

HV Pilot – Findings Report

[D1]

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1 Background & Problem

1.1 Project context

National Grid Electricity Distribution (NGED) operates an extensive high-voltage (HV) and low-voltage (LV) network supplying power to homes and businesses across the UK. On the HV network, electricity is carried on multiple “phases” (separate conductors). How load is distributed across these phases has a direct impact on network efficiency, asset health and the ability to connect new demand and generation.

Over time, network changes, incomplete records and operational work can mean that the actual phase connections of some HV overhead lines are uncertain or out of date.

The HV Pilot has been set up to address this challenge. At present, confirming phase connections typically relies on manual site inspections and engineering judgement, which are time-consuming, potentially disruptive and difficult to scale across the entire network.

The HV pilot aims to answer the question:

Can we reliably and cost-effectively determine the phase configuration of HV overhead lines at scale, using data and analytics rather than widespread manual inspections?

1.2 HV Pilot overview

Two complementary techniques are being trialled:

- **Smart meter–based approach**
  - Uses smart meter (SM) voltage data from the Data Communications Company (DCC).
  - Compares voltage patterns at customer premises with reference voltages from LV and HV monitoring devices (LV monitoring at secondary substations and PQube devices at primary substations).
  - Builds on learning from the Smart Meter Innovations and Test Network (SMITN) project to infer phase connections from measured voltage behaviour over time.
- **Imagery-based approach**
  - Uses helicopter-captured images (and associated GPS/orientation metadata) and LiDAR to build a virtual model of the overhead network and physically trace which conductor is connected where.
  - CGI Machine Vision then processes survey images, clustering them into continuous views along power lines and extracts information about network configuration.

The two methods are designed to be complementary:

- The smart meter method uses electrical behaviour (how voltages change) to infer phase.
- The image-based method uses physical evidence (what the poles and conductors look like) to infer configuration.

1.3 Pilot scope and datasets

The pilot focuses on a defined trial area within NGED’s network:

- Seven HV feeders have been identified as the core trial sites.
- Within these feeders there are 925 secondary substations, serving approximately 8,045 customers.

- The core area may later be extended by adding a further feeders once raw image data is available for visual analysis.

To support the algorithms, the HV Pilot draws on a combination of network master data and historical measurement data:

- Network / master data
  - HV and LV topology (from Electric Office – EO)
  - MPAN and network-premise linkage data (from CROWN)
  - Smart meter inventory, including MPAN to SM ID mapping and aggregation group definitions
- Measurement data
  - Smart meter voltage histories and aggregated LV feeder demand
  - LV monitoring measurements (GridKey, VisNet, PRESense) at distribution substations
  - PQube monitoring at primary substations providing a three-phase voltage reference
  - Aerial image datasets sourced from National Grid Electricity Distribution aerial surveys

1.4 Problem statement

The HV Pilot seeks to address uncertainty in the phase connections of HV overhead lines by trialling data-driven methods that use smart meter and monitoring data, alongside aerial imagery and LiDAR, to infer phase configuration at scale. The aim is to enable more accurate modelling of phase unbalance and to support better planning, operation and investment decisions, without relying solely on manual field inspections.

The high-level objectives are:

- Identify HV phase connections for two-wire sections of HV overhead line in the trial area.
- Develop and test a range of algorithms (both smart-meter-based and imagery-based) for phase identification.
- Assess accuracy and cost-effectiveness of these approaches compared with site-based inspections.
- Demonstrate a data platform and machine-vision capability that can be reused or scaled beyond the pilot.

2 Approach

2.1 Image-based method processing approach

The HV Pilot uses helicopter captured images of overhead lines, together with GPS and orientation metadata (and LiDAR where available), to reconstruct the physical layout of the network. The goal is to form continuous "branches" of line, identify intersections between branches, and provide structured inputs for machine-vision models that infer configuration and connectivity. The table below summarises each stage of this pipeline and shows which steps are complete and which are still work in progress.

Step	Stage	What happens	Pilot Status
1	Image metadata processing	Extract timestamp, GPS location and camera/aircraft orientation from each survey image. Standardise this metadata so that images can be accurately plotted in space and time and compared to one another across the survey.	Complete
2	Image adjacency graph	Construct a graph data structure where each node represents an image and edges represent "adjacency" relationships between images (i.e. images taken close together in space, time and orientation). This graph captures how images relate to one another along the power line routes and underpins the image adjacency and clustering logic.	Complete
3	QGIS layer generation	Using the graph and metadata, generate QGIS layers that contain points for each image location and lines suggesting candidate connections or segments between images. These layers allow the visualisation of survey coverage and relate the images to the existing network geography in a standard GIS tool.	Complete
4	Line-branch image set creation	Use the adjacency graph and spatial layers to group images into line branches (sequences of images following the same overhead line). For each branch, create an image set that provides near-continuous visual coverage of that span of network for subsequent machine-vision analysis (e.g. conductor positions, cross-arms and configuration).	Complete
5	Single phase branch detection	This step extracts individual line information from each image. The Machine Vision platform will evaluate the line branch images and extract line meta data. These images typically show a primary set of lines consisting of 3 conductors (primary line) and a secondary or branch set of lines (branch line) with 2 conductors. The primary line conductors will be numbered from right to left, or bottom to top, 1 to 3. The secondary conductors will be numbered based on their connection to the primary lines. Subsequent steps will look at the global orientation, and connections to	WIP – initial findings are covered below

		try to determine the phase name. This step does however provide an insight into the phase distribution.	
6	Branch orientation determination	Develop logic to determine the direction of travel/orientation for each branch (i.e. which way along the branch the sequence runs). Consistent orientation supports interpretation of conductor positions and mapping branches back onto the logical network model.	WIP
7	Branch-intersection modelling	Define a “branch intersection” concept to identify where branches intersect or join (for example at junction poles, tees or crossings). This enables more accurate reconstruction of overall network topology from imagery and helps align imagery-derived branches with existing network records.	WIP
7	Intersection reporting	Generate intersection report that summarises identified branch intersections, highlighting complex or ambiguous areas.	WIP

2.2 Processing environment

The imagery processing for the HV Pilot runs within a CGI-managed Azure environment. Survey images are stored in Azure Storage. A Docker container running the CGI Machine Vision Client on a GPU-enabled Windows VM reads the images, executes the pipeline, and writes outputs back to storage. Processed data is then transferred to a presentation environment (e.g. QGIS / the main HV Pilot platform).

The below diagram shows a high-level overview of how the processing environment is structured:

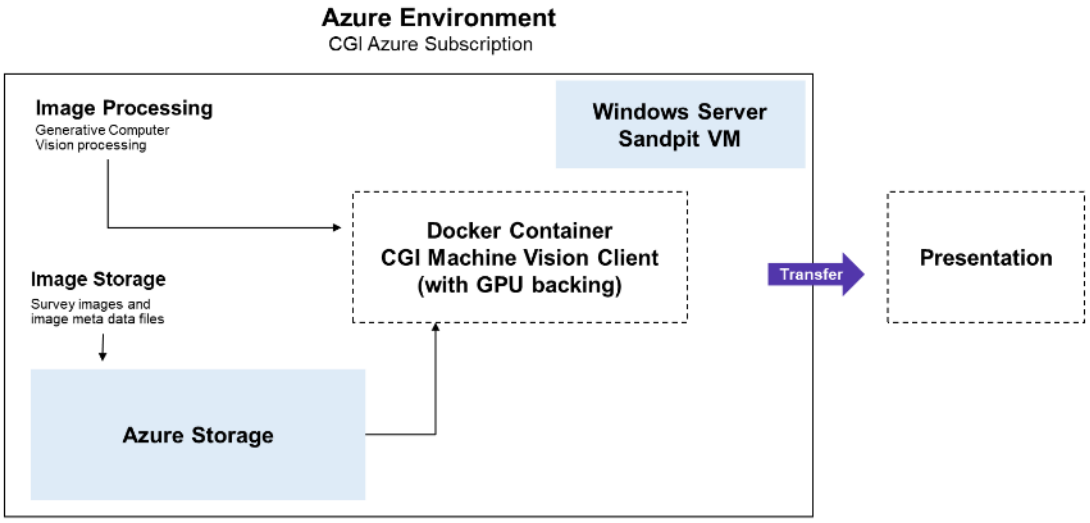


Figure 1 - Image Processing Environment

3 Initial findings

3.1 Object extraction and semantic interpretation

The example span in Figures 2 to 4 demonstrates the current capability of the imagery pipeline:

- From a standard survey photograph (Figure 2), the segmentation step isolates the poles and conductors from the background (Figure 3).
- The semantic interpretation step then converts these segmented objects into a network-style representation, with coloured lines representing individual conductors and the branch connection at the tee pole (Figure 4).

This shows that the core computer-vision components are functioning as intended: poles and conductors can be detected and turned into structured geometric objects that are suitable for further analysis (e.g. branch building, intersection detection, and ultimately configuration inference).

An early observation from this work is that there appears to be a bias in the way lines are selected at branches. Where multiple combinations of lines are geometrically plausible at a junction, the current logic tends to favour certain combinations over others. This reinforces the need for the branch/intersection algorithms (and later, supply-direction inference) to incorporate additional constraints beyond simple geometry, so that ambiguous junctions are resolved consistently.



Figure 2 - Reference Image



Figure 3 - Image with segmentation

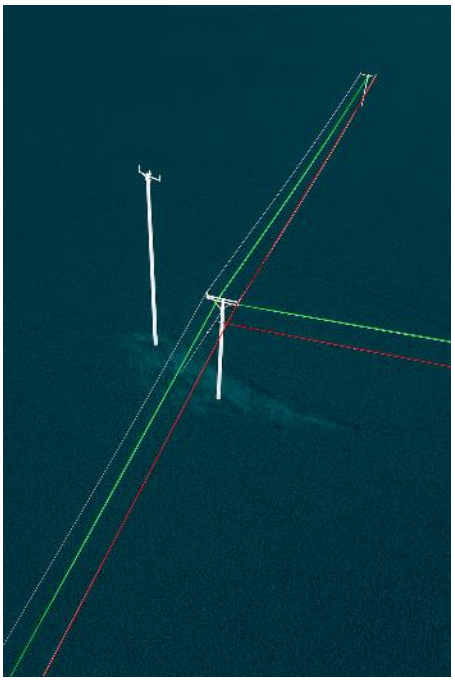


Figure 4 - Image with semantic objects

3.2 Spatial coverage, metadata correlation and branch building

Figures 5 and 6 illustrate how image metadata is being used to reconstruct the survey coverage and build branches:

The QGIS view (Figure 5) shows all surveyed images plotted over the trial area, with points and lines representing image locations and inferred adjacency. This provides a clear visual check of coverage and highlights locations where the helicopter flight path loops back over the same area.

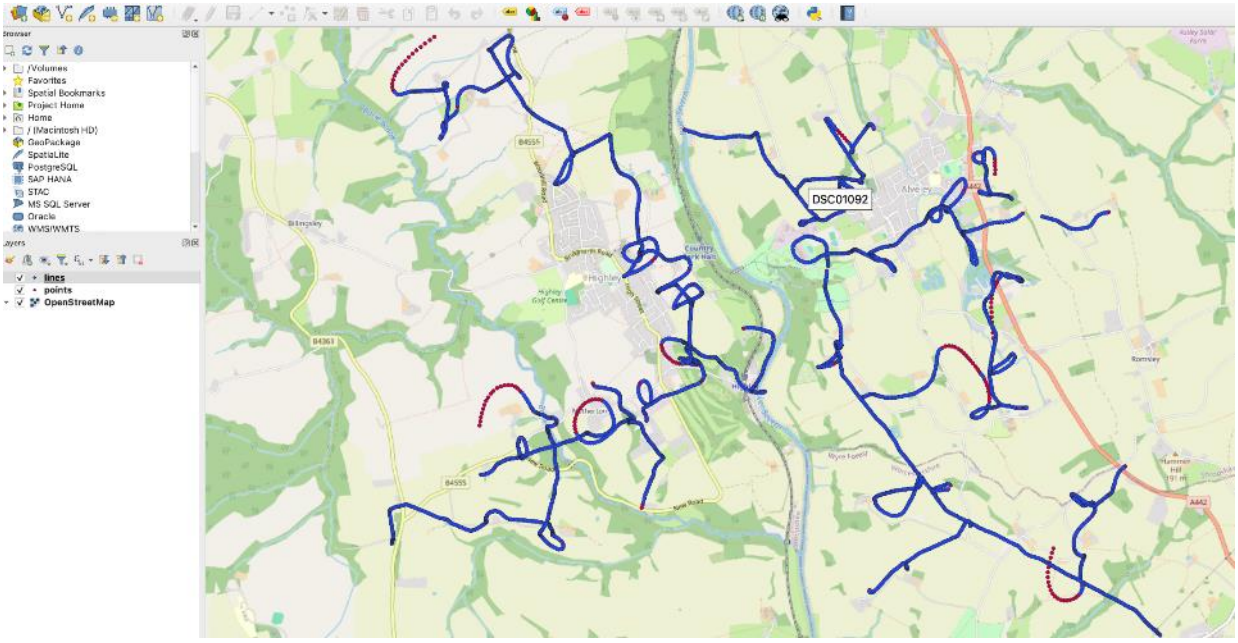


Figure 4 - QGIS view

The branch-mapping example (Figure 6) plots individual images by easting and northing and connects them into a smooth curve. This demonstrates that metadata correlation is working well: timestamps, GPS positions and orientation are sufficiently consistent to order images correctly and build continuous branches along the line.

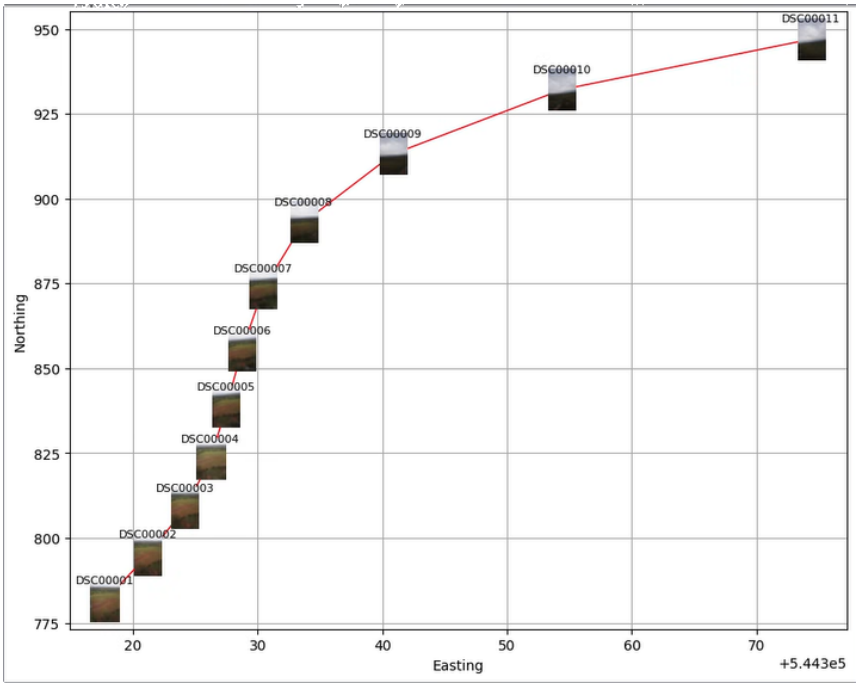


Figure 6 5 - branch mapping example

3.3 Single Phase Branch Detection

3.3.1 Metadata captured

Based on initial subset of branch line images, we have been able to extract and generate the following metadata:

Field	Source	Description
ImageName	Extracted from image	Name of the survey image
Northing		The location of the image
Easting		The location of the image
Group	Generated via Machine Vision	The group number of lines for the branch
Phase Number		The logical phase number within the branch
Primary Line		E.g. A,B,C
Secondary Line		E.g. X,Y,Z

Other extracted meta data, such as the bearing, may also be written for future processing.

3.3.2 Example showing how the metadata relates to an image

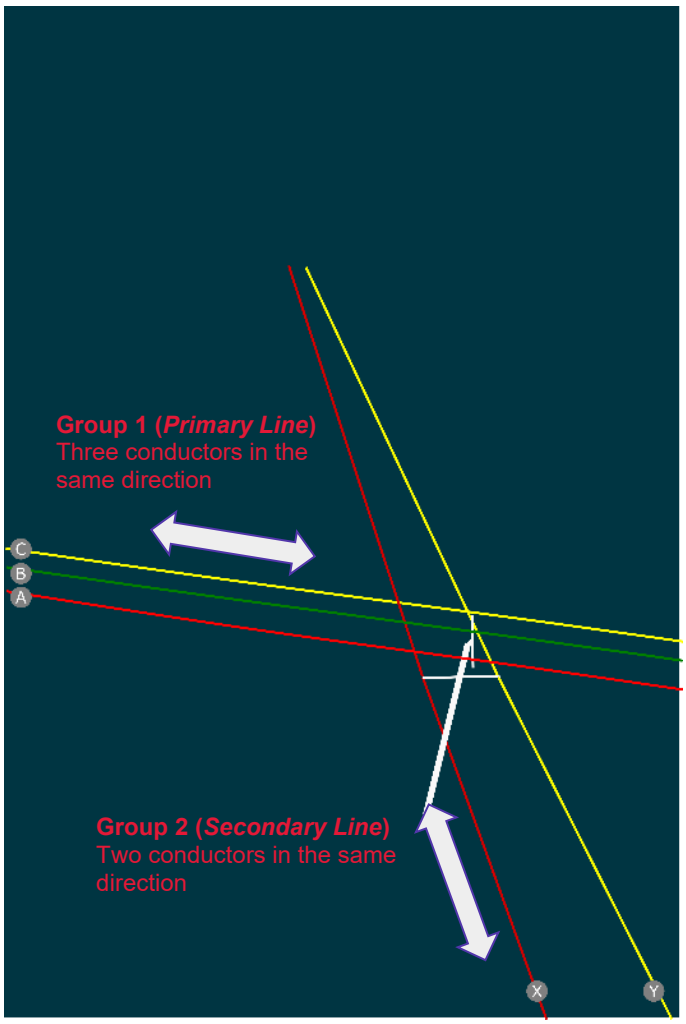


Figure 6 - Semantic Line Image

Figure 7 shows an example of how the metadata relates to an image:

The algorithm organizes conductors that share the same orientation (heading) into distinct line groups for analysis.

- **Primary Line (Group 1):** In this example, the primary group consists of three conductors, labelled A, B, and C from bottom to top, and visually distinguished by the colours red, green, and yellow.

- **Secondary Line (Group 2):** The secondary group includes conductors labelled X and Y (with Z as a potential addition, though not present in this image).

To maintain continuity across junctions, these color assignments are carried through the connection points (for example, the conductor labelled A in the primary group connects to X in the secondary group).

Note: The labels A/B/C and X/Y/Z are provisional and serve as local identifiers within each image or branch, allowing the algorithm to track geometric relationships and continuity through network junctions. The definitive phase names (L1, L2, L3) is assigned later, once the orientation and supply direction of each branch are determined and the mapping is propagated along the network route.

This approach enables accurate tracking of conductor paths and supports subsequent steps in network topology reconstruction.

3.3.3 Extracted dataset example

The table below shows what the raw metadata looks like for an example image set.

There is one record per detected conductor (line) in each image after grouping wires into line groups and assigning a relative line index.

How to Interpret a Data Row:

- Each row corresponds to a specific survey image (e.g., DSC00463.JPG, listed as Field “1” in the table).
- The "primary group" refers to the main set of conductors in the image, with each line (e.g., labelled "A") identified relative to its position within the group. The primary group are typically labelled “A” through “C”.

- If a conductor from the "secondary group" (e.g., labelled "Z") is visible, it is paired with the corresponding primary conductor in that frame, based on the path of a junction wire between the two lines.

- The Easting and Northing values provide the geographic location of the helicopter for the image, enabling precise mapping of conductor positions within the network. The location data along with date and time of the image allows us to correlate a specific pole with others.

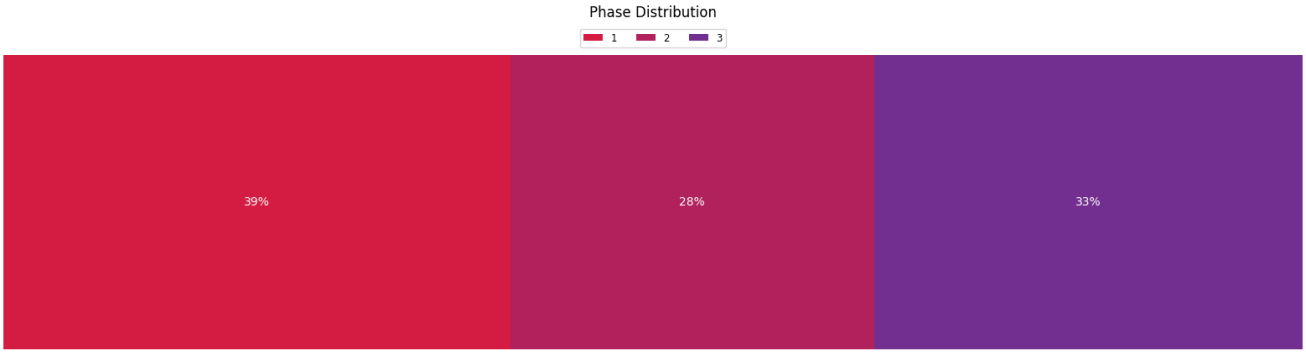
- Use these details to trace conductor continuity and verify network topology across multiple images.

The following are example records for a group of 17 images:
Image set: *20240109_B_2_WA_600017_HaverfordWestPowerStation_PG*
Region: *600017_034*

Field	ImageName	PhaseNumber	Primary Line	Secondary Line	Northing	Easting
1	DSC00463.JPG	1	A	Z	5740584.886	365513.197
1	DSC00463.JPG	2	B	Y	5740584.886	365513.197
1	DSC00463.JPG	3	C	X	5740584.886	365513.197
2	DSC00526.JPG	1	A	Z	5740603.773	365540.24
2	DSC00526.JPG	2	B	Y	5740603.773	365540.24
2	DSC00526.JPG	3	C	X	5740603.773	365540.24
3	DSC00645.JPG	1	A	X	5740628.372	365691.652
3	DSC00645.JPG	2	B		5740628.372	365691.652
3	DSC00645.JPG	3	C	Y	5740628.372	365691.652
4	DSC01043.JPG	1	A	X	5740537.201	367853.763
4	DSC01043.JPG	2	B		5740537.201	367853.763
4	DSC01043.JPG	3	C	Y	5740537.201	367853.763
5	DSC01090.JPG	1	A	X	5740538.347	368437.993
5	DSC01090.JPG	2	B		5740538.347	368437.993
5	DSC01090.JPG	3	C	Y	5740538.347	368437.993
6	DSC01150.JPG	1	A	Y	5740548.812	368541.507
6	DSC01150.JPG	2	B	X	5740548.812	368541.507
6	DSC01150.JPG	3	C		5740548.812	368541.507
7	DSC01185.JPG	1	A	Y	5740557.469	368421.756
7	DSC01185.JPG	2	B		5740557.469	368421.756
7	DSC01185.JPG	3	C	X	5740557.469	368421.756

8	DSC01253.JPG	1	A	Y	5740524.503	369218.929
8	DSC01253.JPG	2	B	X	5740524.503	369218.929
8	DSC01253.JPG	3	C		5740524.503	369218.929
9	DSC01382.JPG	1	A	X	5740486.004	370314.497
9	DSC01382.JPG	2	B	Y	5740486.004	370314.497
9	DSC01382.JPG	3	C	Z	5740486.004	370314.497
10	DSC01563.JPG	1	A	X	5740499.788	370328.624
10	DSC01563.JPG	2	B	Y	5740499.788	370328.624
10	DSC01563.JPG	3	C	Z	5740499.788	370328.624
11	DSC01701.JPG	1	A	Y	5740542.338	371205.479
11	DSC01701.JPG	2	B	X	5740542.338	371205.479
11	DSC01701.JPG	3	C		5740542.338	371205.479
12	DSC01741.JPG	1	A	X	5740610.61	371689.991
12	DSC01741.JPG	2	B	Y	5740610.61	371689.991
12	DSC01741.JPG	3	C	Z	5740610.61	371689.991
13	DSC01818.JPG	1	A	X	5740605.011	371688.605
13	DSC01818.JPG	2	B	Y	5740605.011	371688.605
13	DSC01818.JPG	3	C	Z	5740605.011	371688.605
14	DSC01850.JPG	1	A	Z	5740585.314	372089.962
14	DSC01850.JPG	2	B	Y	5740585.314	372089.962
14	DSC01850.JPG	3	C	X	5740585.314	372089.962
15	DSC01949.JPG	1	A	Z	5740584.939	372108.412
15	DSC01949.JPG	2	B	Y	5740584.939	372108.412
15	DSC01949.JPG	3	C	X	5740584.939	372108.412
16	DSC02027.JPG	1	A	Z	5740559.337	372531.7
16	DSC02027.JPG	2	B	X	5740559.337	372531.7
16	DSC02027.JPG	3	C	Y	5740559.337	372531.7
17	DSC02038.JPG	1	A	X	5740544.323	372625.409
17	DSC02038.JPG	2	B		5740544.323	372625.409
17	DSC02038.JPG	3	C	Y	5740544.323	372625.409

From the set evaluated the following statistics have been generated:



The numbers are logical phase ID’s. Further work is needed to map the logical phase ID’s to actual L1, L2 and L3 lines.

Limitations

As the phase distribution was derived using non-randomly sampled data it is expected to contain bias towards the portion of the network sampled. It still indicates that the network contains a non-uniform distribution, however, the exact distribution network wide is unknown.

4 Lessons learned

4.1 What has worked well so far

Metadata correlation has been effective. The model can reliably:

- sequence images along a line using time, position and orientation, and
- reconstruct branches that match the expected physical route, as shown in Figure 5 and 6.

The combination of image adjacency graph + QGIS visualisation provides a practical way to:

- verify survey coverage, and
- spot obvious anomalies or gaps early in the process.

From the single-phase image mapping the model can:

- Determine the primary and secondary lines*
- Determine the interconnection the interconnect links *

4.2 Key challenges identified

Loops in the survey flight path (visible in Figure 5) create complex overlapping trajectories.

- In these areas, the adjacency graph has multiple plausible paths between images, which:
  - complicates branch building, and
  - contributes to the observed bias in line selection at branches.
- Additional logic is required to distinguish “true” network direction from artefacts of the survey path.

From the single-phase image mapping the following challenges have been identified:

- The general image quality is poor. Many images are slightly out of focus, have motion blur artifacts or have details hidden. This impacts accuracy of the meta data. The impact is being quantified, but these issues can be mostly resolved by the following:
  - Increase the resolution of the images takes (at least 4K)
  - Use a faster exposure time when taking images
  - Take a burst of images for each pole so that several images can be scanned for missing details.

5 Recommendations / next steps

Based on the interim results, the next steps are:

- Complete branch mapping across the full pilot dataset (currently work in progress).
- Create a robust branch-intersection model to identify where branches join, tee or cross.
- Expand the image set for single phase branches.
- Determine supply direction for each branch, so that branches can be oriented consistently and aligned with the logical network model.
- Generate an intersection report summarising junctions and complex areas for review.
- Create a dedicated intersection QGIS data layer to support visual inspection and reconciliation with existing network records.
- Compare imagery-derived branches and intersections to power-meter data and QGIS layers from the smart-meter/monitoring stream, to understand where the two approaches agree or diverge.
- Investigate pole mounted transformers and all the combinations of connections to and from these.
- See key challenges around image quality.

