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Wire System Aging Assessment and Condition Monitoring (WASCO)

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April 2007

Abstract

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains some test results of a method for wire system condition monitoring, developed at the Halden Reactor Project, called LIRA (LIne Resonance Analysis), which can be used on-line to detect any local or global changes in the cable electrical parameters as a consequence of insulation faults or degradation.

Key words

Condition monitoring, cable aging, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA, positron

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Abstract

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains some test results of a method for wire system condition monitoring, developed at the Halden Reactor Project, called LIRA (LIne Resonance Analysis), which can be used on-line to detect any local or global changes in the cable electrical parameters as a consequence of insulation faults or degradation.

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Introduction

There is a continued interest worldwide [1] in the safety aspects of electrical wire (cable) system aging in industrial installations. Aging of a wire system can result in loss of critical functions of the equipment energized by the system, or in loss of critical information relevant to the decision making process and operator actions. In either situation, unanticipated or premature aging of a wire system can lead to unavailability of equipment important to safety and compromise public health and safety.

The U.S. White House National Science and Technology Council Committee on Technology has issued a report in 2000 [2] where safety issues on wire systems were addressed. The conclusions of this report are important to understand the weak points of the current status and which topics should be addressed in future research. The recommendations of the Committee can be summarised as follows:

- Increase co-operation between industry and research institutes, also internationally.
- Improve design and functionality of wire systems.
- Develop advanced wire system condition monitoring techniques.

Current techniques to evaluate aging properties of electric cables include electric properties tests [3,4]. While known to be difficult, advancements in detection systems and computerised data analysis techniques may allow ultimate use of electrical testing to predict future behaviour and residual life of cables.

The LIRA method

LIRA is based on transmission line technology, like Time Domain Reflectometry (TDR). However, it enhances the diagnosis performance by including a proprietary algorithm to evaluate an accurate line impedance spectrum from noise measurements. Figure 1 shows the estimated impedance for a PVC instrument cable 100m long, in the 0-10 MHz range.

Line impedance estimation is the basis for local and global degradation assessment. Tests performed with LIRA show that thermal degradation of the wire insulation and mechanical damage on the jacket and/or the insulation do have an impact on the insulation capacitance C and at a lesser degree on the conductor inductance L. Direct measurement of C (and L) would not be effective because the required sensitivity has the same magnitude of the achievable accuracy, due to the environment noise normally present in installed cables (especially for unshielded twisted pair cables. Some results were achieved with coaxial cables [4]). LIRA monitors C variations through its impact on the complex line impedance, taking advantage of the strong amplification factor on some properties of the phase and amplitude of the impedance figure.

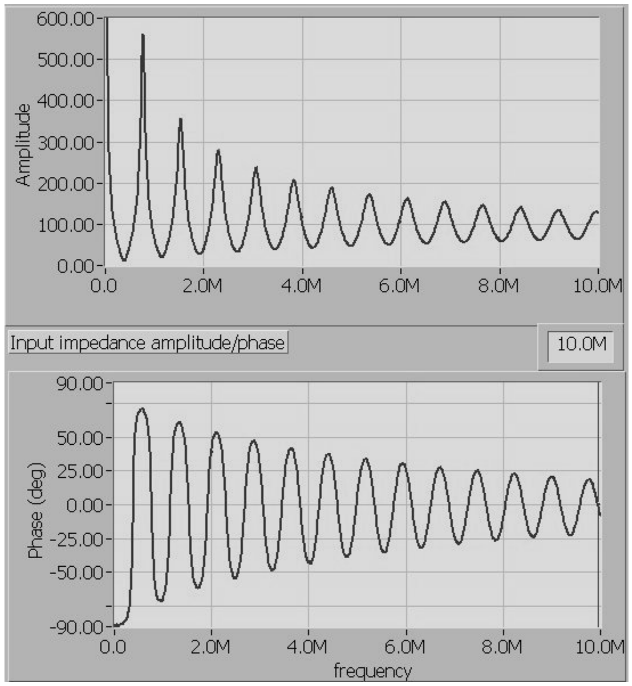

Figure 1. Impedance of an unmatched transmission line.

One of these possible monitoring techniques is the so called zero-crossing phase monitoring method [3], that can be used to monitor and assess cable global degradation. This method tries to correlate the impedance phase shift from zero (a resonance condition) to the insulation degradation. Although LIRA implements also this technique, it has the following drawbacks:

Resonance values (and the corresponding zero-crossing conditions) do not depend only on the cable electric parameters, but also on the cable length and the reactive component of the connected load. In other words, this technique needs a reference for each tested cable (not just each cable type), from which a zero-crossing deviation can be monitored. This method is effective for continuous real-time monitoring of cable state (for example in aerospace applications), but not for diagnosing degradation in old installed cables.

It is difficult to discriminate between cable faults (degradation) and load faults (changes in load reactance).

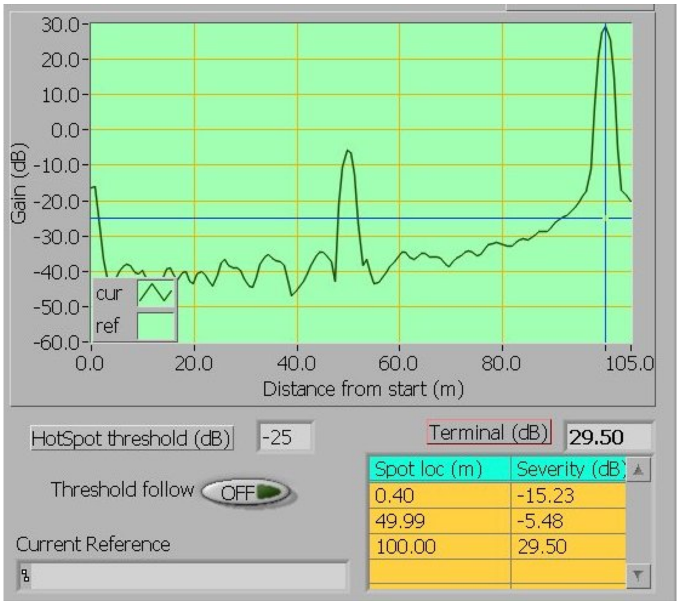

Figure 2. Hot Spot detection in LIRA.

Hot spots due to localized high temperature conditions and local mechanical damage to the insulation are detectable by LIRA through an algorithm starting from the line impedance spectra (see Figure 2). The next chapters show some results achieved in 2005 and 2006 in the framework of the NKS project (Nordic Countries Nuclear Safety Research).

LIRA structure

LIRA is composed of several software and hardware modules, as depicted in Figure 3. The hardware modules are:

- The LIRA modulator, where the cable under test is connected.
- The LIRA Generator, that controls the AWG (Arbitrary Waveform Generator), currently a National Instruments PXI-5422, 200 Ms/s. It supplies a low voltage (1-3V), white noise signal or signal sweep to the system.
- The LIRA DSO (Digital Storage Oscilloscope), currently a National Instruments PXI-5124, 200 Ms/s digitizer. It is a 2 channel digitizer for the 2 signals coming from the modulator, the reference signal (CH0) and the signal modulated by the cable impedance (CH1).

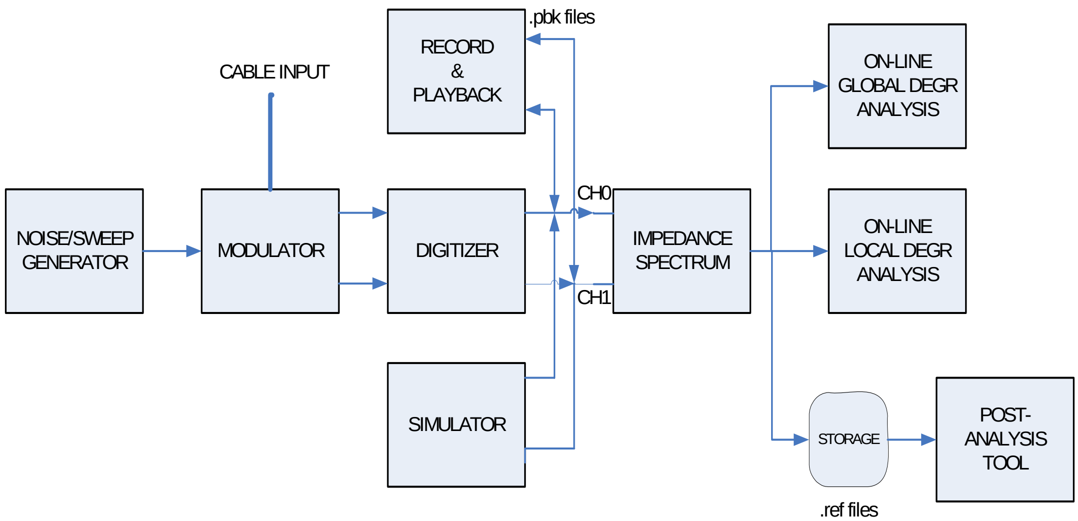

Figure 3. LIRA Block Diagram.

Ringhals Experiments June 26th, 2006

Scope of the test

This experiment was conducted on 4 low-voltage, triaxial (conductor, inner shield, outer shield), PVC insulated cables. The cables are named A, C, E and G.
After the first measurements on the 4 cables, one of them, cable G, was disconnected at the penetration and partially extracted from the conduit and then reinserted. After this procedure a new measurement on cable G was taken, to verify if some damage was occurred to the insulation/jacket as a consequence of this movement.
The 4 cable have been in operation for about 30 years.
The cable end were connected to ionization chambers (high impedance), for cable A, C and E. Cable G was open at the end.

Cable A

cable A
26/6/2006

initial measurement, 142m
termination connected to ionization chamber
penetration at about 109m, 3 meter
long
modulator TF-001

INPUT
PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	5
OffsetCH1	0
RangeCH1	1.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	0
HotSpotThreshold	12
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs
(Hz)

343254	703760	1046659	1430830	1785805
2188990	2550863	2969164	3328795	3751717
4104494	4542405	4887426	5338306	5676433
6142344	6453003	6937894	7181673	7724887
7943588	8493107	8700700	9244120	9413457
9957190	10163664	10693338	10929405	11459219
11695103	12234503	12472415	13017854	13271645
13817301	14074170	14626735	14875680	15443428
15667547	16254530	16451128	17064574	17232856
17900027	96225505	96918859	97605752	97787443
97913107	98338540	98674853	99349458	

Estimated cable length	142.4	m		
Phase velocity ratio	0.794			
Char Impedance	71.8	ohm	1608318	Hz
Line Attenuation	9.9	dB/km	1608318	Hz
	1.4	dB		

SPOT DETECTED:

Location (m)	Severity (dB)
0.6	80
142.4	29.4

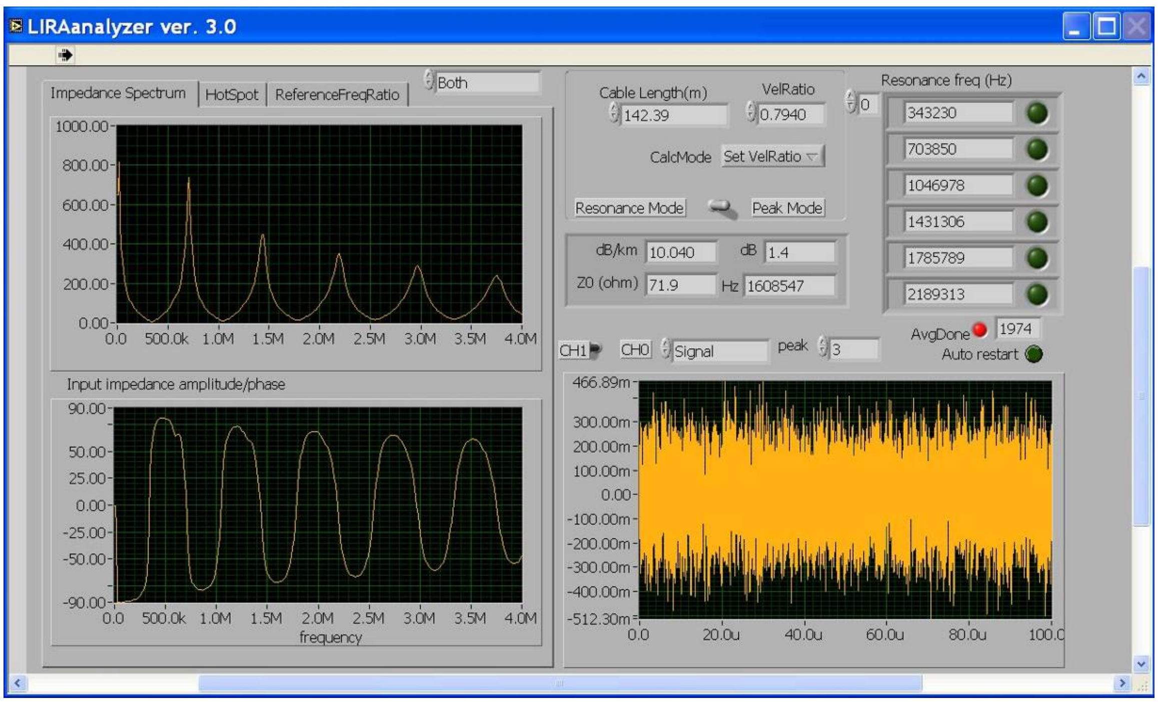

Figure 4

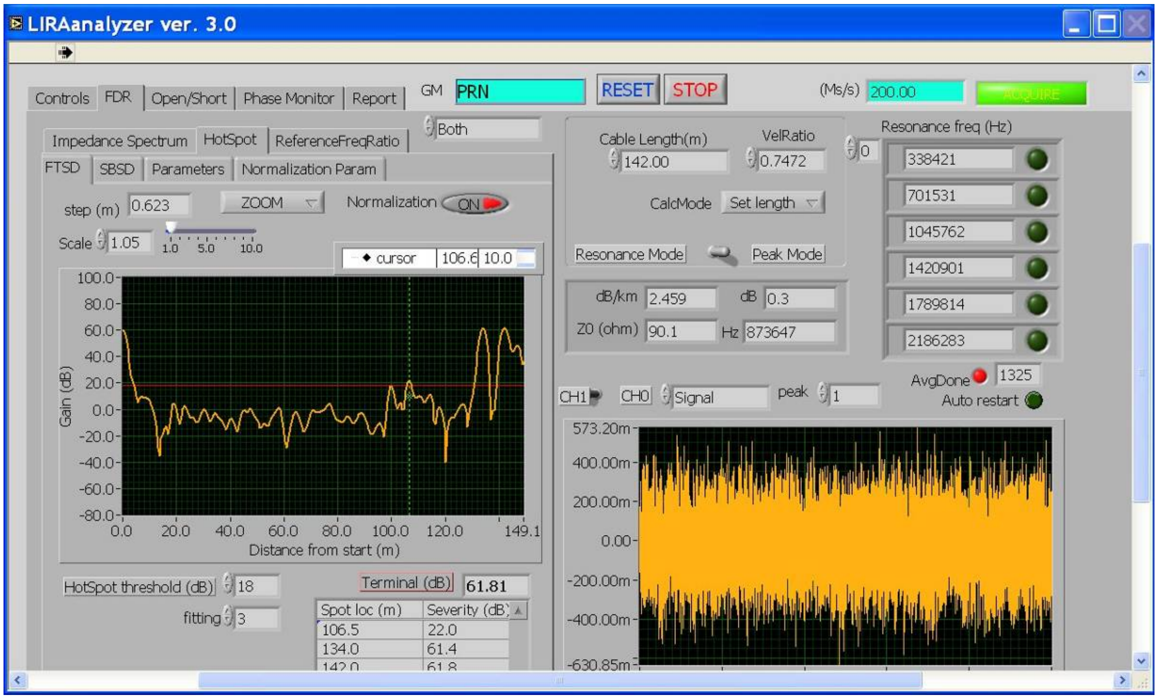

Figure 5

A cable length of 142m was input, corresponding to an estimated (peak mode) PV ratio of 0.794, a high value, but not unusual for coaxial/triaxial cables. The characteristic impedance was 72 ohm.

The 2 peaks at about 105m are the outer and inner penetration. The double peak at the end is due to the attached ionization chamber. No hot spots are visible on cable A.

Cable C

cableC
26/6/2006

initial measurement, 142m
termination connected to ionization chamber
penetration at about 109m, 3 meter long
modulator TF-001

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0

RangeCH0	5
OffsetCH1	0
RangeCH1	1.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	2
HotSpotThreshold	15
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

295212	597345	953680	1304877	1691315
2069506	2457589	2851469	3234398	3635111
4006279	4420368	4782890	5208739	5547352
5995792	6297823	6758781	7021541	7518824
7722884	8255112	8491333	8994007	9253498
9755027	10035673	10538462	10820402	11329337
11603053	12124750	12390734	12922975	13188464
13728966	13990529	14539467	14792778	15351167
15581468	16155384	16363606	16974772	17140466
17830203	89355614	89622625	89947965	90610475
90808852	91566121	92009844	92559943	92984371
93378410	93905975	94375498	95663458	95815331
96406018				

Estimated cable length	143	m
Phase velocity ratio	0.794	

Char Impedance	74.4	ohm	1880410	Hz
Line Attenuation	13.4	dB/km	1880410	Hz
	1.9	dB		

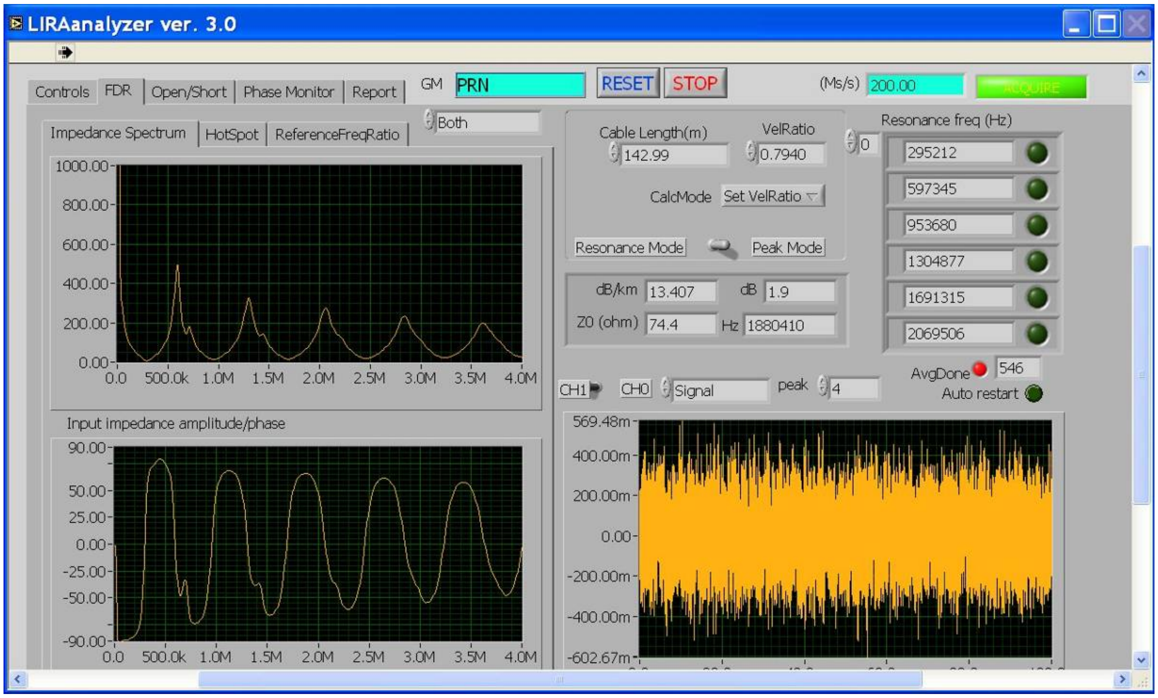

Figure 6

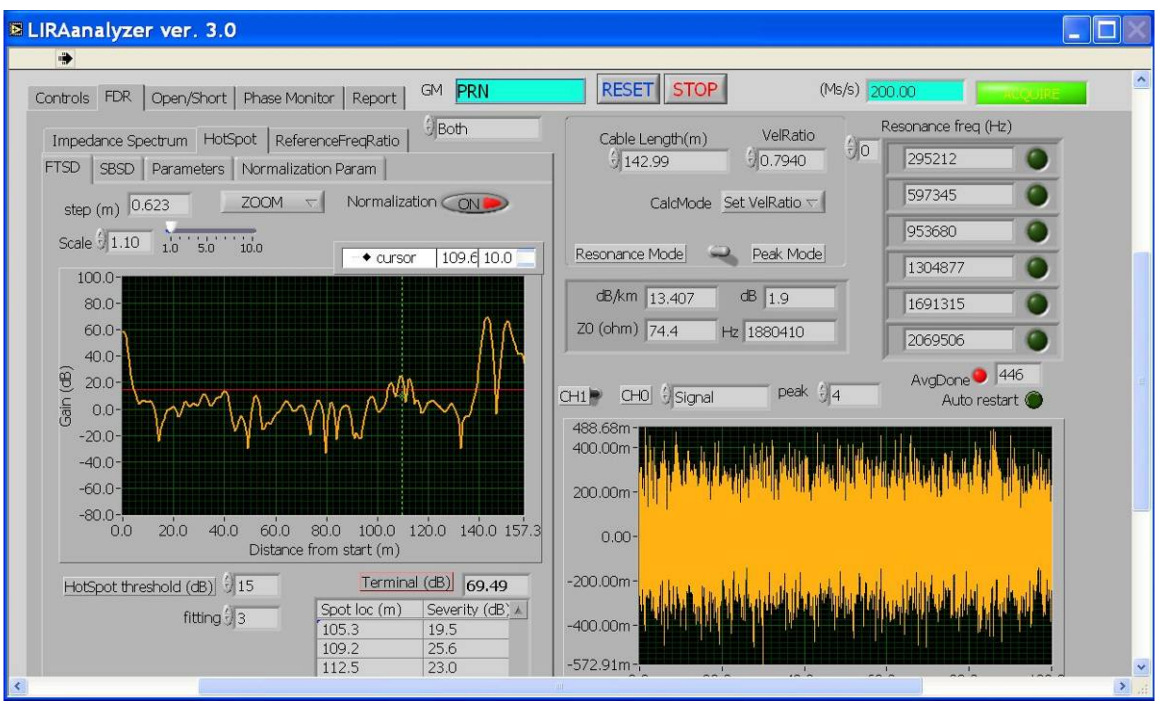

Figure 7

Cable C had the same behavior as cable A. The spot diagram suggests the following locations for the penetration:
external connection: 105.5m
internal connection: 112.5m

Cable E

cable B
26/6/2006

initial measurement, 142m
termination connected to ionization chamber
penetration at about 109m, 3 meter long
modulator TF-001

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	5
OffsetCH1	0
RangeCH1	1.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe

Zoom spectral lines		300
HotSpotMode		2
HotSpotThreshold		15
Topology	Off	
Order		12
Imp Components	Both	

RESULTS

Resonance freqs (Hz)

332670	677758	1021618	1388358	1746632
2140926	2508431	2912679	3276705	3686015
4042682	4465267	4812347	5243449	5562895
6012079	6290499	6733143	6971898	7415929
7614135	8109123	8372832	8856402	9136724
9627352	9927217	10411050	10707843	11205080
11497562	11999683	12279561	12793466	13058003
13589508	13829551	14387852	14564627	18848170
19642051	20446502	21231258	85225703	85340905
85953875	86085069	86759858	86888056	87511770
87638260	87750109	88569884	88725679	89258308
89371513	91570007	92208060	92597181	93015769
93389966	93759764	94152421		

Estimated cable length	142.5	m		
Phase velocity ratio	0.794			
Char Impedance	73.5	ohm	1567495	Hz
Line Attenuation	10.7	dB/km	1567495	Hz
	1.5	dB		

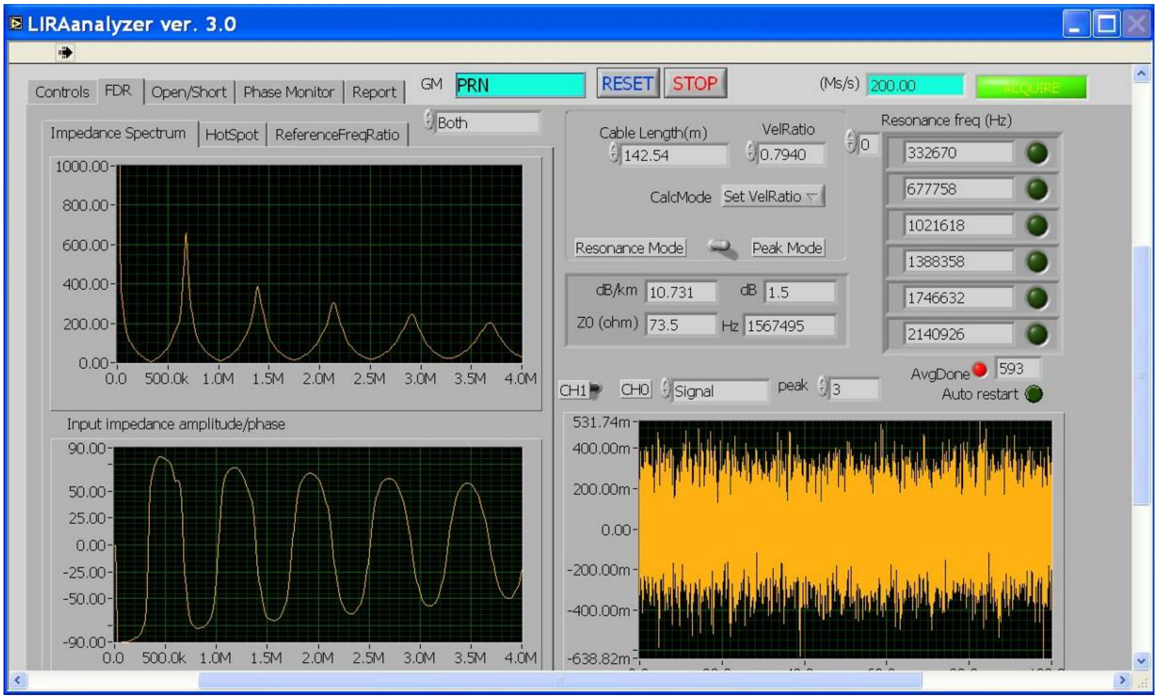

Figure 8

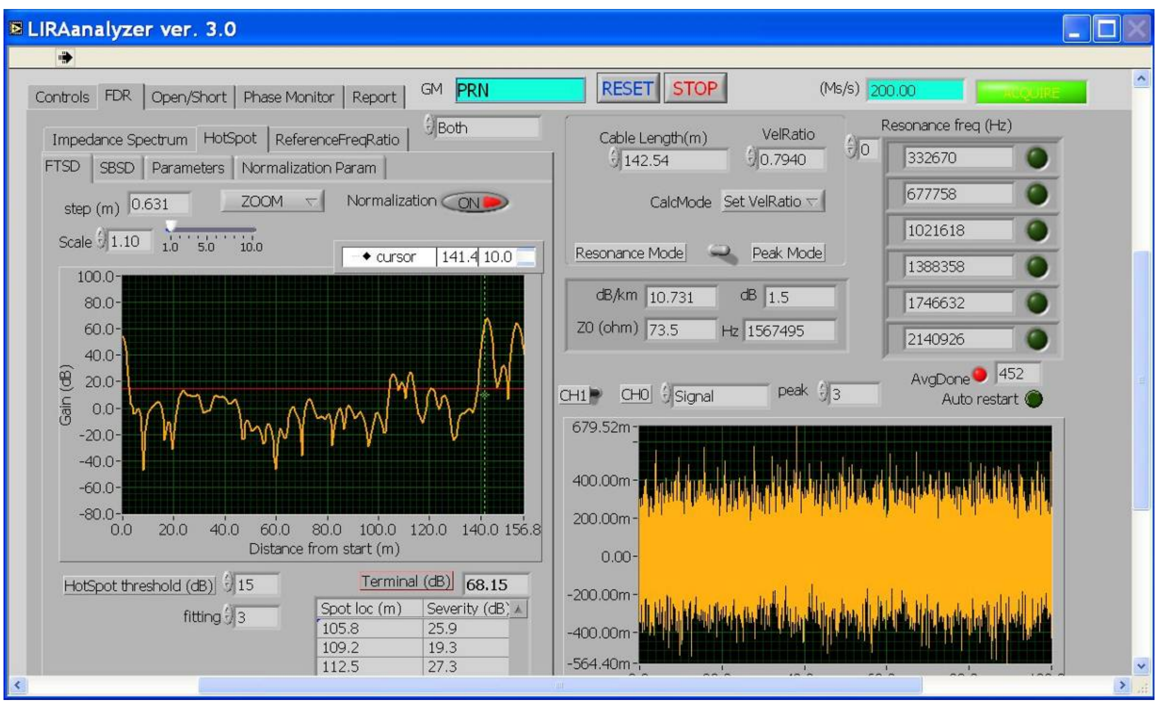

Figure 9

Cable E is identical to the previous ones, with the same locations for the penetration. No other findings.

Cable G

Measurements on cable G have been performed in 3 steps:

1. Initial measurement, as in cable A, C and E. However cable G was the spare cable and was not connected to the ionization chamber. The terminal was open.
2. Measurement after disconnection of the cable at the outside of the penetration (105m).
3. Measurement after the planned cable movement (partially out and back in).

Initial measurement

spare cable G
26/6/2006

initial measurement, 140m
termination is open
penetration at about 105m, 3 meter long

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	5
OffsetCH1	0
RangeCH1	1.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0

Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	2
HotSpotThreshold	16
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

413859	834825	1249676	1677552	2087395
2518689	2927221	3362408	3767457	4212564
4612311	5062626	5459345	5914960	6291982
6758713	7137784	7606697	7970069	8465085
8825560	9316047	9674701	10163339	10517593
11013312	11358629	11862658	12204429	12711988
13049868	13559474	13896894	14409030	14745252
15260234	15594348	16111350	16432985	16960065
17271598	17818459	18110826	18680315	18959552
19531129	19800178	20379666	20629287	21228717
21476809	22083178	22339738	22937941	23189700
23791320	24026997	24637266	24861535	25495624
25691629	26381632	26522203	27223017	27396607
28067918	28246877	28911011	29099407	29771275
29942900	30627211	30784055	31485927	31621472
32345813	33216085	34935098	35752129	36607863
37461124	84255956	85129980	85914540	86750641
86914217	87445455	87808690	88245716	88754342
89061001	89612286	89856372	90391676	90919095
91079262	93453212	93894567	94056365	

Estimated cable length	140	m		
Phase velocity ratio	0.794			
Char Impedance	74.5	ohm	1042251	Hz
Line Attenuation	4.2	dB/km	1042251	Hz
	0.6	dB		

SPOT DETECTED:

Location (m)	Severity (dB)
105.5	17.2
109.3	22.6
112.8	20.6
140	91.3

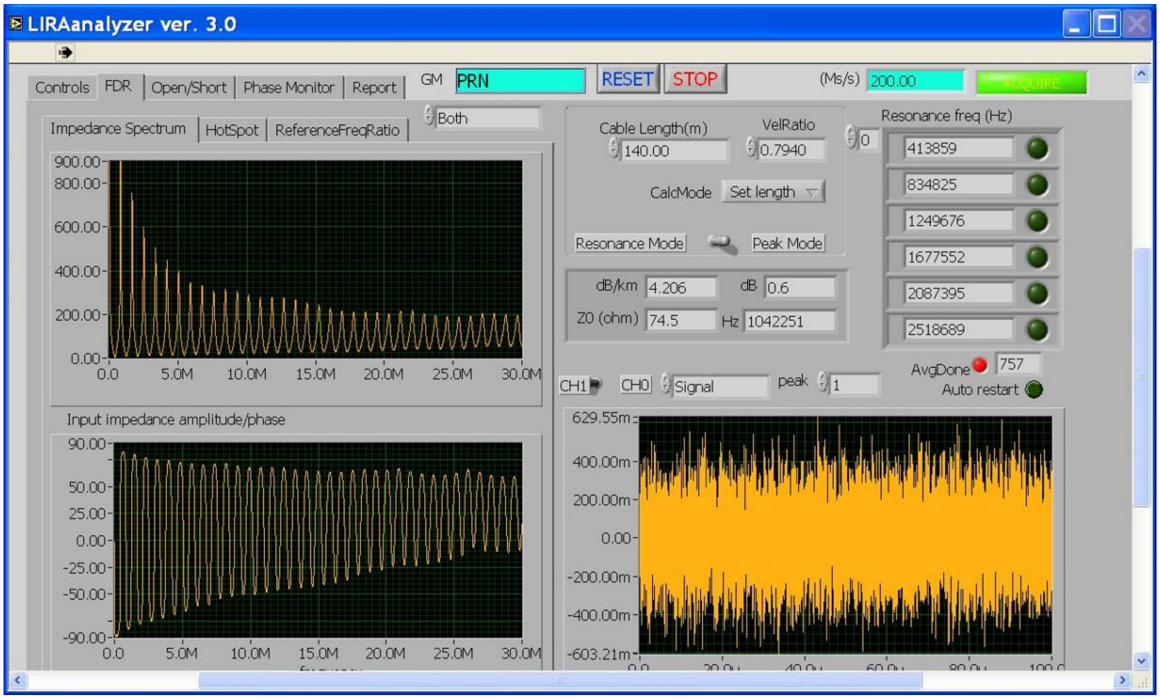

Figure 10

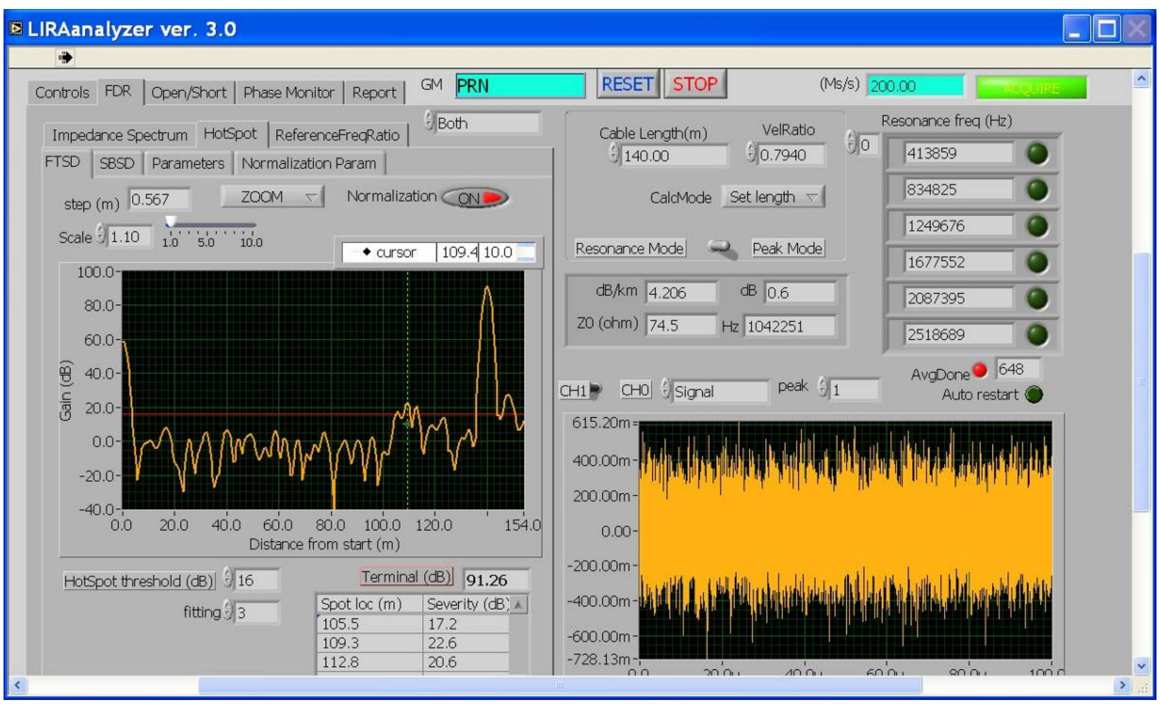

Figure 11

Cable G was open at the end (see the missing double peak at the end, Figure 11). The length is 2m shorter because of that. The location of the penetration is exactly the same as the previous cases. The cable is in good shape.

After disconnection

The cable was disconnected at the external penetration connection, 105.5m, see Figure 11.
Figure 12 and 13 show the measurement on this part of the cable, where all the parameters are the same, but the length is 105.5m. In the spot picture, Figure 10, the penetration spikes have disappeared.

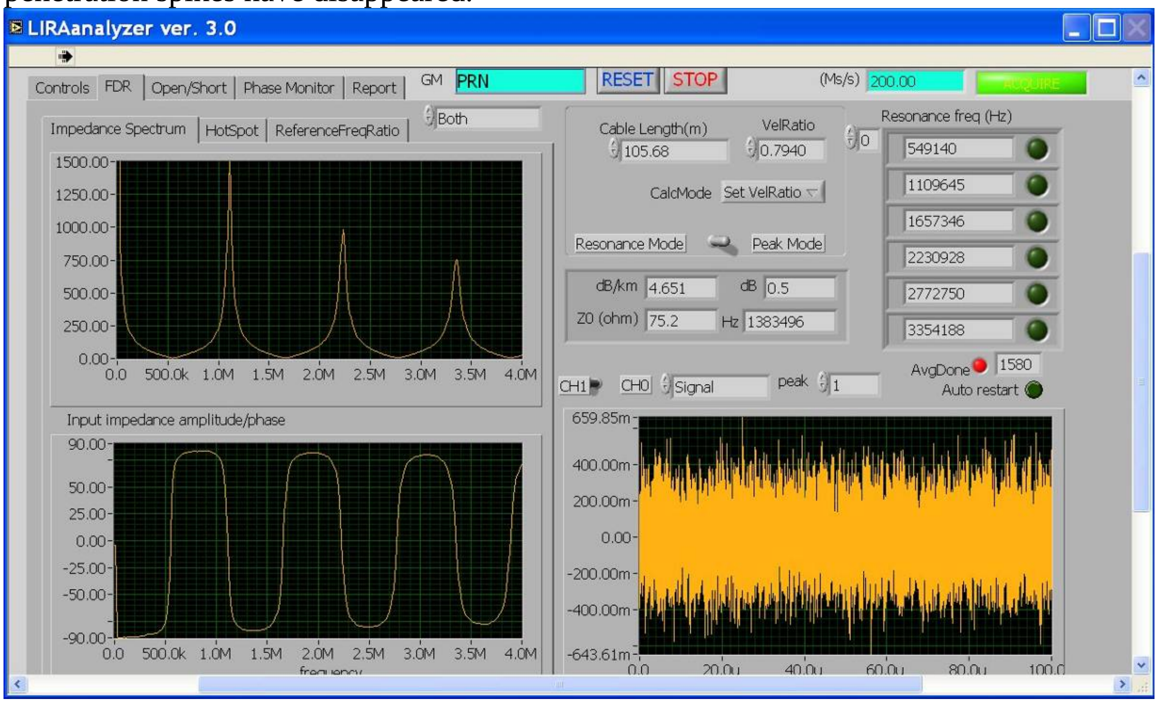

Figure 12

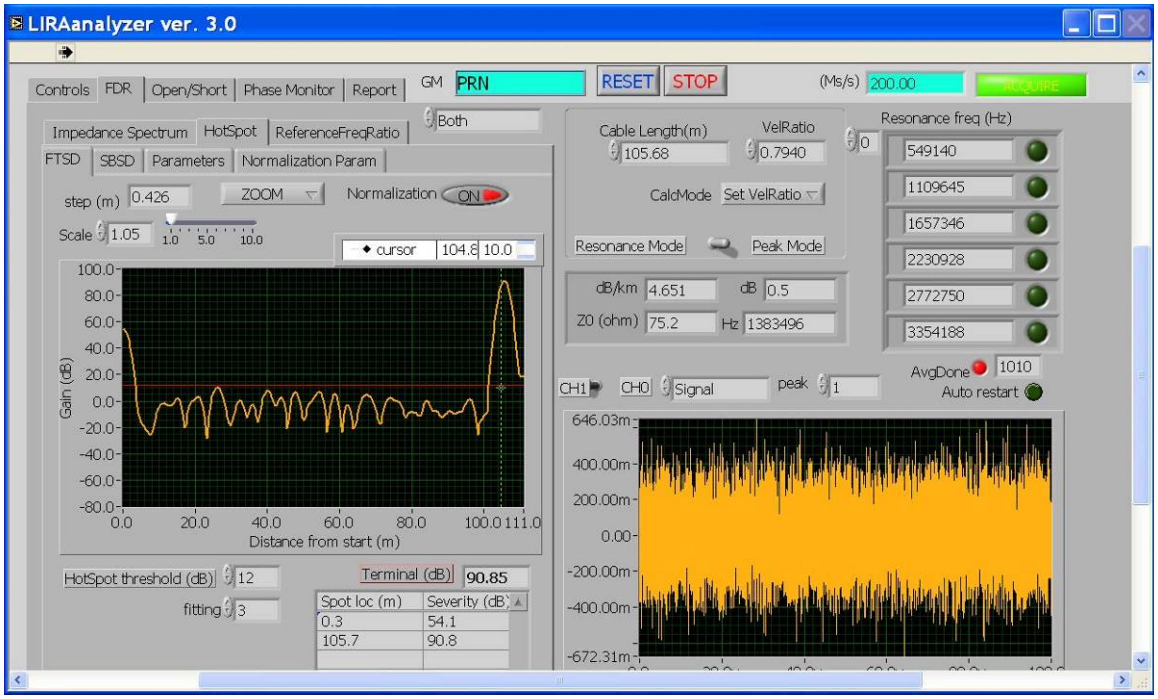

Figure 13

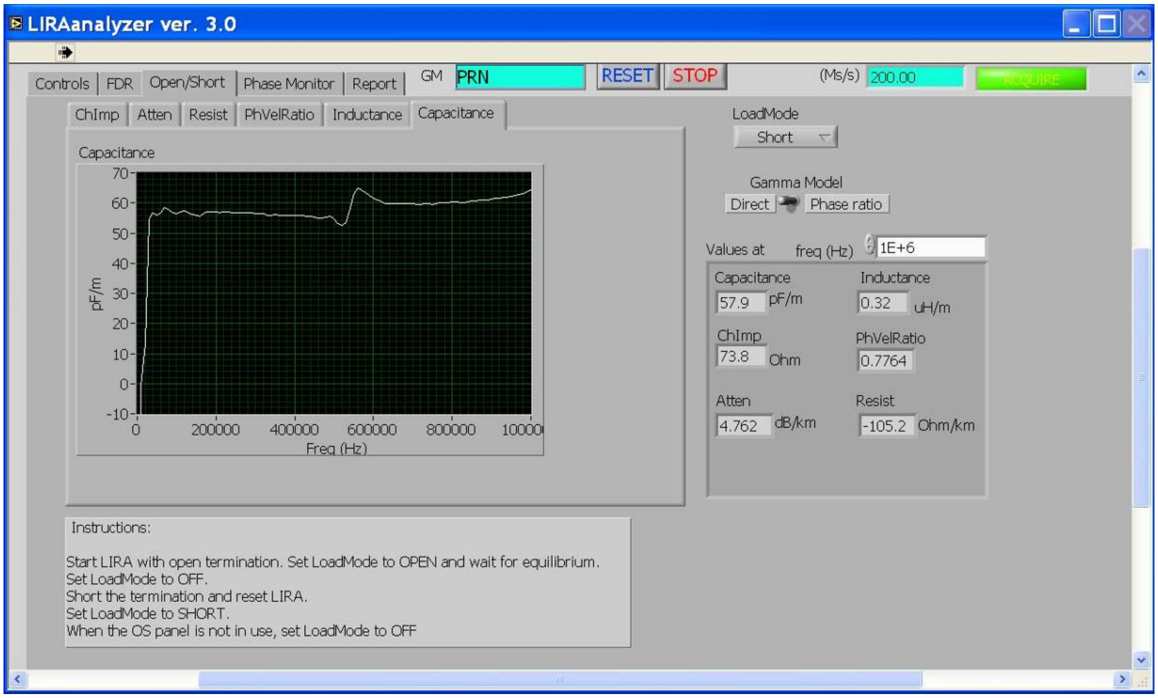

Figure 14

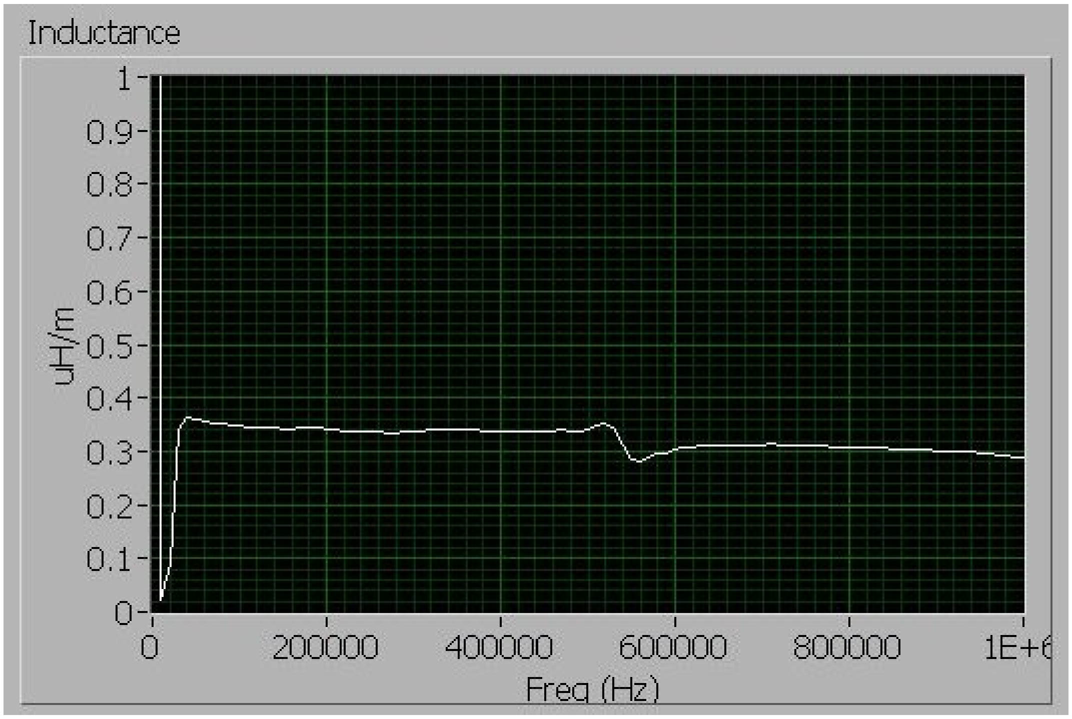

Figure 15

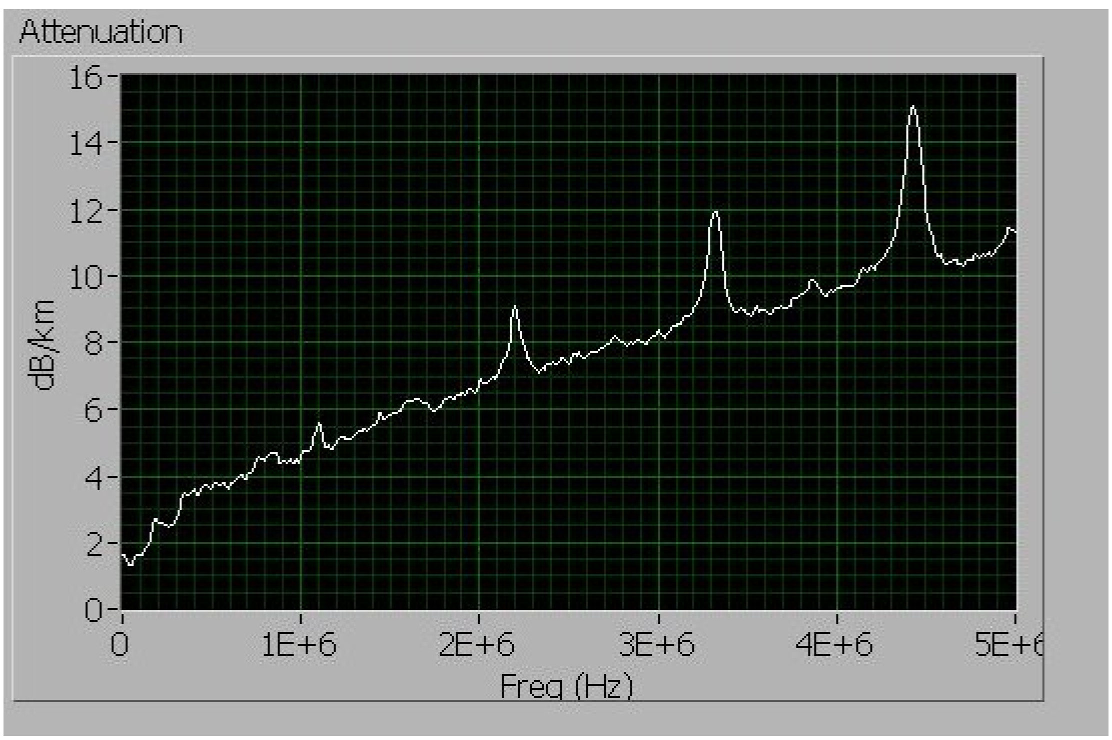

Figure 16

Figure 14 to 16 represent the result of the open/short test to estimate important electric parameters of the cable as a function of frequency. The following table summarizes these results in the range 0.5-1 MHz:

Characteristic impedance (ohm)	74
Capacitance (pF/m)	58
Inductance (uH/m)	0.32
Attenuation (dB/km)	4.7
Phase Velocity Ratio	0.776

The PV ratio estimated with the Open/Short method is slightly lower than the value estimated on-line in peak-mode (0.794), which is however calculated at 1.4 MHz .This is consistent with the theory, because PV ratios increase with frequency at relatively low frequency (below 5 MHz)

Final Measurement

A final measurement was taken on the same cable segment, after extracting it for about 50m and reinserting it in its original position.
Figure 17 to 20 show the results of the final measurement, where the blue line is the reference, initial measurement and the yellow line is the final. In Figure 17 and 18 a complete overlap is visible, but not very meaningful because small but important local changes would not show up visually in the impedance graph. Figure 19and 20 show that nothing critical has happened as a consequence of the cable movement.

All the measurement shown so far have been performed using the conductor and the inner shield, leaving the outer shield open. However, using the 2 shields some additional information about the jacket condition was produced. Figure 21 and 22 show the results of a measurement performed with the inner and outer shield as signal wires. The spike at 85m would be worth an additional visual inspection, although something strange on the jacket was reported at that location during the operation of cable extraction and reinsertion.

cableG
26/6/2006

modulator TF-001
report after removing back and forth

INPUT PARAMETERS

GM PRN

RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	5
OffsetCH1	0
RangeCH1	1.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	0
HotSpotThreshold	15
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

548722	1109861	1657414	2230477	2773145
3353442	3887672	4480408	5004283	5606541
6110156	6735409	7237014	7867559	8345195
8990579	9469352	10117520	10590430	11247887
11708003	12373007	12825450	13499016	13950965
14626936	15072121	15752893	16190563	16883426
17306447	18018852	18415022	19148712	19535327
20280078	20644072	21412267	21769535	22533508
22900622	23664576	24020755	24796433	25134859
25936957	26230818	27085314	27357688	28204232
28494338	29324498	29621570	30460436	30745049
31590415	31865572	32723209	32982968	33862670
34090928	34980555	35224013	36103214	36350309
37229782	37478635	38364017	38594404	39505729

	39701945	40649509	40826431	41766483	41962823
	42889137	43091898	44030384	44202640	45167926
	45329167	46284245	46465687	47408357	47596757
	48538611	48720068	49661650	49850885	50764348
	50987768	51899191	52115309	53032775	53233093
	54176639	54354367	55298428	55467702	56427903
Estimated cable length		105.7	m		
Phase velocity ratio		0.794			
Char Impedance		74.7	ohm	2501811	Hz
Line Attenuation		7.2	dB/km	2501811	Hz
		0.8	dB		
SPOT DETECTED:					
Location (m)		Severity (dB)			
	0.6	78.3			
	105.7	65.9			

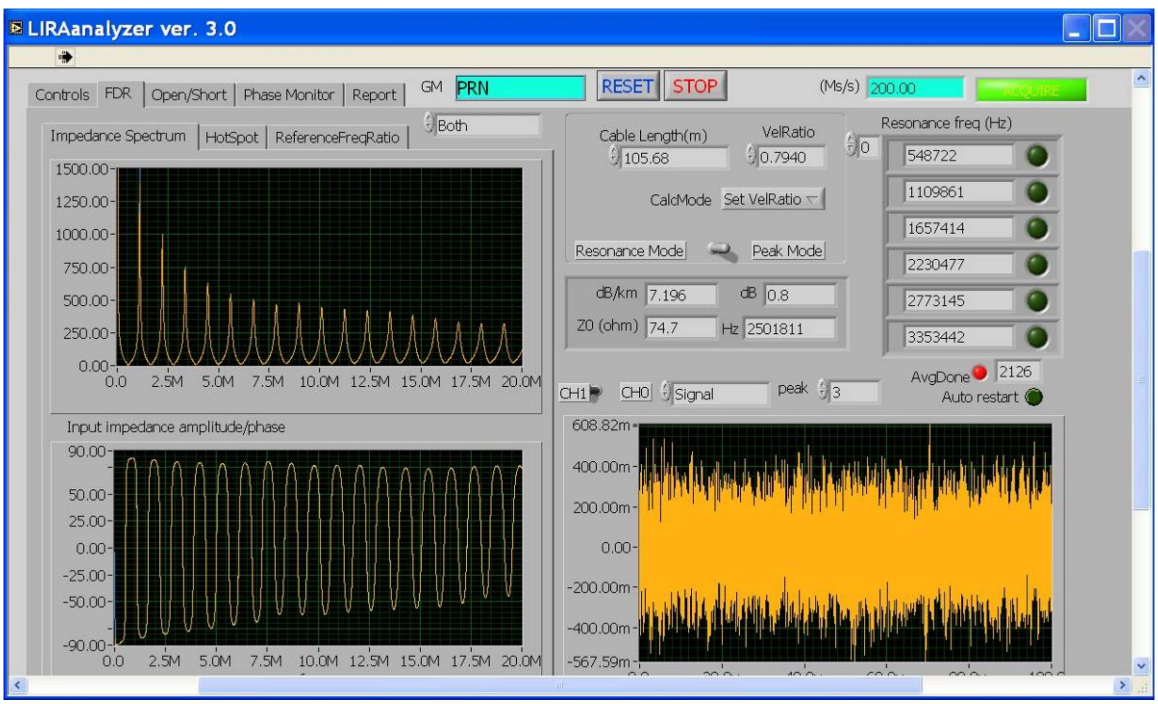

Figure 17

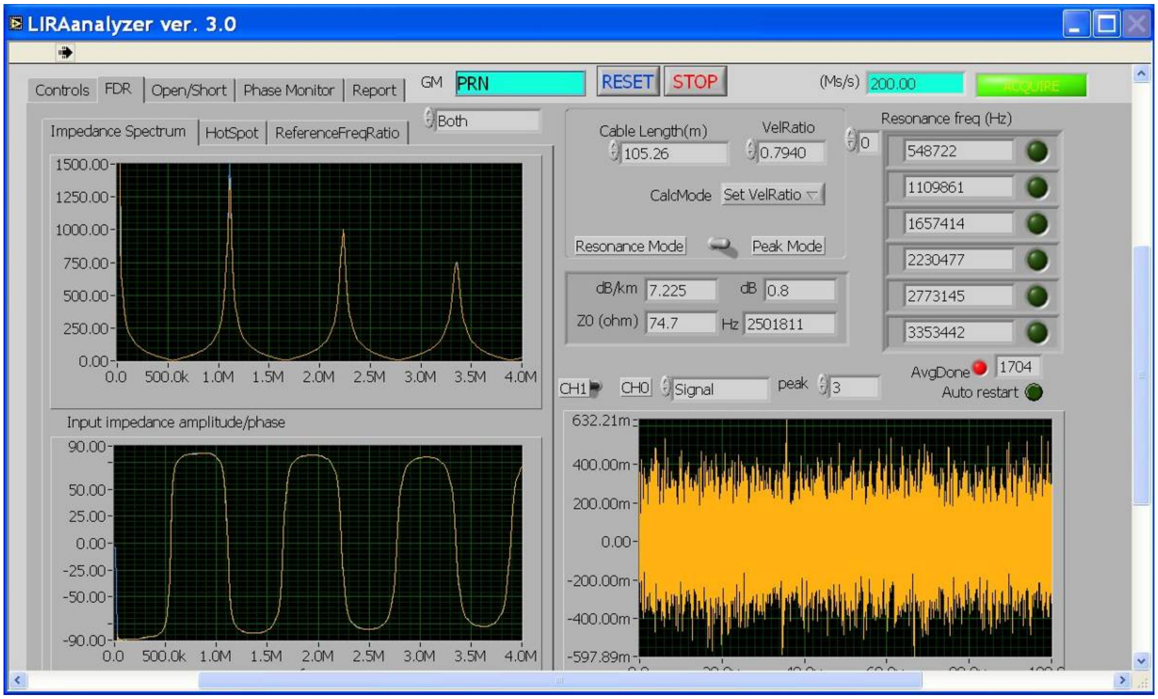

Figure 18

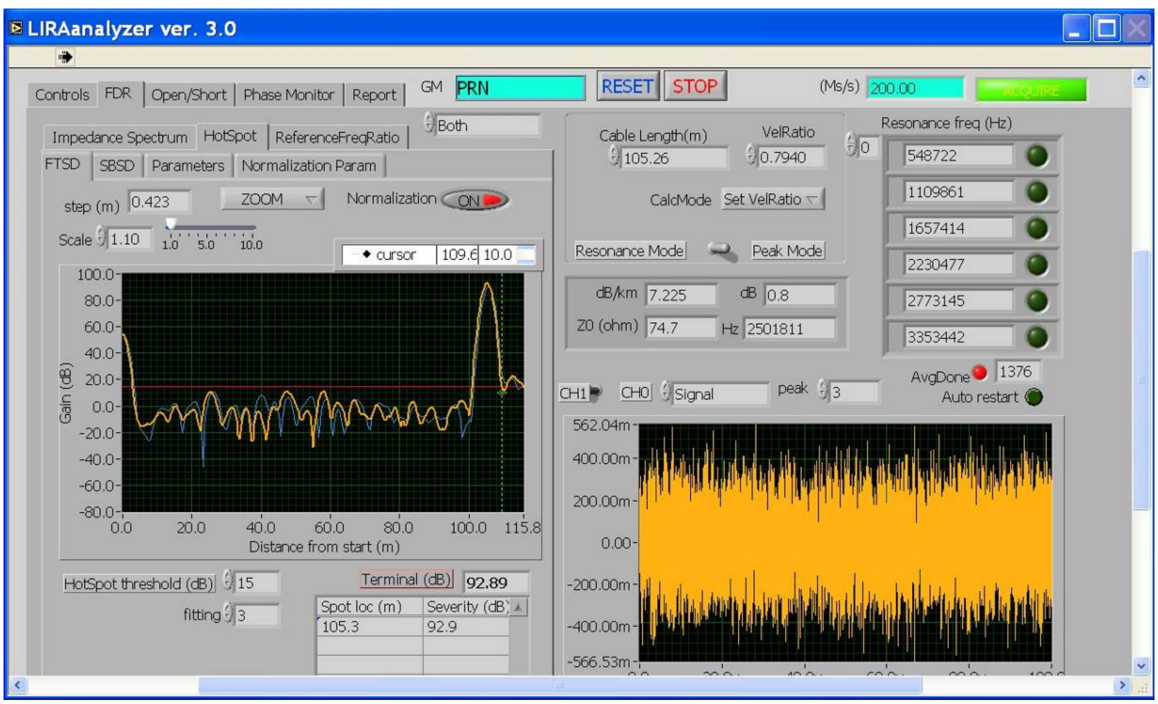

Figure 19

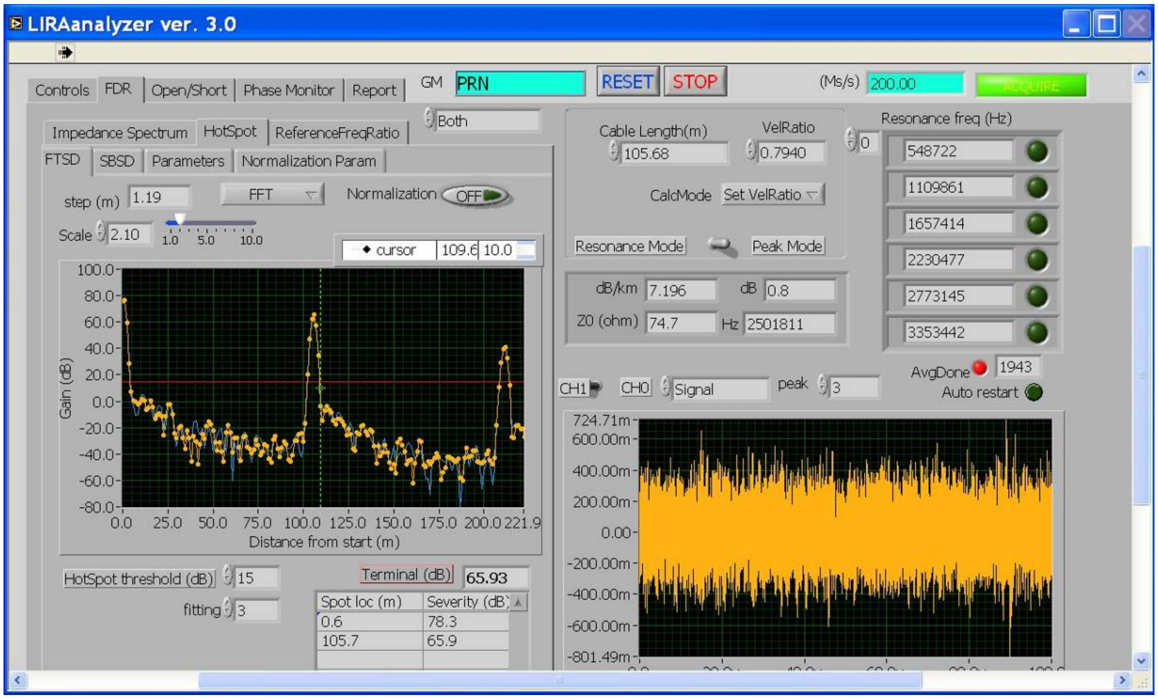

Figure 20

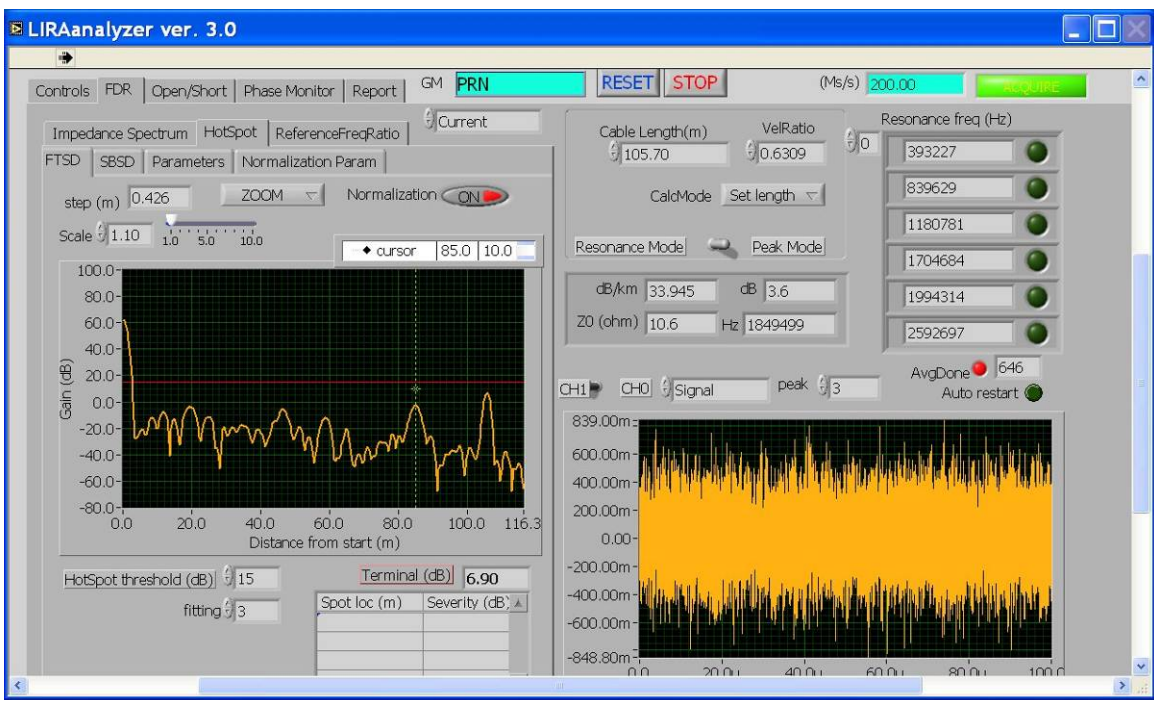

Figure 21

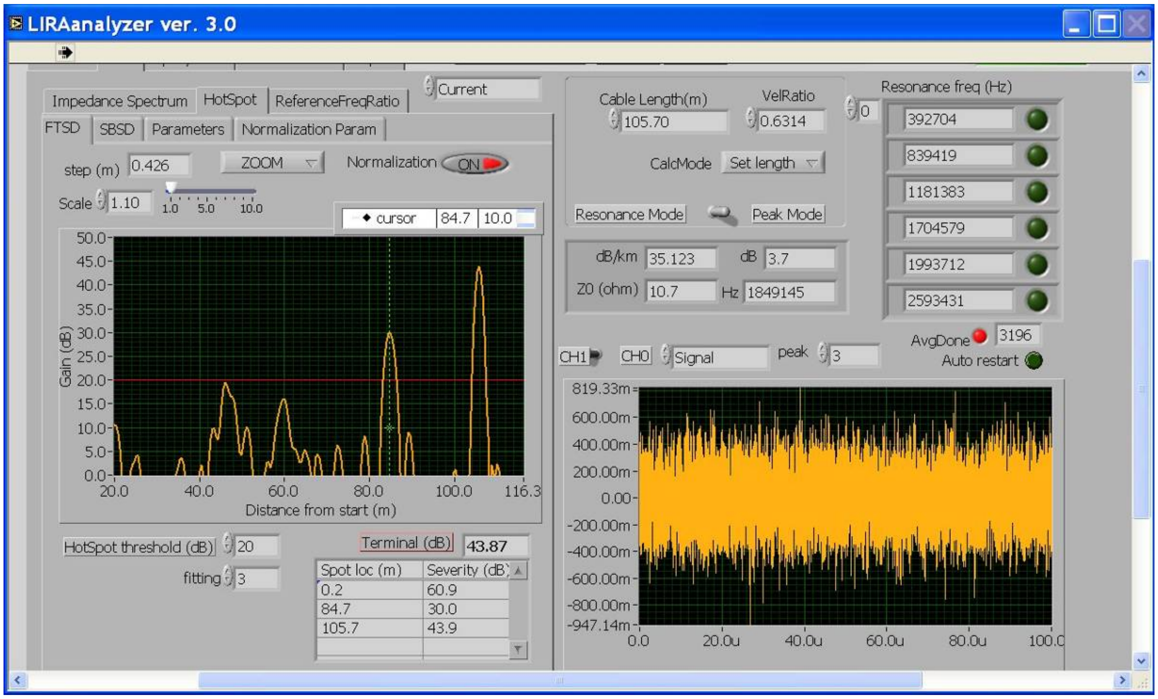

Figure 22

Simulated Tests

The Open/Short tests and the estimation of the main electrical parameters of the cable can be used to develop a cable model and run simulated experiments, with simulated hot spots and aging conditions.
Simulated tests are extremely important to assess the sensitivity of LIRA for a particular cable to hot spots, mechanical faults and global aging conditions.

Figure 23and 24 represent the results of a simulated test using the LIRA automatically generated model for the cable G after disconnection (105.5m), open ended. Compare with the real measurements in Figure 18 and 19.

Figure 25 shows the result of a simulated measurement on cable G with a 0.5m hot spot at 65m. The hot spot severity is +5 pF/m, which would result from a minor thermal degradation at that location.

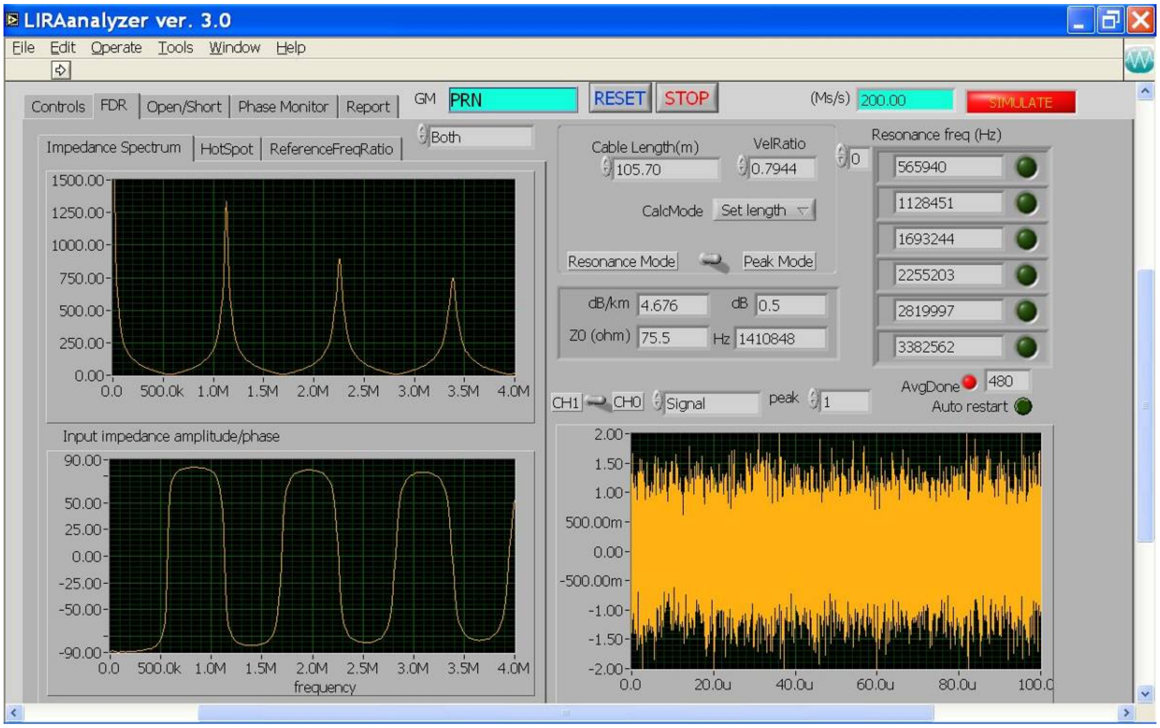

Figure 23

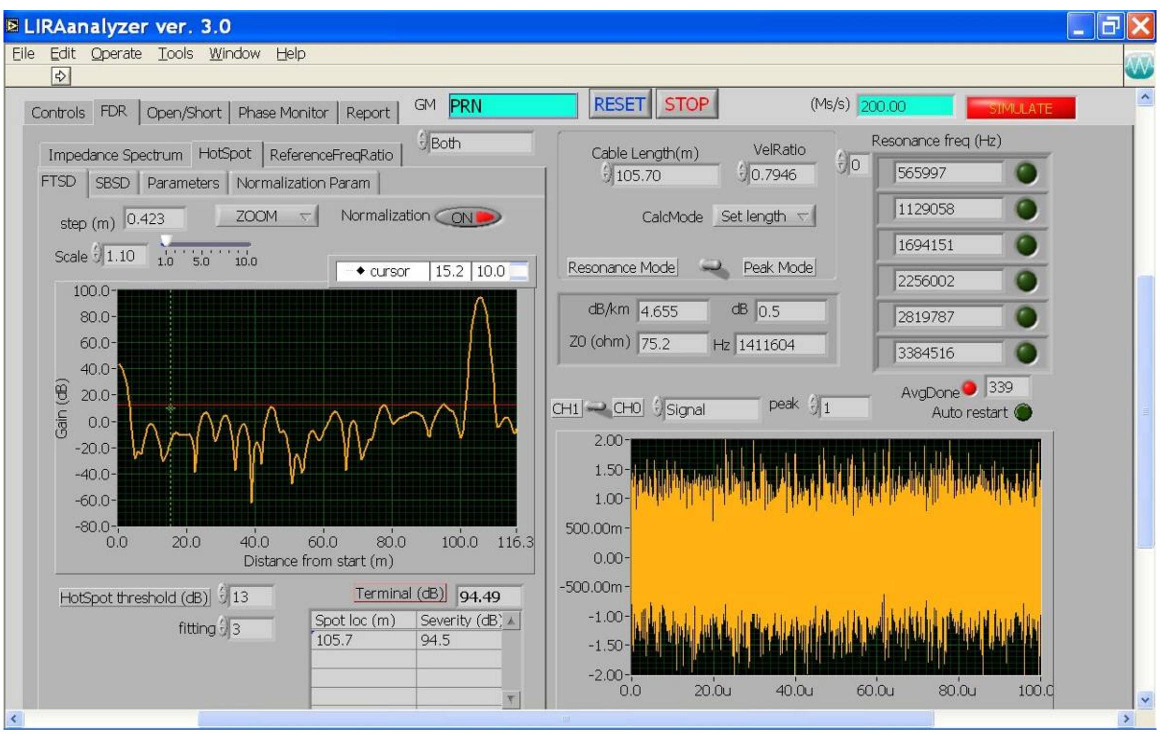

Figure 24

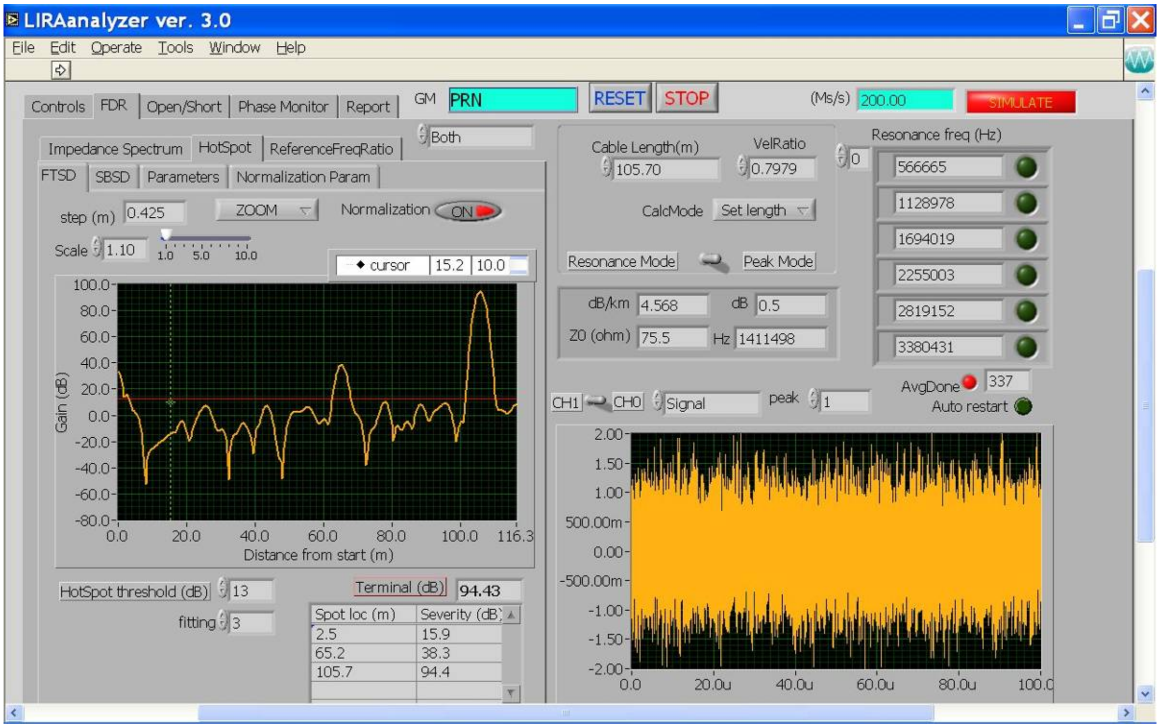

Figure 25

Barsebäck Experiment July 5th, 2006

Scope of the Test

A total of 10 installed cables have been tested using a compiled version of LIRA 3.0 and a maximum scan frequency of 200 Ms/s (see Figure 26), corresponding to 100MHz.

Figure 26 LIRA 3.0 during Barsebäck Tests

The cables were low voltage, open end at the terminal, composed of 2 segments of PVC/PVC insulation/jacket in some cases and PVC/PVC connected to XLPE/CSPE (Rockbestos) in other cases. The cable lengths varied from 60 to 120 meter.

Aging conditions of these cables were not known, although all of them have been in operation for about 20-25 years.

Test results

91006-X28.3

91006-X28.3
open end

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	2

OffsetCH1	0
RangeCH1	0.5
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	100
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0
HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	0
HotSpotThreshold	11
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

288524	536169	818971	1085910	1401122
1688306	1954803	2278410	2517441	2894203
3116647	3466968	3606244	4076053	4254671
42423328	42563393			

Estimated cable length	115	m		
Phase velocity ratio	0.4618			
Char Impedance	123.2	ohm	677570	Hz
Line Attenuation	8.4	dB/km	677570	Hz
	1	dB		

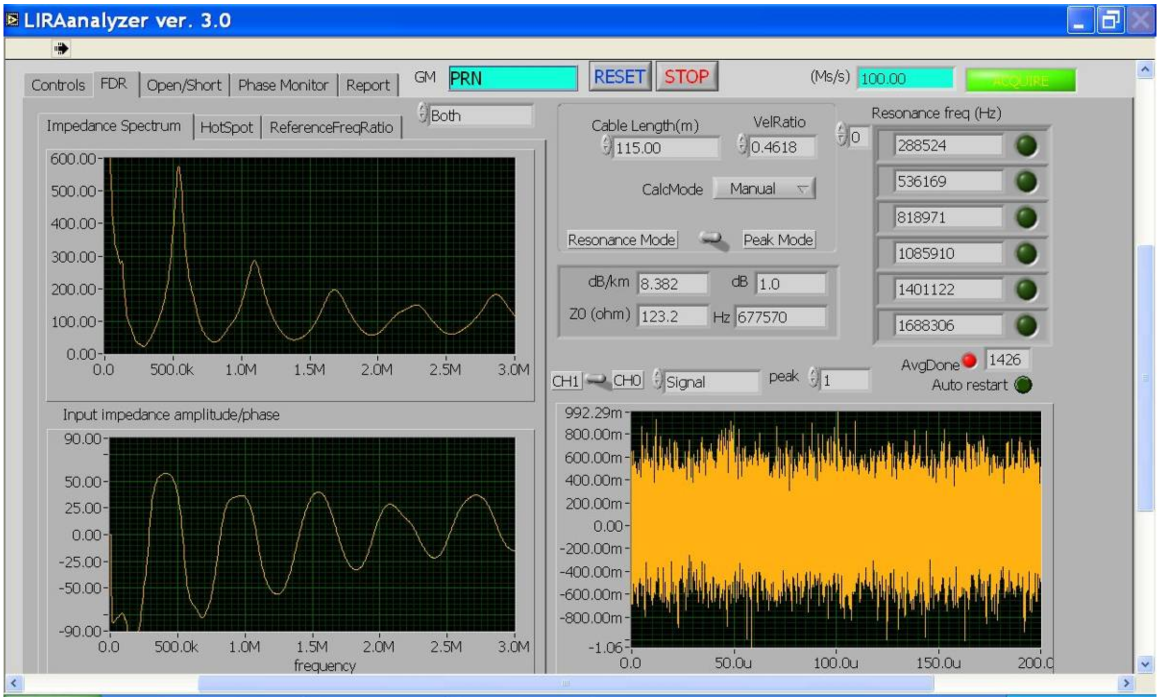

Figure 27 Impedance amplitude and phase for frequencies 0-3MHz

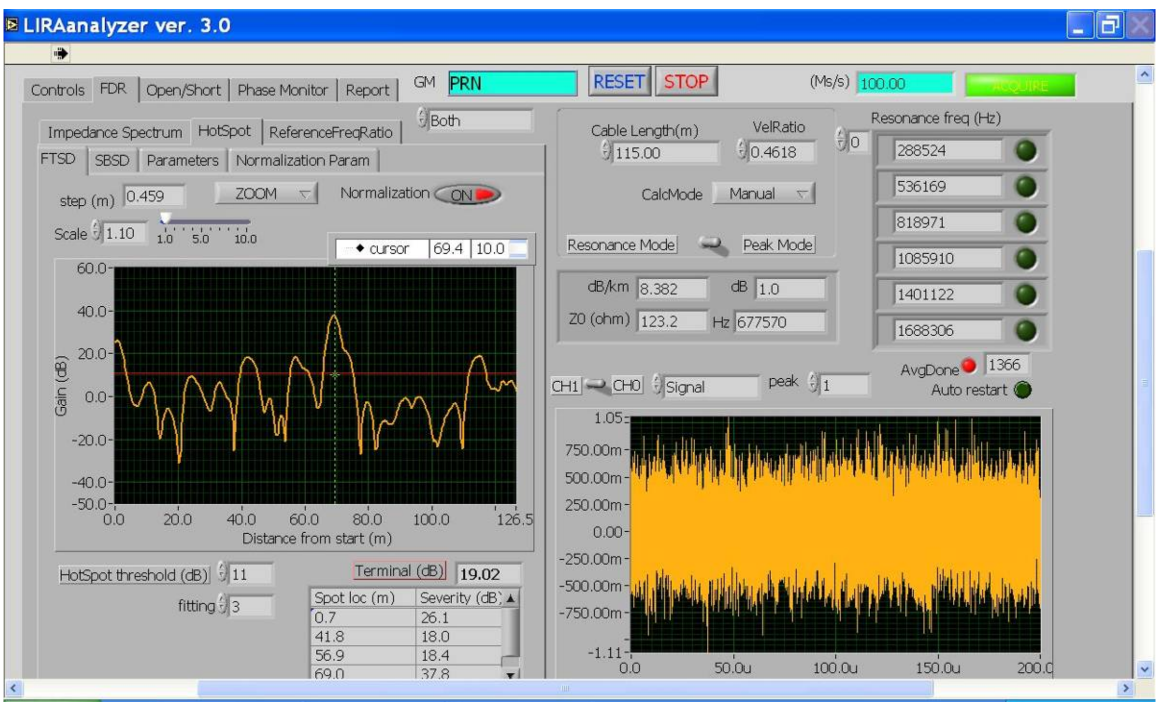

Figure 28 Spot spectrum with open termination at 115m and segment connection at 69m

Cable attenuation of about 8 dB/km, which is high, and the relatively large cable length (about 115m), suggested to lower the scan rate to 100 Ms/s.

The cable length value of 115 m is an input value and was approximately known. The spot locations accuracy is consequent to the accuracy of this number. The Phase Velocity ratio of 0.4618 is also a consequence of the total known cable length. New PVC insulated signal cables have an average PV ratio of 0.52-0.54, a value of 0.46 suggests some thermal aged condition (PV ratio decreases linearly with aging). At the moment, no correlation exists between PV ratio and global aging conditions (work is in progress on that).

Figure 28 shows the spot spectrum along the entire cable length of 115m. The big spot (38 dB) at 69m is the connection between the 2 segments. The termination peak is at 20 dB (at 200 Ms/s it almost disappears). Two spots, one at 42m and another at 57m, both at 18 dB, would be worth of visual inspection, because they exceed the background noise set at 10 dB in this case.

System 495

system 495

PVC/PVC open end

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	3
OffsetCH1	0
RangeCH1	1
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	100
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0

HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	0
HotSpotThreshold	5
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

638729	1273147	1888933	2514603	3106585
3860785	4454254	5241923	5818082	6612528
7043079	7771183	8222379	9359550	9524115
10675546	10974385	40884344	41853729	42041866
42171078	42304382	42410136	42559953	42712491
42932151	43079881	43271855	43393570	

Estimated cable length	50.5	m		
Phase velocity ratio	0.4098			
Char Impedance	107.1	ohm	2201768	Hz
Line Attenuation	46.4	dB/km	2201768	Hz
	2.3	dB		

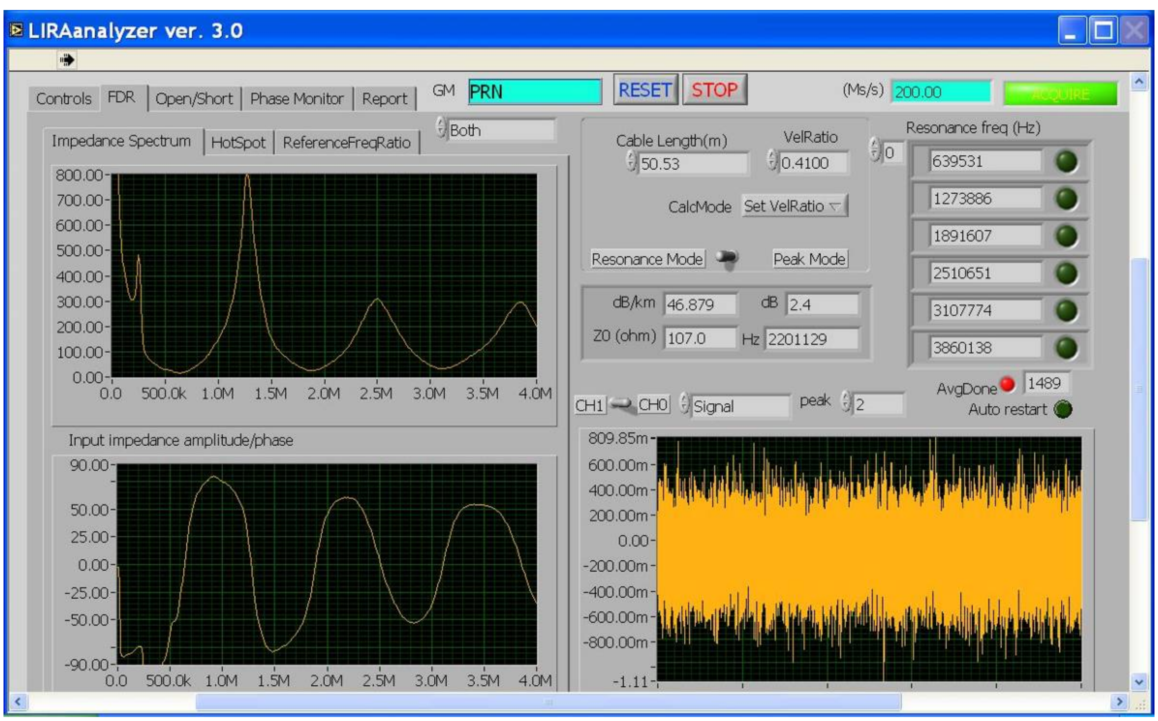

Figure 29

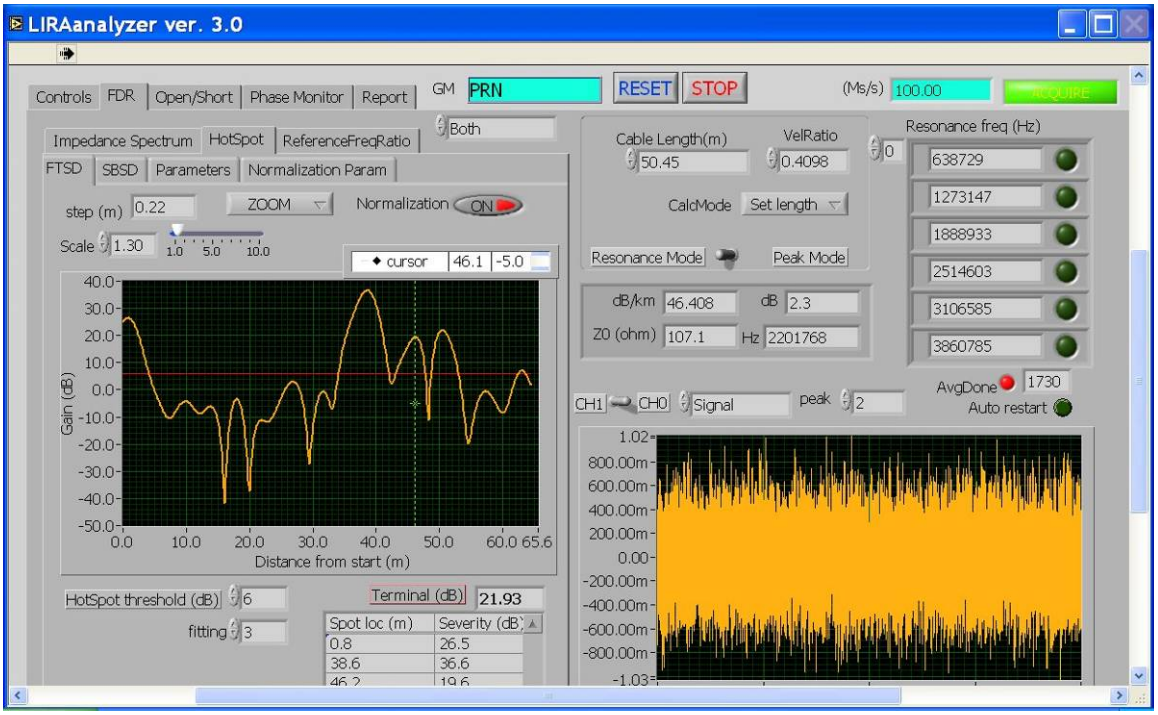

Figure 30

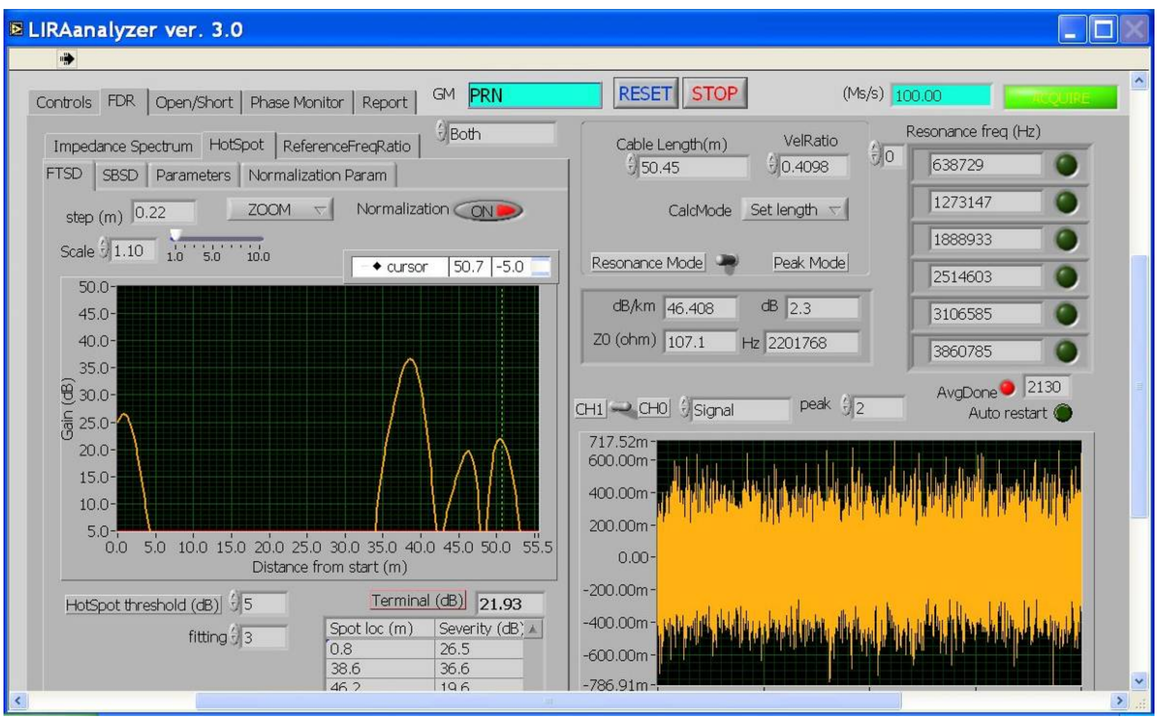

Figure 31

This cable was only 51m long, same kind of insulation of the previous one. PV ratio slightly lower (0.41) than before.
The junction is visible (37 dB) at 38.6m, while another discontinuity is visible (see Figures 29 and 30) close to the terminal, at 46m. Figure 31 represents the same case at different scale.

Discontinuities close to the termination may pose a challenge for the identification of the termination spike, when the two spike heights are comparable (like in this example). Actions are in progress to address this case.

System 495 Div II

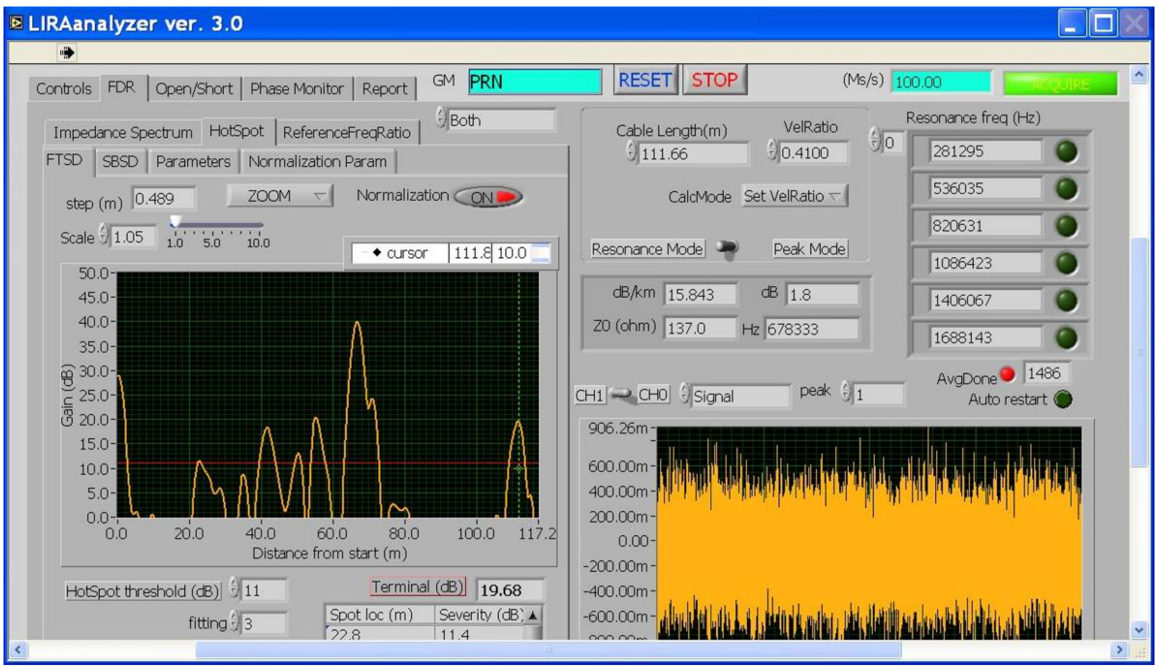

Figure 32

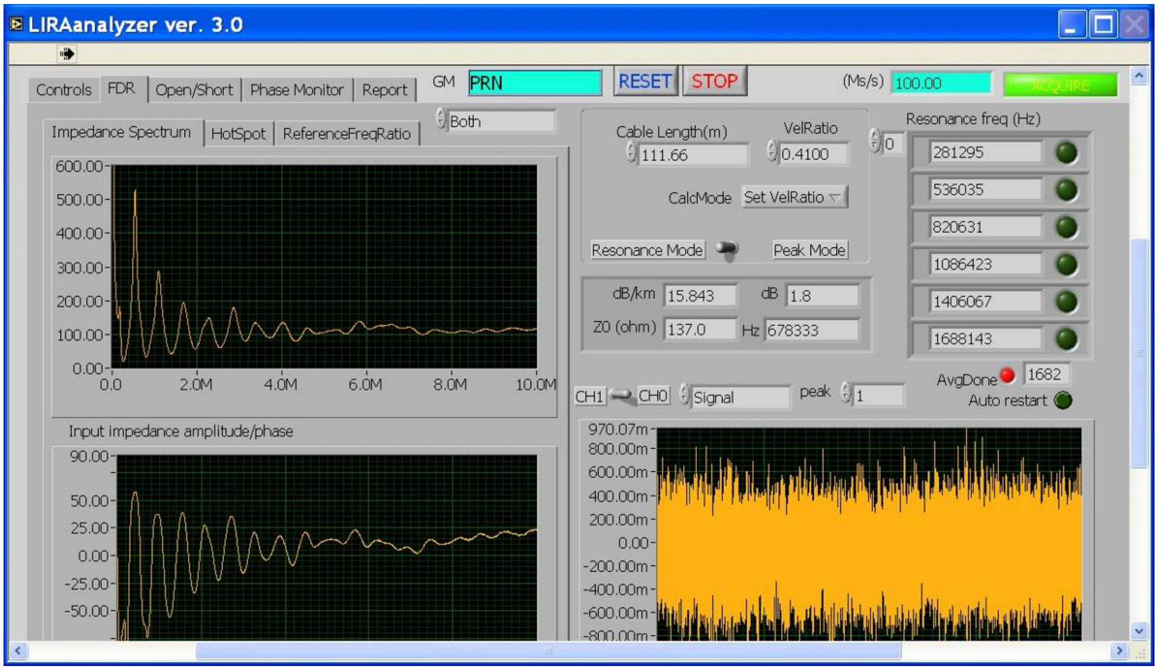

Figure 33

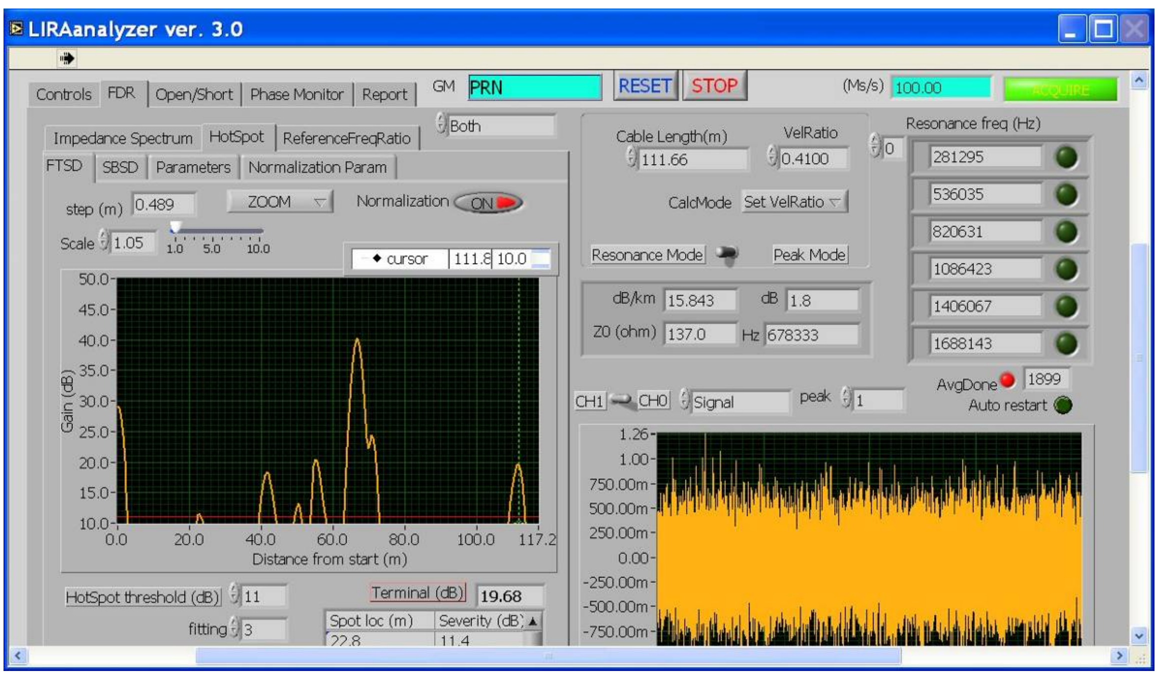

Figure 34

This cable, same type of Div I seen before, has been tested setting the PV ratio to 0.41, same value as the previous case, because the length was not known.
The corresponding estimated length of 111.6m was in agreement with a rough estimate from the plant personnel.

A junction at 67m is visible here (Figure 33 and the scaled one in Figure 34). Two other peaks are visible, at 42m and 55m, whose height is comparable to the termination height.

314V86

This and the following cables are composed of 3 segments:

1. A PVC/PVC segment outside containment
2. A penetration segment
3. A XLPE/CSPE (Rockbestos) segment inside the containment

The termination was open in all cases.
The accuracy of these tests is somewhat reduced, because of the multi segment setup, where different segments have different electric characteristics. The current LIRA version does not handle accurately multi segment cables, although a multi-segment LIRA model is in preparation and should be ready in 2007.

sys 314V86

PVC plus penetration plus XLPE (Rockbestos)

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	3
OffsetCH1	0
RangeCH1	1
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0

Feedback res.		0			
Balancing res.		0			
Splitter res.		0			
HotSpotWindow		Low Sidelobe			
Zoom spectral lines		300			
HotSpotMode		2			
HotSpotThreshold		-12			
Topology		Off			
Order		12			
Imp Components		Both			

RESULTS

Resonance freqs (Hz)					
	395406	755899	1145234	1589368	2006532
	2440420	2723307	3240705	3628802	4166023
	4371909	4851835	5199641	5852570	6125107
	6465043	6807348	7547264	7784743	9153938
	9443905	10005669	10682854	11080383	11715152
	11873228	12454898	12592472	27754566	28045502
	29100267	29948459	30392765	30580079	31422799
	31922483	32152199	54998944	55838462	56716945
	56853581	56976281	57106321	57280746	57418109
	57634997	57764677	57913037	58033074	58158328
	58324120	58499907	58650207	59013199	59264111
	59408548	59540940	59666051	59802462	59928607
	60051665	60233509	60360289	60497818	60641206
	60974732	61349348	61588548	62108642	62500461
	62623715	62759240	62907676	63048016	63189698
	63335447	63469570	63610263	63783750	63918354
	64129186	64250689	64467592	64592520	68959755
	69468532	69874179	70018097	70205064	70335962
	70458427	70580258	70840686	71002880	71255634
	71687558	71842379	72041074	72296251	72679173
Estimated cable length		112	m		
Phase velocity ratio		0.6293			
Char Impedance		122.5	ohm	950567	Hz
Line Attenuation		0.5	dB/km	950567	Hz
		0.1	dB		

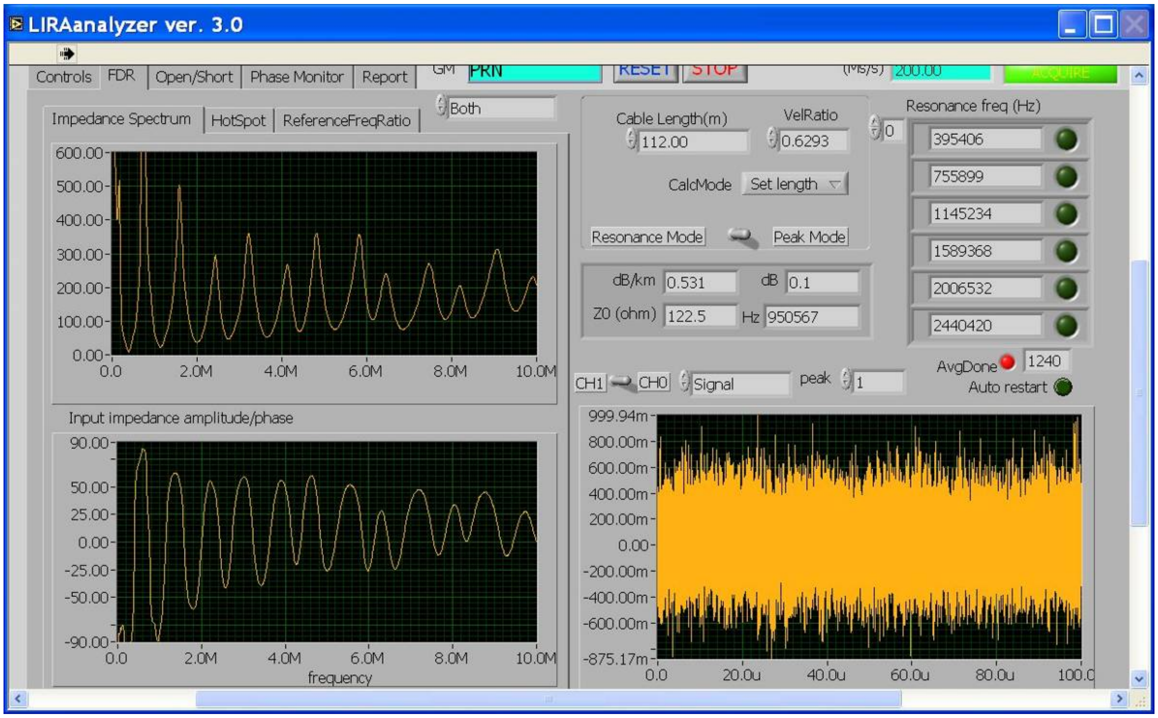

Figure 35

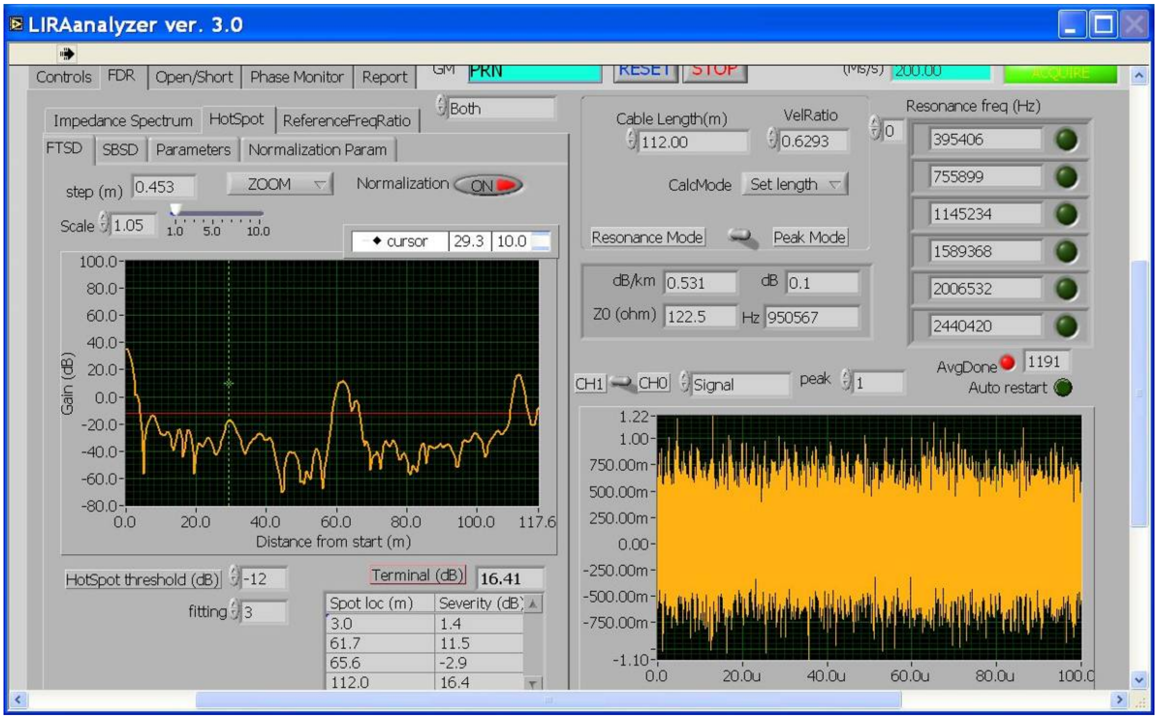

Figure 36

The cable length was set in this test to the known value of 112m and the resulting PV ratio was 0.629. This value corresponds to a weighted average of the PV ratio of the PVC and XLPE segments. The higher value respect to the previous tests is due to the higher PV ratios of XLPE cables. Note also the much less attenuation of this case (0.5 dB/km), visible also in Figure 10, due to the minor attenuation of Rockbestos cables.

The penetration is visible in Figure 36, between 61.7m and 65.6m. The first segment is the PVC type, the second segment is XLPE.

The better attenuation of this case allowed the use of 200 Ms/s and a consequently better resolution, as visible in Figure 36.

No other findings in this test case.

314V145

sys 314V145

PVC plus penetration plus XLPE (Rockbestos)

INPUT PARAMETERS

GM	PRN
RecLen	20000
Layout	HRP-FT01
OffsetCH0	0
RangeCH0	3
OffsetCH1	0
RangeCH1	1
ChirpLength	200000
ChirpMinFreq	1000
ChirpMaxFreq	50000000
block size	400
SampleRate (Ms/s)	200
Resistence	50 Ohm
Resistence	50 Ohm
averaging mode	RMS averaging
weighting mode	Linear
number of averages	300
ImpWindow	Low Sidelobe
phase offset	0
Band (%)	100
PhaseShape	0
Feedback res.	0
Balancing res.	0
Splitter res.	0

HotSpotWindow	Low Sidelobe
Zoom spectral lines	300
HotSpotMode	2
HotSpotThreshold	8
Topology	Off
Order	12
Imp Components	Both

RESULTS

Resonance freqs (Hz)

318673	684061	1074972	1473403	1796871
2086998	2499524	3102026	3584565	3948640
5299183	6210814	6883991	7925453	8178981
9442567	9910696	10834893	11324305	12624234
39724209	39856952	40234512	41647388	42799849

Estimated cable length	122	m		
Phase velocity ratio	0.6295			
Char Impedance	104	ohm	879517	Hz
Line Attenuation	8.9	dB/km	879517	Hz
	1.1	dB		

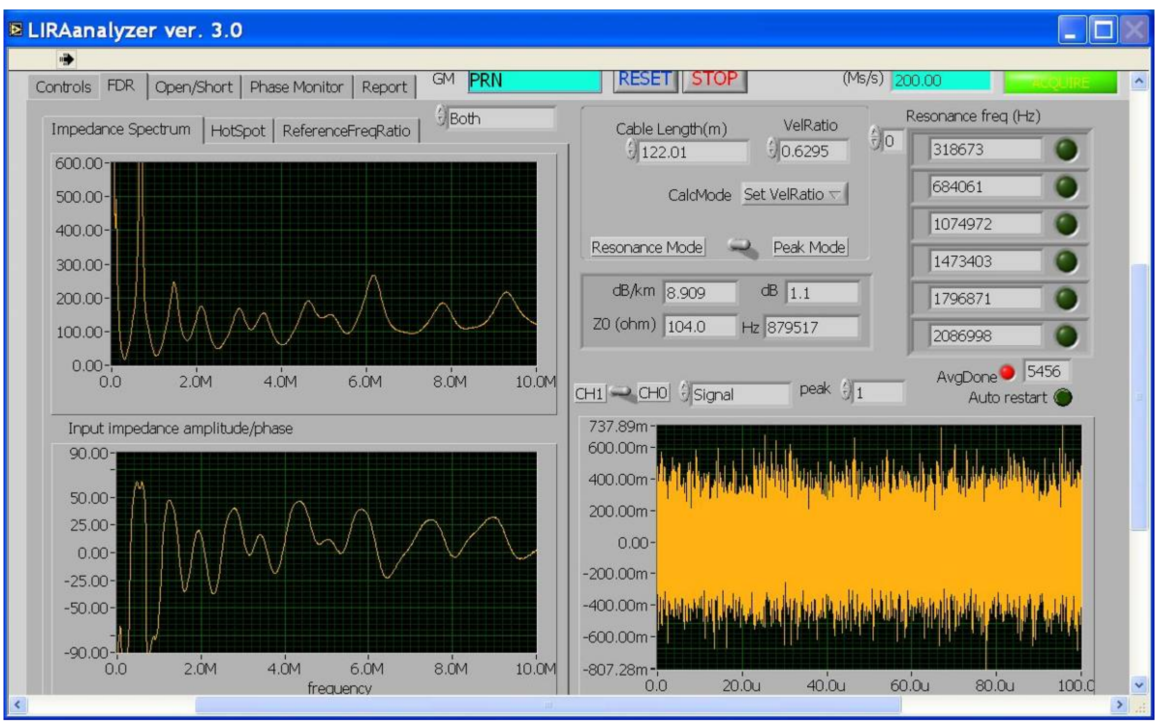

Figure 37

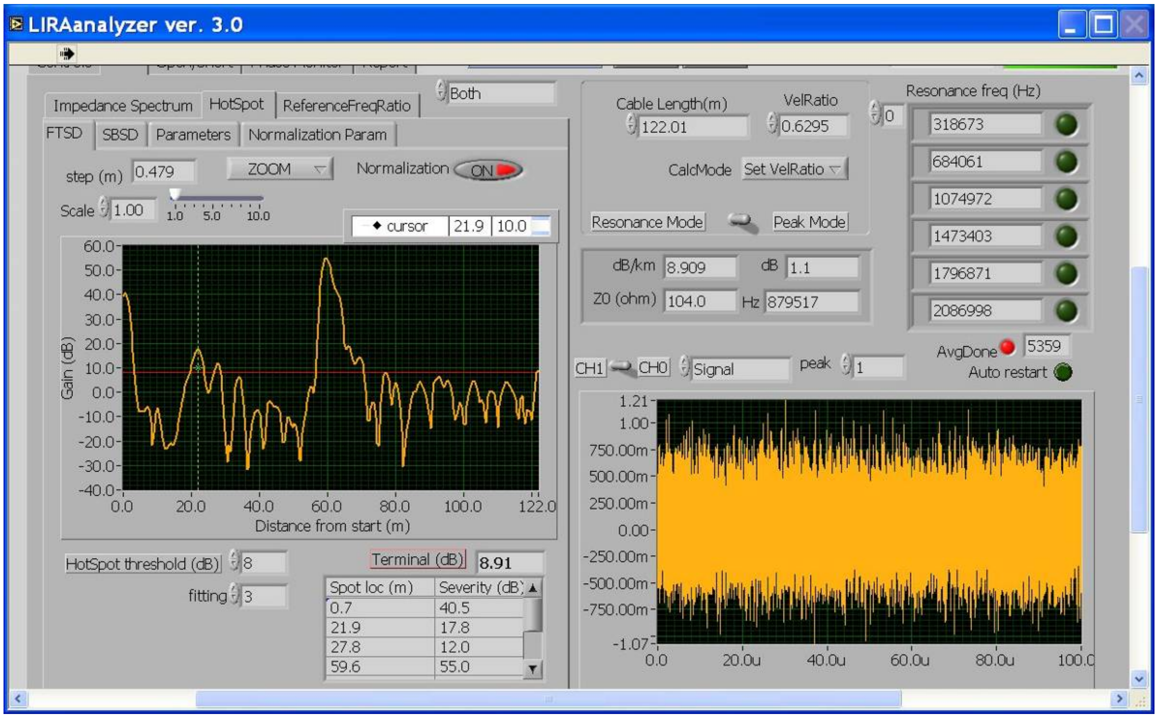

Figure 38

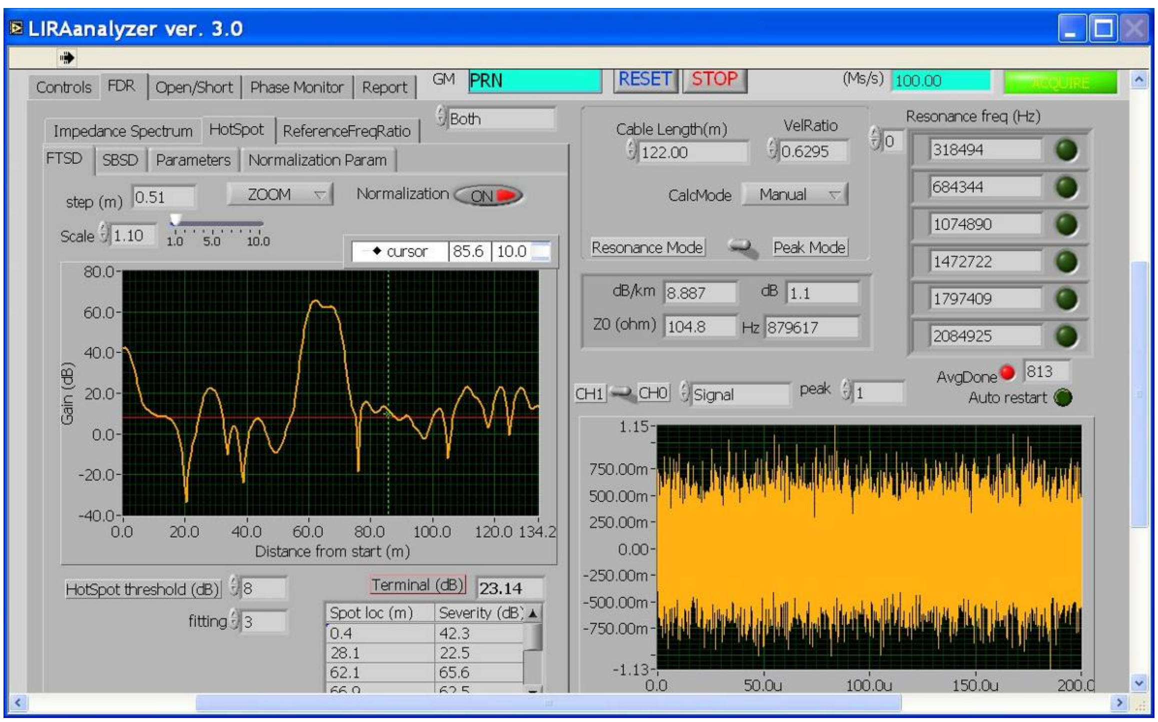

Figure 39

The length of this cable was not known exactly, although comparable to 314V86. Using the same PV ratio of 0.629, the resulting length was 122m.

Figure 38 shows the spot spectrum at 200 Ms/s, Figure 39 shows the same case at 100 Ms/s.

In this test, beside the penetration at 60m, another spot is visible between 22 and 28m , which is at +18dB, a value comparable to the termination height. A visual inspection is recommended.

314V11 and 314V12

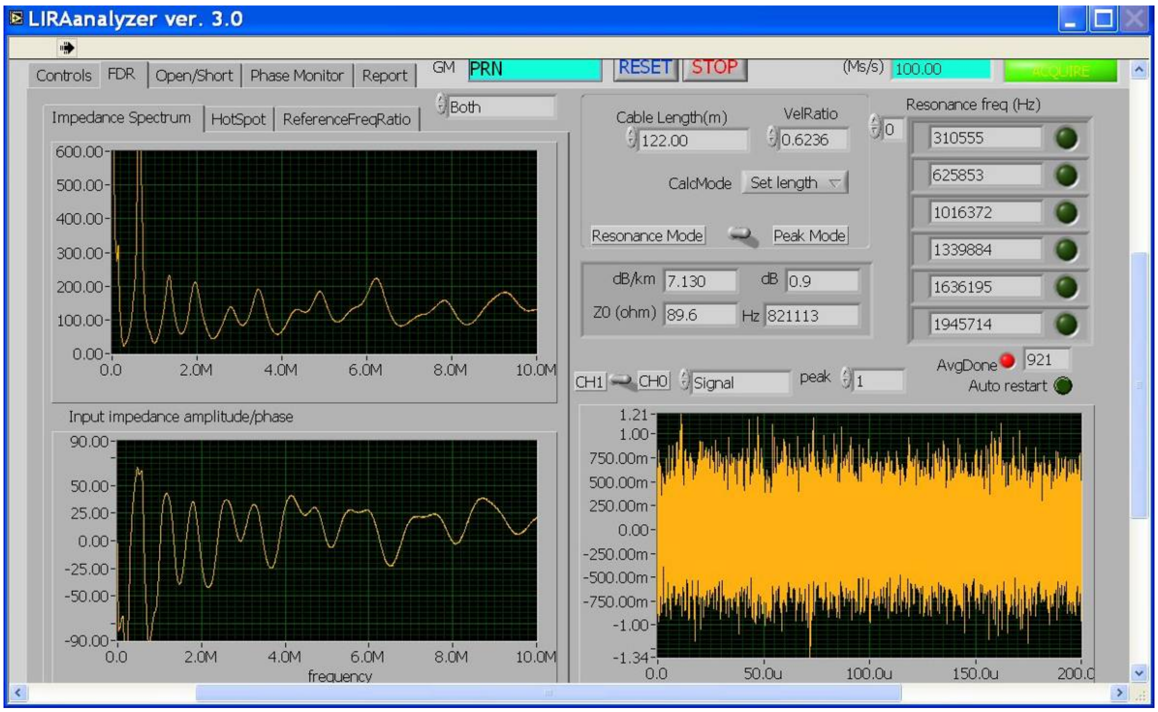

Figure 40

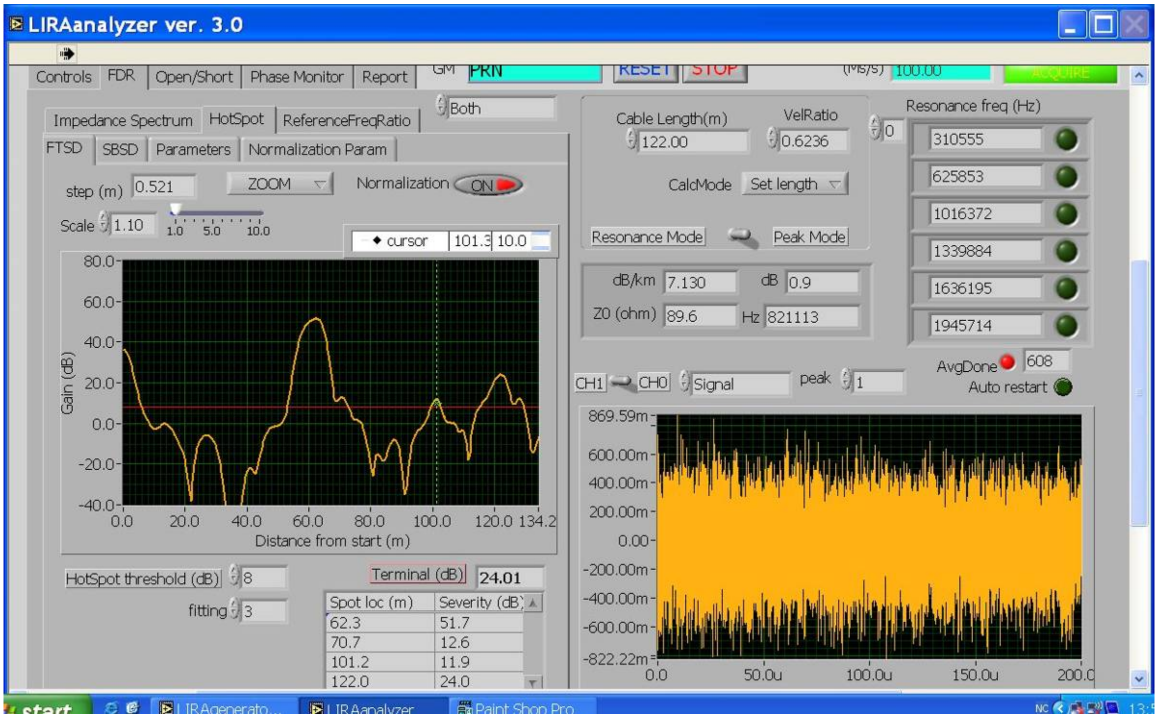

Figure 41

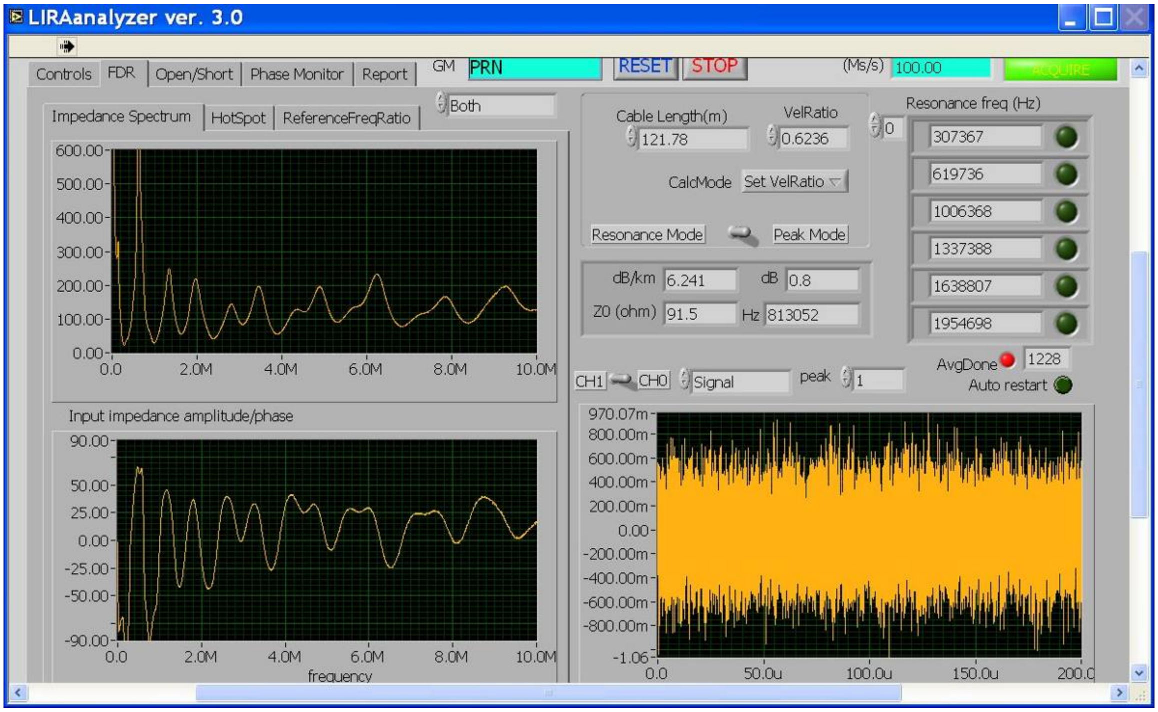

Figure 42

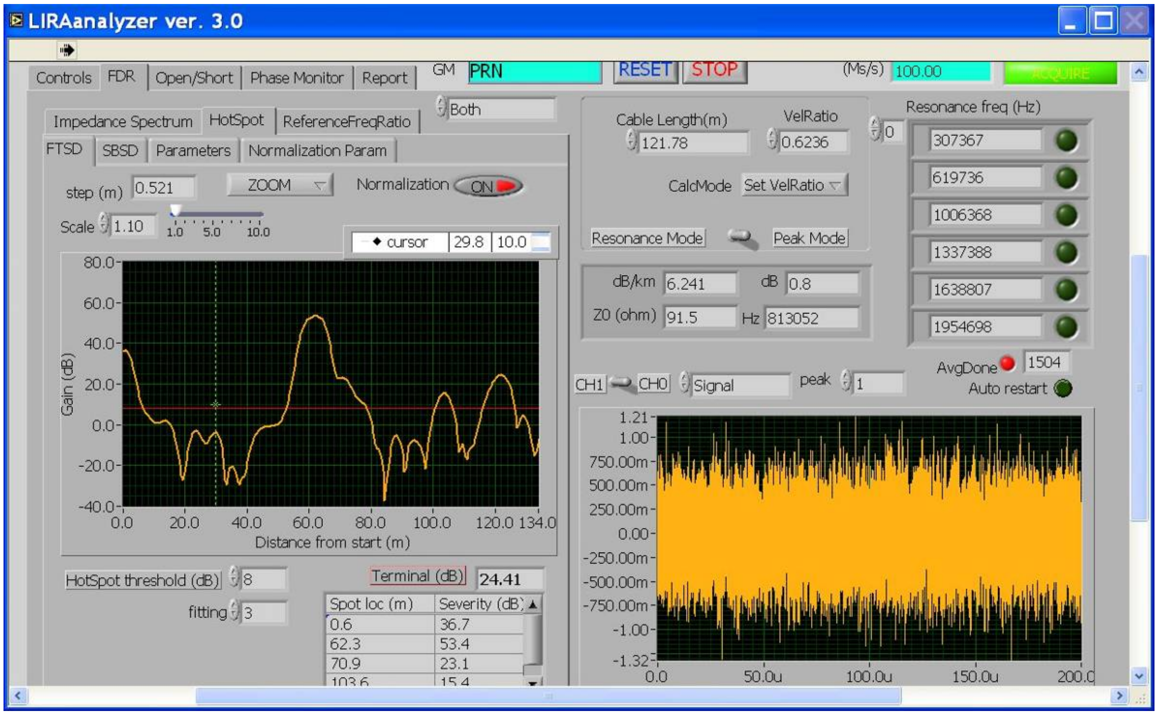

Figure 43

314V11 (Figure 40 and 41) and 314V12 (Figure 42 and 43) are very similar and they have the same length.
The penetration starts at 62m (total length 122m).
The spike at 103.5m has been confirmed.

354V411

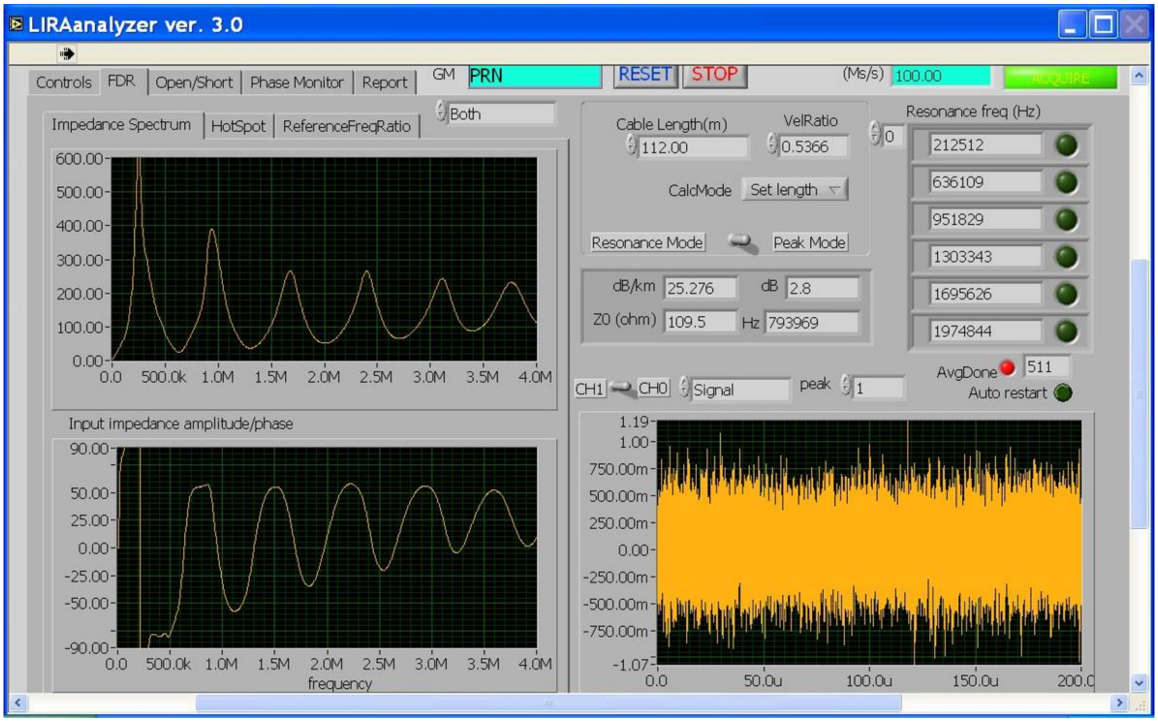

Figure 44

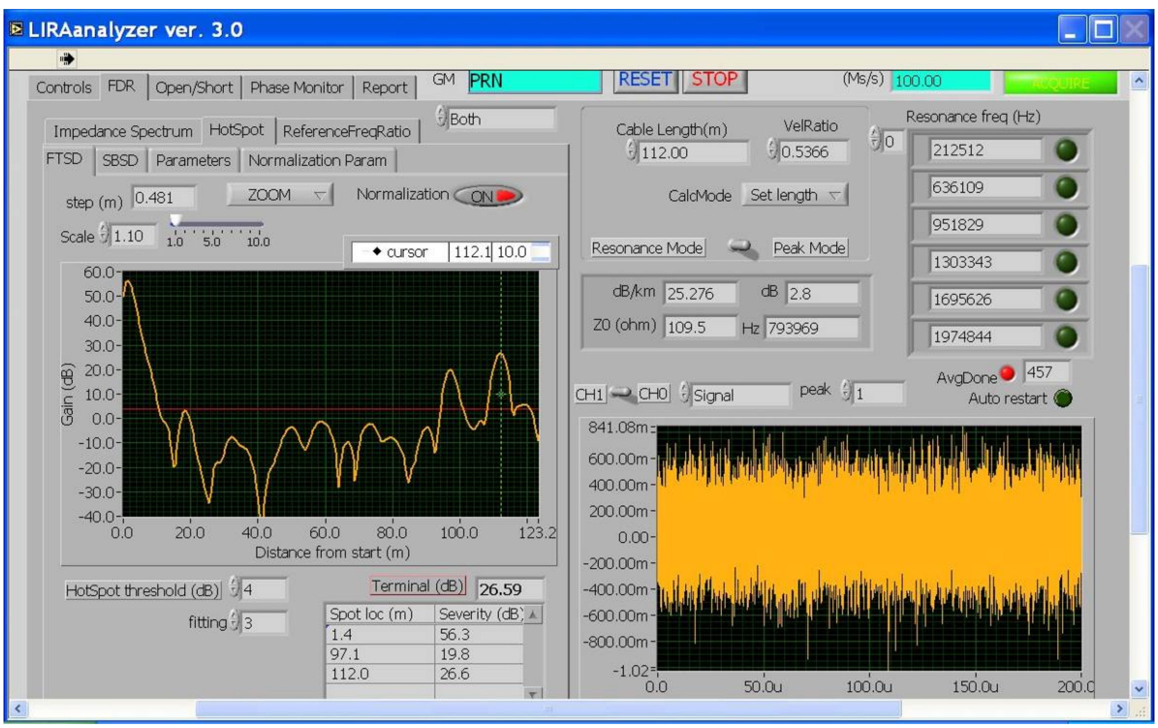

Figure 45

The last test was a 112m PVC cable with a junction at 97m, visible in Figure 45. No other spike above background is visible.

The PV ratio of this cable was 0.53. Cable termination was shorted, as visible in Figure 44 (impedance zero at 0 Hz).

Conclusions

The tests performed in 2005-2006 showed that LIRA could identify localized thermal damage to insulation that had not progressed to the point where the insulation had totally failed. These tests indicated that LIRA could identify aging before end of the qualified life. The results further indicate that LIRA will be useful in assessing the condition of cables located in conduits that are suspected of having been subjected to localized thermal/radiation aging. Similarly, LIRA could be used to assess cables in trays that are difficult to access. The tests of the Ringhals triaxial cables showed that LIRA could function in nuclear power plant environments. The tests showed that the noise in the plant did not adversely affect the LIRA performance.

References

[1] P.F. FANTONI, "*NPP Wire System Aging Assessment and Condition Monitoring: State-Of-the-Art Report*" Halden Reactor Project (HWR-746) (2004).

[2] "*Review of Federal Programs for Wire System Safety*" United States White House (2000)

[3] D. ROGOVIN and R. LOFARO, "*Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in NPP*" USNRC (NUREG/CR-6904) (2006)

[4] K.S. CHANG-LIAO, T.K. CHUNG, H.P. CHOU, "Cable Aging Assessment by Electrical Capacitance Measuring Technique" *Proc. NPIC&HMIT 2000,* Washington D.C., Nov. 2000, (2000).

[5] P.F. FANTONI, "*Wire System Aging Assessment and Condition Monitoring: The Line Resonance Analysis Method (LIRA)*" Halden Reactor Project (HWR-788) (2005).

[6] P.F. FANTONI and A. NORDLUND, "*Wire System Aging Assessment and Condition Monitoring (WASCO)*" Nordic Nuclear Safety Research (NKS-130) (2006).

[7] P.F. FANTONI and G.J. TOMAN, "*Wire System Aging Assessment and Condition Monitoring Using Line Resonance Analysis (LIRA*)**",** NPIC&HMIT 2006 Conference, Albuquerque, USA, 12-16 November 2006.

Bibliographic Data Sheet **NKS-157**

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Author(s)	Paolo F. Fantoni
Affiliation(s)	Institutt for energiteknikk, IFE, Norway
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No. of references	7
Abstract	Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains some test results of a method for wire system condition monitoring, developed at the Halden Reactor Project, called LIRA (LIne Resonance Analysis), which can be used on-line to detect any local or global changes in the cable electrical parameters as a consequence of insulation faults or degradation.
Key words	Condition monitoring, cable aging, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA, positron

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