Sentinel – deep dive

Novel fault location for overhead lines

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LCNI conference

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Sentinel deep dive – overview

Project drivers and objectives	Fault location techniques	Hardware design
Installation	Testing and simulation	Next steps

The problem

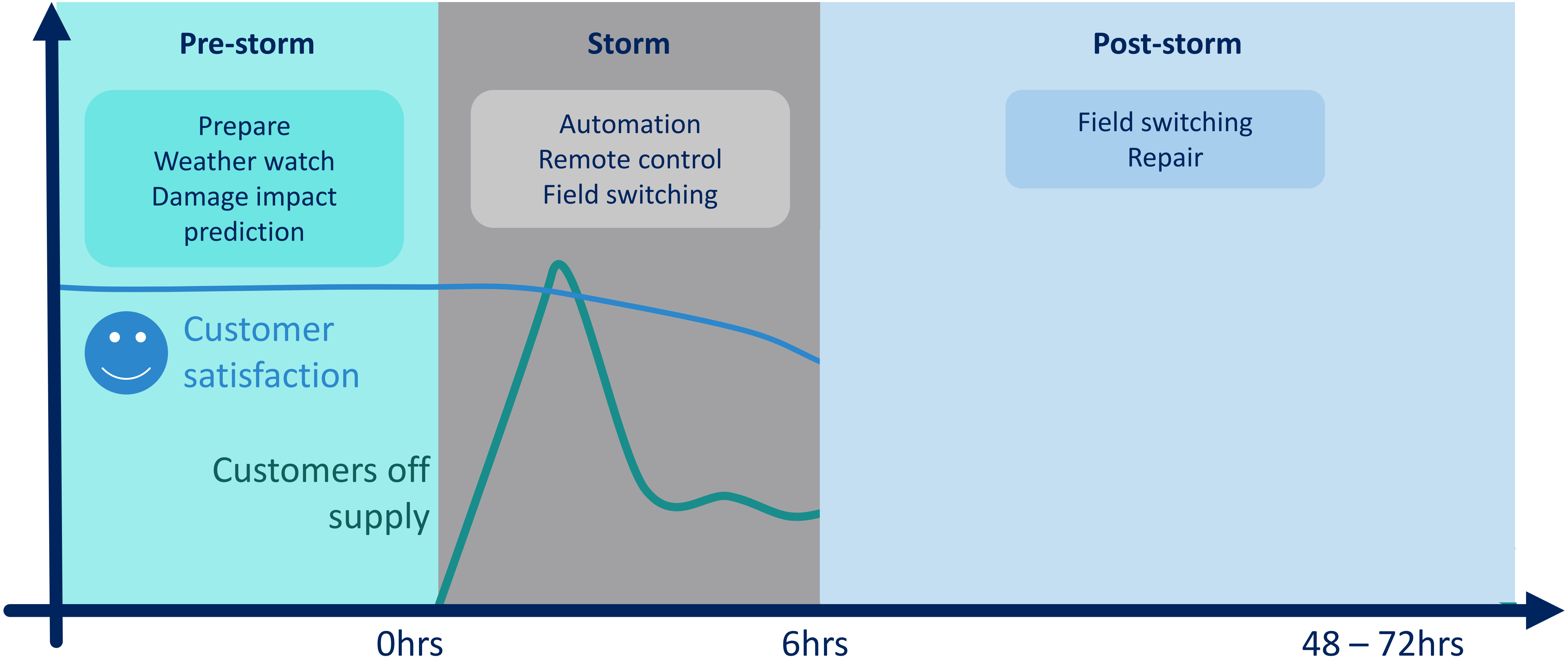
Faults on rural OHL networks can be difficult to detect and locate
Transient/emerging
Broken conductor
Low clearance

In storm situations there can be multiple faults on single circuits

Traditional location techniques are time consuming, dangerous and lead to poor customer experience

Some faults, if left undetected, can present a serious danger to life

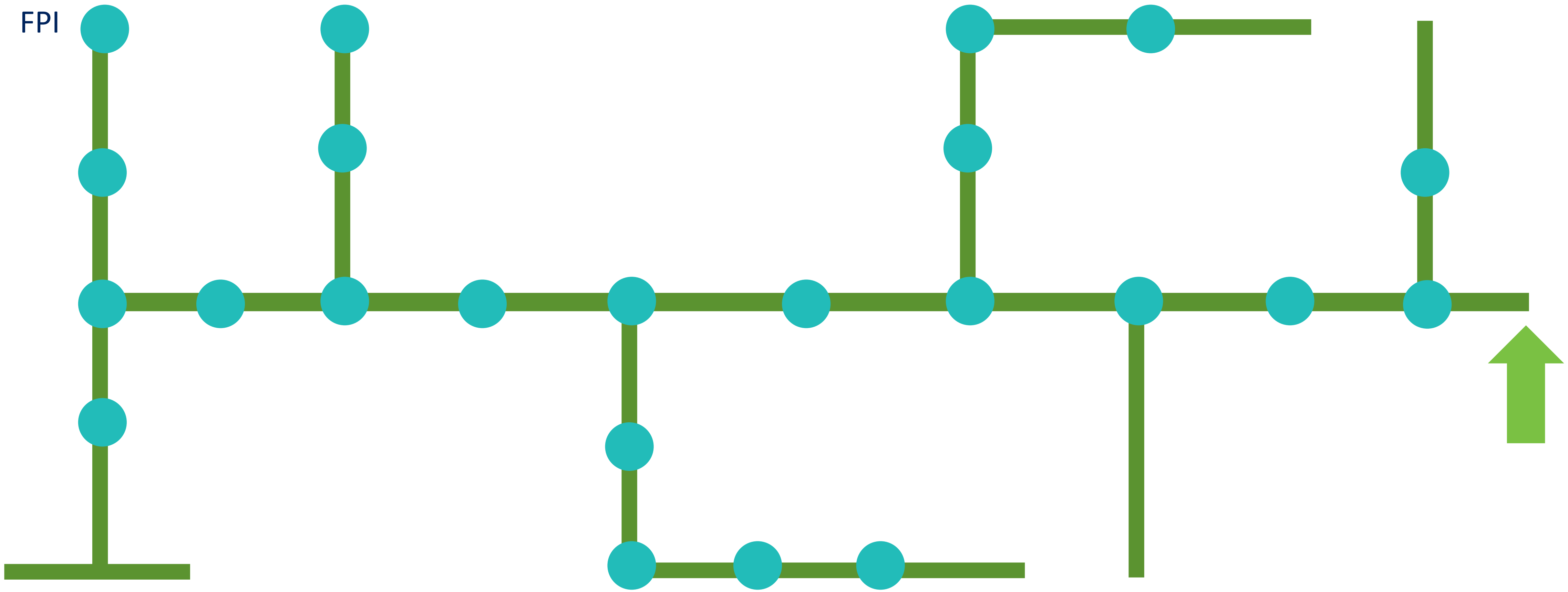
Current timeline



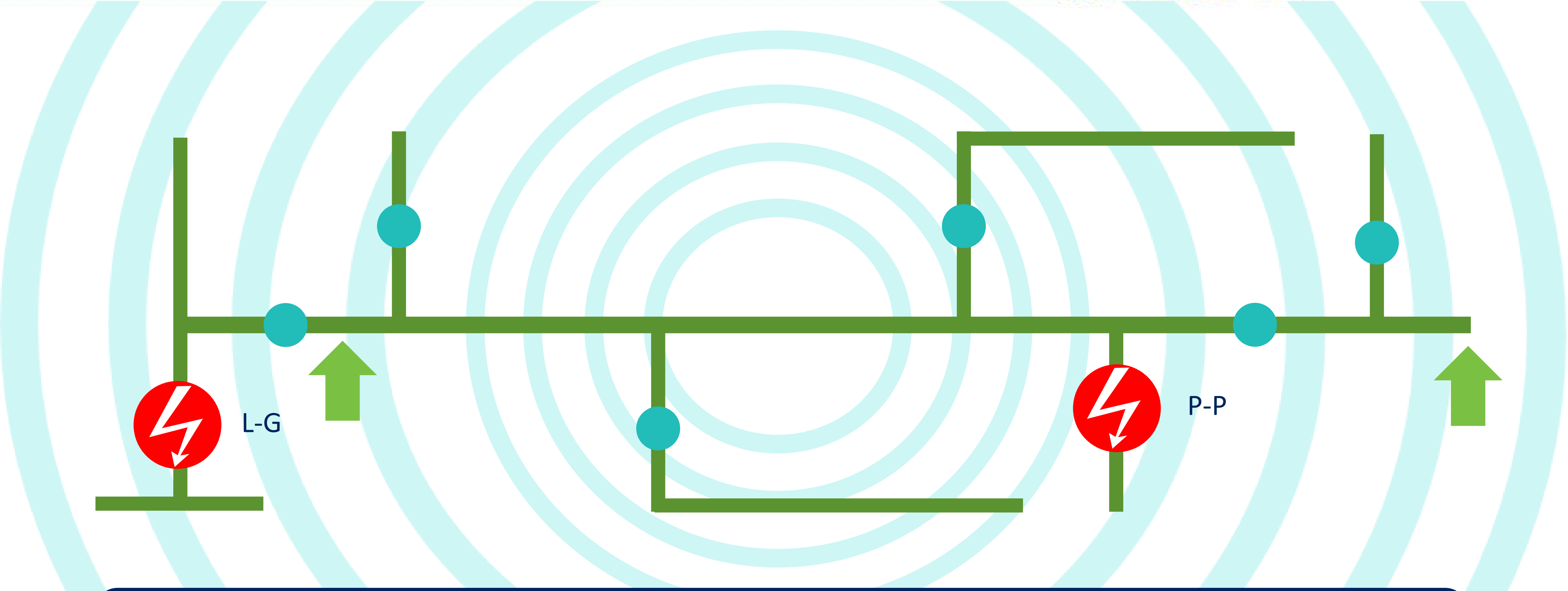
How do you minimise time to repair?

What does it look like?

What is Sentinel?



What is Sentinel?



Finds multiple faults of multiple types
on a rapidly reconfiguring network in near real time

Project drivers

Objective	Output	Right teams to right location	Location techniques	Integrate with real time systems
Find damage in real time Optimise deployment of repair teams	Fault location system Location within 500m for high current faults Section for low current/low lines (worst case)	Maximising productivity of repair teams Reduces safety risk	Uses a combination of different location techniques	Responds to changes in network configuration

Project objectives

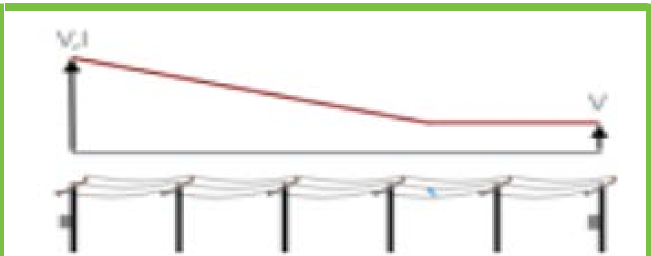
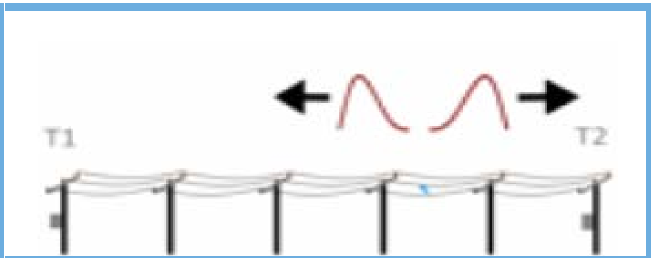
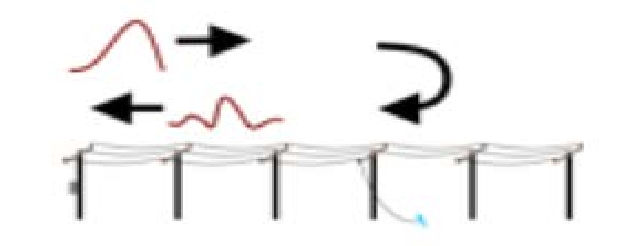
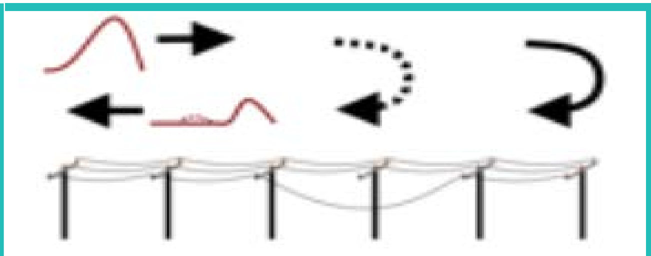
Install and demonstrate a number of different fault location techniques

Develop the hardware and software needed

Develop preferred methods of installation of equipment

Compare and contrast the performance against theory and other available methods

Sentinel fault location techniques

Fault location technique and associated sample rates			Sensor requirements
Multiple ended location of faults (MELF)		LF 0-12.8kHz	Accurate voltage and current transducers
Travelling wave Location of faults (TW)		HF 50kHz-5MHz	Low accuracy voltage transducer
Time domain Reflectometry Location of faults (TDR)		HF 50kHz-5MHz	Low accuracy voltage transducer
Time domain Reflectometry Lowered line Detection (TDR)		HF 50kHz-5MHz	Low accuracy voltage transducer

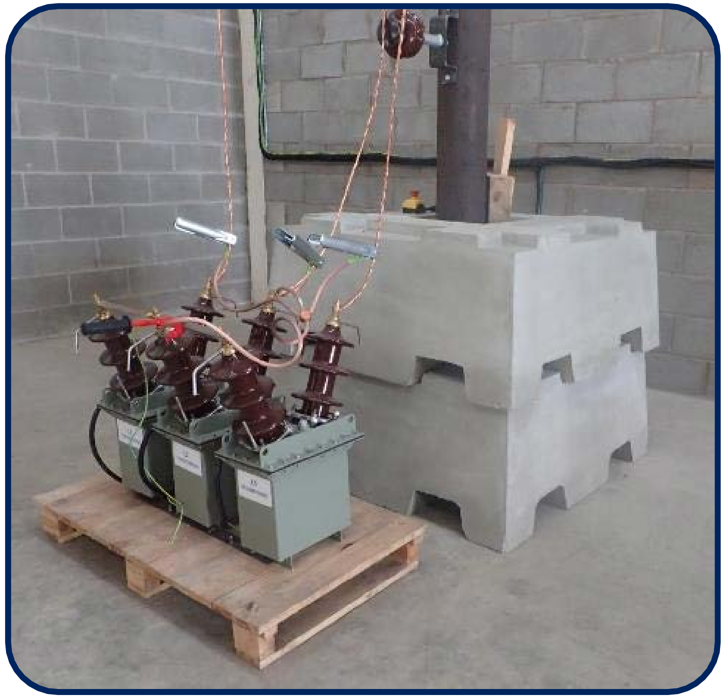
Prototyping and testing – lowered line experiments

Camlin test facility

Total length = 80 m approx.
Line to line = 1.1 m
Line to ground = 2 m

Span lengths (pole to pole)
1st span = 30 m
2nd span = 10 m
3rd span = 15 m
4th span = 25 m

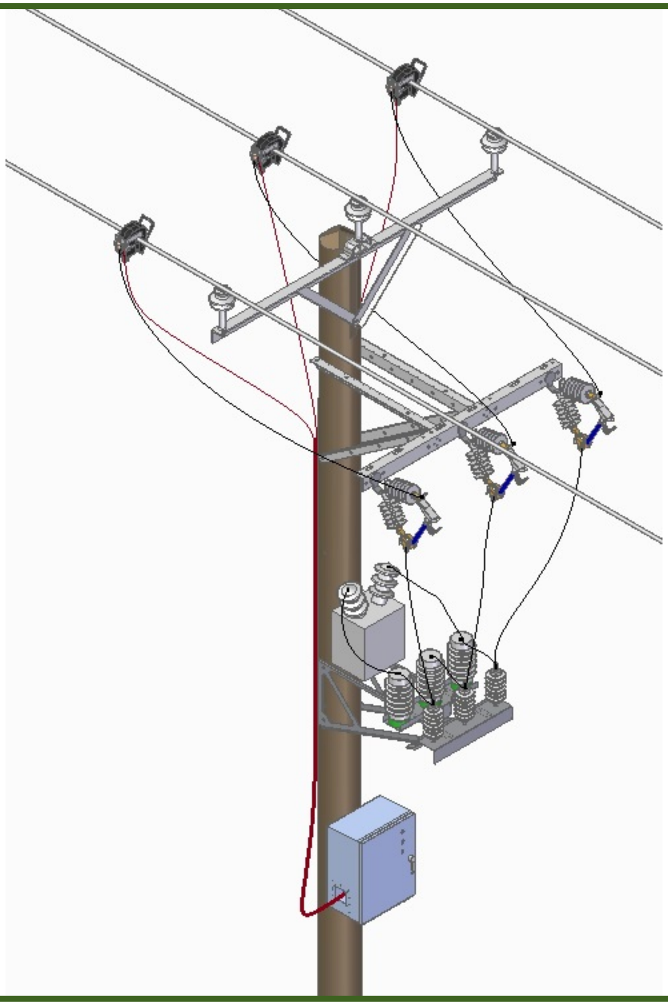
Prototyping and testing – Sentinel 11 kV live testing



Prototyping & testing – Overhead line construction

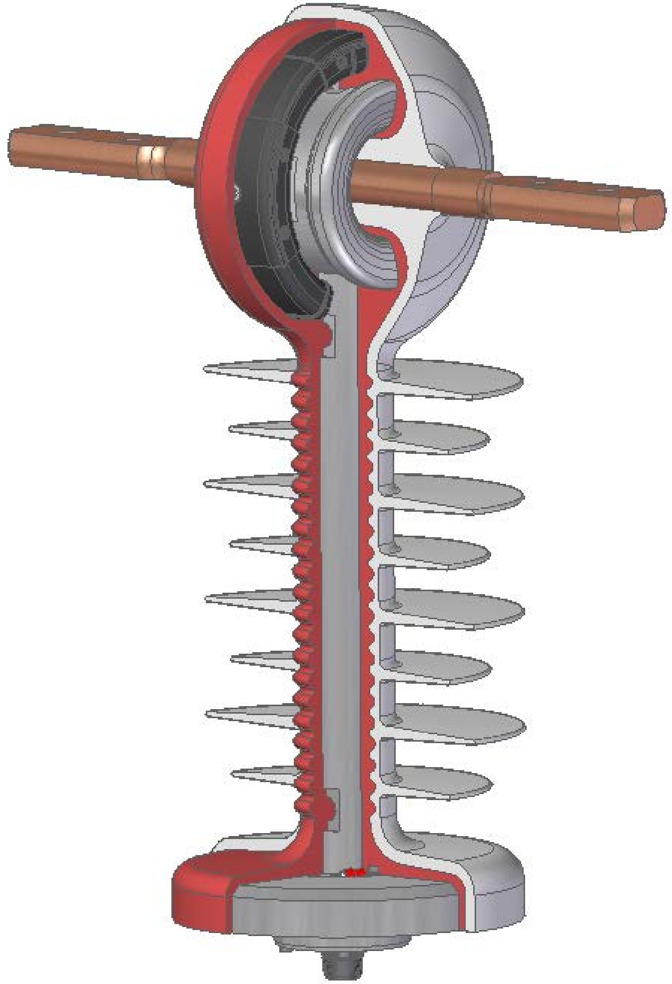
CAMLIN Overhead line

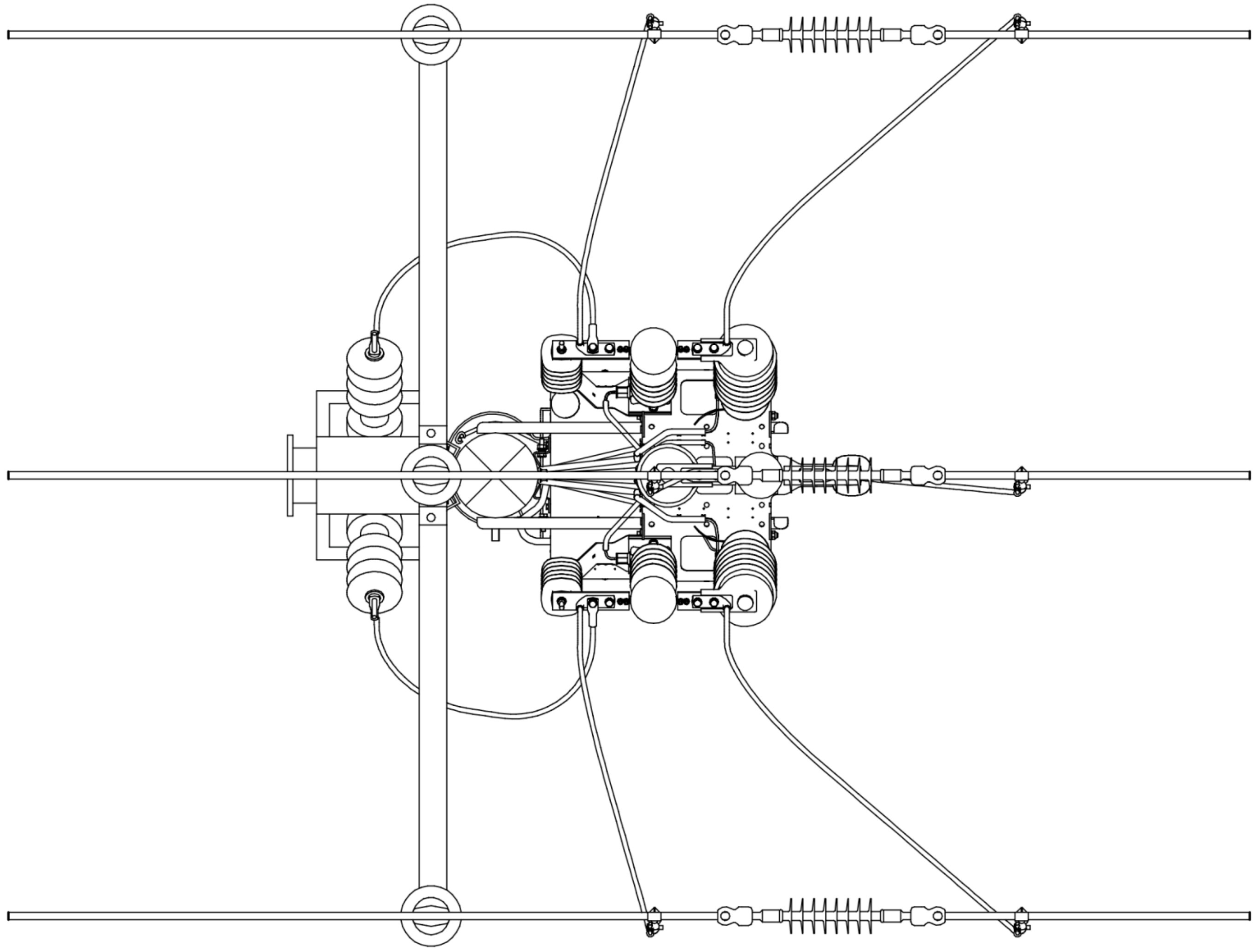
Sentinel pole – pole hardware component design



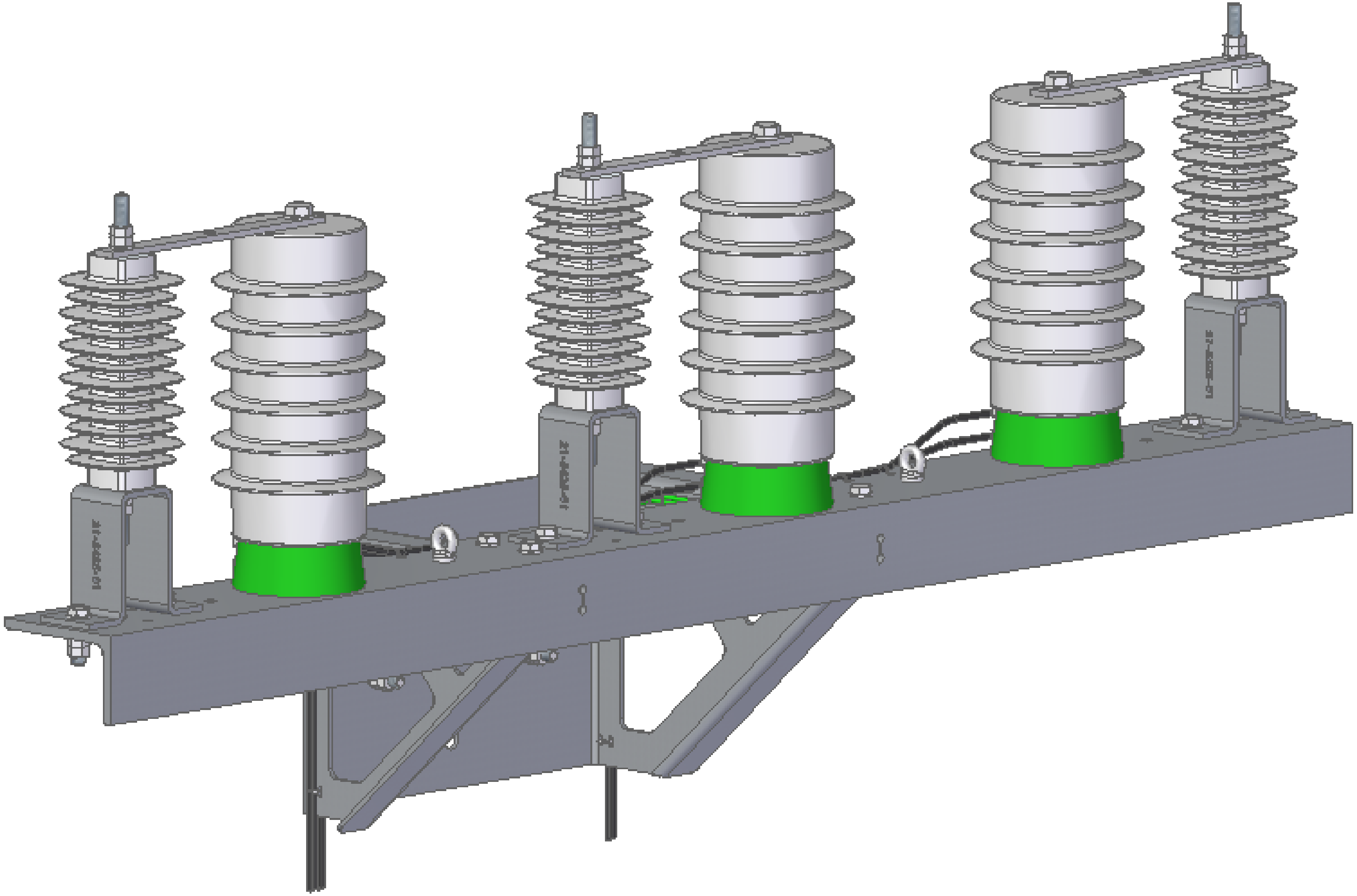
- Current sensors
- Voltage sensor & HF coupler
- Surge arresters
- Voltage transformer
- Sentinel cabinet

Current sensor, off-the-shelf solution

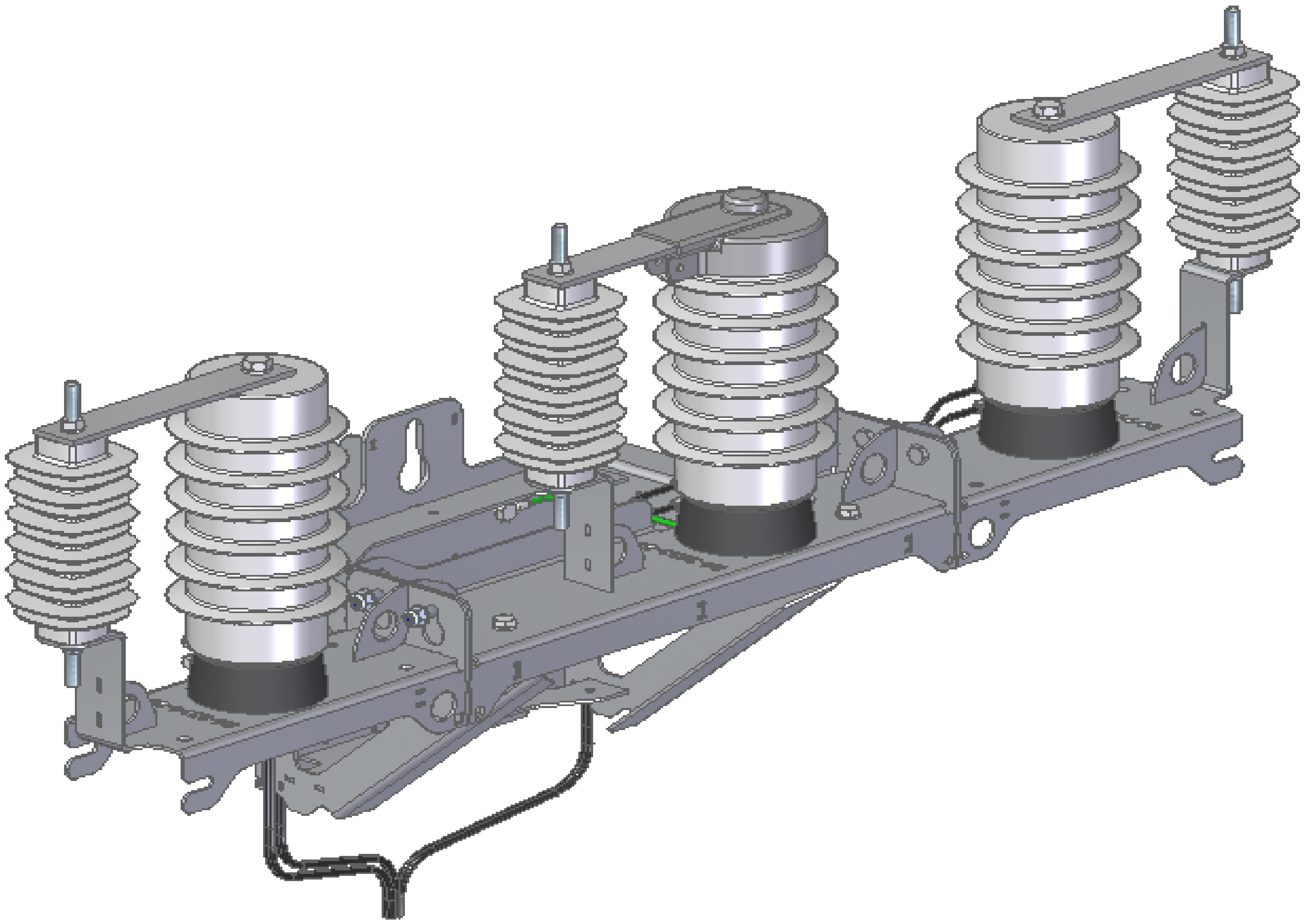




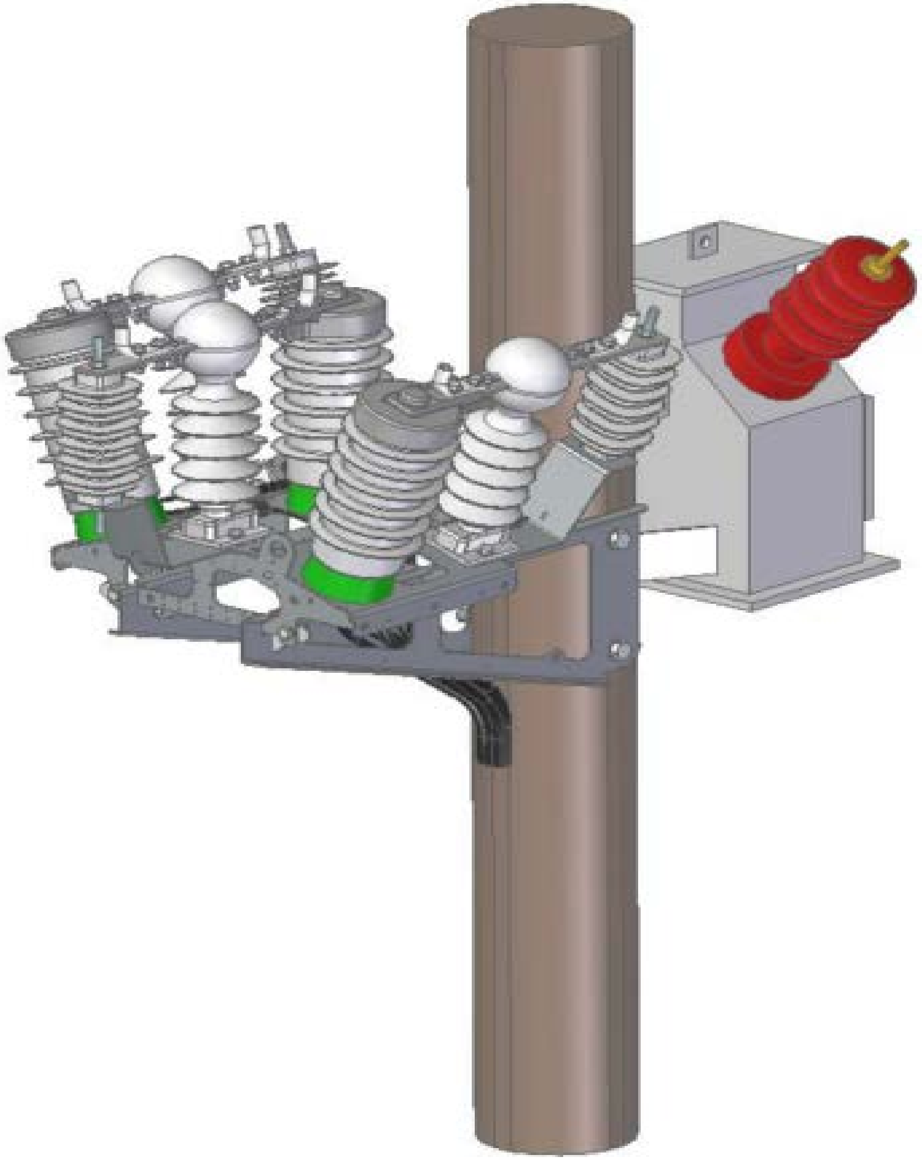
Voltage sensor crossbar (VSC)



Voltage sensor crossbar (VSC)



Combined voltage and current sensor



Connected via flying section

Off the shelf current sensor

Site selection and approvals

Trial circuit selection	Approval for use of new equipment	Codes of practice drafted	Trial installation at Electricity North West training academy – led to redesigns	Reviewed and approved codes of practice

Installations and practical considerations

Training

Field engineers and control room

Installation phase 1

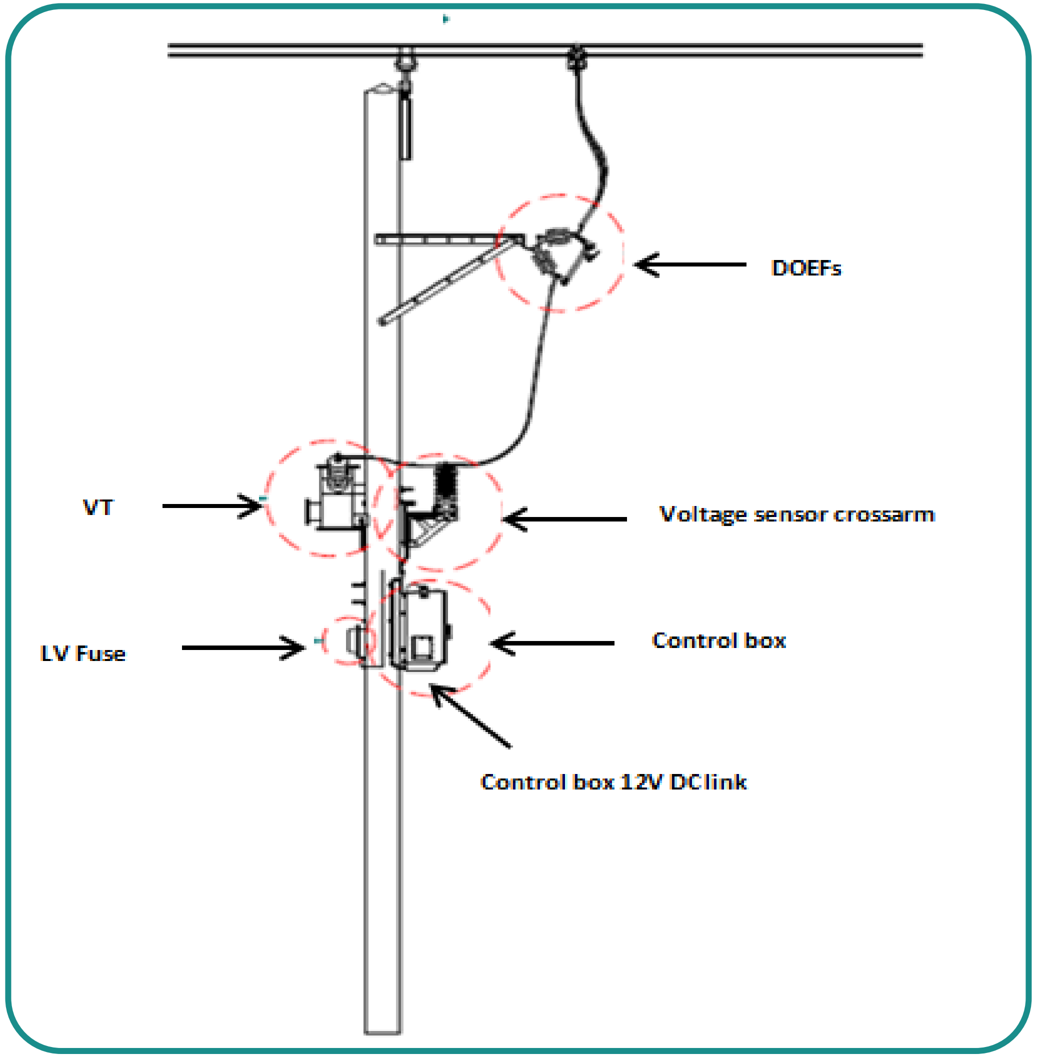
30 units

Data gathering for development of algorithms

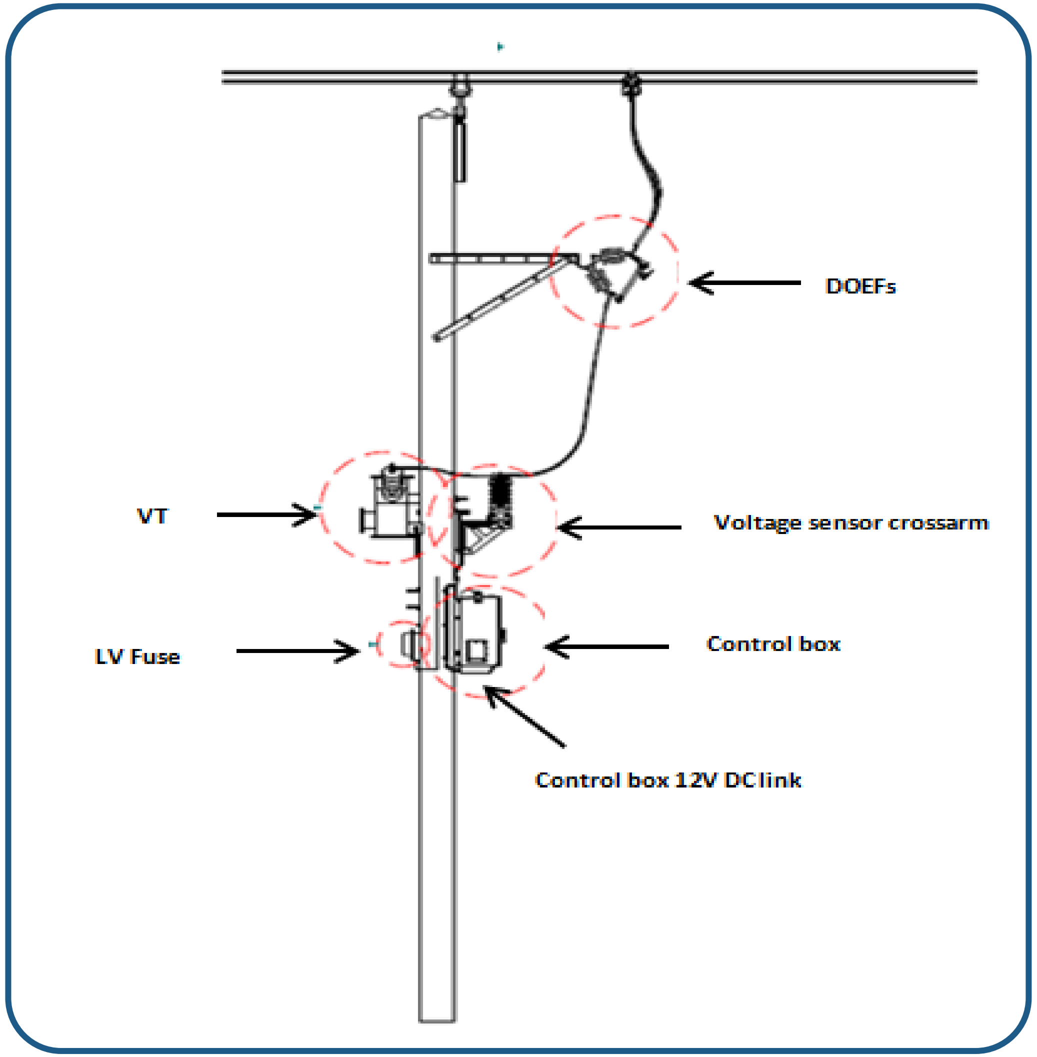
Installation phase 2

70 units currently installed

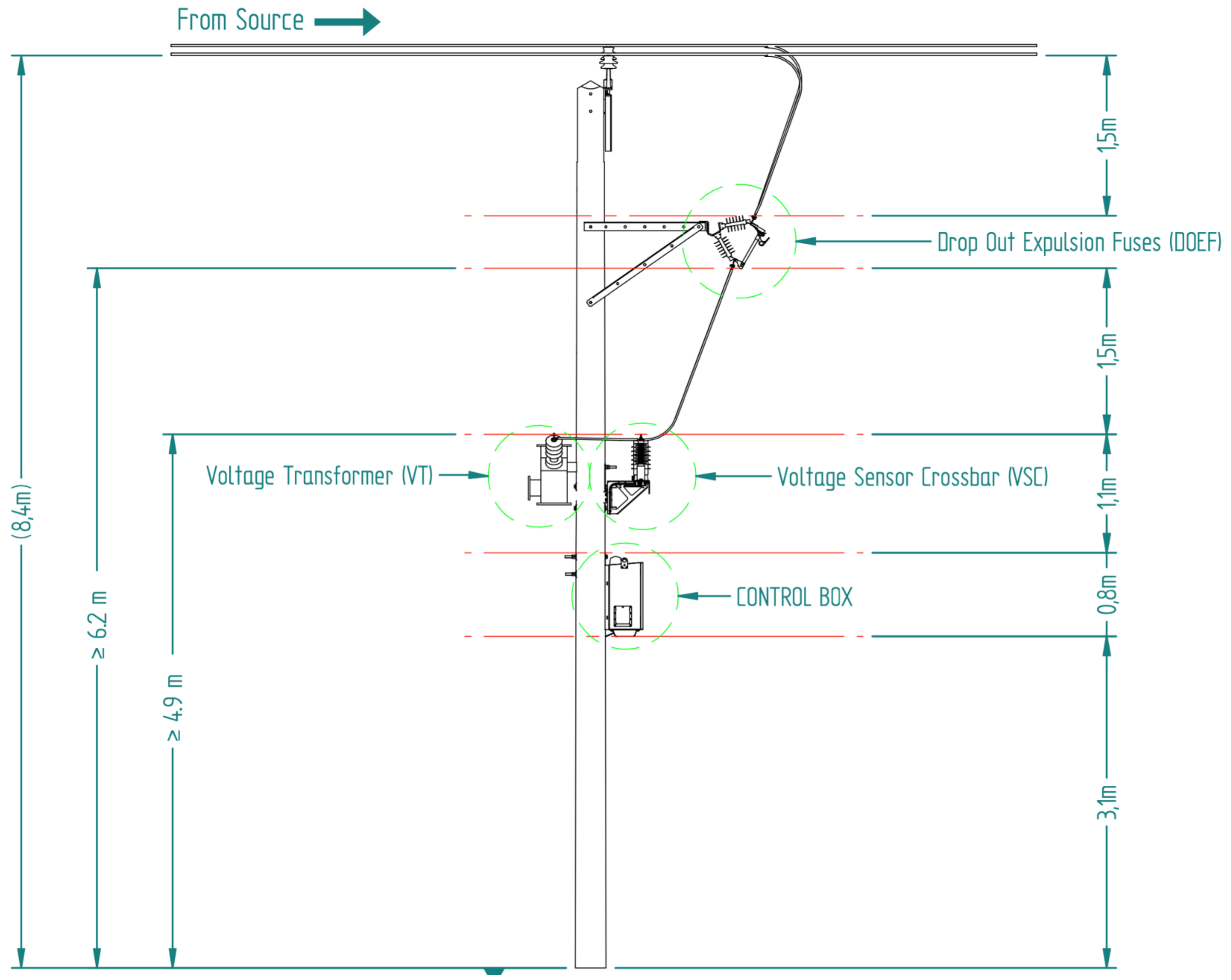
Sentinel voltage sensor 3-phase installation



Sentinel voltage sensor 1 phase installation



Spacing layout diagram



Overhead line

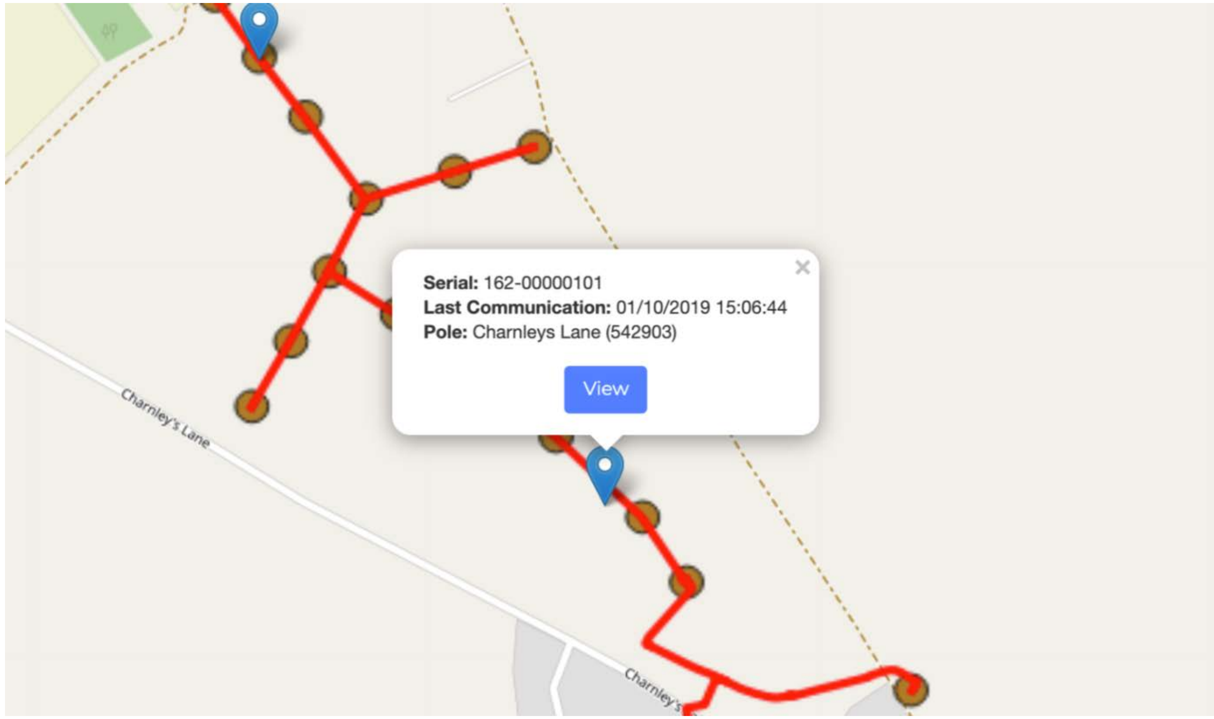
HV zone

LV zone

Datum – ground level

Dashboard

Device 162-00000101



EVENT TYPE	EVENT TIME	RECEIVED TIME	DETAILS
POWER_UP	07/08/2019 15:04	07/08/2019 15:06	Fpga Firmware Version: 0.11.0.7 Modem Firmware Version: Platform Version: 4.19.45-Dnm3pv2+G54c77e7 Software Version: 2.3.0 Wireless Version:
POWER_UP	17/06/2019 19:59	17/06/2019 19:59	Fpga Firmware Version: 0.11.0.7 Modem Firmware Version: 20.00.403 Platform Version: 4.19.45-Dnm3pv2+G54c77e7 Software Version: 2.3.0 Wireless Version:

Measurements

Phase 1	6165 V	0 A
Phase 2	6225 V	0 A
Phase 3	6256 V	0 A

Last updated on: 01/10/2019 15:06:44

Temperatures

CPU	28.018°C
CPU PCB	32.25°C
FPGA	43°C
FPGA PCB	30.5°C

Last updated on: 01/10/2019 15:06:44

Pole detail

Pole name:	Pole 10
Pole number:	542903
Pole location:	Charnleys Lane
Pole longitude:	-2.93°
Pole latitude:	53.68°
Pole notes:	Plant Ref: 540435

GPS

Longitude	-2.93°
Longitude error	6.92m
Latitude	53.68°
Latitude error	6.95m
Altitude	10.52m
Altitude error	23.00m
Fix type	3D
Satellites number	18

Last updated on: 01/10/2019 15:06:44

Power supply

Mains	●
Battery	●

Last updated on: Unknown

Version

Software version	2.3.0
Platform version	4.19.45-dnm3pv2+g54c77e7
FPGA firmware version	0.11.0.7
Modem firmware version	
Wireless version	

Last updated on: 07/08/2019 15:04:23

Lowered power lines – detection

Theory

Proof of concept measurements

Simulation results

Technical challenges

Network coverage considerations

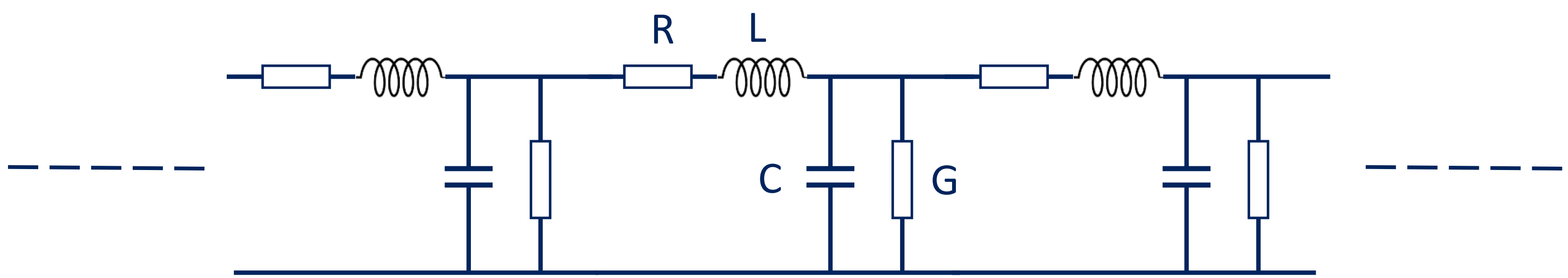
Network behaviour

Sentinel hardware can transmit high frequency signals onto the overhead line network, superimposed upon the 50 Hz mains frequency

This signal will propagate along the line as a wave at close to the speed of light

Signals travelling in a line – theory

The lumped-element model is applicable when circuit size is much greater than signal wavelength:



For lossless lines:

Characteristic Impedance of line, $Z_0 = \sqrt{\frac{L}{C}}$

Propagation Velocity, $v = \frac{1}{\sqrt{LC}}$

For lossy lines:

Characteristic Impedance of line, $Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$

Propagation Velocity, $v = \frac{\omega}{Im\{\sqrt{(R+j\omega L)(G+j\omega C)}\}}$

L depends on geometry

C depends on geometry and the relative permittivity

Dispersion and attenuation

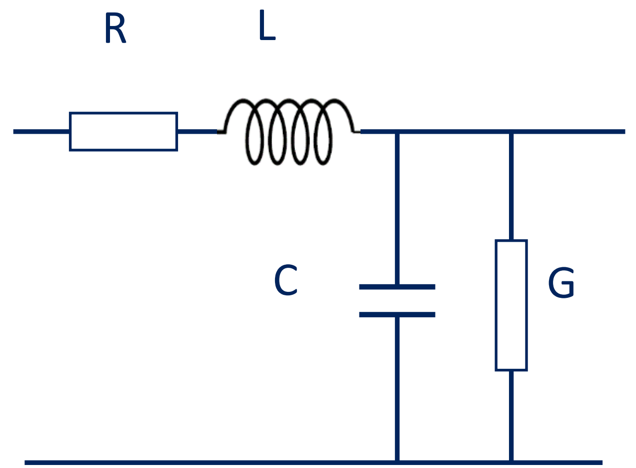
Considering the lumped element model:

The resistive components are uniformly lossy

This leads to signal attenuation

The reactive components are frequency dependent and attenuate high frequencies more

This leads to dispersion of the signal



The further the signal travels in the network, the more difficult it is to distinguish features

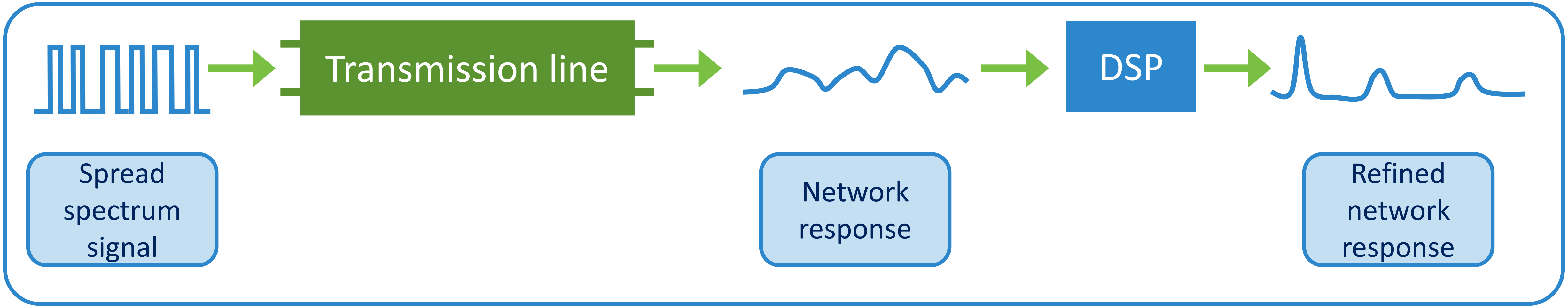
Spread Spectrum TDR

Ideally we would like to inject a very short but very high voltage pulse to overcome attenuation and dispersion problems

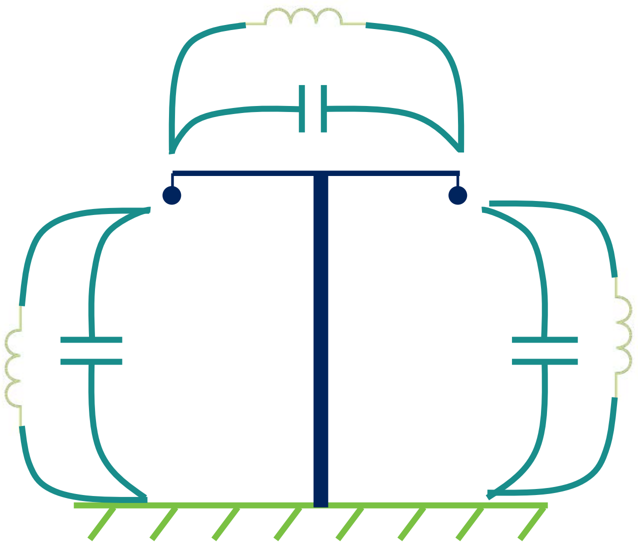
This is not practical due to:
Safety concerns, hardware constraints and emissions constraints

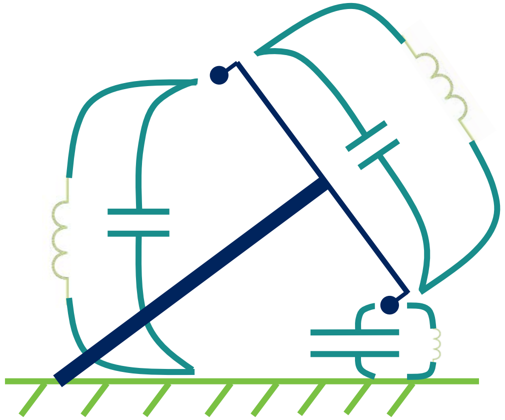
An alternative is to spread the same energy over a large frequency band but at a much lower amplitude

We can use advanced signal processing techniques to sharpen the network response of the network as if we had transmitted a sharp pulse



Lowered lines from a TDR view





Lines have capacitance and inductance between them and to ground.
These define the inductance and capacitance of the transmission line, which define the characteristic impedance:

$$Z_0 = \sqrt{\frac{L}{C}}$$

Using the equations for capacitance and inductance from a wire to a conducting plane:

$$C_{PG} = \frac{2\pi\varepsilon l}{\ln\left(\frac{d}{a} + \sqrt{\frac{d^2}{a^2} - 1}\right)}$$

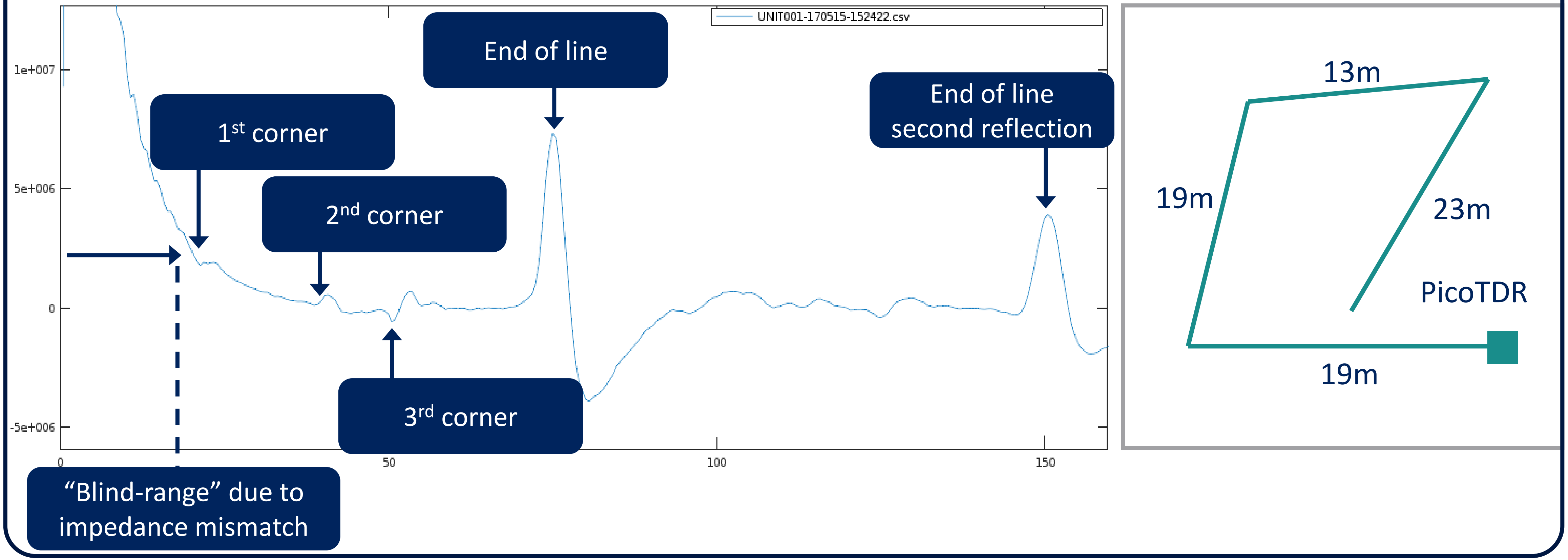
$$L_{PG} = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{2d}{a}\right) + \frac{Y}{2}\right]$$

We see that in this example, for the dropped line, capacitance should increase while inductance should decrease, leading to a decrease in Z_0.

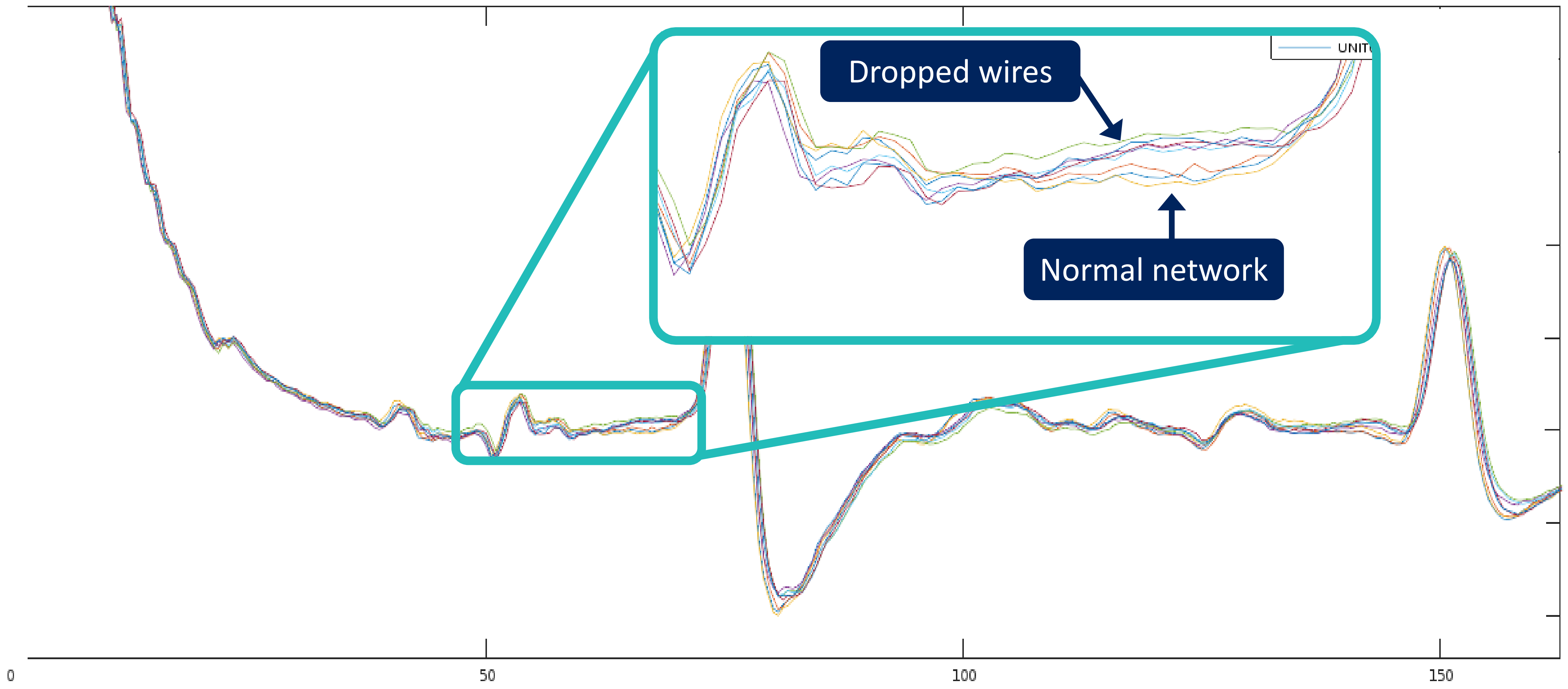
Mini-MV test line measurements

Measurements have been taken across the following variables:

● Phase-phase and phase-earth transmission modes ● Dry ground and wet ground conditions ● Normal network, 1 wire lowered, 2 wires lowered

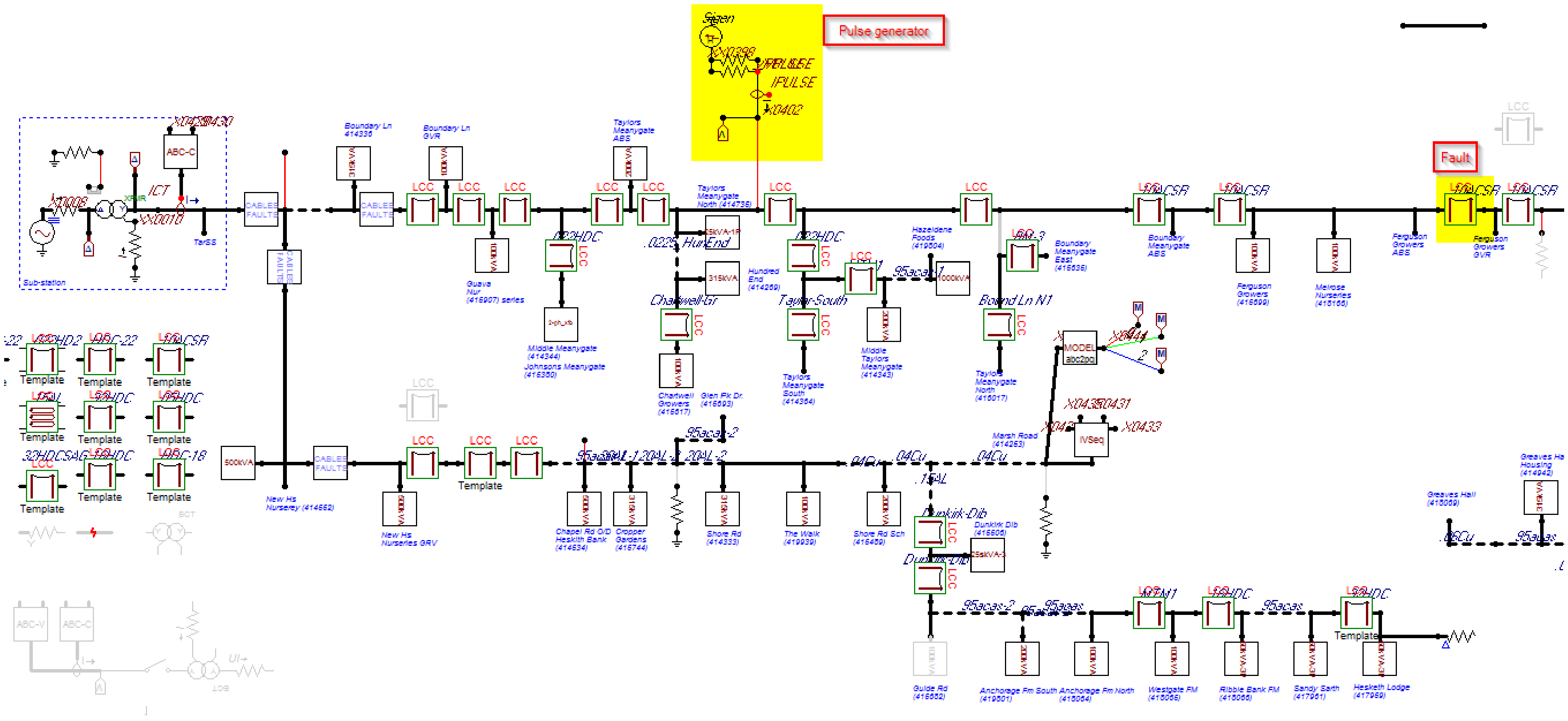


Lowered wires results



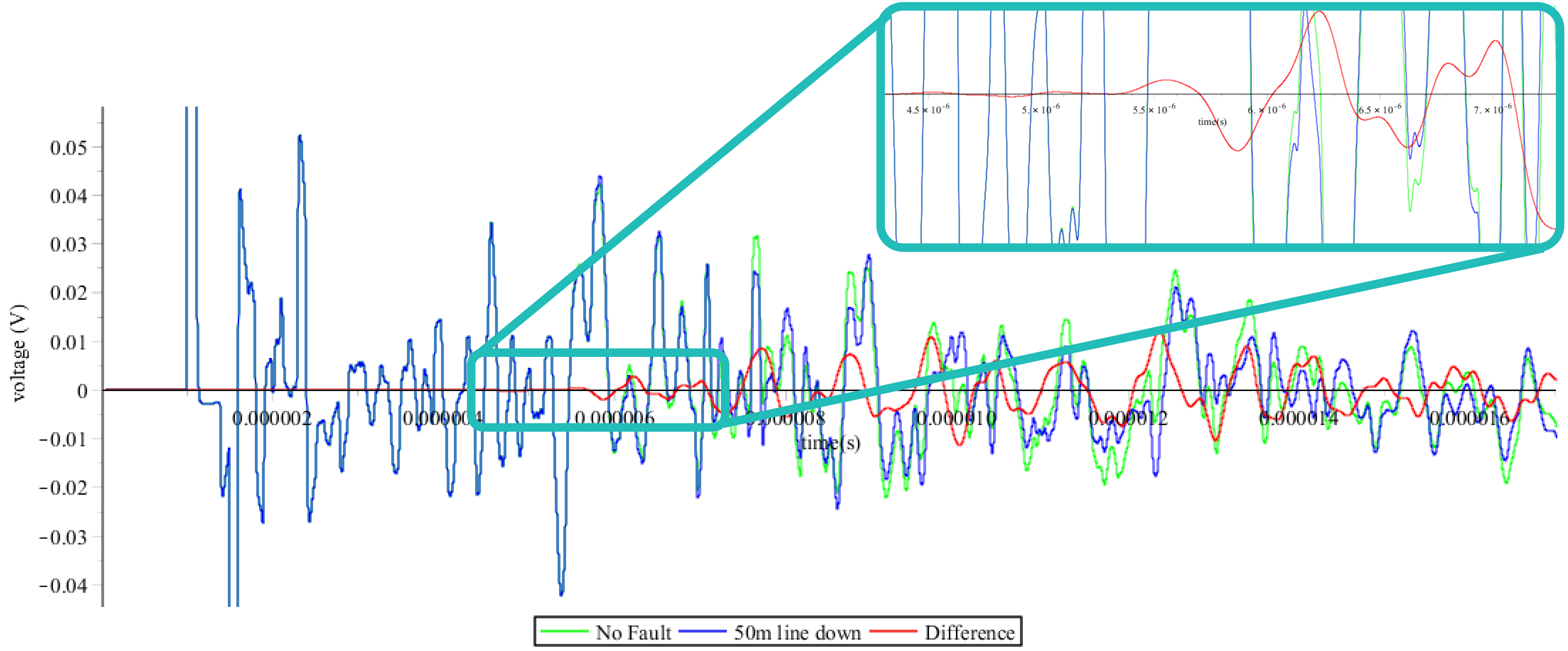
Simulation results

Simulations of the first Sentinel circuit (Boundary Lane) were conducted in EMTP



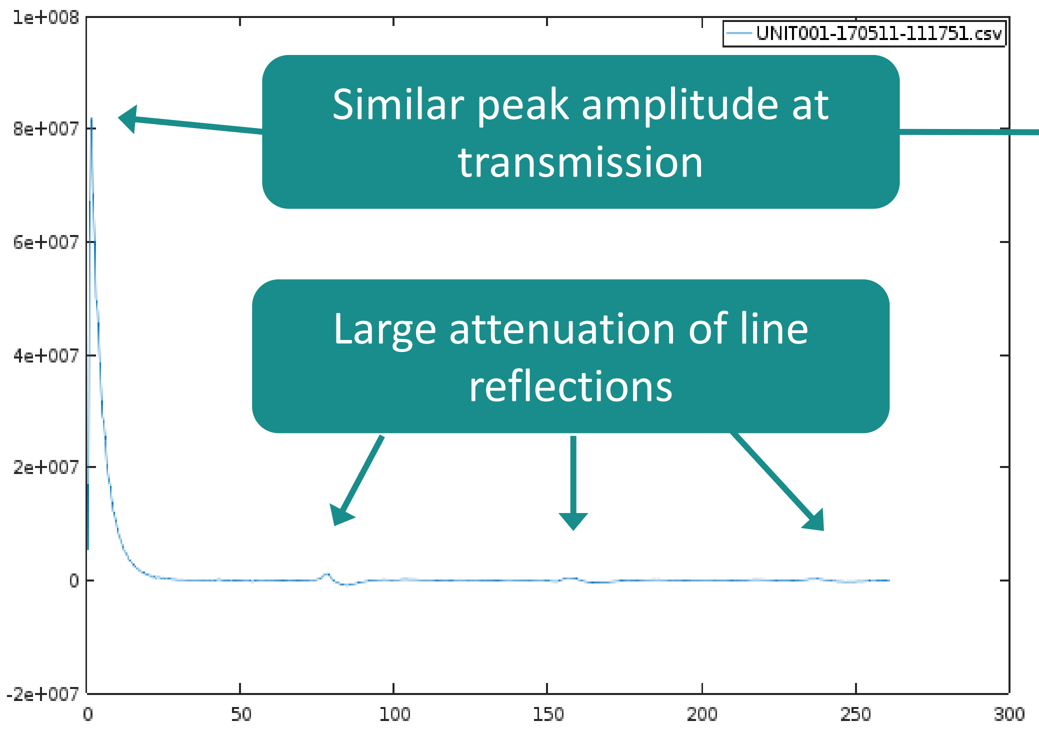
Simulation results

Boundary Lane network – 50m line down

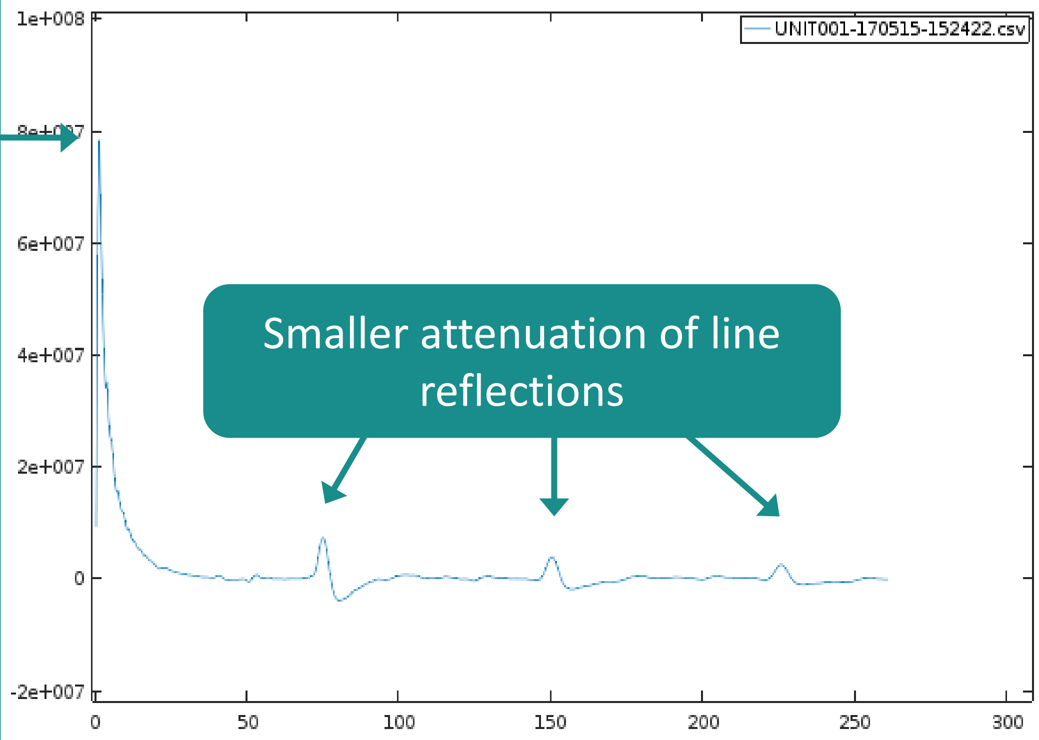


Technical challenges – environmental

Dry ground conditions

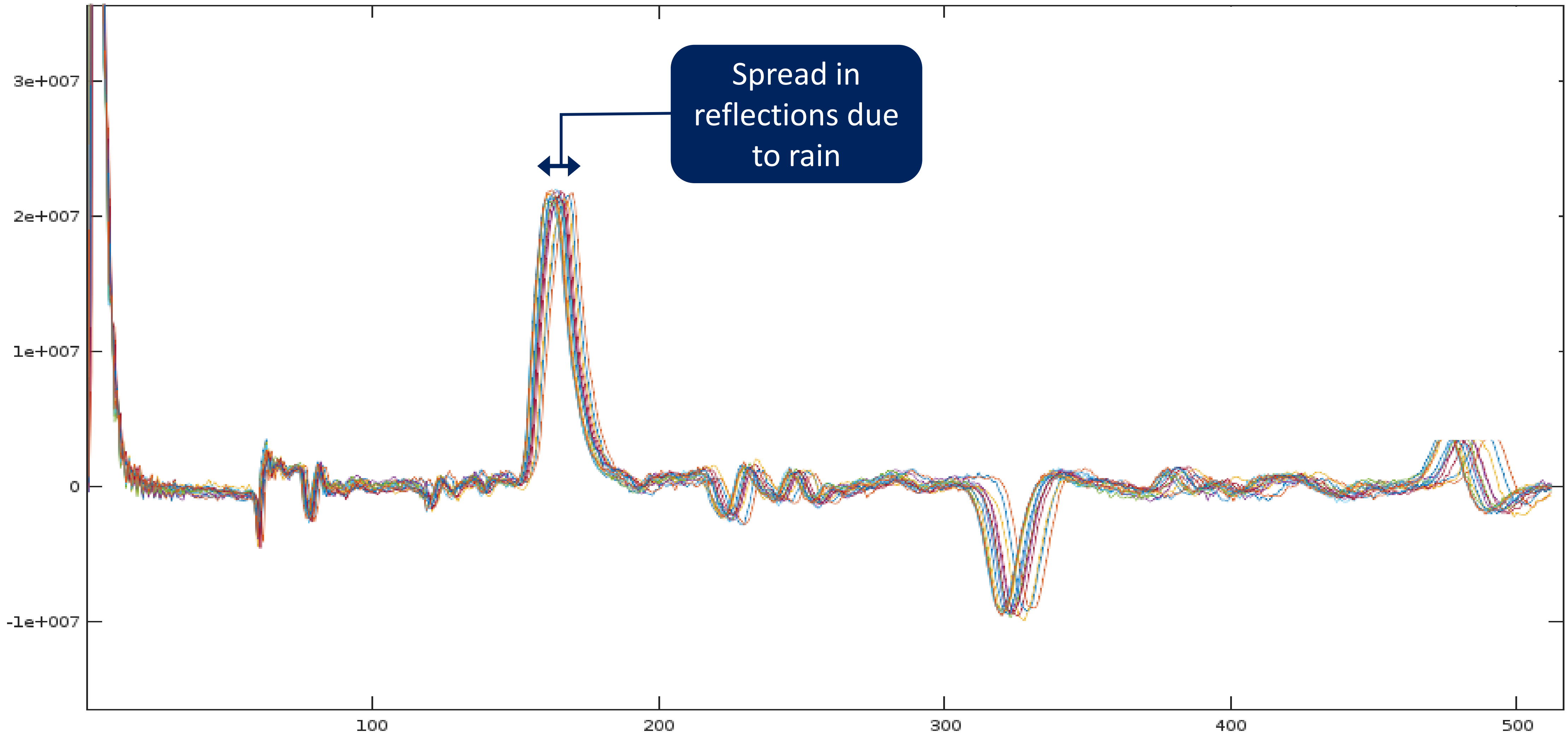


Wet ground conditions



Technical challenges – environmental

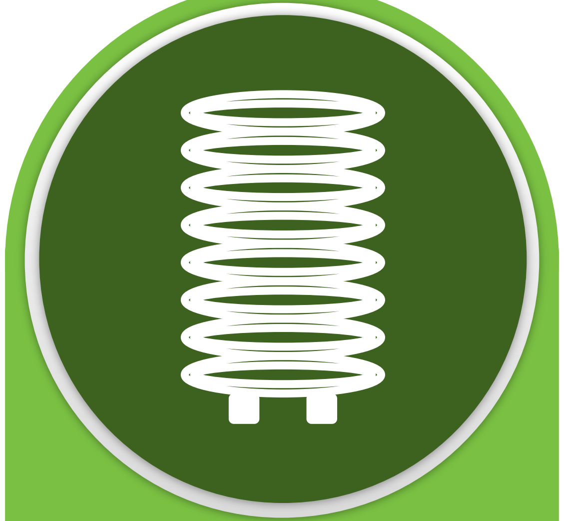
Measurements from Storm Doris



Technical challenges – geometry

Network configuration challenges

During fault conditions, network switches and fuses can operate, leading to different TDR traces



At the device level, large changes in network response can be averaged in different “bins”

At the server level, locations of differences can be correlated with network switch locations

Network coverage

Blind range

Eliminated by optimal impedance matching & multiple measurement points.

Sensitivity

Dependant on physical parameters, signal and noise levels

Distance improved by long term statistical characterisation, spread spectrum TDR

Attenuation due to overhead line to cable transitions – optimise the location of Sentinel units.

Installations

Should be analysed and optimised for detection performance

Critical areas can be targeted

Detection of lowered line will need to provide confidence level

Progress/next steps

Installation progress	Verification	Design process	NMS integration	Application of HV faults for calibration
Complete installation rollout in early 2020	Verification of algorithm with real fault detected on network	Simplifying design and installation process	Automatic state detection Results directly to NMS	Development of RAMS for application of HV faults Approval from senior management team Install test system for simulation of lowered conductor Develop overall test plan for HV faults

QUESTIONS & ANSWERS

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