PNNL-34815
M3LW-23OR0404025

Light Water Reactor Sustainability Program

Extended Bandwidth Spread Spectrum Time Domain Reflectometry Cable Test for Thermal Aging, Low Resistance Fault, and Water Detection

September 2023

U.S. Department of Energy

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Extended Bandwidth Spread Spectrum Time Domain Reflectometry Cable Test for Thermal Aging, Low Resistance Fault, and Water Detection

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September 2023

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy

SUMMARY

In 2022, researchers at Pacific Northwest National Laboratory (PNNL) used the Accelerated and Real-Time Environmental Nodal Assessment (ARENA) cable and motor test bed to characterize spread spectrum time domain reflectometry (SSTDR) and compare the responses of an SSTDR instrument to those of a frequency domain reflectometry (FDR) instrument. Results showed both techniques could detect and locate cable anomalies such as phase-to-phase low resistance and shorts, thermal insulation damage, mechanical insulation damage, and the presence or absence of water in some conditions. The SSTDR tests used a commercial instrument provided by LiveWire Innovations Inc. This commercial instrument performed tests at 6, 12, 24, and 48 MHz bandwidth. The results of these tests were compared to FDR tests where bandwidths could be extended up to 1.3 GHz, although the best responses for cable tests were from 100 to 500 MHz. Lower bandwidth signals can propagate better along the cable while higher bandwidths have higher resolution for impedance change reflections allowing more precise indication of location and separation of anomalies. The 2022 research found that FDR responses were clearer than SSTDR and speculated that a higher bandwidth SSTDR could more successfully detect and locate cable anomalies. One advantage of the SSTDR system investigated was that it was designed for energized online use up to 1,000 volts, which may be a significant advantage for nuclear power plant use. The LiveWire SSTDR instrument is an established product in the rail and aircraft industry and updating the SSTDR hardware parameters is difficult to justify without more conclusive testing. Therefore, a software adjustable laboratory SSTDR instrument was developed by PNNL and was used to test extended bandwidth SSTDR cable tests. Within the ARENA test bed, 42 cable conditions were tested with the PNNL SSTDR, FDR, and the LiveWire SSTDR—each operating at four different bandwidths. Observations and conclusions regarding the relative performance of the three instruments over different bandwidths are note below.

Responses of the PNNL SSTDR (at 50 MHz) and the LiveWire SSTDR (at 48 MHz) were similar. The PNNL SSTDR higher frequency bandwidths behaved as expected showing sharper peaks and higher noise. This validated the PNNL SSTDR as a reasonable implementation of the SSTDR technology.

Lower bandwidth SSTDR responses (particularly 6 and 12 MHz) may have increased value for use within longer cables but were not particularly effective at identifying anomalous cable behavior in the 100 ft cables tested here. The higher bandwidths of the PNNL SSTDR (50, 100, 200, and 400 MHz) did not provide substantially clearer cable reflectometry responses, but having the higher frequency responses available did add to the cable test evaluation.

Strong responses to shorts and low impedance faults between phases were particularly evident in the higher bandwidth PNNL SSTDR and the FDR data.

Measurements were repeatable, with similar responses obtained from a thermally aged cable for tests taken a month apart.

Signal noise was affected in the unshielded cable by the local in-tray cable arrangement including proximity to metal edges and rungs of the cable tray. Foam isolation of the cable from the tray metal reduced in both FDR and SSTDR responses.

Cable condition monitoring in nuclear power plants will likely benefit from both more informative off-line testing methods and from the development of on-line methods for continuous monitoring of cables in use. The LWRS-funded ARENA test bed was a valuable resource for this development and direct comparison of nuclear electrical cable condition monitoring technologies. Test results are targeted to guide industry advancement of testing and monitoring tools for cable aging management.

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, for the Light Water Reactor Sustainability (LWRS) Program Materials Research Pathway. The authors extend their appreciation to Pathway Leads Dr. Xiang (Frank) Chen and Dr. Leo Fifield for LWRS programmatic support. This work was performed at the Pacific Northwest National Laboratory (PNNL). PNNL is operated by Battelle for the U.S. Department of Energy under contract DE-AC05-76RL01830. This constitutes a project deliverable milestone M3LW-23OR0404025. The program also acknowledges Livewire Innovation Inc. for supplying their commercial SSTDR cable test instrument and for their support throughout the program evolution.

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ACRONYMS

ARENA	Accelerated and Real-Time Environmental Nodal Assessment
AWG	Arbitrary Waveform Generator
BW	bandwidth
CPE	chlorinated polyethylene
dB	decibels = 20 $Log_{10}(V_{output}/V_{input})$
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
FDR	frequency domain reflectometry
LWRS	Light Water Reactor Sustainability Program
MHz	Megahertz
NDE	nondestructive evaluation
NPP	nuclear power plant
PN	pseudo-random noise
PNNL	Pacific Northwest National Laboratory
SSTDR	spread spectrum time domain reflectometry
V	time variant voltage response measured by the reflectometry instrument
Vmax	maximum voltage in the reflectometry response plot
VNA	vector network analyzer

FIGURES

TABLES

1. INTRODUCTION

Nearly 20 percent of the electricity produced in the United States comes from nuclear power plants (NPPs) (Joskow 2006), which were originally qualified for an operational lifetime of 40 years (Gazdzinski et al. 1996). A majority of U.S. NPPs have applied for and been granted 20-year extensions following the original license period. Within NPPs, electrical cables are susceptible to aging and degradation. These cables are commonly low and medium voltage and are critical infrastructure required for power, control, and instrumentation associated with safety and operational systems (Gazdzinski et al. 1996). These cables may be exposed to environmental stressors, such as elevated temperature, moisture, and gamma radiation. Such stressors can cause degradation and eventual failure of electrical cables, which may lead to loss of safety systems if not detected and managed (IAEA 2012). Continued use of NPP cables beyond the initial qualification period is justified by a comprehensive cable aging management program, which includes inspection and test of some or all safety related critical cables to assure the cables can perform under normal operation and under a design-basis event. Practically all utilities include some form of cable nondestructive examination (NDE) in their aging management program because performance testing to assure acceptable cable function is more cost effective than replacing all cables that exceed their qualified life. Utilities are continually working to improve test quality and reduce costs associated with their cable NDE programs, such as with the usage of online condition monitoring. However, online condition monitoring is burgeoning technology that has yet to be adopted by NPPs.

Reflectometry tests are nondestructive and can detect and locate NPP electrical cable anomalies. In principle, reflectometry tests inject a high frequency chirp wave onto the cable conductor end. If the wave encounters an impedance change, part of the energy is reflected back to the initiation point where it can be detected. Noise suppression techniques, such as processing the data in the frequency domain as with a frequency domain reflectometer (FDR) or a spread spectrum time domain reflectometer (SSTDR), suppress noise and allow interpretation of subtle, low level reflected signals. FDR tests typically produce the lowest noise and clearest signals but currently cannot be applied to live cable systems because FDR test instruments cannot withstand operating voltages. On the other hand, SSTDR technology has hardened circuitry that can test energized low voltage cables up to 1 kV and therefore is suitable for online condition monitoring of low voltage cables.

Previously, Pacific Northwest National Laboratory (PNNL) and LiveWire Innovation Inc. conducted work using PNNL's Accelerated and Real-Time Environmental Nodal Assessment (ARENA) cable and motor test bed (Glass, Fifield, and Prowant 2021) and LiveWire Innovation's commercial SSTDR instrument to evaluate commercial SSTDR cable test technology (Glass et al. 2022). The report concluded that:

- Both FDR and SSTDR were able to detect and locate cable anomalies, which included:
  (1) the presence of water for an undamaged non-shielded cable (but not for shielded cable),
  (2) thermal damage from a section of the cable passing through an oven heated to 140°C for 62 days.
  (3) phase-to-phase low resistance (312-Ω, 400-Ω, and 675-Ω) faults.
- FDR data taken at 100, 300, and 500 MHz bandwidth (BW) demonstrated remarkable peaks at the position corresponding to the water bath location and oven entry and exit for thermal aging along the cable.
- SSTDR data taken at 6, 12, 24, and 48 MHz also showed peaks for the cable entry to and exit from both the water bath and the thermal aging ovens but were not as clear as the FDR peaks.
- As the definition of BW varies between SSTDR and FDR, further evaluation of SSTDR data indicated that a higher BW SSTDR may yield clearer cable test results. In practice, having a broader range of frequencies for either SSTDR or FDR cable tests could improve the probability

of detection. While lower BWs propagate further distances along the cable, reflection resolution is improved with higher BWs. Making such a change to the selected commercial system was not warranted without further evaluation, and researchers realized that a laboratory instrument implementation of an SSTDR could support software adjustment of test BWs, windowing, and other signal processing methods to guide hardware and firmware changes to LiveWire's or other vendor's commercial instruments.

The PNNL SSTDR is a software controlled and laboratory-based instrument that was developed (under a separate contract) to allow extended BW plus a software adjustable windowing function and other subtle adjustments of the SSTDR algorithm. The PNNL SSTDR incorporates an arbitrary waveform generator (AWG) to produce a broad frequency pseudo-random noise (PN) code and a digitizing oscilloscope to capture the incident and reflected waveform. The captured signal is then processed using Python code to fully evaluate SSTDR measurements. A more detailed description of the PNNL SSTDR development is contained in (Glass et al. 2023).

This report is submitted in fulfillment of the deliverable for the Light Water Reactor Sustainability Program (LWRS) Milestone Report M4LW-23OR0404027 describing evaluation of the extended BW PNNL SSTDR instrument. The evaluation considered the lower BW commercial instrument, the software laboratory-based instrument PNNL SSTDR, and the more flexible FDR technique implemented with a Copper Mountain vector network analyzer (VNA) (Copper_Mountain 2020). This work is part of an overall effort to develop a technical basis for assessing cable insulation aging and degradation in NPPs. Previous related work has included:

- ARENA test bed development (Glass, Fifield, and Prowant 2021),
- Effect of thermal aging on cable inspection methods (Glass et al. 2022, Glass et al. 2021),
- Cable moisture detection (Glass et al. 2021), and
- Distributed cable assessment approaches (Glass et al. 2016).

2. FREQUENCY DOMAIN REFLECTOMETRY (FDR)

FDR is being used in NPPs particularly to locate areas of concern (AMS 2019). The FDR instrument—typically a VNA—is connected to two cable conductors, with one considered the primary conductor under test and the other considered as the system ground, as shown in (Figure 1), or to a parallel conductor within the cable bundle (Glass et al. 2017). The instrument directs a swept frequency chirp along the conductor and then listens for any reflection caused by an impedance change along the cable length. By listening and detecting reflections in the frequency domain then transforming to the time domain with an inverse Fourier transform (IFT), significant noise immunity and sensitivity to subtle impedance changes can be achieved. BW for FDR is software adjustable up to 1.3 GHz, but experience has shown that the best responses occur from 100 MHz to 500 MHz for cable anomaly detection. Higher BW FDRs produce sharper peaks capable of spatially resolving more closely spaced impedance changes, but higher frequencies do not propagate as far along the cable length. FDR instruments are restricted to relatively low voltages and currently cannot tolerate testing on energized cable systems.

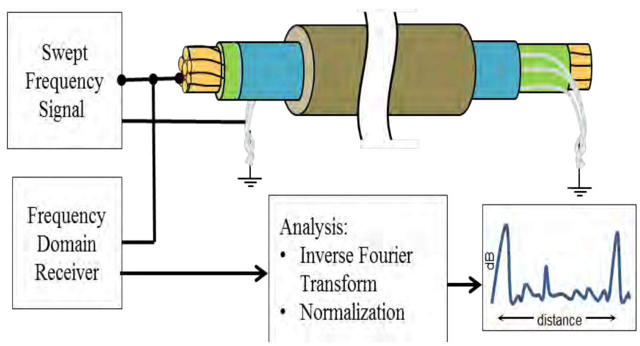


Figure 1. FDR cable test introduces a swept frequency chirp onto a conductor then listens for any reflection from any impedance change along the cable length. Listening is captured in the frequency domain then transformed to time domain using an IFT (Glass et al. 2017).

3. LIVEWIRE SSTDR

The LiveWire commercial SSTDR, as seen in Figure 2, produces similar distance-to-fault plots as FDR; however, all processing is in the time domain. A PN code is input onto the cable conductor, and the instrument listens for any reflected response from cable anomalies. Reflected signals are processed with an autocorrelation function that compares the input PN code to the reflected signals. The wiring in-line maintenance aid SSTDR instrument used in this work produced results with BWs of 6, 12, 24, and 48 MHz. In addition, the autocorrelation algorithm produced a robust noise tolerant signal response. However, results from the 2022 study (Glass et al. 2022) showed nosier data than FDR tests, which were hypothesized to indicate that higher BW SSTDR measurements could help with analysis and probability of detection. In addition, the commercial LiveWire system can be used for online measurements on systems up to 1,000 V.

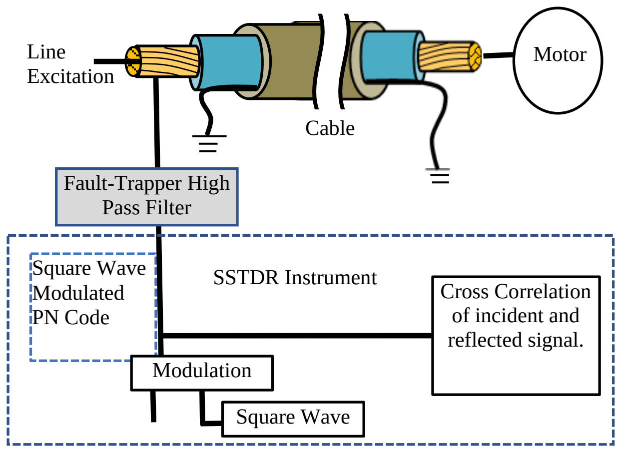


Figure 2. LiveWire SSTDR cable test applies PN code modulated with a square wave carrier frequency through a high pass filter to the conductor for cross correlation analysis to minimize noise and allow measurements on energized cable up to 1 kV.

4. PNNL SSTDR

PNNL developed a flexible laboratory-based SSTDR system to investigate SSTDR sensitivities to different cable impedance discontinuities at higher BWs (to 500 MHz) than were possible with the commercial LiveWire system. The PNNL SSTDR system consists of the components shown in the block diagram of Figure 3, and the physical configuration is shown in Figure 4. In the block diagram, the SSTDR signal is created by the AWG, which generates a voltage output at a specific sampling rate. The AWG provides the ability to create a time series waveform representative of an SSTDR signal. The AWG provides two outputs for a single waveform as a differential pair, the (+), or 0-degree waveform is used as the signal injected down the cable line, and the (−) or 180-degee waveform is used as a reference to correlate against the (+) signal as it is received. This method provides a phase and time synchronous copy of the SSTDR waveform to a Python code where the cross correlations analysis is performed. The correlation analysis produces a response between −1 and +1. In addition, similar to FDR, distance along the cable is estimated using velocity of propagation. A more complete description of the PNNL SSTDR system can be found in (Glass et al. 2023).

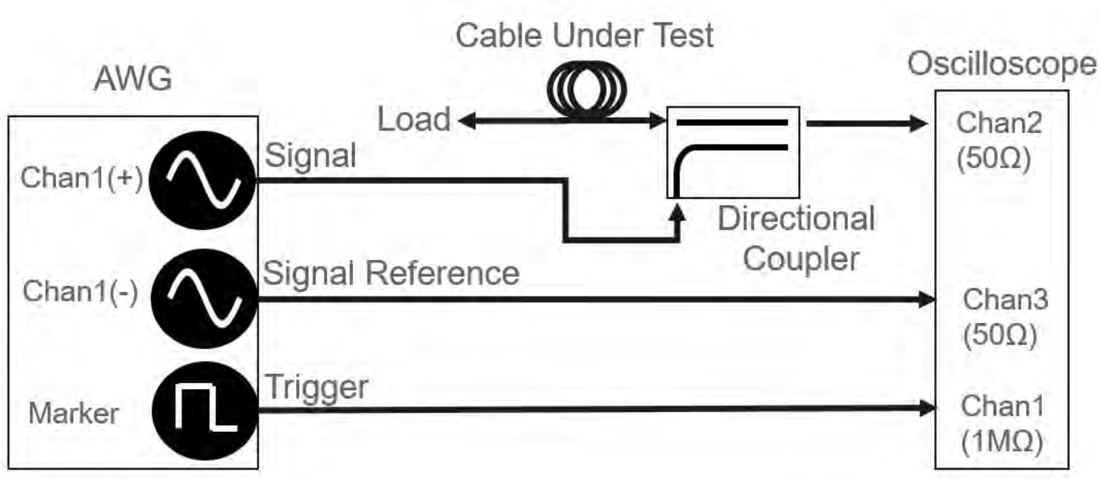


Figure 3. Block diagram of PNNL SSTDR System.

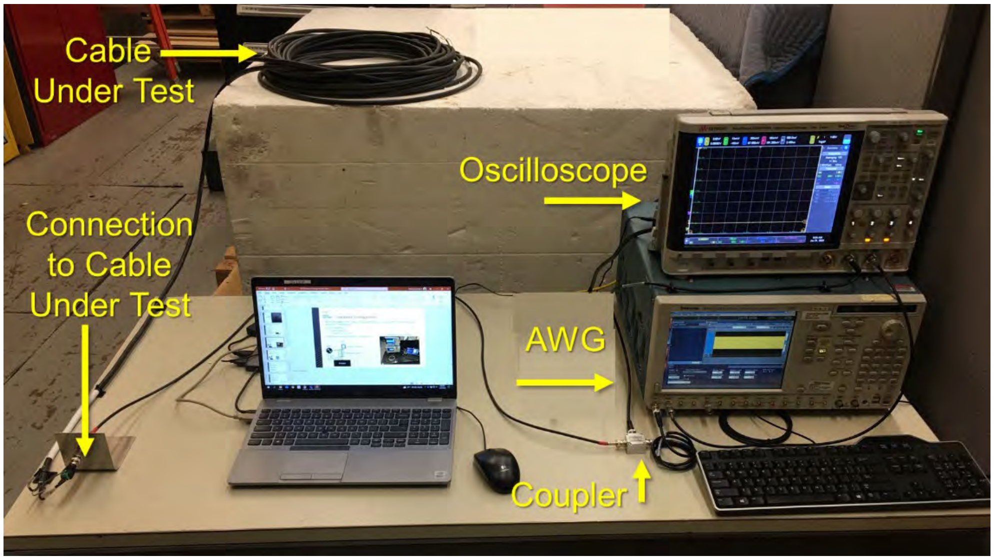


Figure 4. PNNL SSTDR hardware test configuration.

5. ARENA CABLE AND MOTOR TEST BED

To evaluate the degradation of electrical cables, particularly the interaction of electrical cable test technologies with various damage mechanisms, PNNL developed the ARENA test bed (Glass et al. 2023); see Figure 5. The vision behind creating this facility was to establish a modular test facility that allows for implementation of a broad range of test methods to detect faults and anomalies in a variety of cables and systems in a controlled environment. The test setup was similar for the 2022 work, and as much as possible, the test arrangement was repeated for this round of FDR and SSTDR cable tests.

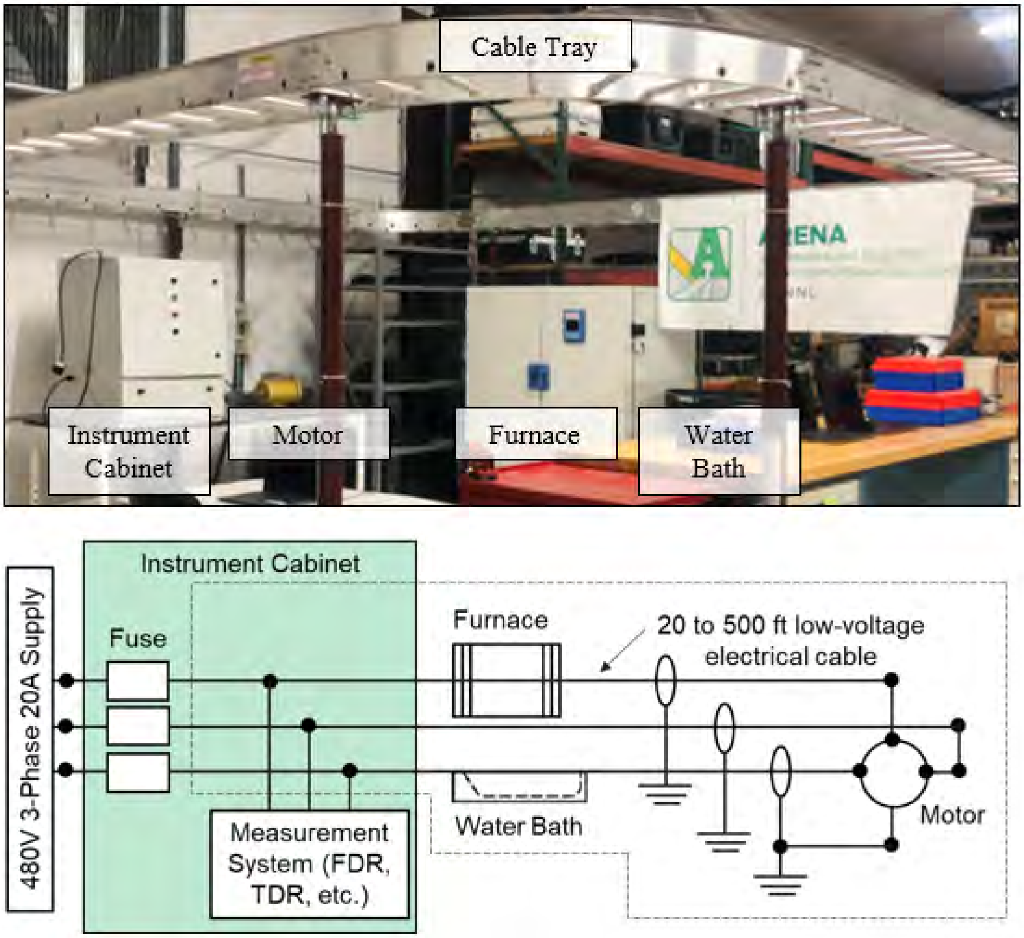


Figure 5. The ARENA test bed (top) digital image and (bottom) schematic (Glass et al. 2023).

6. TEST RESULTS

6.1 Initial Test Matrix Results

To evaluate the efficacy of the PNNL SSTDR with extended frequency BWs, cables were tested in the ARENA cable and motor test bed. Evaluated cables were low voltage, tri-core, shielded, and non-shielded cables manufactured by General Cable® (Catalog number 383830). The overall specifications for the selected cables are given in Table 1. Both shielded and non-shielded cable variants consisted of three 14 AWG conductor wires insulated by ethylene-propylene rubber (EPR) and protected by a chlorinated polyethylene (CPE) jacket. Additionally, the shielded cable contains an aluminum foil shield layer between the jacket and insulated wires. The cables have a voltage rating of 600 V and an operating temperature rating of 90°C. All FDR and SSTDR tests were performed on cables of around 100 ft length.

Table 1. Manufacturer information for the cables selected for evaluation.

Manufacturer	P/N	Jacket	Insulation	Type
General Cable	354800	CPE	EPR	Shielded
6-903-SH 14AWG-3/C FR-EP 600V FR-EPR/CPE Foil Shielded 600V E-2				
General Cable	383830	CPE	EPR	Non-Shielded
6-903-G 14AWG-3/C FR-EP 600V FR-EPR/CPE Non-Shielded 600V E-2				

Tests were conducted using (1) an undamaged cable with open, short, 100 ohm, 312 ohm, and 2k ohm terminations at the distal cable ends, (2) thermally aged cable, which entered and exited an oven at 45 to 75 ft, (3) phase-phase and phase-shield low resistance faults at 26 ft, and (4) water immersion in a water bath from 61 to 67 ft. A total of 42 test conditions were evaluated and example plots are shown in Figures 6, 7, 8, 9, 10, 11, 13, 14, 15, and 17. The full dataset is shown in the appendices and results are plotted both as a linear amplitude (see Appendix 1) and in decibels (dB) (see Appendix 2). In addition, results were normalized since the BW and window functions can significantly influence amplitude responses and relative responses are more relevant for practical cable diagnostics. Normalization is also helpful for comparing results from different instruments. The normalization process incorporated was as follows:

1. Window the data from 0 feet to the full cable length based on the cable end peak at the approximate correct distance from the signal injection end. The cables under test were, for the most part, approximately 100 ft in length with a 25 ft test lead bringing the total cable test length to 125 ft.

2. The full reflectometry plot was scaled such that the maximum cable reflectometry peak was set at 0 dB. Typically, this was the first peak corresponding to the test lead, but it could also be a strong anomaly response in the center of the cable or the cable end response. The data normalization was expressed as dB by the equation below:

   $$dB = 20 \, Log_{10} (V/Vmax)$$

   where V = reflected voltage magnitude as a function of time and distance along the cable. Thus, if $V = Vmax$, then dB = 0. If $V = 0.5 * Vmax$, then dB = -6.

3. The normalized reflectometry response in arbitrary units are simply $V/Vmax$ and are scaled between 0 and 1.

Data can be viewed in either dB or magnitude arbitrary units, and each display has its own advantages. The dB response compresses the full dataset and allows some visibility of the lower-level changes between the responses from the two cable ends but still allows viewing the cable end response. The magnitude plots can show more subtle responses but may require the higher peaks associated with the cable ends to be truncated. An example of this is shown in Figure 6 and Figure 7.

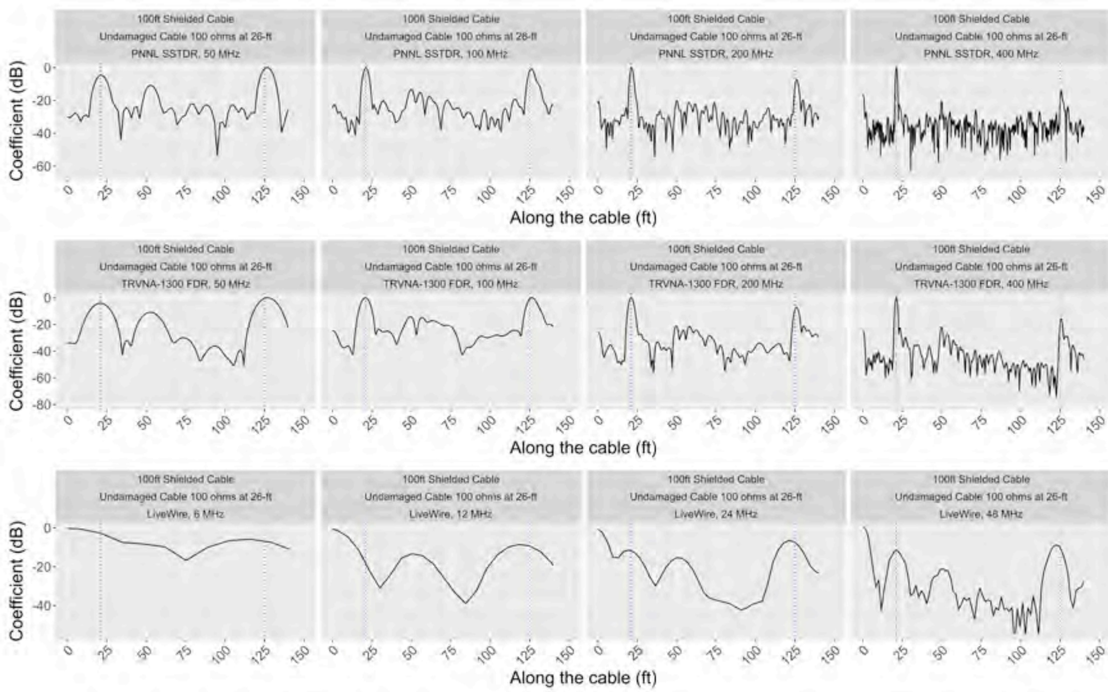


Figure 6. dB response for 100 ft shielded and undamaged cable with 100 ohms at 26 ft (shown as approximately 50 ft on plot due to test lead). The blue vertical line marks the beginning of the cable after the test lead and the peak corresponding to the cable end.

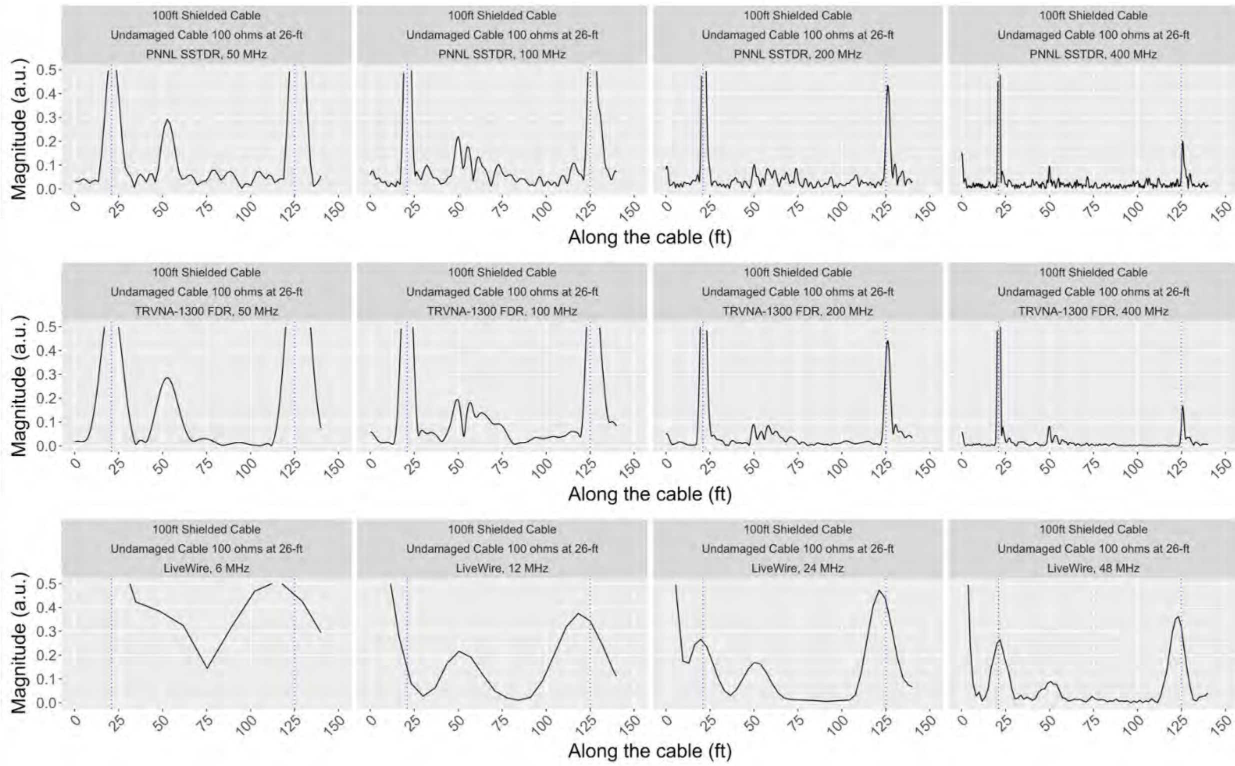


Figure 7. Magnitude response for 100 ft shielded and undamaged cable with 100 ohms at 26 ft (shown as approximately 50 ft on plot due to test lead).

6.2 LiveWire SSTDR @ 48MHz BW vs. PNNL SSTDR 50MHz BW

Following development of the PNNL SSTDR, one of the first questions was how it compared to the commercial LiveWire SSTDR instrument. The 50 MHz BW selection for the PNNL SSTDR was expected to be close to the LiveWire SSTDR results at 48 MHz BW. An overlayed plot of these BWs from the two instruments are shown for an undamaged cable (Figure 8) and for a 100 *Ω fault* at 26 ft (Figure 9). The cable end and fault peaks were of similar width and the relative amplitudes were comparable between the instruments. The offset in the cable end location stems from differences in the velocity of propagation calibration and was not of concern for this study. This was interpreted as good agreement between measurements from the two instruments.

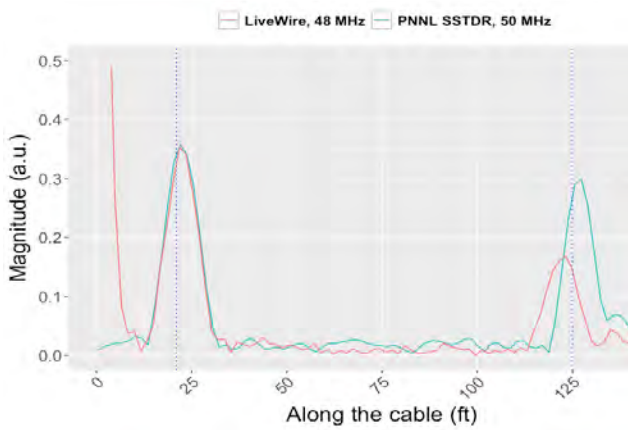


Figure 8. Undamaged cable plot from LiveWire @ 48 MHz and PNNL SSTDR @ 50 MHz BW.

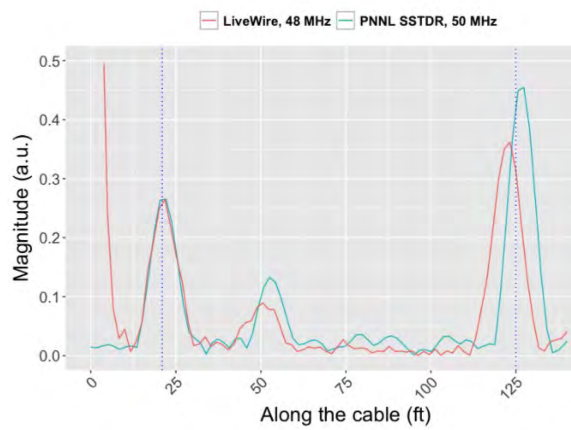


Figure 9. 100 Ω fault at 26-ft from LiveWire @ 48MHz and PNNL SSTDR @ 50MHz BW.

6.3 Retest of Thermal Aging Comparison to Initial Test Round

There was some concern that the indications from the 60 day thermally aged cable were not as obvious as had been previously observed. There was also an interest to repeat earlier measurements to check for measurement repeatability after a period of time. The thermally aged cable was still in place from tests performed a month earlier, so the tests were repeated. Responses are shown in Figure 10 and Figure 11. The two test conditions (measurement 1 and measurement 2) were essentially the same except that they were separated by more than one month. The largest differences were noted in the LiveWire SSTDR response, but overall, the measurements were remarkably similar. Much of the plots are separated by a line width or less.

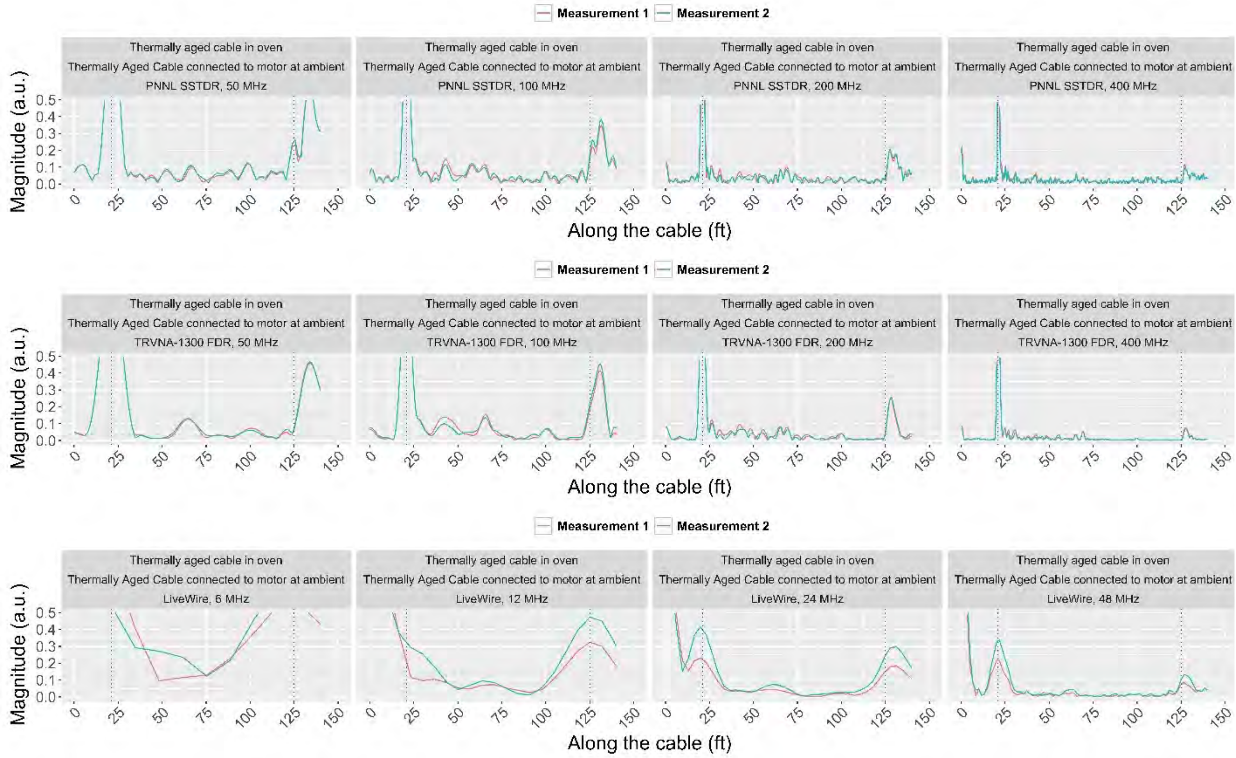


Figure 10. Measurement repeatability tests separated by one month; thermally aged cable in oven connected to motor at ambient temperature.

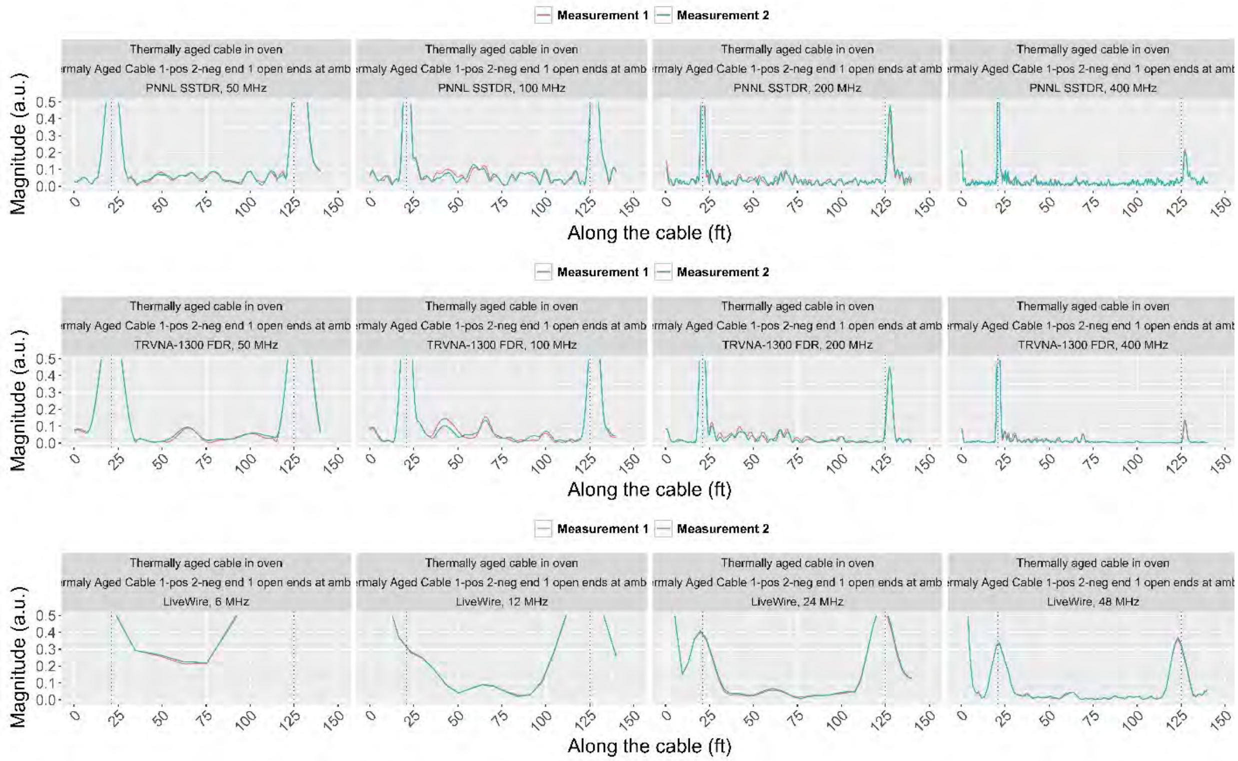


Figure 11. Measurement repeatability tests separated by one month; thermally aged cable in oven open ends at ambient temperature.

6.4 Metal Proximity Unexpected Indication

We were perplexed at a persistent indication at an apparently undamaged cable location that was similar in magnitude to the subtle oven entry and exit indications with unshielded cable particularly in the 100 MHz FDR plot. Careful examination of the location of the cable within the steel cable tray showed that the cable was quite close to or touching the cable tray sides, and FDR responses were also known to respond to proximity to metal like the metal rungs of the cable tray. To eliminate potential influence from the steel cable tray, the tray was lined with foam and the cable was spaced away from the tray sides (Figure 13). This significantly reduced the unexplained indication at 40 ft in the FDR responses (Figure 13). This was clearly observed for the 100 MHz FDR data and to a lesser extent in the 200 and 400 MHz FDR data and the 100 and 200 MHz PNNL SSTDR data.

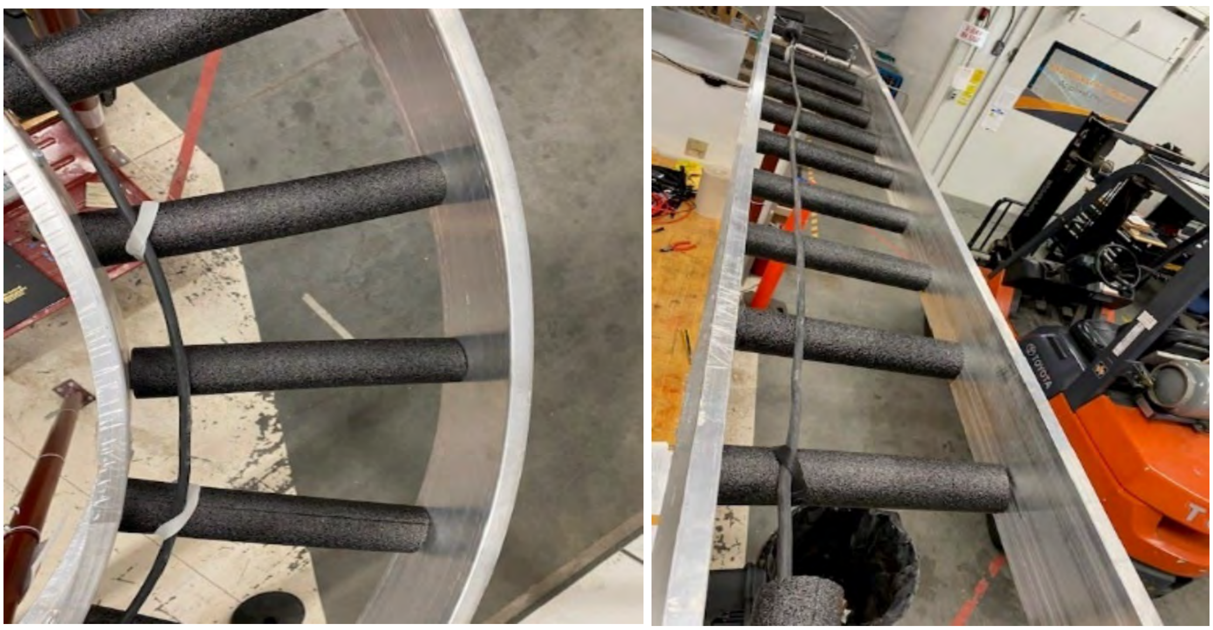


Figure 12. Unshielded cable resting on foam and separated from steel cable tray.

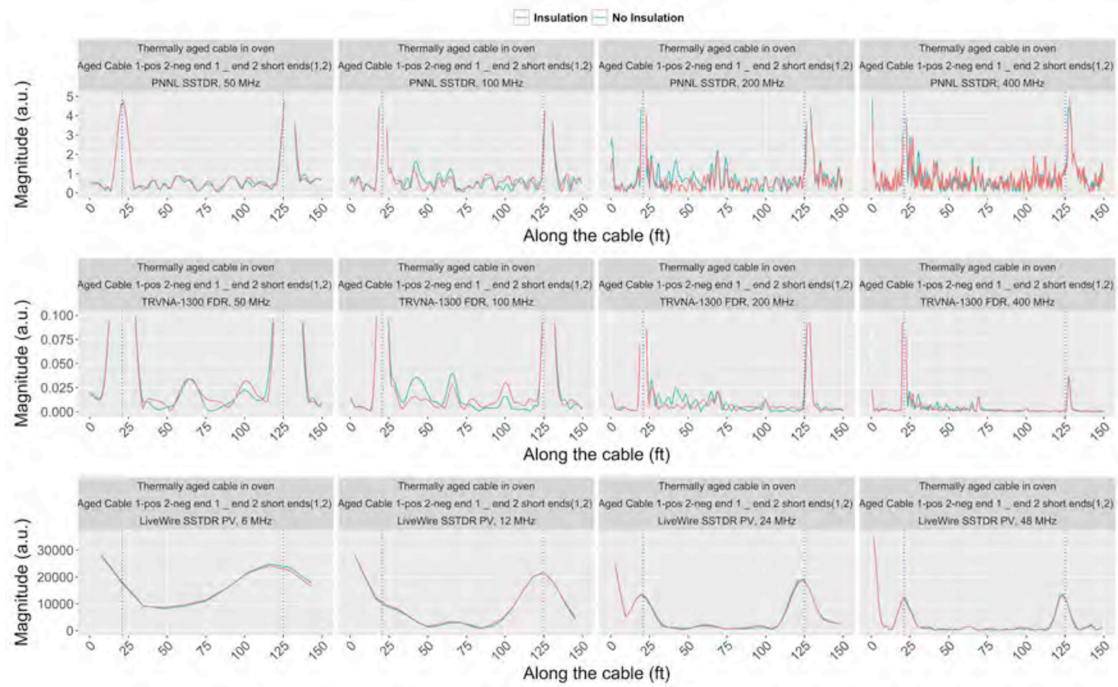


Figure 13. Overlayed reflectometry plot with and without foam insulation between cable and cable rack. Note reduced peak amplitude at 40 ft, particularly for 100 and 200 MHz BW plots with foam insulation. Entry and exit from the oven at 60 and 100 ft are observed clearly on the FDR plots at 50 and 100MHz and to a lesser degree only on FDR 200 and 400 MHz and perhaps (mostly for oven entry) for PNNL SSTDR @ 50 and 100 MHz.

6.5 Phase-to-Phase Faults

Phase-to-phase faults were detected to varying degrees depending on the instrument and BW. Responses to 100, 312, and 2k ohms at 26 ft are shown in Figure 7, Figure 14, and Figure 15. Generally, the higher frequency PNNL SSTDR and FDR plots showed responses most clearly. The 100 ohm fault was seen by FDR, PNNL SSTDR, and LiveWire, but LiveWire did not detect the 312 ohm or 2k ohm faults. This seemed to be a case where the higher PNNL SSTDR BW improved detection.

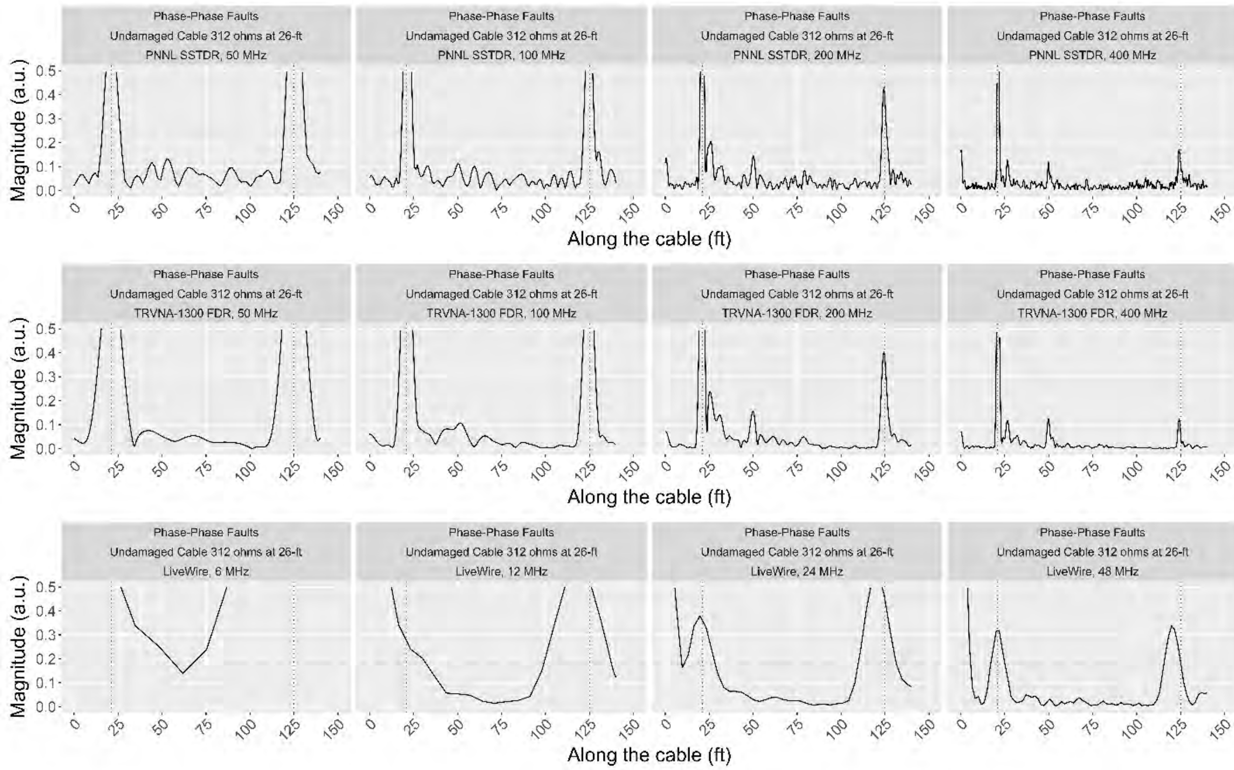


Figure 14. Magnitude response for 100 ft cable with 312 ohm fault at 26 ft (26 ft on cable, 50 ft on plot due to test lead).

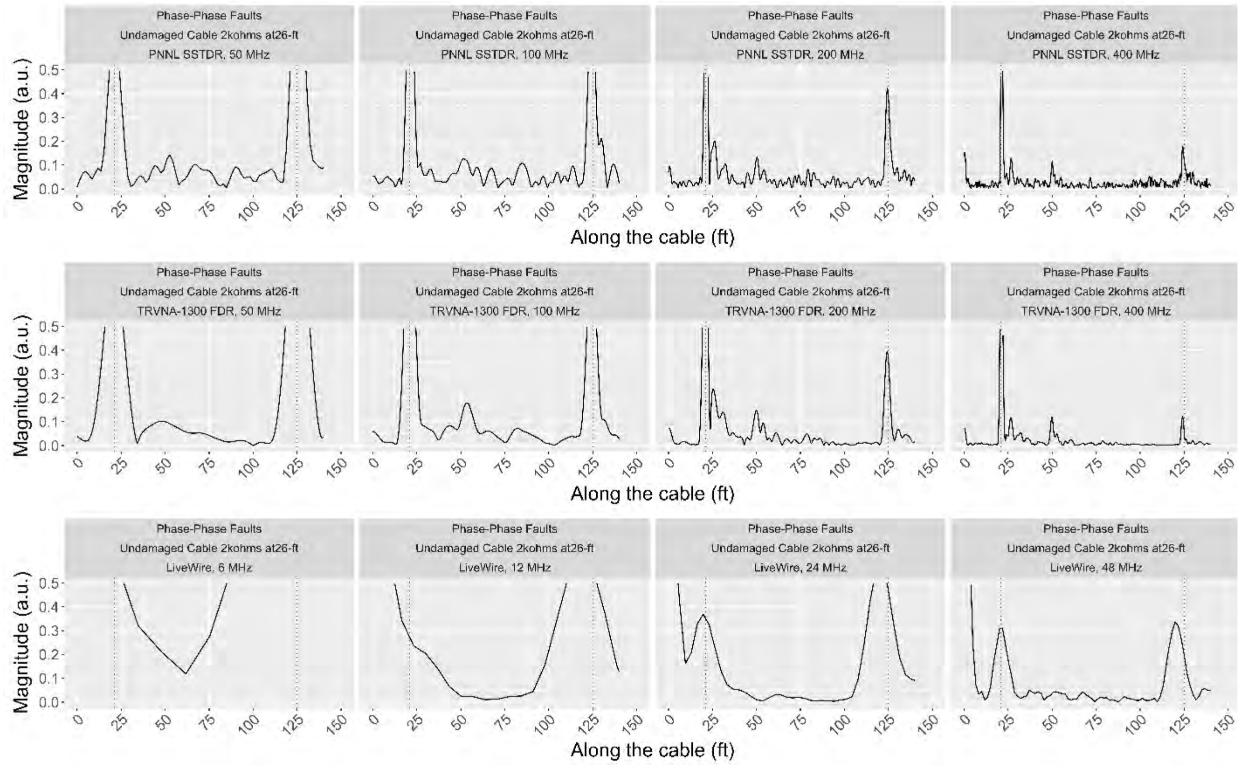


Figure 15. Magnitude response for 100 ft cable with 2k ohm fault at 26 ft (26 ft on cable, 50 ft on plot due to test lead).

6.6 Water Detection with an Unshielded Cable

The submerged section of the unshielded cable in the ARENA water bath at 60 ft along the cable (Figure 16) can be seen in Figure 17 as a single peak in the 50 and 100 MHz FDR and the 48/50 MHz SSTDR responses. The PNNL SSTDR 100, 200, and 400 MHz BW have peaks that seem to correlate with the cable entry and exit from the water bath, but the surrounding noise makes this hard to confirm with certainty. As expected, there were no peaks observed in the shielded cable passing through the water bath.

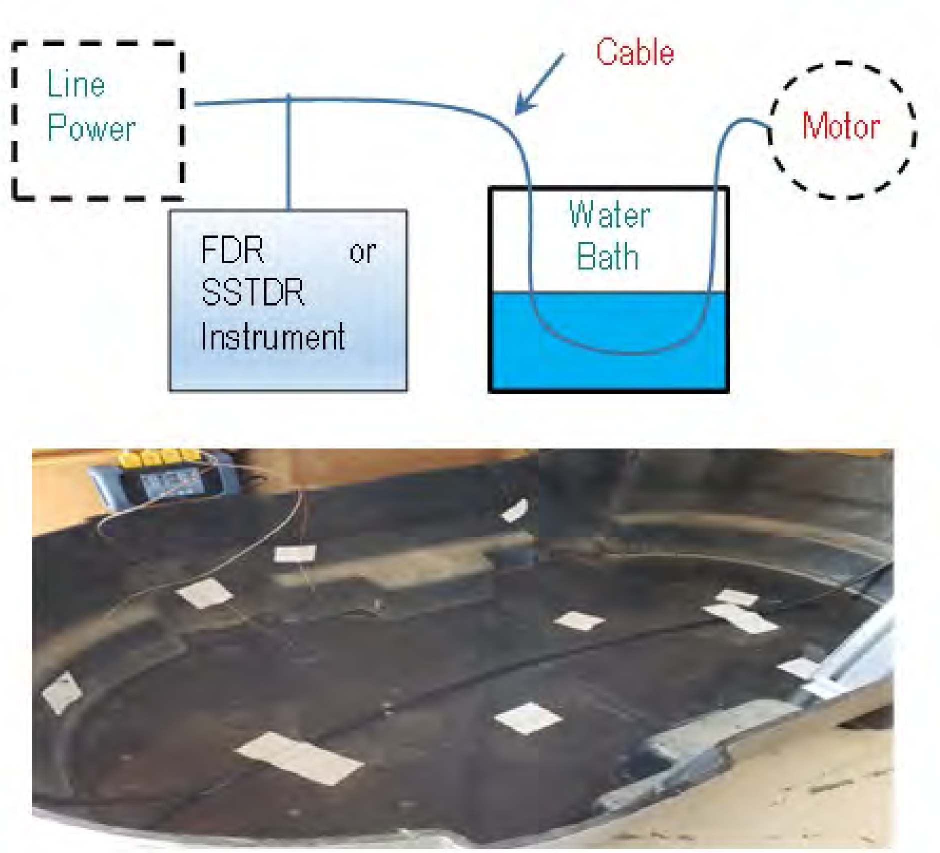


Figure 16. Water bath test configuration shown connected to live power (above) and photographed in cable in the water bath (below). Tests shown in this report did not have the cable energized but this has been shown in earlier reports.

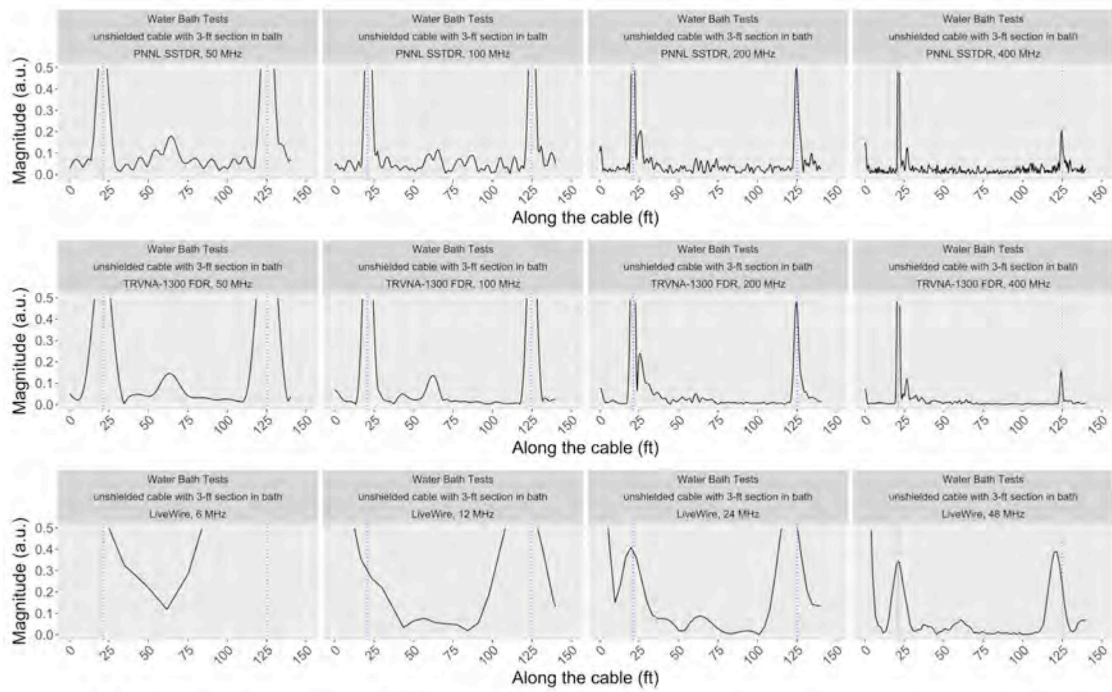


Figure 17. Water bath tests, unshielded cable with 3 ft section in bath.

6.7 Subjective Anomaly Detection Ability among Reflectometry Techniques

Interpretation of cable reflectometry plots is complicated. As shown in the examples above, some techniques and frequencies produce clear detection of some types of flaws, but the relative responses vary based on the nature of the flaw, the technique, and the BW. The test matrix was subjectively evaluated according to guidelines of Table 2, and results are shown in Table 3.

Table 2. Subjective evaluation guidelines for reflectometry measurement data.

Condition assessed for FDR/BW, LiveWire SSTDR/BW, PNNL SSTDR/BW	Value/Color
Undamaged cable – Ends visible; no anomalous peaks	1
Undamaged cable –Ends visible; unexplained peaks observed	0
Undamaged cable – Ends not visible; reflectometry response not apparent	−1
Anomalous cable – Ends visible and damage response clearly visible	1
Anomalous cable – Ends visible and damage response weakly or possibly visible	0
Anomalous cable – Ends visible but no clear anomalous response noted	0
Anomalous cable – Ends not visible and no anomalous damage response noted	−1

Table 3. Test matrix and subjective evaluation of magnitude reflectometry plots for 42 test cases.

	Key: Green conditions are for undamaged cable	PNNL SSTDR				FDR				LiveWire			
	Key: Yellow conditions are for anomalous cable condition	50	100	200	400	50	100	200	400	6	12	24	48
#	Test condition												
1	100ft Shielded Cable, 100 ohm phase - shield at distal end	1	1	1	1	1	1	1	1	-1	-1	1	1
2	100ft Shielded Cable, 2k ohm phase - shield at distal end	1	1	1	1	1	1	1	1	-1	0	1	1
3	100ft Shielded Cable, 312 ohm phase - shield at distal end	1	1	1	1	1	1	1	1	-1	-1	1	1
4	100ft Shielded Cable, Undamaged Cable (short distal end)	1	1	1	1	1	1	1	1	-1	1	1	1
5	100ft Shielded Cable, Short phase-shield at distal end	1	1	1	0	1	1	1	1	-1	1	1	1
6	100ft Shielded Cable, Undamaged Cable (short distal end)	1	1	1	1	1	1	1	1	-1	0	1	1
7	100ft Shielded Cable, Undamaged Cable 100 ohms at 26-ft	1	1	0	1	1	1	0	1	-1	1	1	1
8	100ft Shielded Cable, Undamaged Cable 2kohms at 26-ft	1	1	1	1	1	1	1	1	-1	-1	1	1
9	100ft Shielded Cable, Undamaged Cable 2kohms at distal end	1	1	1	1	1	1	1	1	-1	1	1	1
10	100ft Shielded Cable, Undamaged Cable 312 ohms at 26-ft	1	1	1	1	1	1	0	1	-1	1	1	1
11	100ft Shielded Cable, Undamaged Cable 312 ohms at distal end	1	1	1	1	1	1	1	1	-1	1	1	1
12	100ft Shielded Cable, Undamaged Cable connected to motor	1	1	1	1	1	1	1	1	-1	1	1	1
13	100ft Shielded Cable, Undamaged Cable short at 26-ft	0	0	0	0	0	0	0	0	-1	-1	0	0
14	Additional Testing, cable wirenut splices	0	0	0	0	0	0	0	0	-1	0	0	0
15	100ft Shielded Cable, 100 ohm phase - shield at distal end	1	1	1	1	1	1	1	1	-1	1	1	1
16	Phase-Phase Faults, Undamaged Cable 100 ohm at distal end	1	1	1	1	1	1	1	1	1	1	1	1
17	Phase-Phase Faults, Undamaged Cable 100 ohms at 26-ft	-1	-1	1	1	-1	1	1	1	-1	-1	-1	-1
18	Phase-Phase Faults, Undamaged Cable 2kohms at distal end	1	1	-1	-1	1	1	1	1	-1	-1	-1	1
19	Phase-Phase Faults, Undamaged Cable 2kohms at26-ft	1	1	1	-1	0	1	1	1	-1	-1	0	1
20	Phase-Phase Faults, Undamaged Cable 312 ohms at 26-ft	-1	-1	1	1	-1	1	1	1	-1	-1	-1	-1
21	Phase-Phase Faults, Undamaged Cable 312 ohms at distal end	1	1	-1	-1	1	0	0	0	-1	1	1	1
22	Phase-Phase Faults, Undamaged Cable connected to motor	1	1	1	1	1	1	1	1	-1	1	1	1
23	Phase-Phase Faults, Undamaged Cable short at 26-ft	1	1	1	1	1	1	1	1	-1	1	1	1
24	Thermally aged cable in oven, Good Undmgd Cable 1-pos 2-neg end1 open ends	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
25	Thermally aged cable in oven, Good Undmgd Cable 1-pos 2-neg end2 open ends	0	0	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
26	Thermally aged cable in oven, Good Undmgd Cable 2-pos 3-neg end1 open ends	1	1	-1	-1	0	0	-1	-1	-1	-1	-1	-1
27	Thermally aged cable in oven, Good Undmgd Cable 2-pos 3-neg end2 open ends	-1	0	-1	-1	-1	1	0	-1	-1	-1	-1	0
28	Thermally aged cable in oven, Good Undmgd Cable 3-pos 1-neg end1 open ends	1	1	-1	-1	0	0	-1	-1	-1	-1	-1	-1
29	Thermally aged cable in oven, Good Undmgd Cable 3-pos 1-neg end2 open ends	-1	0	-1	-1	-1	1	-1	-1	-1	-1	-1	0
30	Thermally aged cable in oven, Good Undmgd Shielded Cable 1-pos 2-neg end1 open ends	0	-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1
31	Thermally aged cable in oven, Good Undmgd Shielded Cable 1-pos 2-neg end2 open ends	0	0	-1	-1	0	0	-1	-1	-1	-1	-1	-1
32	Thermally aged cable in oven, Good Undmgd Shielded Cable 2-pos 3-neg end1 open ends	0	-1	-1	-1	0	0	-1	-1	-1	-1	-1	-1
33	Thermally aged cable in oven, Good Undmgd Shielded Cable 2-pos 3-neg end2 open ends	0	0	-1	-1	1	-1	-1	-1	-1	-1	-1	-1
34	Thermally aged cable in oven, Good Undmgd Shielded Cable 3-pos 1-neg end1 open ends	0	-1	-1	-1	0	0	-1	-1	-1	-1	-1	-1
35	Thermally aged cable in oven, Good Undmgd Shielded Cable 3-pos 1-neg end2 open ends	0	0	-1	-1	1	0	-1	-1	-1	-1	-1	-1
36	Thermally aged cable in oven, Thermally Aged Cable short ends(1,2) at ambient	-1	0	0	-1	1	1	1	-1	-1	-1	-1	1
37	Thermally aged cable in oven, Thermally Aged Cable connected to motor at ambient	-1	1	0	-1	1	1	0	-1	-1	-1	-1	-1
38	Thermally aged cable in oven, Thermaly Aged Cable 1-pos 2-neg end 1 open ends at ambiant	-1	0	0	1	1	1	0	-1	-1	1	1	1
39	Water Bath Tests, shielded cable with 3-ft section in bath	-1	-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1
40	Water Bath Tests, shielded cable with 3-ft section out of bath	1	1	1	1	1	1	1	1	-1	1	1	1
41	Water Bath Tests, unshielded cable with 3-ft section in bath	1	1	-1	-1	1	1	-1	-1	-1	-1	1	1
42	Water Bath Tests, unshielded cable with 3-ft section out of bath	1	1	1	1	1	1	1	-1	-1	0	1	1
	Relative ranking sum by bandwidth	17	17	16	14	16	20	18	20	-21	4	14	17
	Relative ranking sum by measurement system	**64**				**74**				14			

The subjective ranking of the three techniques and their respective BWs are shown in the bottom row of the table summing the columns for each frequency BW. This is recognized only as a figure of merit but does serve to capture and compare all instruments and their available BW data. These totals are shown visually in Figure 18. As expected, scores were highest for FDR and were similar for the PNNL 50 MHz and LiveWire 48 MHz BWs. Scores for the lower frequency LiveWire SSTDR (6 and 12 MHz) and the higher frequency PNNL SSTDR (400 MHz) were lower.

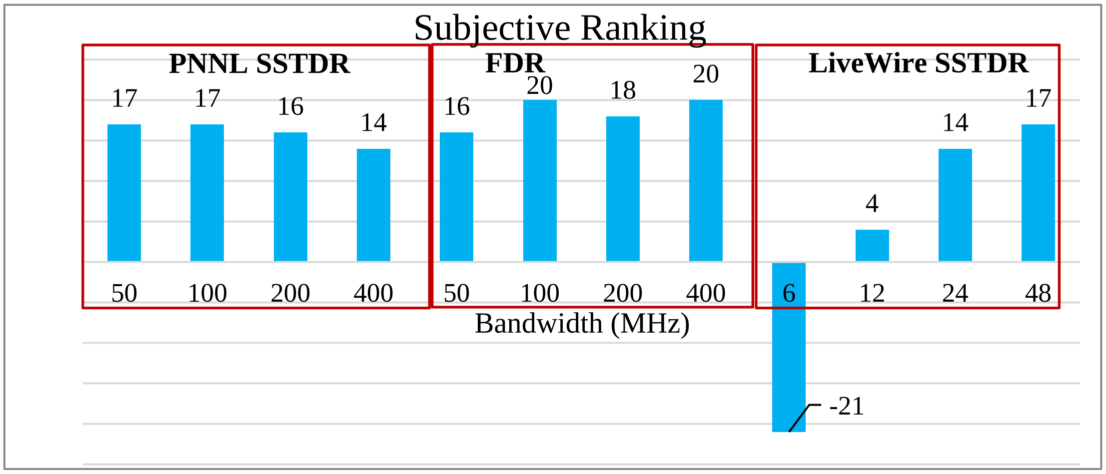


Figure 18. Subjective ranking of instruments and BWs to detect damaged and undamaged reflectometry results.

7. OBSERVATIONS

The objective of this work was to evaluate the PNNL SSTDR against FDR and the LiveWire commercial SSTDR. Although the PNNL SSTDR system used a laboratory AWG and oscilloscope rather than the dedicated instrument manufactured by LiveWire, the PNNL SSTDR was designed to perform a similar SSTDR reflectometry measurement at higher BWs than were possible with the commercial instrument. Observations and conclusions were as follows.

1. Higher BWs show stronger responses to shorts and low impedance faults between phases relative to lower BWs. This appears in all three instruments but is particularly evident in higher BW PNNL SSTDRs and FDRs.
2. The responses of the PNNL SSTDR focused at 50 MHz and the LiveWire 48 MHz BW damaged and undamaged cables were similar.
3. Measurements of the same condition are quite similar. For repeat measurements of the thermally aged samples separated by 1 month, most of the reflectometry measurement was separated by a line width or less.
4. Adding foam and separating the unshielded cable in the cable tray reduced unexplained noise peaks that initially confused detection of the target anomalies.
5. FDR responses seem clearer and generally provide better information than either the lower frequency LiveWire SSTDR or the higher frequency SSTDR.
6. The lower frequency LiveWire results, particularly the 6 and 12 MHz BWs, were not particularly helpful to identify anomalous cable behavior compared to the higher BW alternatives. These lower frequency measurements may be more helpful for longer cables or as indicated in some of the literature for assessing a long array of solar panels. These tests focused on shorter (100 ft) cables as may be used in NPPs.
7. The PNNL 100, 200, and 400 MHz BWs did seem to provide additional information to support anomaly detection, but these higher frequencies as stand-alone tests were not more effective than the LiveWire 48 MHz BW test.

8. CONCLUSIONS

In prior work the PNNL ARENA cable and motor test bed (PNNL 2022) was used to compare the responses of a commercial LiveWire SSTDR instrument and a laboratory FDR instrument in detecting cable shorts, presence of water, and local cable regions of thermal and mechanical damage (Glass et al. 2022). The LiveWire SSTDR can record data at 6, 12, 24, and 48 MHz bandwidth settings for both an unenergized and an energized cable powering a motor. The FDR test could be performed with the cable still connected to the motor, but the cable had to be disconnected from its power source and powered down. The FDR assembly used was capable of bandwidths up to 1.3GHz but the best cable test responses were from 100 to 500 MHz.

The present work evaluated a PNNL-developed SSTDR capability that could extend the SSTDR bandwidth to higher frequencies using software-controlled laboratory instruments. The software adjustable PNNL SSTDR produced similar cable anomaly detection at the lower bandwidths available to the commercial LiveWire SSTDR. Responses to cable shorts and low impedance faults between phases were particularly evident at the higher bandwidths available to the FDR and the PNNL SSTDR. The higher frequency bandwidths of the PNNL SSTDR did not provide substantially clearer test data but did seem valuable for cable tests when considered with the lower frequencies of the commercial instrument. The FDR appeared to provide clearer responses than either of the SSTDR options but remains limited at this time for use with unenergized cables.

Cable condition monitoring in nuclear power plants will likely benefit from both more informative off-line testing methods and from the development of on-line methods for continuous monitoring of cables in use. The LWRS-funded ARENA test bed was a valuable resource for this development and direct comparison of nuclear electrical cable condition monitoring technologies. Test results are targeted to guide industry advancement of testing and monitoring tools for cable aging management.

9. REFERENCES

AMS, Analysis and Measurement Services. 2019. "Innovating New Technologies." AMS. https://www.ams-corp.com/ams-fdr-testing-helps-nuclear-plant-avoid-costly-cable-replacement/.

Copper_Mountain. 2020. "TR1300/1 2-Port 1.3 GHz Analyzer." accessed 08/29/2022. https://coppermountaintech.com/vna/tr1300-1-2-port-1-3-ghz-analyzer/.

Gazdzinski, R.F, W.M. Denny, G.J. Toman, and R.T. Butwin. 1996. SAND96-0344 Aging Management Guidline Fior Commercial Nuclear Power Plants - Electrical Cable and Terminations

Glass, S W, A M Jones, L S Fifield, and T S Hartman. 2016. Distributed Electrical Cable Non-Destructive Examination Methods for Nuclear Power Plant Cable Aging Management Programs. Pacific Northwest National Laboratory, Richland, WA

Glass, S W, A M Jones, L S Fifield, T S Hartman, and N Bowler. 2017. Physics-Based Modeling of Cable Insulation Conditions for Frequency Domain Reflectometry (FDR). PNNL-26493, Pacific Northwest National Laboratory, Richland, Washington

Glass, S W;, M.P.; Spencer, L S; Fifield, A; Sriraman, and M S Prowant. 2021. PNNL-31934 Nondestructive Evaluation (NDE) of Cable Moisture Exposure usingFrequency Domain Reflectometry (FDR).

Glass, S.W., L S. Fifield, and M Prowant. 2021. PNNL 31415 PNNL ARENA Cable Motor Test Bed Update.

Glass, S.W., A. Sriraman, M. Prowant, M.P Spencer, L.S. Fifield, and S. Kingston. 2022. PNNL-33334 Nondestructive Evaluation (NDE) of Cable Anomalies using Frequency Domain Reflectometry (FDR) and Spread Spectrum Time Domain Reflectometry (SSTDR).

Glass, S.W., J R Tedeschi, M.P.; Spencer, J. Son, M. Elen, and L.S. Fifield. 2023. PNNL-34511 Laboratory Instrument Software Controlled Spread Spectrum Time Domain Reflectometry for Electrical Cable Testing. Richland Washington

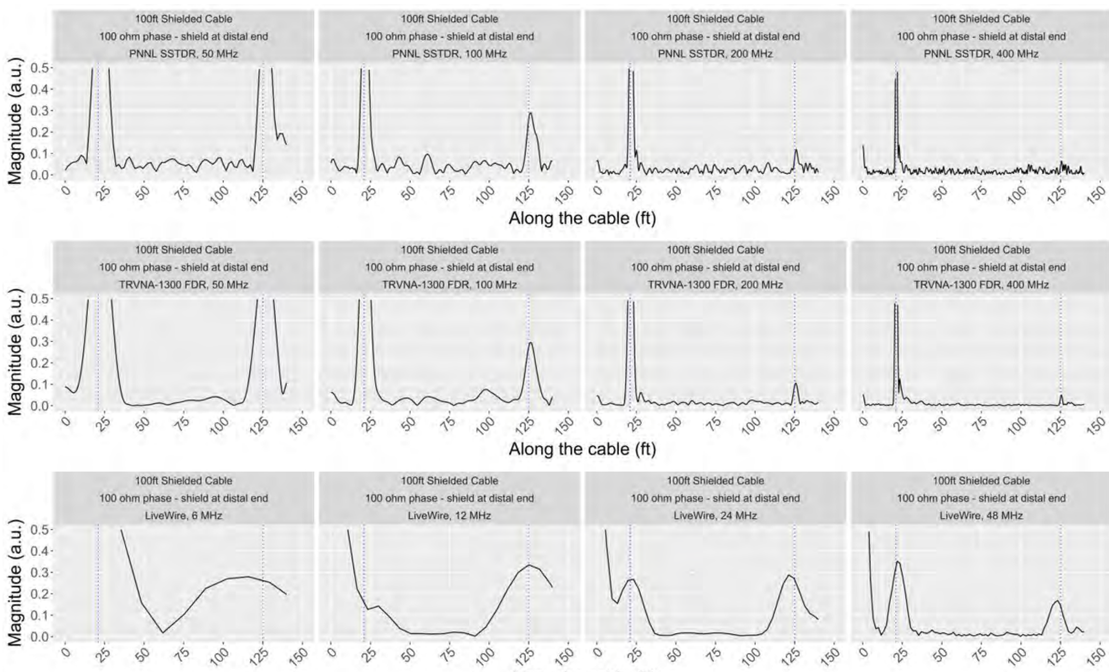
IAEA. 2012. Assessing and Managing Cable Ageing in Nuclear Power Plants. International Atomic Energy Agency (IAEA), Vienna

Joskow, P.L. 2006. The Future of Nuclear Power in the United States: Economic and Regulatory Challenges.

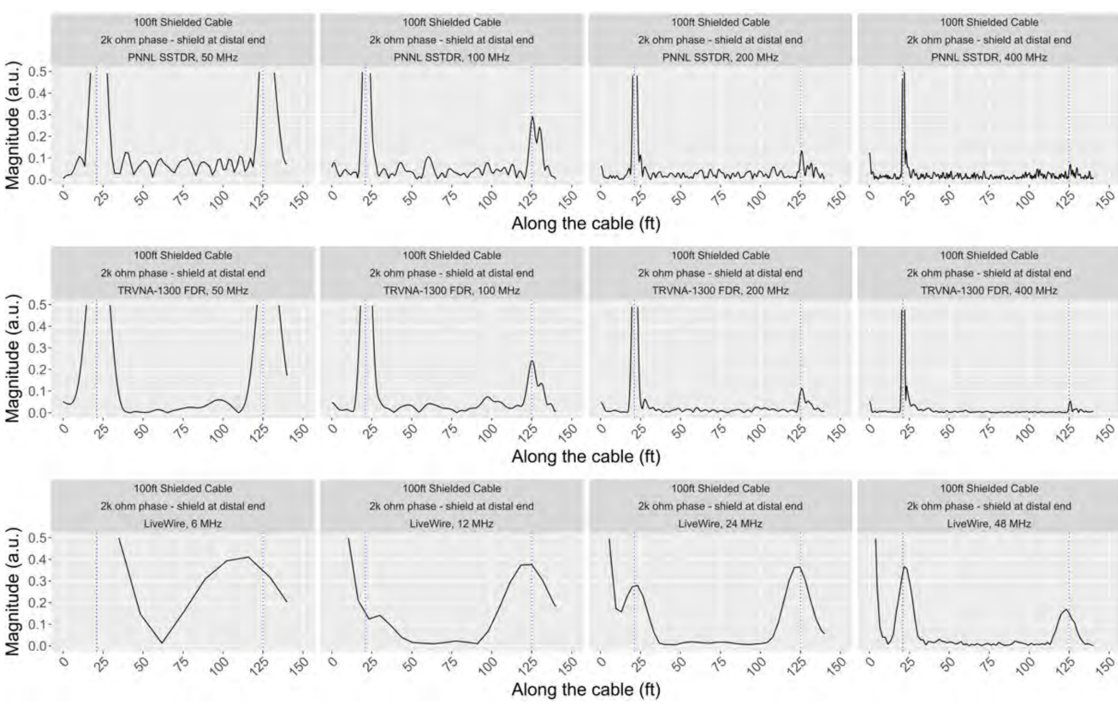
PNNL. 2022. "Accelerated Real-Time Environmental Nodal Assessment (ARENA) Test Bed" accessed 09192023. https://www.pnnl.gov/arena

Appendix 1: Magnitude response of PNNL SSTDR, FDR, and LiveWire SSTDR for 42 test conditions

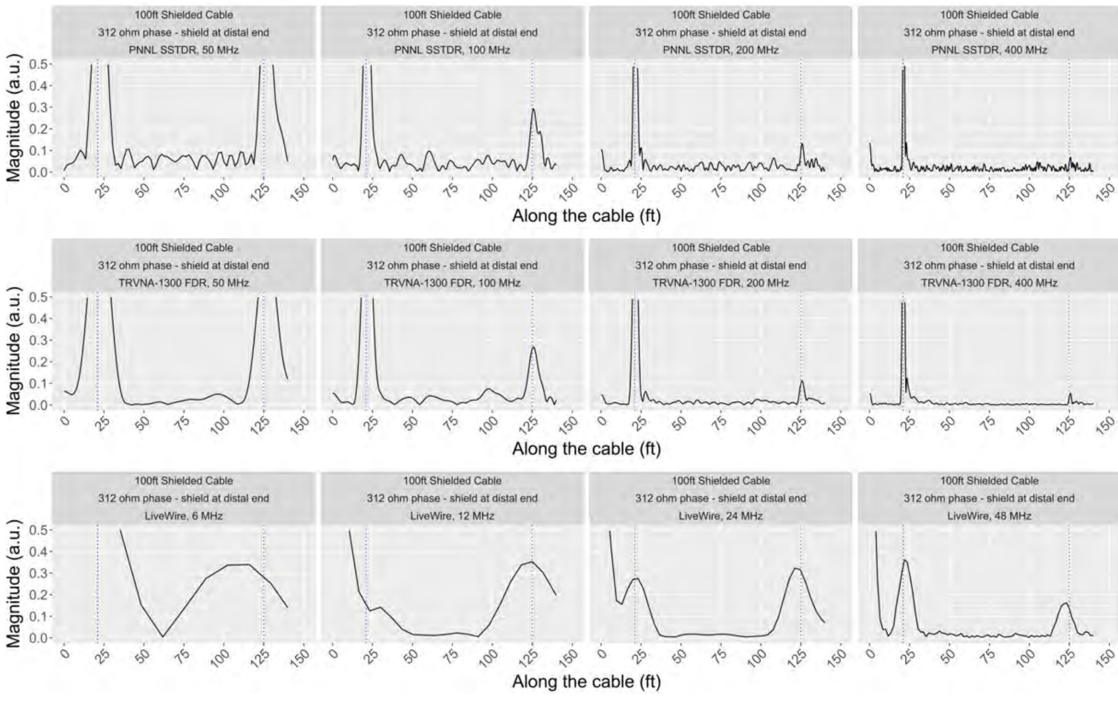
1. 100ft Shielded Cable, 100 ohm phase - shield at distal end



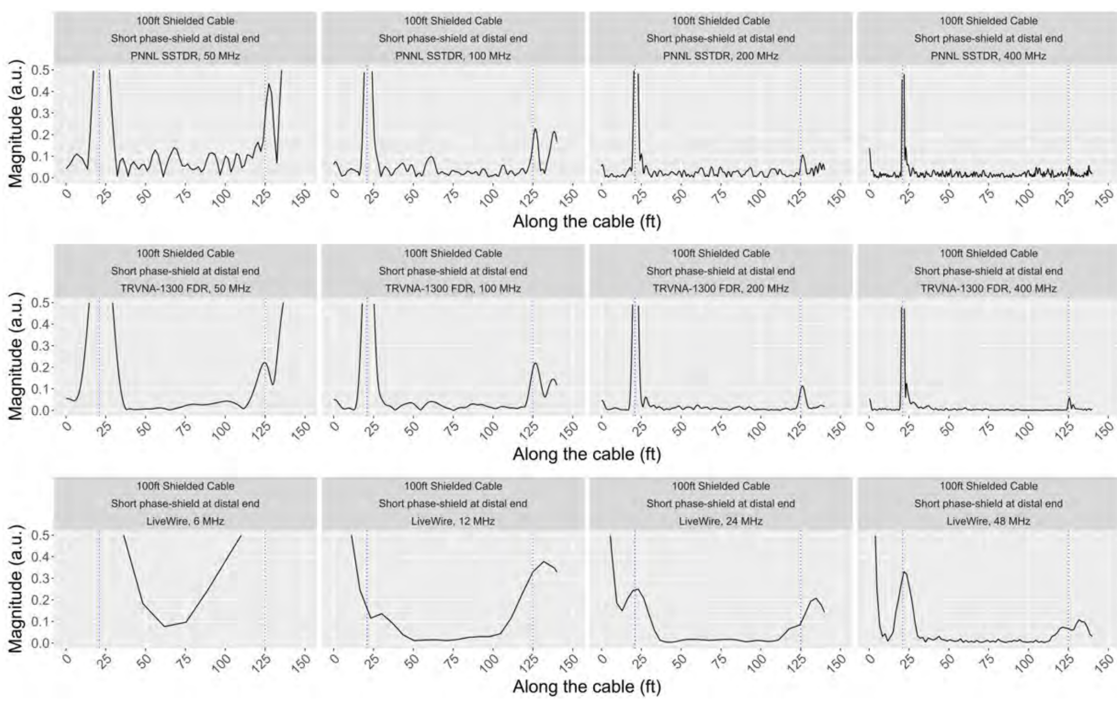
2. 100ft Shielded Cable, 2k ohm phase - shield at distal end



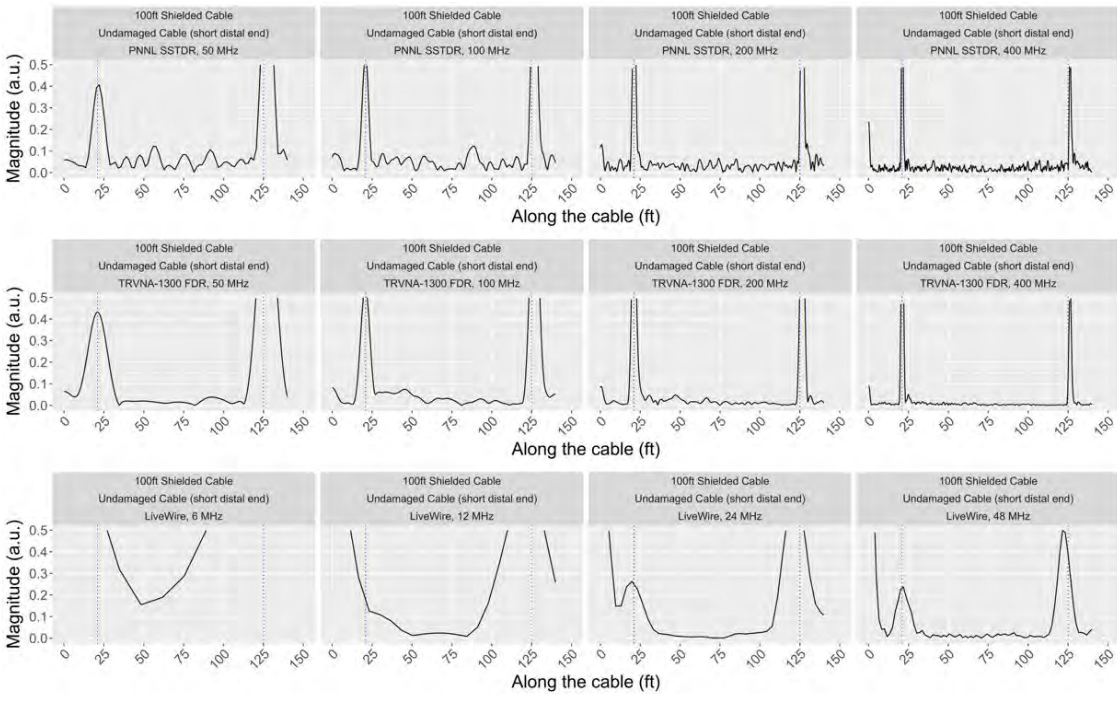
3. 100ft Shielded Cable, 312 ohm phase - shield at distal end



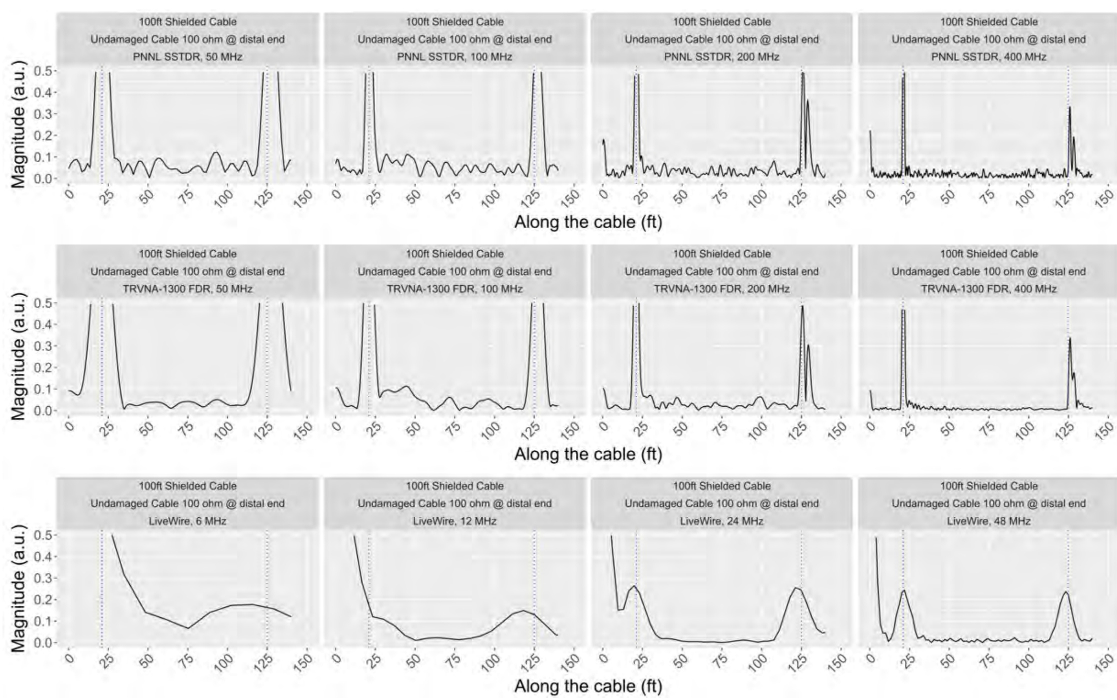
4. 100ft Shielded Cable, Short phase-shield at distal end



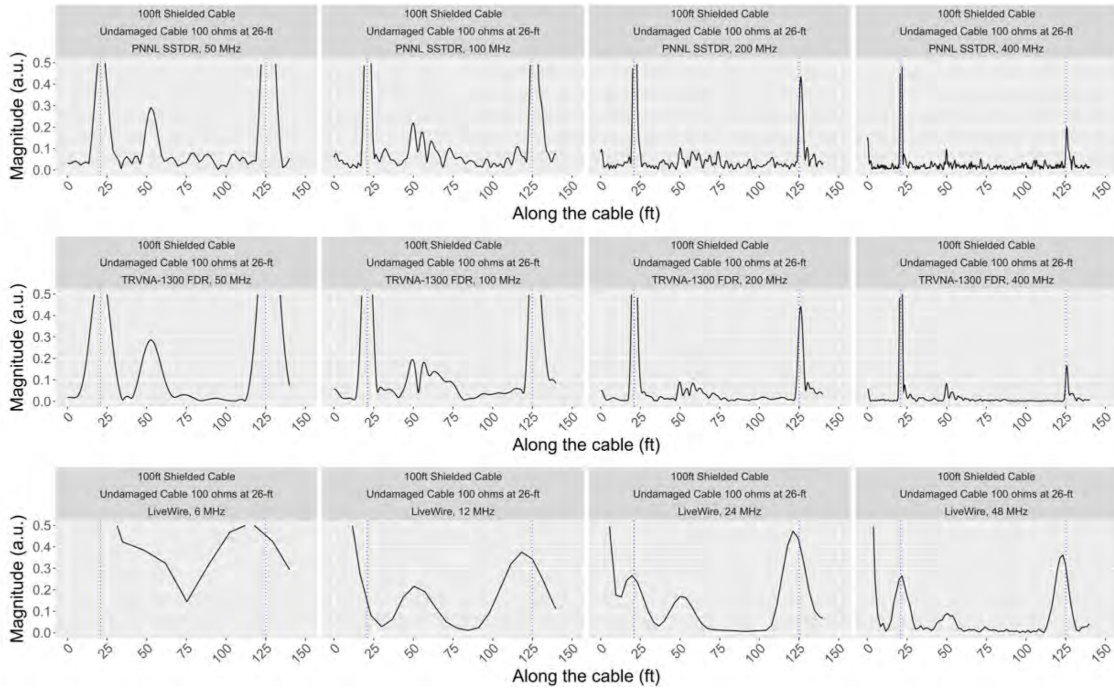
5. 100ft Shielded Cable, Undamaged Cable (short distal end)



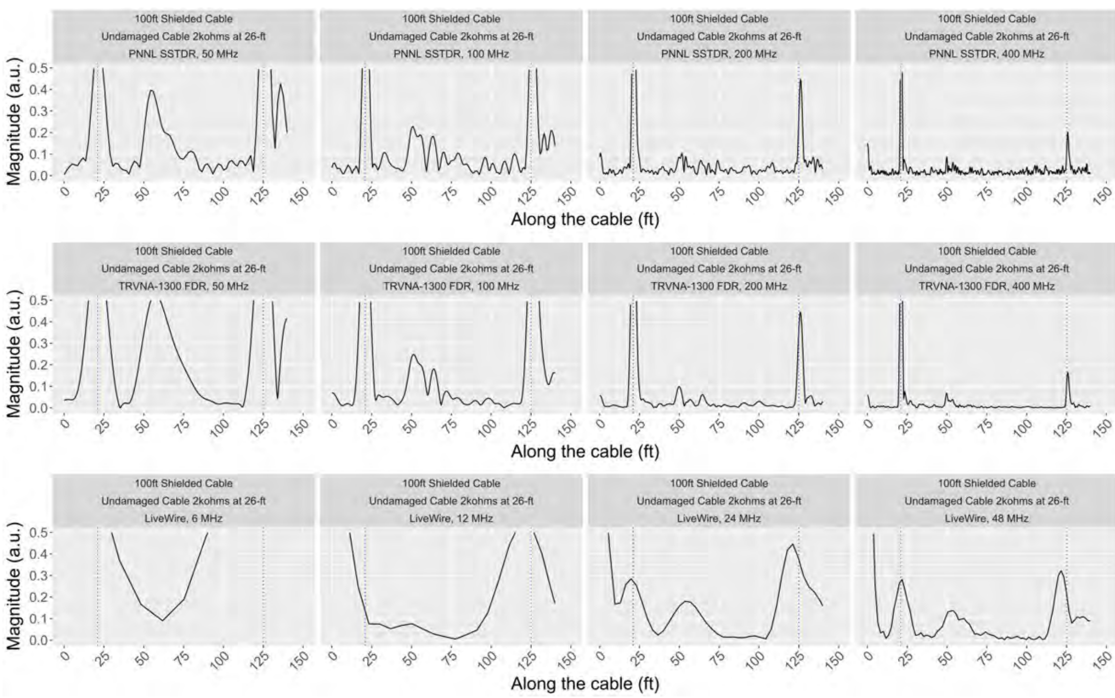
6. 100ft Shielded Cable, Undamaged Cable 100 ohm @ distal end



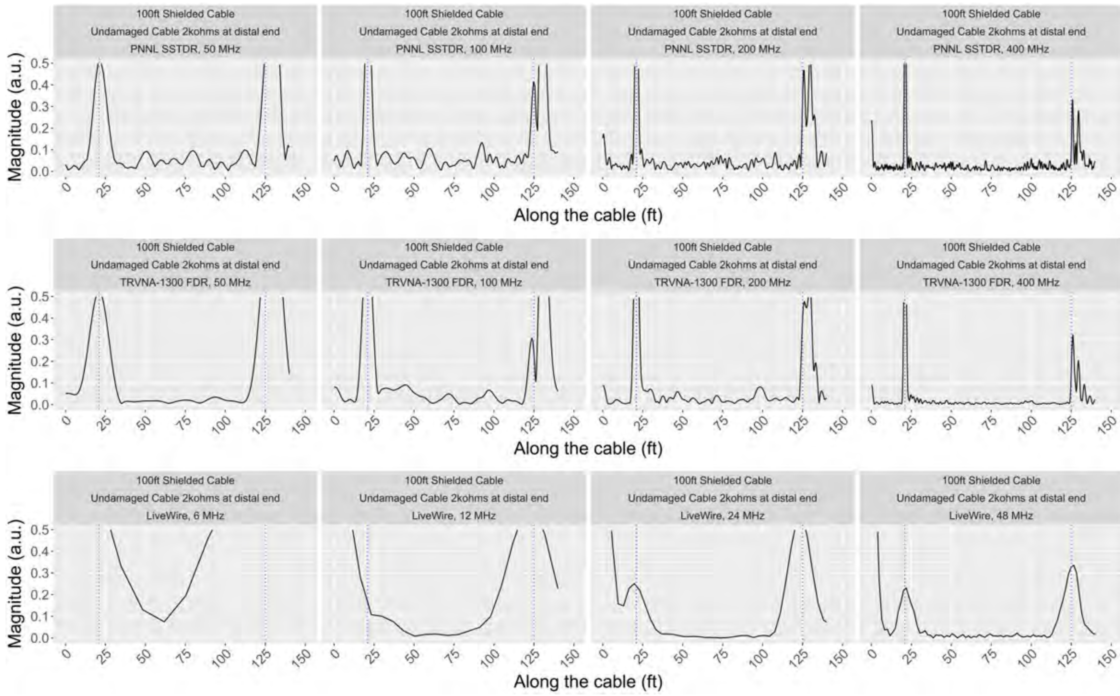
7. 100ft Shielded Cable, Undamaged Cable 100 ohms at 26-ft



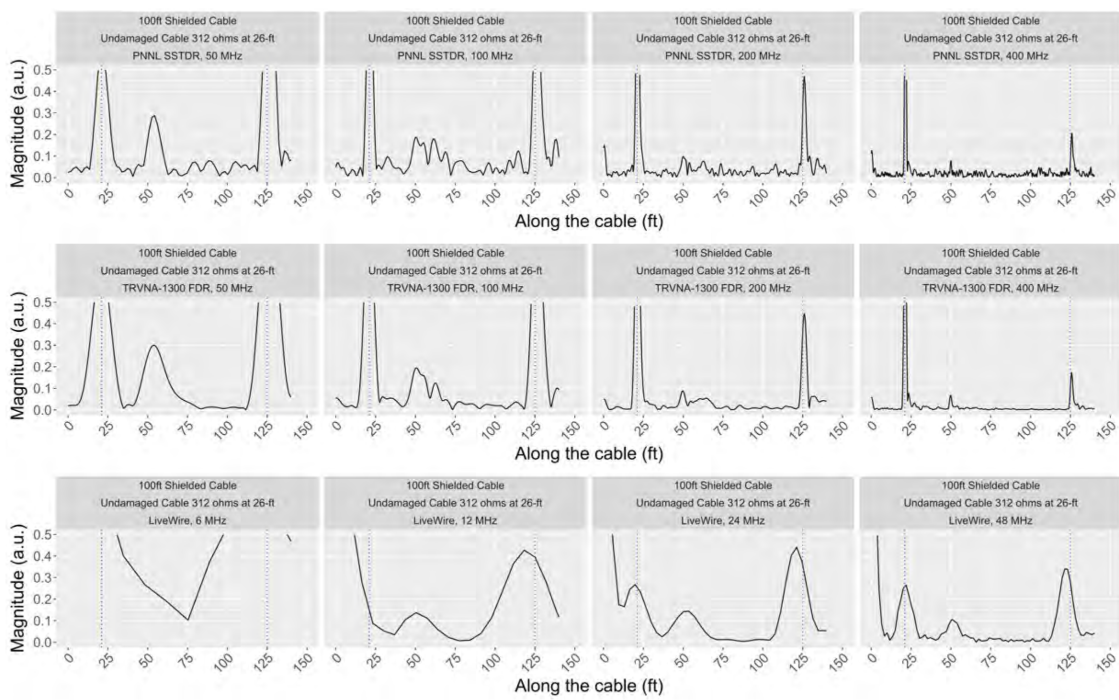
8. 100ft Shielded Cable, Undamaged Cable 2kohms at 26-ft



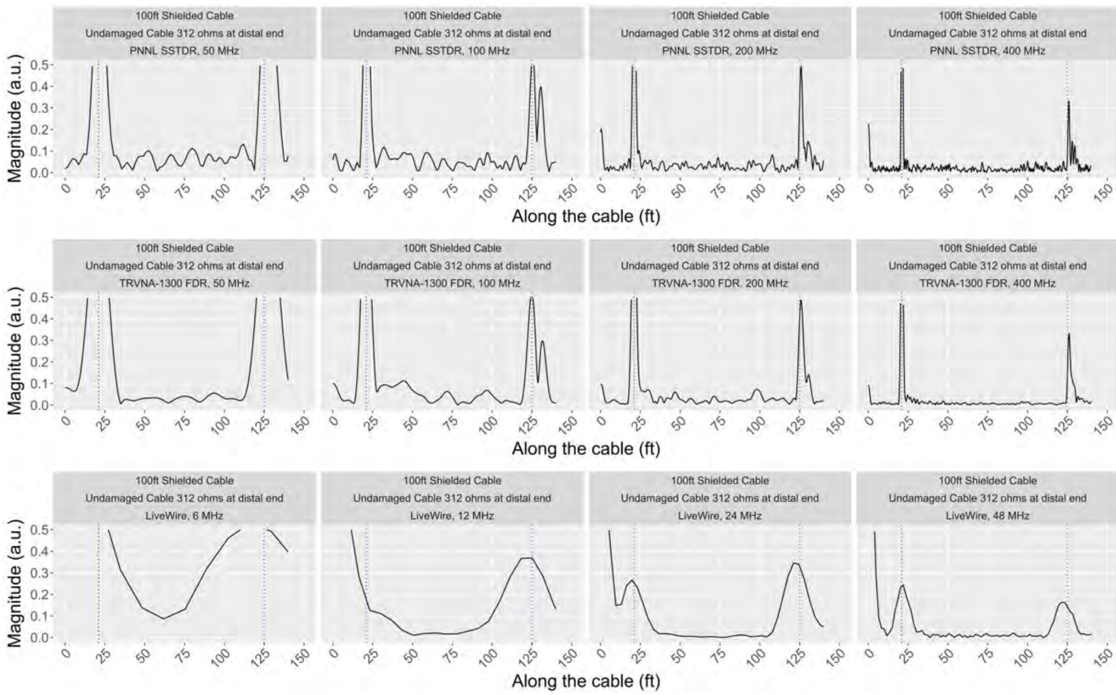
9. 100ft Shielded Cable, Undamaged Cable 2kohms at distal end



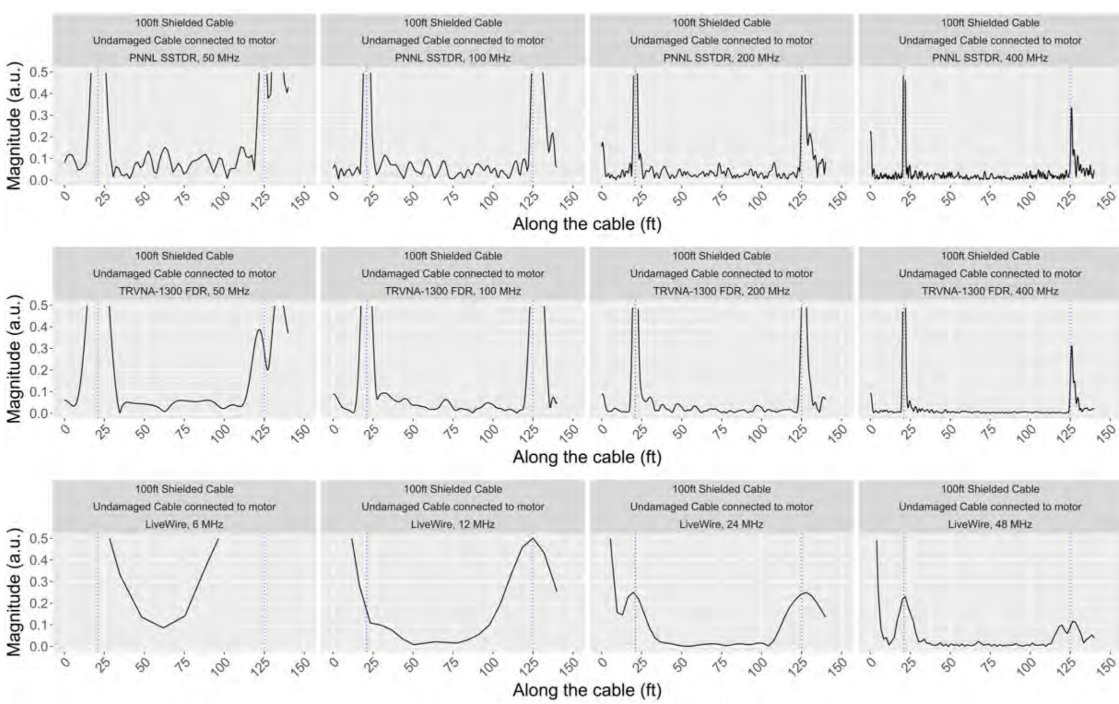
10. 100ft Shielded Cable, Undamaged Cable 312 ohms at 26-ft



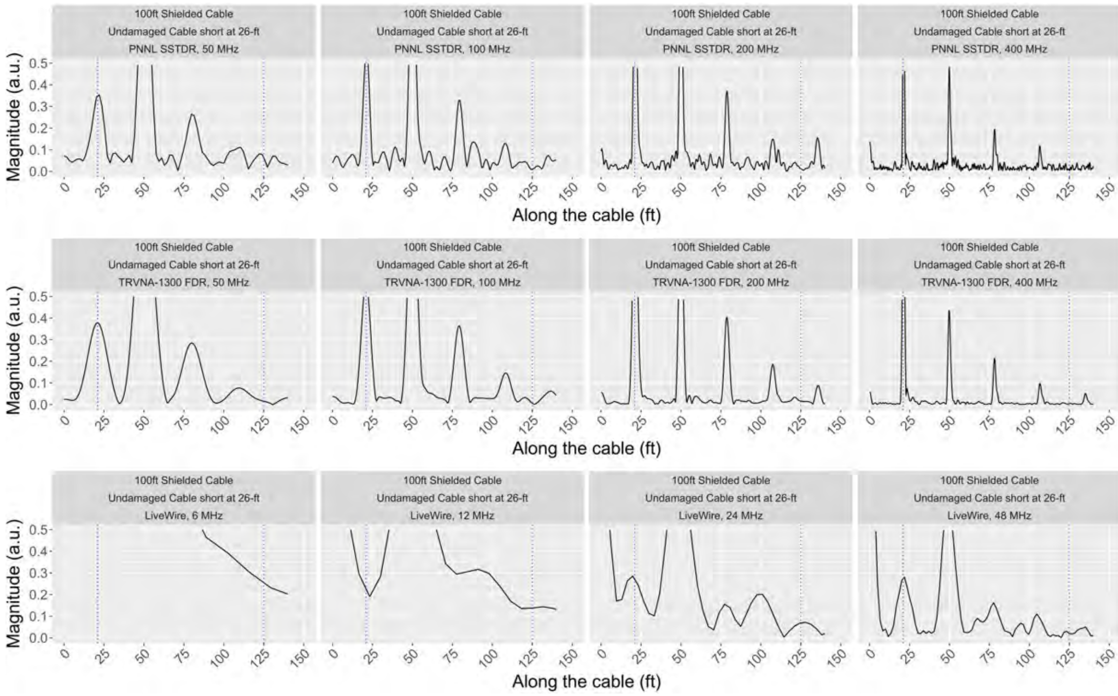
11. 100ft Shielded Cable, Undamaged Cable 312 ohms at distal end



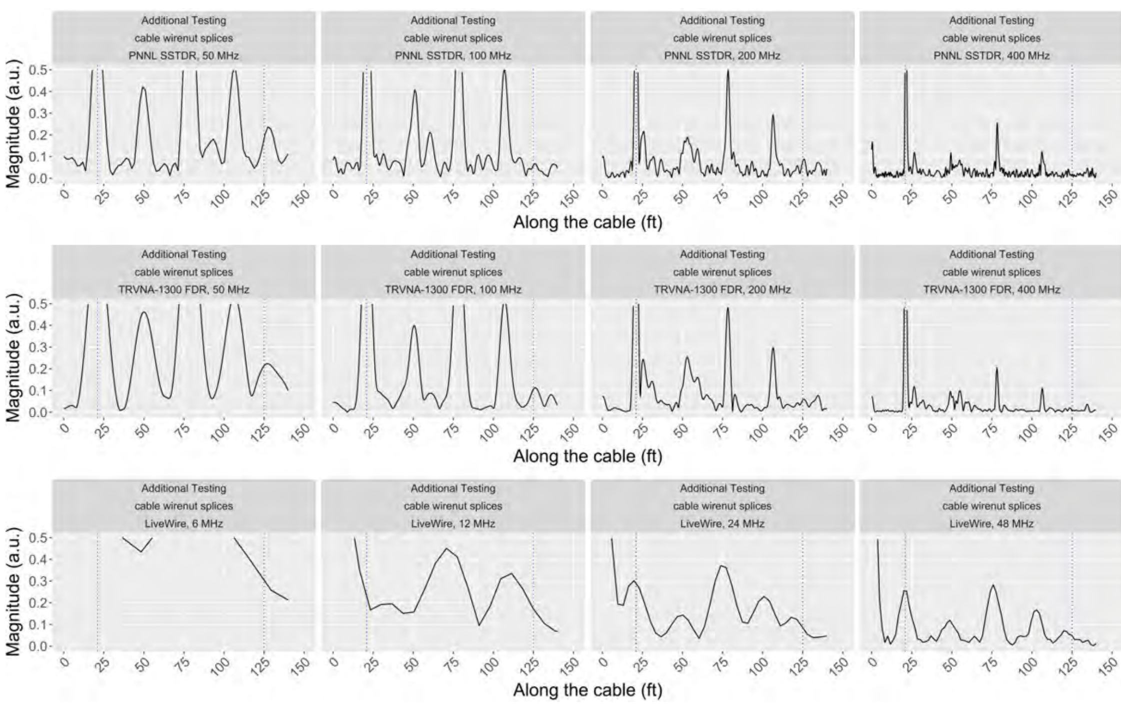
12. 100ft Shielded Cable, Undamaged Cable connected to motor



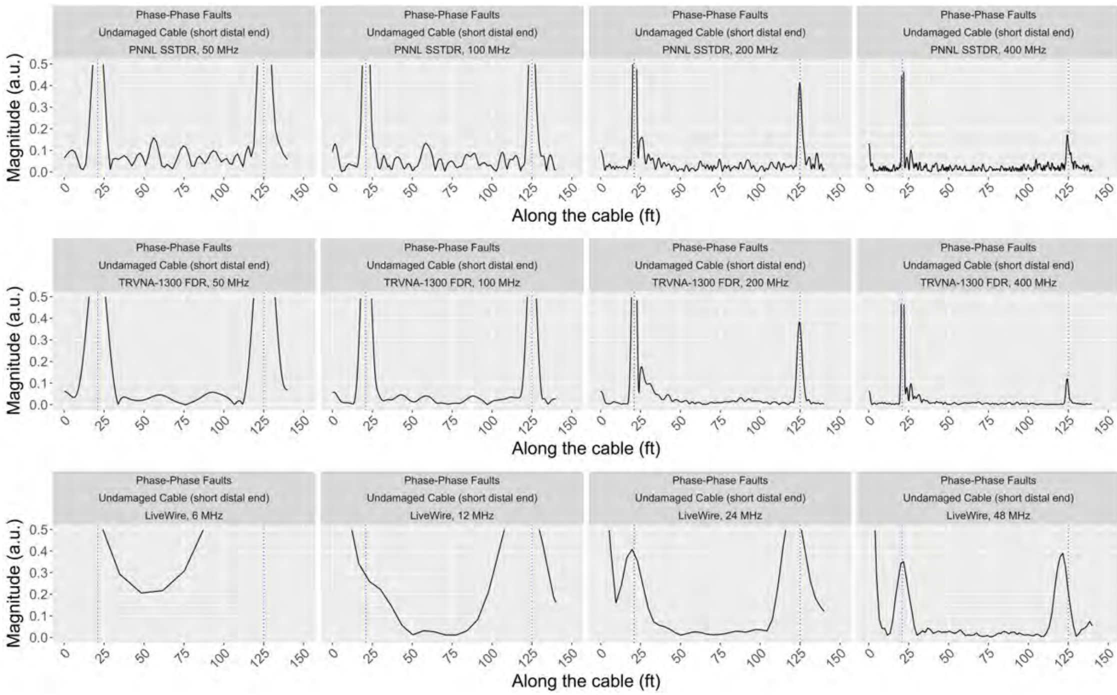
13. 100ft Shielded Cable, Undamaged Cable short at 26-ft



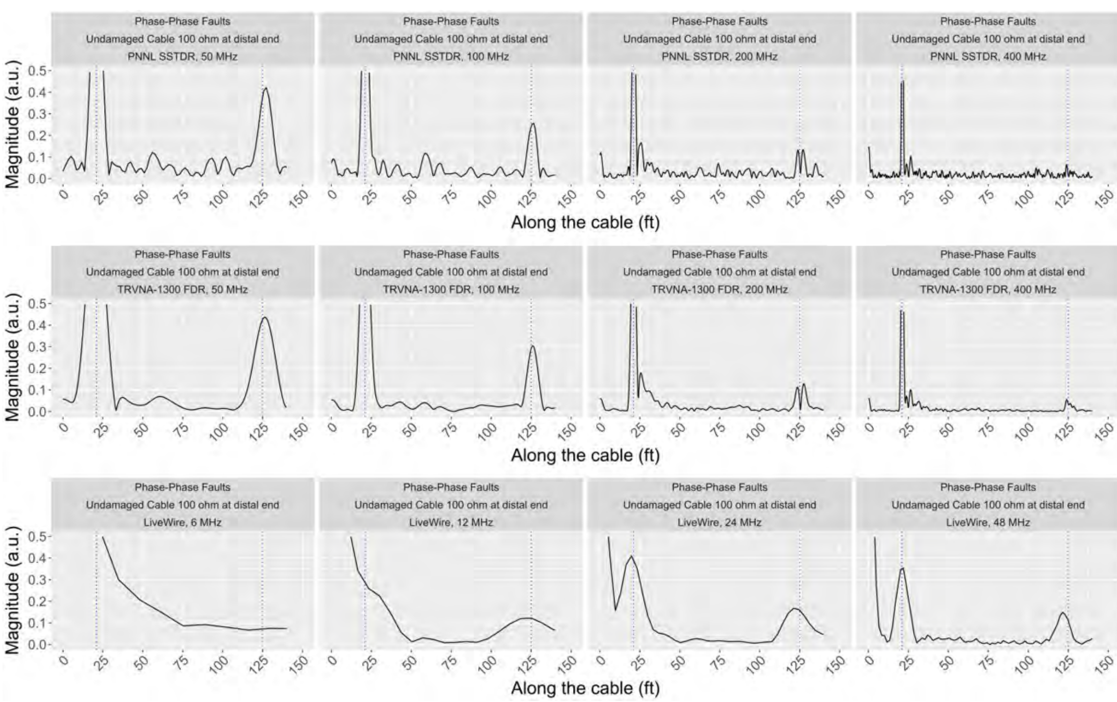
14. Additional Testing, cable wirenut splices



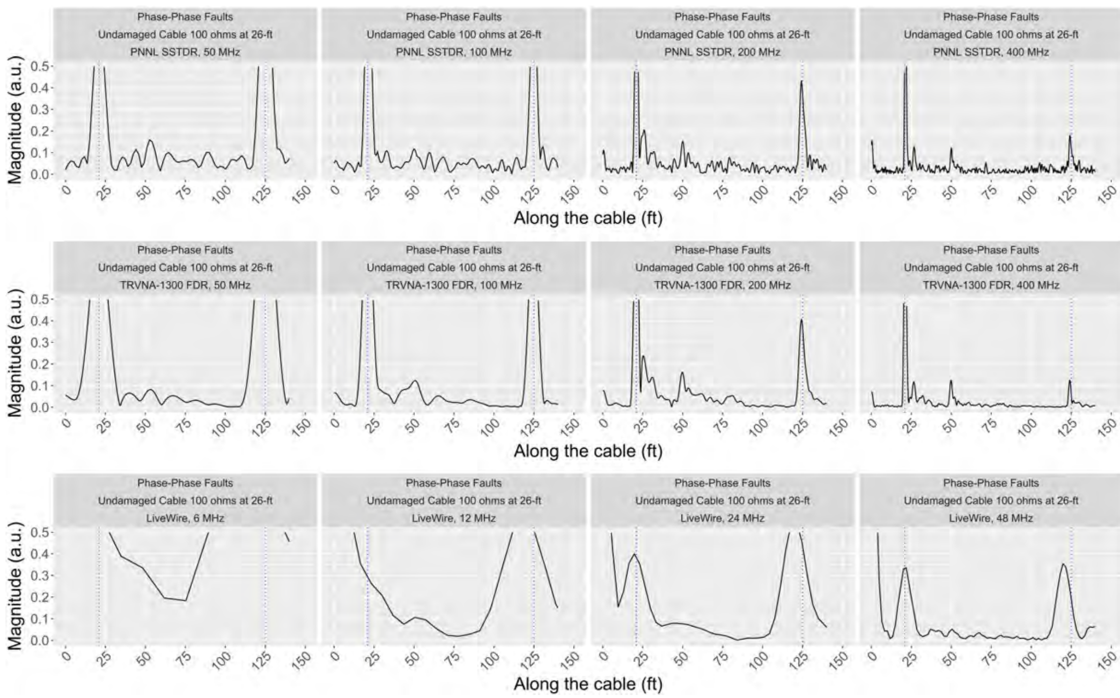
15. Phase-Phase Faults, Undamaged Cable (short distal end)



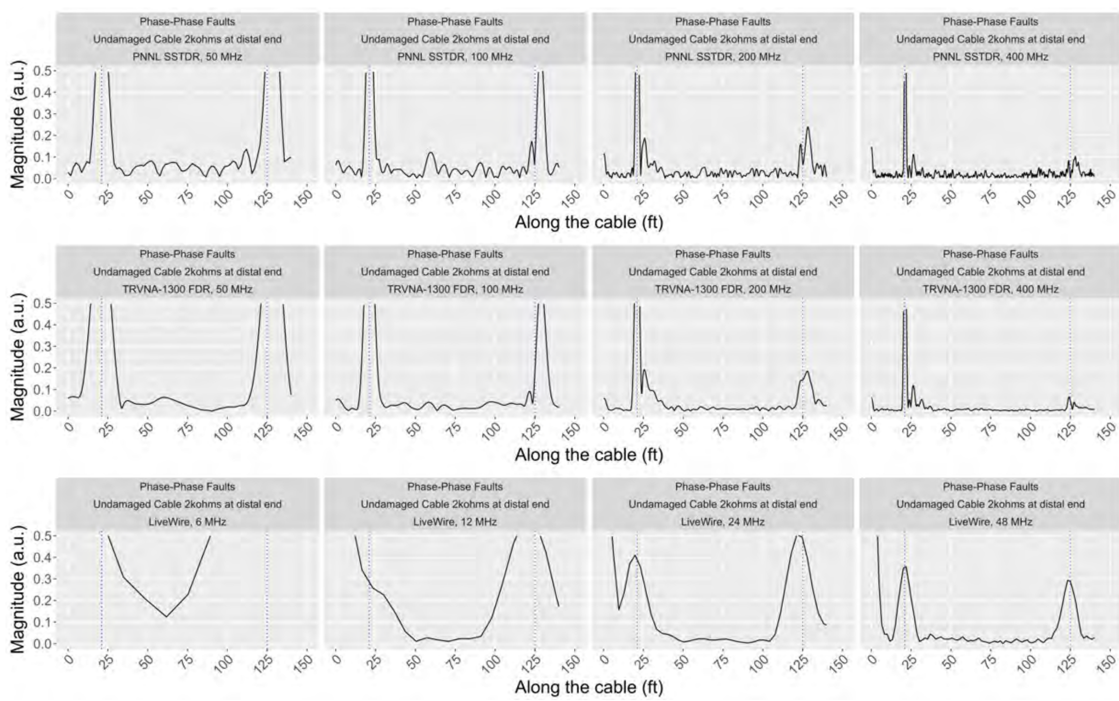
16. Phase-Phase Faults, Undamaged Cable 100 ohm at distal end



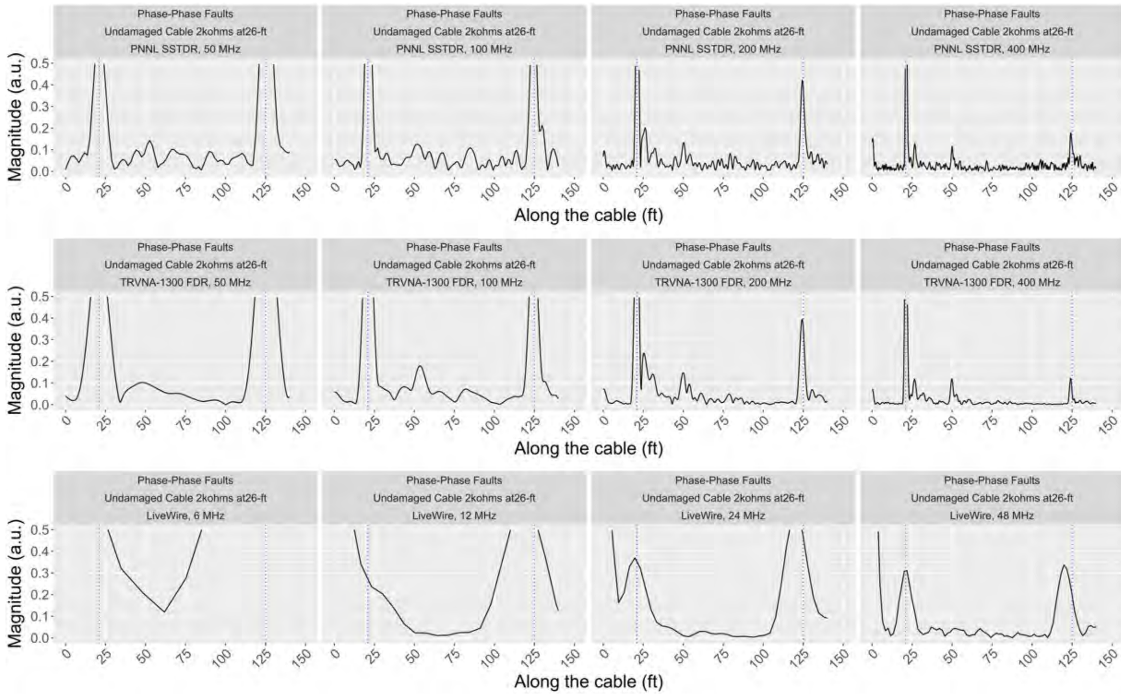
17. Phase-Phase Faults, Undamaged Cable 100 ohms at 26-ft



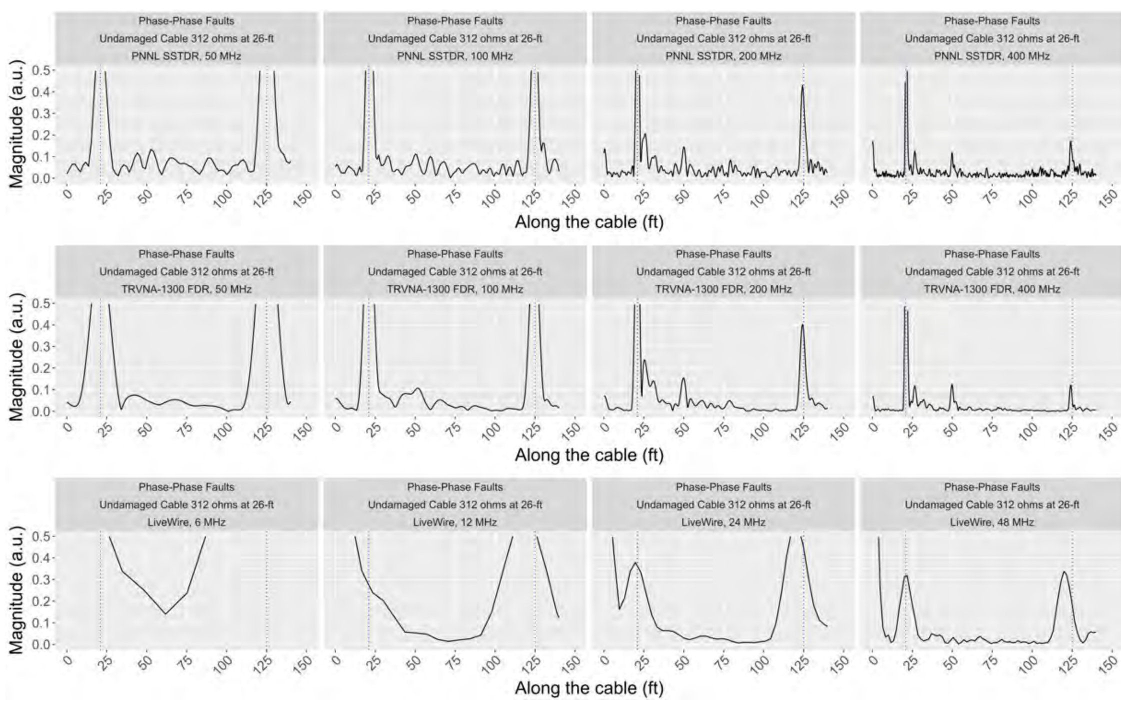
18. Phase-Phase Faults, Undamaged Cable 2kohms at distal end



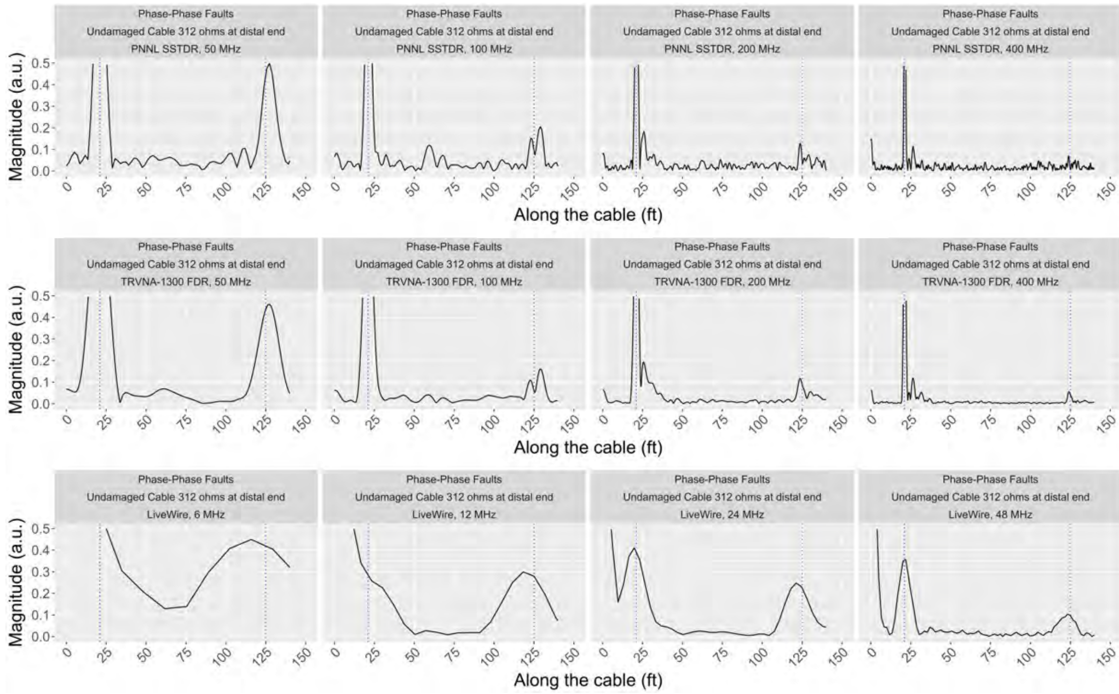
19. Phase-Phase Faults, Undamaged Cable 2kohms at 26-ft



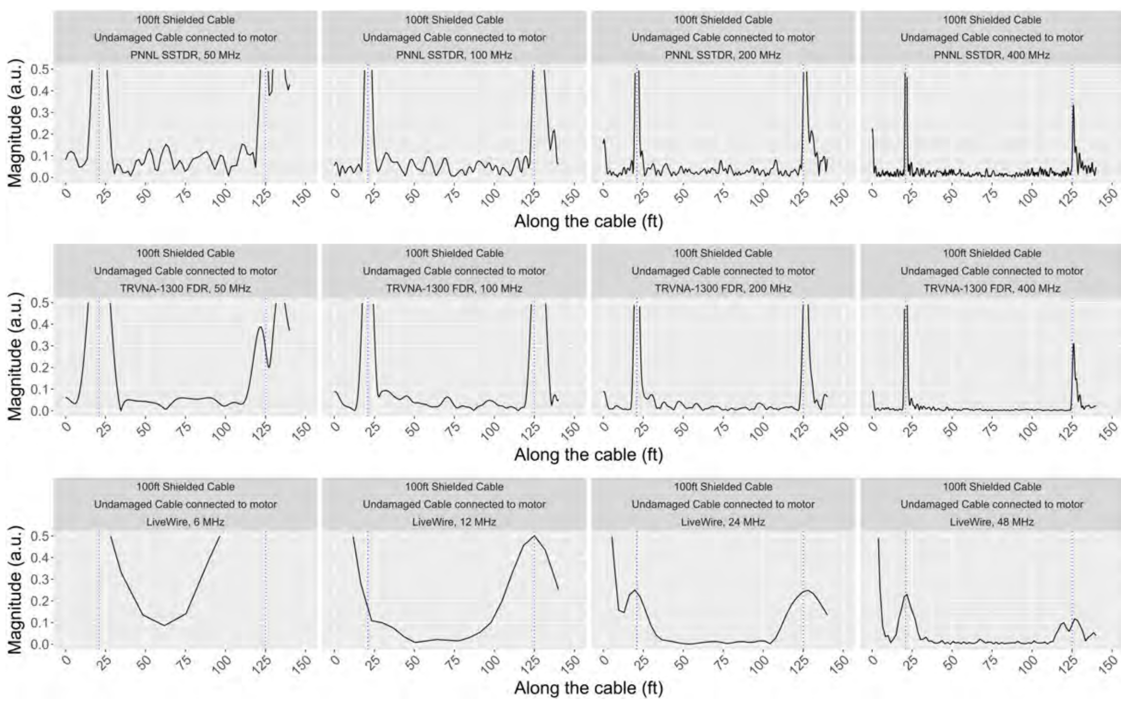
20. Phase-Phase Faults, Undamaged Cable 312 ohms at 26-ft



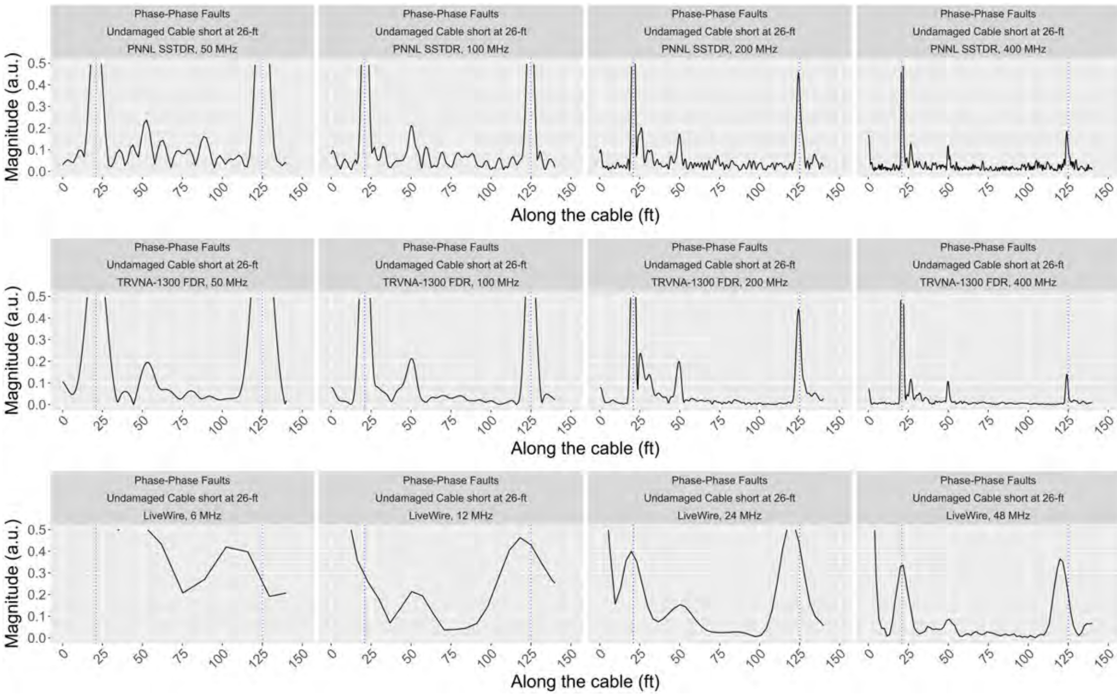
21. Phase-Phase Faults, Undamaged Cable 312 ohms at distal end



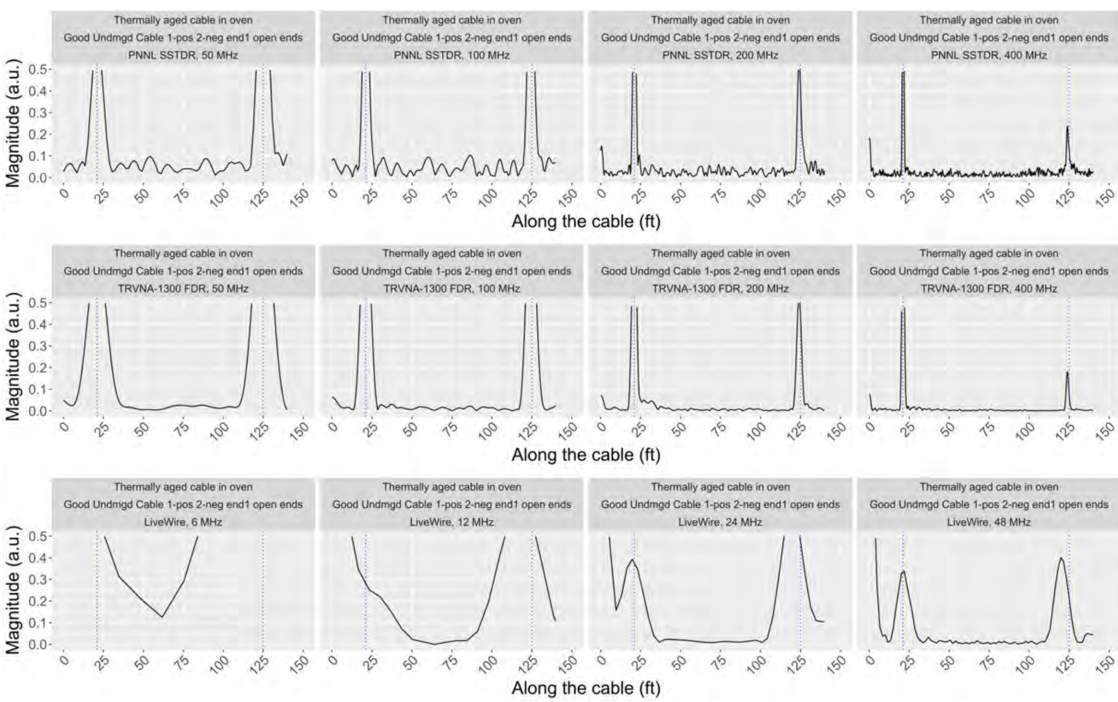
22. Phase-Phase Faults, Undamaged Cable connected to motor



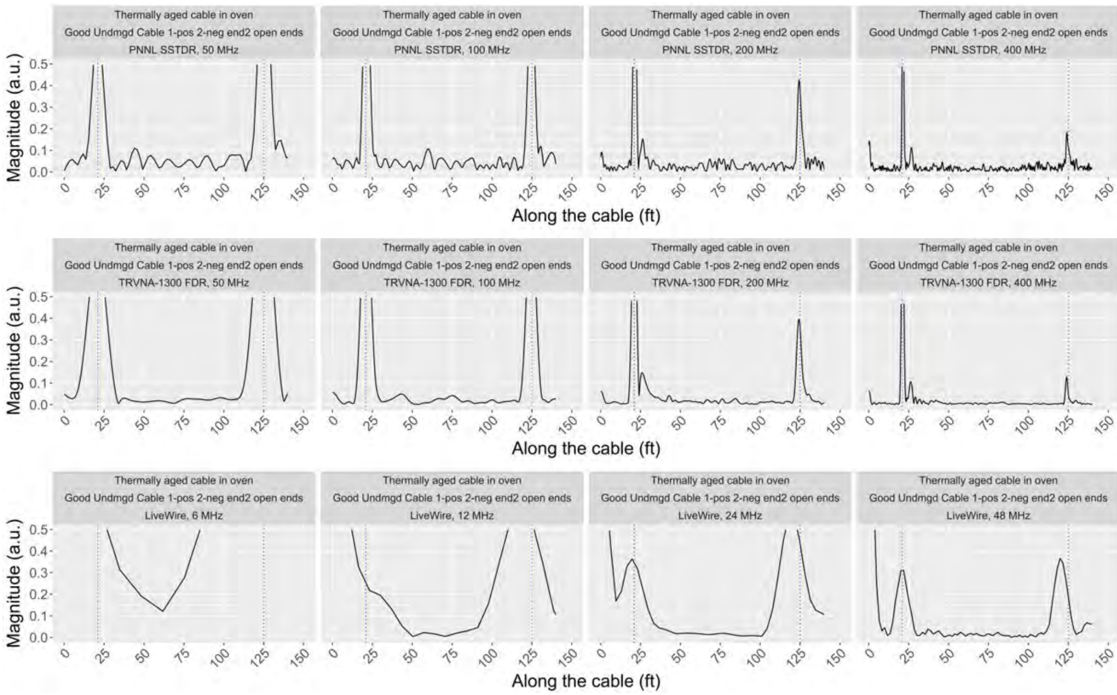
23. Phase-Phase Faults, Undamaged Cable short at 26-ft



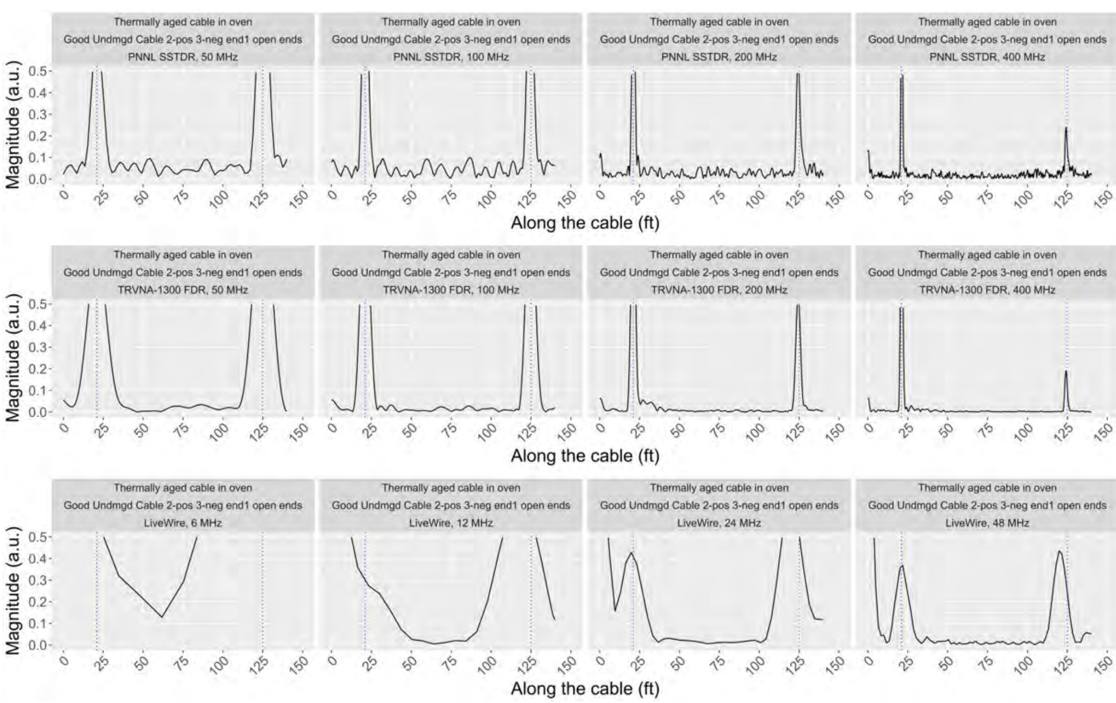
24. Thermally aged cable in oven, Good Undamaged Cable 1-pos 2-neg end1 open ends



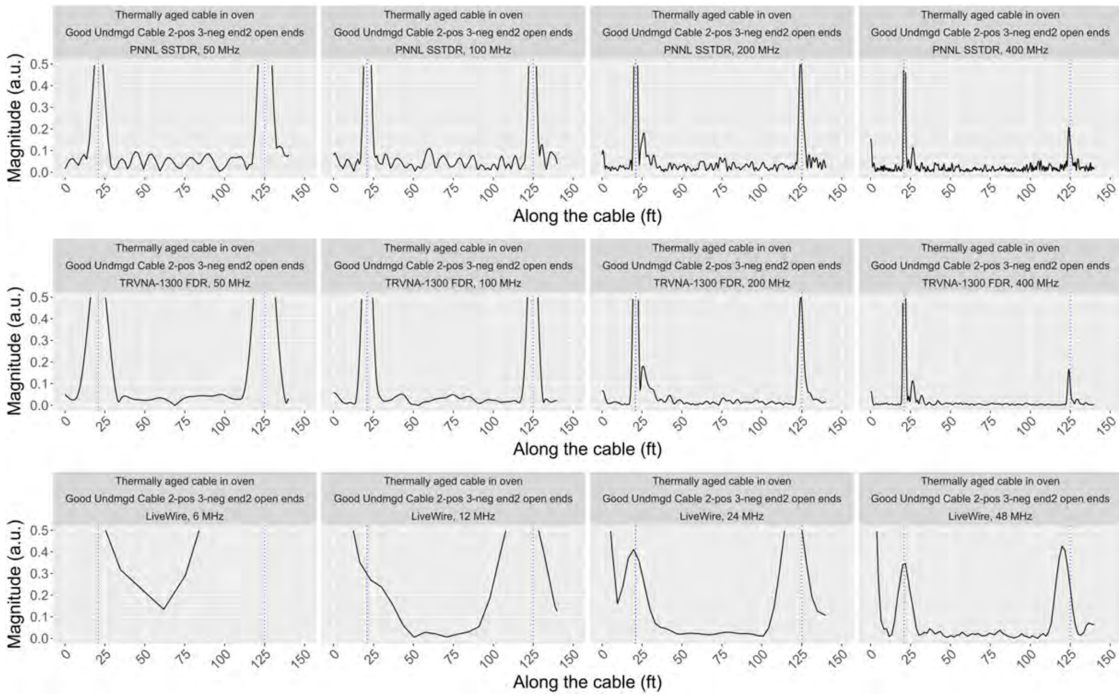
25. Thermally aged cable in oven, Good Undamaged Cable 1-pos 2-neg end2 open ends



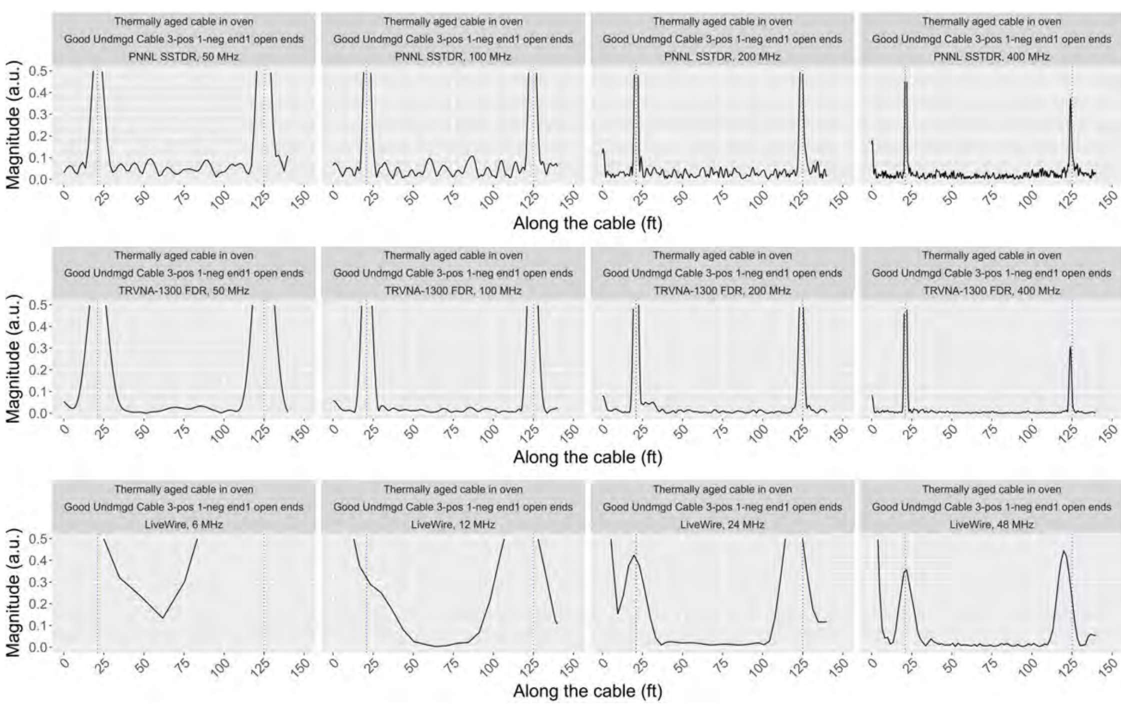
26. Thermally aged cable in oven, Good Undamaged Cable 2-pos 3-neg end1 open ends



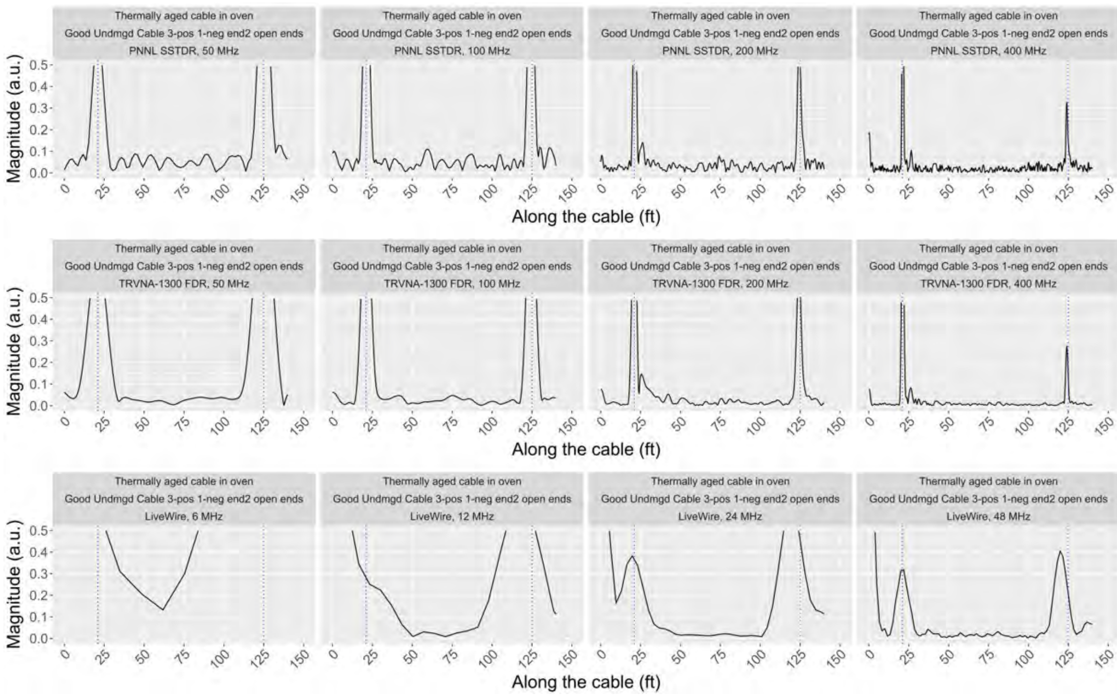
27. Thermally aged cable in oven, Good Undamaged Cable 2-pos 3-neg end2 open ends



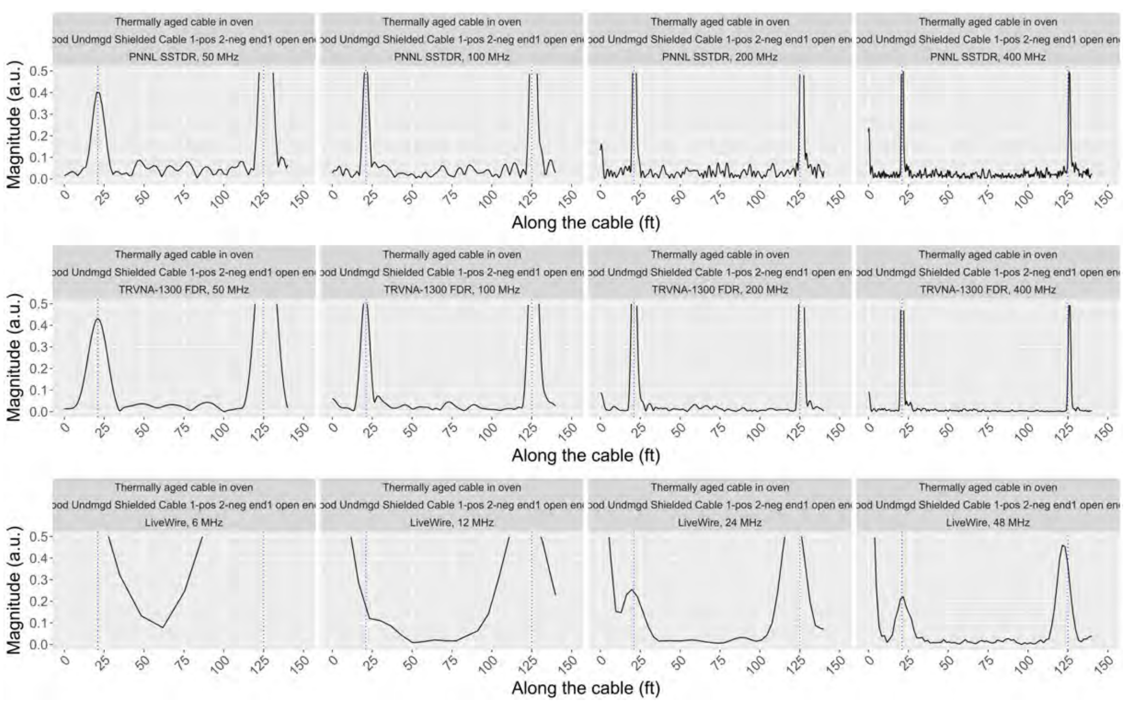
28. Thermally aged cable in oven, Good Undamaged Cable 3-pos 1-neg end1 open ends



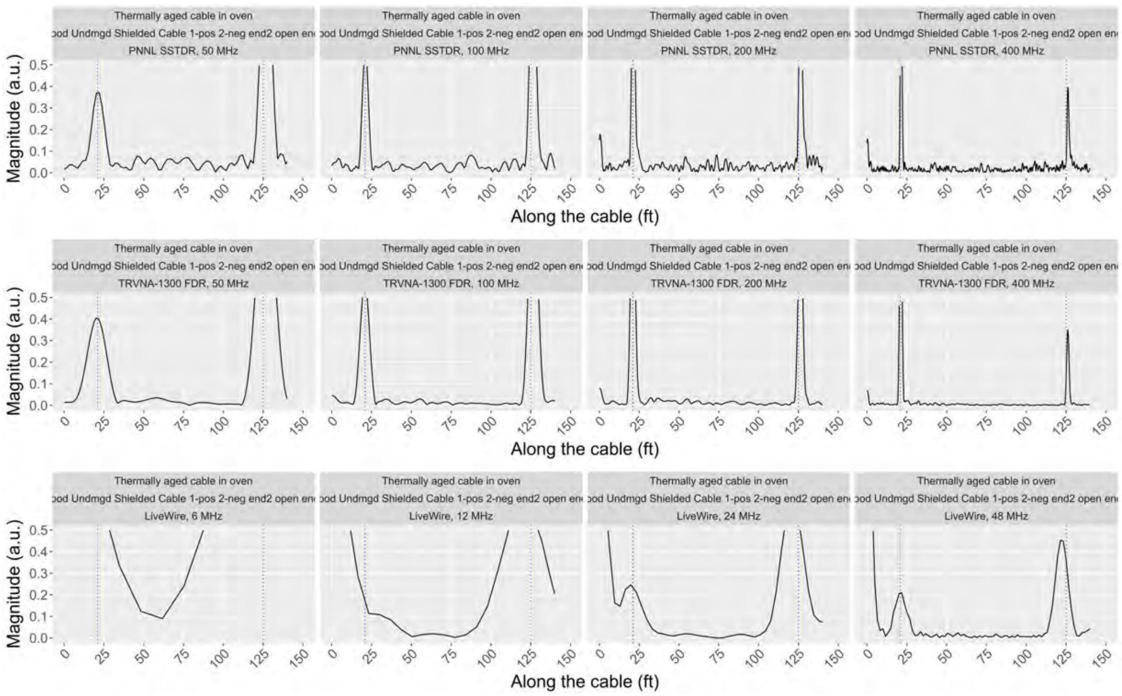
29. Thermally aged cable in oven, Good Undamaged Cable 3-pos 1-neg end2 open ends



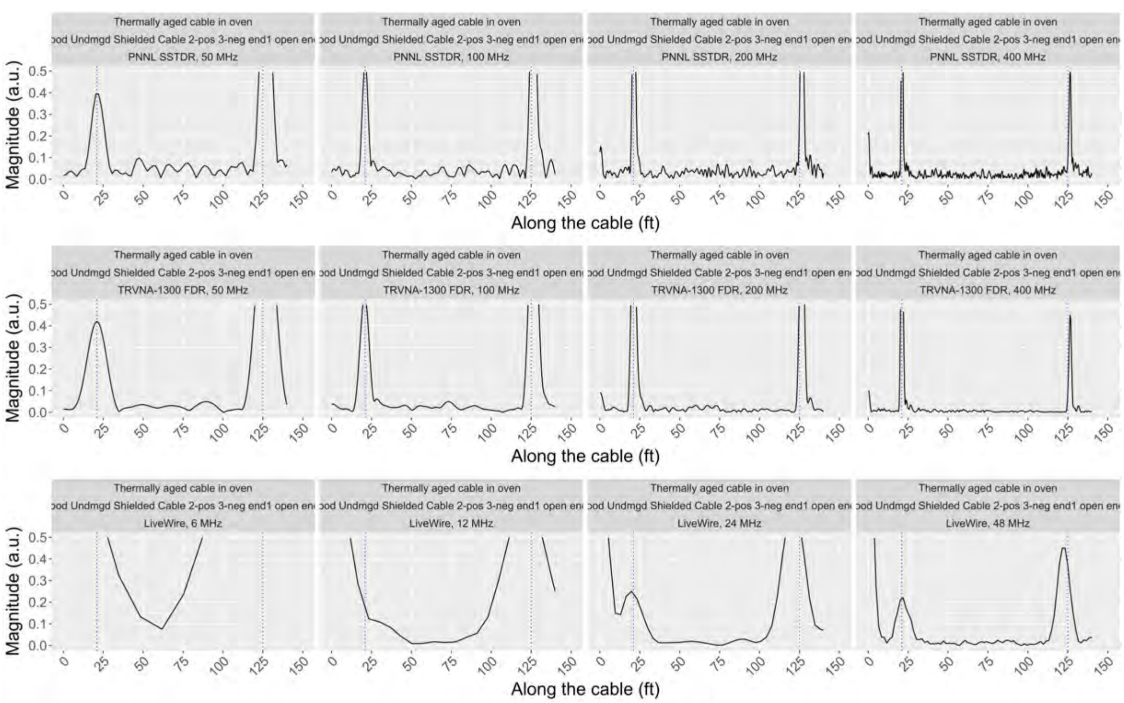
30. Thermally aged cable in oven, Good Undamaged Shielded Cable 1-pos 2-neg end1 open ends



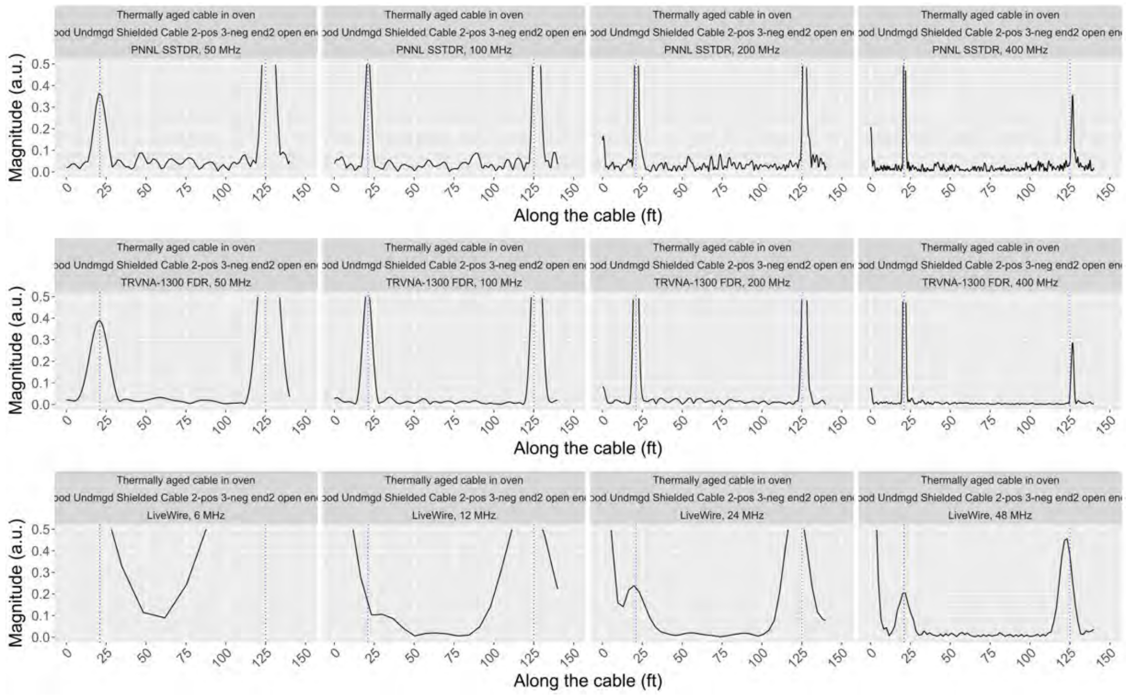
31. Thermally aged cable in oven, Good Undamaged Shielded Cable 1-pos 2-neg end2 open ends



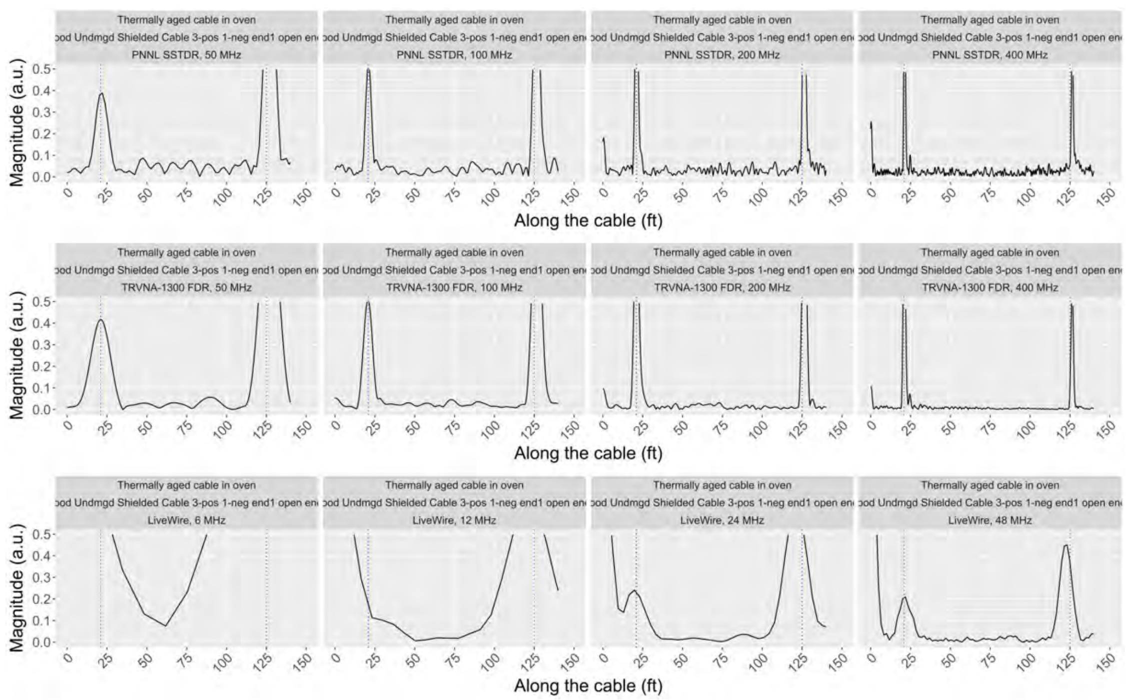
32. Thermally aged cable in oven, Good Undamaged Shielded Cable 2-pos 3-neg end1 open ends



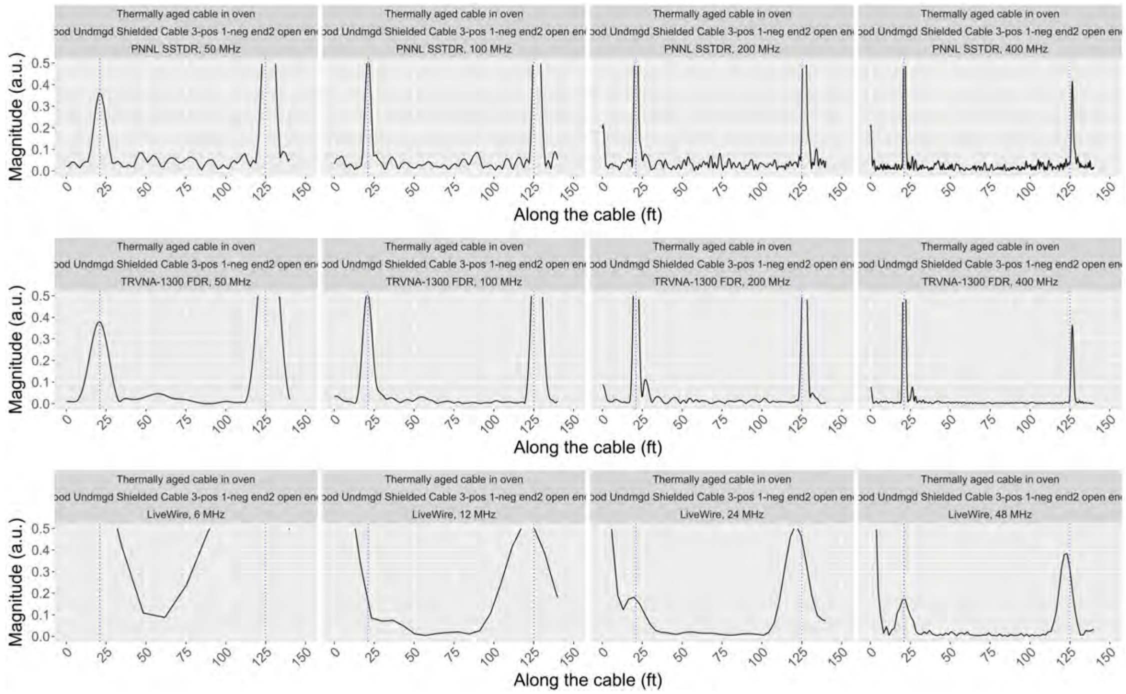
33. Thermally aged cable in oven, Good Undamaged Shielded Cable 2-pos 3-neg end2 open ends



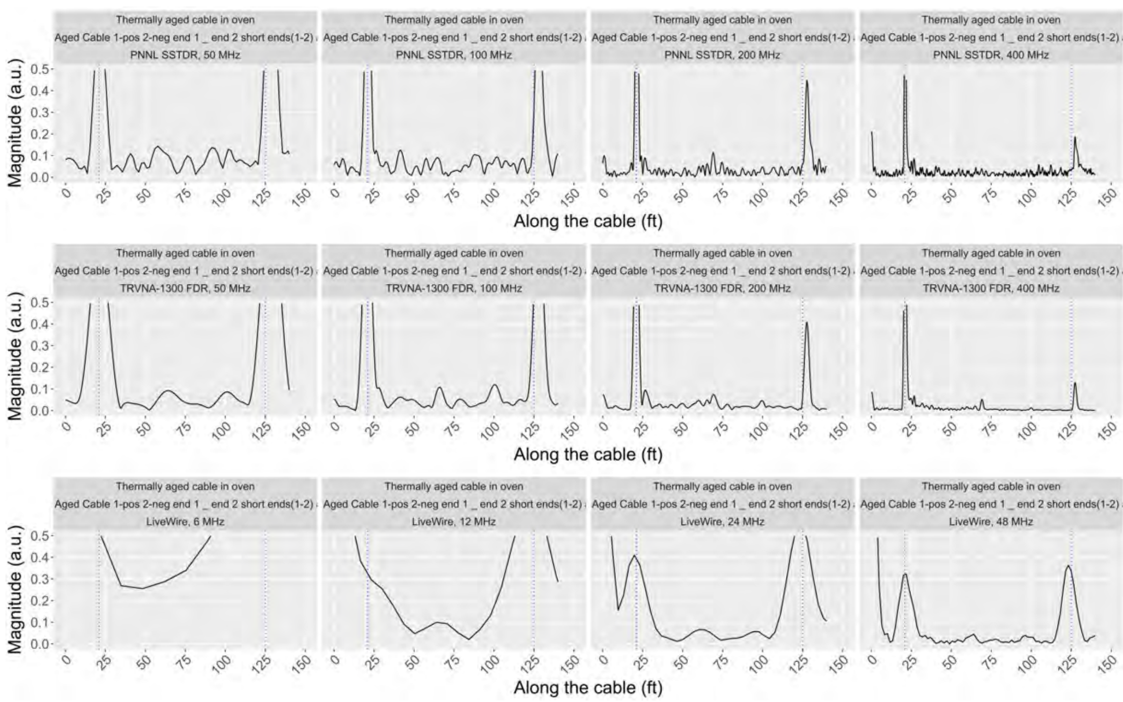
34. Thermally aged cable in oven, Good Undamaged Shielded Cable 3-pos 1-neg end1 open ends



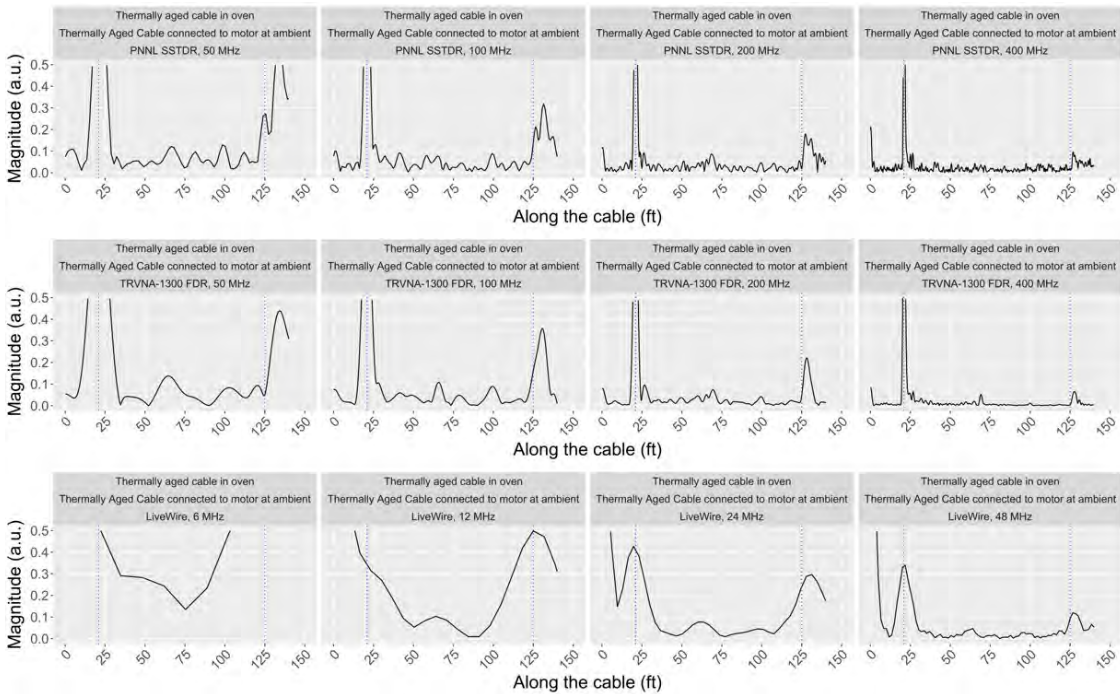
35. Thermally aged cable in oven, Good Undamaged Shielded Cable 3-pos 1-neg end2 open ends



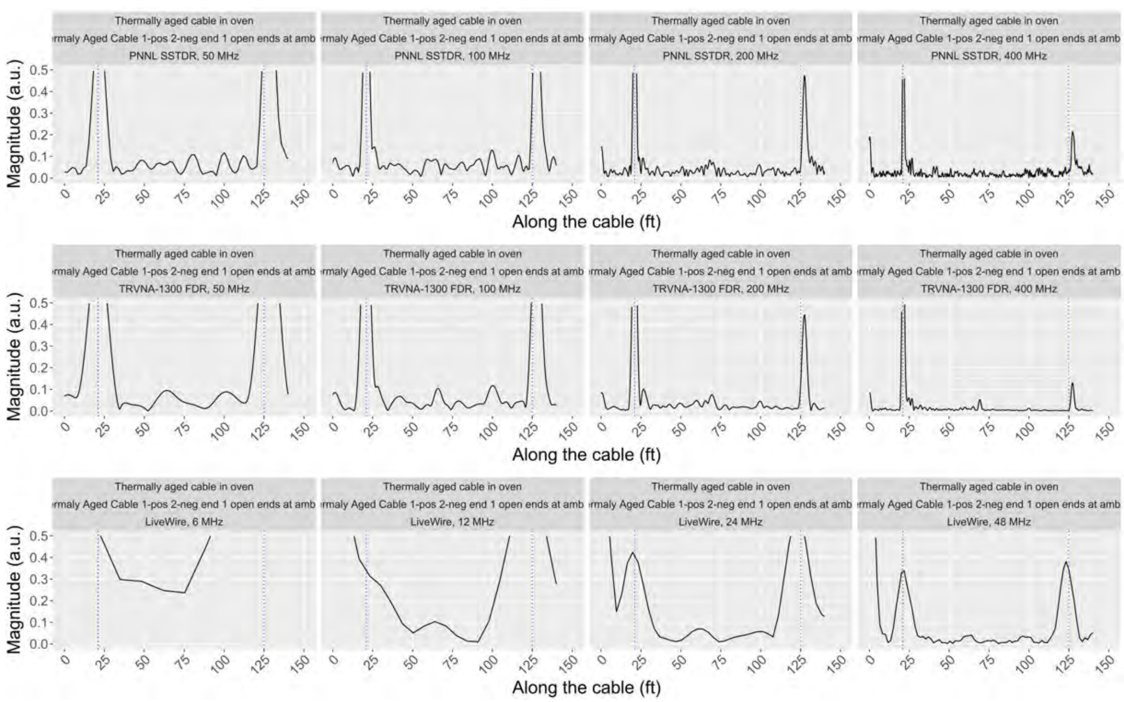
36. Thermally aged cable in oven, Thermally Aged Cable 1-pos 2-neg end 1 _ end 2 short ends(1-2) at ambient



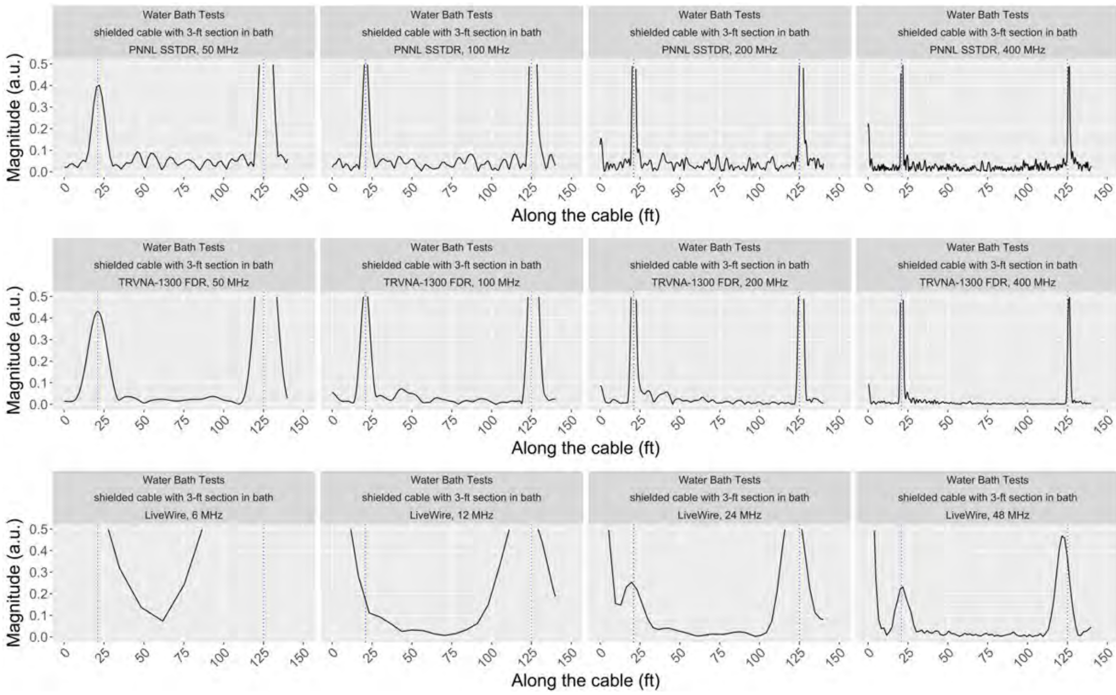
37. Thermally aged cable in oven, Thermally Aged Cable connected to motor at ambient



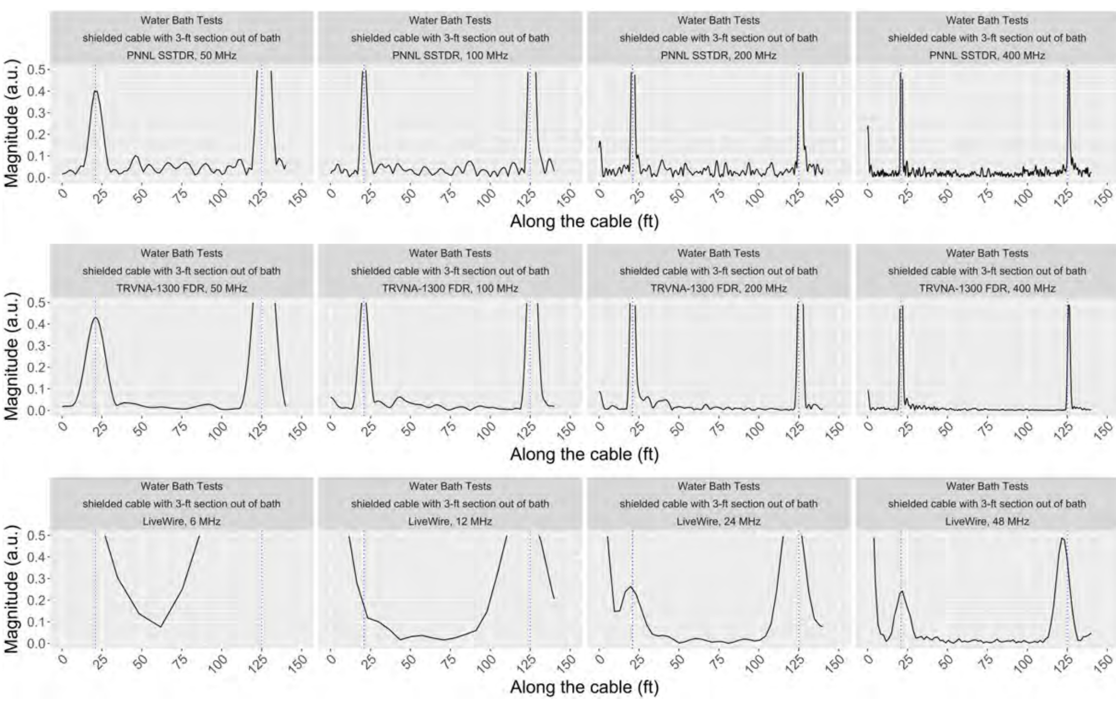
38. Thermally aged cable in oven, Thermally Aged Cable 1-pos 2-neg end 1 open ends at ambient



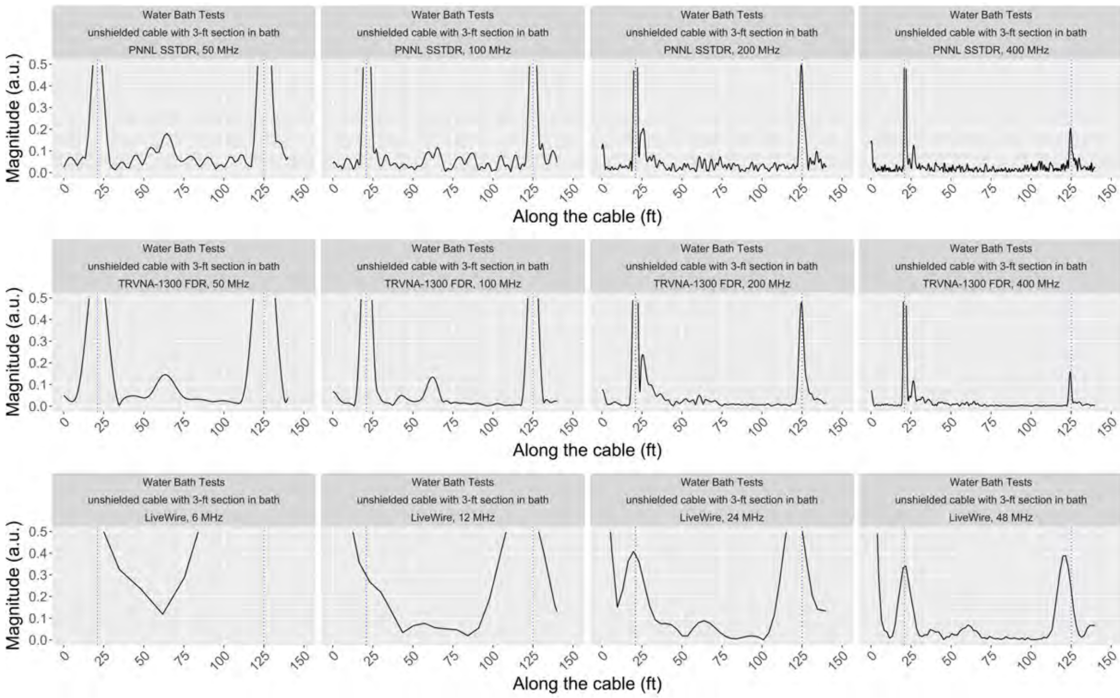
39. Water Bath Tests, shielded cable with 3-ft section in bath



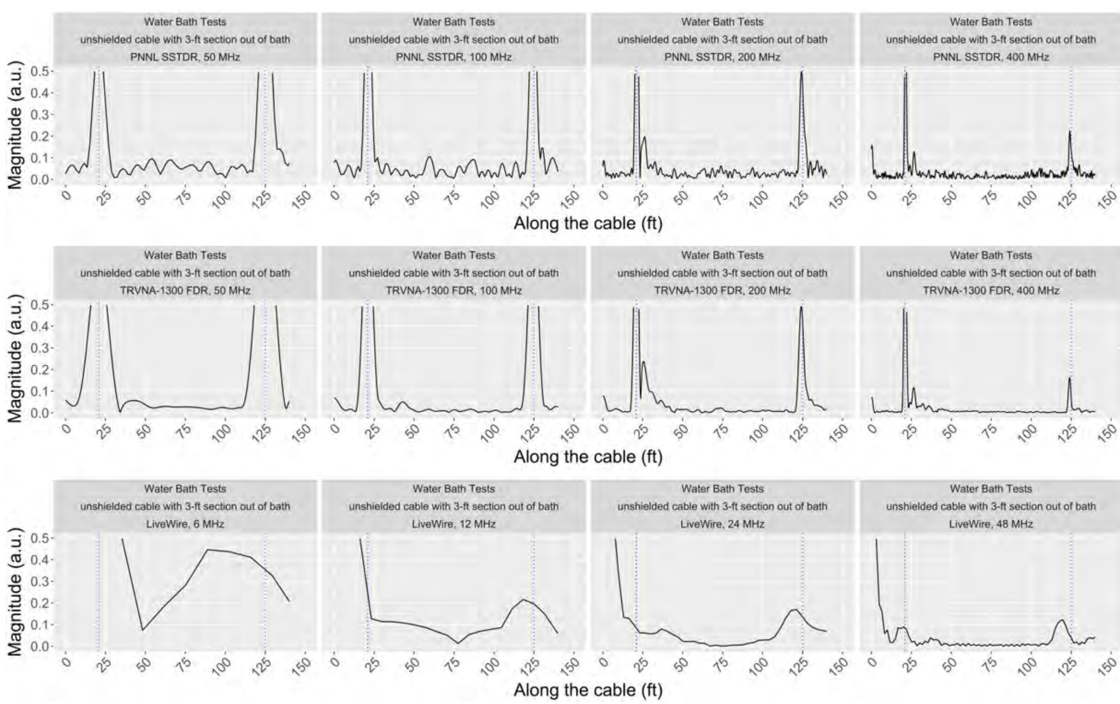
40. Water Bath Tests, shielded cable with 3-ft section out of bath



41. Water Bath Tests, unshielded cable with 3-ft section in bath

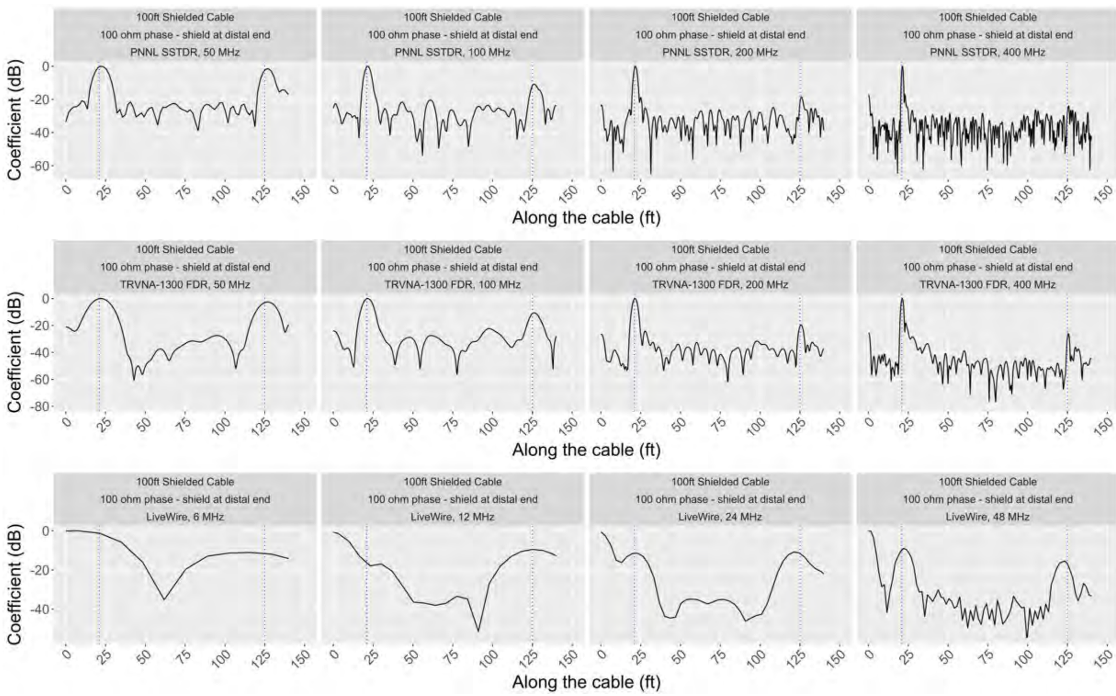


42. Water Bath Tests, unshielded cable with 3-ft section out of bath

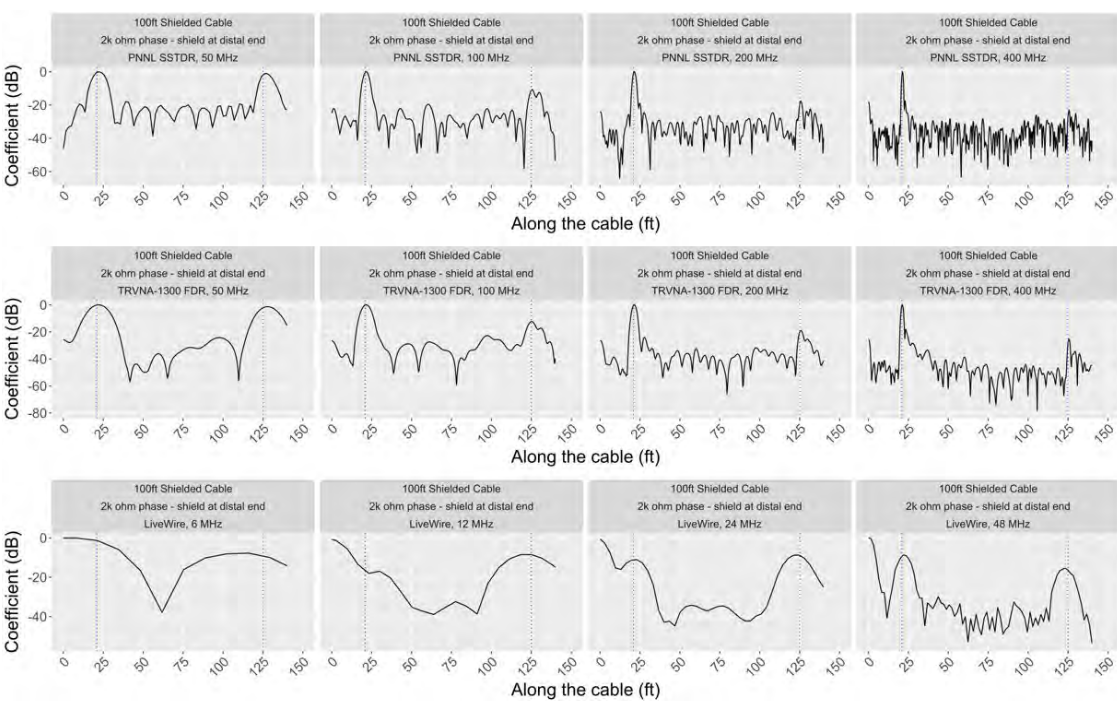


Appendix 2: dB response of PNNL SSTDR, FDR, and LiveWire SSTDR for 42 test conditions

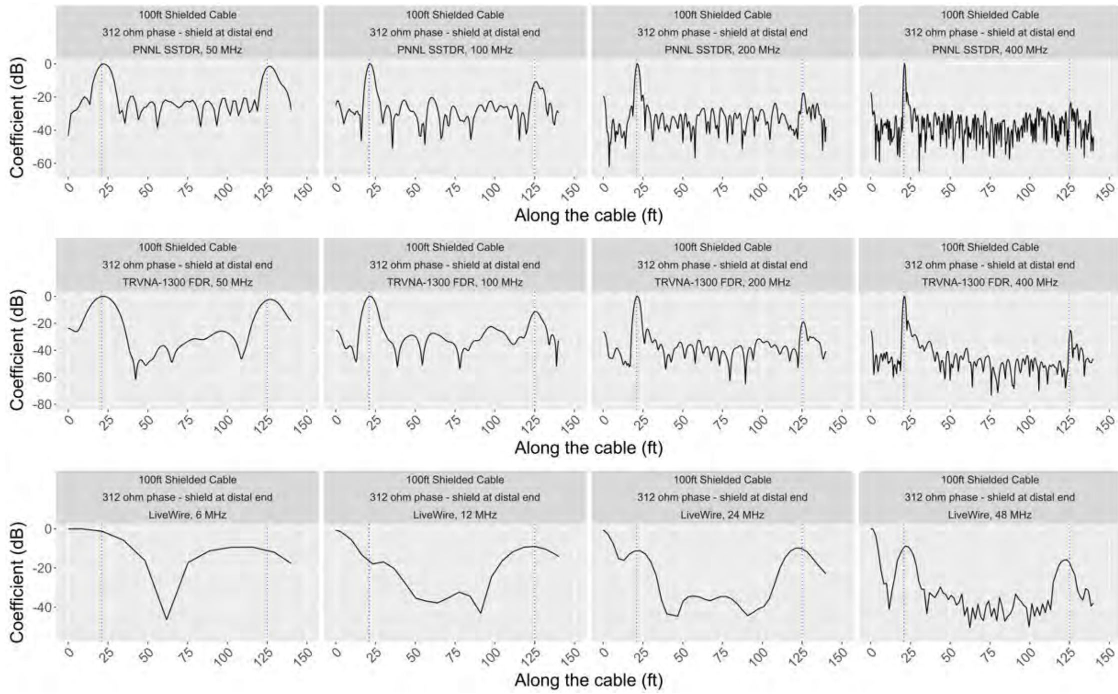
1. 100ft Shielded Cable, 100 ohm phase - shield at distal end



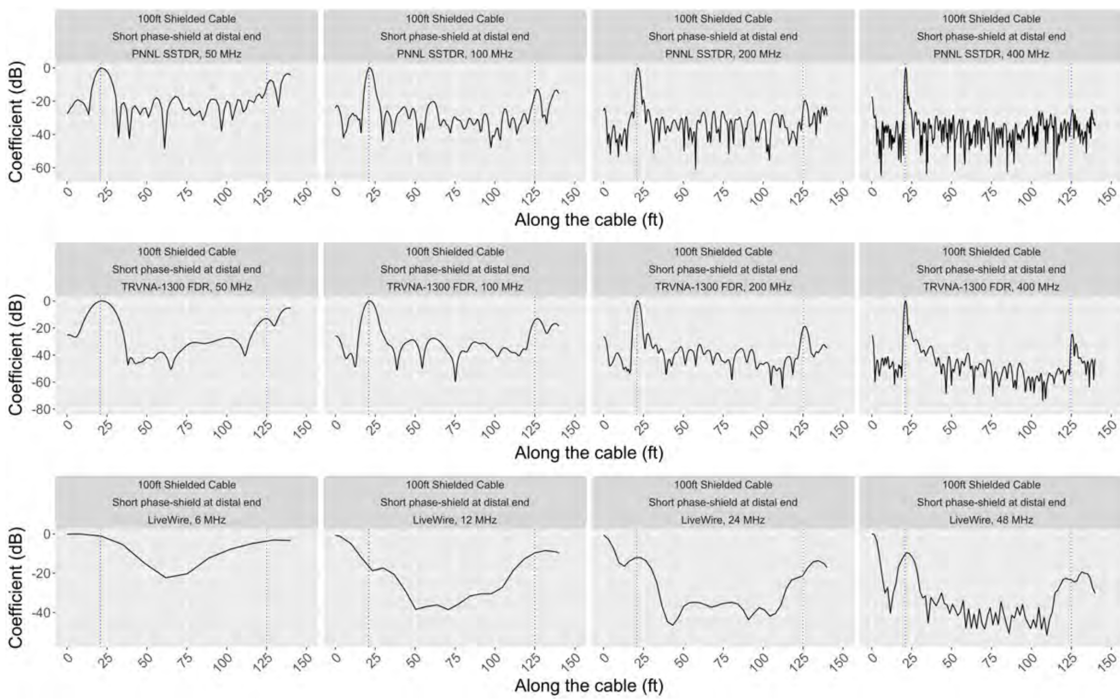
2. 100ft Shielded Cable, 2k ohm phase - shield at distal end



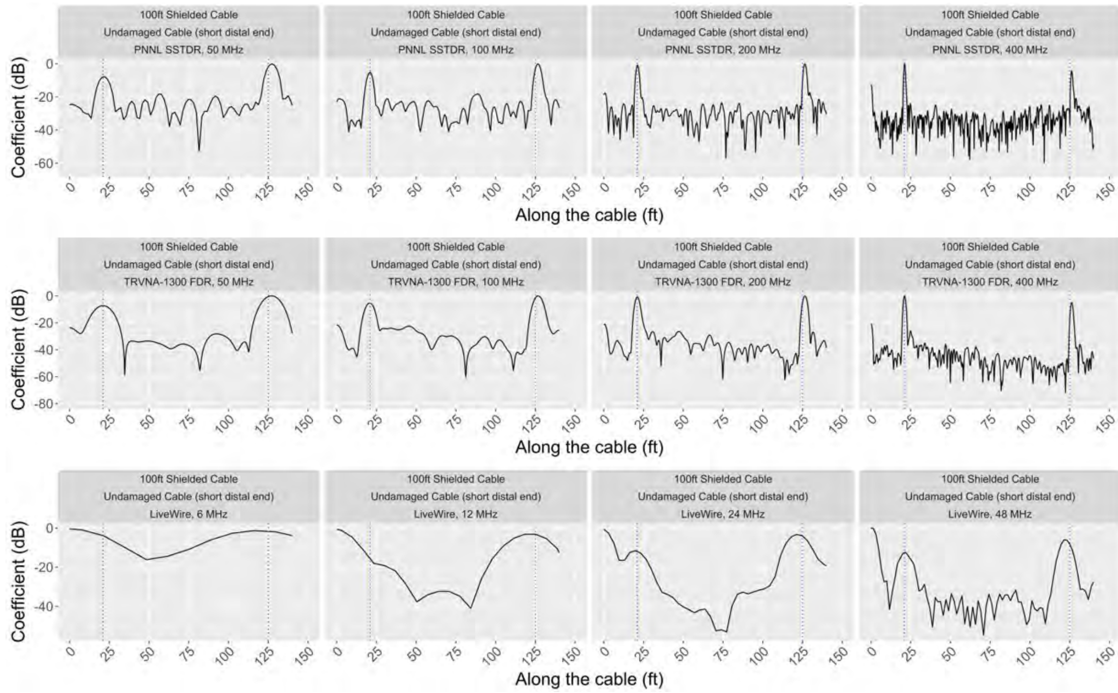
3. 100ft Shielded Cable, 312 ohm phase - shield at distal end



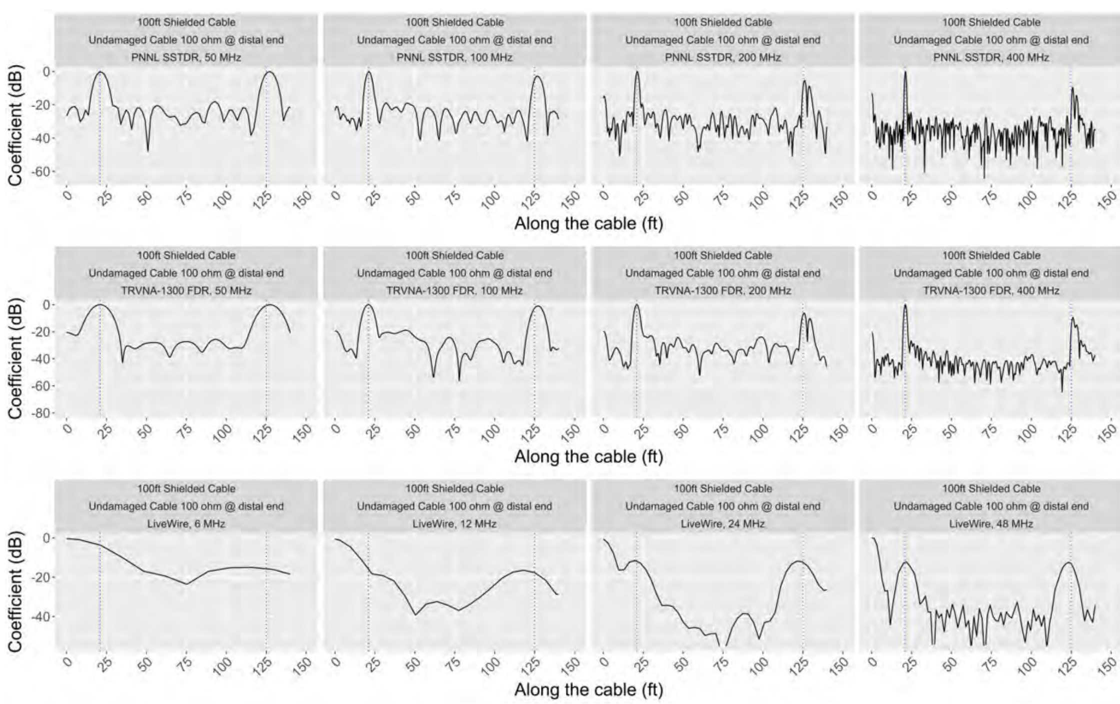
4. 100ft Shielded Cable, Short phase-shield at distal end



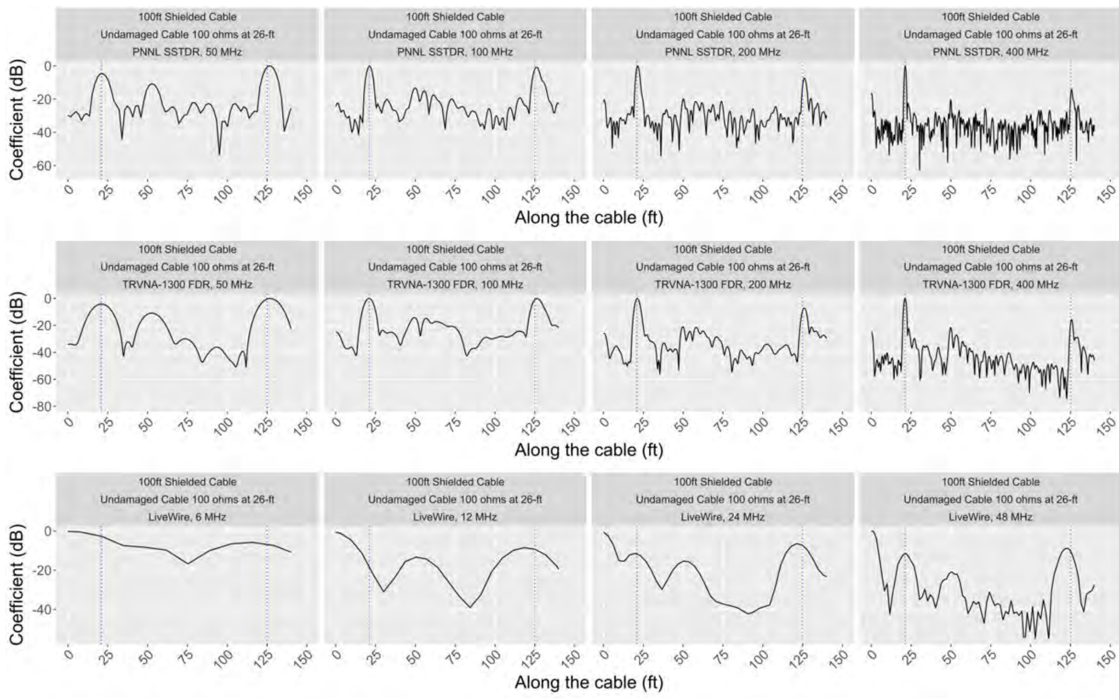
5. 100ft Shielded Cable, Undamaged Cable (short distal end)



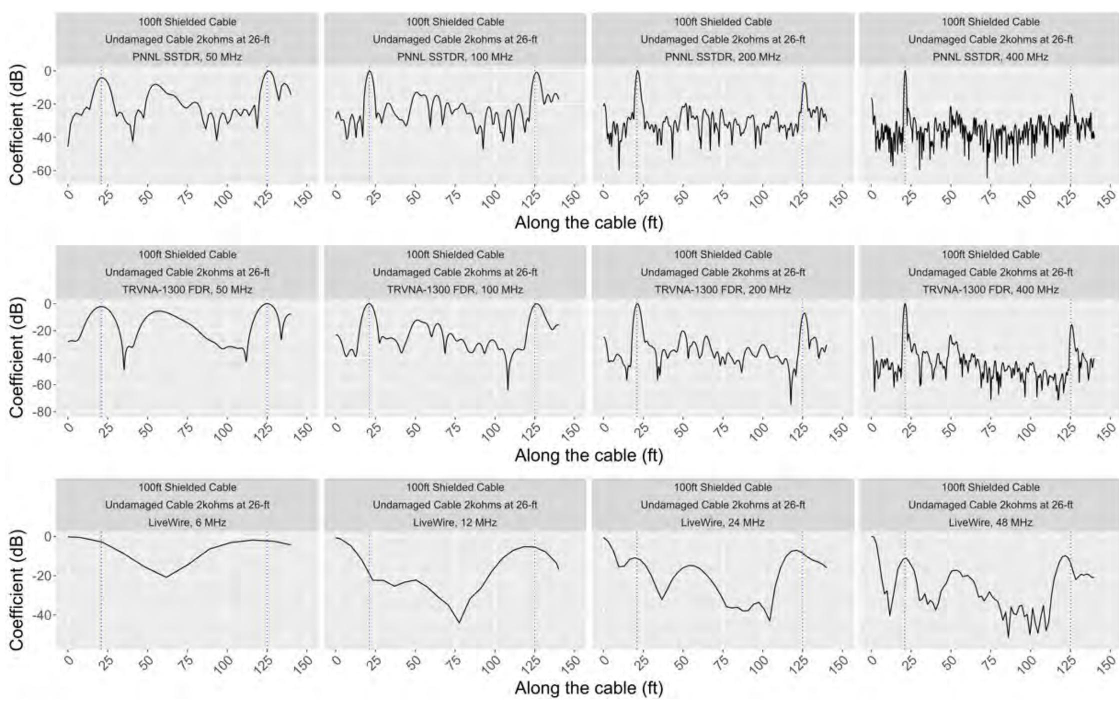
6. 100ft Shielded Cable, Undamaged Cable 100 ohm @ distal end



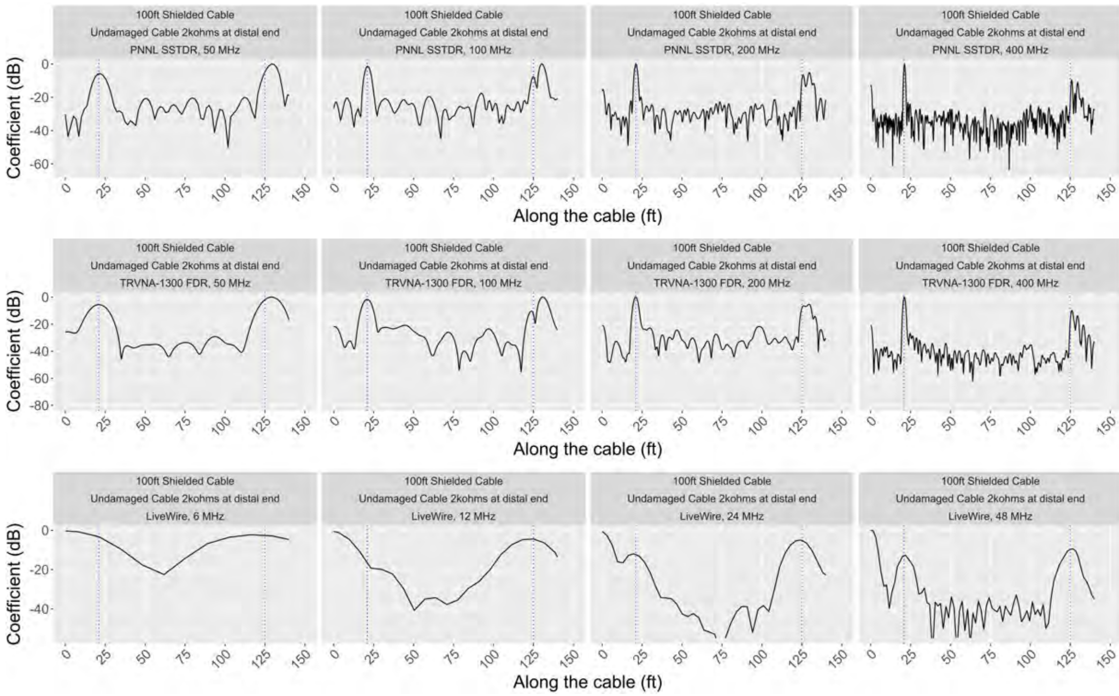
7. 100ft Shielded Cable, Undamaged Cable 100 ohms at 26-ft



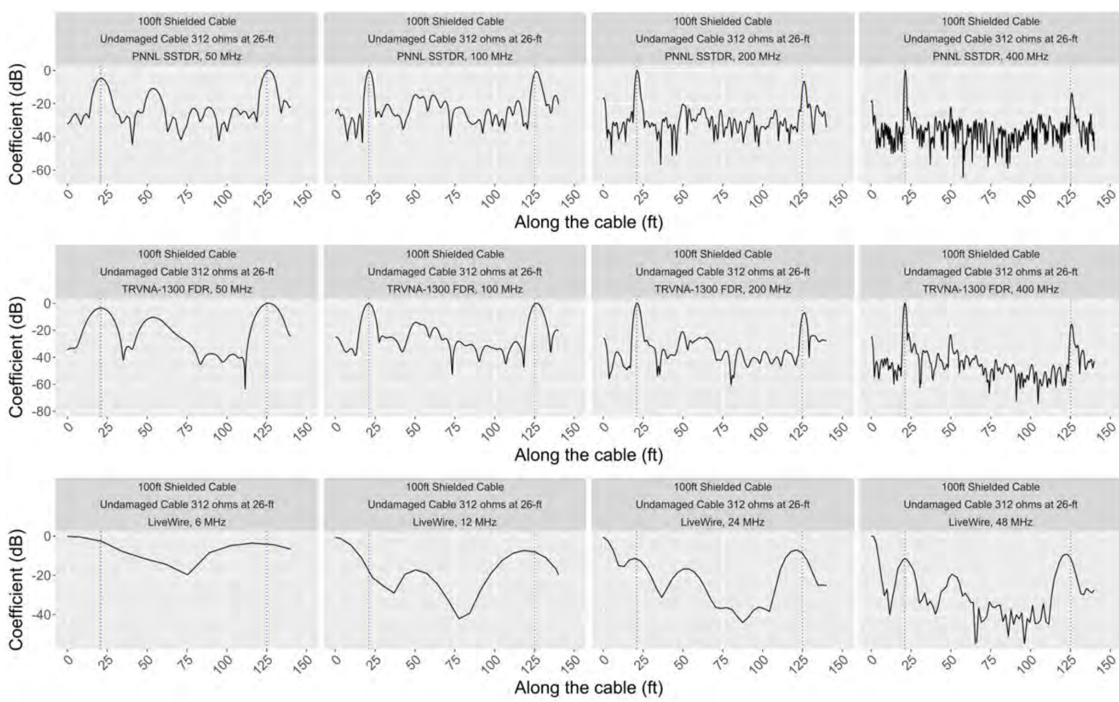
8. 100ft Shielded Cable, Undamaged Cable 2kohms at 26-ft



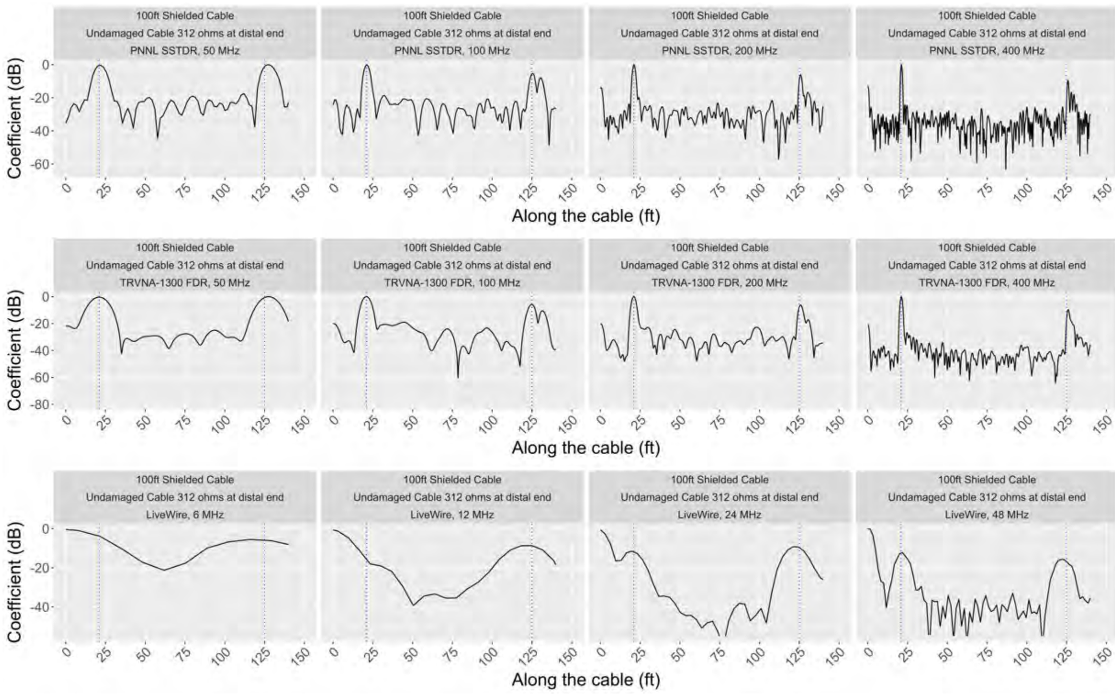
9. 100ft Shielded Cable, Undamaged Cable 2kohms at distal end



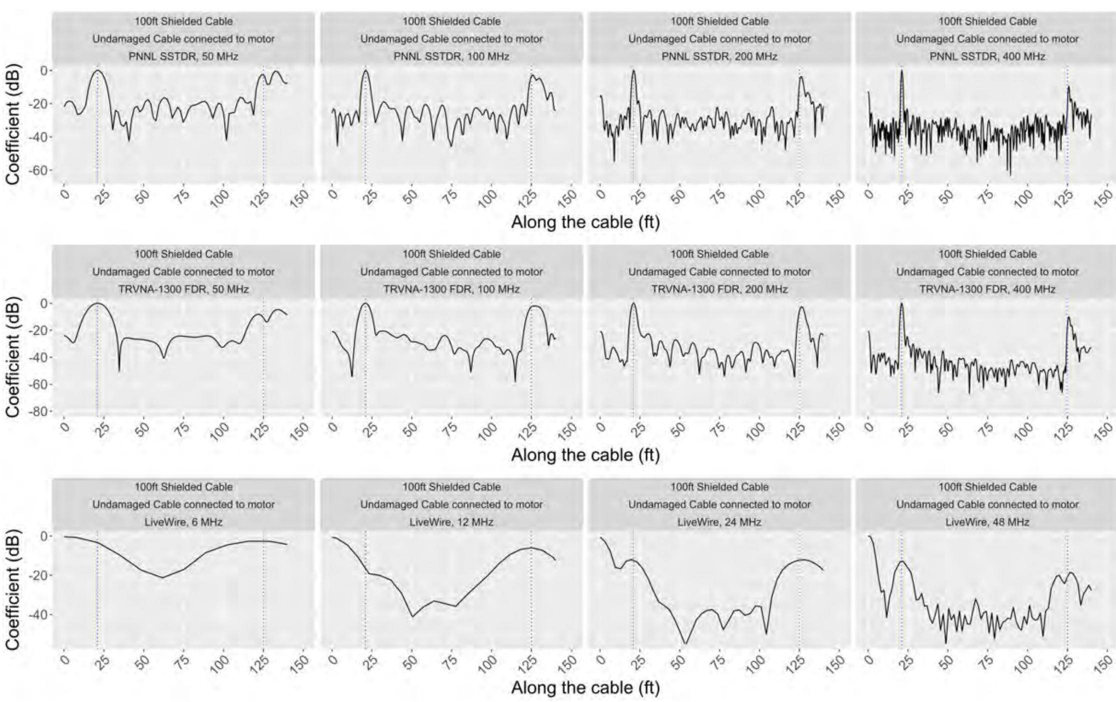
10. 100ft Shielded Cable, Undamaged Cable 312 ohms at 26-ft



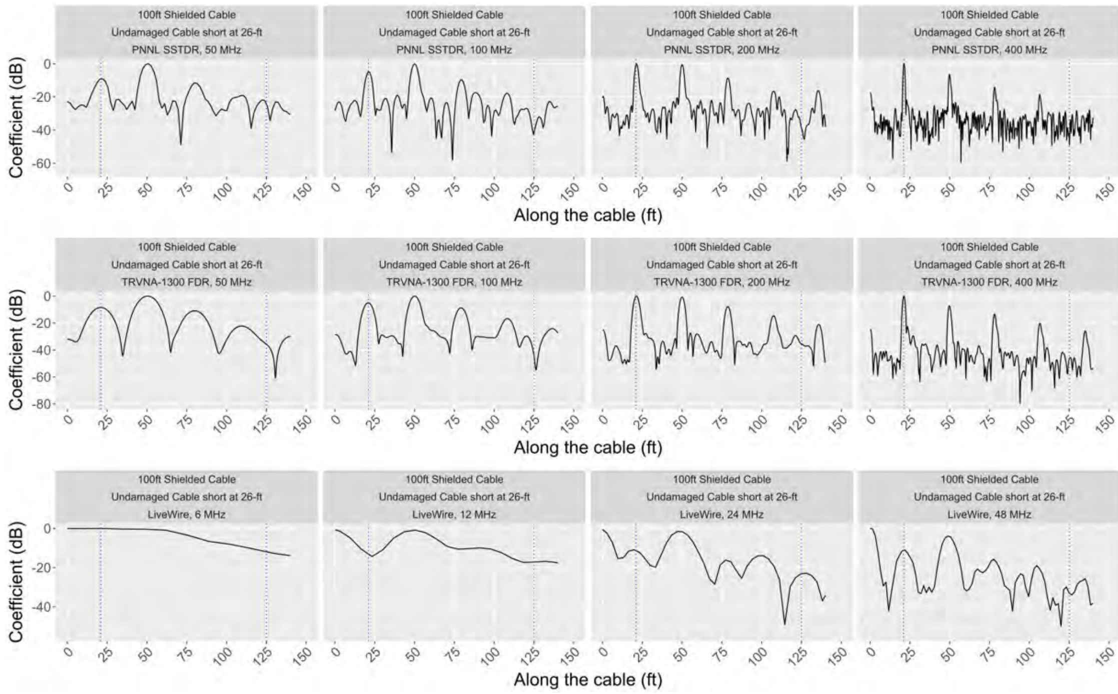
11. 100ft Shielded Cable, Undamaged Cable 312 ohms at distal end



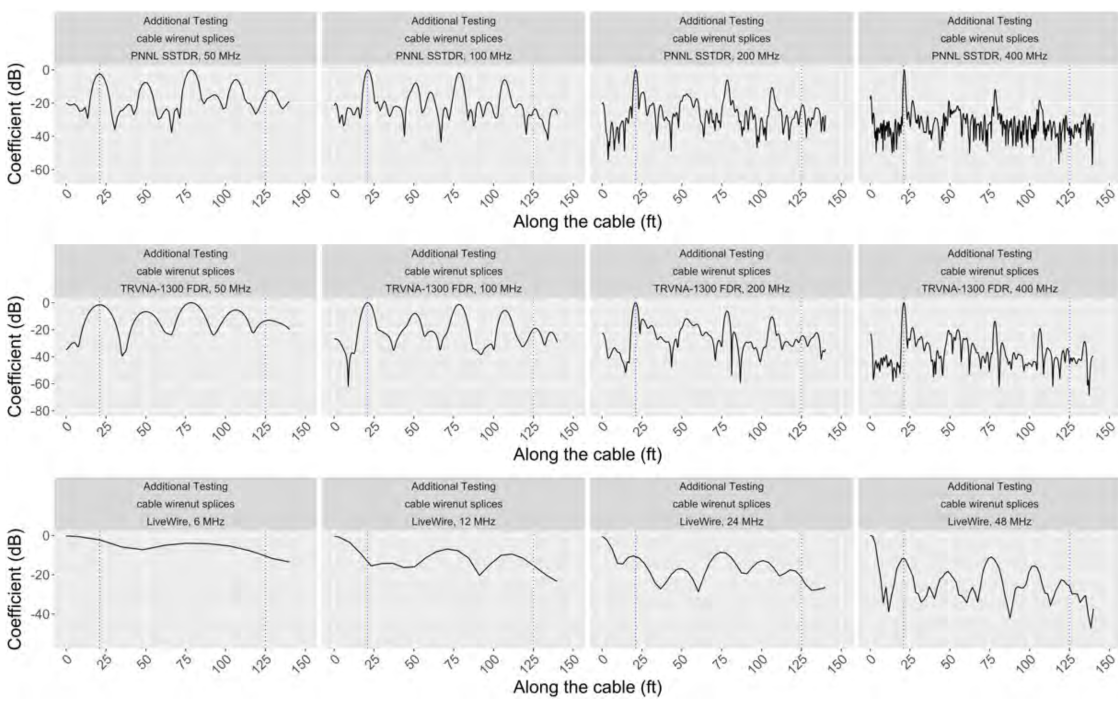
12. 100ft Shielded Cable, Undamaged Cable connected to motor



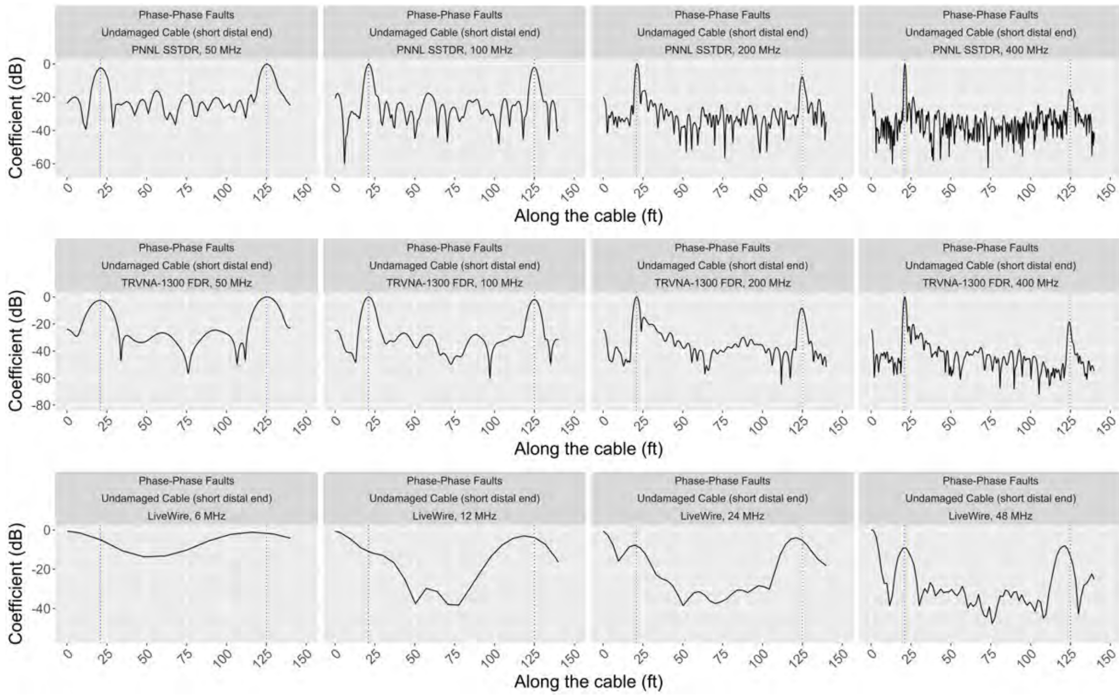
13. 100ft Shielded Cable, Undamaged Cable short at 26-ft



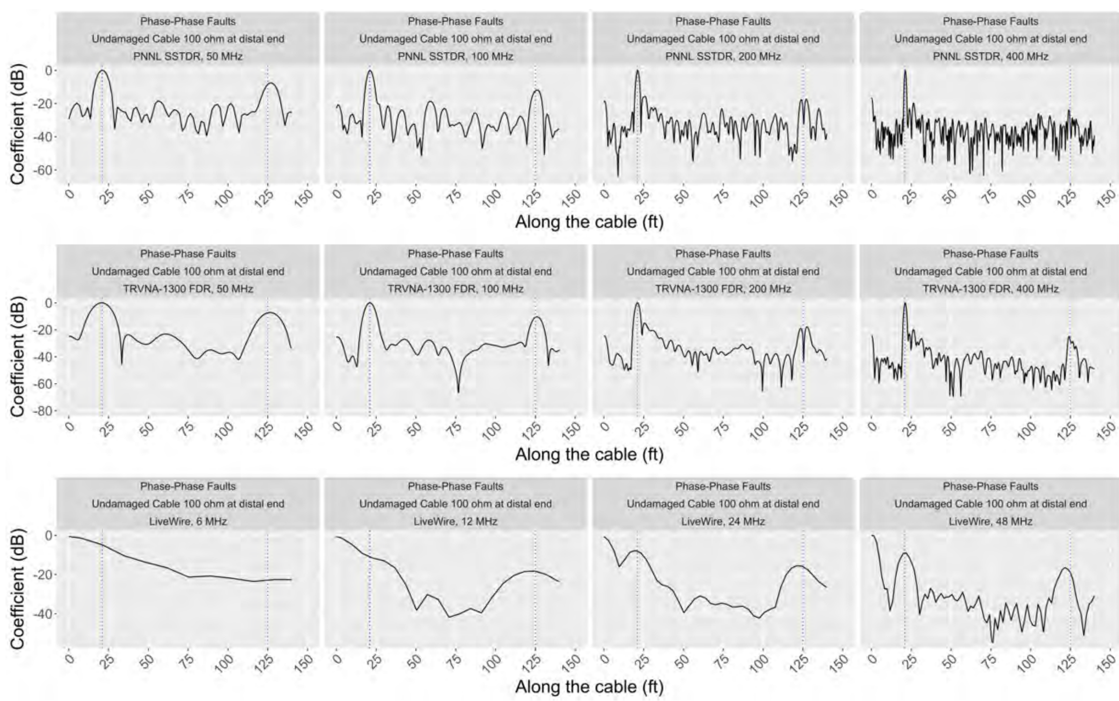
14. Additional Testing, cable wirenut splices



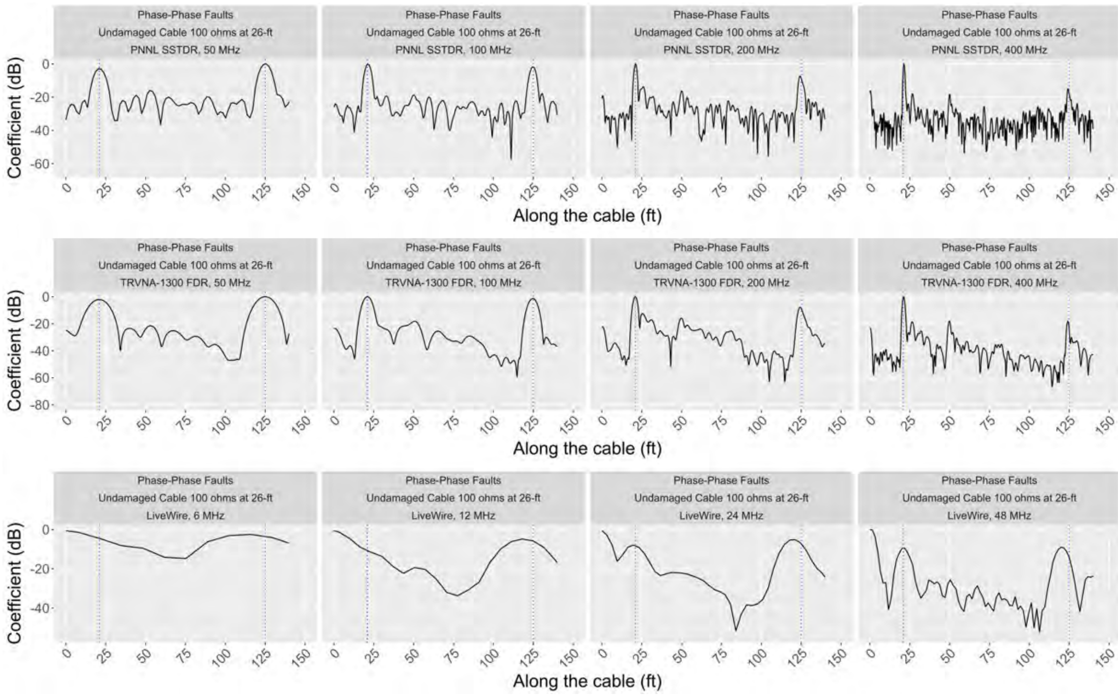
15. Phase-Phase Faults, Undamaged Cable (short distal end)



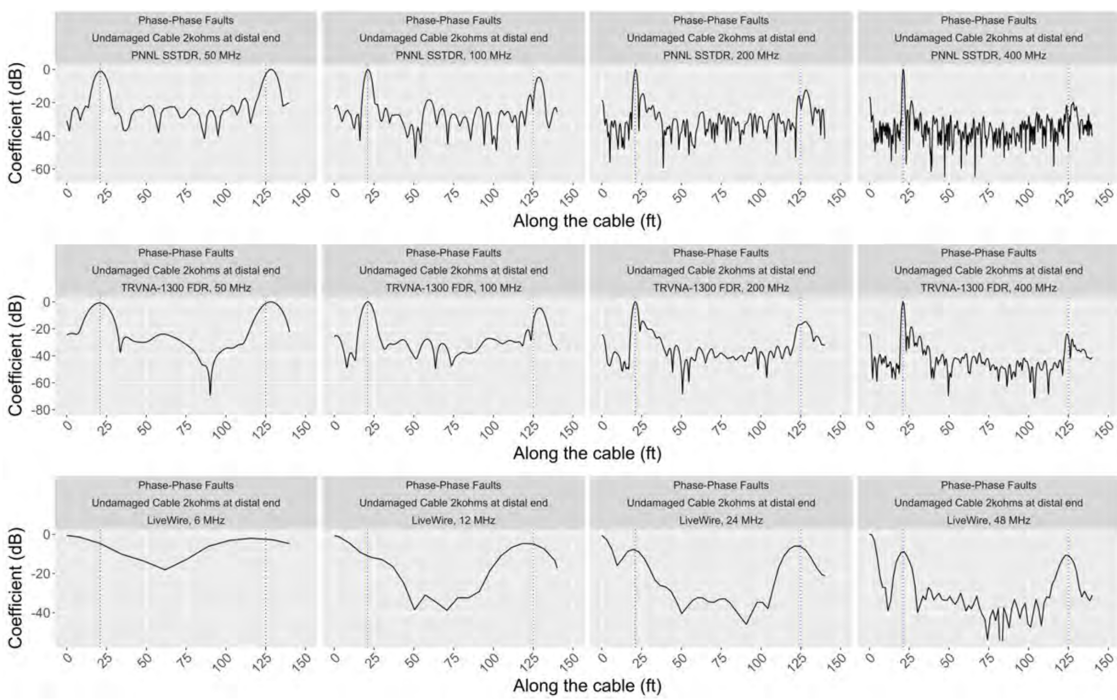
16. Phase-Phase Faults, Undamaged Cable 100 ohm at distal end



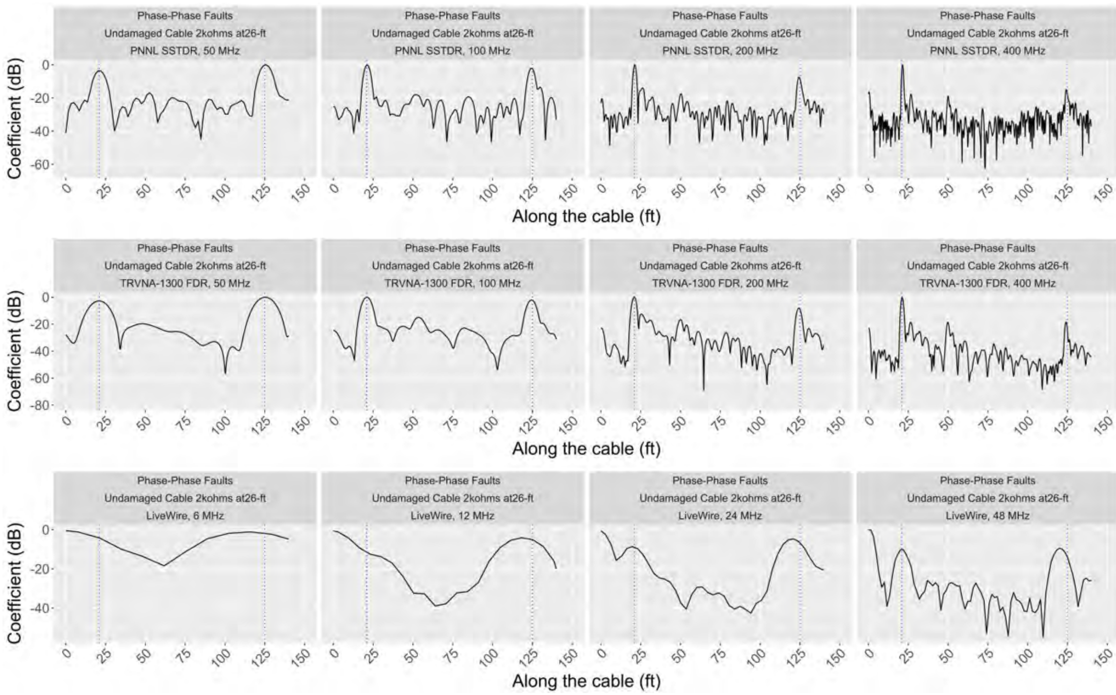
17. Phase-Phase Faults, Undamaged Cable 100 ohms at 26-ft



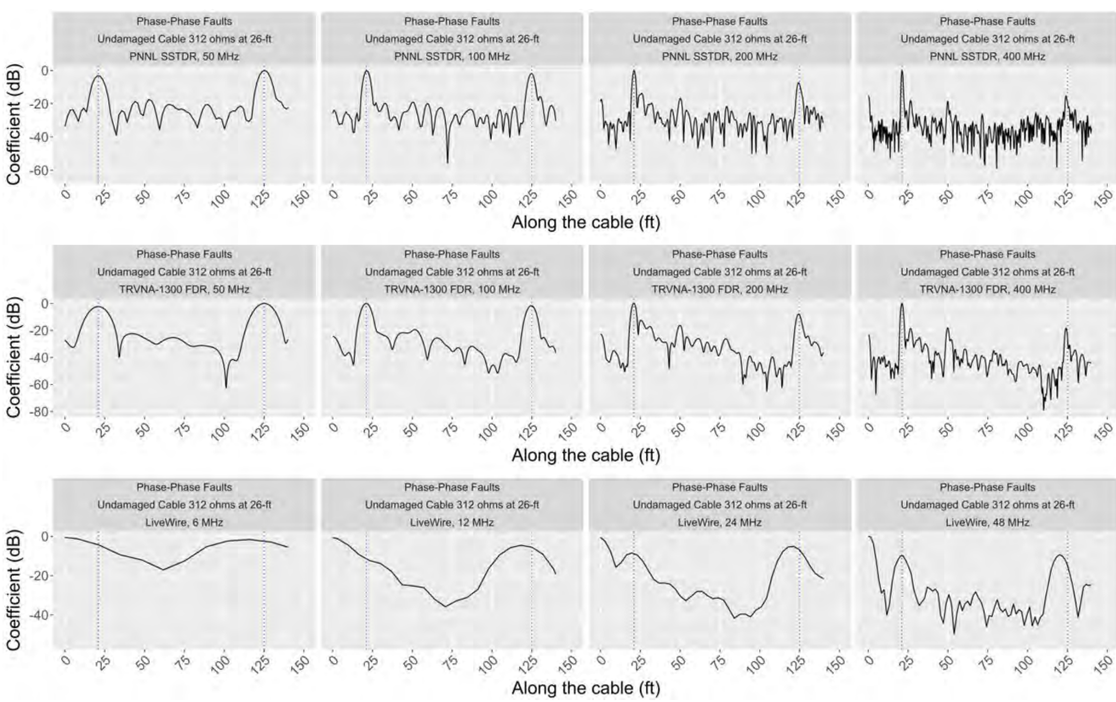
18. Phase-Phase Faults, Undamaged Cable 2kohms at distal end



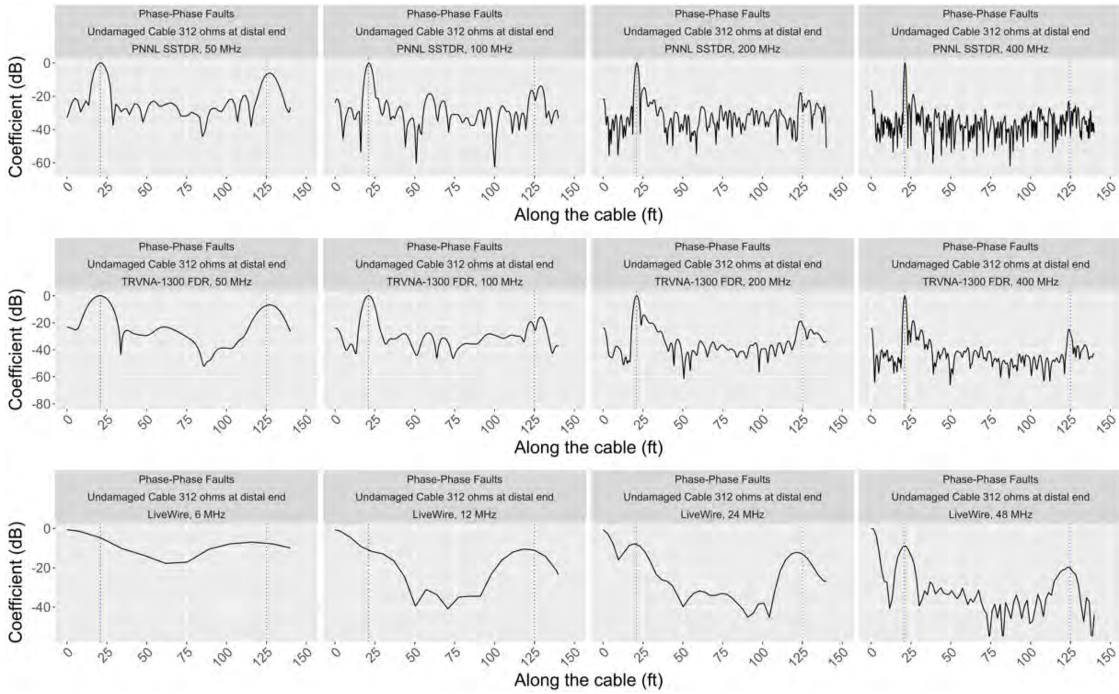
19. Phase-Phase Faults, Undamaged Cable 2kohms at26-ft



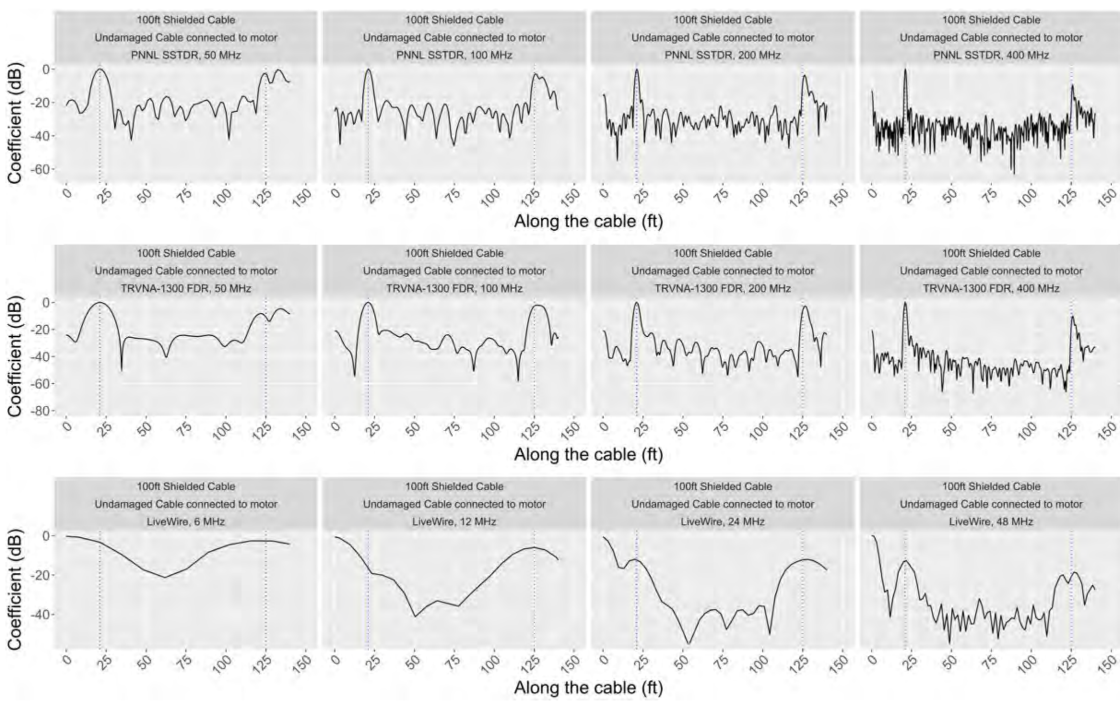
20. Phase-Phase Faults, Undamaged Cable 312 ohms at 26-ft



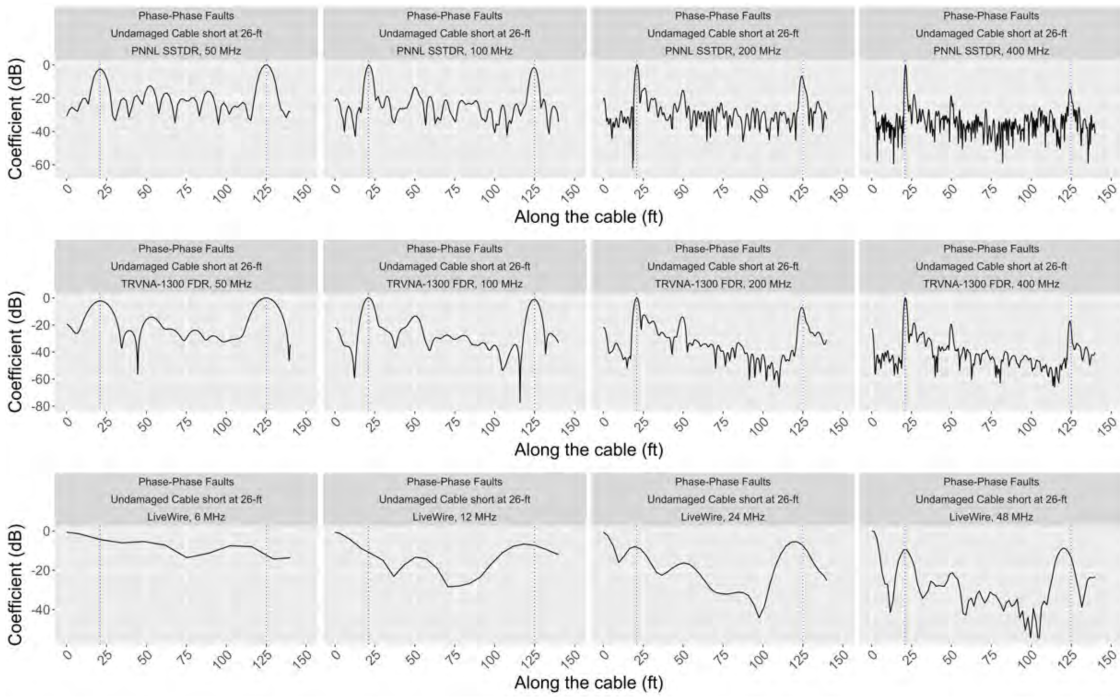
21. Phase-Phase Faults, Undamaged Cable 312 ohms at distal end



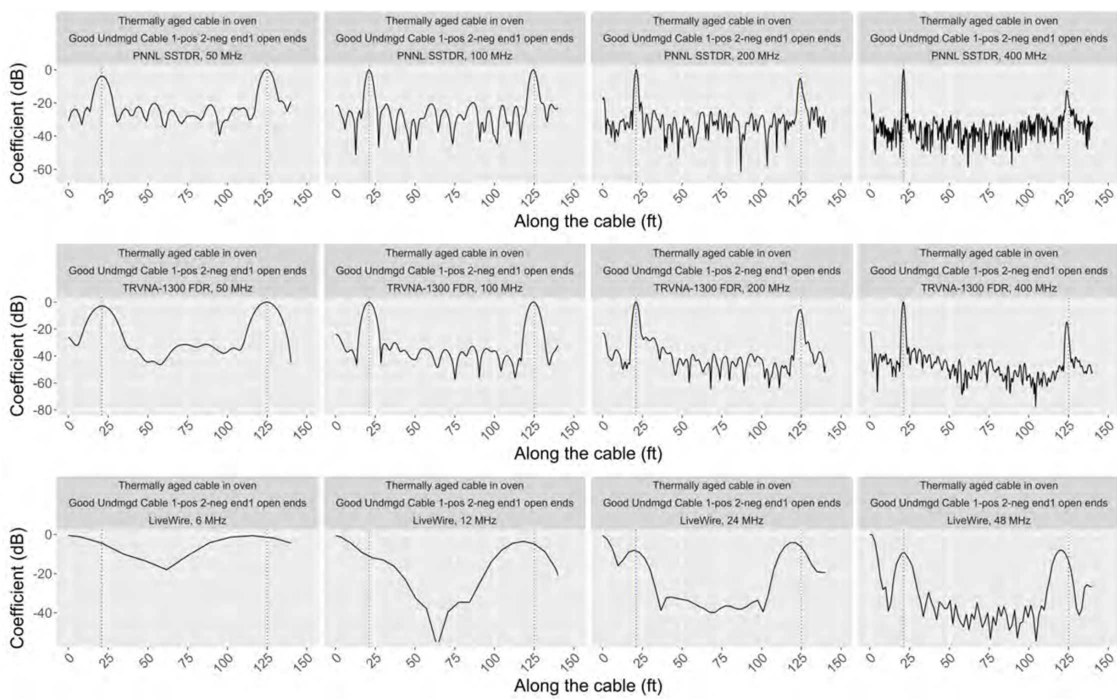
22. Phase-Phase Faults, Undamaged Cable connected to motor



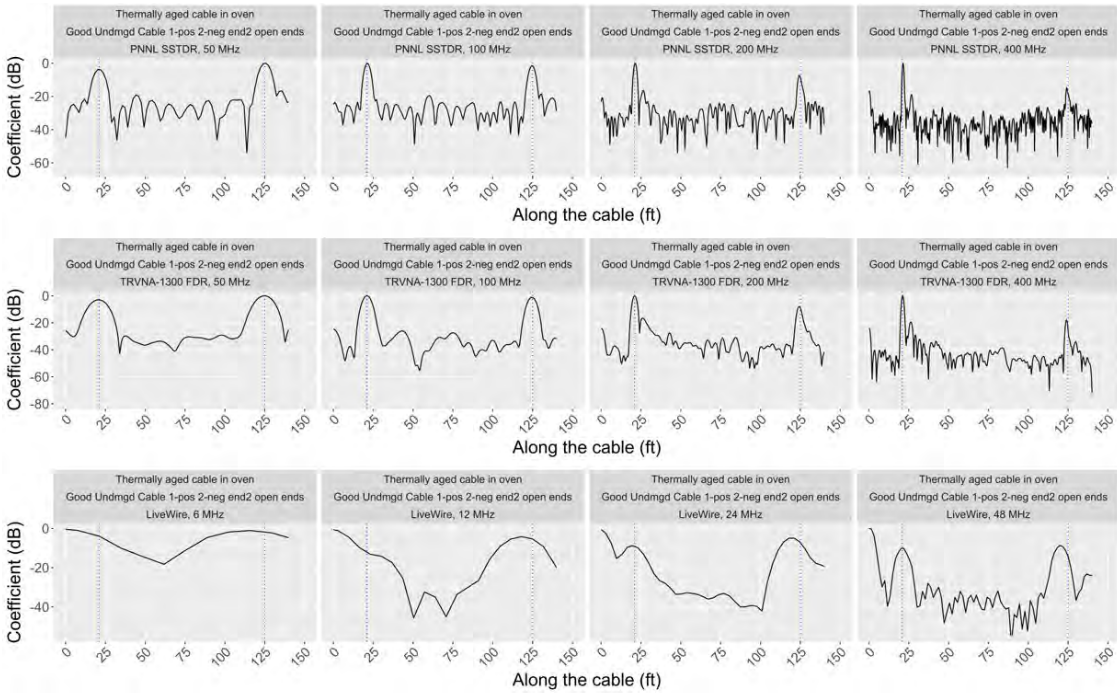
23. Phase-Phase Faults, Undamaged Cable short at 26-ft



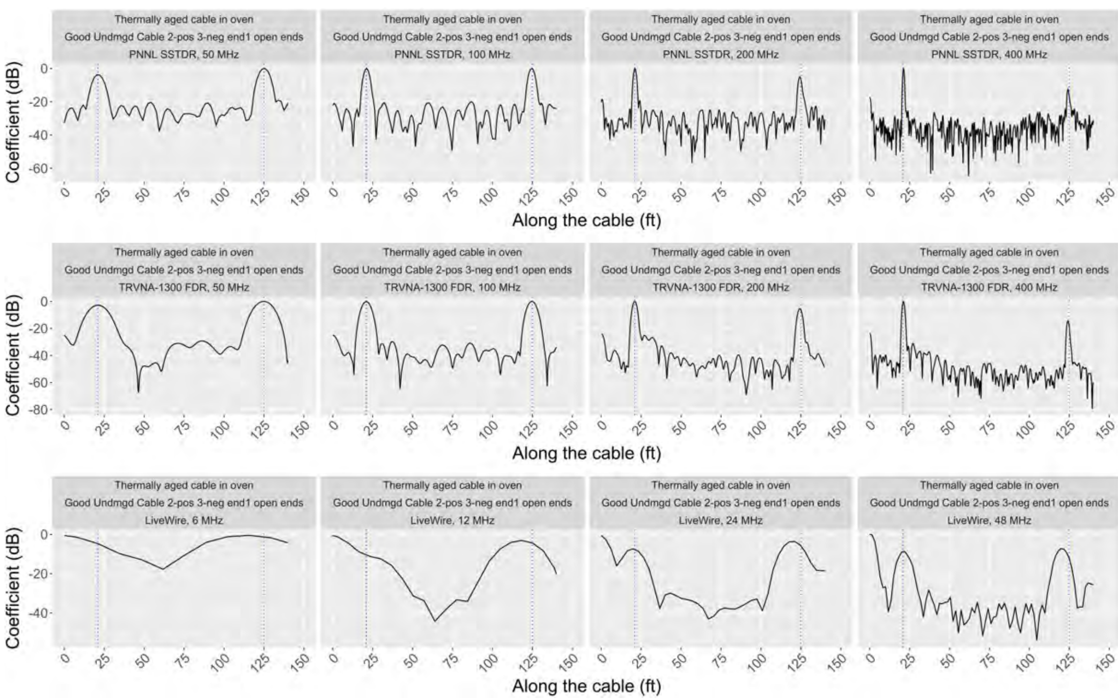
24. Thermally aged cable in oven, Good Undamaged Cable 1-pos 2-neg end1 open ends



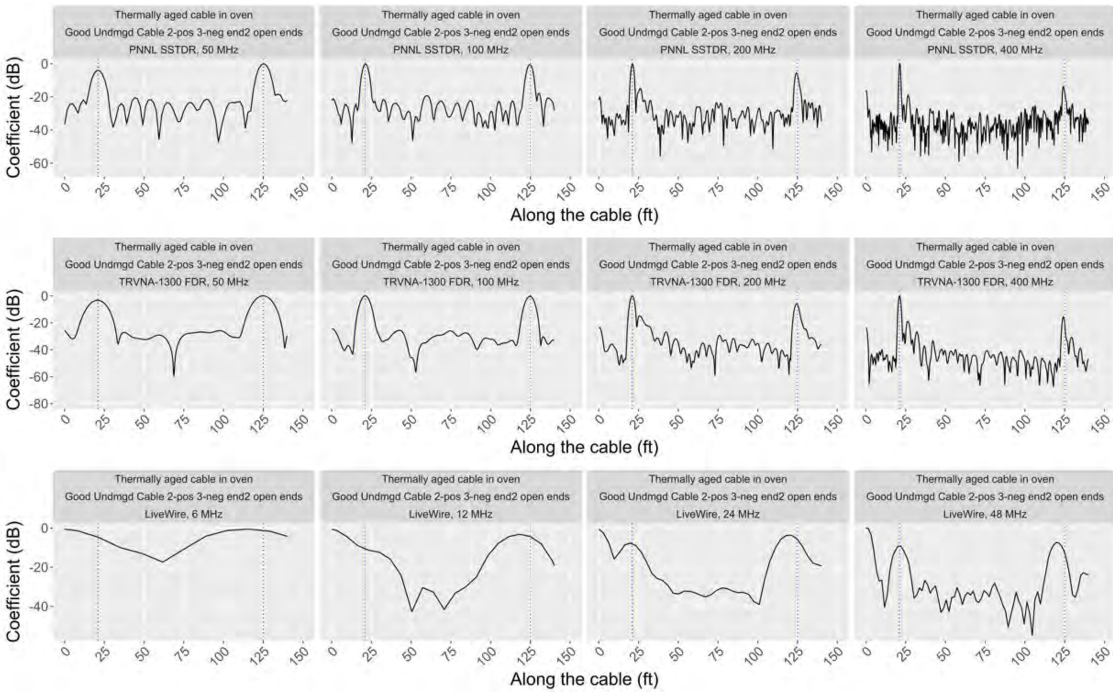
25. Thermally aged cable in oven, Good Undamaged Cable 1-pos 2-neg end2 open ends



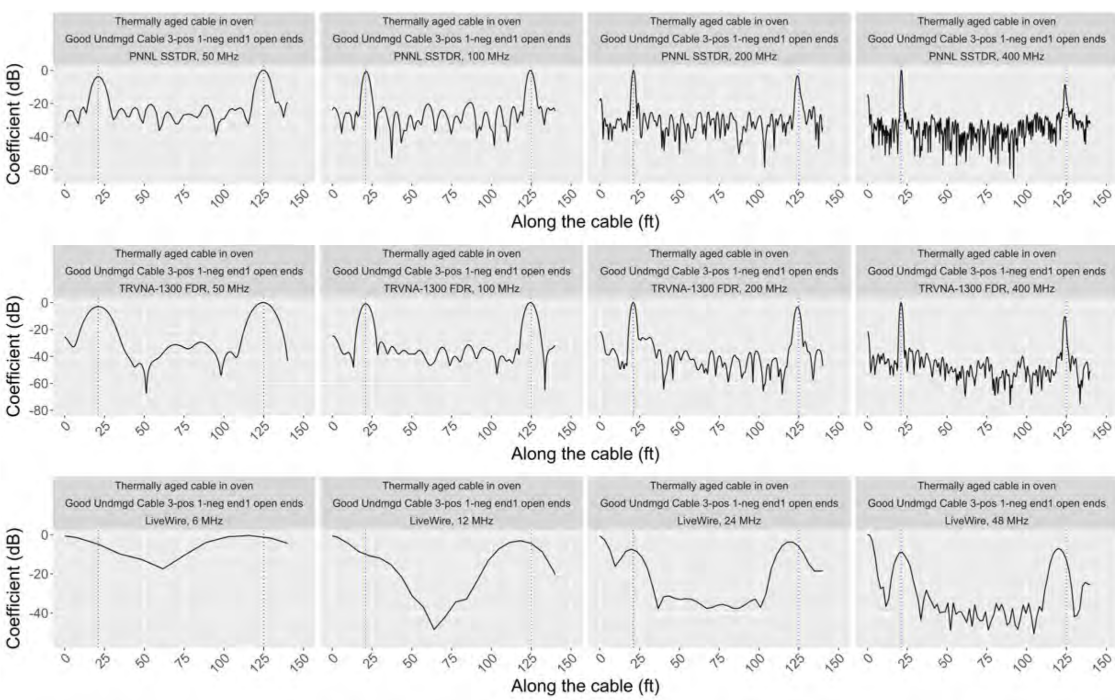
26. Thermally aged cable in oven, Good Undamaged Cable 2-pos 3-neg end1 open ends



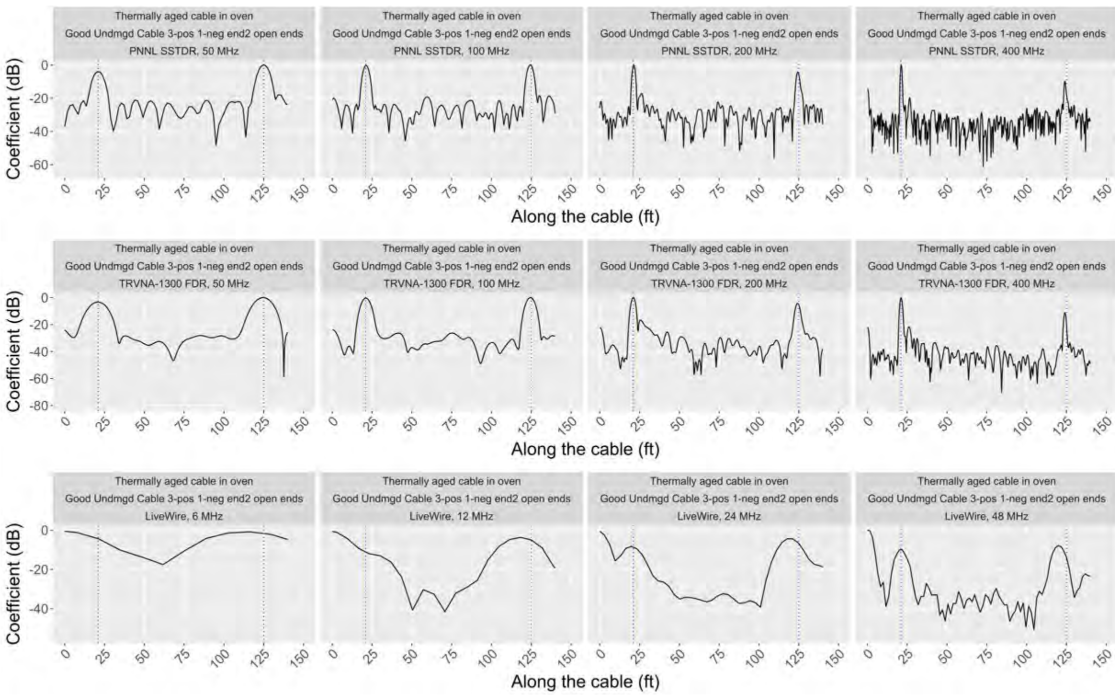
27. Thermally aged cable in oven, Good Undamaged Cable 2-pos 3-neg end2 open ends



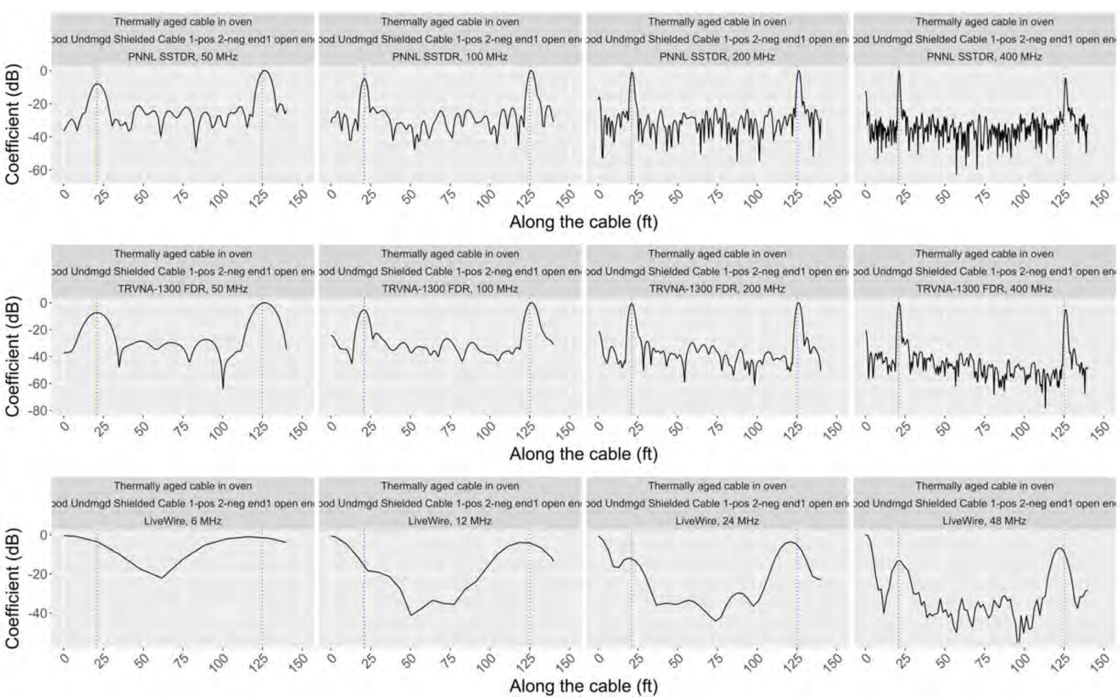
28. Thermally aged cable in oven, Good Undamaged Cable 3-pos 1-neg end1 open ends



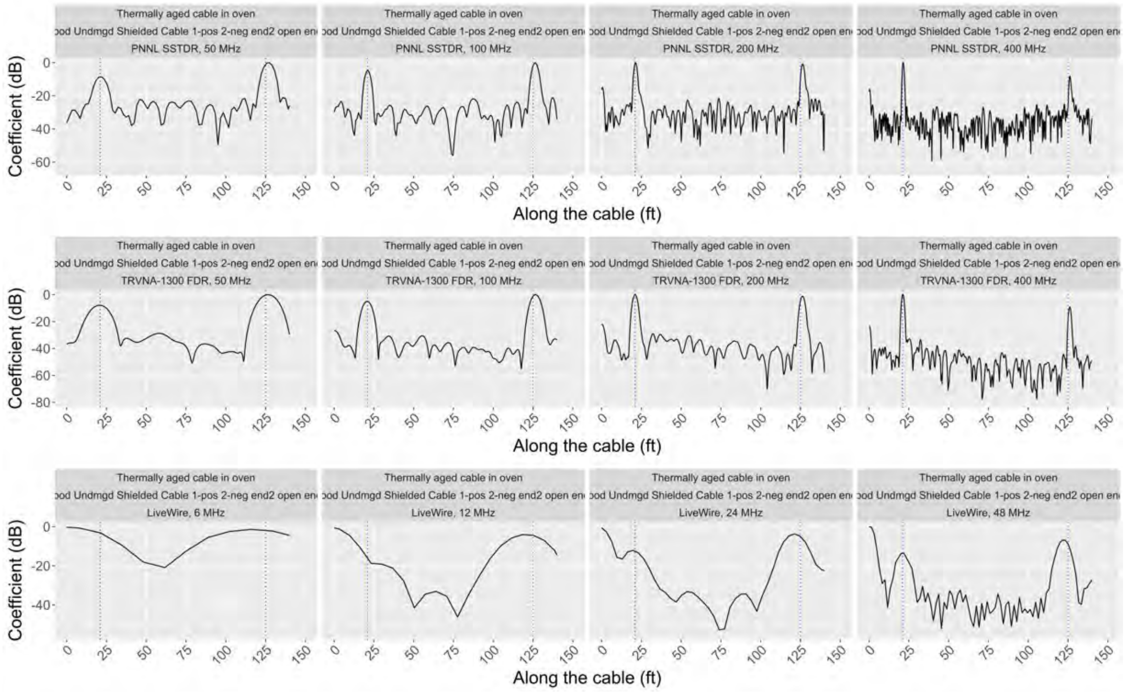
29. Thermally aged cable in oven, Good Undamaged Cable 3-pos 1-neg end2 open ends



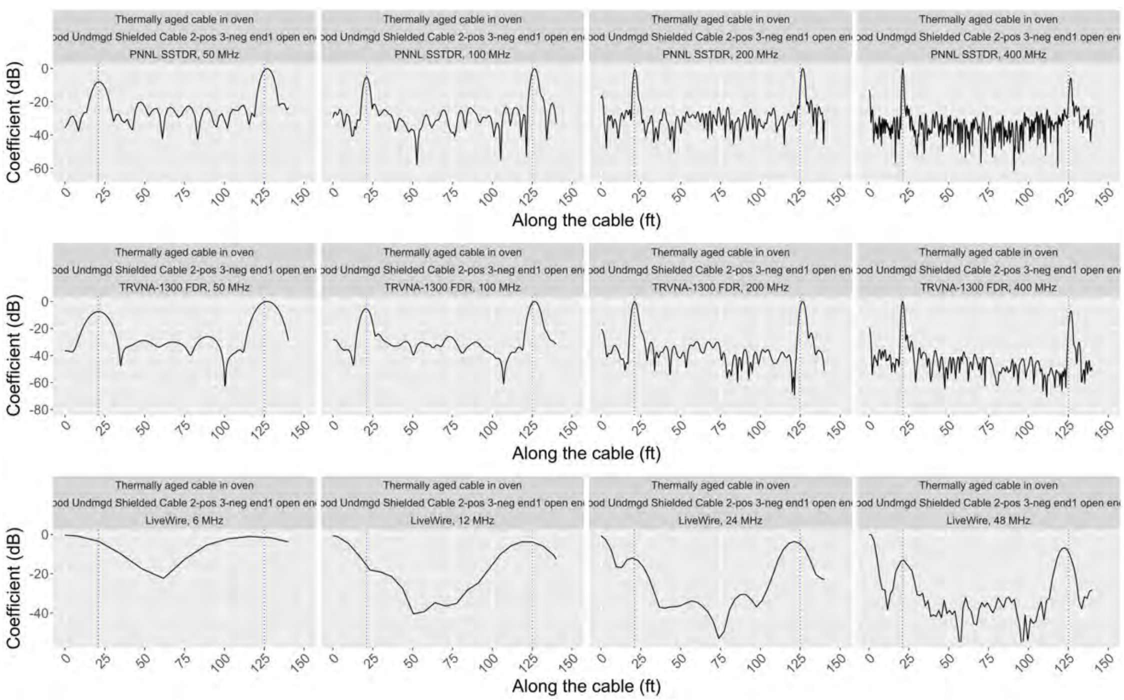
30. Thermally aged cable in oven, Good Undamaged Shielded Cable 1-pos 2-neg end1 open ends



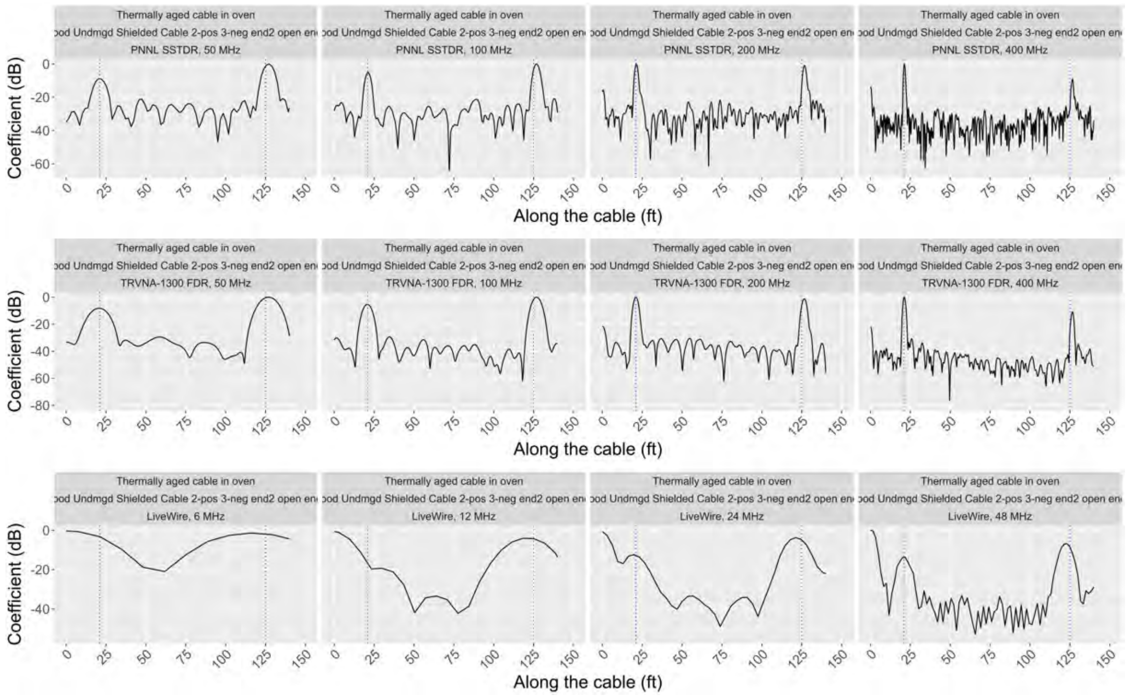
31. Thermally aged cable in oven, Good Undamaged Shielded Cable 1-pos 2-neg end2 open ends



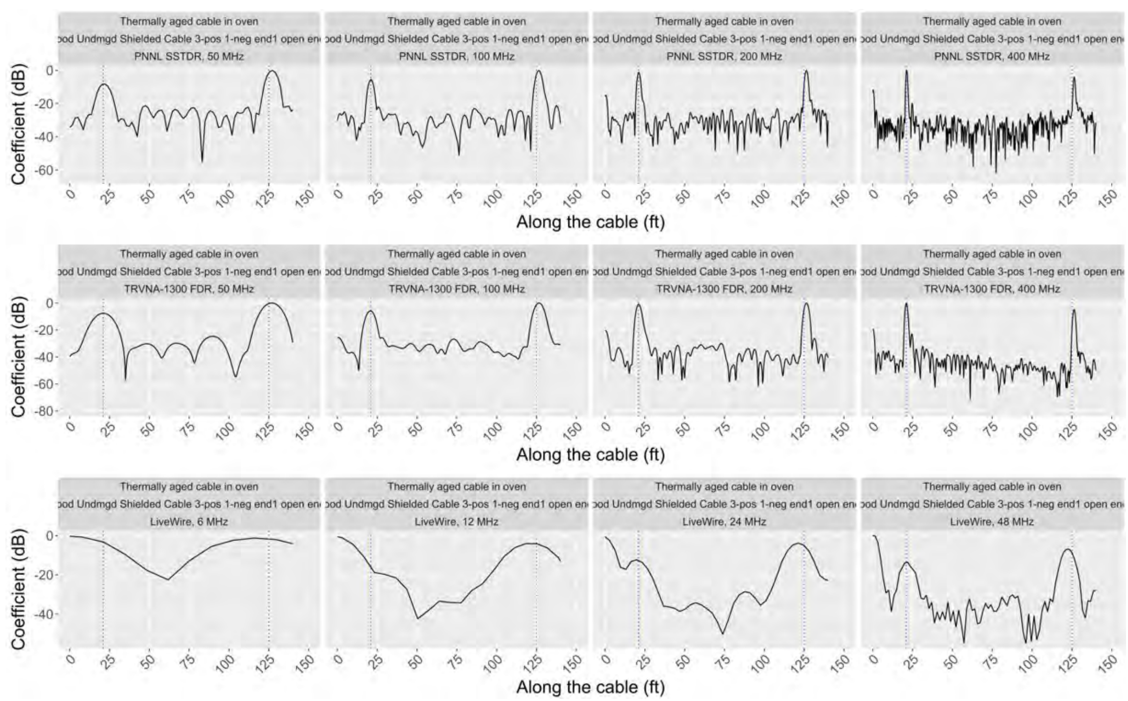
32. Thermally aged cable in oven, Good Undamaged Shielded Cable 2-pos 3-neg end1 open ends



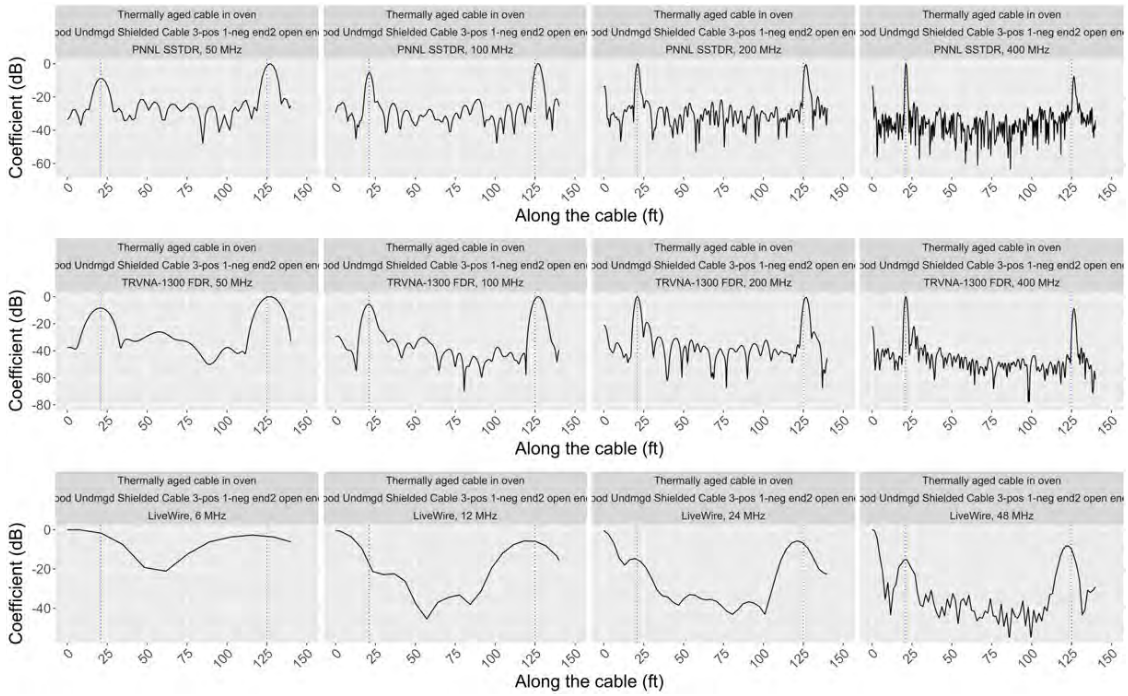
33. Thermally aged cable in oven, Good Undamaged Shielded Cable 2-pos 3-neg end2 open ends



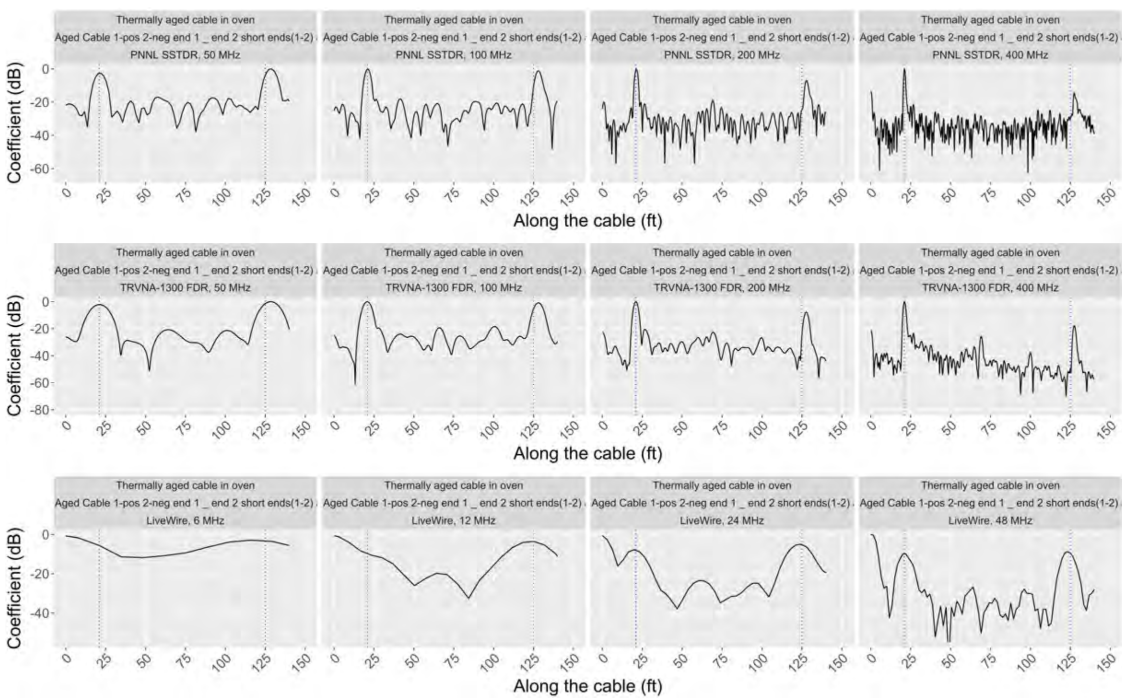
34. Thermally aged cable in oven, Good Undamaged Shielded Cable 3-pos 1-neg end1 open ends



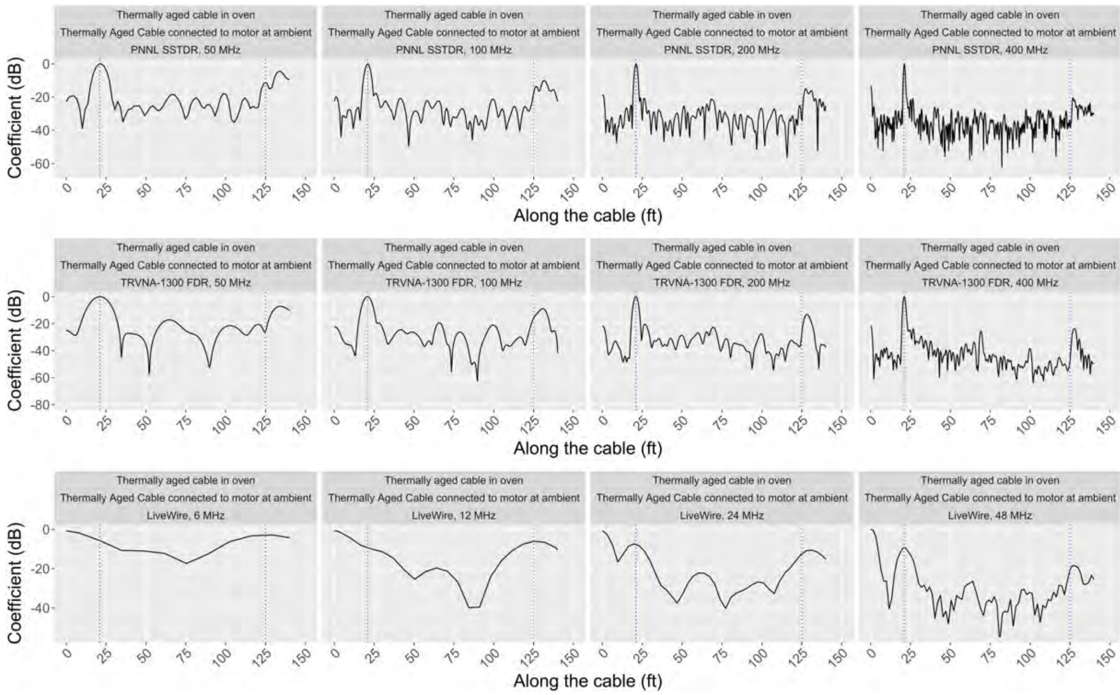
35. Thermally aged cable in oven, Good Undamaged Shielded Cable 3-pos 1-neg end2 open ends



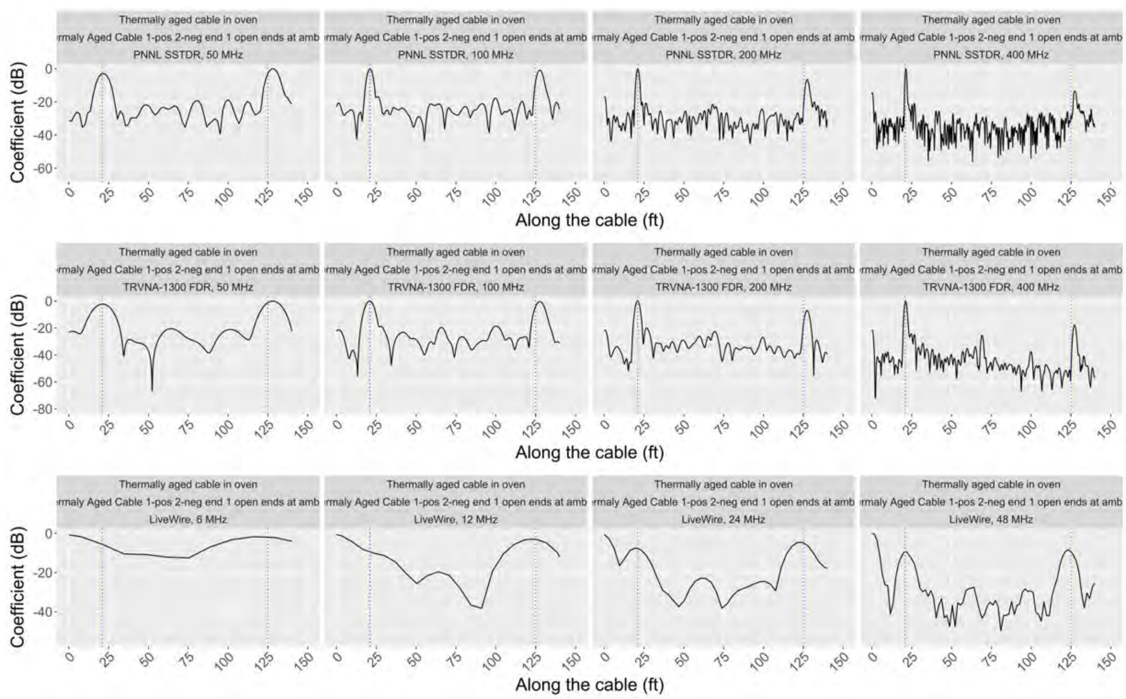
36. Thermally aged cable in oven, Thermally Aged Cable 1-pos 2-neg end 1 _ end 2 short ends(1-2) at ambient



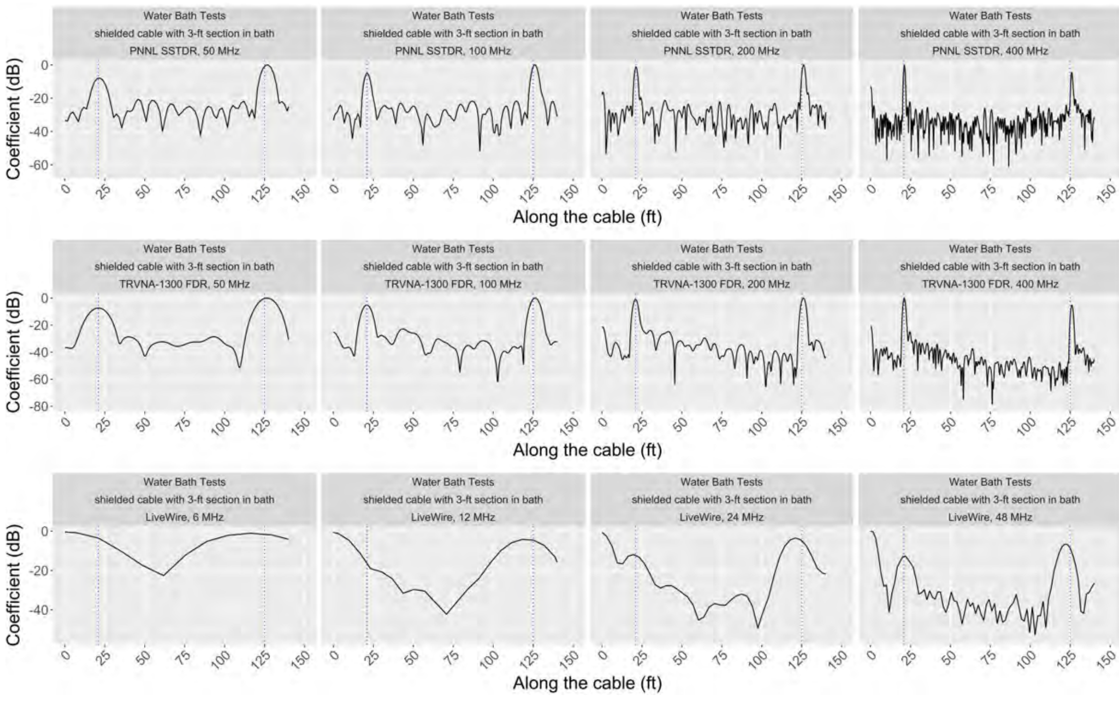
37. Thermally aged cable in oven, Thermally Aged Cable connected to motor at ambient



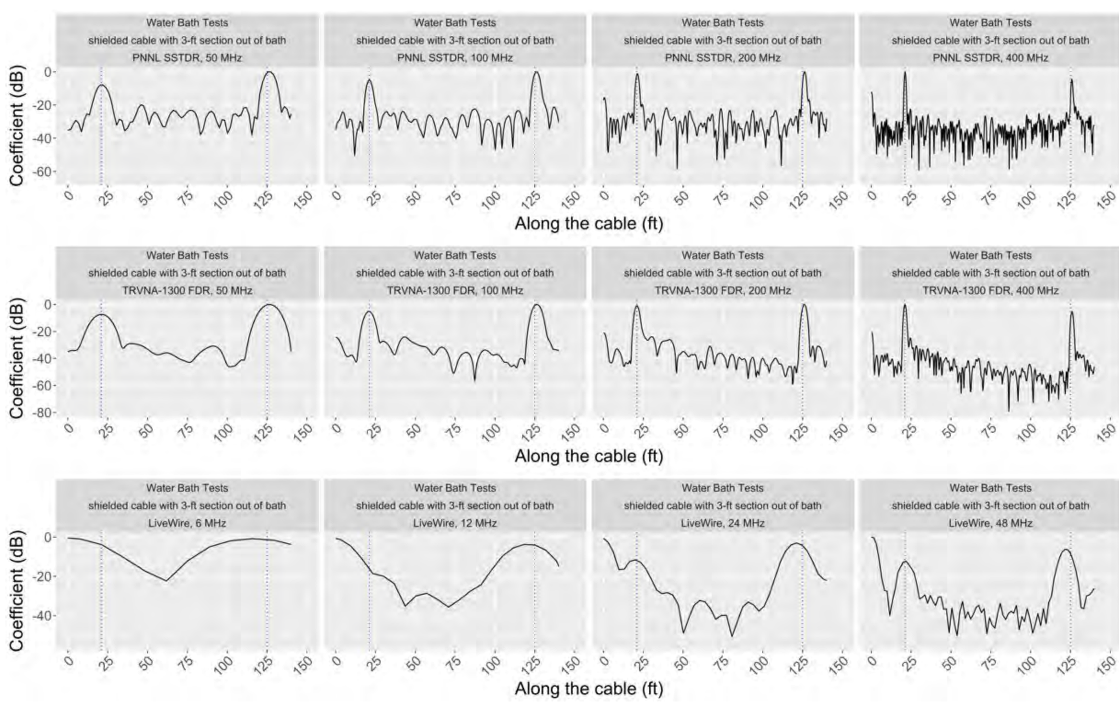
38. Thermally aged cable in oven, Thermaly Aged Cable 1-pos 2-neg end 1 open ends at ambient.



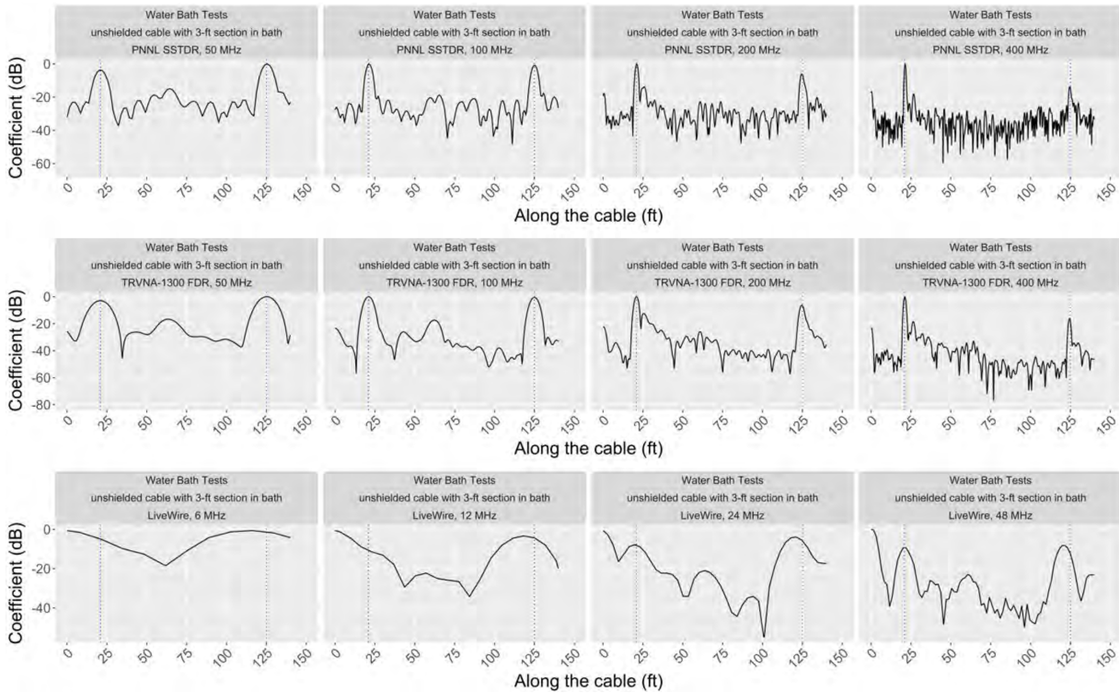
39. Water Bath Tests, shielded cable with 3-ft section in bath



40. Water Bath Tests, shielded cable with 3-ft section out of bath



41. Water Bath Tests, unshielded cable with 3-ft section in bath



42. Water Bath Tests, unshielded cable with 3-ft section out of bath