ABSTRACT FOR THE CATHODIC PROTECTION SESSION.

APPLICATION OF CATHODIC PROTECTION UNDER SEVERE STRAY CURRENT INTERFERENCE AND VERIFICATION OF THE EFFECTIVENESS.

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ABSTRACT

There is some advice available in the standards to assist in the application and evaluation of the effectiveness of cathodic protection applied in areas of stray current interference by the measurement of pipe-soil-potentials. It is the author's view that although this advice is given with good intentions it is seldom of much use.

Simply measuring potentials is unlikely to provide the assurances required that the structures are not at risk from corrosion.

This case study of a project in a European City details how critical structures were cathodically protected and the effectiveness validated by the use of electrical resistance probes.

The project is a clear example of how a careful and detailed active corrosion protection design based on information provided by the client is sometimes simply not worth the effort. This project shows that in spite of the careful design the system actually worked!

During the electrification of an old urban Metro traction system two previously un-identified large diameter pressurised sewage pipes were identified as an impediment that could stop the entire project.

Two separate pipes crossed the tracks at two locations (about 500m apart). One pipe crossed at an angle of around 60 degrees and the other at 90 degrees. Both pipes were so close to the tracks that they were actually visible. The pipes were reported as carrying pressurised sewage, about 1m diameter, bare cast iron, more than 60 years old, condition unknown, and no known way to inspect them.

Construction constraints imposed by the owner of the pipes and the track constructor were simple:

- The pipes cannot be changed or taken out of service

- Pipes cannot be buried or diverted
- Guarantee required that the pipes will never corrode
- This guarantee has to be demonstrated and proved
- Rail tracks cannot be raised because of existing overhead infrastructure (bridges and roads)
- Track foundations cannot be moved and will shield cathodic protection current
- No interference to the track signalling systems from any cathodic protection

The paper will show how the design evolved and the changes in construction accommodated to provide a fully functioning cathodic protection system combined with an effective corrosion monitoring system.

The data is collected automatically throughout every day and sent to host computers where the performance is reviewed on a monthly basis.

The design is based on the use of a flexible linear Anodeflex anode and criteria established from the standard relating to the Cathodic Protection of Complex Structures.

The cathodic protection design is fully integrated with the stray current management and control system.

1. Introduction

Cathodic protection principles are very well known and easy to understand. The practical application of cathodic protection and assessment of the residual corrosion risk is not so easy to achieve.

This case study concerns two critical pipes that run beneath an existing d.c. railway line in a city environment. The pipes are very old. No one knows exactly how old, but certainly older than 60 years. As part of the expansion of the metro system the d.c. track and power feeds were to be upgraded but the owners of the pipes refused to give permission for the expansion of the metro unless the security of their pipes could be guaranteed.

We were a part of the engineering team that designed the rail expansion and were responsible for mitigating and monitoring stray currents from the system. Our design brief covered the track formation, stray current collection system, and interfaces with traction and signalling designers.

2. Design Requirements

For once the design requirements were quite simple:

1. Guarantee that the pipes would not leak.

2. Provide a dynamic monitoring system that showed that the corrosion had been stopped.
3. Design life of 50 years.

Before undertaking the design all the available information was collected from the operators of the pipeline, designers of the track system, the signalling system and the traction power system. Because the pipes were so old there were no construction records left. Sadly there were no inspection records either, since they were unable to access either the internal or external surfaces of the pipe. The crown of the pipes were visible since they slightly above the surface of the ground beneath the tracks.

We were in full possession of the traction system details and the proposed operating conditions of the new metro, so we were not too concerned about that.

The key feature for any design is to establish what you want to achieve, what information you have and what you need to deliver. Having collected all of the information that is available it is then necessary to proceed in a logical manner.

3. What are the risks?

From Faraday's Law we know that if d.c. current leaves steel through an electrolytic path such as soil or water then there will be a metal loss of about 9.1 kg yr^{-1} (i.e. 9.1 kg per amp per year).

Atomic mass of iron	$m_a := 55.85$
Electric current	$i := 1\ A$
Faraday's constant	$K_f := 9.65 \cdot 10^7\ \frac{C}{kg}$
Valence	$v := 2$
Lapsed time	$dt := 3.15 \cdot 10^7\ s$

Mass of metal removed $\quad m := \dfrac{m_a \cdot i \cdot dt}{v \cdot K_f} = 9.115\ kg$

1A DC for one year will consume 9.115 kg of steel

There are two trains every 10 minutes (one up and one down). The transit time for each train is 20 seconds. The lines run for an average of 16 hours per day for 364 days a year. If you factor all of those times into Faraday's equation you get a potential metal loss of 0.041 kg per hour, which over one year equates to 3.65 kg. This simplification assumes that all of the traction current will pass through the pipe. As a rule of thumb we can expect approximately 2.5 $mA.m^{-1}$ of stray current per track for a well-designed railway.

Since the affected track length is 300 m and we have two tracks then we can expect at least 1.5 A for a well-designed system. Even 1.5A discharging from the pipe would mean a metal loss of 10.24 kg.

Mass of metal removed per transit $$m := \frac{m_a \cdot i \cdot dt}{v \cdot K_f} = \left(1.736 \cdot 10^{-5}\right)\ \boldsymbol{kg}$$

Number of transits per hour $$n := \frac{3600\ \boldsymbol{s}}{40\ \boldsymbol{s}} = 90$$

Metal loss in one hour $$m_{hour} := m \cdot n = 0.002\ \boldsymbol{kg}$$

$$m_{day} := m_{hour} \cdot 18 = 0.028\ \boldsymbol{kg}$$

$$2.5\ \boldsymbol{mA} \cdot m^{-1} \cdot 300\ m = 0.75\ \boldsymbol{A} \qquad m_{year} := m_{day} \cdot 364 = 10.238\ \boldsymbol{kg}$$

4. What are the options?

It is clear that making a “perfect” traction system with perfect isolation of the tracks from the ground would not reduce the corrosion risks to an acceptable level.

Mitigation possibilities were narrowed down to :

a) Move the pipes.
b) Replace the pipes with HDPE.
c) Move the tracks so they are further away from the pipes.
d) Optimise the track configuration and apply dynamic cathodic protection.

When the options were considered it was established that:

I. The pipes could not be moved or taken out of service due to their unknown condition and lack of space. There is a bridge above the pipes and it carries a major road route. So option (a) was not possible.
II. The pipes could not be replaced because the pipes cannot be taken out of service. So option (b) was not possible.
III. The tracks could not be moved because of the bridge overhead, which meant that there was only just enough headroom for the trains with the tracks in their existing position. So option (c) was not possible.
IV. This was the only remaining option.

5. Track design

It is beyond the scope of this presentation to speak in detail of the various track formation and sub-station configurations that can aid in reducing the stray currents. The actual track configuration we had at one crossing was a slab track arrangement with a stray current collection mat embedded in it. The stray current collection mat was floating and isolated from the traction return circuit. The other pipe was beneath clean and dry ballast. Meticulous attention was paid to the construction of the stray current collection mat to ensure optimum performance. During construction the stray current collection mat and the structural reinforcing steel were checked before and after concrete pouring to ensure there was no contact between them and that the resistance was acceptably low.

Track to earth resistance was measured for both tracks using the procedures given in the annexe of EN 50122-2 before the sections were joined.

Track conductance was measured along the entire section and for both tracks.

This meant that we were certain that the best possible mechanical and electrical configuration was installed to reduce the magnitude of the stray currents.

Unfortunately there were three exacerbating electrical configurations that we could not change. Firstly the pipe crossings are within 300 m of a traction sub-station and were therefore in a region where stray currents would be at their highest value i.e. a large voltage cone. Secondly there was a workshop area within 250 m where there was a combination of 25 kV test tracks and separate d.c. traction power systems.

To reduce the effect of the depot and workshop power systems a series of insulated rail joints (IRJ) were installed on the various tracks.

Thirdly there was an interface with a different traction system and railway operator within 450 m. This system was also a three rail system but with the traction earth tied in to the sub-station earth. The two systems were separated with a series of IRJs

6. Cathodic protection design

As with all cathodic protection designs full information was acquired on the structures to be protected.

Pipe material:	Cast iron (guess from the pipeline operator)
Coating:	Disappeared
Pipe outside diameter	1 m (guess from the pipeline operator)
Pipe length:	15 m (guess from the pipeline operator because one pipe disappeared beneath station platforms and the other under a roadway)
Design life:	50 years
Power supply available:	Yes. 240 V a.c. 50 Hz
Area for groundbed:	None

Monitoring requirements: Continuous for transformer-rectifiers and pipe to soil potentials

Continuous measurement of the actual corrosion rate

In common with all impressed current designs the surface area was calculated, current density requirements estimated, and the voltage and current requirements determined.

The only problem was where to install a groundbed. Available space was severely restricted so an Anodeflex was selected on the basis that it could deliver sufficient current over the entire length of the pipes to either cathodically protect the pipe or raise the soil potential sufficiently to keep the pipe in an electrically neutral condition (EN 14505 cathodic protection of complex structures).

During the course of construction, however, some new facts emerged:

1. Pipeline was actually installed inside a brick tunnel and they were afraid to disturb the brick tunnel
2. Additional reinforcement was necessary for the track so the groundbed space was even more restricted.
3. Additional steel supports were provided for the tracks.

This severely restricted the space available for an anode groundbed. Eventually the groundbed was installed in trenches between concrete slabs.

There are some preliminary calculations that were carried out to try and assess the level of the risk. Amongst the calculations and simple modelling performed were:

- Traction current model based on worst case scenarios e.g. assuming a maximum length train filled with very fat corrosion engineers going on holiday

- Simultaneous train departures in both directions using maximum traction current (approximately 6 kA each) combined with regenerative breaking

- Failed IRJs

- Zone of influence (using a re-arranged formula from EN 50162 as previously presented at CEOCOR by Dr Buchler)

- Simplistic Kirchoff's Laws for the area of pipe crossings.

Traction Current Model

Although not as sophisticated as the professional modelling that is provided by, for example, Elsyca the model we developed was going to be far from perfect because of the lack of knowledge of the pipeline and traction systems. We used PSpice to model the tracks and leakage. Drainage diodes are incorporated at each sub-station but are left out of circuit. Switching the diodes in circuit increases the stray currents and for a single feed section of track can raise the rail to earth voltage above the recommended maximum of 60 V.

Zone of influence

The formula to estimate the zone of influence of the traction/stray current is calculated using the re-arranged formula. The formula is rather cumbersome but is easily managed within professional mathematics software. We use Mathcad Prime 3.0.

The formula is:

$$A_K := \frac{\sqrt{\left(\left(-s_{tg} + \left(\left(s_{tg}\cdot s_{tg} + 4\cdot e^{\left(\ln\left(L_i\cdot\left(L_i+s_{tg}\right)\right) - U_c\cdot 2\cdot \frac{\pi}{\left(\frac{m_{sr}\cdot\pi\cdot 2}{\left(\ln\left(b\cdot\left(b+s_{tg}\right)\right)\right) - \left(\ln\left(a\cdot\left(a+s_{tg}\right)\right)\right)}\right)}\right)}\right)\right)\right)\right)}}{2}$$

$$A_K = 30.724$$

Stray current activity calculations. (50122-2)
The RMS value of the changes in rail potential gradient corresponds to the potential shift c
the metallic installations.

The RMS value of the changes in rail potential gradient is proportional to the stray current activity.

Maximum allowable **anodic** shift is 300 mV

Actual data

$n := 3600$	number of the measured data
$U_i := 961\ mV$	instantaneous value of potential gradient (V)
$U_a := 9.5\ mV$	average of the potential gradient (V)

$$U_{SCA} := \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\left(U_i - U_a\right)^2\right)}$$

$$U_{SCA} = 951.632\ mV$$

Kirchoff's Law

KIRCHOFFS LAW

GIVEN

$R1 := 6.089 \cdot 10^{-6}\ \Omega$ $R2 := 90\ \Omega$ $R3 := 6.089 \cdot 10^{-6}\ \Omega$ $R4 := 90\ \Omega$ $R6 := 90\ \Omega$

$R5 := 6.089 \cdot 10^{-6}\ \Omega$

$V1 := 750\ V$

GUESS VALUES FOR THE THREE CURRENTS

$I1 := 5\ A$ $I2 := 5\ A$ $I3 := 5\ A$

$I1 := 50\ mA$ $I2 := 50\ mA$ $I3 := 50\ mA$

$$(R1 + R2) \cdot I1 - R2 \cdot I2 = 750\ V$$
$$-R2 \cdot I1 + (R2 + R3 + R4) \cdot I2 - R4 \cdot I3 = 0\ V$$
$$-R4 \cdot I2 + (R4 + R5 + R6) \cdot I3 = 0\ V$$

$$\mathbf{find}(I1, I2, I3) = \begin{bmatrix} 25 \\ 16.667 \\ 8.333 \end{bmatrix} A$$

7. Cathodic protection system

Due the inaccessibility of the system combined with the danger of fatalities if the pipeline failed and the 50 year design life, only highly reliable and well proven components could be selected. Each pipe was provided with its own cathodic protection system comprising an Anodeflex linear anode laid approximately 0.75m from the pipe and following the contours of the available space between the reinforcement and supports. The anode was powered by a potentiostatic phase angle thyristor control transformer-rectifier. A terracotta pot style permanent copper|copper sulphate reference electrode provides the control signal.

The transformer-rectifiers were set to control to a potential of -1.5 volts for one system and -1.2 volts for the system outside the station.

The design current density was 50 mA m^{-2}.

8. Monitoring

Two independent monitoring systems were installed for each pipe.

The first system is manufactured by Weilekes Elektronik and measures the transformer-rectifier output values (voltage and current) and the pipe-to-soil potential. The data is automatically transmitted to the remote host computer via the GSM network. The system can also be remotely operated to switch the units on and off and also to provide intensive data logging.

Data examples are given at the end of the paper.

Interpretation of rapidly fluctuating potentials to provide assurance that there is no external corrosion is difficult and can always be challenged.

The second system is independent of the first system and was provided by MetriCorr. This system provides many valuable parameters:

- Pipe-to-soil potential (using a separate reference electrode)
- Current flowing through the integral 1 cm^2 coupon (allowing calculation of the a.c. and d.c. current density)
- Spread resistance
- Corrosion rate (in µm per year)
- Coupon thickness
- Calculated off potential

The data is transmitted via the GSM system to a remote computer where it is plotted.

The data example shows clearly and unequivocally that the corrosion rate is zero (top graph).

The second graph shows that the potentiostatic control system is working effectively.

The third graph shows the calculated off potential is -1.3 volts.

The fourth graph shows that the current density required to achieve protection is more than 2 A x m^{-2}.

It would not have been possible to validate this level of performance by analysis of the fluctuating pipe-to-soil potentials.

Examples of the data plots are given at the end of the paper.

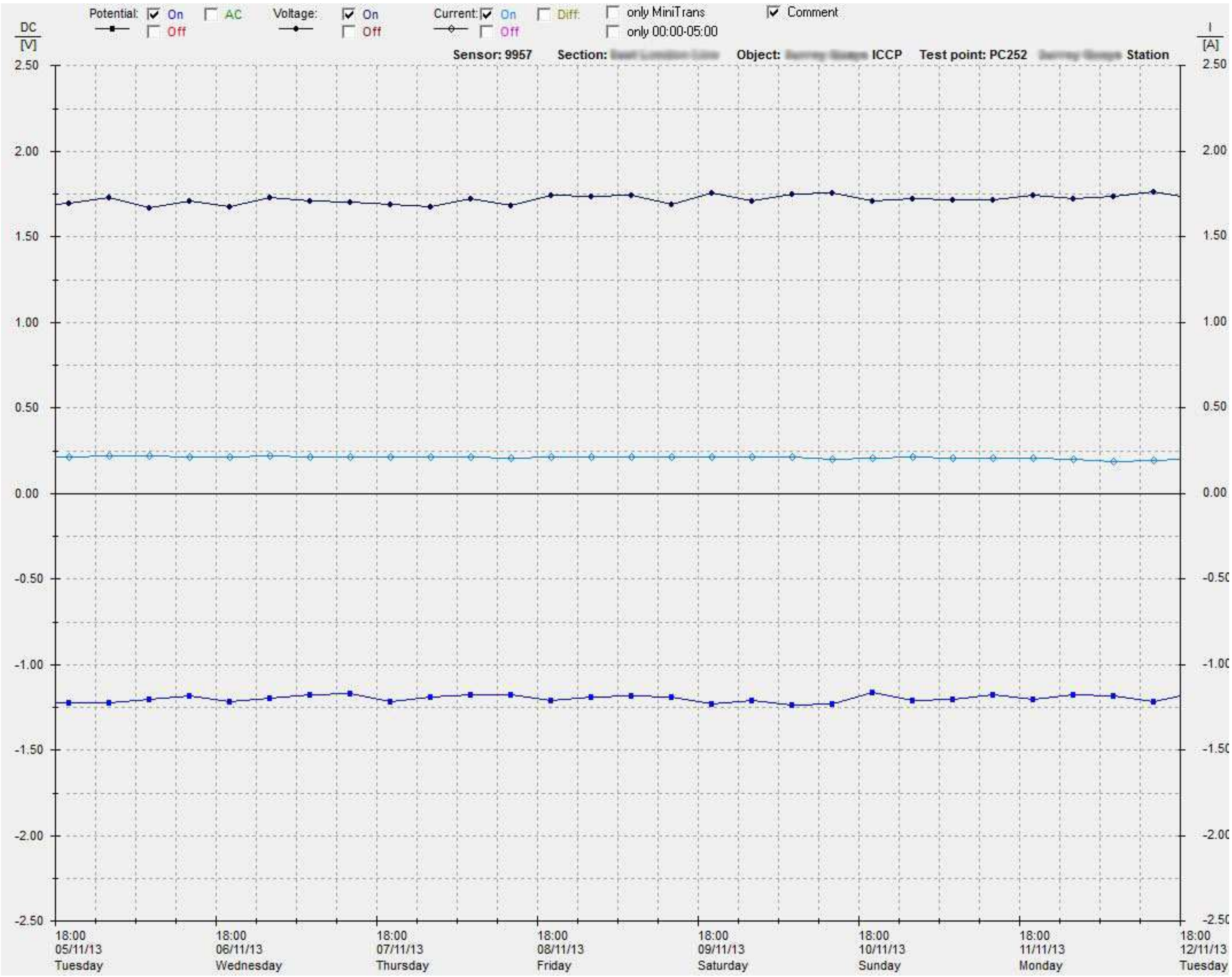
9. CONCLUSIONS

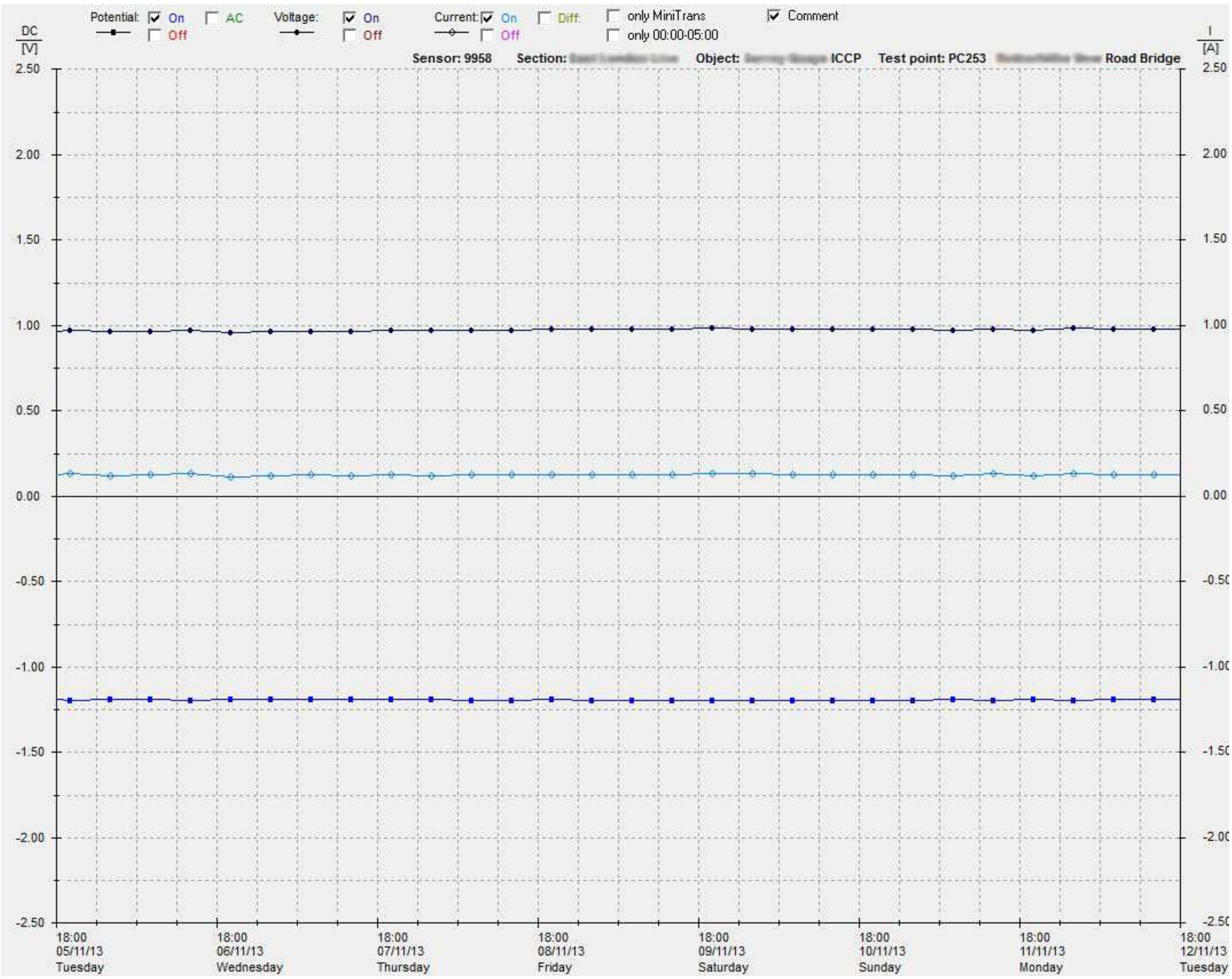
The system has been operating successfully now for more than 5 years and the corrosion rate is still zero. On this basis the metro line continues to operate.

Lessons learned?

1. Linear anodes can provide effective cathodic protection where other systems cannot even be considered.
2. Electrical resistance probes provide evidence that the corrosion is reduced to acceptable limits, or eliminated altogether. This is more reliable than analysing potentials and guessing.
3. In stray current situations always use the best equipment and components because the consequences of failure are serious and retrofitting is impossible.
4. The installed system was very different from the originally design system but in spite of all the changes in construction the system has worked effectively. It would be nice to claim that it worked due to the experience, diligence and exceptional qualities of the design and installation team – but we were just lucky!
5. Using close anodes meant that there was no adverse effect on the track signalling.

TR characteristics and pipe-to-soil potentials

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Voltage: On Off
Current: On Off Diff:
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Sensor: 9958
Section:
Object: ICCP
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2.50
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18:00 05/11/13 Tuesday
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Examples of MetriCorr probe data plot.