Pipeline Coating Resistance Estimation using Influence from a CP Rectifier

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ABSTRACT

Pipeline cathodic protection designs and AC interference studies, whether completed using conventional calculations or computer modeling, are heavily dependent on the quality of the pipeline's coating. Coating resistance is often coarsely estimated using established values from literature where pipeline age, coating type, and subjective Operator feedback are used as guiding parameters. However, in practice, coating resistance is also heavily dependent on the quality of installation, historical pipeline operating conditions, and repair activity. This paper uses voltage-drop influence survey data from a cathodic protection rectifier to estimate a pipeline's attenuation constant and corresponding coating resistance. The field survey method for completing the IR influence survey is described and the calculations methods for obtaining the pipeline's attenuation constant and coating resistance are developed. The results from several such surveys are examined to understand both the successes and challenges with this technique, as well as some of the applications in both cathodic protection system remediation and AC mitigation modeling.

Key words: Coating Resistance, Coating Conductance, Attenuation, AC Mitigation, Cathodic Protection, Rectifier Influence, Cathodic Protection Survey

INTRODUCTION

Pipeline coating resistance is a fundamental variable in cathodic protection and AC interference models. For cathodic protection design, it underlies attenuation calculations, current distribution, and has an impact on overall current requirement. For AC interference models, it has an impact on the magnitude and span of induced AC voltages. For new pipelines, typical values are usually selected from industry standard reference guides by the design engineer based on the coating type, however uncertainty about the actual coating condition remains. For in-service pipelines, particularly older pipelines with vintage coating types, the uncertainty is much greater due to less rigorous quality control at installation and scarce records pertaining to operational and maintenance history. These factors combine to contribute to wide ranges in coating resistance versus what would be commonly selected from textbook lookup values.

This paper describes a field survey method to determine a rectifier's sphere of influence and an accompanying analysis method to calculate a pipeline's attenuation constant and coating resistance using the sphere of influence data. This analytical method of obtaining a coating resistance can then be used in place of the subjective coating resistance estimation as part of a cathodic protection design or AC interference model.

PIPELINE BACKGROUND

The pipeline system that was the subject structure for this paper consists of two parallel transmission pipelines that transport natural gas throughout the central and southern areas of the province of British Columbia. Details for the individual pipelines are described below:

Table 1 - Pipeline Information

Pipeline	Installation Date	Primary Coating Type	Coating Condition
Line 1	1950s	Coal Tar / Asphalt Enamel	Fair / Poor
Line 2	1970s	Polyethylene (PE) Tape	Fair / Poor

The pipelines are protected entirely via impressed current cathodic protection (ICCP) systems; the majority of which are positioned along the right-of-way with the remaining located inside compressor stations. The nominal spacing between ICCP power sources is ~14 km, however the distance varies depending on geographical challenges, availability of AC power and historically observed cathodic protection levels. The compressor stations are electrically continuous with the mainline piping along the entire right-of-way due to legacy construction practices.

Both pipelines are collocated with an NPS 12 foreign pipeline for a large portion of their alignment and all three pipelines are cross-bonded at regular intervals to equalize cathodic protection levels along the right-of-way.

Each of the three pipelines have had various repairs and upgrades made to them over their operational history. Examples include anomaly remediation digs, class upgrades and new horizontal direction drill sections to manage geohazards. With each intervention, new coating types (fusion bond epoxy, abrasion resistant overcoat, etc.) are introduced into the pipeline system.

The pipeline right-of-way traverses a variety of terrains, ranging from semi-arid to mountainous. Soil type, seasonal temperature and average rainfall vary widely and contribute to the difficulty in quantifying representative attenuation behaviour.

FIELD SURVEY METHOD

A set of rectifiers was selected across the subject pipeline system to perform the field survey. The list of rectifiers chosen was based on two primary factors; geographic position and quality of ICCP system design/installation. Varying geographic position was considered in the selection to investigate environmental differences on attenuation behaviour for seemingly similar pipeline attributes. Quality of the ICCP system design/installation was deemed necessary to exclude ICCP systems with characteristics that were likely to negatively influence the study (very high circuit resistance, inadequate remoteness, missing records, etc.). A listing of test stations upstream and downstream of these target rectifiers was generated to define a survey scope.

A single rectifier was interrupted (1 s OFF, 3 s ON), and a CP surveyor recorded ON and OFF potential readings at the test station nearest the rectifier. The surveyor then travelled upstream, collecting ON and OFF readings at all accessible test stations, until the measured IR was less than ~10 mV; this value was selected as a practical limit so that the surveyor could clearly identify in the field that interruption was still observable on their multimeter, while also being sufficiently low as to consider that the rectifier's influence was negligible. Once the upstream limit was found, the surveyor would return to the rectifier and survey downstream until the < 10 mV threshold was passed. This would conclude a survey set for the rectifier of interest, rectifier interruption would end, and the survey process was repeated at the next rectifier of interest.

IR SURVEY ANALYSIS METHOD

The classic DC attenuation formulas[1] model a pipeline's lineal structure resistance a coating conductance as a transmission line, as shown in Figure 1.

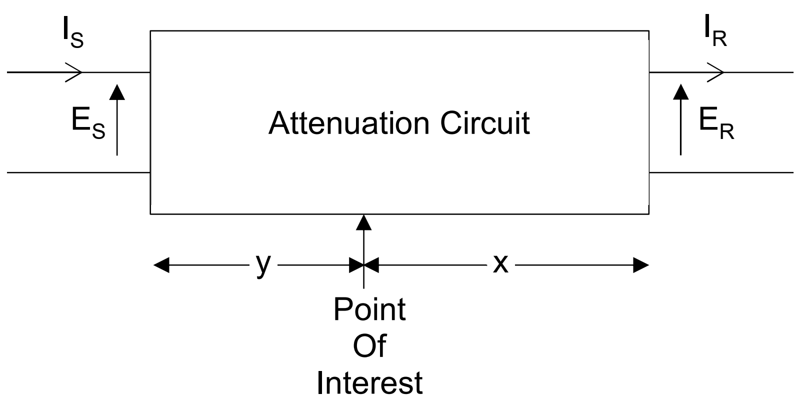

Figure 1. Pipeline DC Attenuation Circuit

The DC attenuation formulas provide a general equation to calculate a potential shift at any location along a pipeline relative to a sending end potential (i.e. a CP current source), as shown in [Equation 1]:

$$E = E_S \cosh(\alpha y) - R_G I_S \sinh(\alpha y) \quad [1]$$

Where:

- E is the potential shift at point 'y' distance from sending end
- E_S is the sending end potential, i.e. the potential shift at the CP current source
- α is the pipeline's attenuation constant
- R_G is the pipeline's characteristic resistance
- I_S is the sending end current, i.e. the current from the CP current source towards the sending end

Note that the DC attenuation calculations are used in terms of a unit length; for all calculations in this report, the unit length is set to 1 km.

The pipeline's characteristic resistance, R_G, is a function of the pipeline's lineal resistance and coating resistance. One formulation for calculating R_G is shown in [Equation 2]:

$$R_G = \sqrt{R_{SO} R_{SS}} \quad [2]$$

Where:

- R_G is the pipeline's characteristic resistance
- R_{SO} is resistance looking into the attenuation circuit with the far end open circuited
- $R_{SS}$is resistance looking into the attenuation circuit with the far end short circuited

For an electrically long pipeline, i.e. a lossy pipeline, changes to the load end of the attenuation circuit will not impact the circuit's resistance seen at point 'y', therefore R_{SS} = R_{SO}, and the sending end current is simply the product of the sending end potential and the characteristic resistance looking into the attenuation circuit, as shown in [Equation 3]:

$$I_S = \frac{E_S}{R_G} \quad [3]$$

[Equation 3] can be rearranged to solve for E_S and substituted into [Equation 1], which then reduces to [Equation 4]:

$$E = E_S \cosh(\alpha y) - R_G I_S \sinh(\alpha y) \quad [1]$$
$$E = E_S \cosh(\alpha y) - E_S \sinh(\alpha y)$$
$$E = E_S [\cosh(\alpha y) - \sinh(\alpha y)]$$
$$E = E_S e^{-\alpha y} \quad [4]$$

[Equation 4] describes the attenuation of the potential shift along an electrically long pipeline based on the location of an observation point 'y' relative to the sending end potential E_S given the pipeline's attenuation factor α. Put another way, [Equation 4] describes the IR shift at a location along an electrically long pipeline relative to a CP current source, and it rolls off in a simple exponential manner proportional to the pipeline's attenuation factor α.

The field data was tabulated, with the IR drop for each test station, for each rectifier interruption, calculated according to [Equation 5]:

$$IR = E_{ON} - E_{OFF} \quad [5]$$

Each test station was enumerated based on its stationing, in kilometers, and these were normalized to the position of the rectifier at $y[0]$. The IR was then plotted using the normalized stationing, with the vertical axis plotted on a logarithmic scale. Curves for the upstream and downstream IR attenuation, $E_{U/S}$ and $E_{D/S}$, according to [Equation 4], were then plotted; the same upstream and downstream attenuation constants apply to Line 1 and Line 2 as they are electrically bonded, therefore the IR readings at either pipelines' test station is effectively a mixed potential of both pipelines as seen by the reference electrode. These attenuation curves were adjusted to make a visual fit to both pipelines' IR readings.

Sample plots for rectifier R-6 for the two pipelines are shown in Figure 2. The full set of plots for all characterized rectifiers are shown in Appendix A.

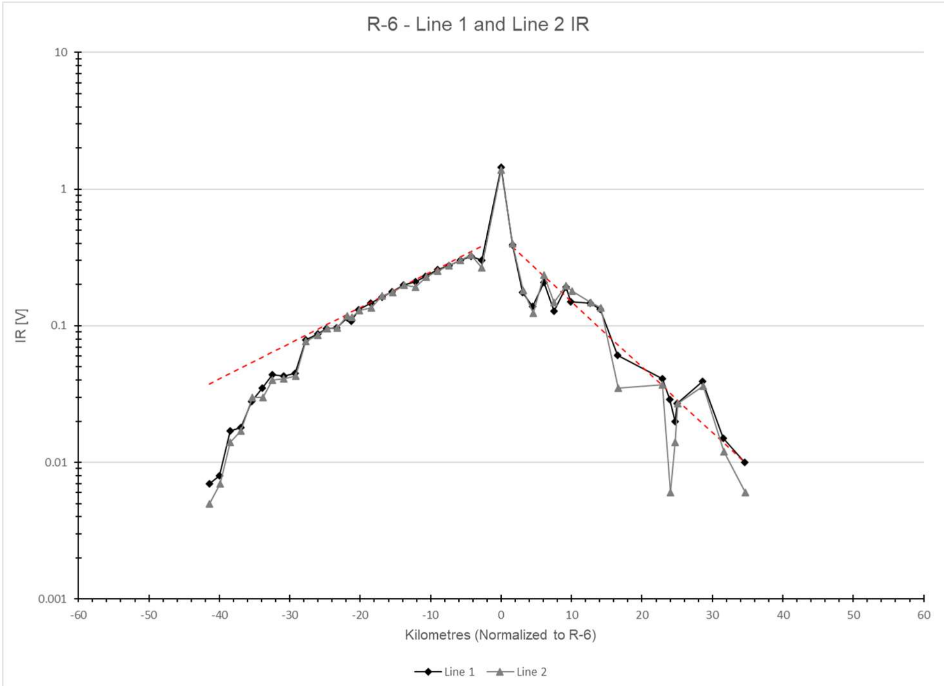

Figure 2: Rectifier R-6 – Line 1 and Line 2 IR

IR SURVEY RESULTS

Several features are visible in these plots:

- An IR peak near the rectifier, that does not follow the $E_S e^{-\alpha y}$ curve. This is due to the test point at or near $y[0]$ being influenced from local anode bed gradient; the effect is typically gone at the next upstream and downstream test stations. Note that increasing E_S will shift the attenuation curve up or down but will not impact its slope as this is governed solely by α.

- The slopes on either side of a rectifier are not the same, and in some cases may be significantly different. The observed attenuation curve is the net effect of all coating defects on either side of the rectifier; the rectifier "sees" different characteristic resistances when "looking" upstream or downstream.

  In the case of a rectifier at a compressor station, it is expected that the downstream pipelines (i.e. the outlets from the compressor station) operate at a higher temperature than the upstream / inlet side, and therefore the coating is assumed to be more degraded on the downstream side.

  This was observed at R-3 (located at a compressor station, impacting its downstream attenuation factor) and R-5 (downstream of a compressor station, impacting its upstream attenuation factor), however it was not observed at R-7, which is also located at a compressor station. This discrepancy may be due to different operating conditions at the compressor station (e.g. operating pressure, temperature, piping arrangements, pump types, coating type / repairs), and as the compressor stations are bonded to the pipelines, the impact of this point impedance will impact bulk coating resistance but the effect will vary based on the size of the compressor station and its grounding grid; these effects were not explored as part of this paper.

- There are many IR "spikes," primarily shifting to lower IR values, throughout the "linear" sections of the IR curves. Many of these excursions were correlated with a variety of pipeline features, such as cased crossings (which could potentially be shorted), readings being taken at riser sites with gravel (which may impact the magnitude of the measured potentials due to reference electrode contact resistance), or collocations with other rectifiers (whether Company- or foreign-owned), and may be within their anode gradients. Measurements recorded close to coating defects would also result in locally lower IR values. As the curve fit was visual and struck a balance between the Line 1 and Line 2 IR plots, these excursions could be ignored. Known features at select excursions are identified in the markups in Appendix A; the term "Company Rectifier (ON)" refers to a rectifier that is providing CP to the subject pipelines, and is ON (i.e. not interrupting) while the survey data was recorded.

The rectifier's Sphere Of Influence (SOI), i.e. the approximate points upstream and downstream where the IR diminished below 10 mV, and the upstream and downstream attenuation factors are listed in Table 2.

Table 2. Sphere of Influence and Calculated Attenuation Constants

Rectifier	SOI – L1 [km]	SOI – L2 [km]	$\alpha_{U/S}$	$\alpha_{D/S}$
R-1	73	74	0.06	0.09
R-2	90	88	0.07	0.06
R-3	97	94	0.05	0.14
R-4	90	91	0.09	0.08
R-5	62[1]	62[1]	0.22	0.05
R-6	74	71	0.06	0.11
R-7	98[1]	100	0.06	0.07
R-8	74[1]	71[1]	0.12	0.11
R-9	80[1]	78[1]	0.11	0.07
R-10	36[1]	45[1]	0.08	0.22
1. SOI extrapolated from available data				

ATTENUATION FACTOR ANALYSIS

With the attenuation factors established, they can be further analyzed to calculate the pipelines' combined coating conductance. [Equation 6] shows a formulation for α, which is rearranged to solve for g in [Equation 7]:

$$\alpha = \sqrt{rg} \quad [6]$$

$$\alpha^2 = rg$$

$$g = \frac{\alpha^2}{r} \quad [7]$$

Where:

- α is the pipelines' bulk attenuation constant
- r is the pipelines' bulk lineal resistance in Ω/unit length
- g is the pipelines' bulk conductance to earth in S/unit length

As the pipelines are bonded, $\alpha, r,$ and g are bulk factors for the collocated pipelines.

The pipe lineal resistance was calculated for the unit length of 1 km using lookup tables[1] for steel piping lineal resistance and a pipe wall at thickness of 0.375" for Line 1 and Line 2 and at SCH40 (0.406") for the NPS 12 Foreign pipeline. Since there are three pipes in this ROW (NPS 30 Line 1, NPS 36 Line 2, and NPS 12 Foreign for a portion of the survey area) and they are bonded together, the lineal resistance along this grouping is the individual lineal resistance of each pipe in parallel with each other, assuming they are perfectly bonded to each other. This lineal resistance was calculated at:

- 2.25 mΩ for the unit length of 1 km where Line 1, Line 2, and the NPS 12 Foreign pipeline are collocated

- 2.71 mΩ for the unit length of 1 km where the NPS 12 Foreign pipeline is not collocated.

The coating conductances g were used to calculate the specific coating conductance g' according to [Equation 8]:

$$g' = \frac{g}{SA} \quad [8]$$

Where:
- g' is pipelines' bulk Specific Coating Conductance per unit length in S/m^2
- g is the pipeline's bulk conductance to earth in S/unit length
- SA is the surface area of the collocated pipelines in m^2/unit length

Based on the three pipelines' outer diameters (12.75", 30", and 36") the surface area for 1 km is 6,284 m^2. This value is applied to all rectifiers except for R-9 and R-10, where the NPS 12 Foreign pipeline is not collocated; at these rectifiers, the surface area used is 5,267 m^2.

These equations and values, along with the attenuation factors from Table 2 were used to calculate g', which are presented in Table 3.

Table 3. Calculated Attenuation Constants and Coating Conductances

Rectifier	$\alpha_{U/S}$	$\alpha_{D/S}$	$g_{U/S}$ [S]	$g_{D/S}$ [S]	$g'_{U/S}$ [S/m^2]	$g'_{D/S}$ [S/m^2]
R-1	0.06	0.09	1.72	3.86	2.73E-04	6.15E-04
R-2	0.07	0.06	2.08	1.72	3.30E-04	2.73E-04
R-3	0.05	0.14	1.24	9.08	1.97E-04	1.44E-03
R-4	0.09	0.08	3.36	2.90	5.35E-04	4.62E-04
R-5	0.22	0.05	21.02	1.11	3.35E-03	1.77E-04
R-6	0.06	0.11	1.72	5.56	2.73E-04	8.85E-04
R-7	0.06	0.07	1.39	2.08	2.21E-04	3.30E-04
R-8	0.12	0.11	6.20	4.96	9.86E-04	7.89E-04
R-9[1]	0.11	0.07	4.62	1.81	8.76E-04	3.43E-04
R-10[1]	0.08	0.22	2.41	17.45	4.57E-04	3.31E-03
1. NPS 12 Foreign pipeline not collocated at these test areas						

These calculated specific coating conductances were compared to the commonly used coating classifications table from Table 5[2] to generate the coating classifications in Table 4.

Table 4. Coating Classifications

Rectifier	$g'_{U/S}$ [S/m^2]	$g'_{D/S}$ [S/m^2]	Coating Classification (Per Table 5)[1]	
			U/S	D/S
R-1	2.73E-04	6.15E-04	Good	Fair
R-2	3.30E-04	2.73E-04	Good	Good
R-3	1.97E-04	1.44E-03	Good	Poor
R-4	5.35E-04	4.62E-04	Fair	Good
R-5	3.35E-03	1.77E-04	Poor	Good
R-6	2.73E-04	8.85E-04	Good	Fair
R-7	2.21E-04	3.30E-04	Good	Good
R-8	9.86E-04	7.89E-04	Fair	Fair
R-9	8.76E-04	3.43E-04	Fair	Good
R-10	4.57E-04	3.31E-03	Good	Poor

1. The CP3 Manual Table 4-4 provides coating classifications in both S/ft^2 and S/m^2, however there is a simplified conversion factor from S/ft^2 to S/m^2 of 10, rather than 10.76391 (the actual scaling factor between ft^2 and m^2). This ~7.6% discrepancy resulted can result in differences in coating classification based on whether imperial or metric units are used.

   For the purposes of this report, the simple 'round number' metric values from the CP3 Manual Table 4-4 were used.

Table 5. Coating Classification Reference (Per NACE CP3 Manual, Table 4-4)

Long Pipelines with Few Fittings	Average Specific Coating Conductance *g'*	
Quality of Work	**[S/ft^2]**	**[S/m^2]**
Excellent	< 1 x 10^{-5}	< 1x 10^{-4}
Good	1 x 10^{-5} to 5 x 10^{-5}	1x 10^{-4} to 5 x 10^{-4}
Fair	5 x 10^{-5} x 1 x 10^{-4}	5 x 10^{-4} to 1x 10^{-3}
Poor	> 1 x 10^{-4}	> 1x 10^{-3}

Based on the subjective classifications in Table 5, and the possible ranges within 'Good' (a factor of 5) and 'Fair' (a factor of 2), there is little guidance for a cathodic protection or AC modeler / mitigation designer to select a value within these ranges. The testing described in this paper provides practical direction to address this unknown. Also of interest is that typical assumptions based on age, coating type, geography, etc. are inherently limited, as is demonstrated by the best and worst coating qualities – which differed by a factor of 19 from "Good" to "Poor" – being observed downstream and upstream of R-5 in an area that does not have any obvious differences in landform or features.

LIMITATIONS

The fundamental limitations of this coating attenuation analysis method relate to two assumptions: uniformity of coating and electrically long pipelines. The analysis method implicitly assumes that the coating quality is uniform, while the simplification of [Equation 1] to [Equation 4] is only possible for electrically long pipelines – when [Equation 3] is valid. Therefore, this approach cannot be applied to electrically short pipelines, which would generally be pipelines with very good coating quality. In many such cases, however, the coating resistance is typically already known based on the coating type, and there is likely no significant coating damage to characterize.

The pipelines under test were generally simple, with a mostly North-South alignment and frequent cross-bonds, and approximately equal length. This allowed for a simple accounting of pipeline surface area and lineal resistance for the bonded pipelines. More complex piping arrangements, such as facility piping with multiple various lengths and diameters, may not be practical to assess in bulk in the manner presented. Next steps could include extending the mathematical model to incorporate point impedances, which could be used to represent well-grounded stations, shorted casings, etc., as well as points where the pipeline's coating quality changes. This technique could likely also be used to estimate the impedance of stations, which for large stations is difficult to measure using conventional fall-of-potential testing.

The IR survey results also identified some shortcomings that impacted data reliability:

- The readings must be electrically remote from the pipeline being surveyed. Electrical remoteness is not satisfied when surveying near large coating defects (i.e. in their associated voltage gradient), or where the pipeline is continuous with other bare metallic structures such as electrical grounding or steel casings. This can be countered by surveying many test points and expecting that there will be sufficient remote readings to obtain a reliable trendline, or by taking additional readings at a given test point with the reference electrode placed physically remote from the pipeline.

  This is also the case for readings taken at or near a rectifier. In most cases the IR at the rectifier under test is far higher than what is predicted by the trendline due to the reference electrode's position within the anode gradient. In these cases the reading should typically be ignored as measuring with a remote reference electrode may not be practical since the size of the anode gradient might be measured in many hundreds of metres.

- If a pipeline has an electrical short to a bare metallic structure, this will appear in the analysis as a coating defect and increase the calculated coating conductance, even if the actual pipeline coating is in good condition. However, this shorted metallic structure would still have an impact on current requirement and protection levels, so this effect should not be discounted.

- The ON and OFF measurements are subject to the typical potential measurement limitations, e.g. high reference electrode contact resistance, presence of buried liners, reliable interruption, etc. and should be managed and validated in the same manner as a typical CP potential survey.

The tested rectifiers have some overlap in terms of their SOI e.g. rectifier R-2's downstream SOI overlapped with rectifier R-3's upstream SOI. Future work will focus on testing adjacent rectifiers and comparing the calculated coating resistances for the overlapping pipeline segments.

CONCLUSIONS

The field survey method achieved the objective of identifying a rectifier's sphere of influence, with results showing clear differences between the various rectifiers, and the impact of pipeline facilities (e.g. compressor stations) on current attenuation.

The extended analysis method provided a method of calculating a pipeline's effective coating resistance for electrically long pipelines, which can avoid reliance on subjective coating classification lookup tables and can improve reliability of cathodic protection designs and AC models.

There are further opportunities to validate the test and analysis methods, both on the same subject pipeline system – re-testing the same rectifiers and also testing other rectifiers up- and down-stream – or on new pipeline networks.

The limitations of the test and analysis methods should be explored, particularly for complex piping (e.g. facility piping), with the aim of providing analysis/measurement options for pipelines that are not electrically long.

REFERENCES

1. *CP4 – Cathodic Protection Specialist Course Manual,* (Houston, TX: NACE, 2020), p. 4-16

2. *CP3 – Cathodic Protection Technologist Course Manual*, (Houston, TX: NACE, 2014), p. 4:16

APPENDIX A: IR ATTENUATION PLOTS

A.1 R-1

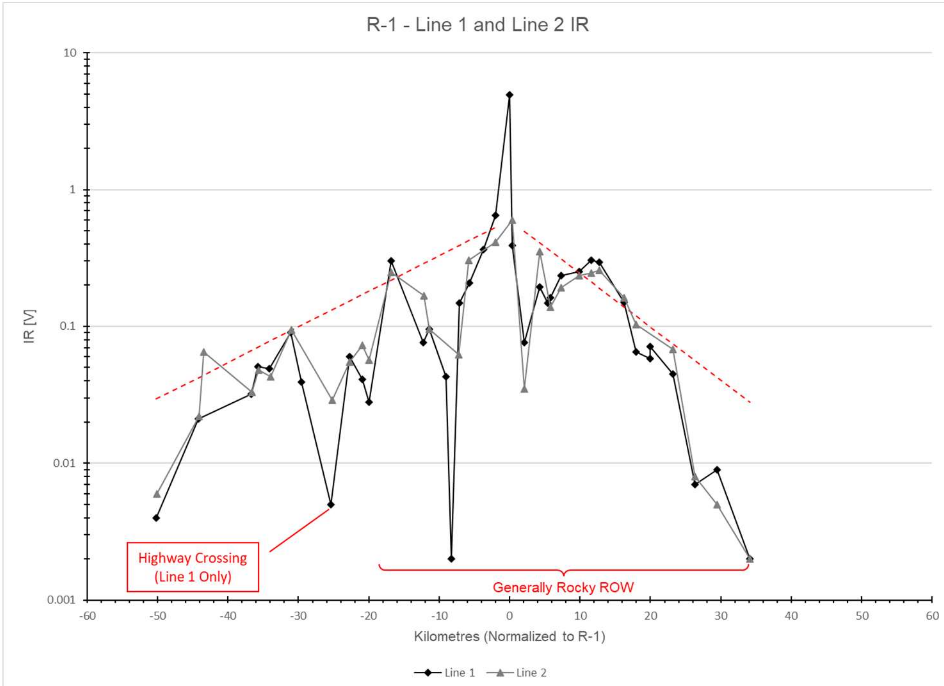

Figure A-3: R-1 – Line 1 and Line 2 IR

A.2 R-2

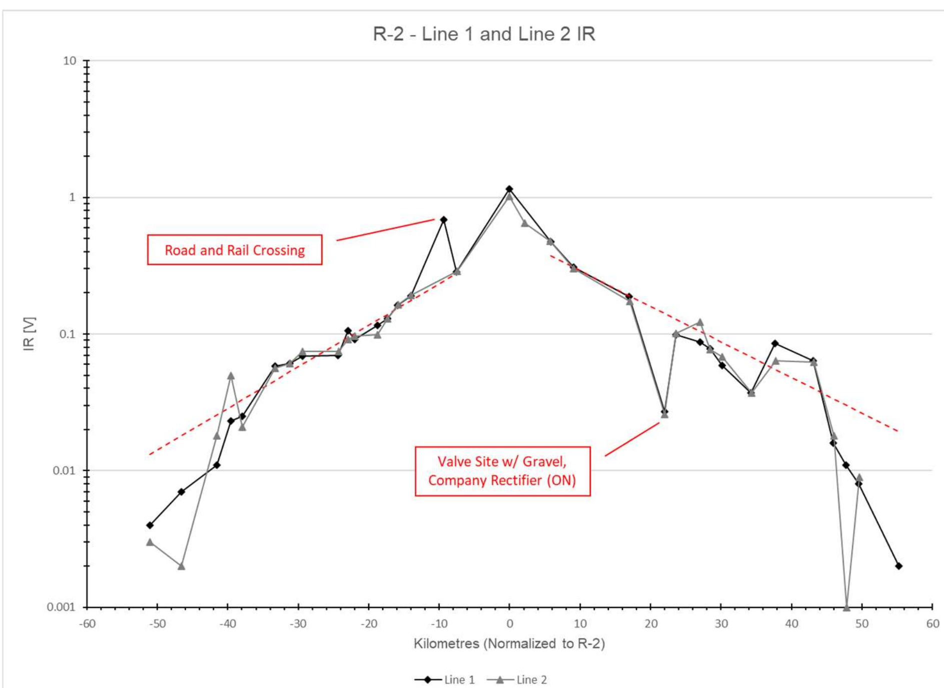

Figure A-4: R-2 – Line 1 and Line 2 IR

A.3 R-3

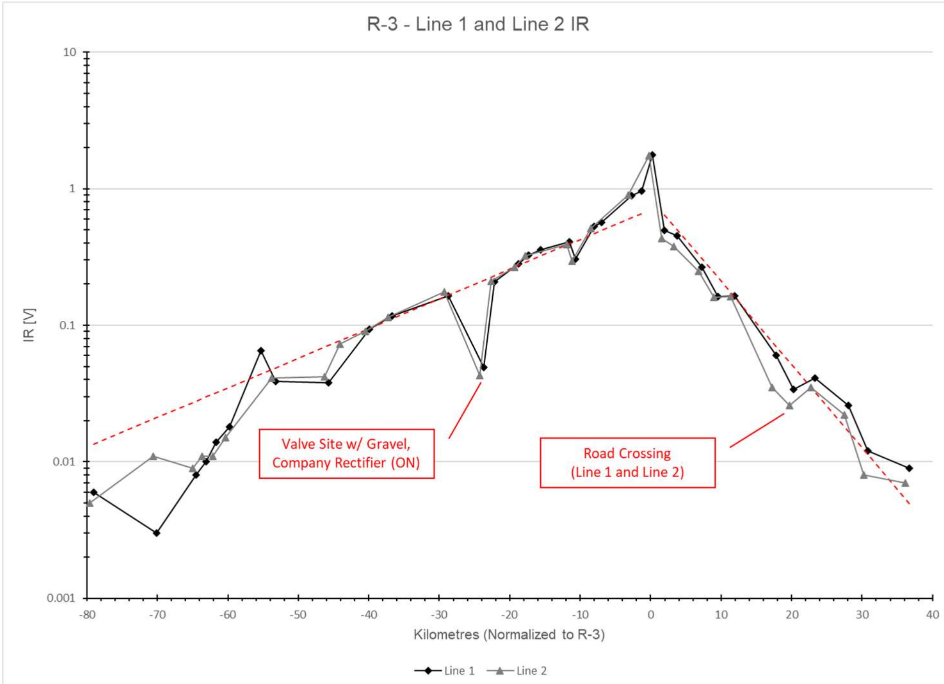

Figure A-5: R-3 – Line 1 and Line 2 IR

A.4 R-4

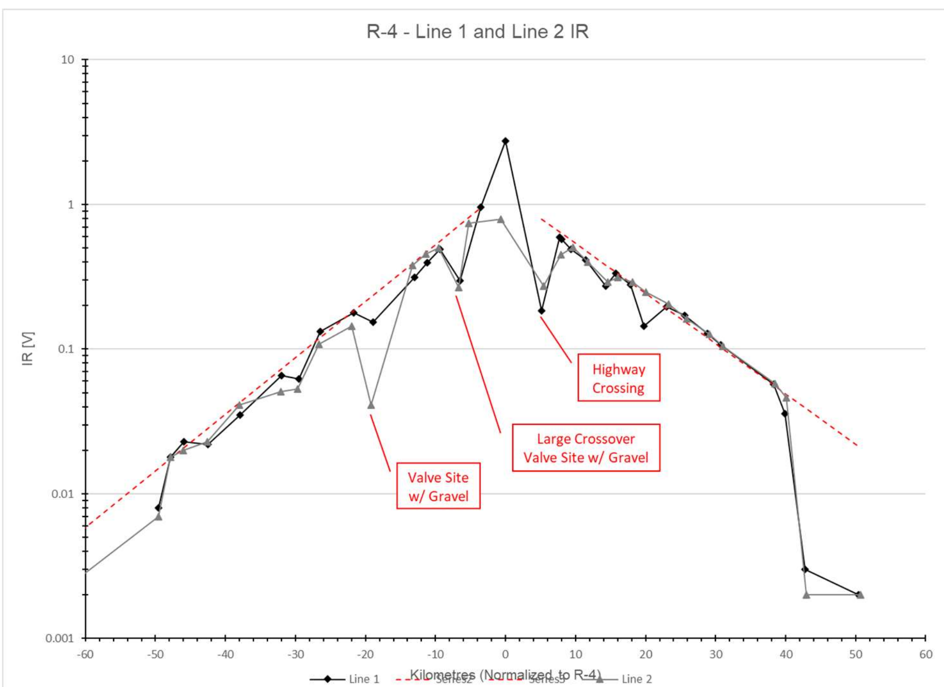

Figure A-6: R-4 – Line 1 and Line 2 IR

A.5 R-5

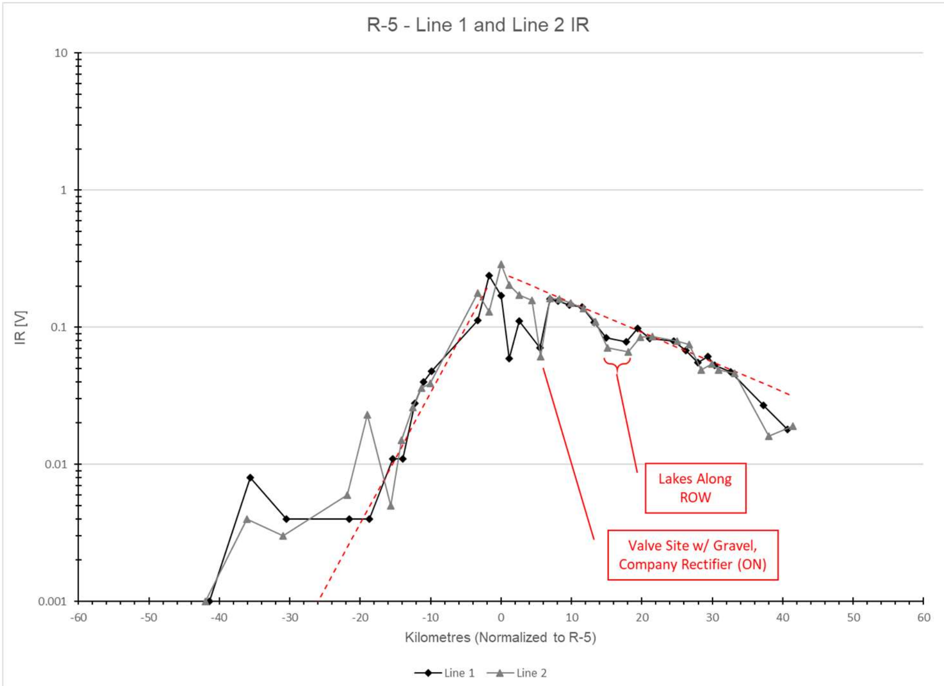

Figure A-7: R-5 – Line 1 and Line 2 IR

A.6 R-6

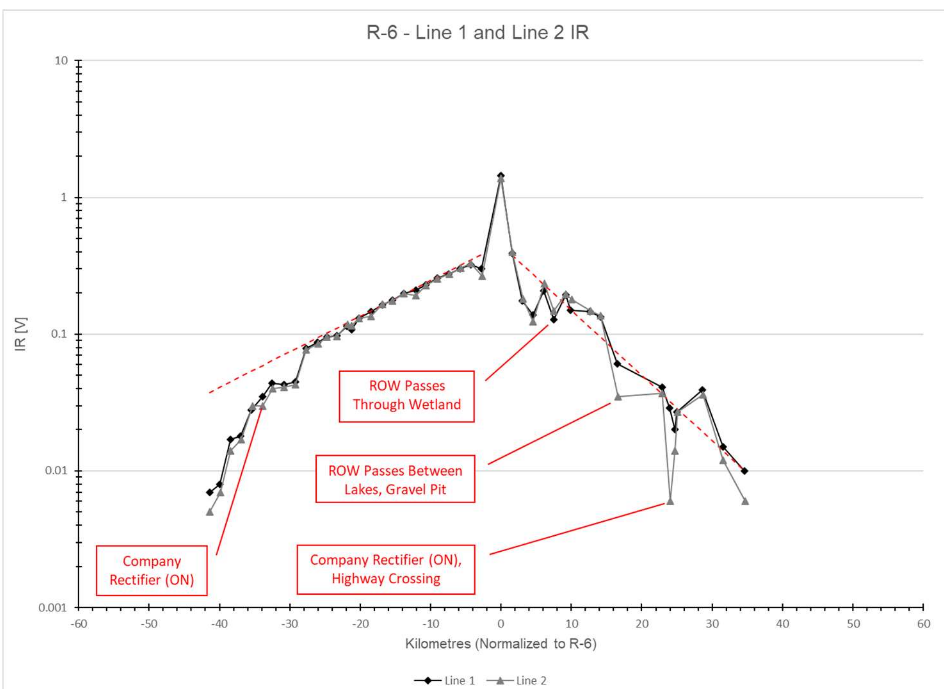

Figure A-8: R-6 – Line 1 and Line 2 IR

A.7 R-7

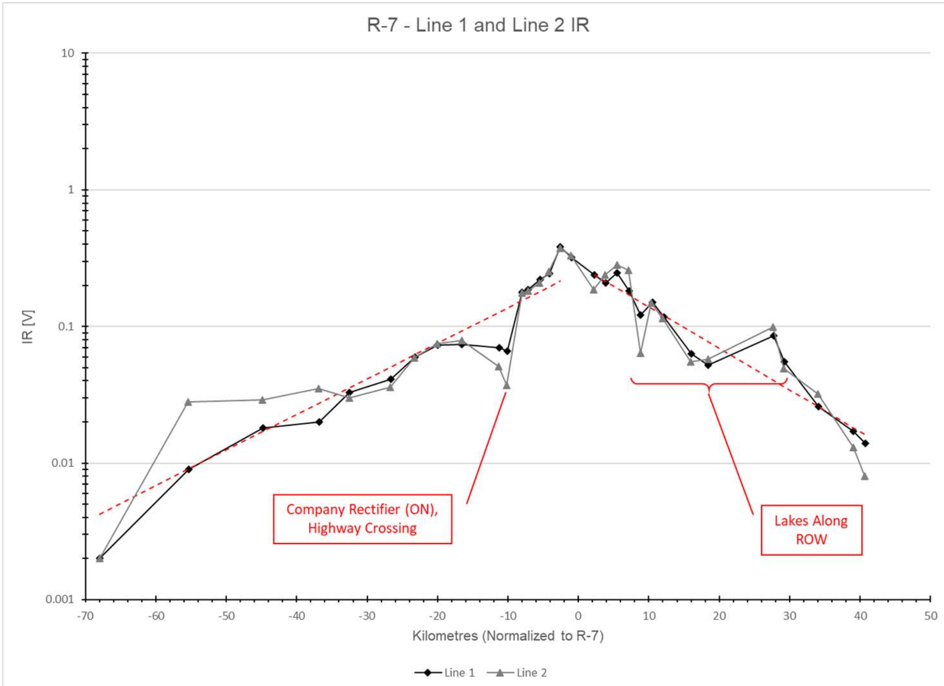

Figure A-9: R-7 – Line 1 and Line 2 IR

A.8 R-8

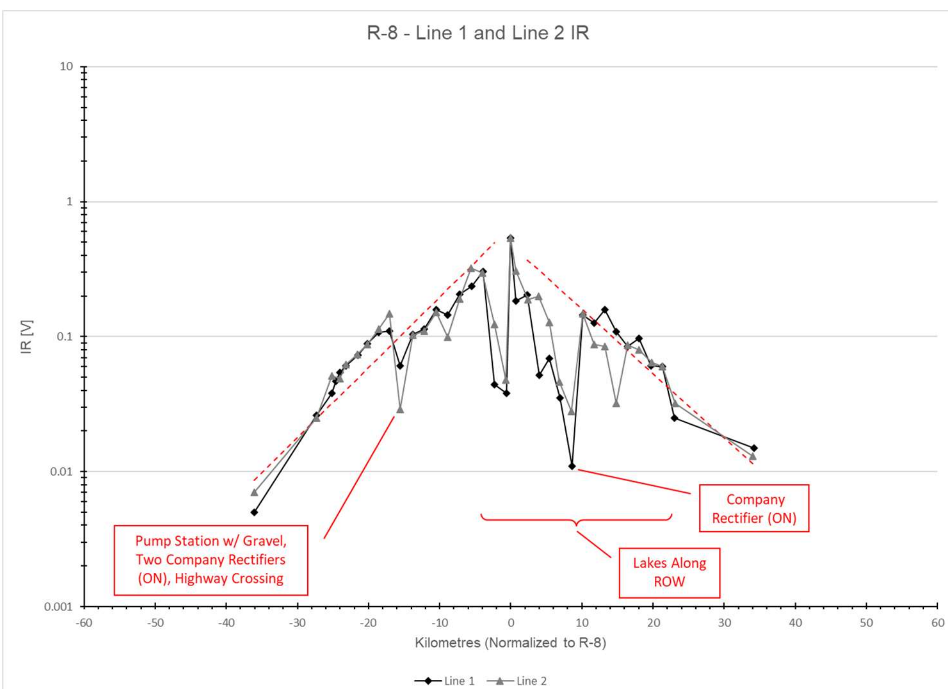

Figure A-10: R-8 – Line 1 and Line 2 IR

A.9 R-9

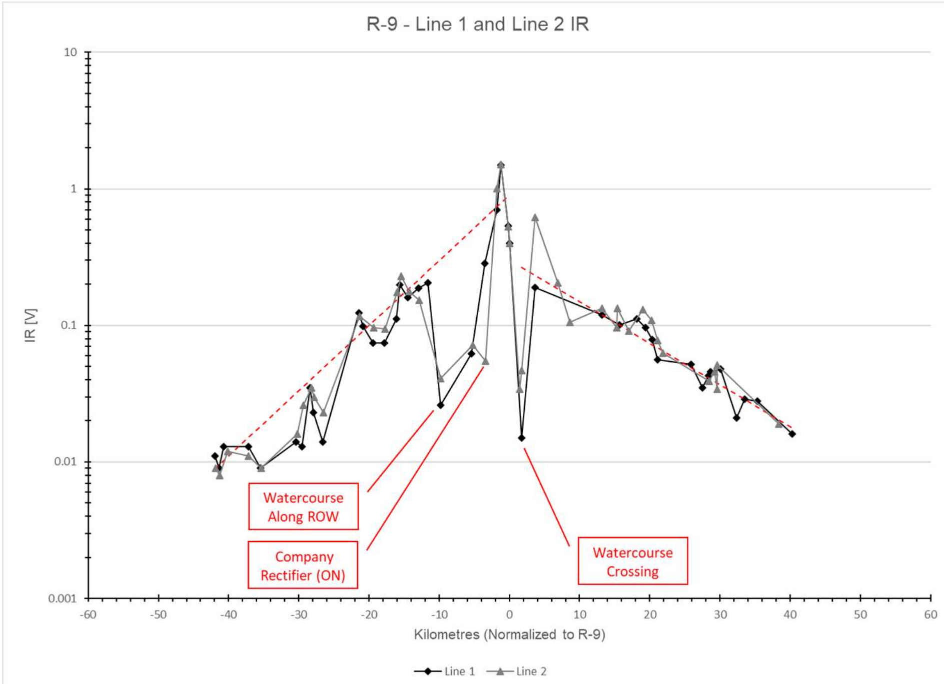

Figure A-11: R-9 – Line 1 and Line 2 IR

A.10 R-10

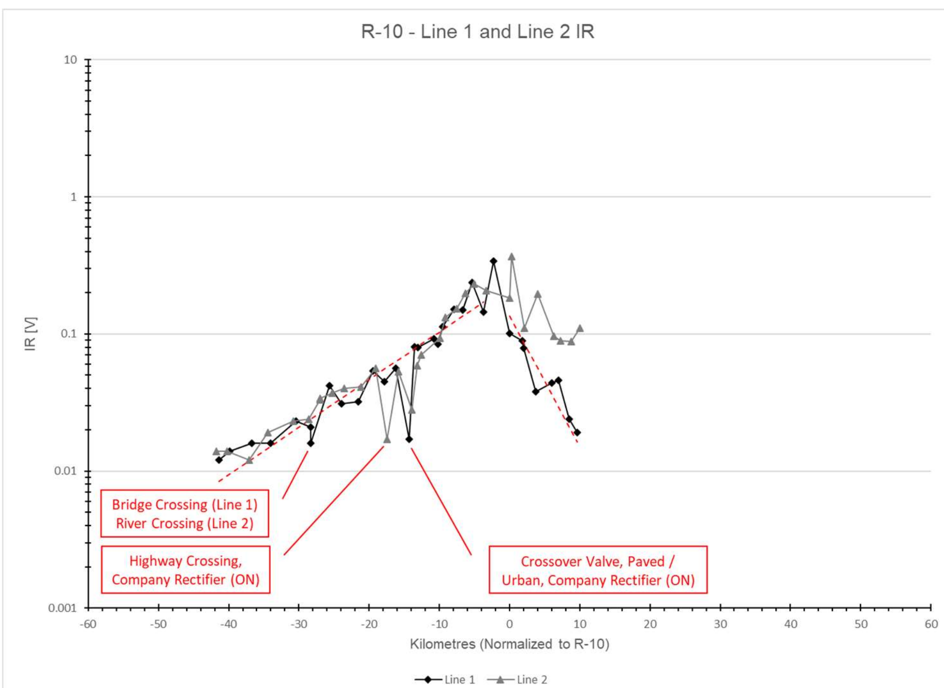

Figure A-12: R-10 – Line 1 and Line 2 IR