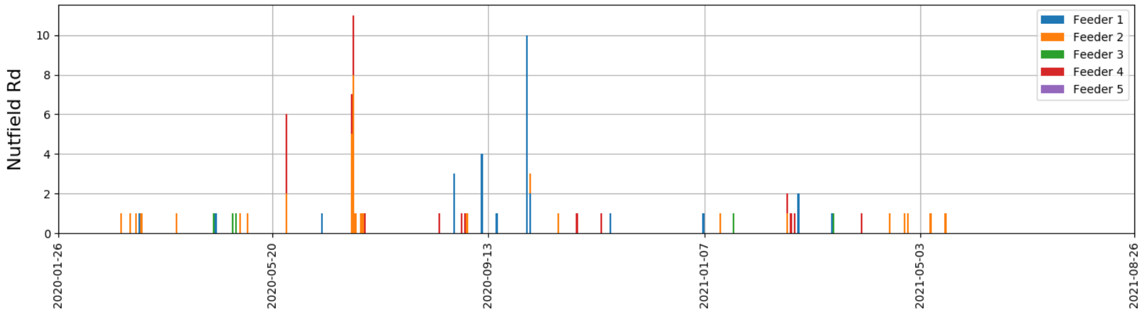

Union St NP - Feeder 1 - Phase to Neutral
Union St NP - Feeder 1 - Phase to Phase
Union St NP - Feeder 2 - Phase to Neutral
Union St NP - Feeder 2 - Phase to Phase
Union St NP - Feeder 3 - Phase to Neutral
Union St NP - Feeder 3 - Phase to Phase
Union St NP - Feeder 4 - Phase to Neutral
Union St NP - Feeder 4 - Phase to Phase
Distance (m)
0
200
400
600
800
1000

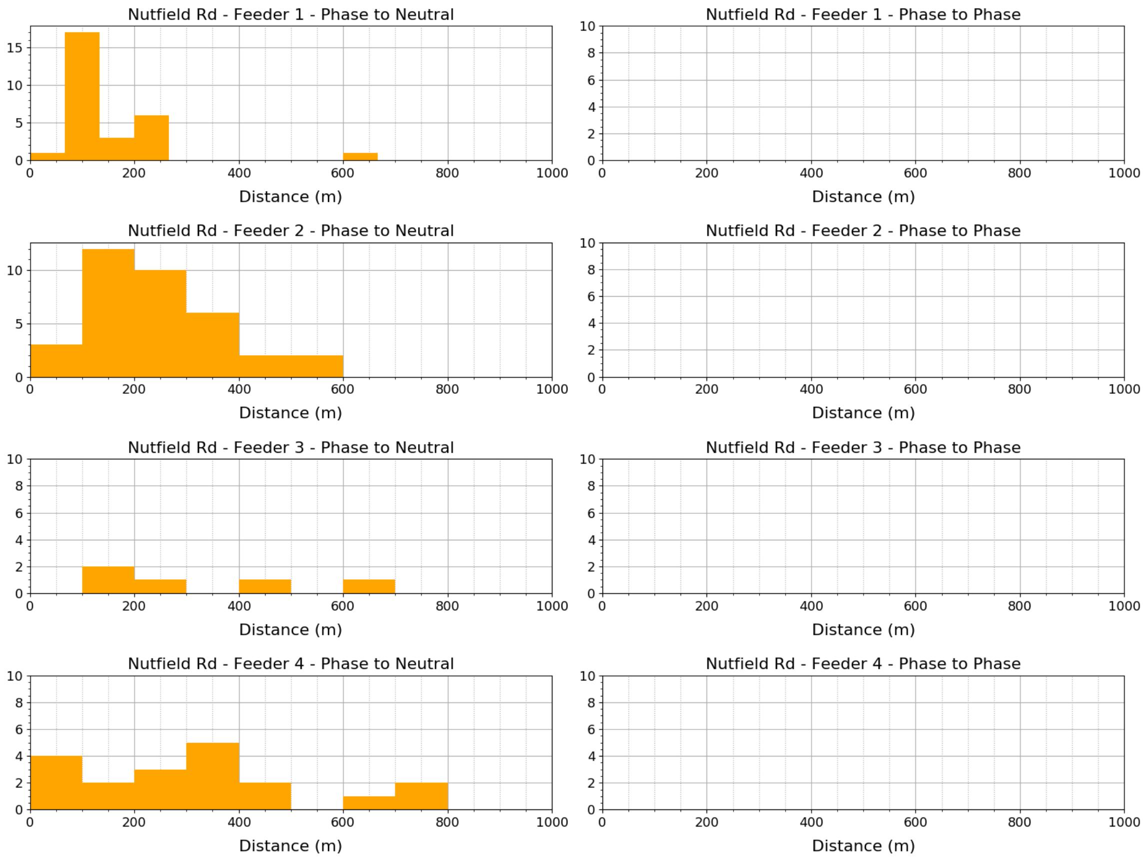
Ravenstone Road



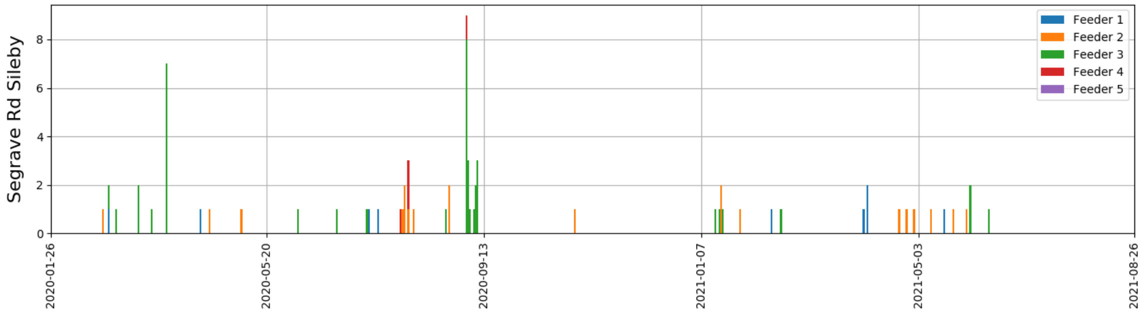


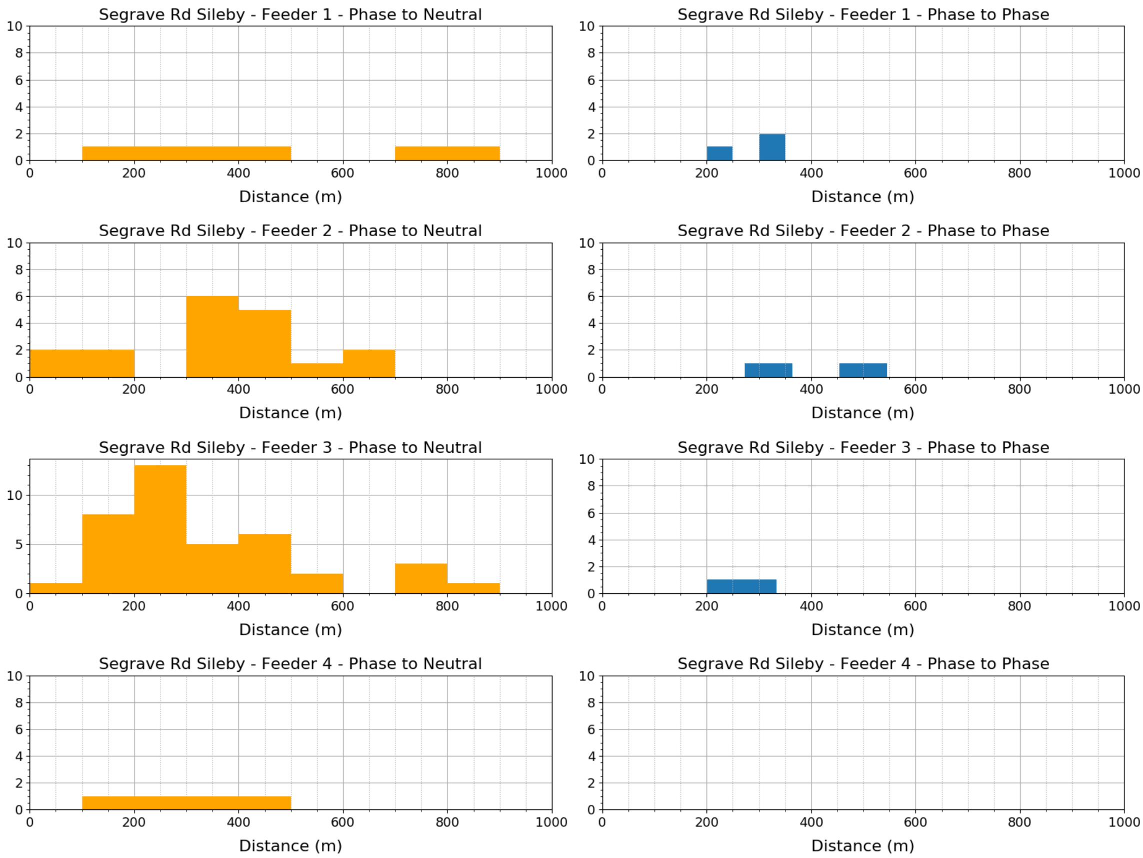
Nutfield Rd


Nutfield Rd
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

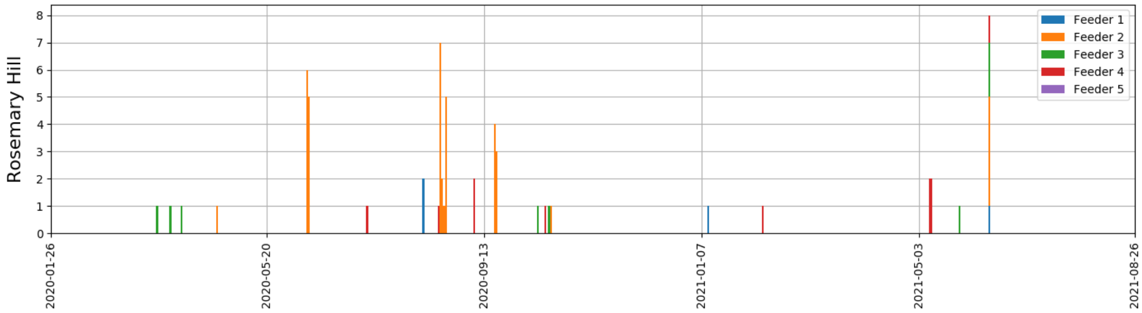

Nutfield Rd - Feeder 1 - Phase to Neutral
Nutfield Rd - Feeder 1 - Phase to Phase
Nutfield Rd - Feeder 2 - Phase to Neutral
Nutfield Rd - Feeder 2 - Phase to Phase
Nutfield Rd - Feeder 3 - Phase to Neutral
Nutfield Rd - Feeder 3 - Phase to Phase
Nutfield Rd - Feeder 4 - Phase to Neutral
Nutfield Rd - Feeder 4 - Phase to Phase
Distance (m)

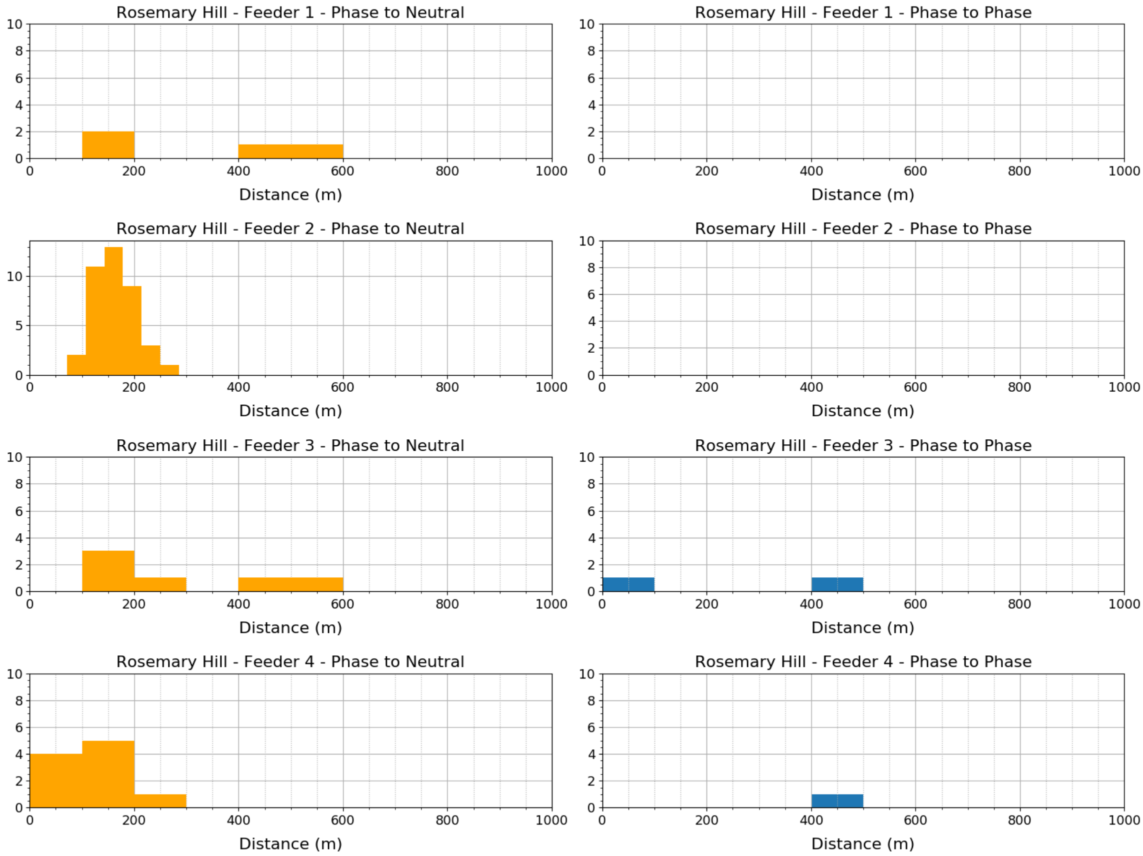
Segrave Rd Sileby



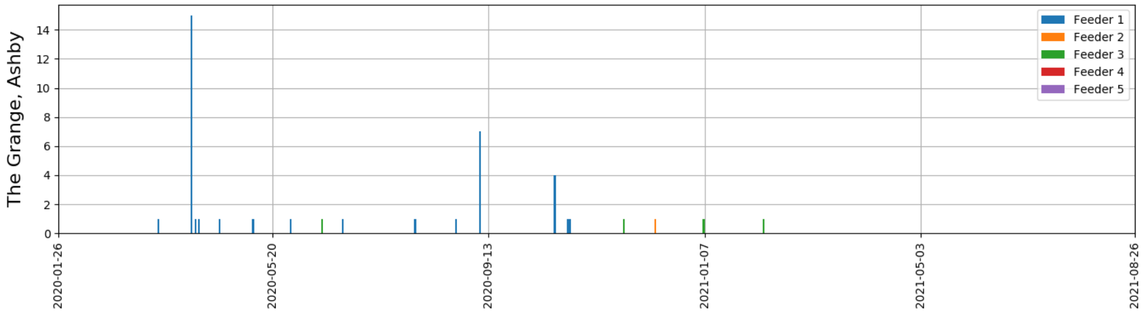


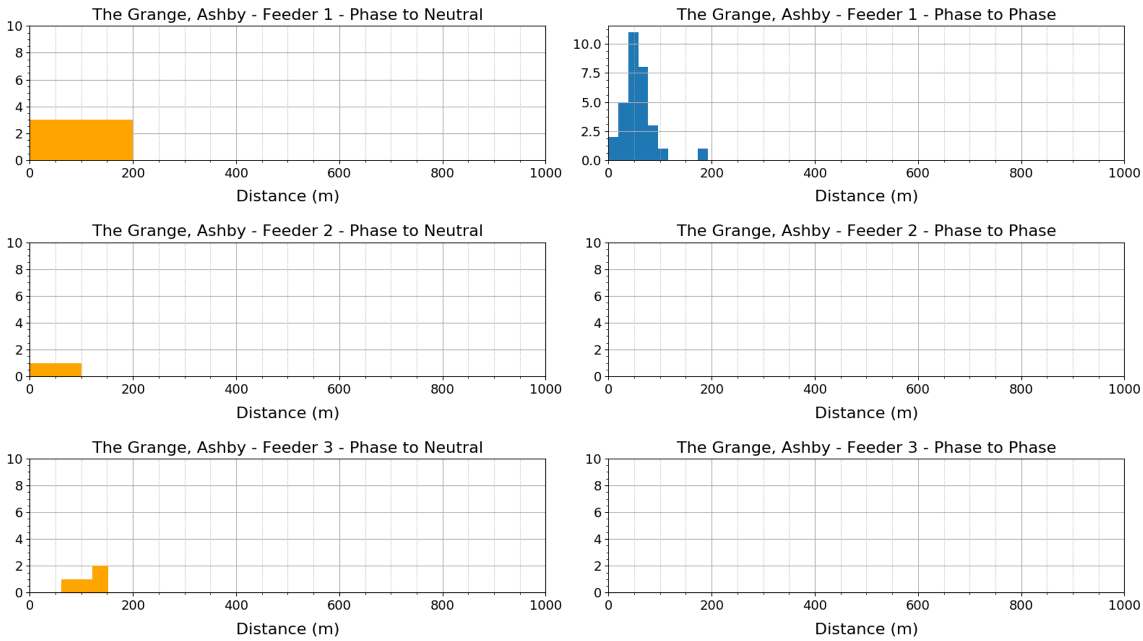
Rosemary Hill



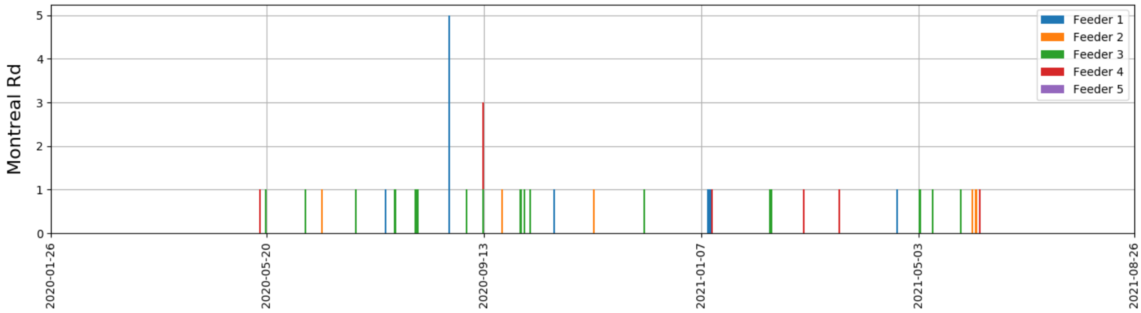


The Grange, Ashby

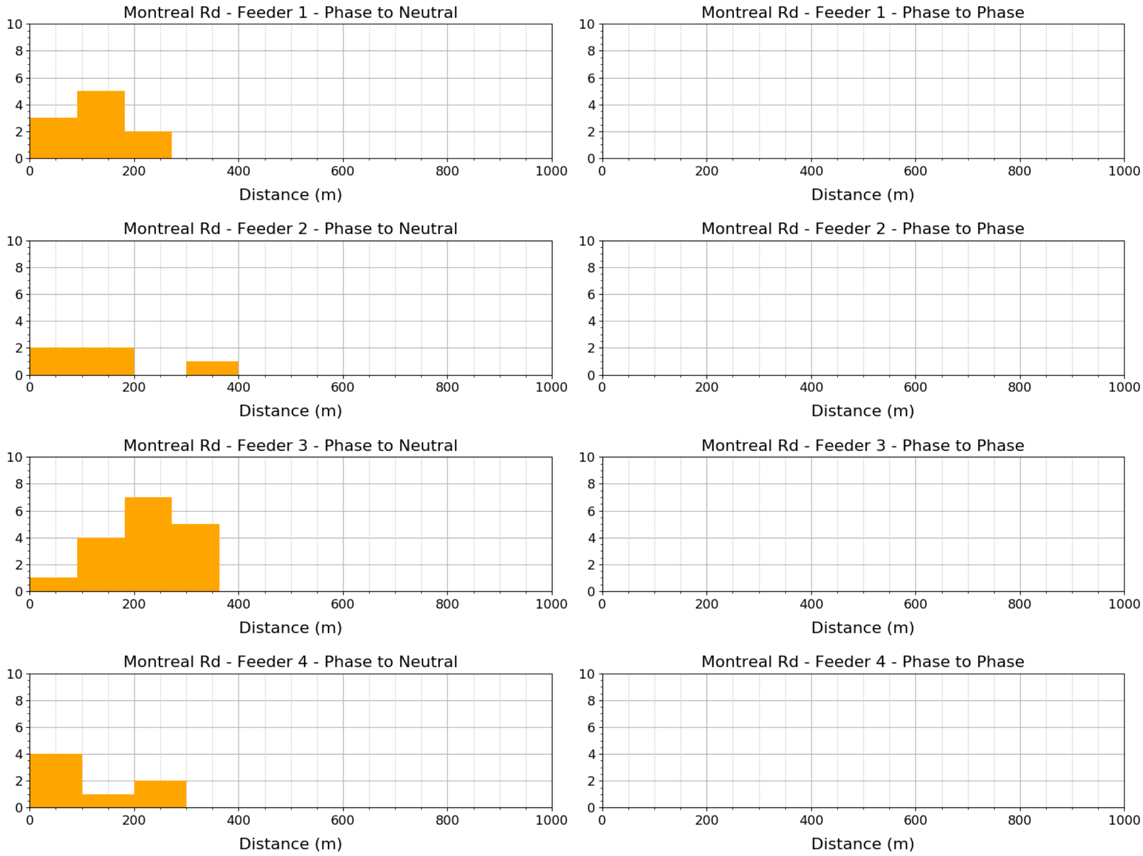




Montreal Rd

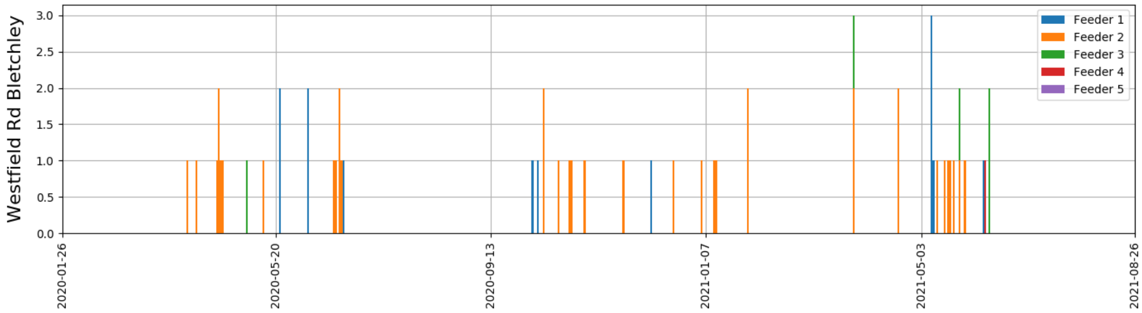


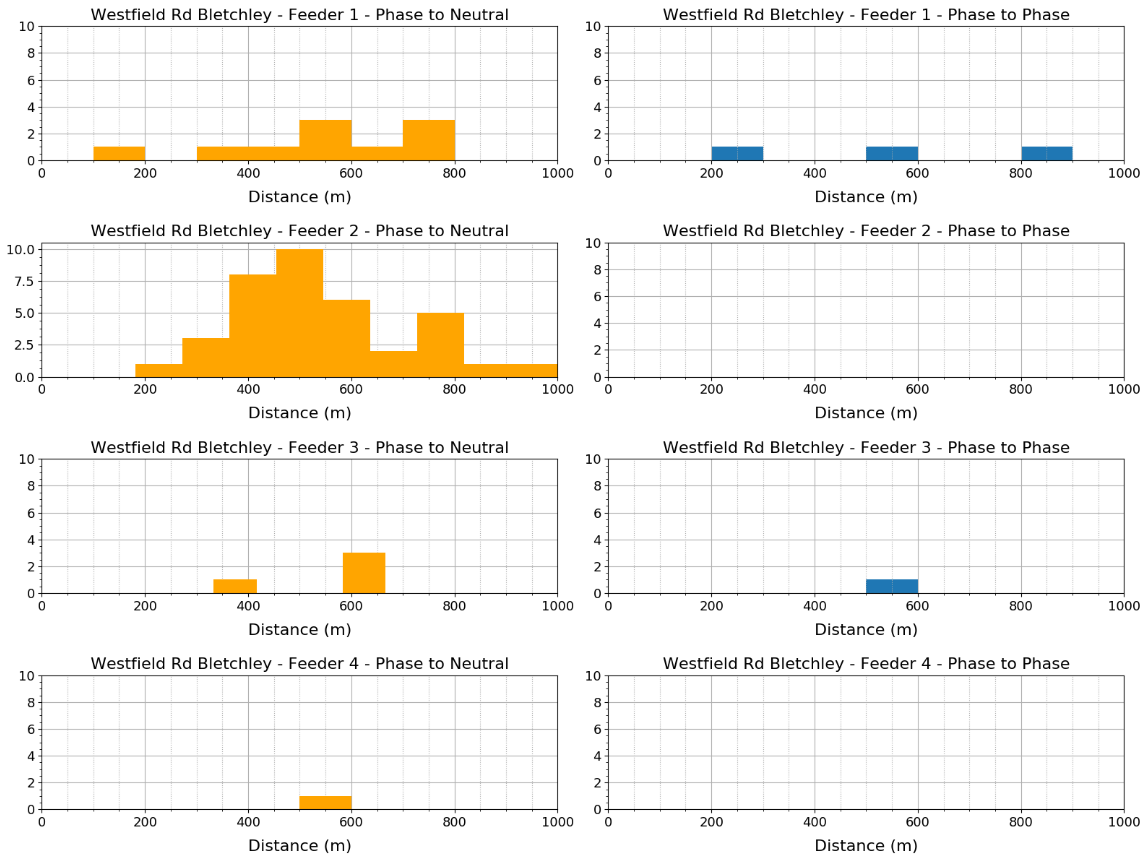
Montreal Rd
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26



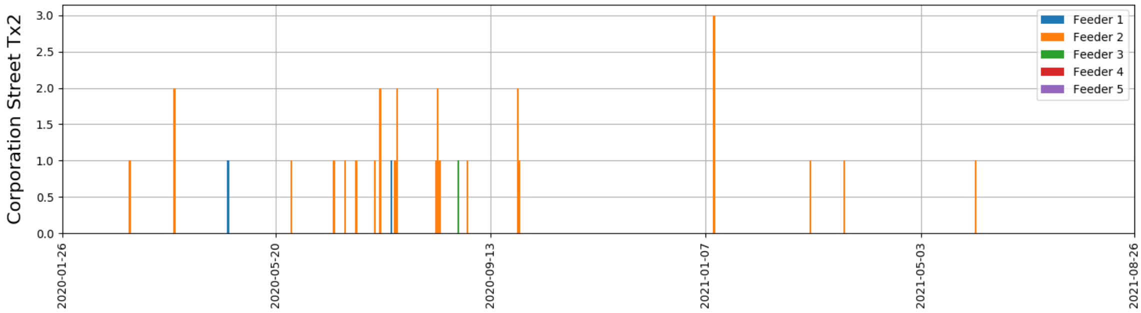
Montreal Rd - Feeder 1 - Phase to Neutral
Montreal Rd - Feeder 1 - Phase to Phase
Montreal Rd - Feeder 2 - Phase to Neutral
Montreal Rd - Feeder 2 - Phase to Phase
Montreal Rd - Feeder 3 - Phase to Neutral
Montreal Rd - Feeder 3 - Phase to Phase
Montreal Rd - Feeder 4 - Phase to Neutral
Montreal Rd - Feeder 4 - Phase to Phase
Distance (m)

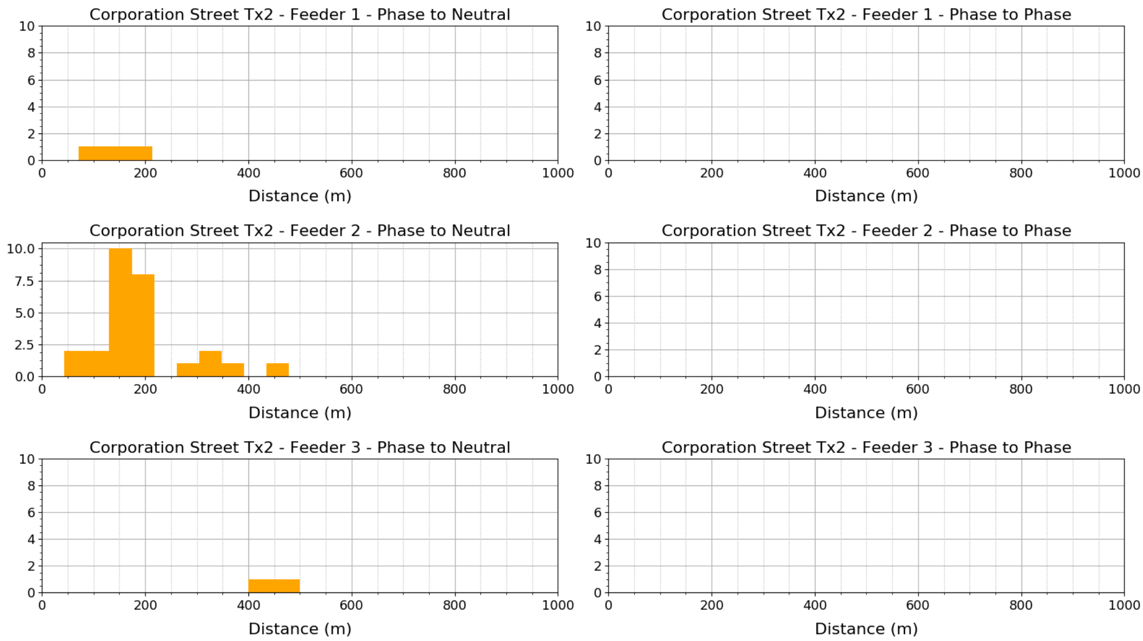
Westfield Rd Bletchley



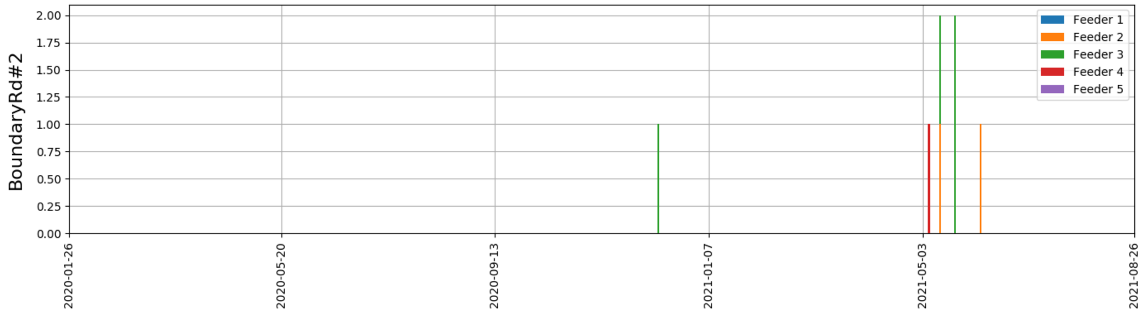


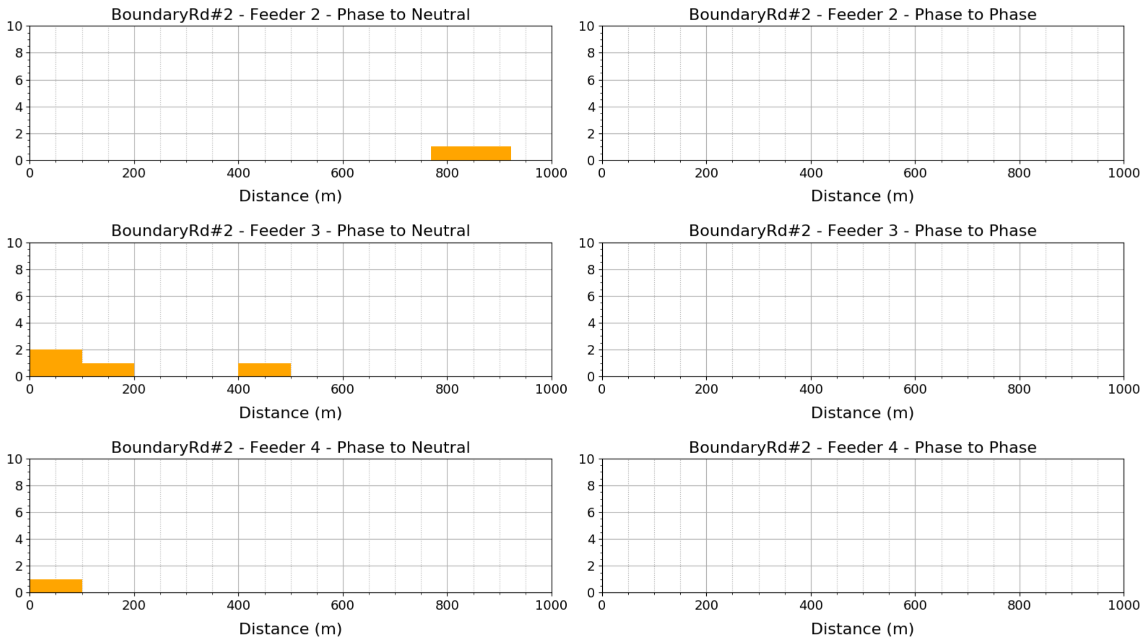
Corporation Street Tx2



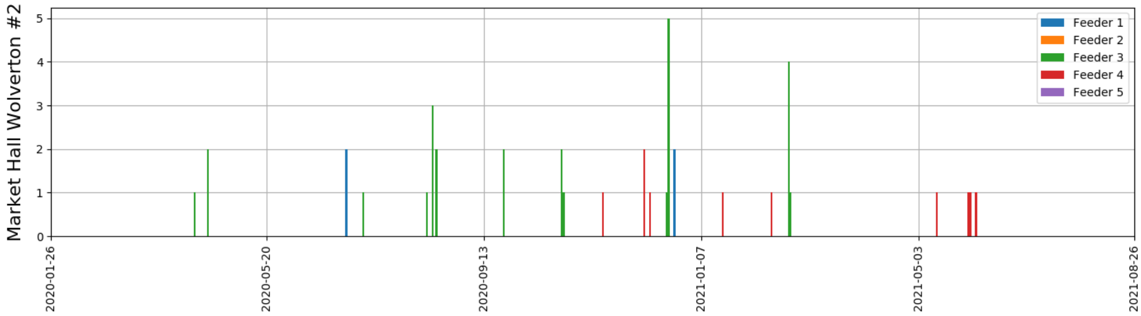


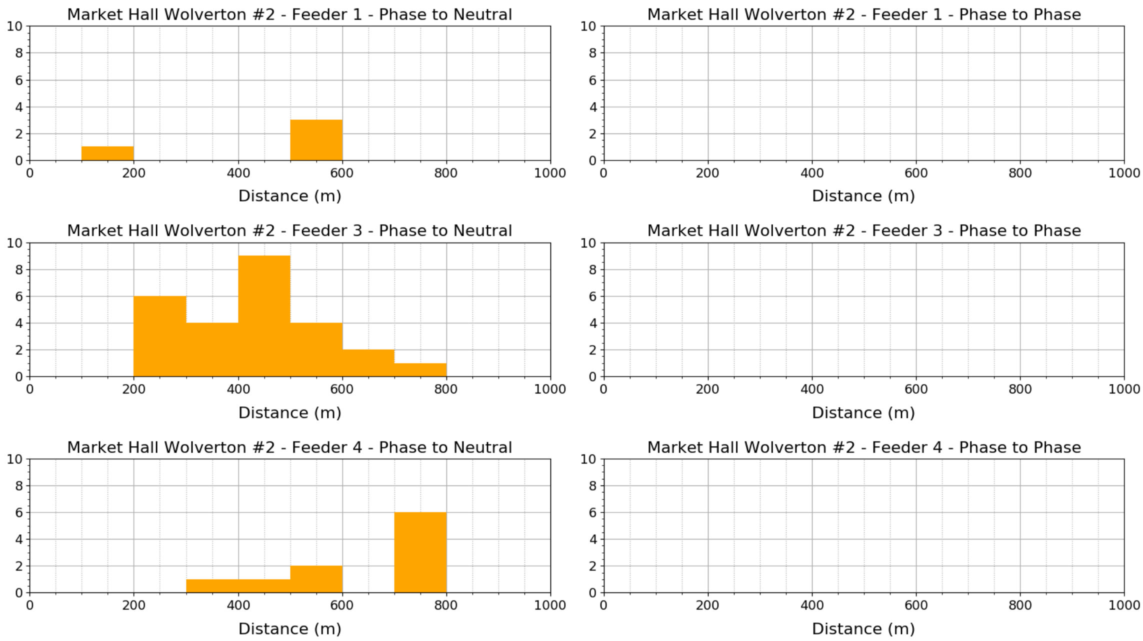
Boundary Rd #2



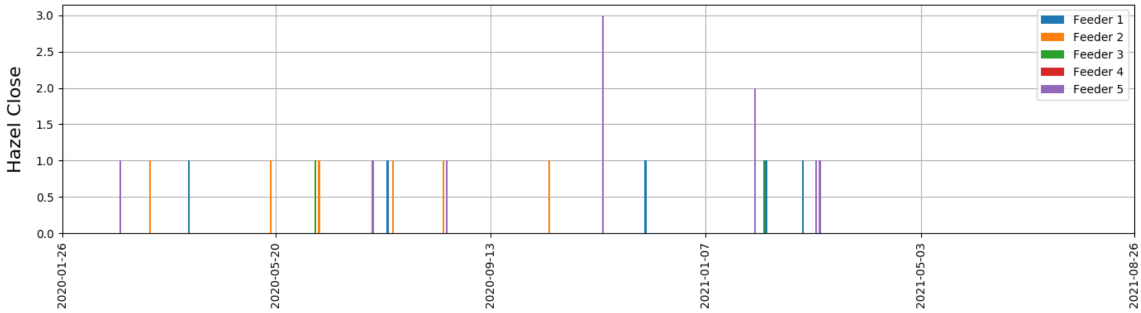


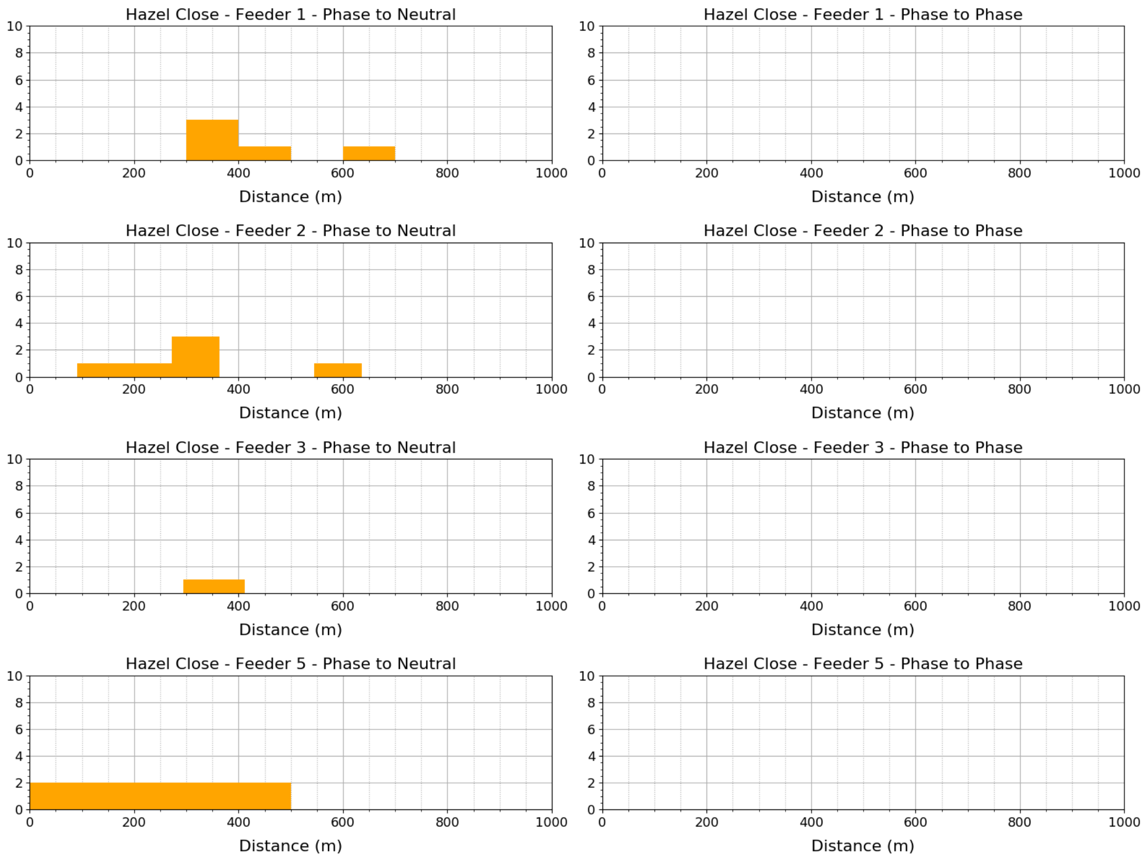
Market Hall Wolverton #2



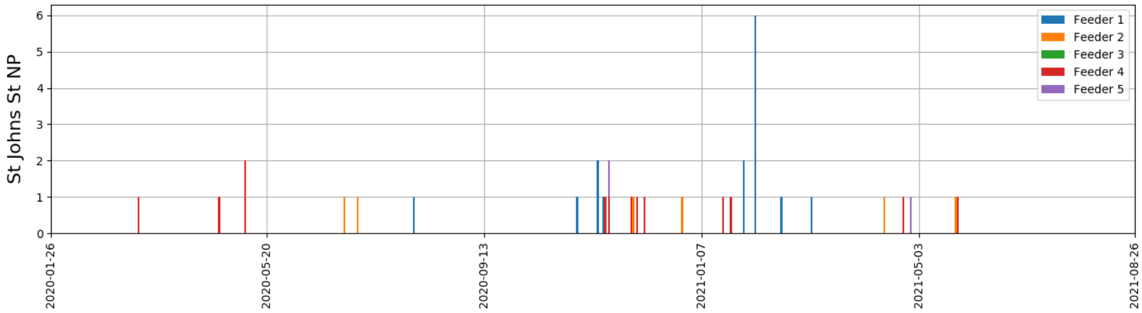


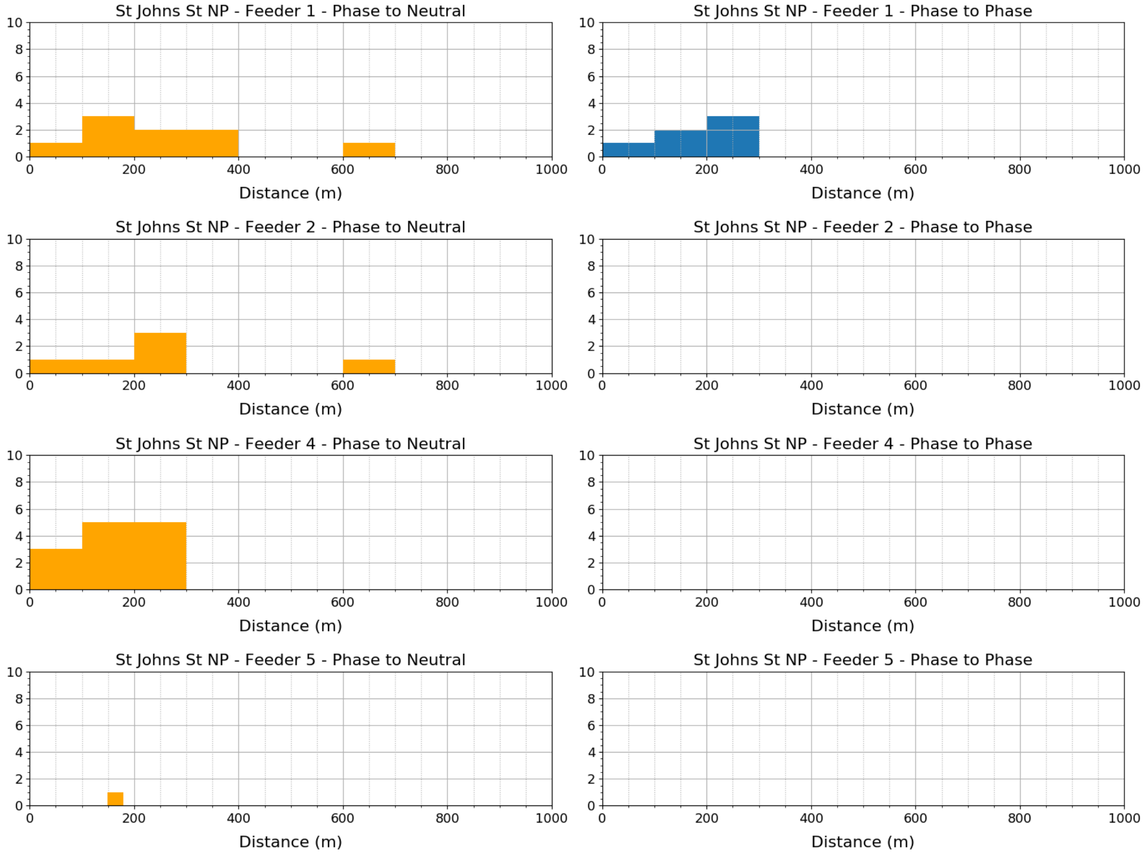
Hazel Close


Hazel Close
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

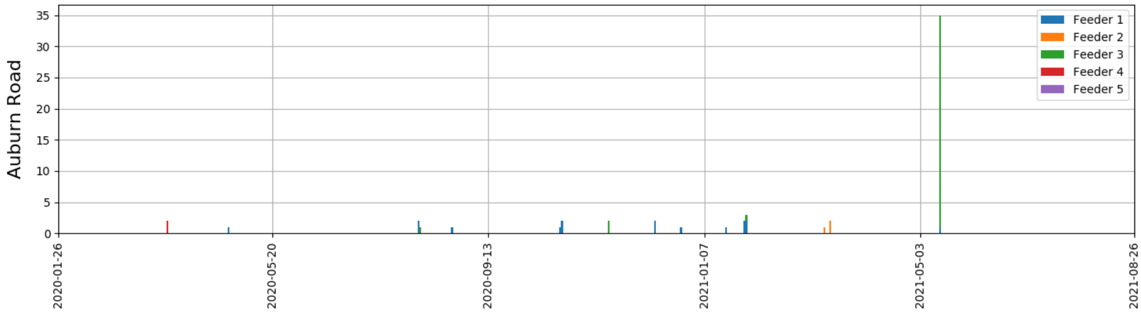

Hazel Close - Feeder 1 - Phase to Neutral
Hazel Close - Feeder 1 - Phase to Phase
Hazel Close - Feeder 2 - Phase to Neutral
Hazel Close - Feeder 2 - Phase to Phase
Hazel Close - Feeder 3 - Phase to Neutral
Hazel Close - Feeder 3 - Phase to Phase
Hazel Close - Feeder 5 - Phase to Neutral
Hazel Close - Feeder 5 - Phase to Phase
Distance (m)

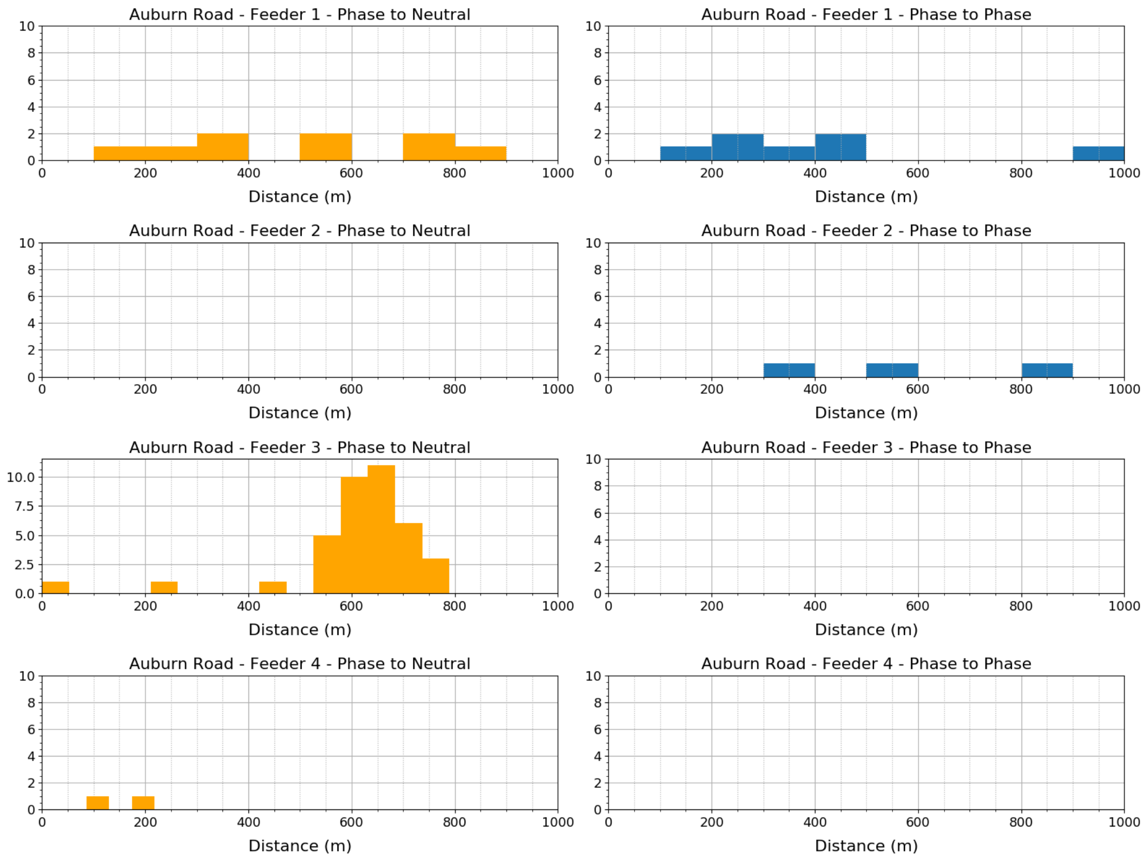
St Johns St NP



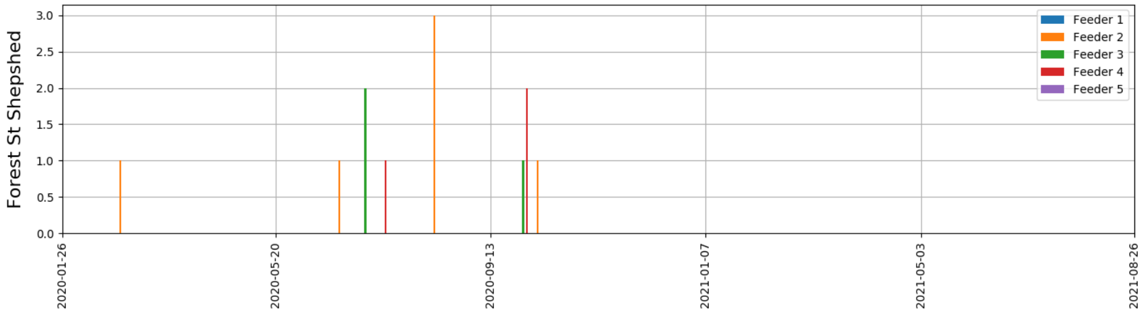


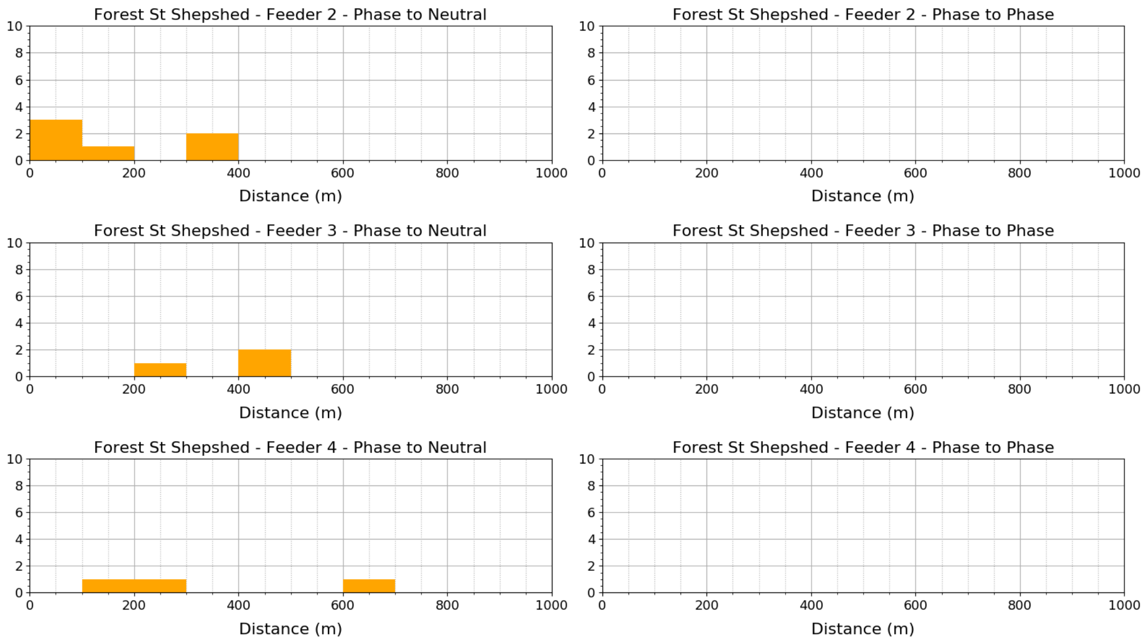
Auburn Road


Auburn Road
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
2020-01-26
2020-05-20
2020-09-13
2021-01-07
2021-05-03
2021-08-26

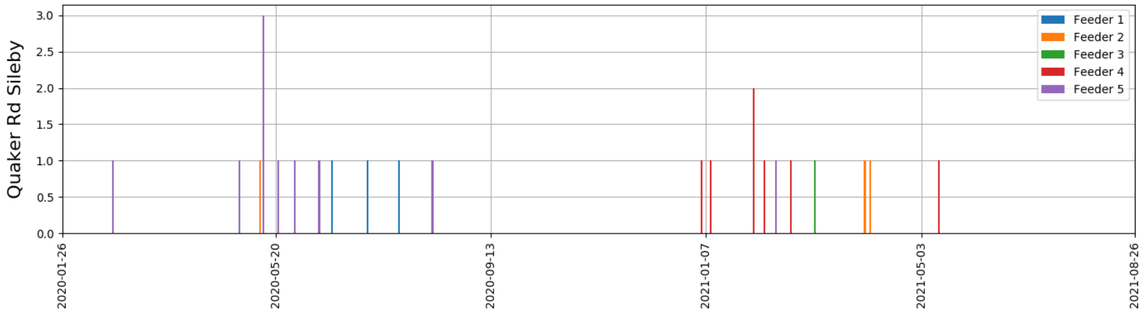

Auburn Road - Feeder 1 - Phase to Neutral
Auburn Road - Feeder 1 - Phase to Phase
Auburn Road - Feeder 2 - Phase to Neutral
Auburn Road - Feeder 2 - Phase to Phase
Auburn Road - Feeder 3 - Phase to Neutral
Auburn Road - Feeder 3 - Phase to Phase
Auburn Road - Feeder 4 - Phase to Neutral
Auburn Road - Feeder 4 - Phase to Phase
Distance (m)

Forest St Shepshed

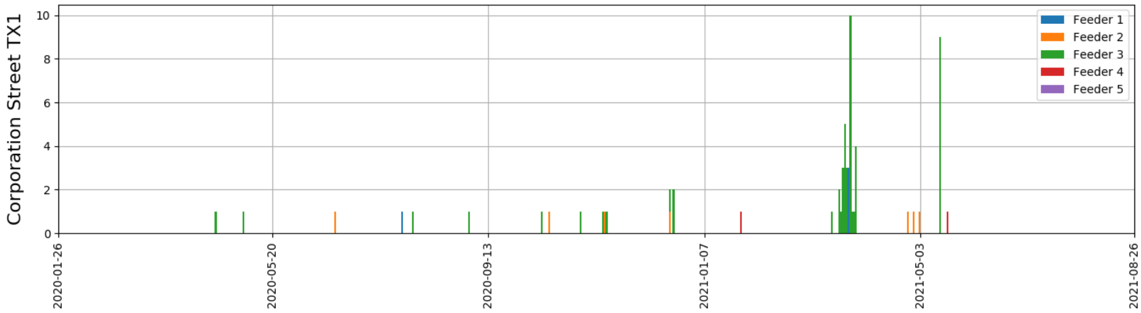


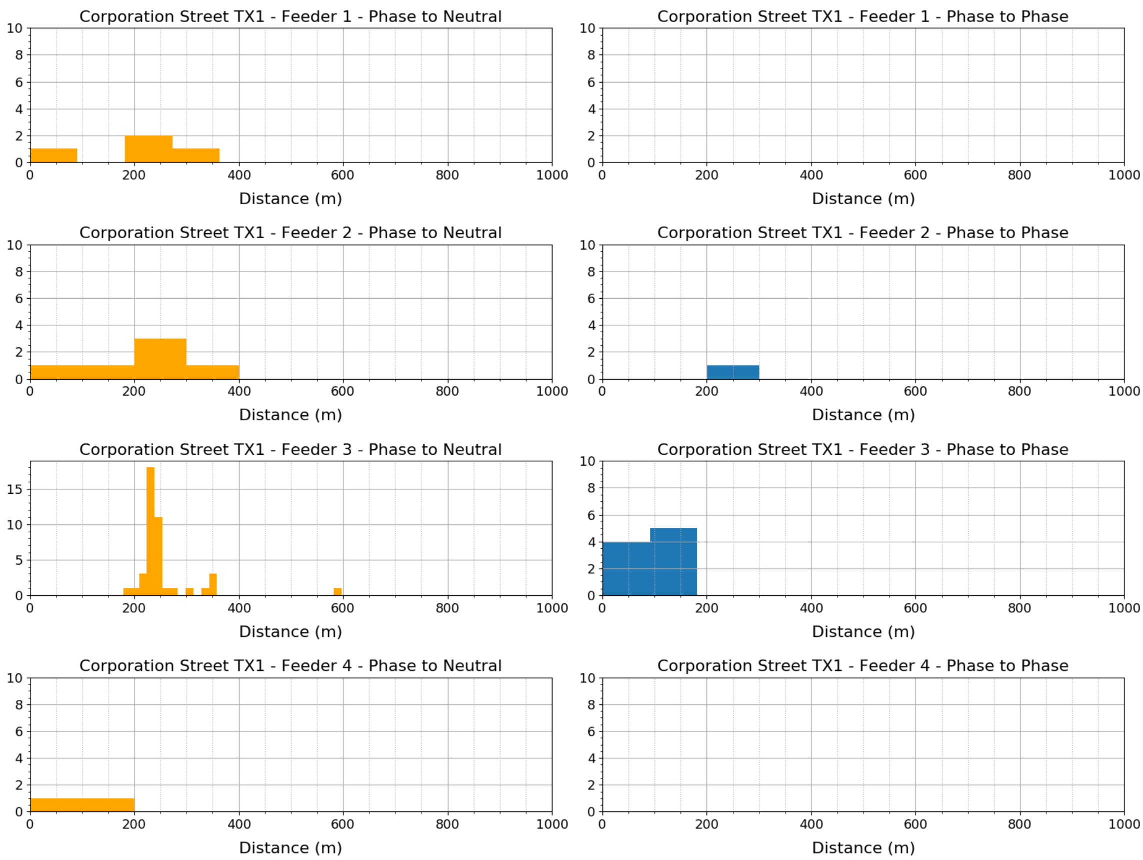


Quaker Rd Sileby

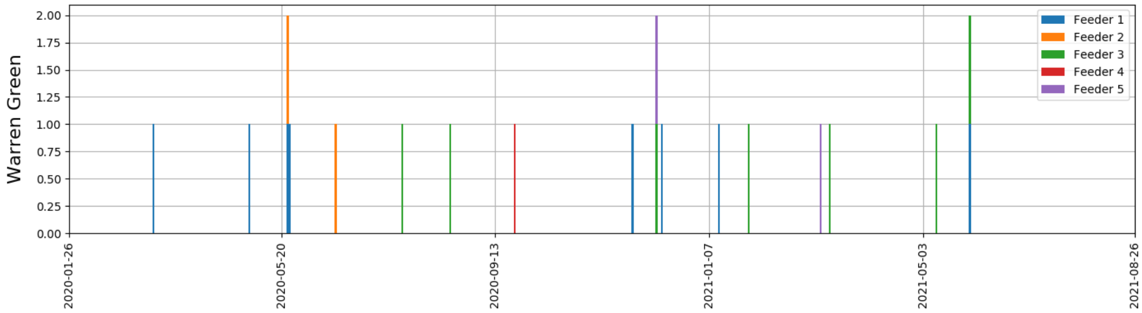


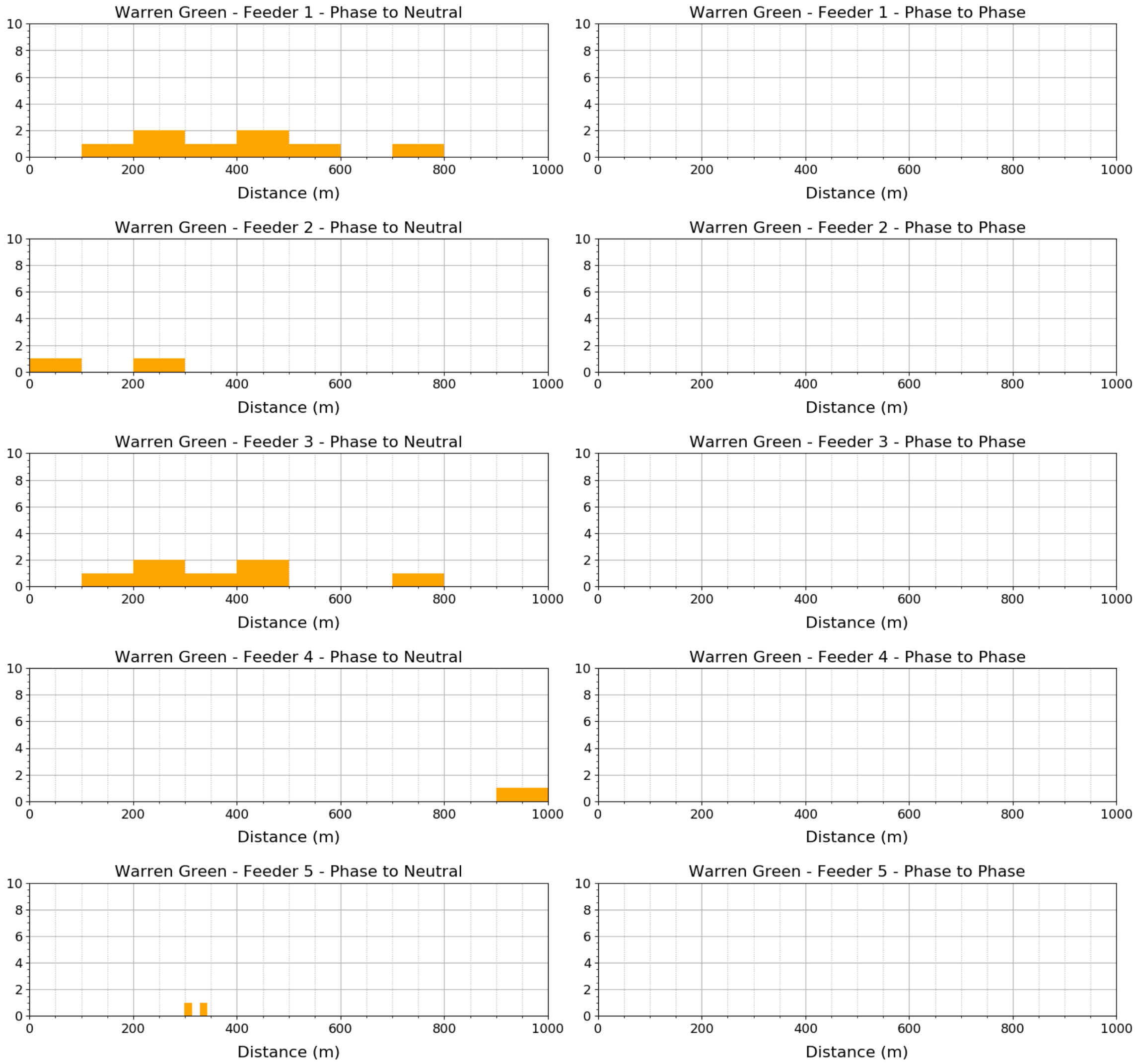
Corporation Street TX1



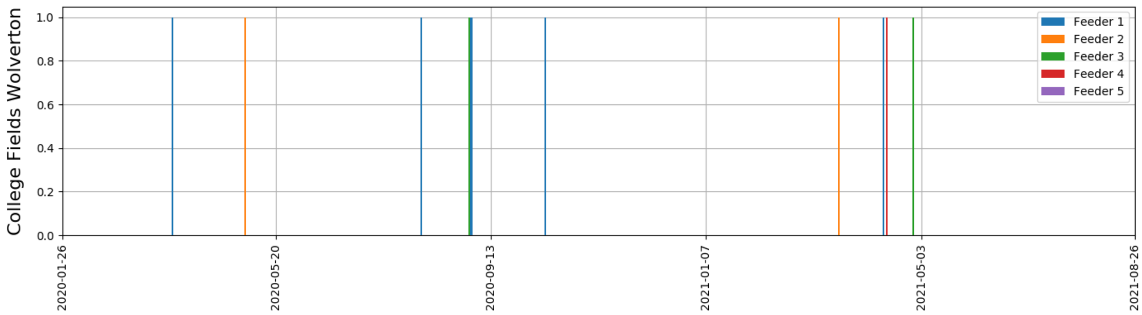


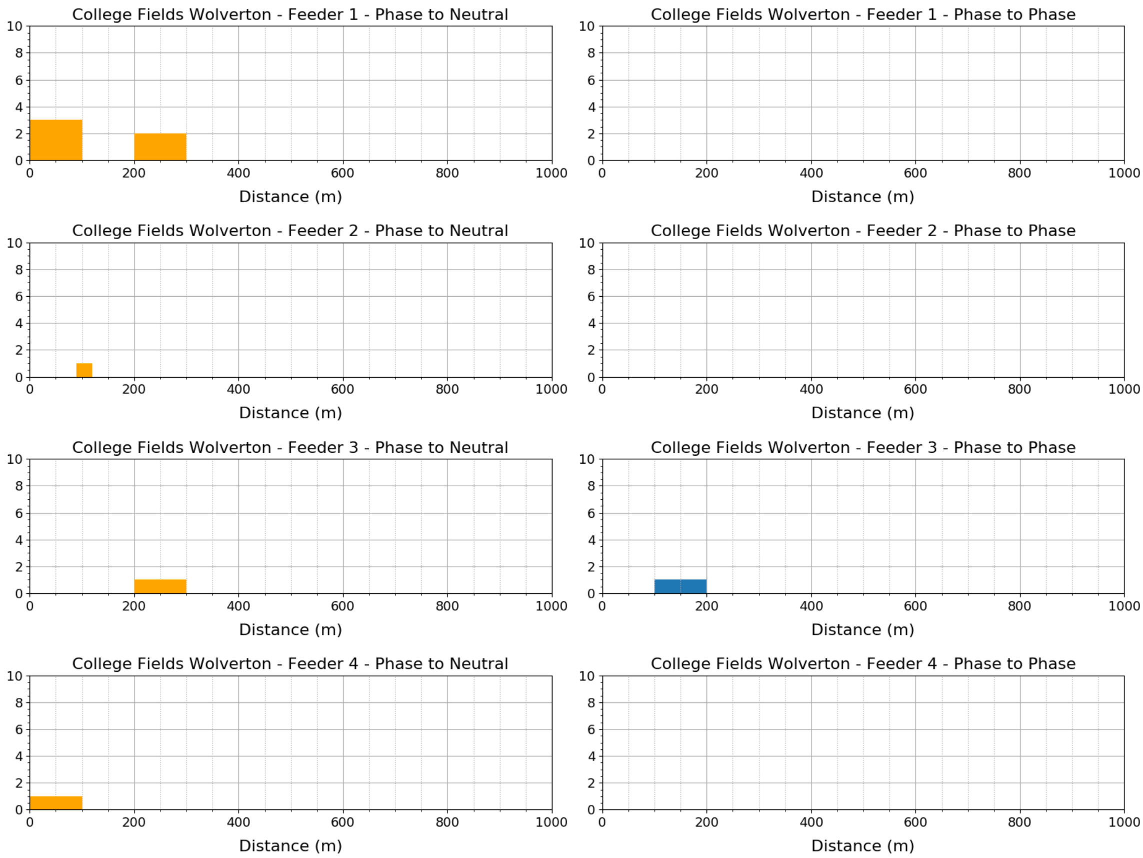
Warren Green



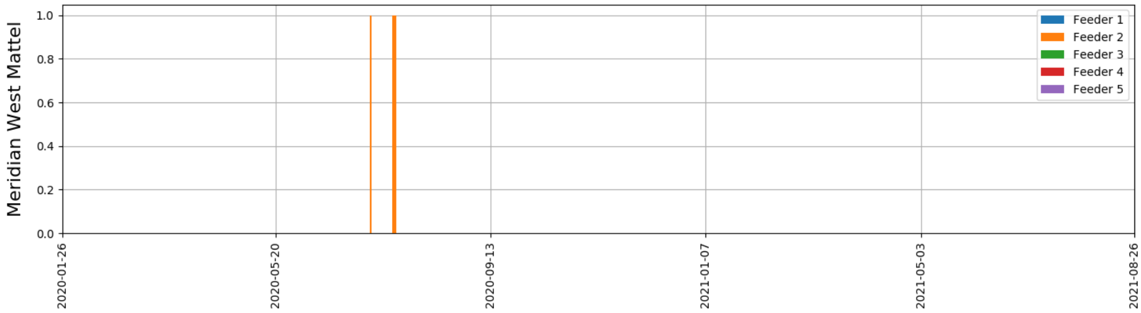


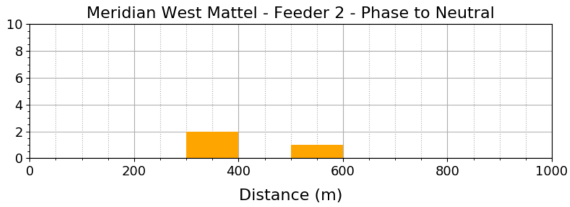
College Fields Wolverton

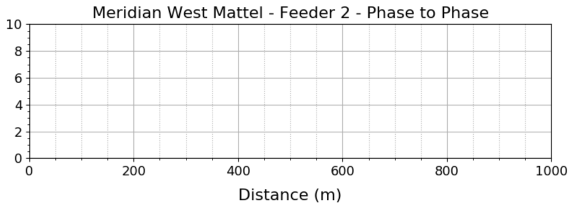




Meridian West Mattel







Templar Av School