

Exponent[®]

Transients: How to Measure, Trace the Source(s), and Evaluate their Effects

MREC Break-out Session

February 12, 2026

About Exponent

Exponent is the only premium engineering and scientific consulting firm with the depth and breadth of expertise to solve our clients' most profoundly unique and urgent challenges.

1967

50+ Years of
Scientific Excellence

950+

Consulting
Staff

90+

Technical
Disciplines

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Offices Across North
America, Europe & Asia

Speakers

- With you today



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Breakout Session Outline

x

Tools

Methods & Matching

Identifying Non-Lightning Sources of VLF Signals

Responding to Alleged Utility Sources of VLF Signals

Tools

x

GPS clock (timing)

Oscilloscope (with saving data)

Monopole antenna

Filters/Amplifiers

Lightning Data

GPS Clock

- **Example: Arbiter Model 1095A/C**
- **Industrial GPS Clock**
- **Outputs a 1 pulse-per-second (pps) signal**
 - ± 250 ns peak;
 - ± 100 ns typical
- **Outputs IRIG-B: Date Code**

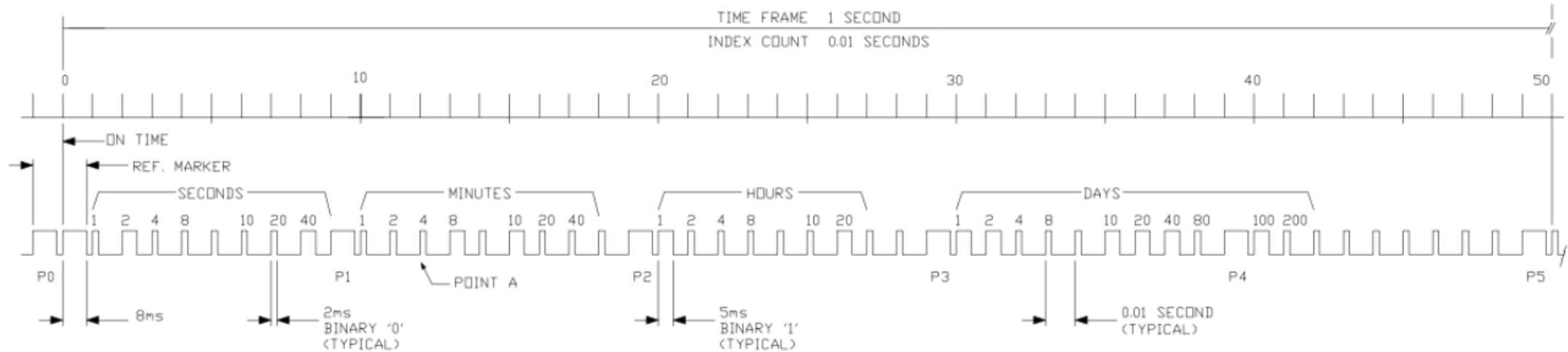


GPS Clock



GPS Antenna

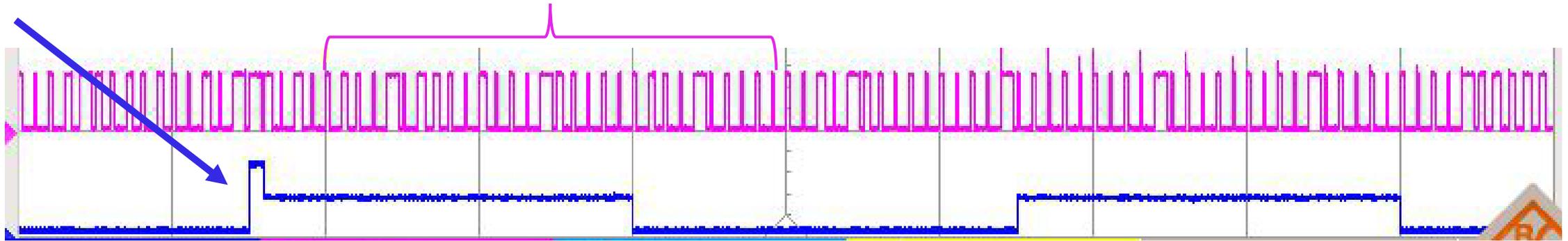
IRIG-B Data Code: Time & Date



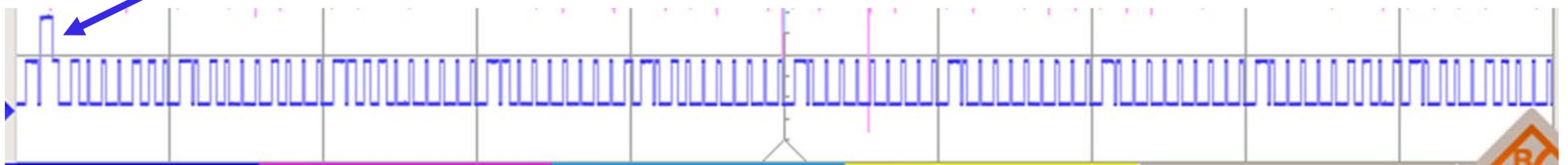
Rising Edge and IRIG-B Data signals

**GPS rising edge
(Start of the second)**

**GPS IRIG-B signal
used to decode
exact absolute time**



**Combined IRIG-B and 1
PPS GPS Signal
(Start of the second)**



Oscilloscopes: Not all Scopes are Created Equal



Saving Data

190-062

190-102

190-202

190-104

190-204

190-504



Record length

Up to 10,000 samples per channel

	190-062	190-102	190-202	190-104	190-204	190-504
Vertical deflection						
Number of channels	2	2	2	4	4	4
Bandwidth	60 MHz	100 MHz	200 MHz	100 MHz	200 MHz	500 MHz
Rise time	5.8 ns	3.5 ns	1.7 ns	3.5 ns	1.7 ns	0.7 ns
Number of scope inputs	2 input channels plus external trigger			4 input channels		
Channel architecture	All inputs fully insulated from each other and from ground Inputs may be activated in any combination					
Input coupling	AC or DC, with ground level indicator					
Input sensitivity	2 mV/div to 100 V/div, plus variable attenuation					
Bandwidth limiter	User selectable: 10 kHz, or full bandwidth					
Normal/invert/variable	On each input channel, switched separately					
Input voltage	CAT III 1000 V/CAT IV 600 V rated, see General Specifications for further details					

	190-062	190-102	190-202	190-104	190-204	190-504
Record length						
Record length	Up to 10,000 samples per channel					
Time base range	10 ns/div to 4 s/div	5 ns/div to 4 s/div	2 ns/div to 4 s/div	5 ns/div to 4 s/div	2 ns/div to 4 s/div	1 ns/div to 4 s/div
	Time base in a 1-2-4-sequence Slower time/division settings using ScopeRecord™ Roll mode (see 'Recorder mode')					
Maximum record length	10,000 samples per channel in scope mode 30,000 points per channel in ScopeRecord™ Roll mode (see 'Recorder mode')					
Timing accuracy	± (0.01 % of reading + 1 pixel)					
Glitch capture	8 ns peak detect on each channel (using real time sampling and data compression, at any timebase setting)					
Display and acquisition						
Display	153 mm (6 in) full-color LCD with LED backlight					
Display modes	Any combination of channels; average on/off; replay					
Visible screen width	12 divisions horizontally in scope mode					
Digital persistence modes	off/short/medium/long/infinite and envelope mode					
Waveform mathematics	One mathematical operation on any 2 input channels: add/subtract/multiply; X-Y-mode Frequency Spectrum using FFT analysis					
Acquisition modes	Normal, Averaged, Auto, Single Shot, ScopeRecord™ roll, glitch capture, waveform compare with automatic "Pass/Fail testing"; Replay					
Trigger and delay						
Source	Input A, B or External (via meter input)			Input A, B, C or D		
Modes	Automatic Connect-and-View™, free run, single shot, edge, delay, dual slope, video, video line, selectable pulsewidth (channel A only), N-cycle					
Connect-and-View™	Advanced automatic triggering that recognizes signal patterns, automatically sets up and continuously adjusts triggering, time base and amplitude. Automatically displays stable waveforms of complex and dynamic signals like motor drive and control signals. Can be switched off if preferred.					
Video triggering (on ch. A)	NTSC, PAL, PAL+, SECAM; Includes field 1, field 2 and line select					
High-res, non-interlaced video	Non-interlaced video with line-select, for line frequencies in the range 14 kHz up to 65 kHz					
Pulse width triggering (on channel A)	Pulse width qualified by time Allows for triggering <t, >t, =t, ≠ t, where t is selectable in minimum steps of 0.01 div or 50 ns					
Time delay	1 full screen of pre-trigger view or up to 100 screens (=1,200 divisions) of post-trigger delay					
Dual slope triggering	Triggers on both rising and falling edges alike					
N-cycle triggering	Triggers on N-th occurrence of a trigger event; N to be set in the range 2 to 99					

Fluke 190-104 ScopeMeter® Test Tool | Fluke

Saving Data

R&S®RTH1002 R&S®RTH1004 HANDHELD OSCILLOSCOPE

Specifications



Maximum acquisition length for slow time bases (greater than or equal to 50 ms/div)	1, 2, 3 or 4 active analog channels	125 ksample for each channel (sample acquisition modes)	125 ksample for each channel (sample on mode)
		62.5 ksample for each channel (high resolution, peak detect, envelope and average acquisition modes)	62.5 ksample for each channel (high resolution, peak detect, envelope and average acquisition modes)



Data Sheet
Version 27.00

ROHDE & SCHWARZ

Make ideas real



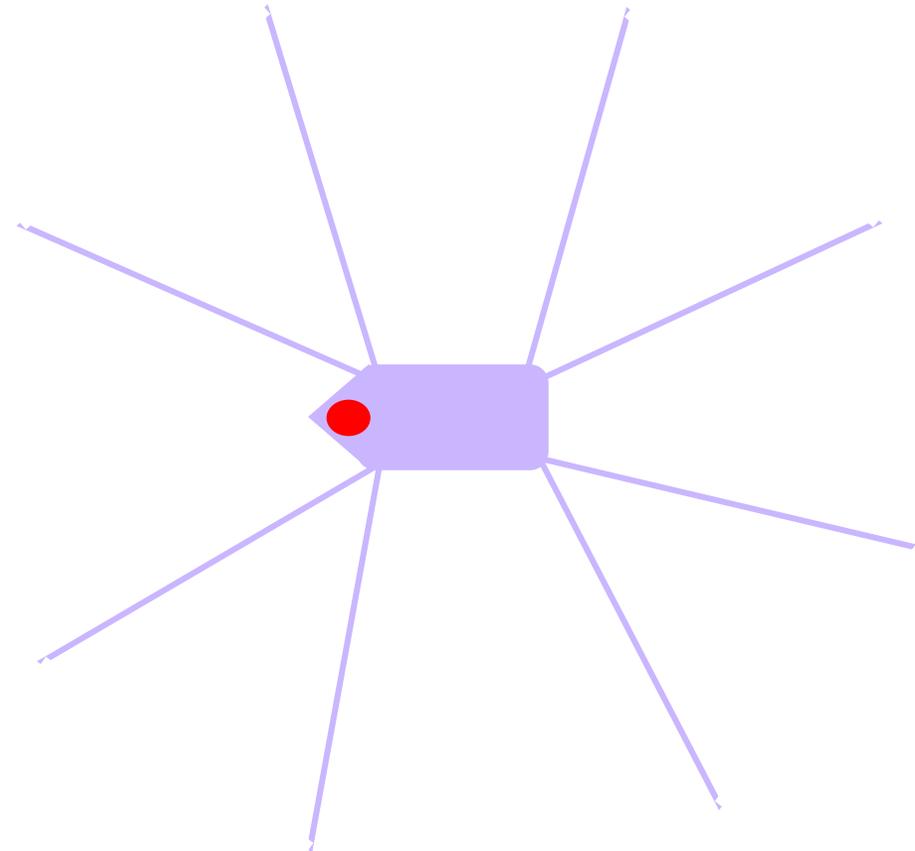
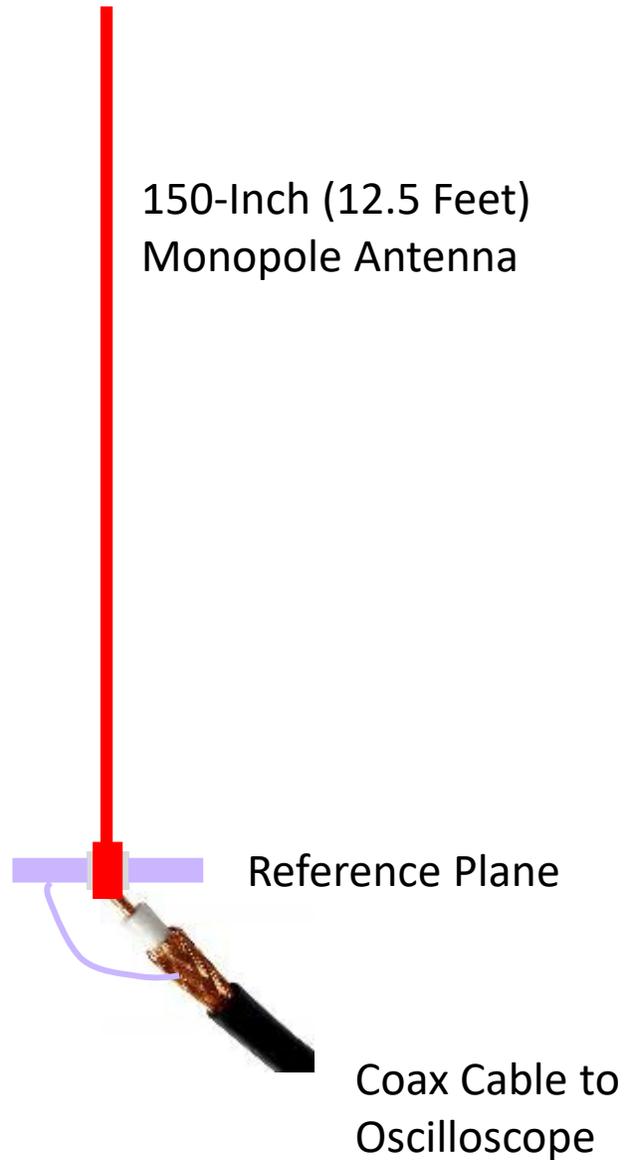
Acquisition system

Maximum realtime sampling rate	R&S®RTH1004	1 active channel with 5 Gsample/s 2 active channels with 2.5 Gsample/s 4 active channels with 1.25 Gsample/s
	R&S®RTH1002	1 active channel with 5 Gsample/s 2 active channels with 2.5 Gsample/s
	definition: active channel	A channel is active if it is either acquired or used as a trigger source.
Maximum acquisition length for fast time bases (less than or equal to 20 ms/div)	1 active analog channel	500 ksample (sample acquisition mode)
		250 ksample (high resolution, peak detect, envelope and average acquisition

Maximum acquisition length for slow time bases (greater than or equal to 50 ms/div)	1, 2, 3 or 4 active analog channels	125 ksample for each channel (sample acquisition modes)	125 ksample for each channel (sample on mode)
		62.5 ksample for each channel (high resolution, peak detect, envelope and average acquisition modes)	62.5 ksample for each channel (high resolution, peak detect, envelope and average acquisition modes)
Acquisition modes	sample	first sample in decimation interval	first sample in decimation interval
	high resolution	average value of samples in decimation interval	average value of samples in decimation interval
	peak detect	largest and smallest sample in decimation interval	largest and smallest sample in decimation interval
	envelope	envelope of acquired waveforms; for timebases requiring decimation, peak-detect is used.	envelope of acquired waveforms; for timebases requiring decimation, peak-detect is used.
average	average of acquired waveforms; for timebases requiring decimation, high resolution is used. Number of averaged waveforms can be power of 2 from 2 to 8192.	average of acquired waveforms; for timebases requiring decimation, high resolution is used. Number of averaged waveforms can be power of 2 from 2 to 8192.	
Realtime waveform acquisition rate	max.	50 000 waveforms/s	50 000 waveforms/s

Monopole Antenna

(Illustrative – Not to Scale)



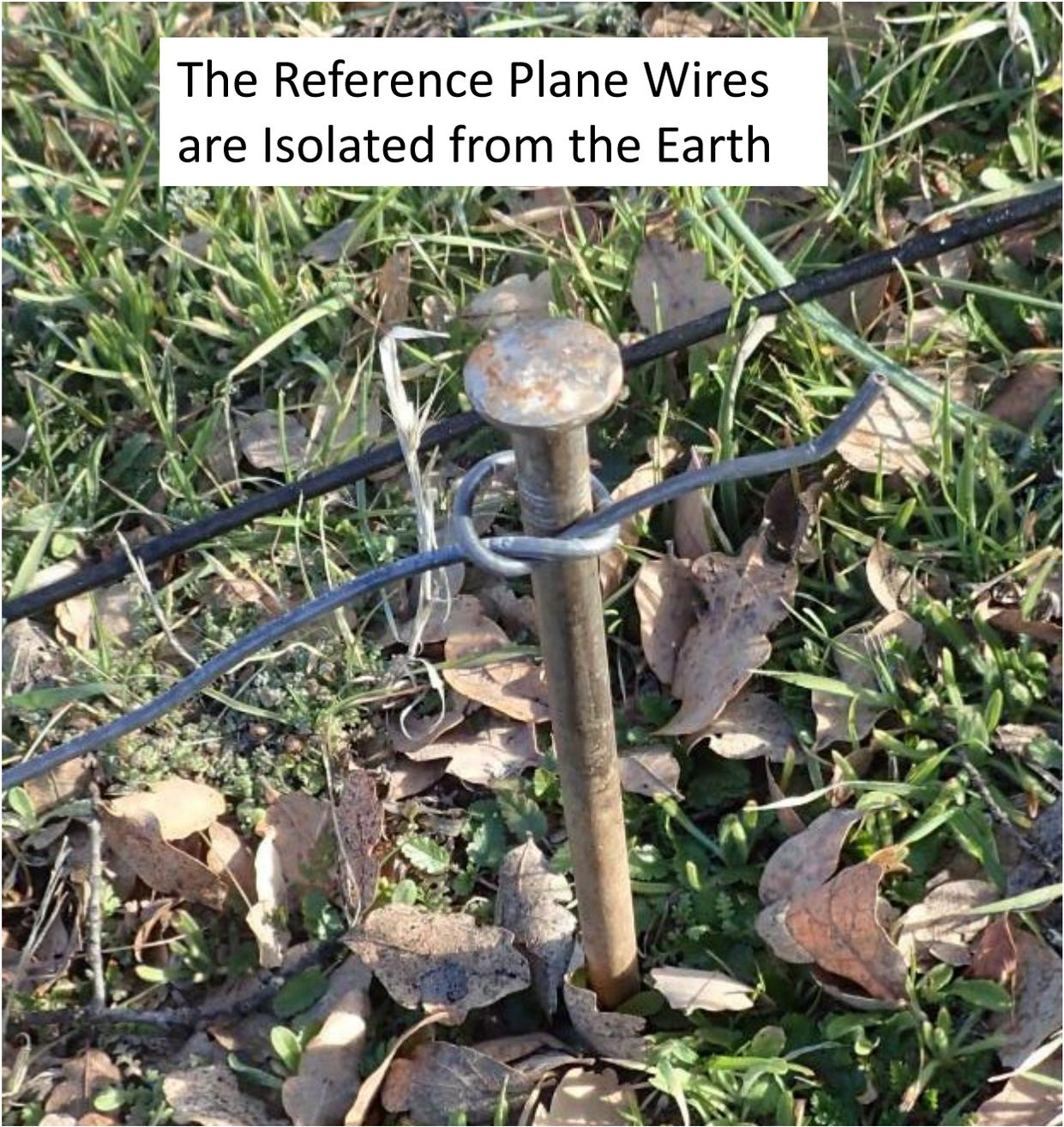
Reference Plane Comprised of

- Mounting plate
- 8: Isolated 16-foot wires

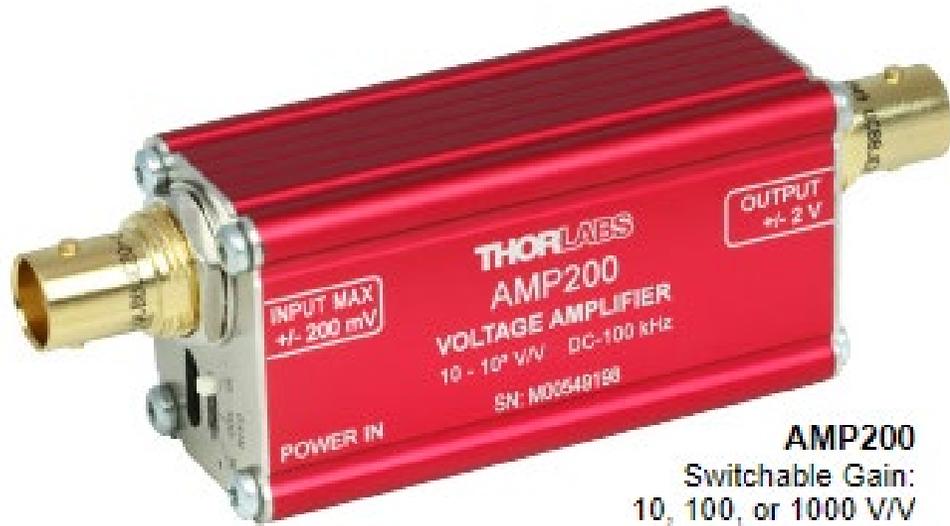
Monopole Antenna



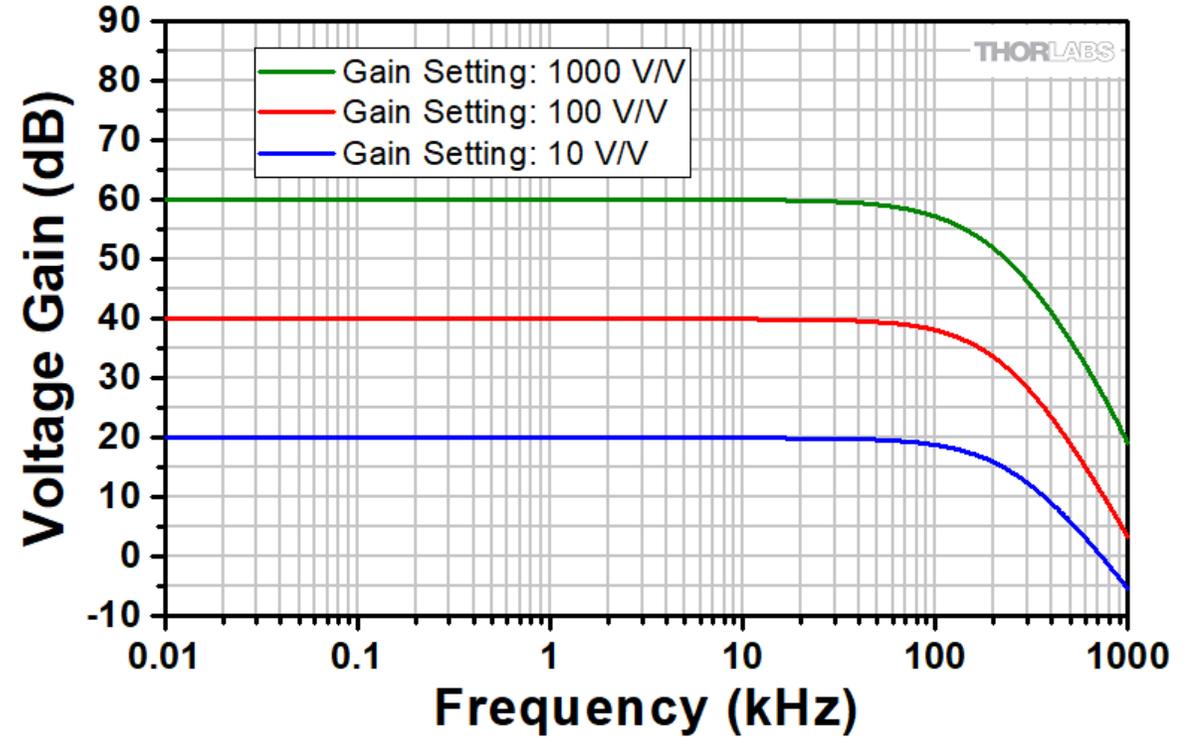
The Reference Plane Wires
are Isolated from the Earth



Thorlabs Amplifier and Frequency Response

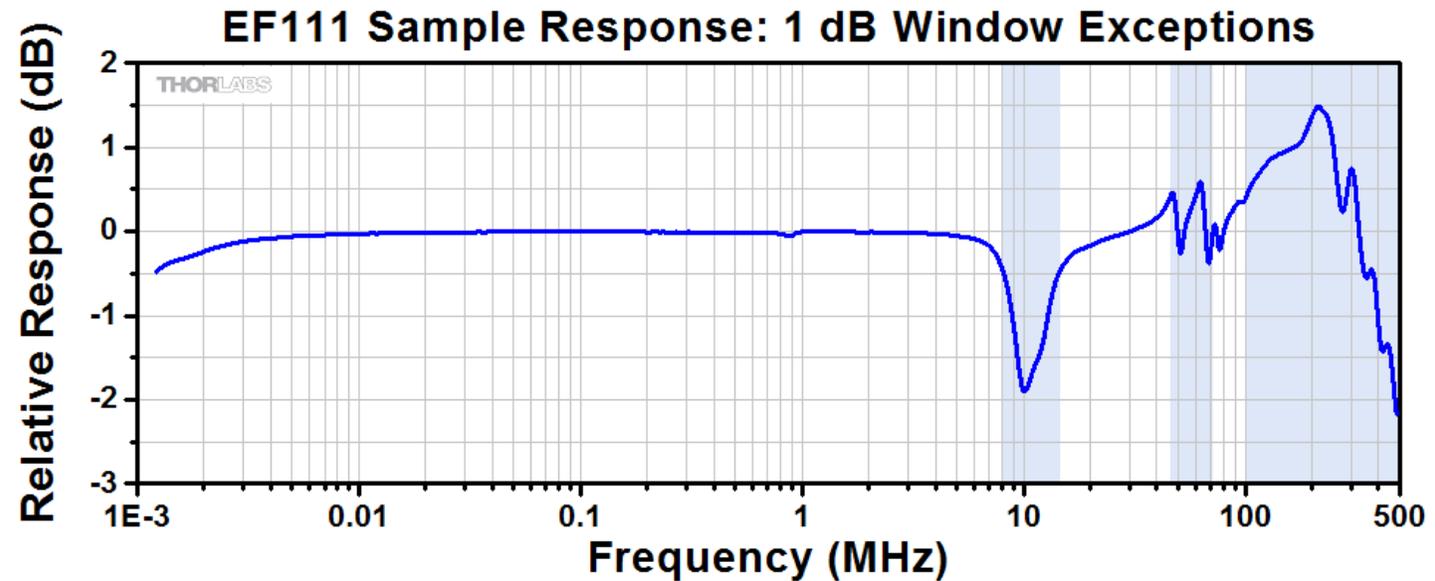
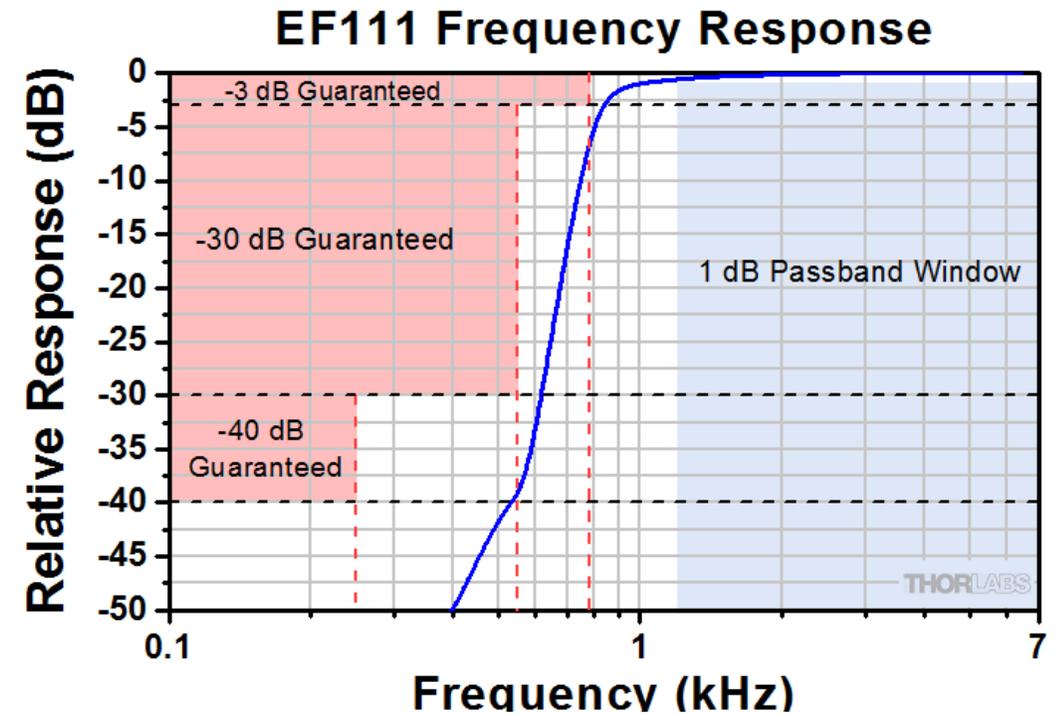


AMP200 Frequency Response



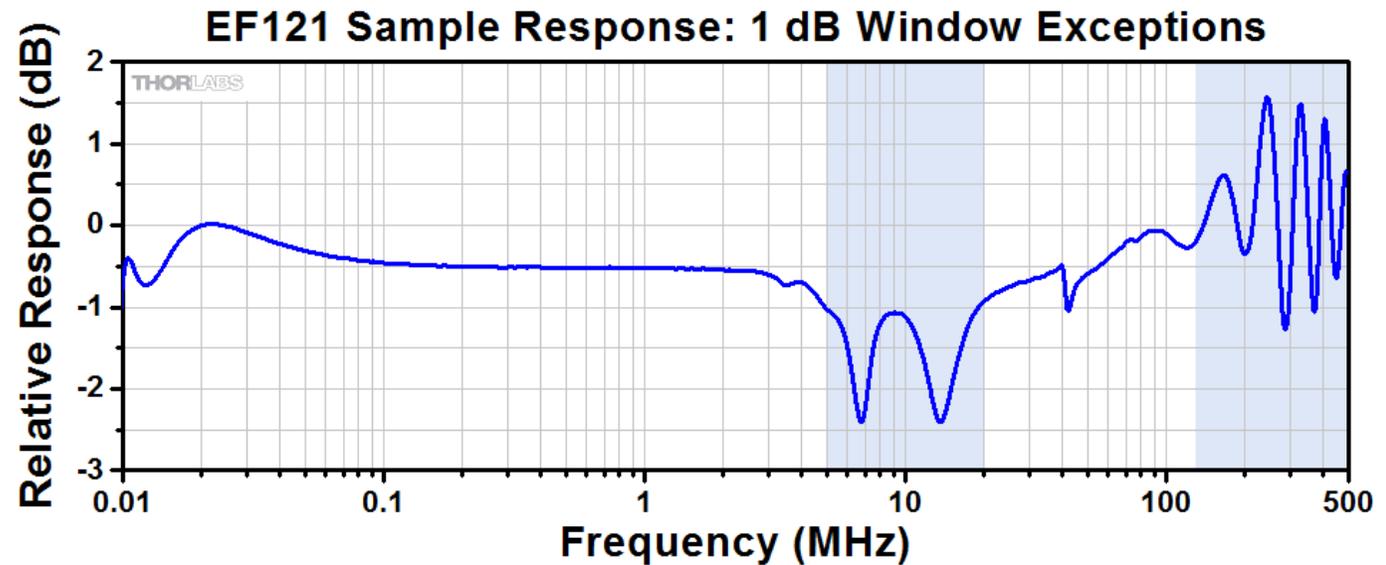
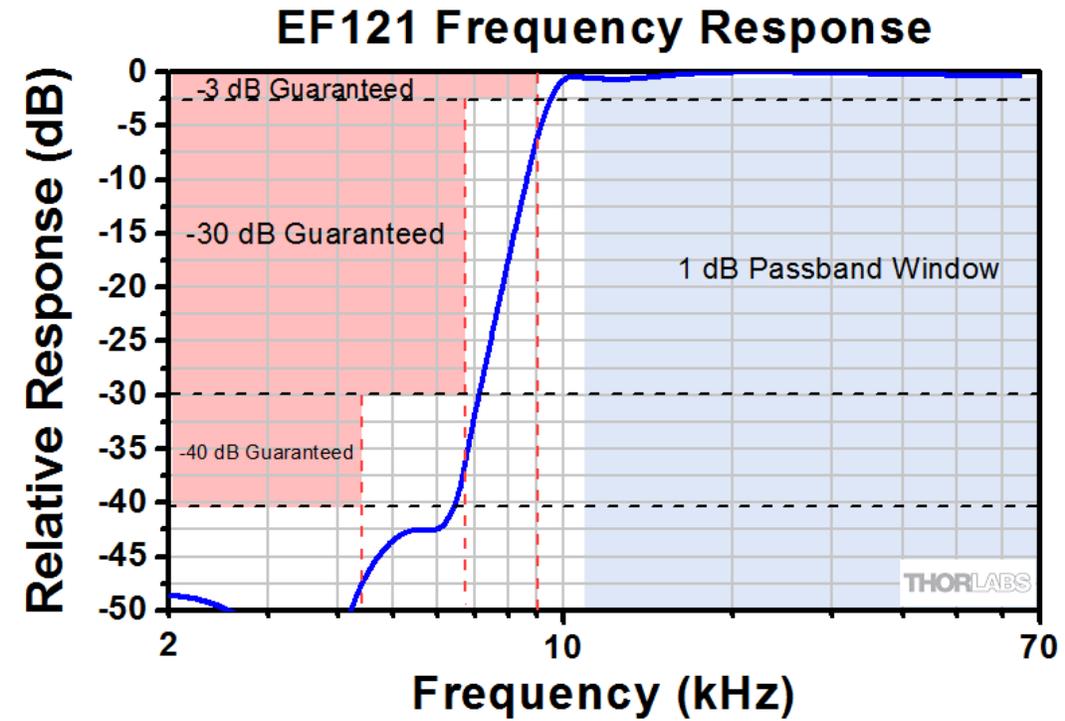
<https://www.thorlabs.com/thorproduct.cfm?partnumber=AMP200>

Thorlabs 1 kHz High-Pass Filter



https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10387&pn=EF121

Thorlabs 10 kHz High-Pass Filter

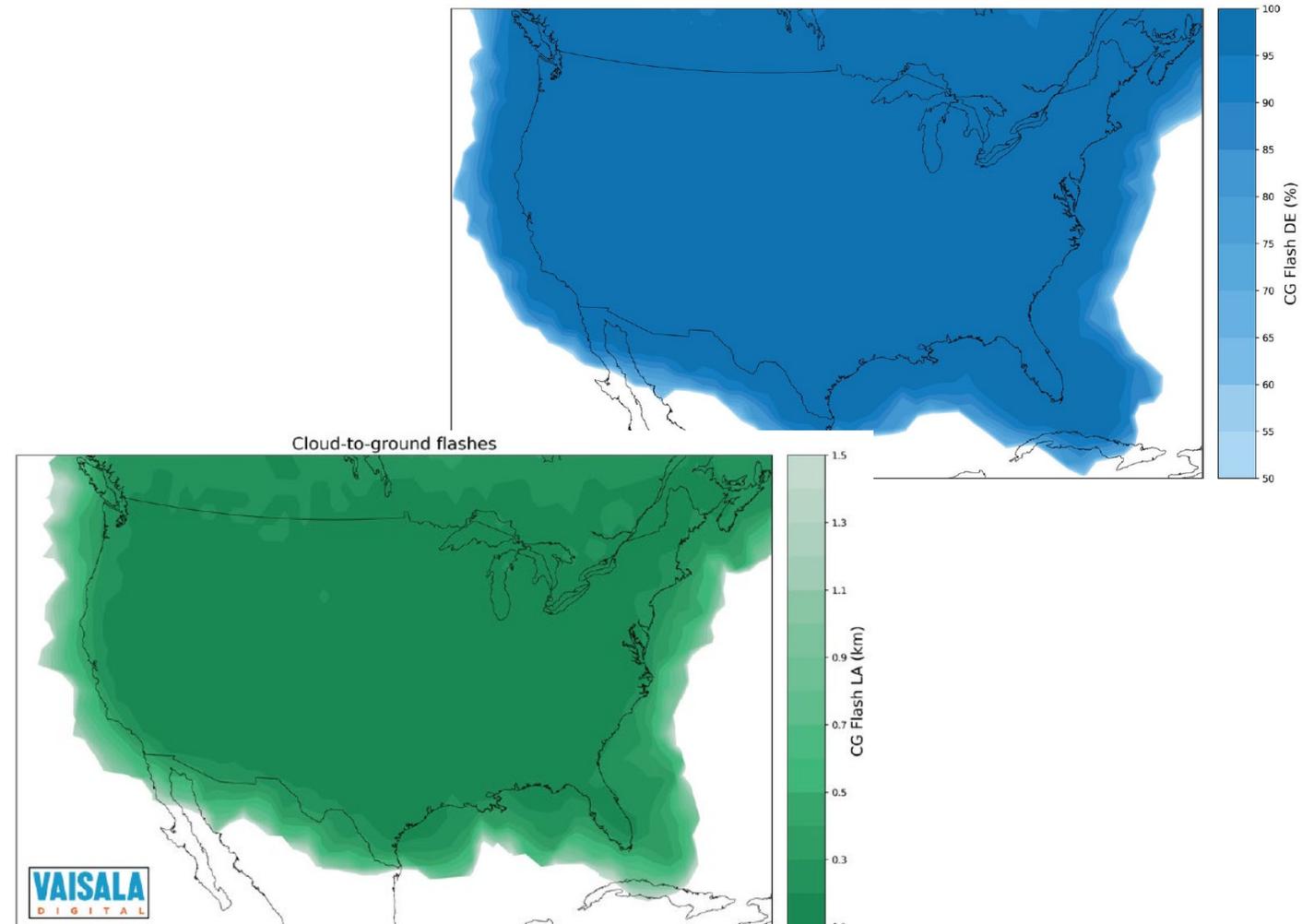


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10387&pn=EF121

Vaisala Lightning Detection Networks: NLDN/NALDN

NLDN (LF/MF Receivers)

- Coverage of the continental U.S.
- **Microsecond timing accuracy**
- Time of arrival
- Magnetic direction-finding
- **<150 meter location accuracy**
- >95% detection efficiency



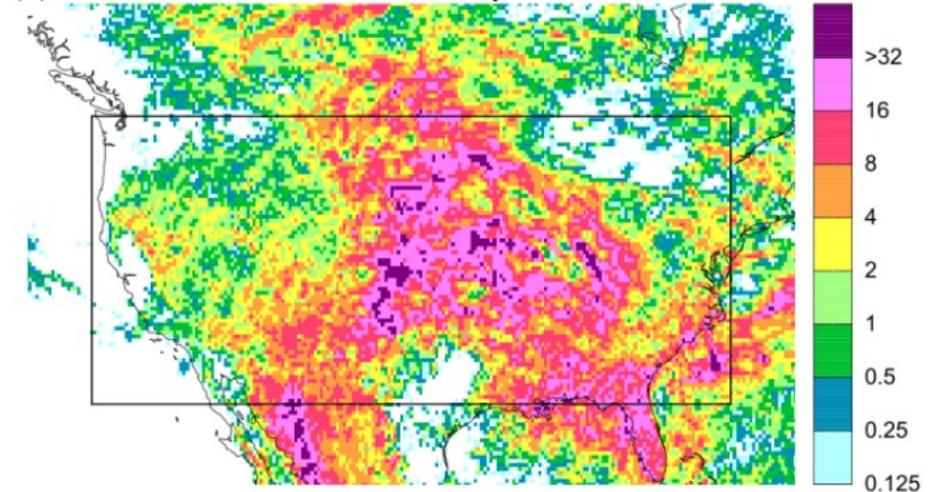
Source; Vaisala_NLDN_2020_Brochure.pdf

Vaisala Lightning Detection Networks: GLD360

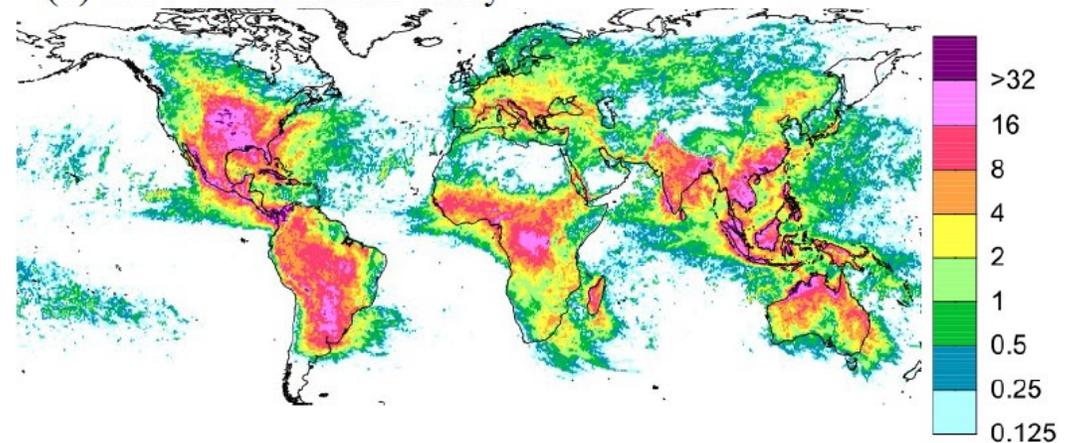
GLD360 (VLF Receivers)

- Global coverage
- **Microsecond timing accuracy**
- Time of arrival
- Magnetic direction-finding
- <1.8 km LA in CONUS
- **~81% DE in CONUS**
- CG \lesssim 70% DE

(b) GLD360 Total Flash Density



(b) GLD Total Flash Density



Source: Rudlosky2017_GLD360_Performance_Relative_to_TRMM_LIS.pdf; Said_and_Murphy_2016_GLD360_Upgrade_Performance.pdf

Lightning Data: Raw Data

Network	Date	Time	Latitude	Longitude	Peak_current (kA)	Azimuth (Deg)	Distance (km)	Travel_time (sec)	Time_adjusted
NLDN	M/D/Y	14:00:00.343	31.8908	-85.6417	8.5	168.1	1496.46	0.004991653	14:00:00.348
NLDN	M/D/Y	14:00:00.346	31.8898	-85.6454	9.3	168.1	1496.49	0.004991753	14:00:00.351
NLDN	M/D/Y	14:00:00.347	31.8935	-85.6548	4.5	168.1	1495.91	0.004989819	14:00:00.352
NLDN	M/D/Y	14:00:00.347	31.8924	-85.6532	3.7	168.1	1496.06	0.004990319	14:00:00.352
NLDN	M/D/Y	14:00:00.350	31.8915	-85.6439	11.6	168.1	1496.34	0.004991253	14:00:00.355
NLDN	M/D/Y	14:00:00.484	31.8405	-85.5315	-8.4	167.8	1504.09	0.005017104	14:00:00.489
GLD	M/D/Y	14:00:00.913	5.6722	-78.3647	-9	167.8	4504.02	0.015023794	14:00:00.928
GLD	M/D/Y	14:00:01.049	5.6758	-78.3621	-13	167.8	4503.7	0.015022726	14:00:01.064
GLD	M/D/Y	14:00:01.050	5.6882	-78.3604	-9.2	167.8	4502.39	0.015018356	14:00:01.066
GLD	M/D/Y	14:00:01.085	5.6689	-78.3623	-9.8	167.8	4504.44	0.015025195	14:00:01.100
GLD	M/D/Y	14:00:01.125	5.6974	-78.3279	-30.3	167.8	4502.15	0.015017556	14:00:01.140
GLD	M/D/Y	14:00:01.196	5.6866	-78.3464	-41.4	167.8	4502.89	0.015020024	14:00:01.211
GLD	M/D/Y	14:00:01.237	0.7417	0.1351	-67.2	135	9917.82	0.033082287	14:00:01.270

This table shows 13 of 1,006,836 lightning strokes recorded during VLF measurements at dairy this day

Lightning Data: Be Careful of Spreadsheets

Network	Date	Time	Label	Time_adjusted
NLDN	M/D/Y	00:00.3		00:00.3
NLDN	M/D/Y	00:00.3		00:00.4
NLDN	M/D/Y	00:00.3		00:00.4
NLDN	M/D/Y	00:00.3		00:00.4
NLDN	M/D/Y	00:00.4		00:00.4
NLDN	M/D/Y	00:00.5		00:00.5
GLD	M/D/Y	00:00.9		00:00.9
GLD	M/D/Y	00:01.0		00:01.1
GLD	M/D/Y	00:01.1		00:01.1
GLD	M/D/Y	00:01.1		00:01.1
GLD	M/D/Y	00:01.1		00:01.1
GLD	M/D/Y	00:01.2		00:01.2
GLD	M/D/Y	00:01.2		00:01.3

Format Cells

Number Alignment Font Border Fill Protection

Category:

- General
- Number
- Currency
- Accounting
- Date
- Time
- Percentage
- Fraction
- Scientific
- Text
- Special
- Custom**

Sample

14:00:00.348

Type:

hh:mm:ss.000

h:mm

h:mm:ss

m/d/yyyy h:mm

mm:ss

mm:ss.0

@

[h]:mm:ss

((\$* ##,##0);_(\$* (#,##0);_(\$* "-"_);_(@_)

((\$* ##,##0);_(\$* (#,##0);_(\$* "-"_);_(@_)

((\$* ##,##0.00);_(\$* (#,##0.00);_(\$* "-"??_);_(@_)

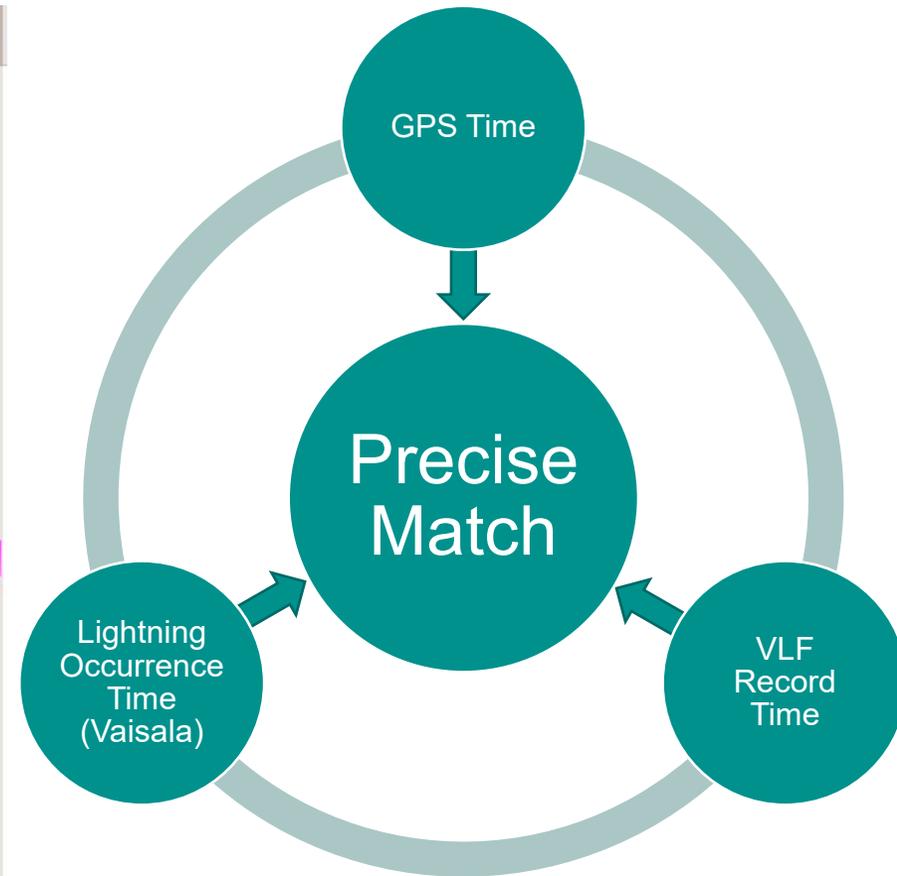
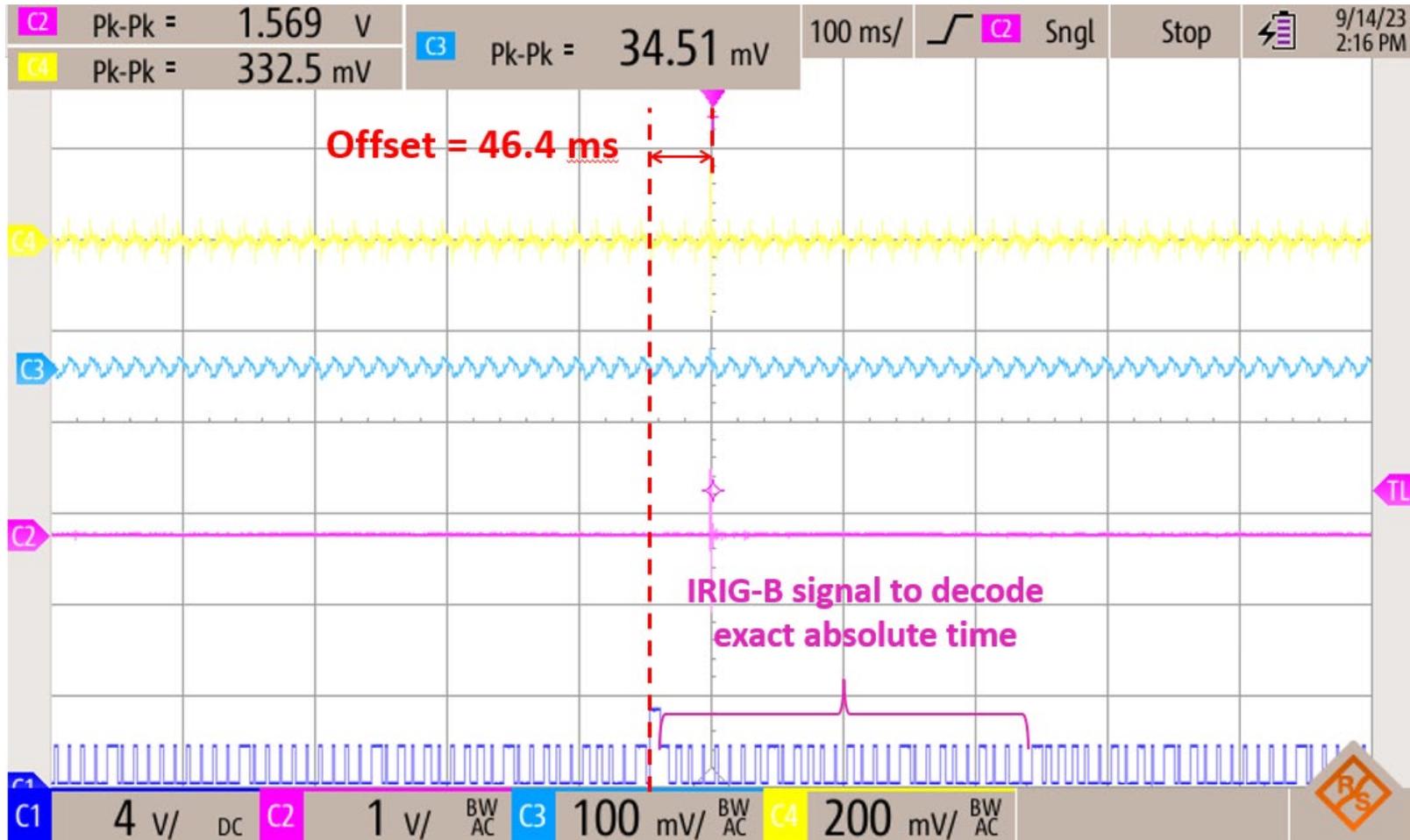
((\$* ##,##0.00);_(\$* (#,##0.00);_(\$* "-"??_);_(@_)

hh:mm:ss.000

Matching Methods

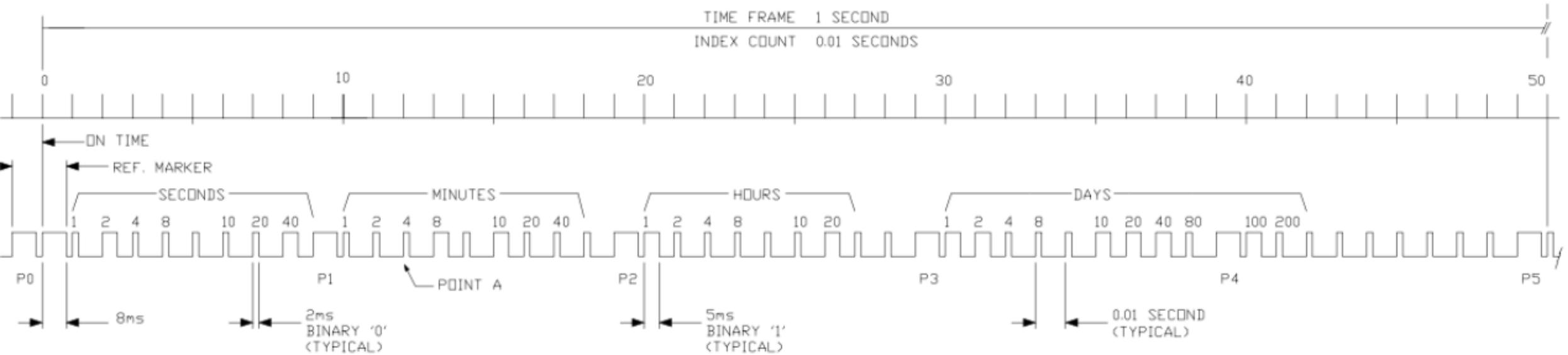
Matching a Recorded VLF Signal to an
Individual Lightning Stroke

Matching VLF Signals to Lightning



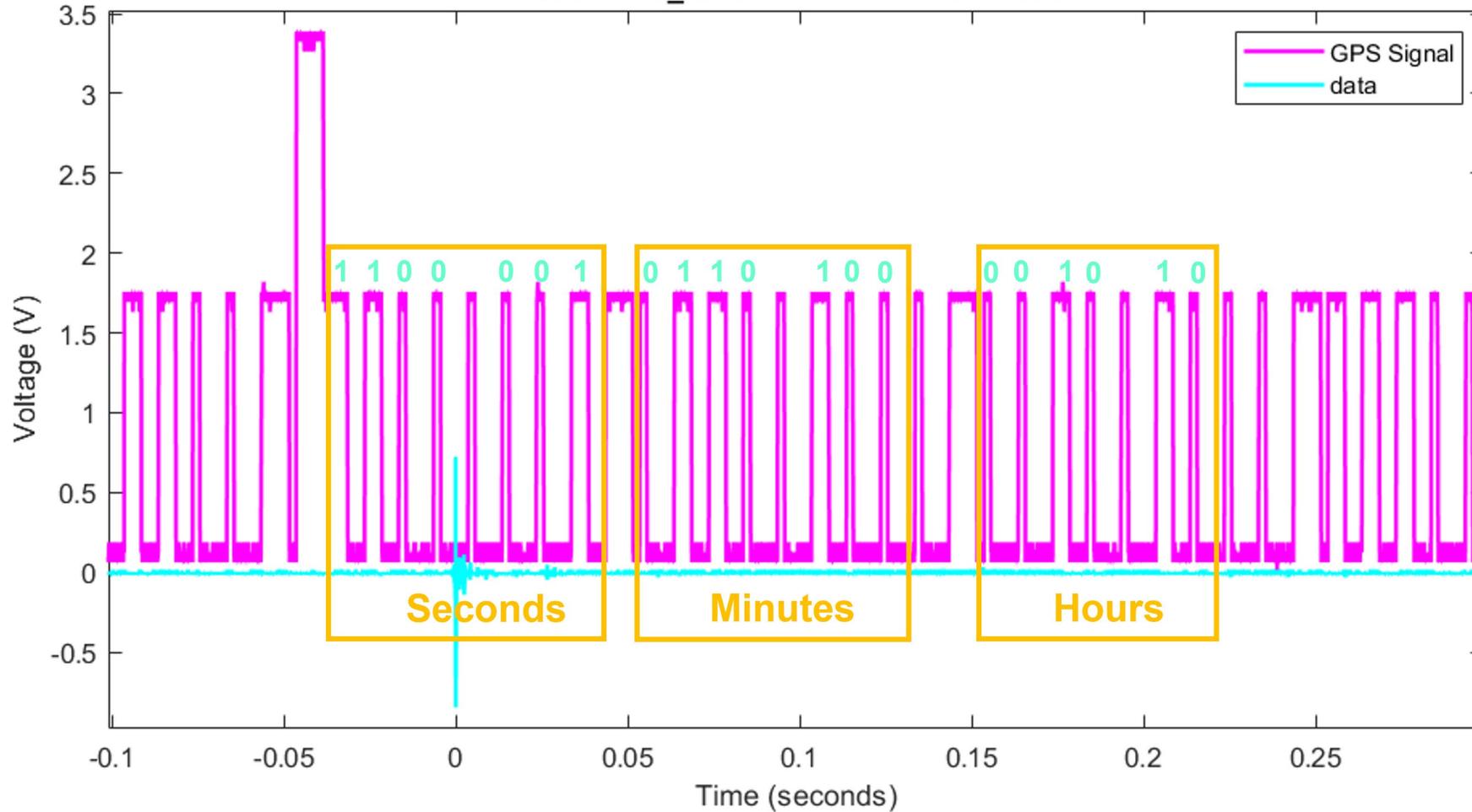
Match: Record time is within less than 1 millisecond (ms) ($1/1000^{\text{th}}$ of a second) of spheric arrival time.
No match: Record time is >1 ms ($1/1000^{\text{th}}$ of a second) from spheric arrival time.

IRIG-B Code



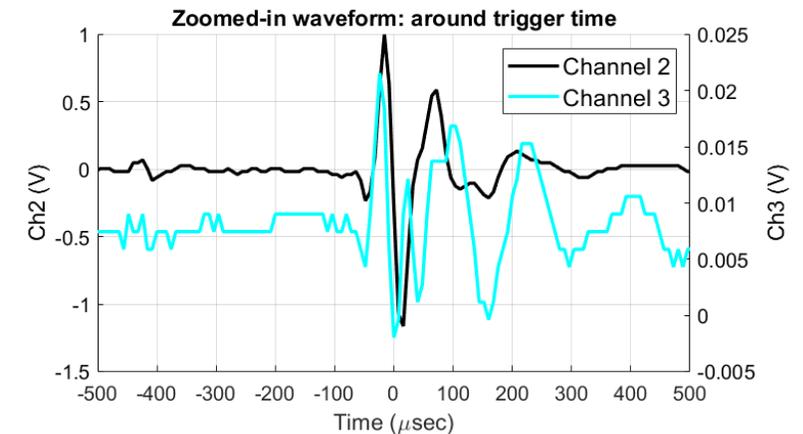
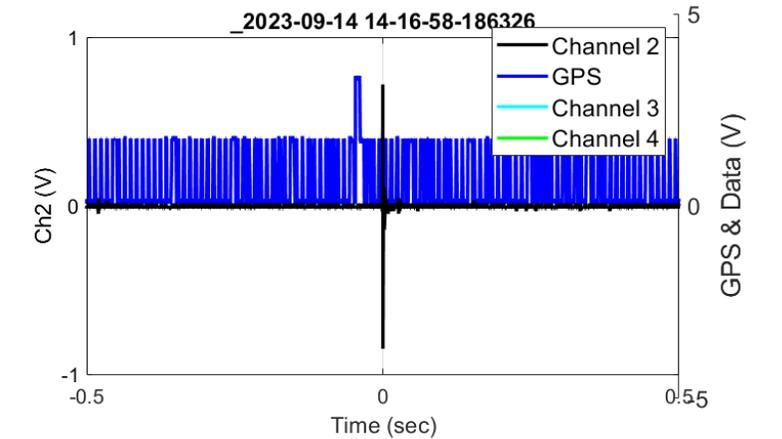
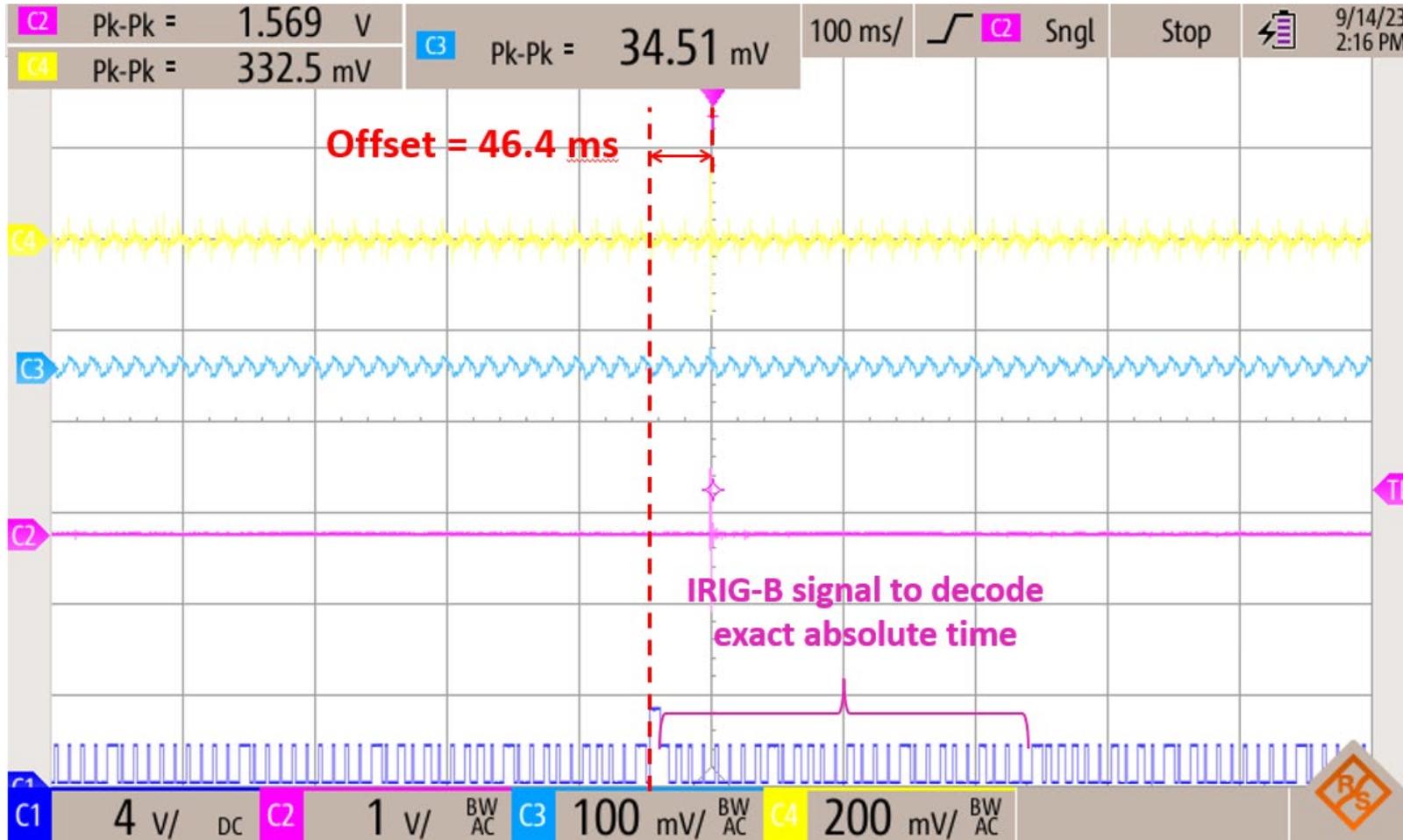
Determining the Precise Time of a VLF Signal Recording

Waveform_2023-09-14 14-16-58-186326



Bit Position	Position Value	Bit Value	Time Increment
1	1	1	1
2	2	1	2
3	4	0	0
4	8	0	0
5	N/A		
6	10	0	0
7	20	0	0
8	40	1	40
Second Sum			43
10	1	0	0
11	2	1	2
12	4	1	4
13	8	0	0
14	N/A		
15	10	1	10
16	20	0	0
17	40	0	0
Minute Sum			16
19	1	0	0
20	2	0	0
21	4	1	4
22	8	0	0
23	N/A		
24	10	1	10
25	20	0	0
26	N/A		
Hour Sum			14
GPS Rising Edge Time			14:16:43

Determining the Precise Time of a VLF Signal

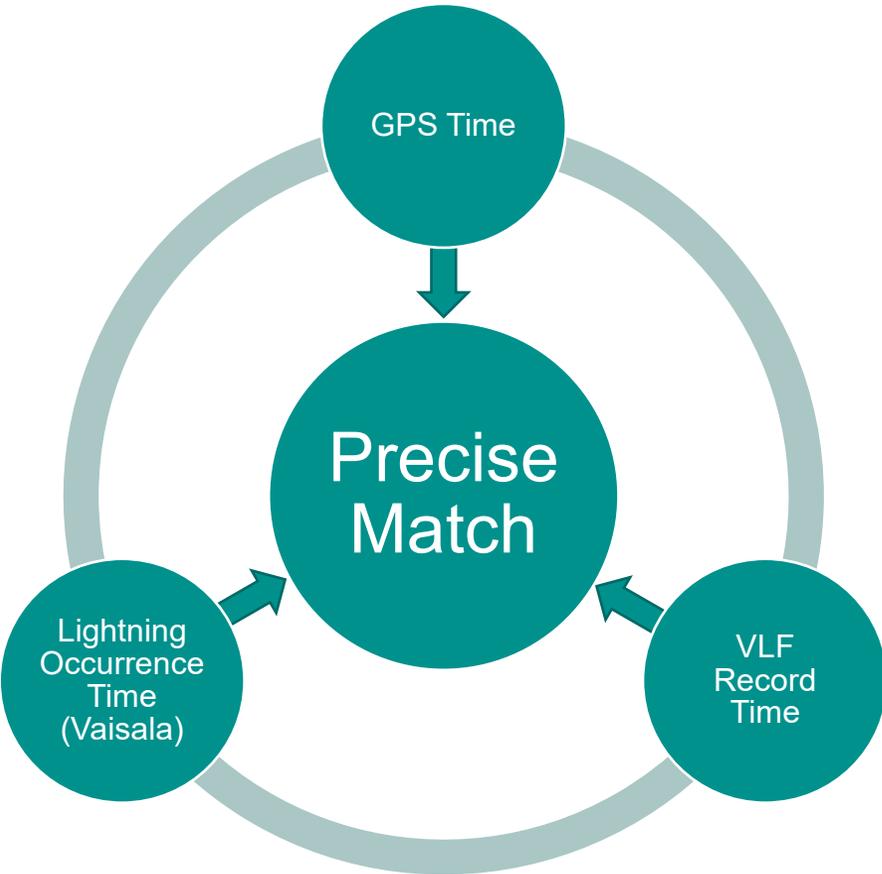


GPS Rising Edge Time: 14:16:43.000000000 ±250 ns peak; < ±100 ns typical (SA off)

VLF signal to GPS Rising Edge Offset: 0.0464 s (46.4 ms)

Precise time of recorded VLF signal: 14:16:43.0464 (GMT)

Matching: First Manually, then Automatically



Record #	Date	GPS Time	Trigger Time	NLDN Data Row	Residual	Peak Current	Distance	Latitude	Longitude
1	Y/M/D	14:54:16.000	14:54:15.694	20055	14.5	-3.2	7590.04	-10.622	-47.3315
2	Y/M/D	14:55:48.000	14:55:48.465	21497	0.1	244.7	6995.26	-15.2516	-70.3863
3	Y/M/D	14:58:13.000	14:58:12.912	23680	1.3	-16.9	9017.51	7.6651	-6.7476
4	Y/M/D	15:00:08.000	15:00:07.557	25297	0.1	82.3	4444.21	5.6879	-81.2317
...									
1346	Y/M/D	03:30:19.000	03:30:18.635	1210478	0.1	-30.7	2882.35	19.3506	-99.032
1347	Y/M/D	03:30:36.000	03:30:36.316	1210731	0.1	9.5	1509.78	31.1674	-94.5536
1348	Y/M/D	03:30:56.000	03:30:55.569	1210996	0.2	-8.3	1432.16	31.8517	-94.3793

Total VLF	1348	
>1 ms	121	9%
<1 ms	1227	91%
residual (median)	0.1	

Identifying Non-Lightning Sources

Fencers

Variable Frequency Drives (VFDs)

Modern Electronics

Power Switching

Fencers

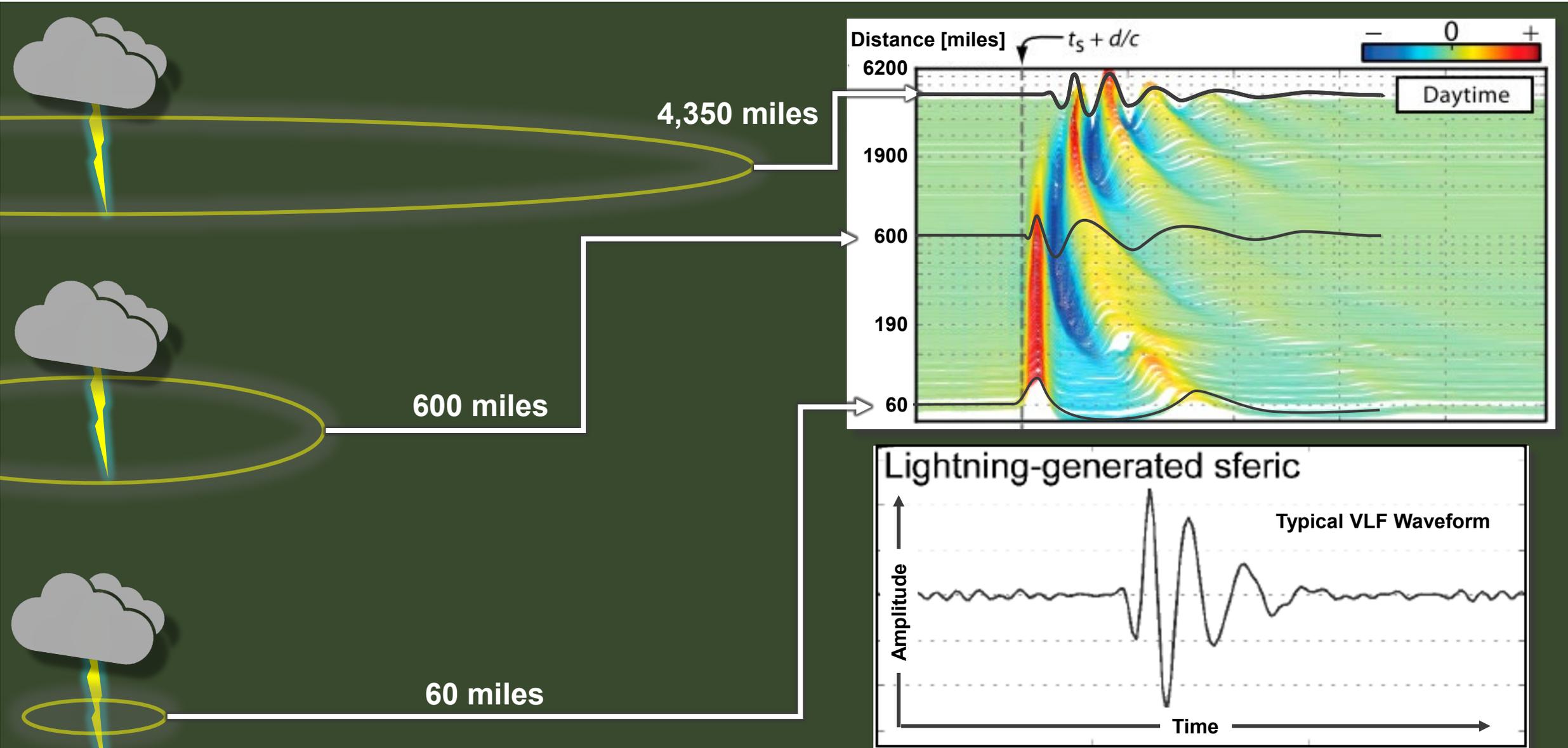
“Fingerprint” – Frequency Content

Fencers

Fencer and Lightning Captured Together

Consistency of Fencer Signals

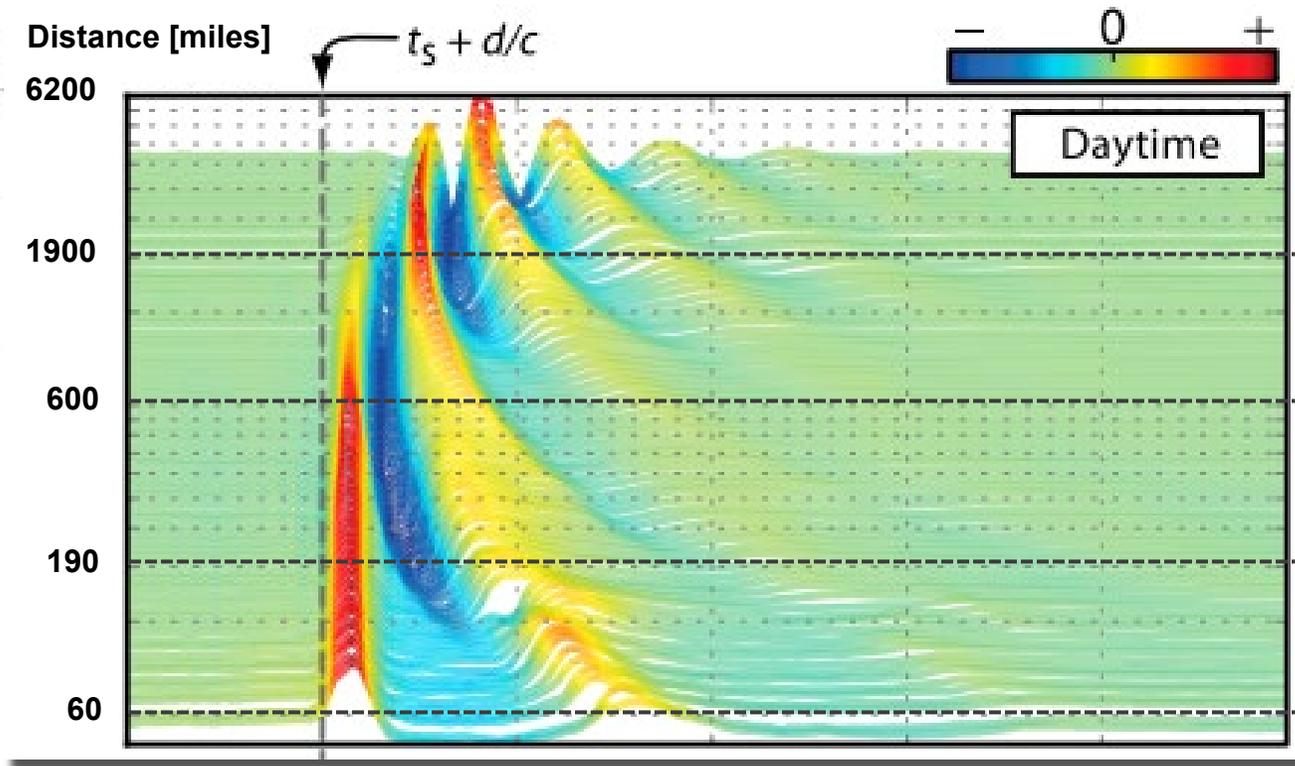
VLF Variation with Distance



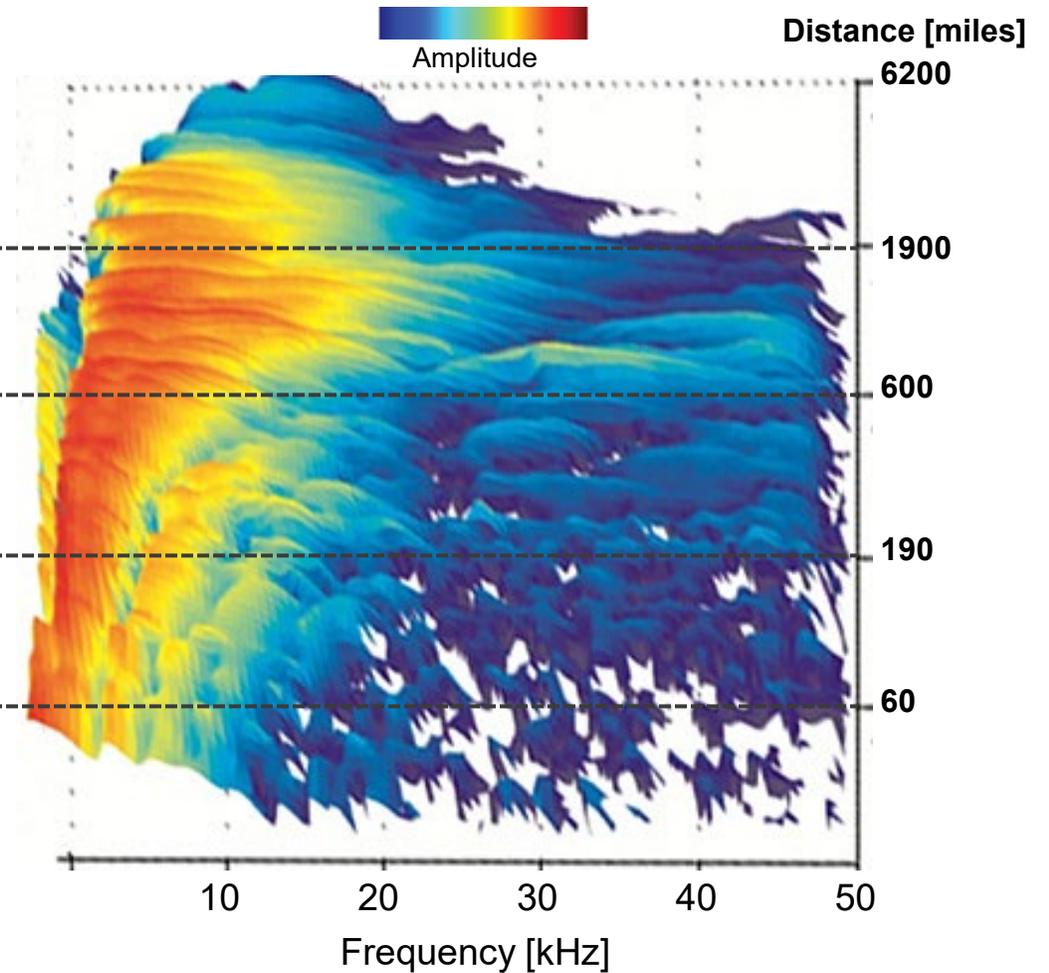
Received at Juneau, Alaska on August 15, 2014

VLF Variation with Distance

Time – Distance Variation

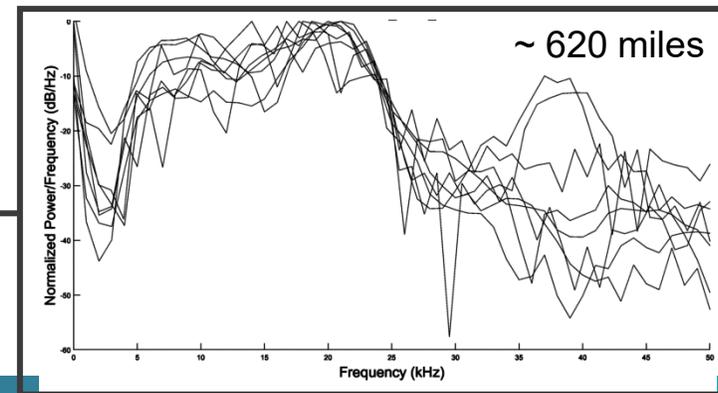
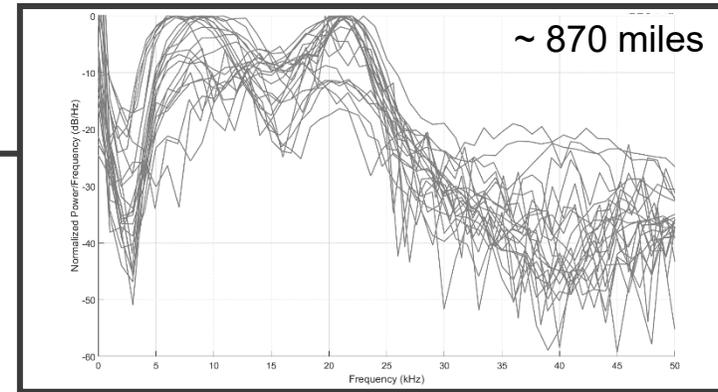
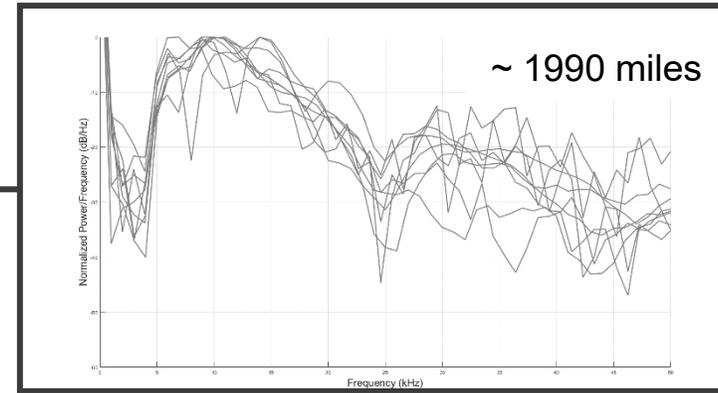
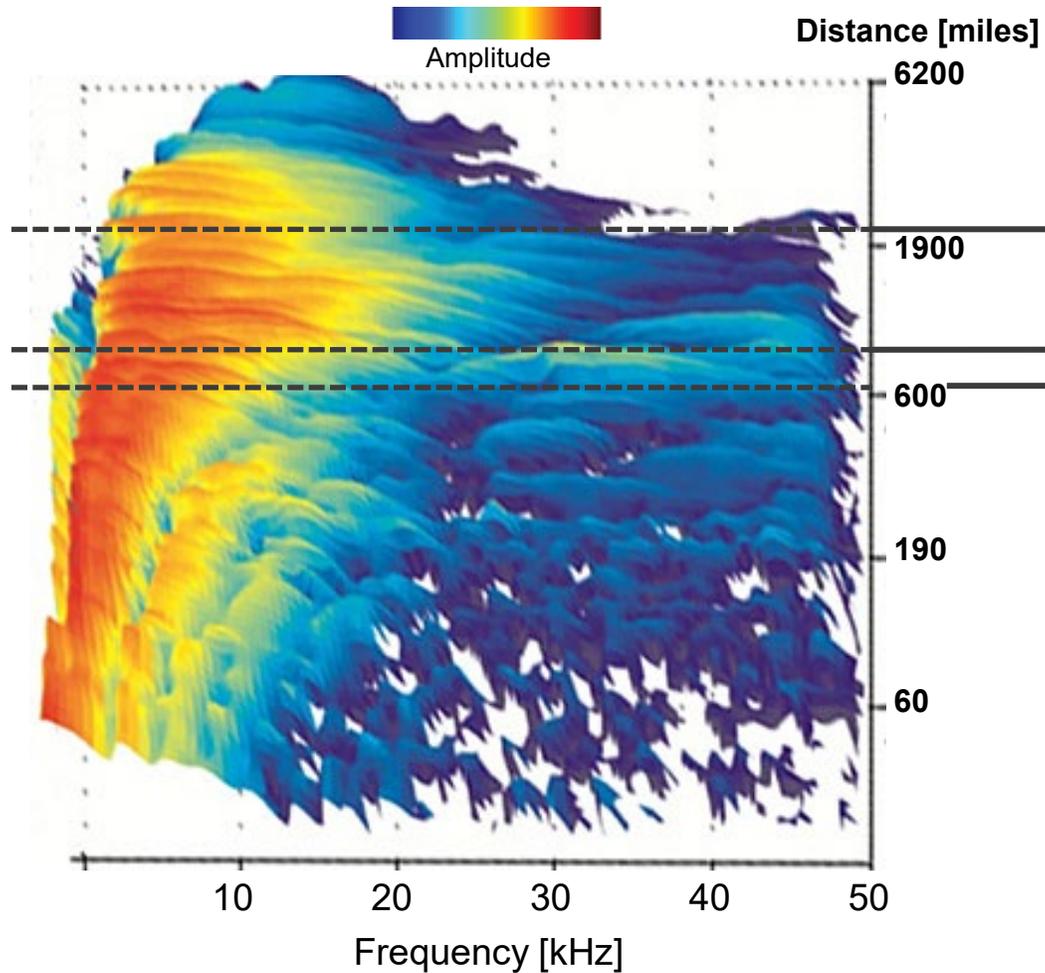


Frequency – Distance Variation (FFT)



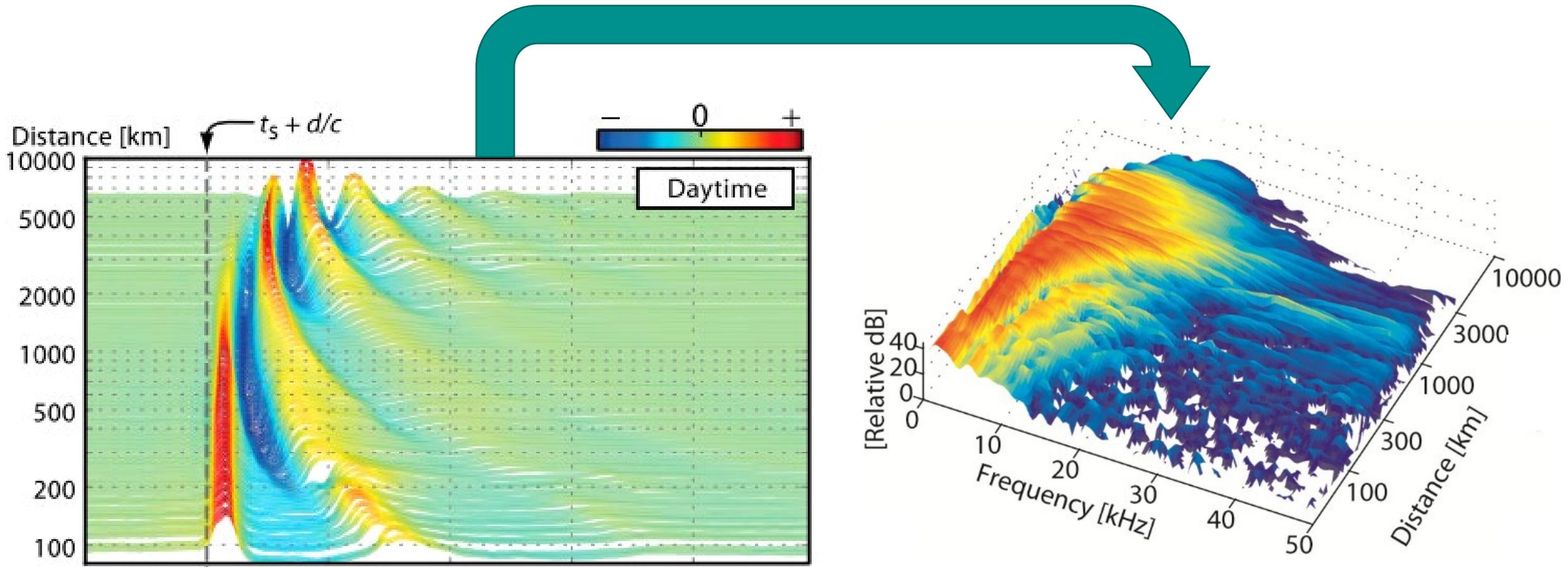
VLF Signal Variation with Distance and Frequency

Frequency – Distance Variation (FFT)



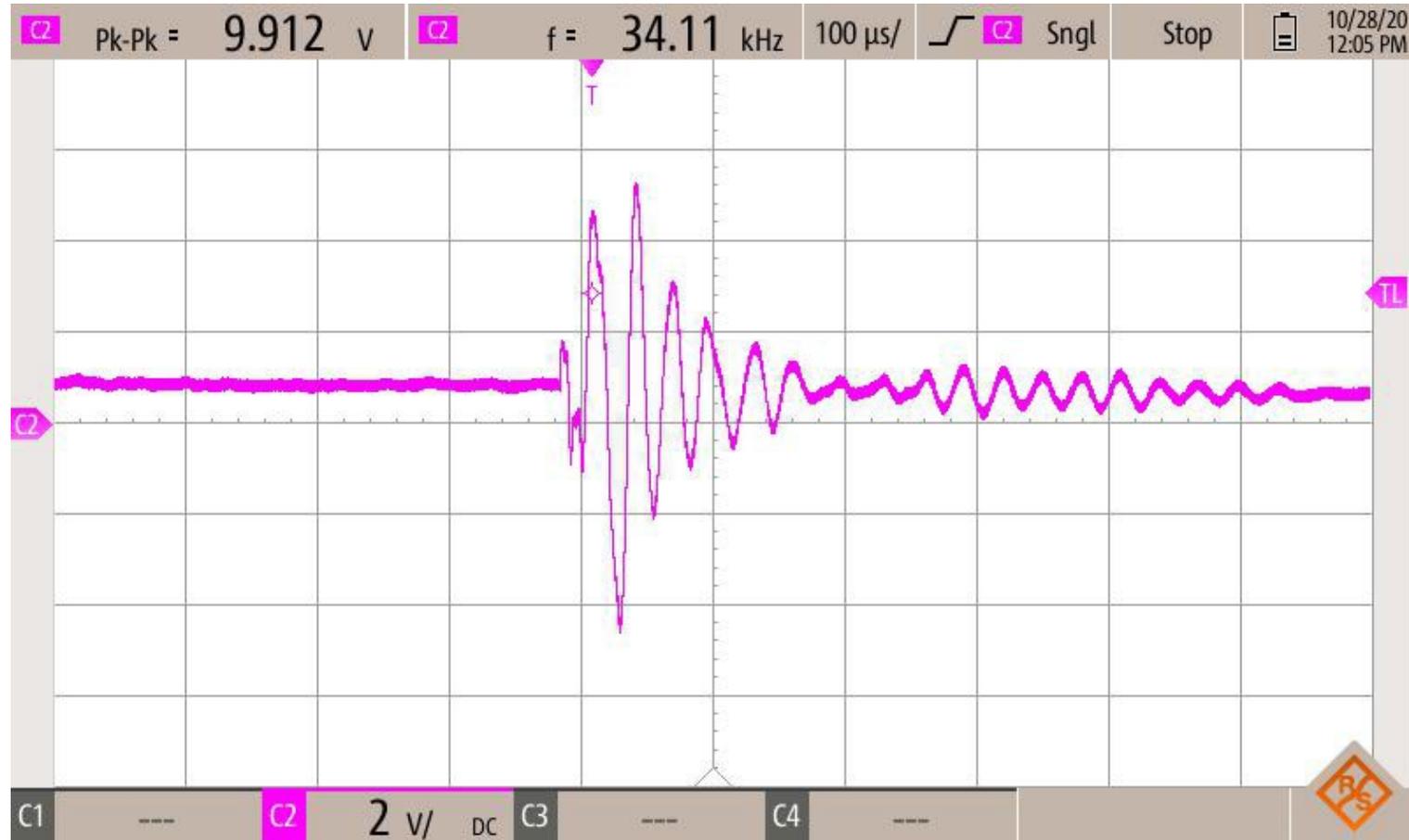
Frequency Variation and the VLF “Fingerprint”

Fourier Transform

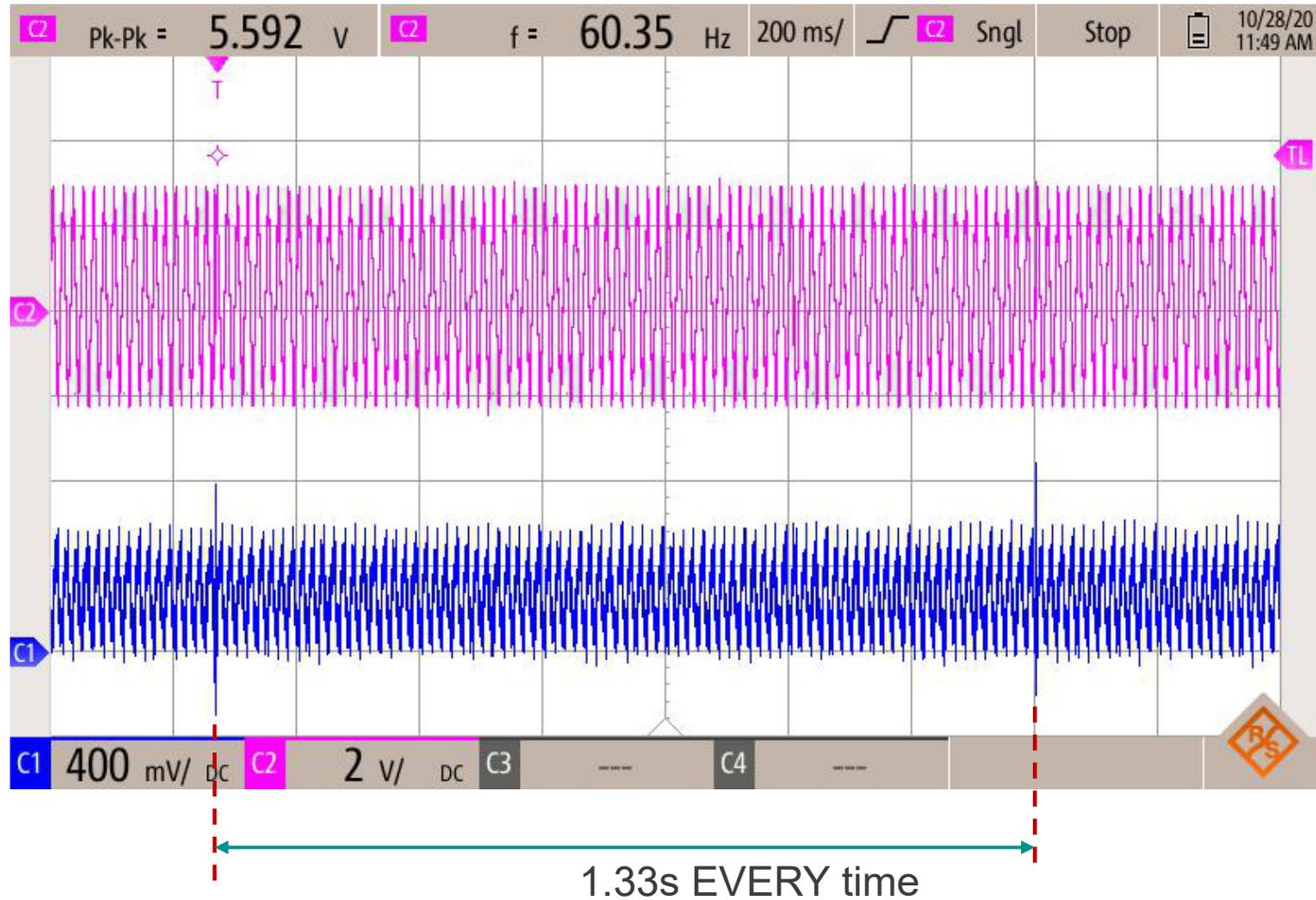


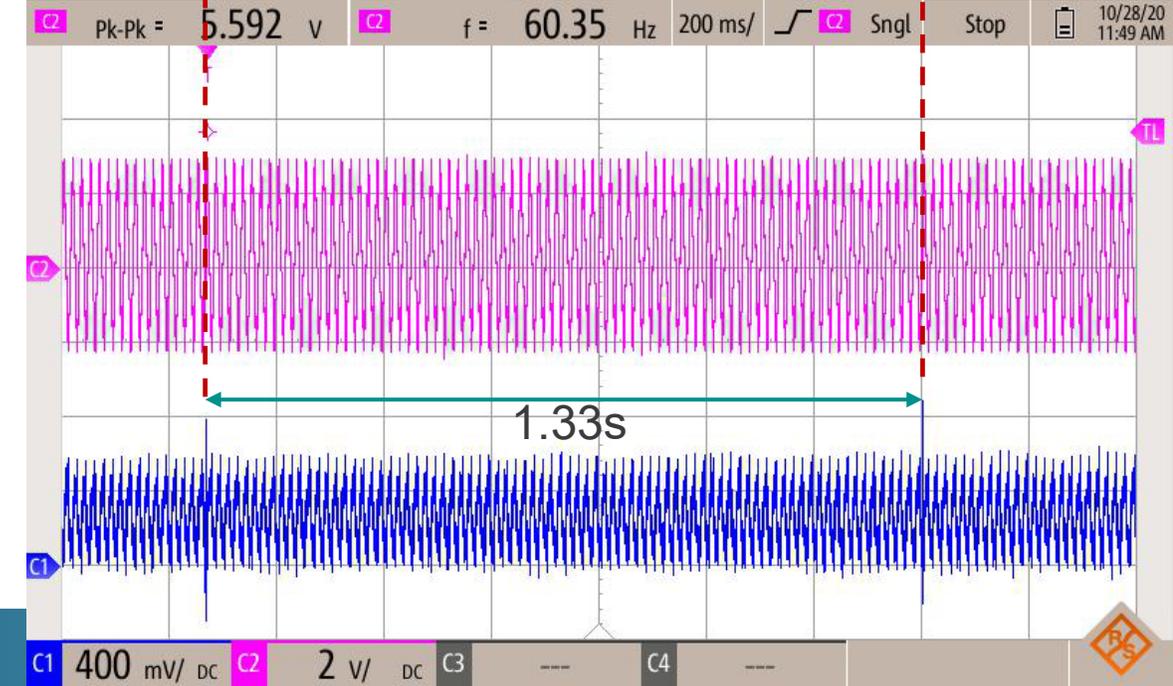
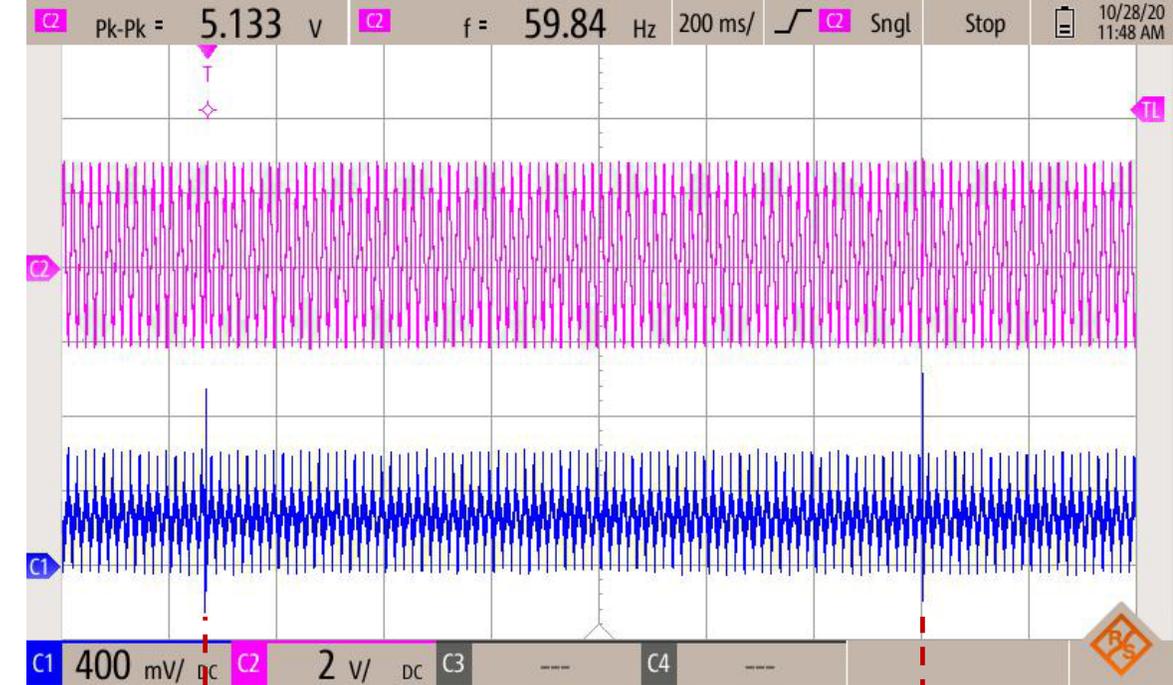
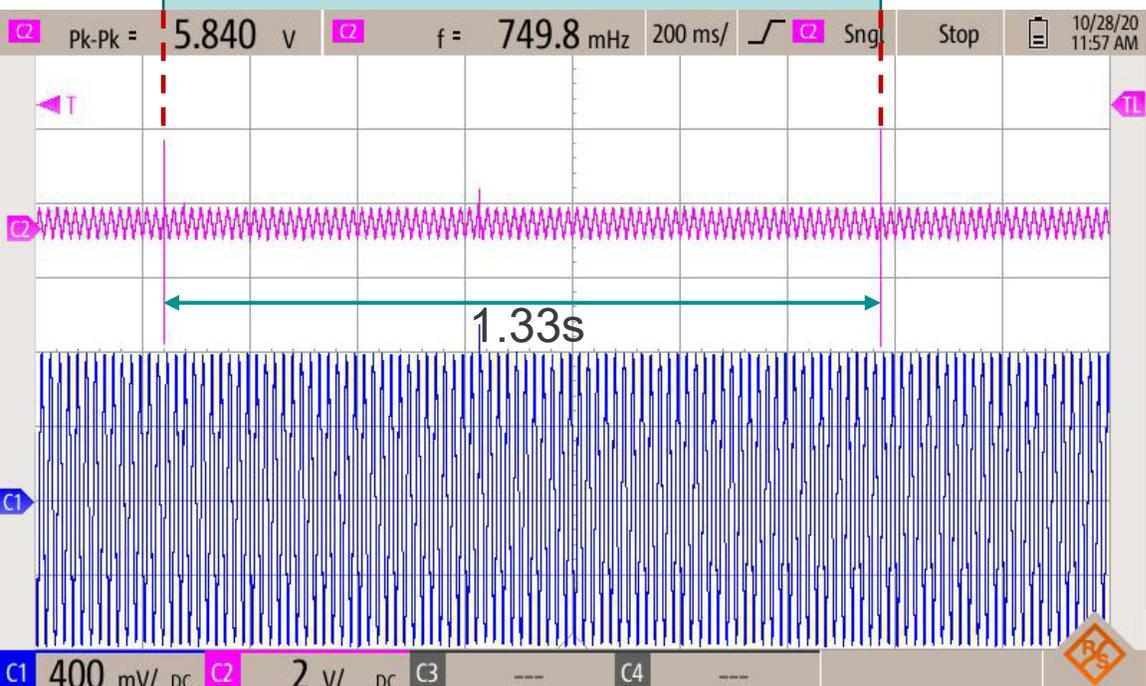
Source: SaidThesis.pdf

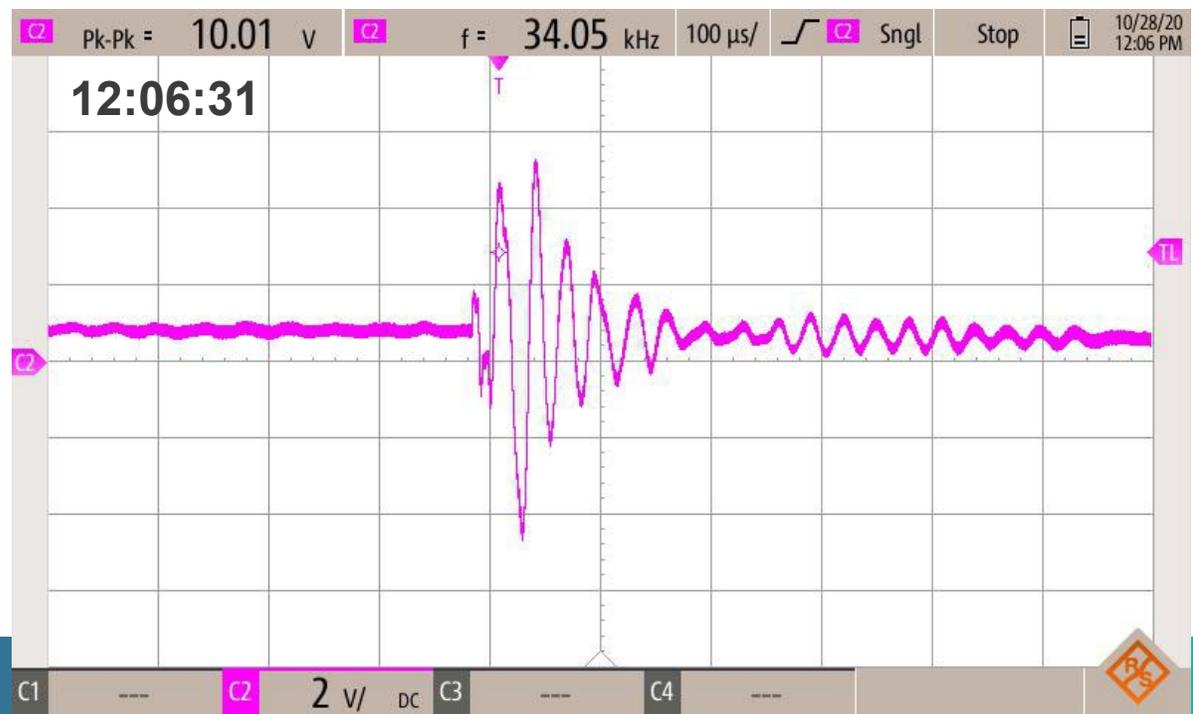
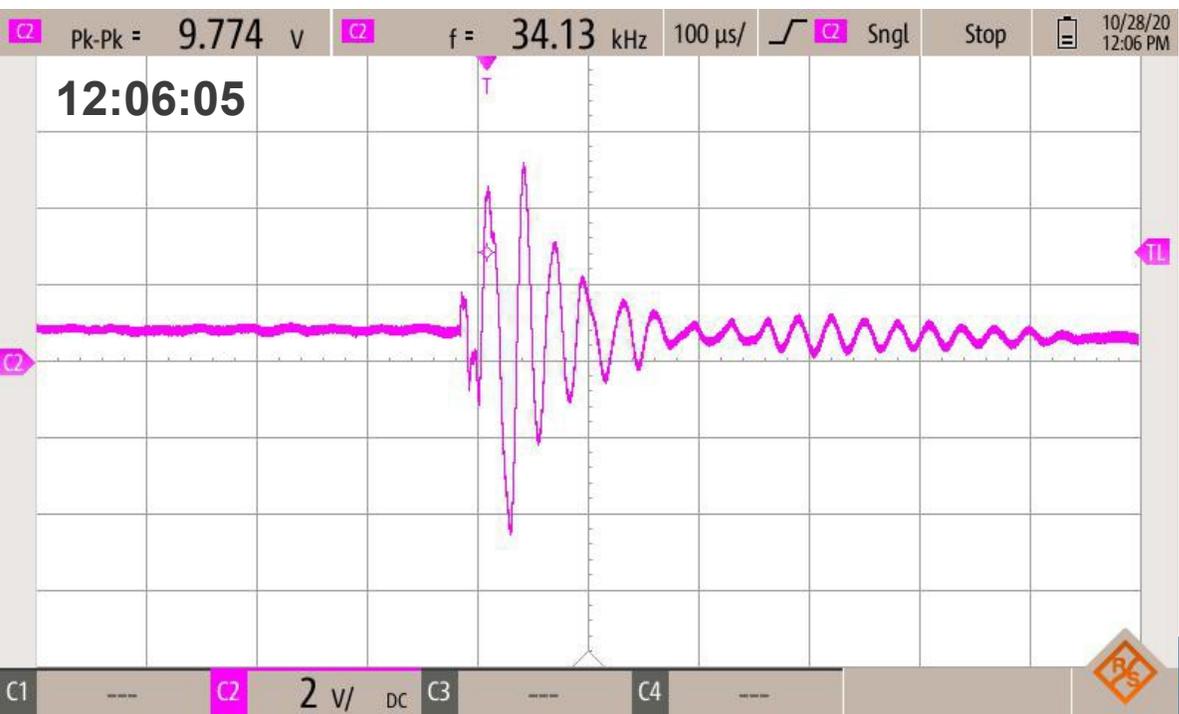
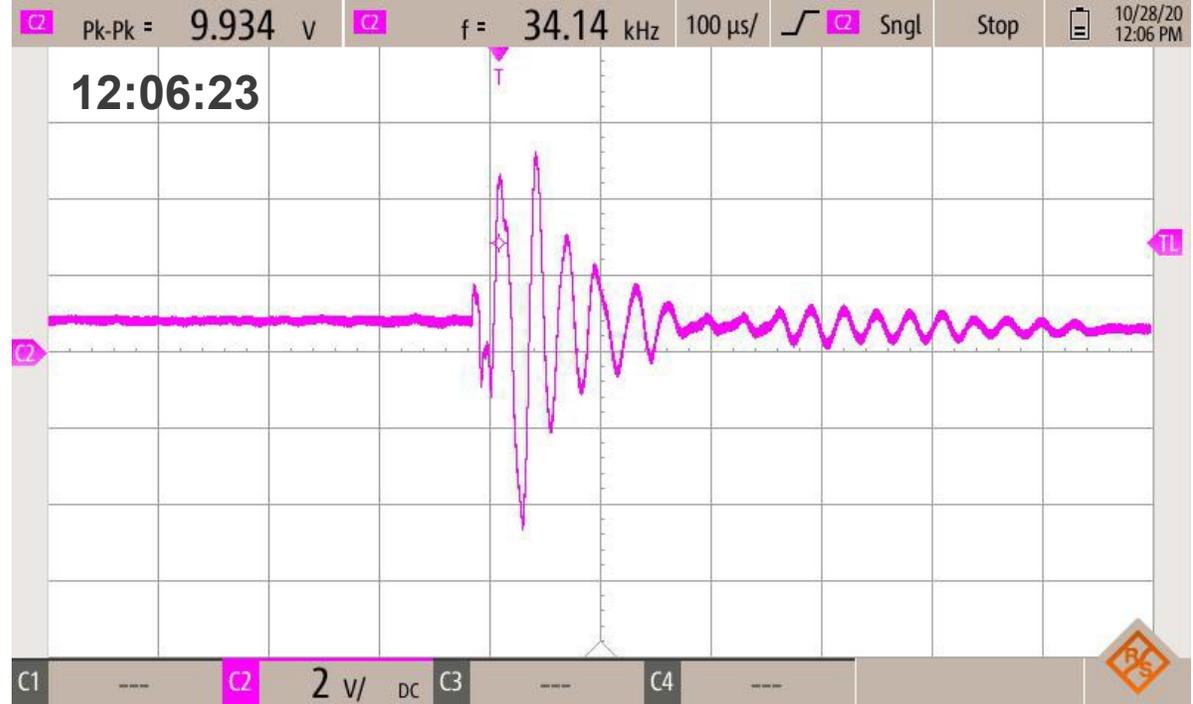
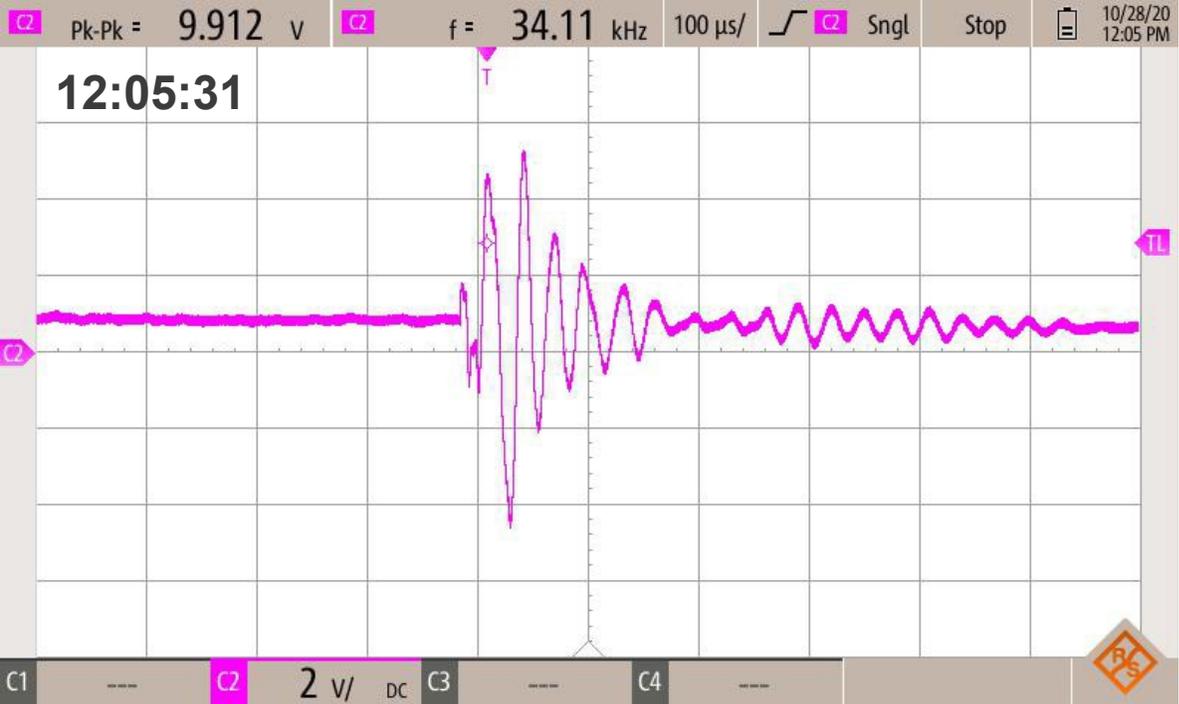
Other VLF Signals: Fencer



Other VLF Signals: Fencer

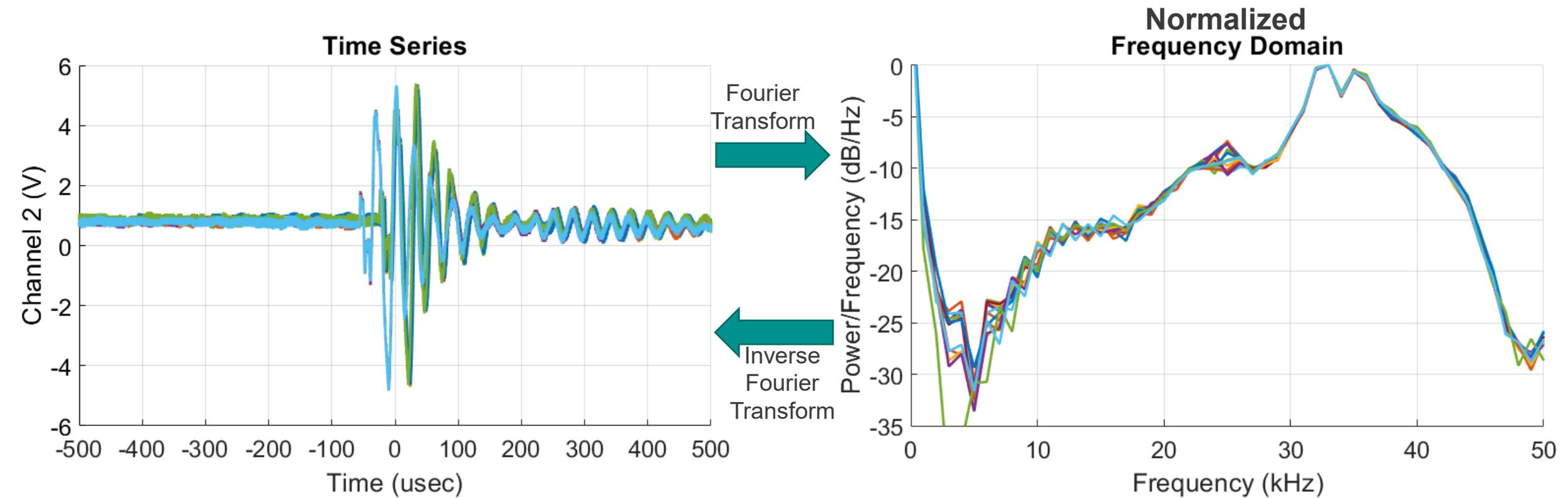




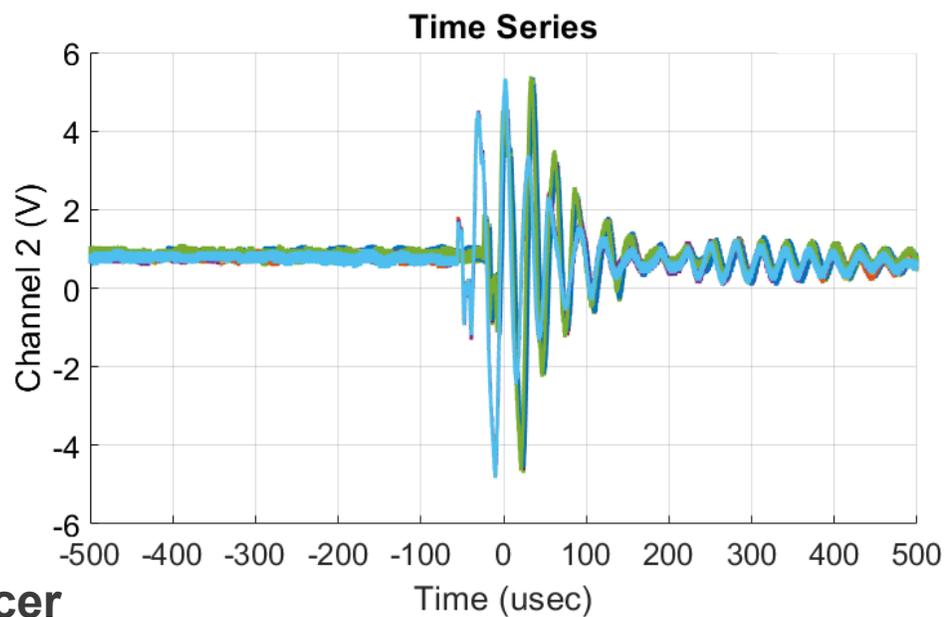


Fencer Signature

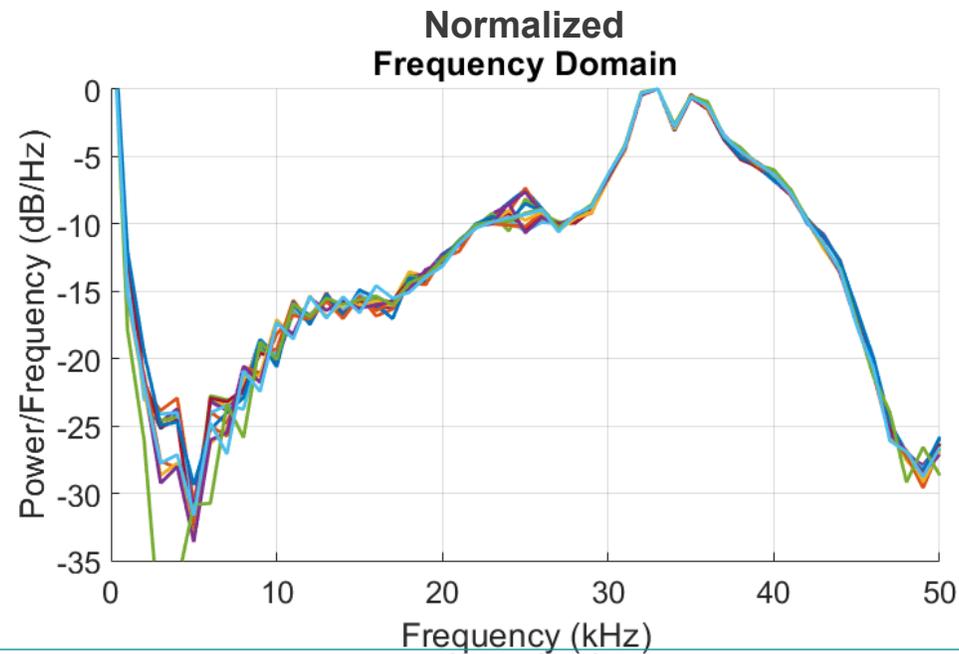
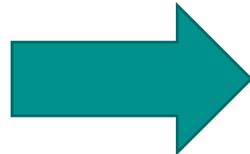
13 separate recordings overlaid



Fencer vs. Lightning

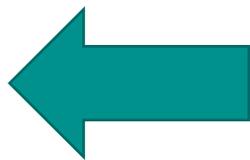
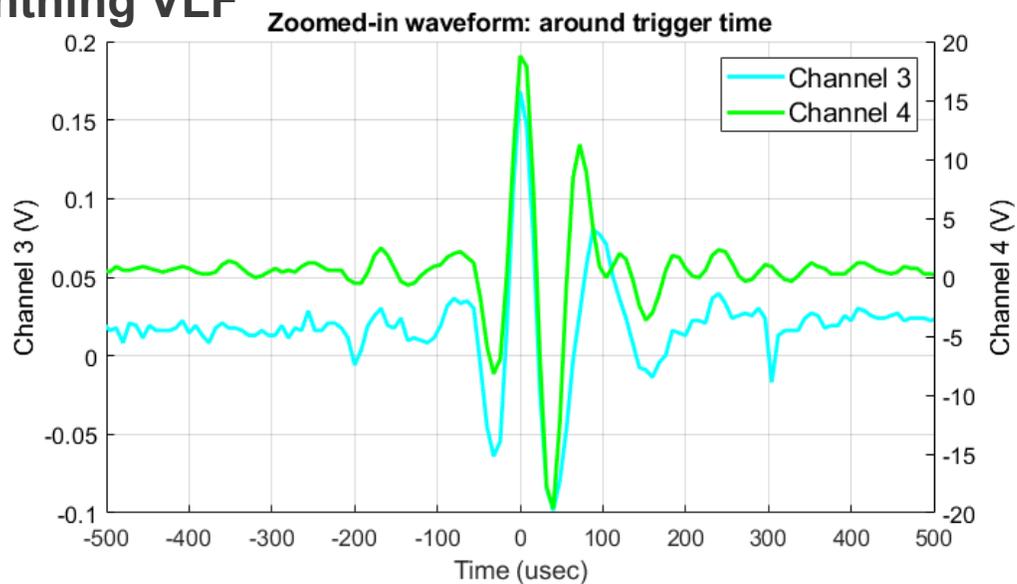


Fourier Transform

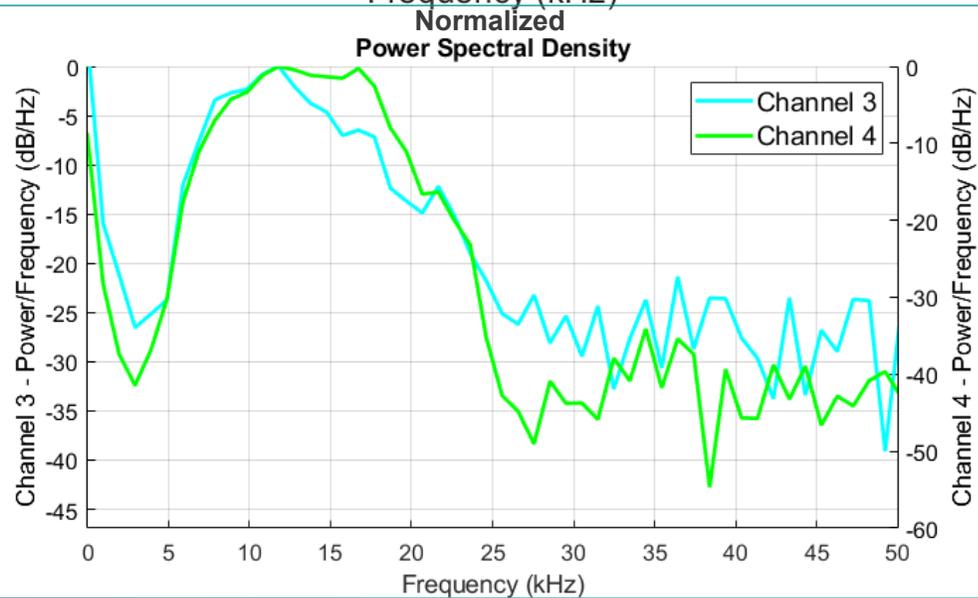


Fencer

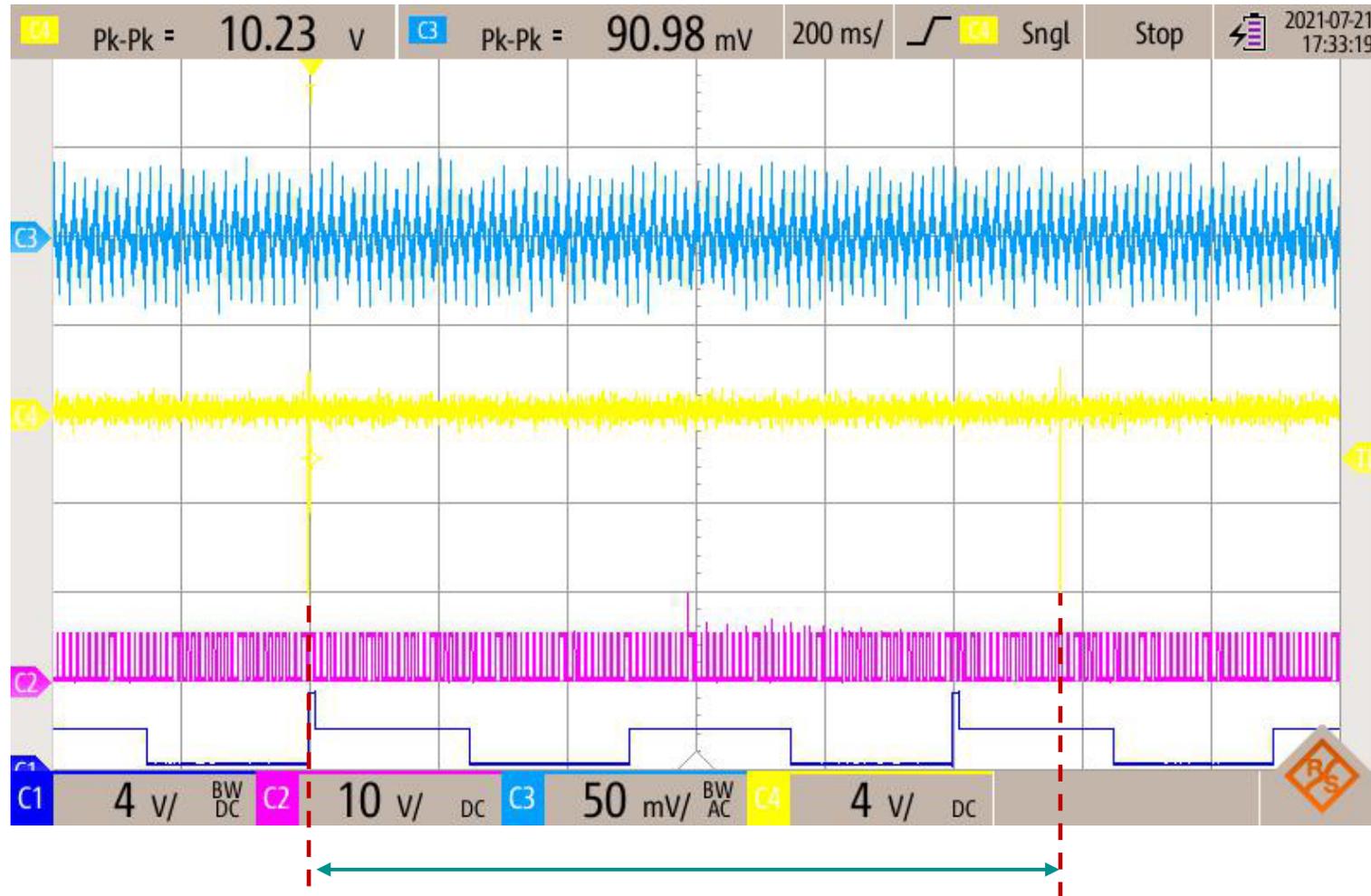
Lightning VLF



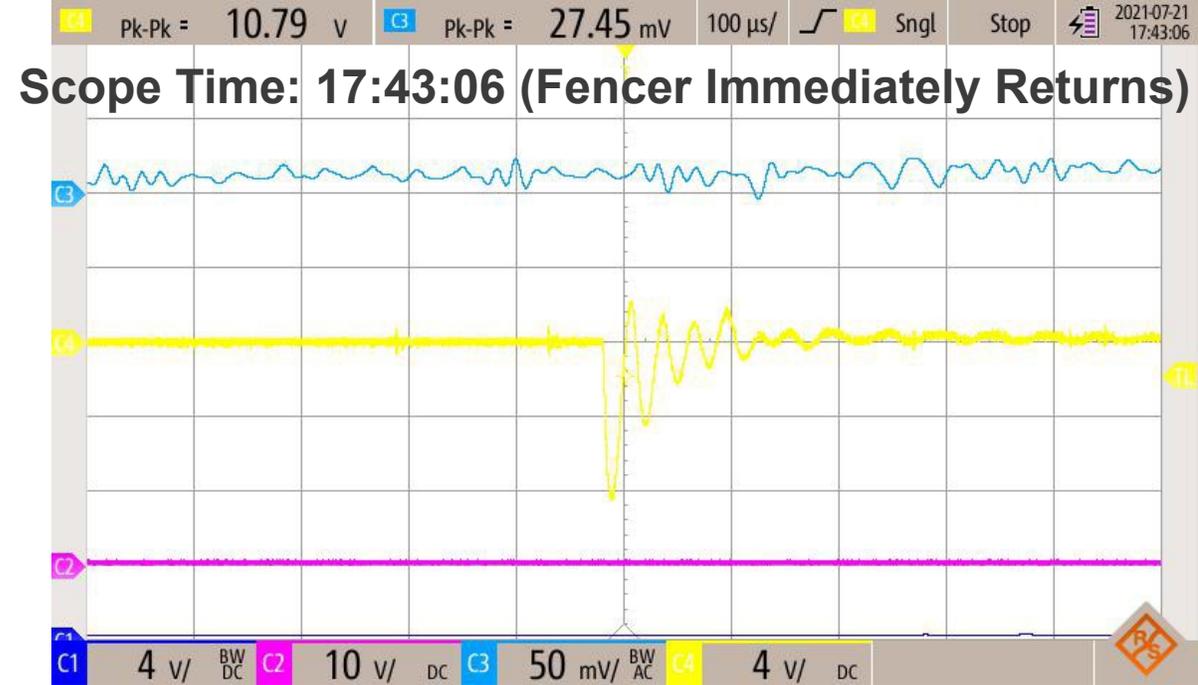
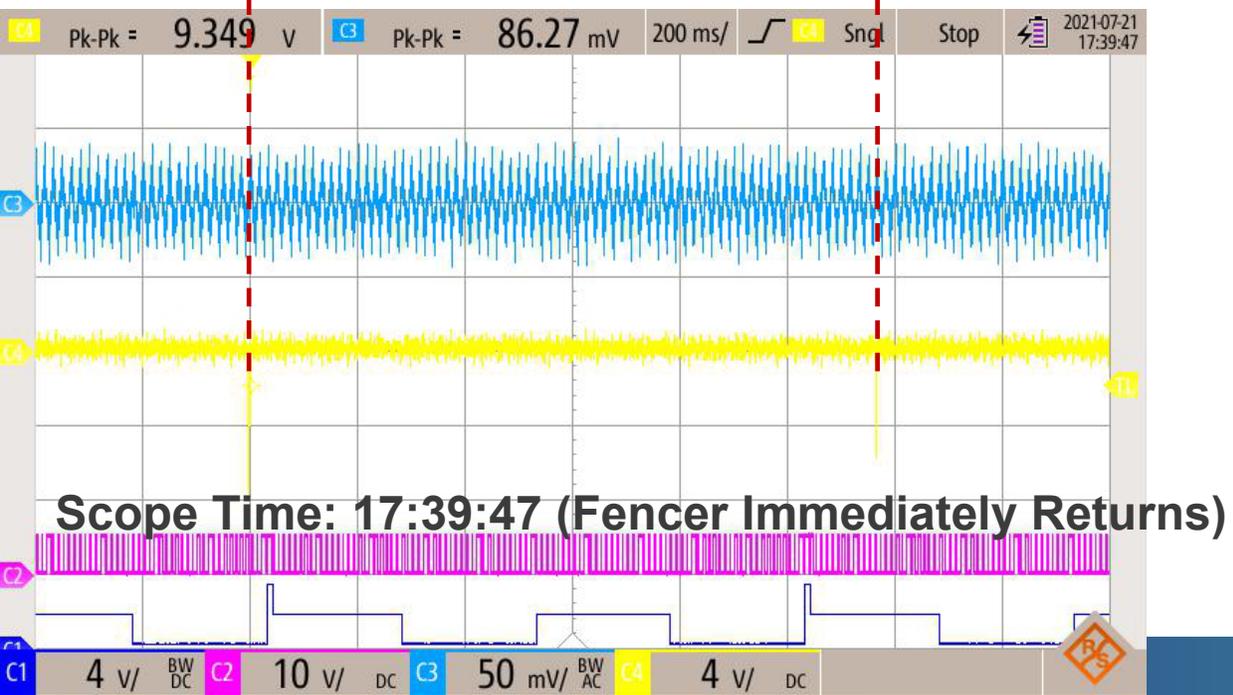
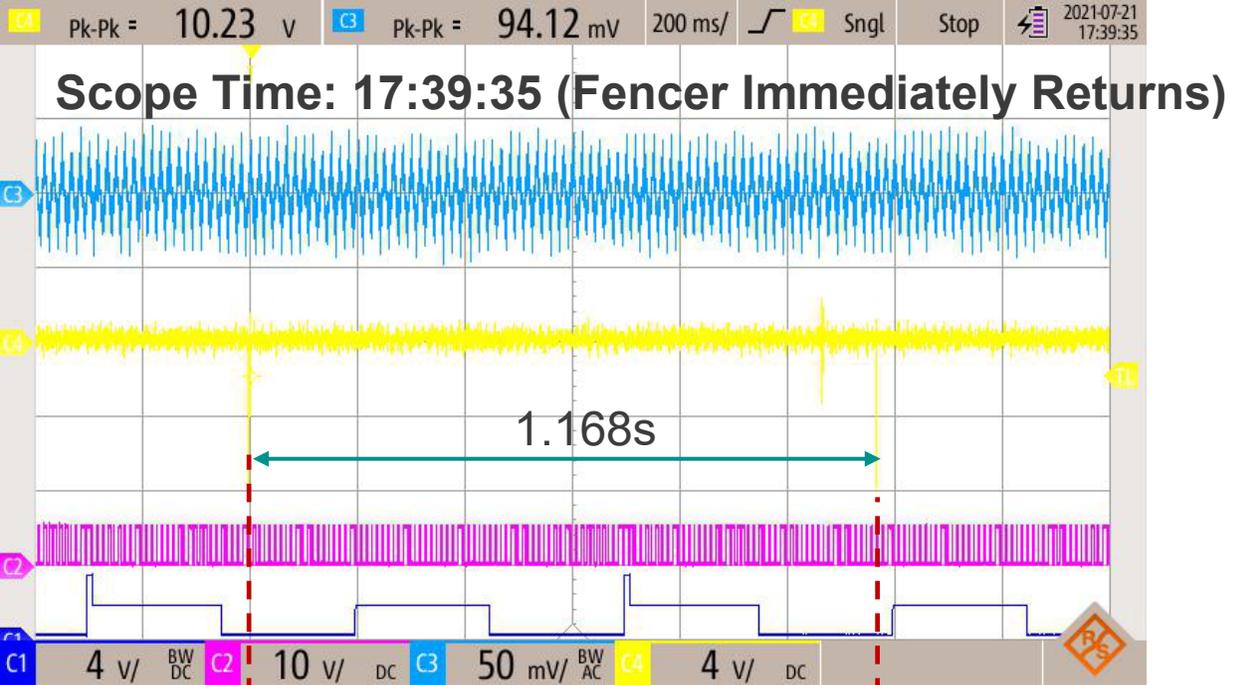
Inverse Fourier Transform



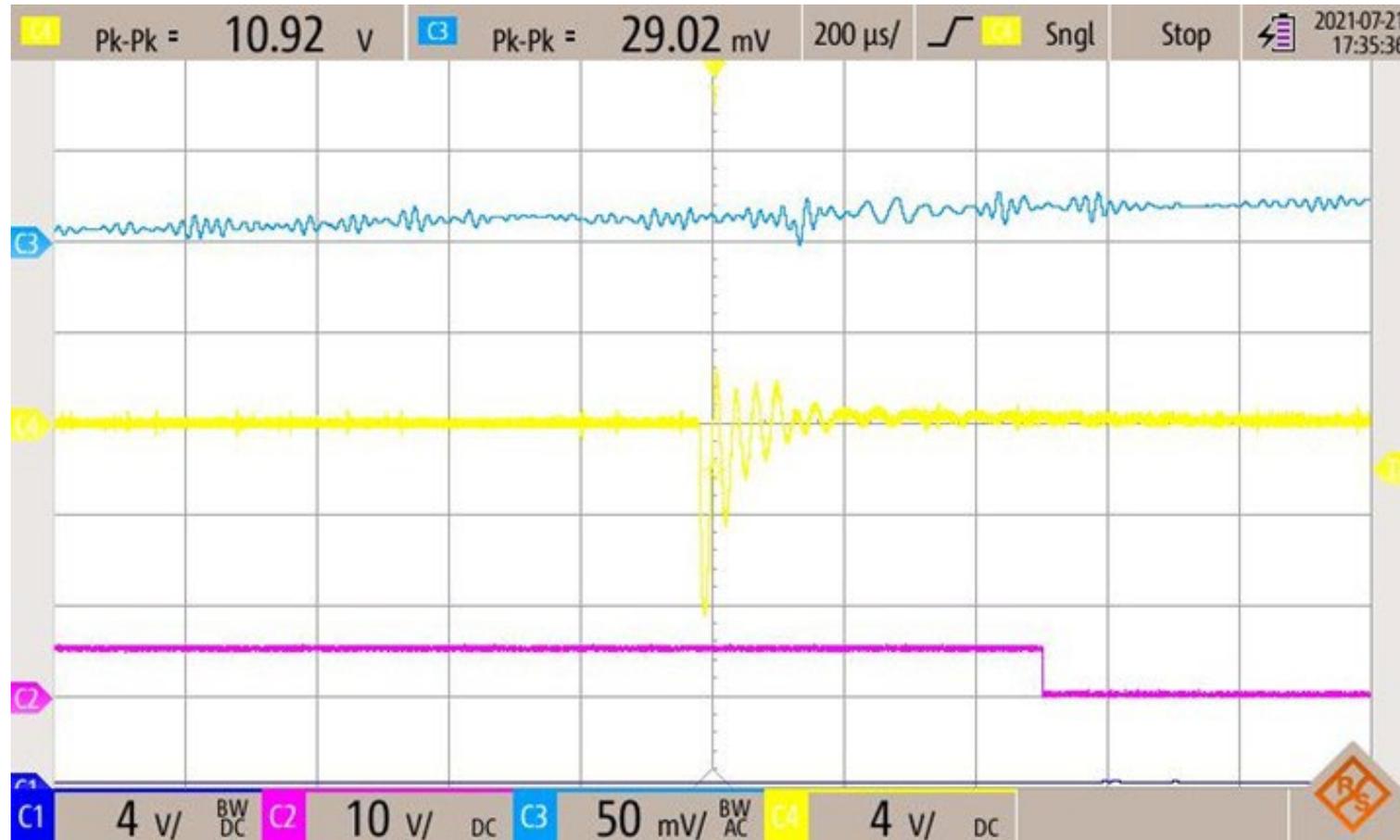
Fencer at a MN Dairy: “Neighbor’s Fencer”



Fencer Turned off by Neighbor at ~17:37:26

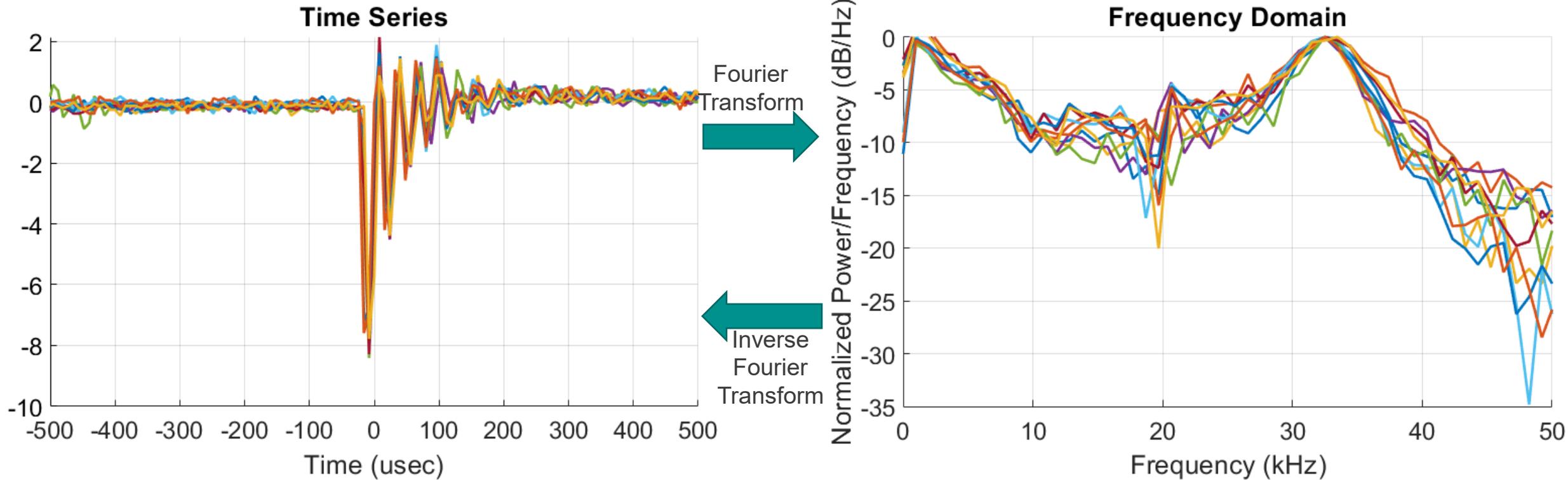


Fencer at a MN Dairy: “Neighbor’s Fencer”

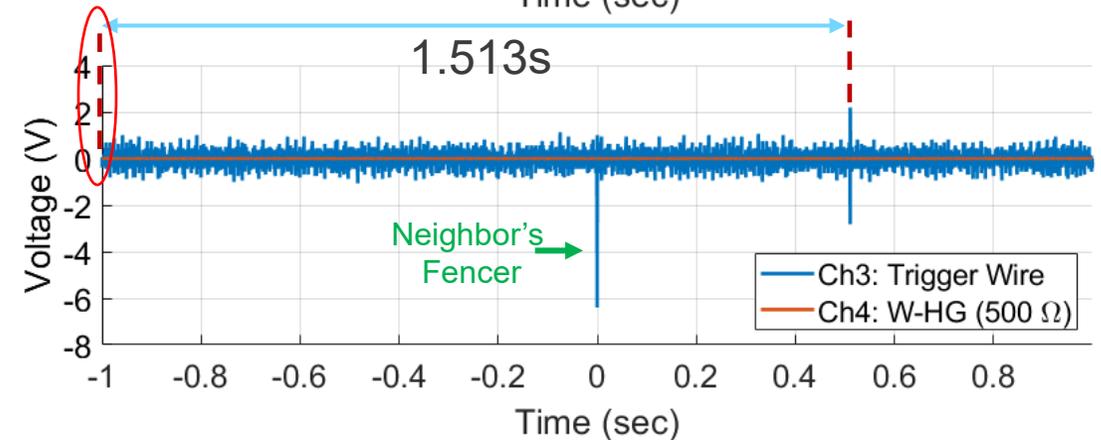
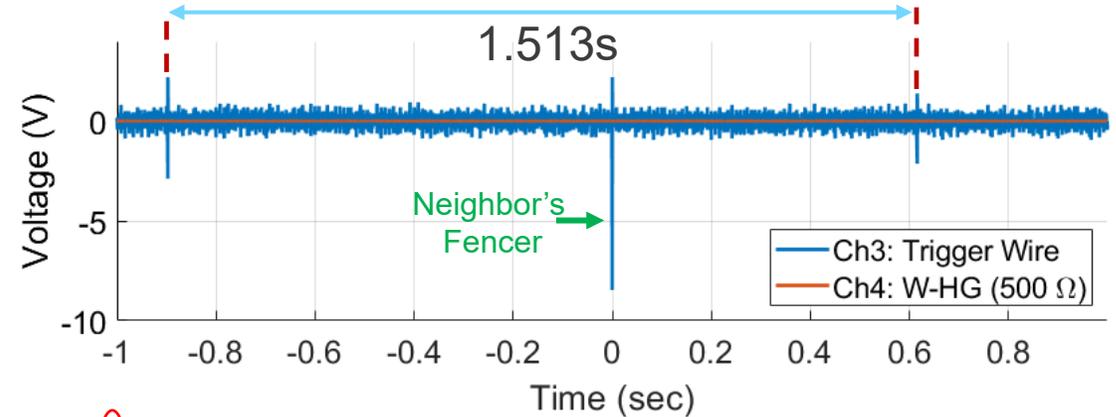
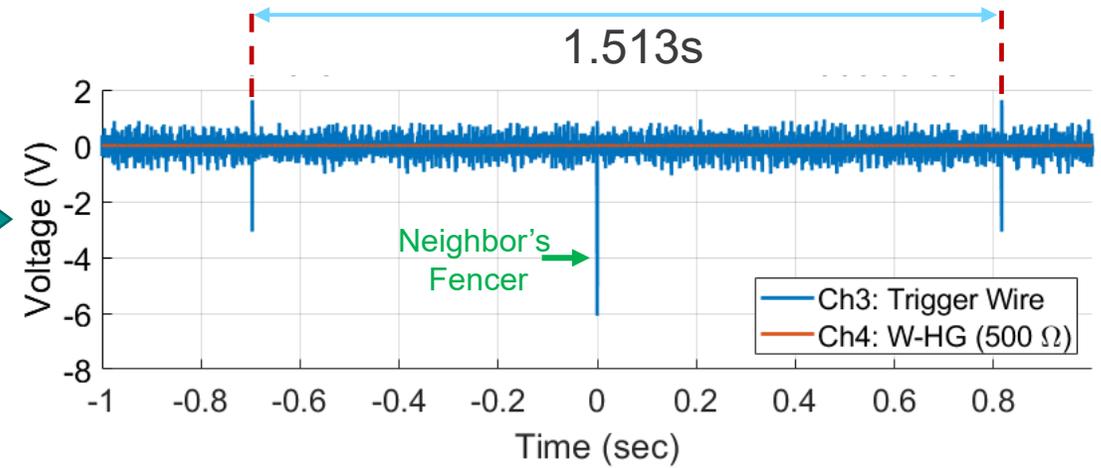
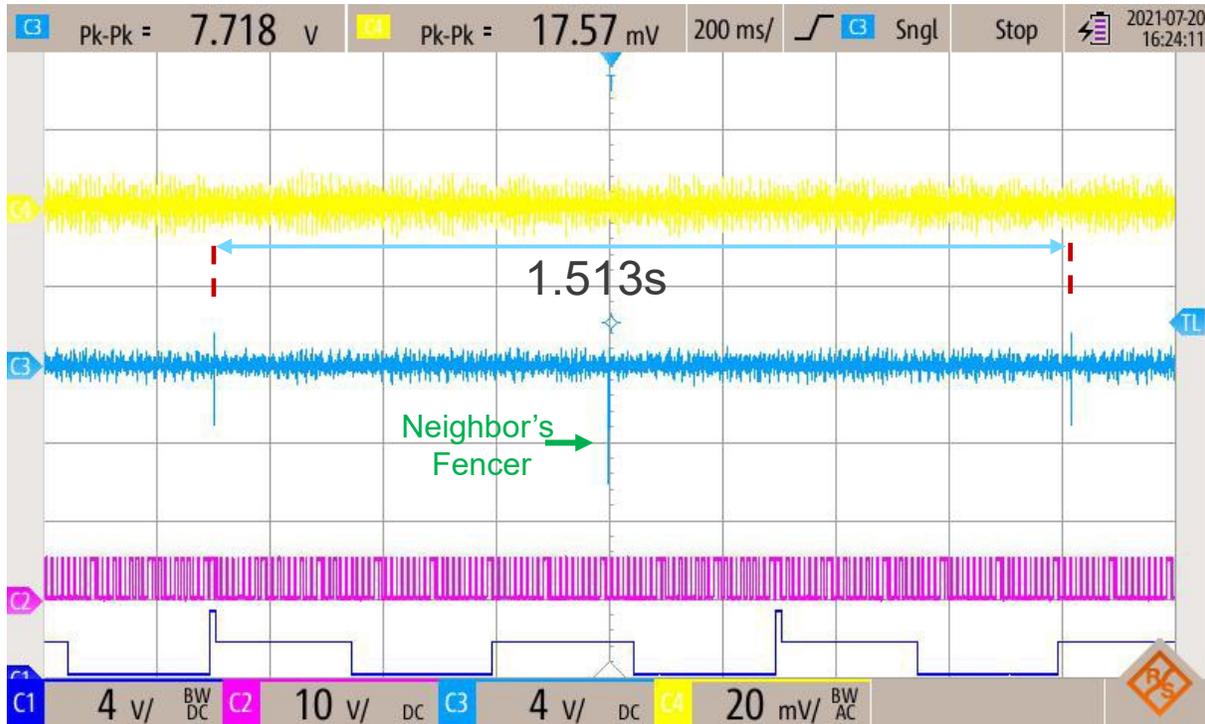
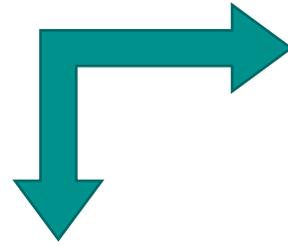


Fencer Measured at MN Dairy

10 separate recordings overlaid

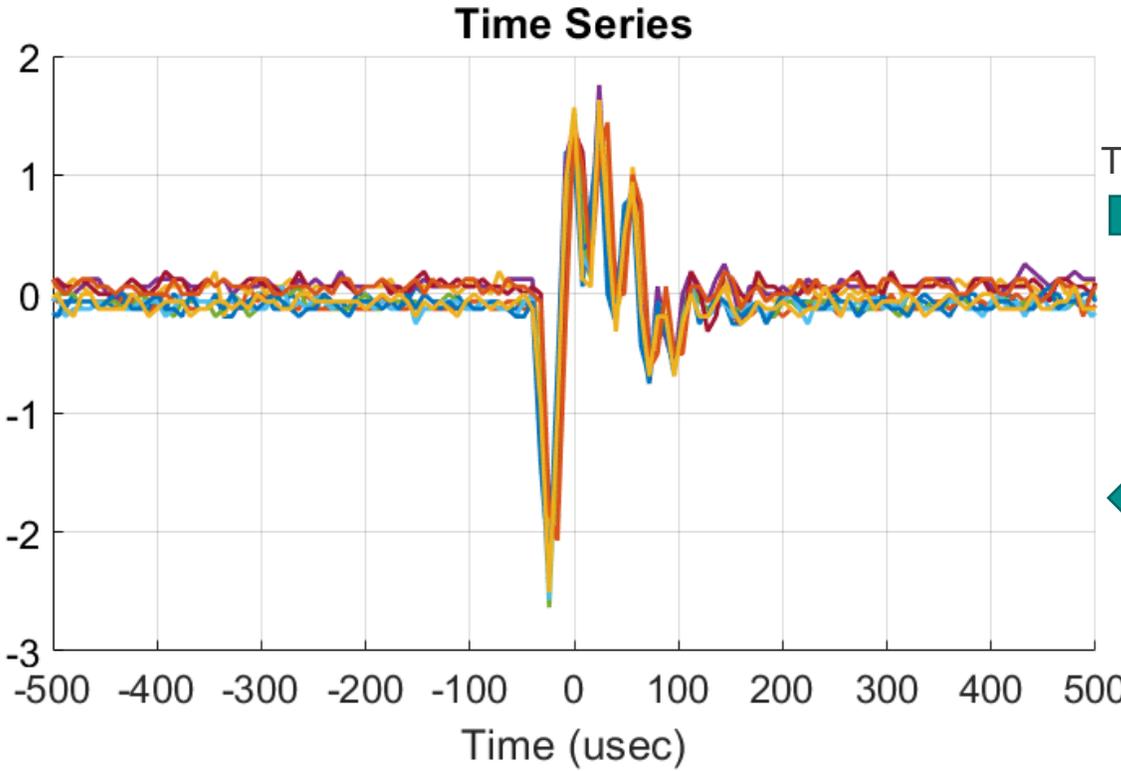


Second Fencer at MN Dairy



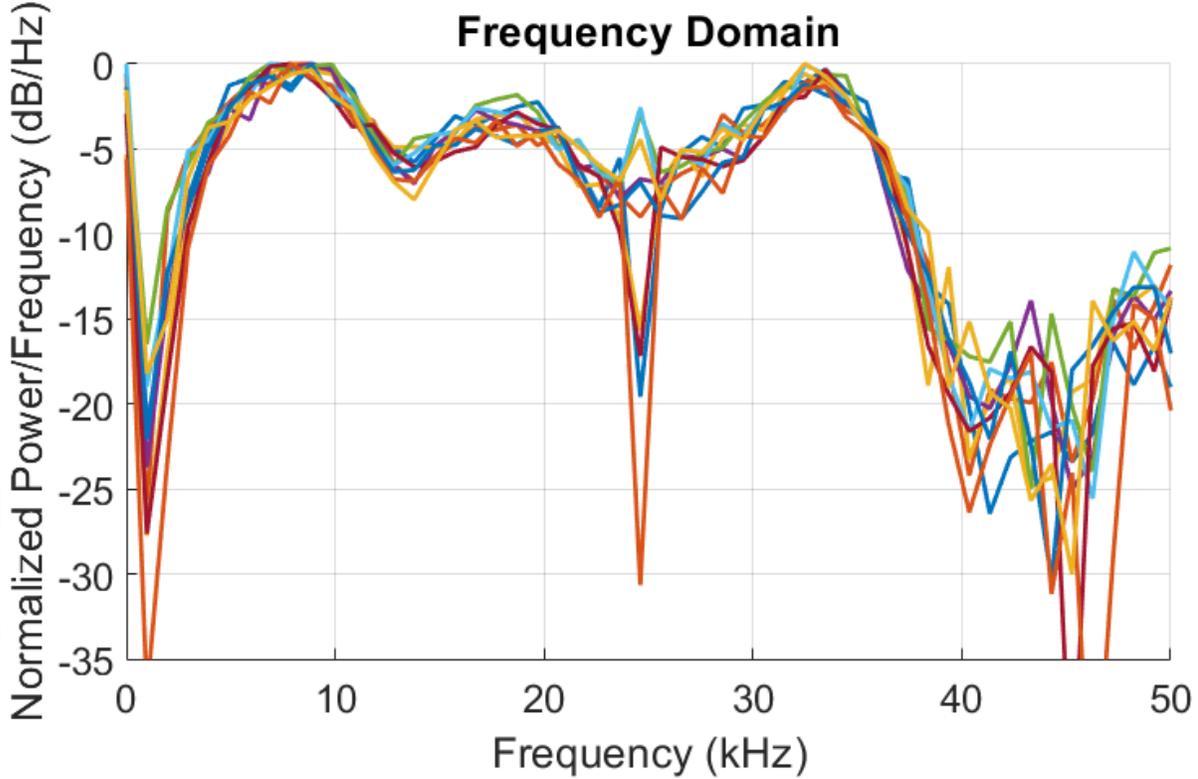
Second Fencer Measured at MN Dairy

10 separate recordings overlaid

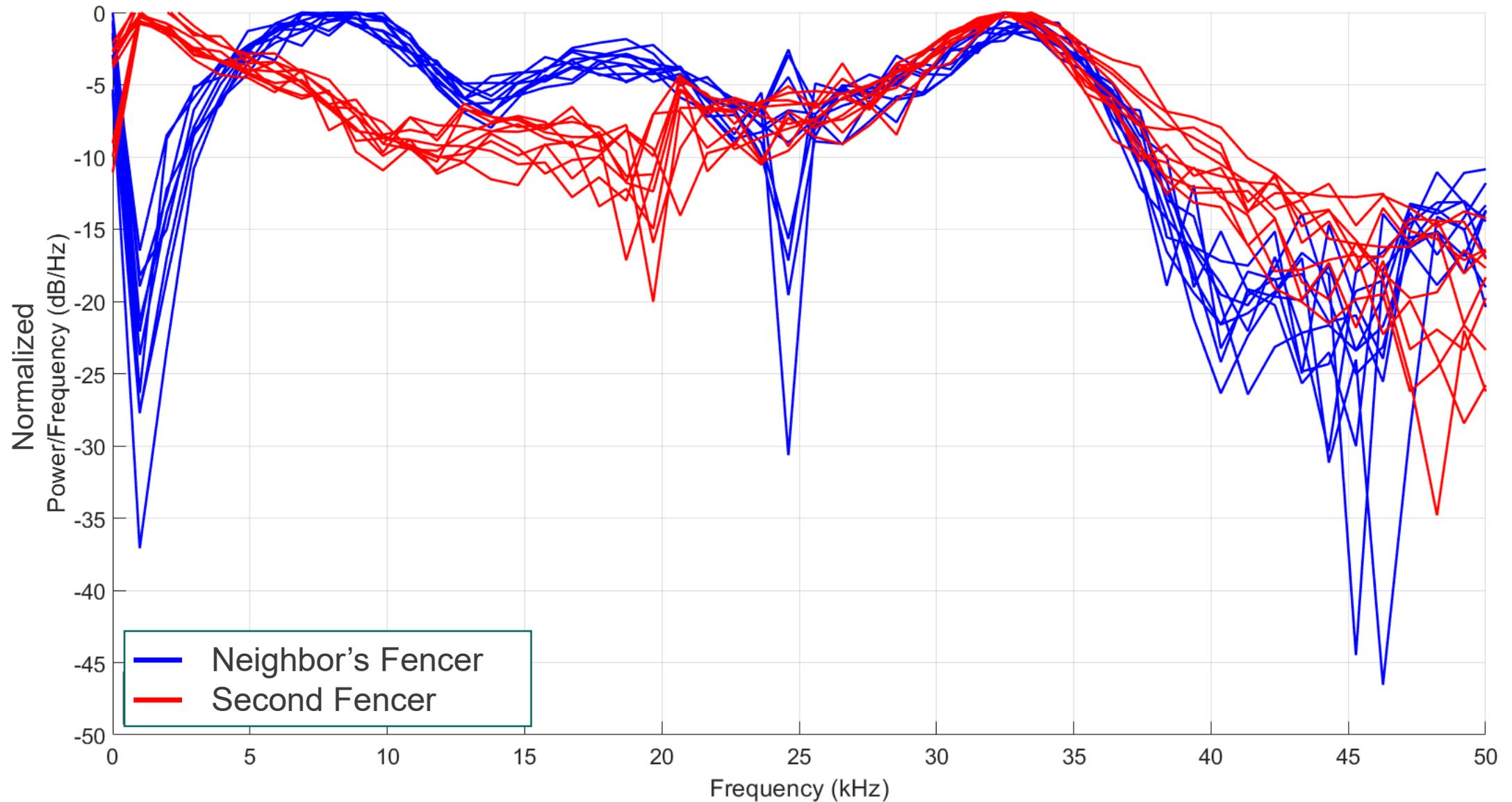


Fourier Transform
➔

←
Inverse Fourier Transform



Comparison of the Spectra of the Two MN Fencers



Variable Frequency Drives (VFDs)

Periodic VLF Signals: VFDs

Highly Repeatable

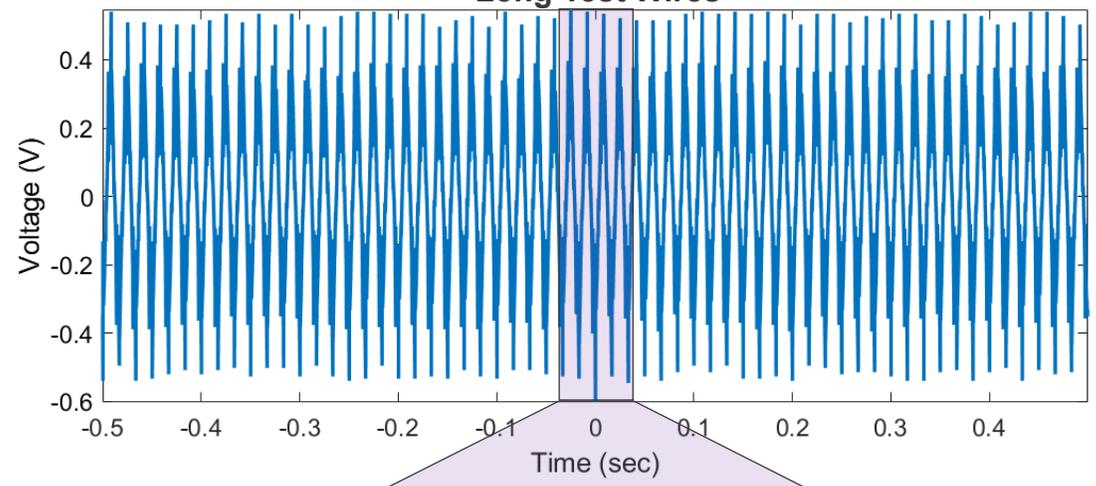
Show up at Cow Contact

Conducted Source – Do NOT show up on
Monopole Antenna

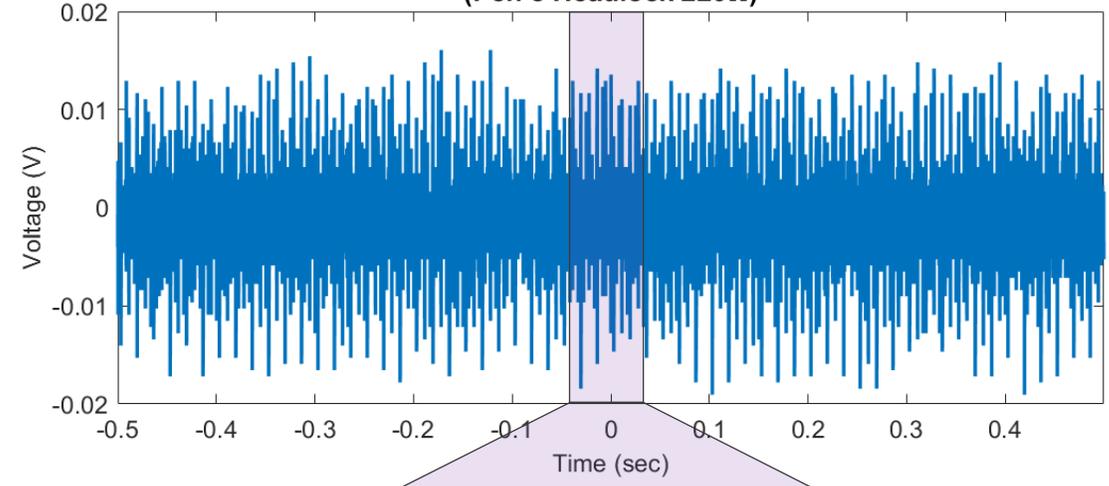
Matching to Lightning Despite a Sea of
VFDs

360 VFDs EVERY second at Cow Contact (with resistor)

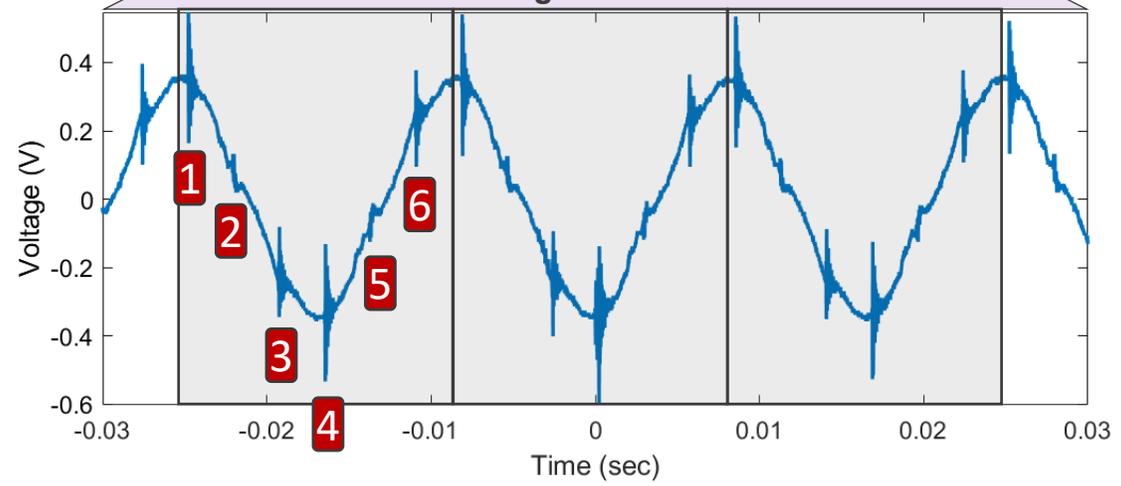
Long Test Wires



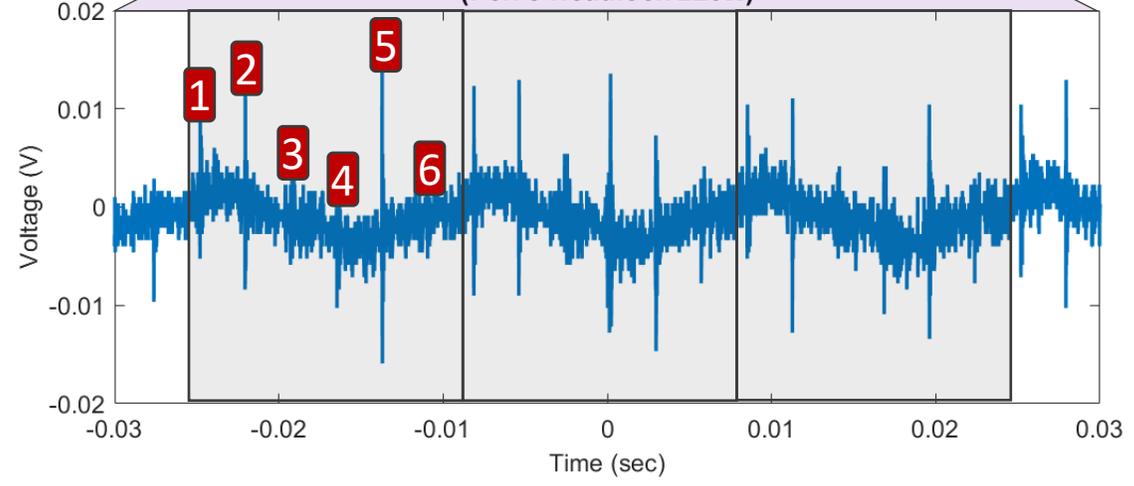
(Pen 8 Headlock 220Ω)



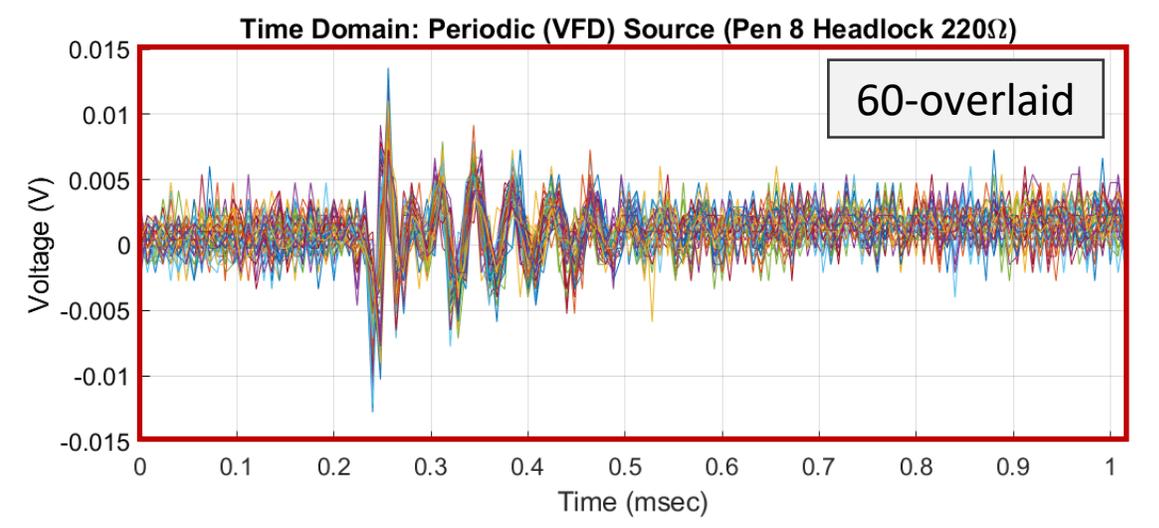
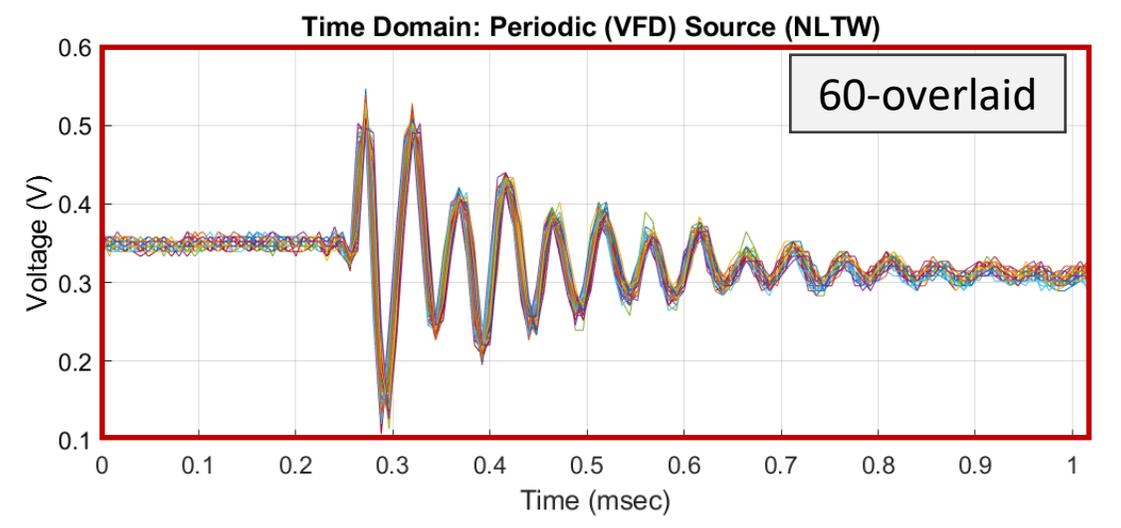
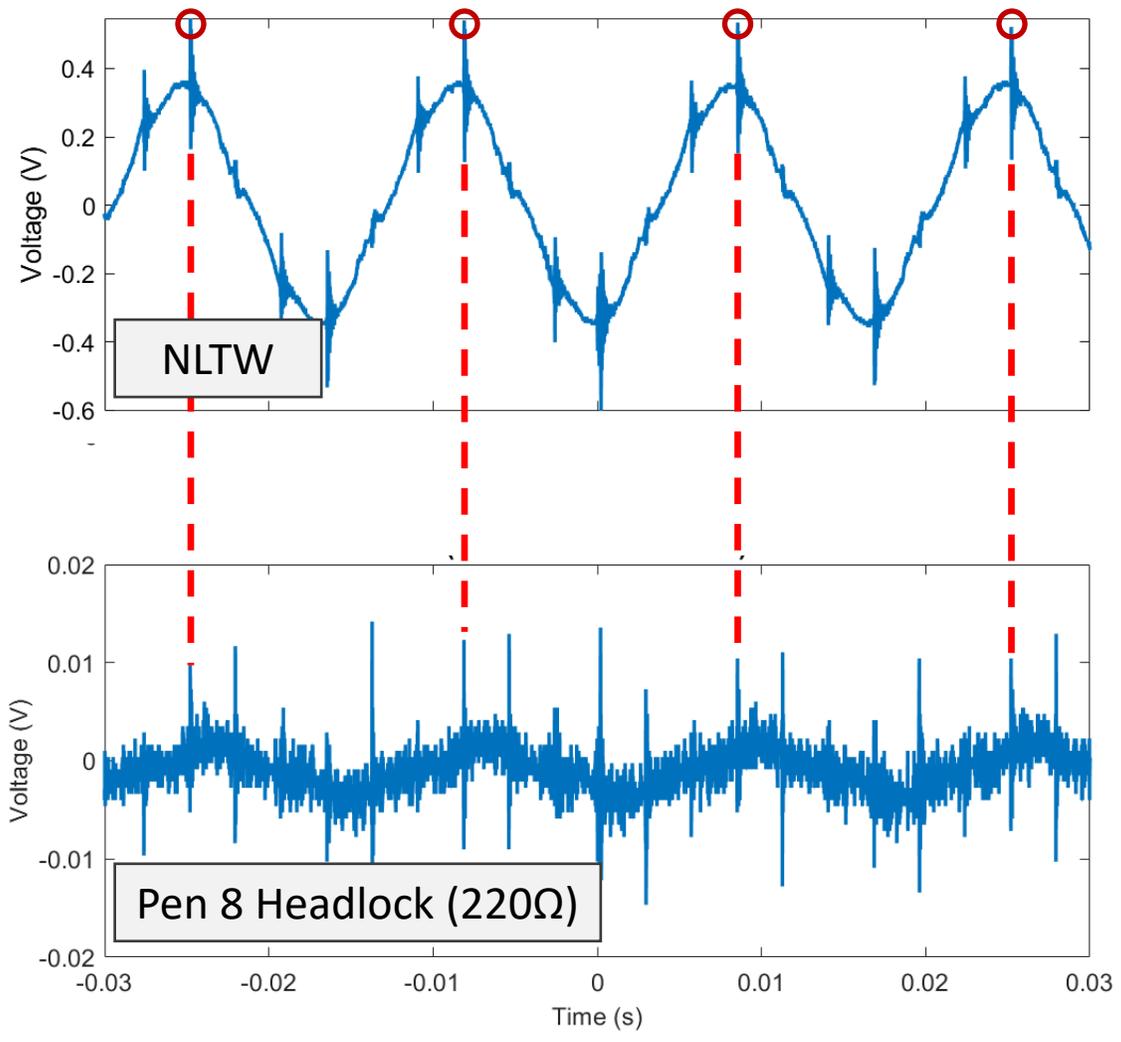
Long Test Wires



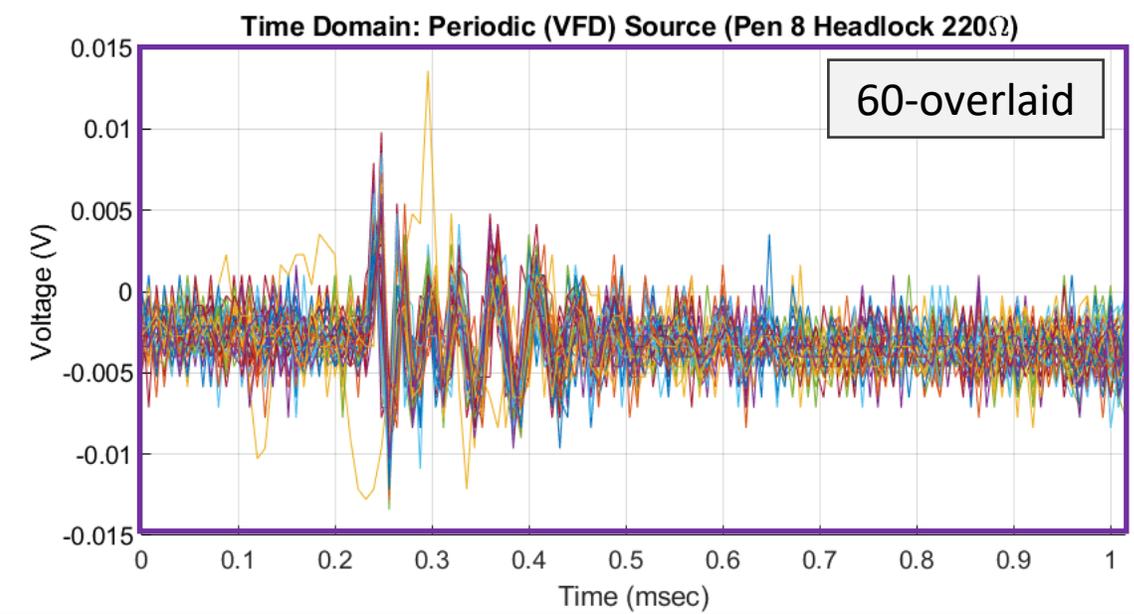
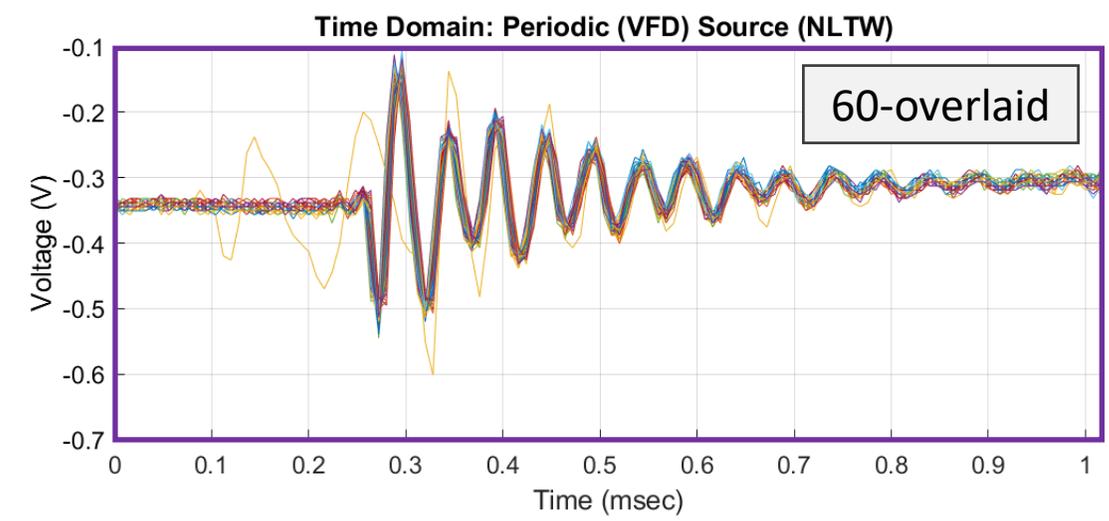
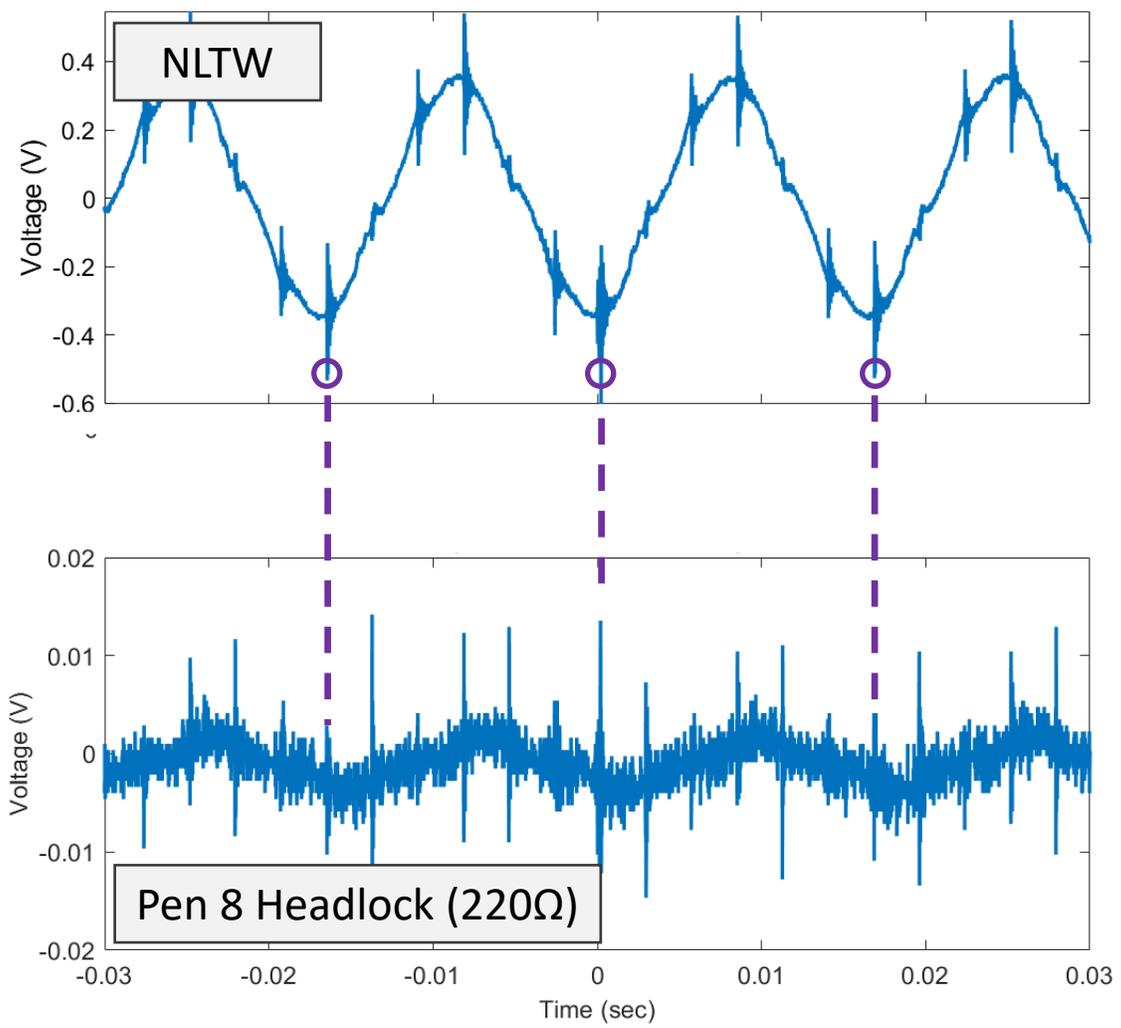
(Pen 8 Headlock 220Ω)



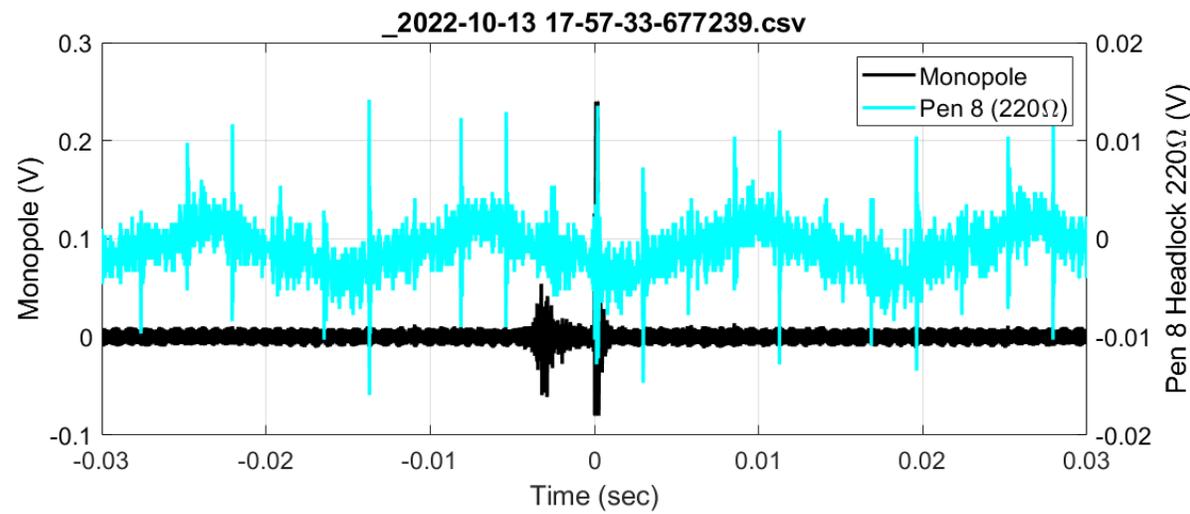
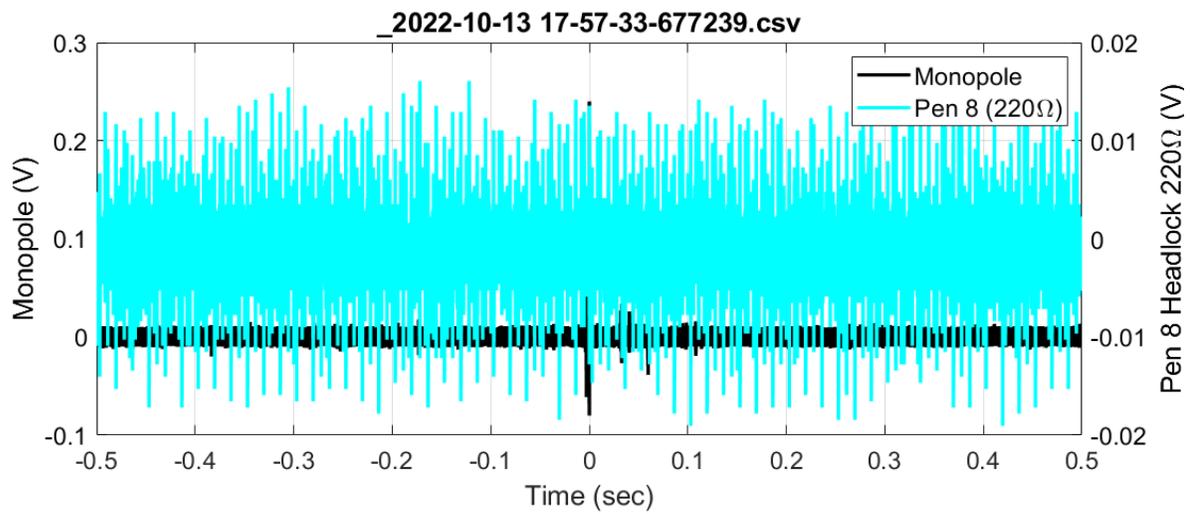
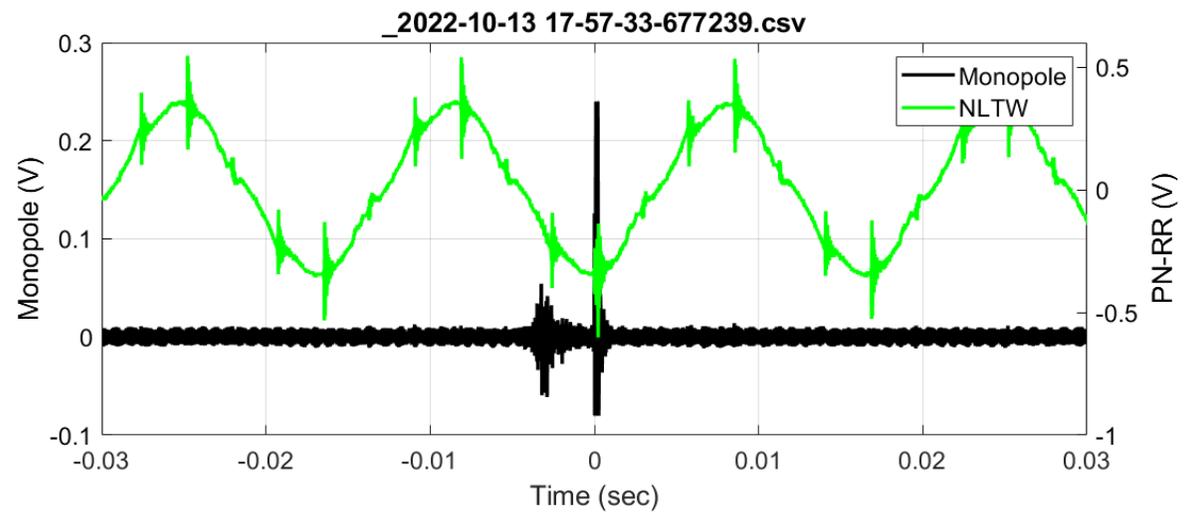
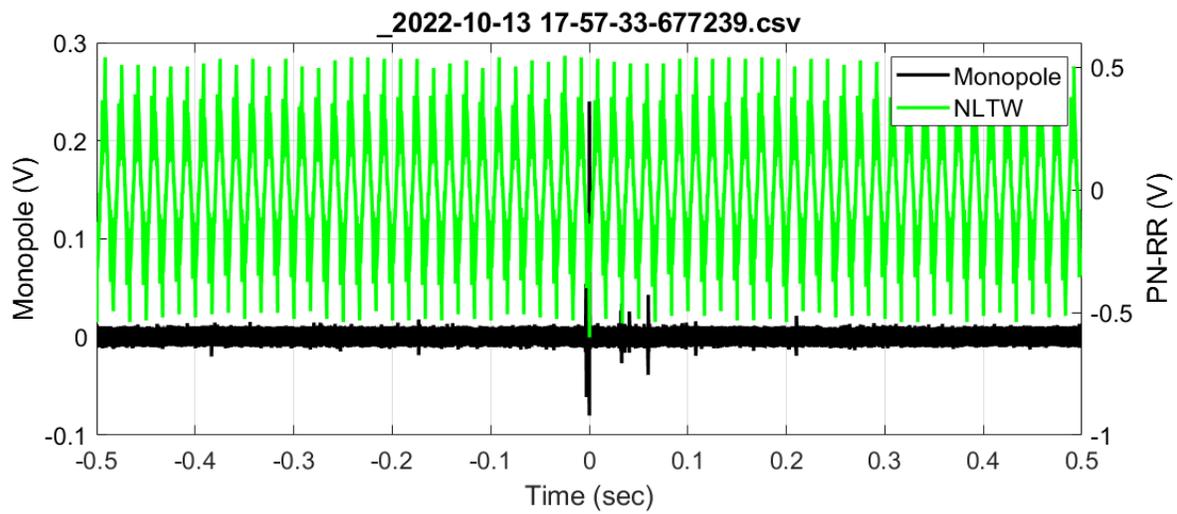
"Peak" VFD's



"Trough" VFD's



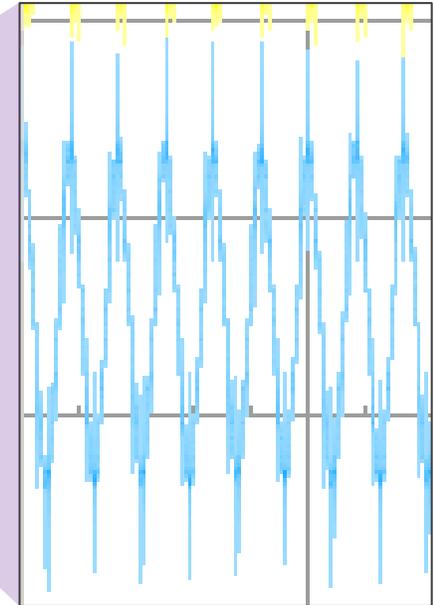
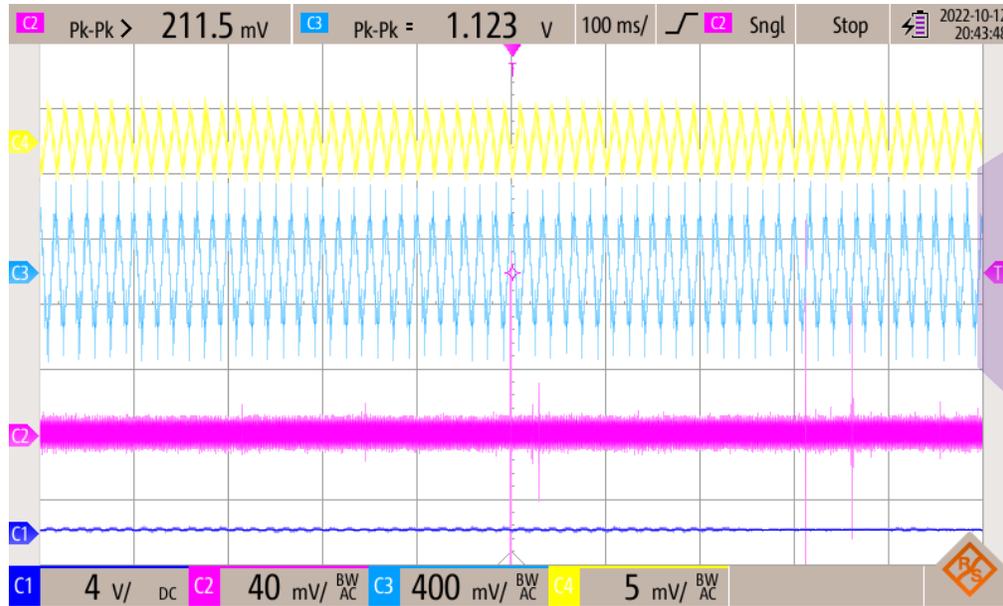
Cutting Through the (Conducted) Noise: Monopole Antenna



VFDs are from the Dairy: Dark Farm Test

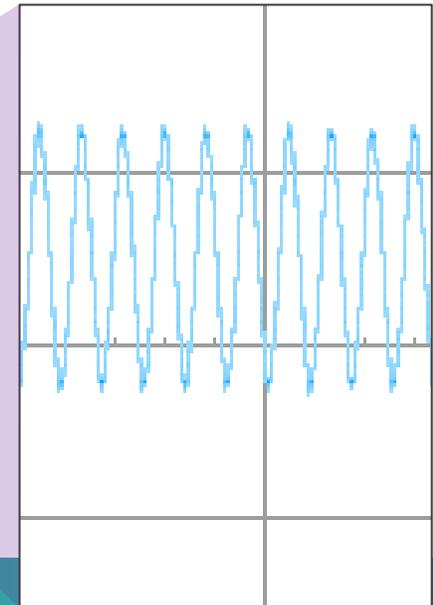
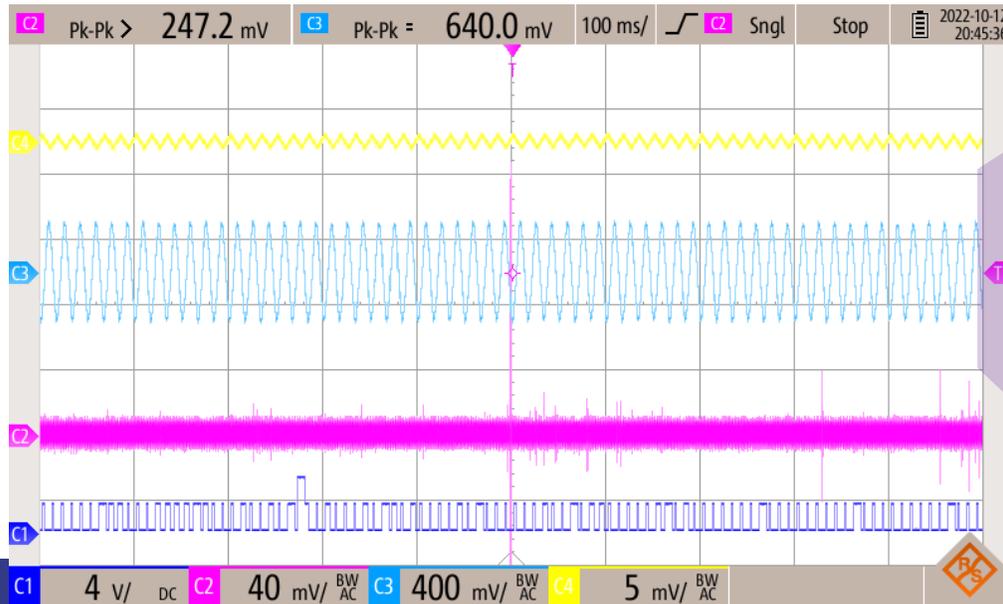
~3:44 pm

Farm on:
360 periodic VLF signals
every second



3:45 pm

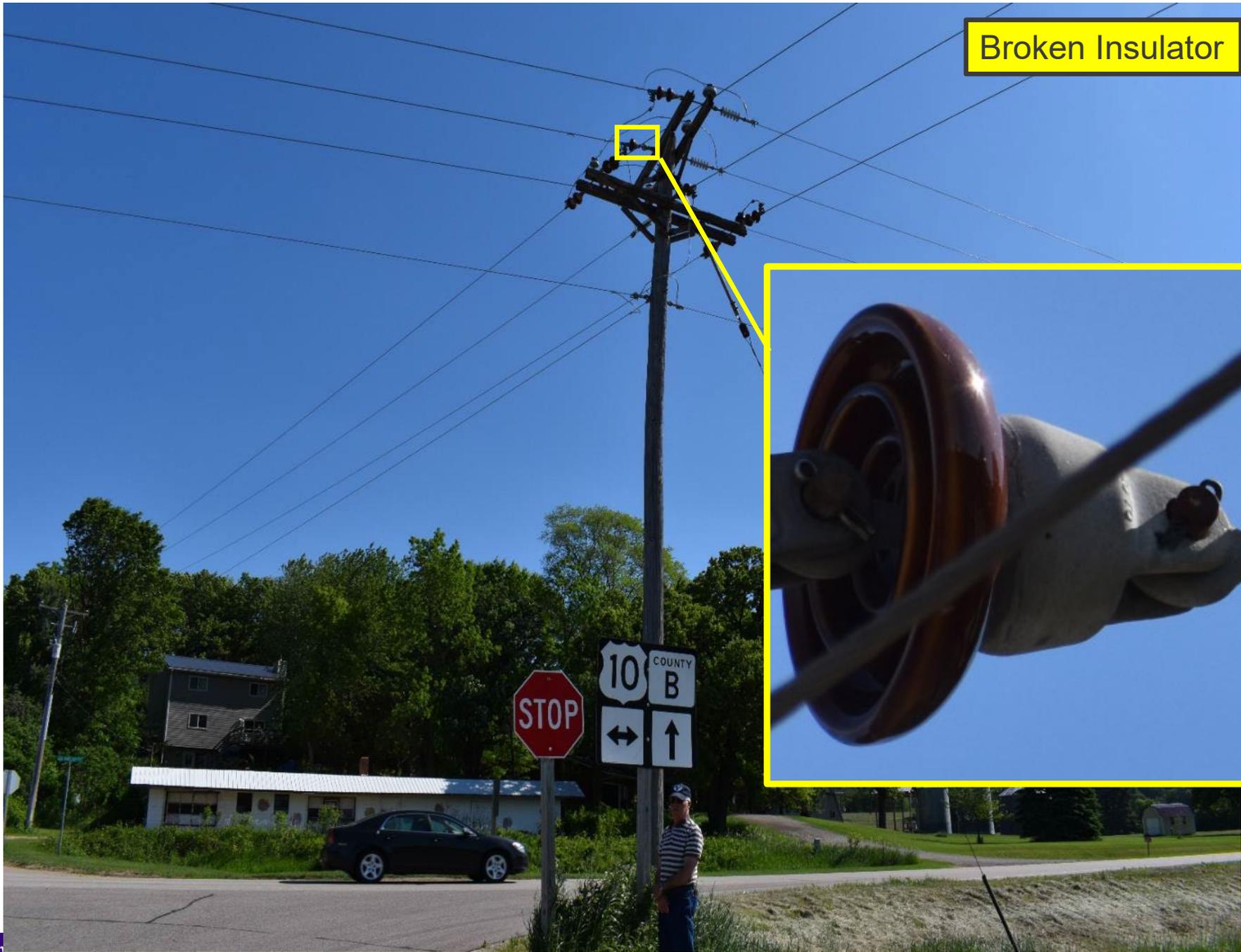
Farm off: Zero periodic
VLF signals



Responding to Alleged Utility Causes of VLF

Allegation: Broken Insulator - Causing VLFs

Broken Insulator



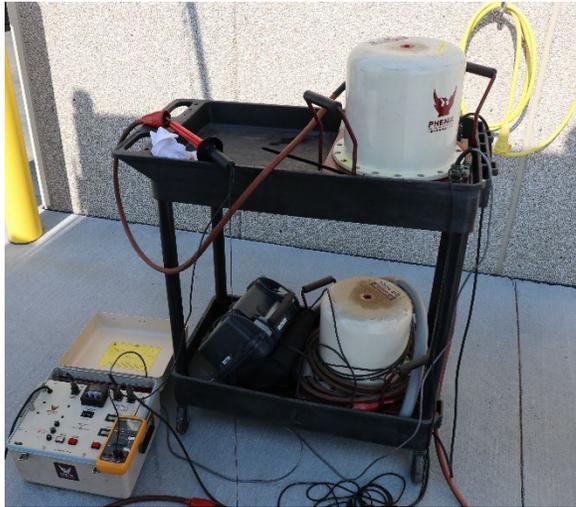
**Inspection for Carbon Treeing.
No evidence of current
conduction on the cross arm.**



No melted metal due to arcing.



Testing at 15,000 Volts



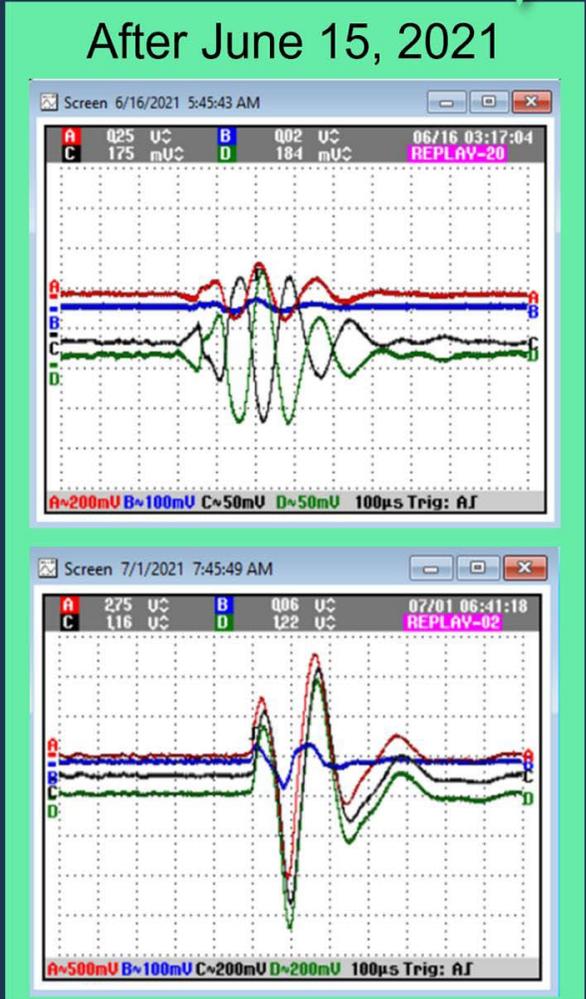
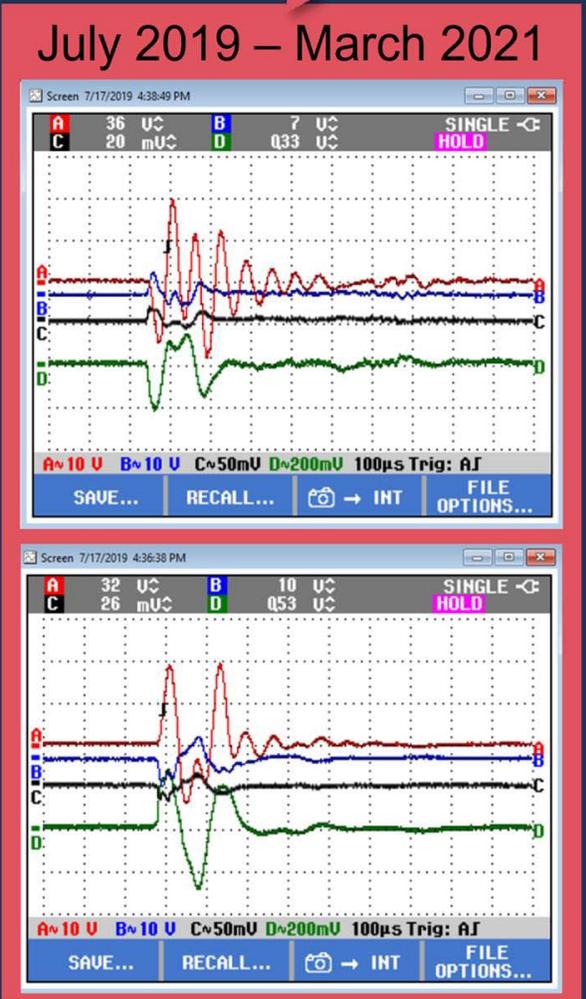
Tap	Phase	Insulator 1 of 2	Insulator 2 of 2	Pair Good?
South	West	>15kV	>15kV	Good
South	Center	>15kV	>15kV	Good
South	East	>15kV	>15kV	Good
North	West	>15kV	>15kV	Good
North	East	>15kV	~5.02kV	Good
West	North	>15kV	>15kV	Good
West	Center	>15kV	~5.53kV	Good
West	South	>15kV	~2.32kV	Good

Measurements Before and After Insulator Repair



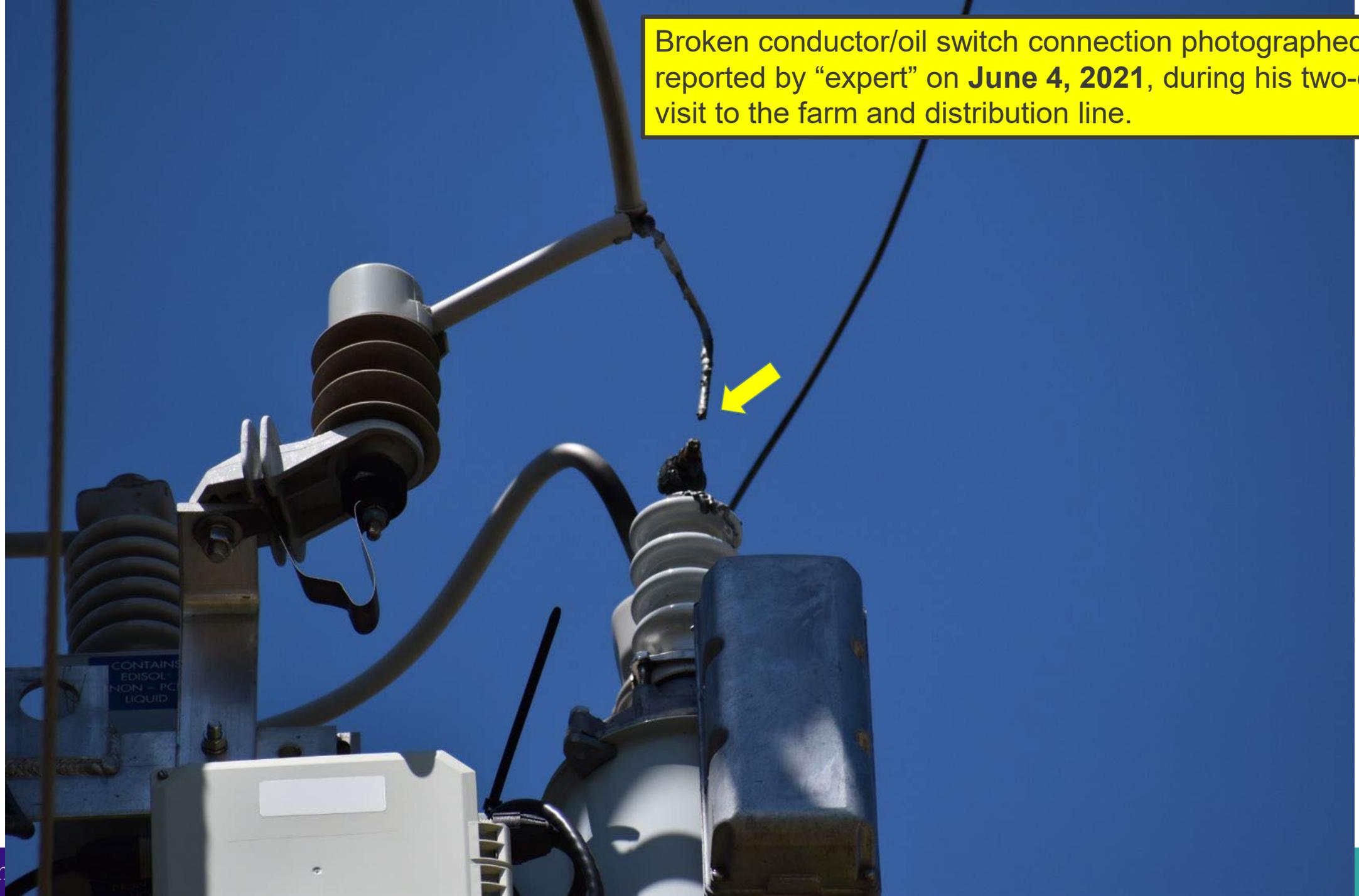
Before Repair

After Repair



Allegation: Capacitor Bank and Broken Wire - Causing VLFs

Broken conductor/oil switch connection photographed and reported by "expert" on **June 4, 2021**, during his two-day visit to the farm and distribution line.





Failed wire termination inspected by Loud.



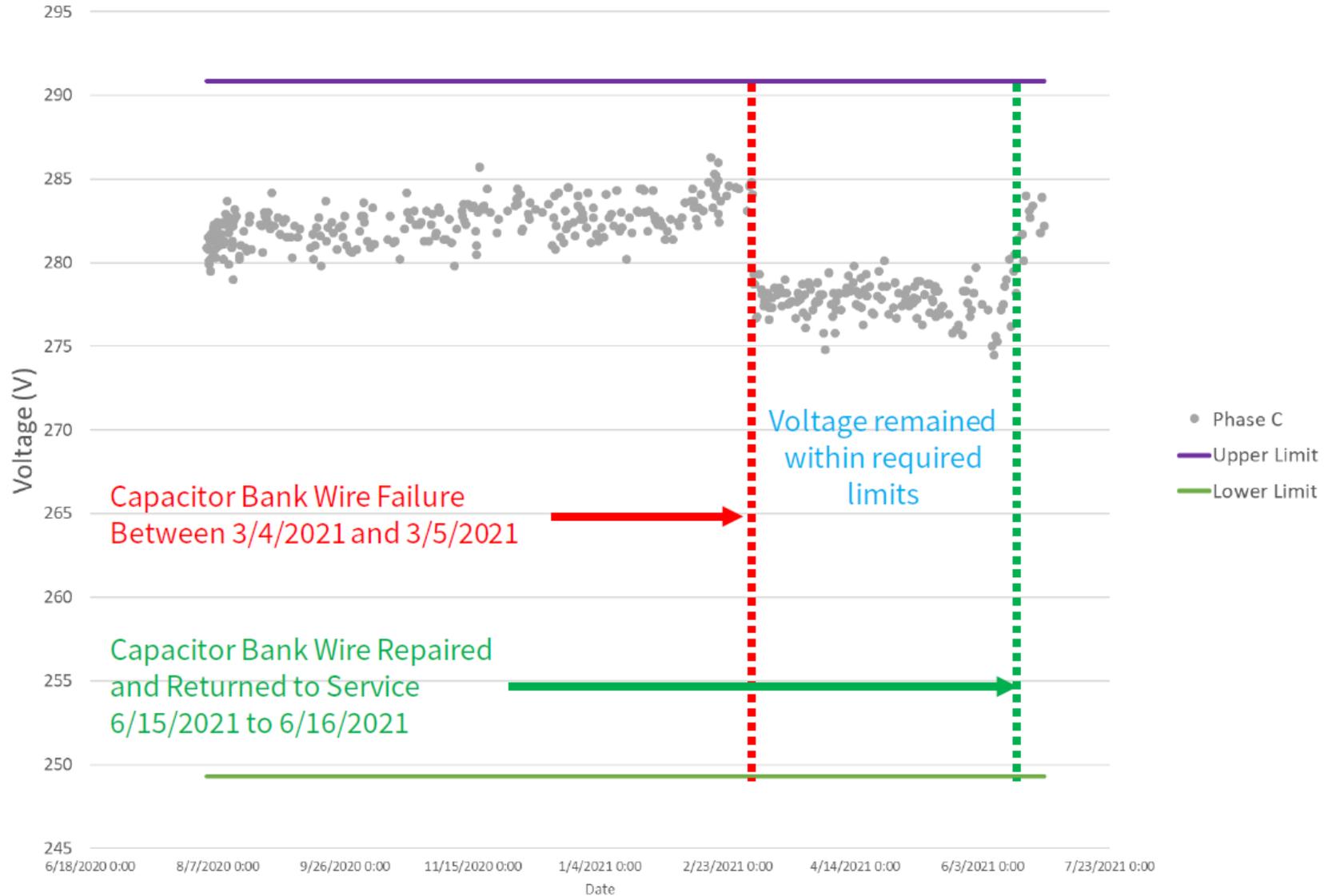
15kV Hipot Test



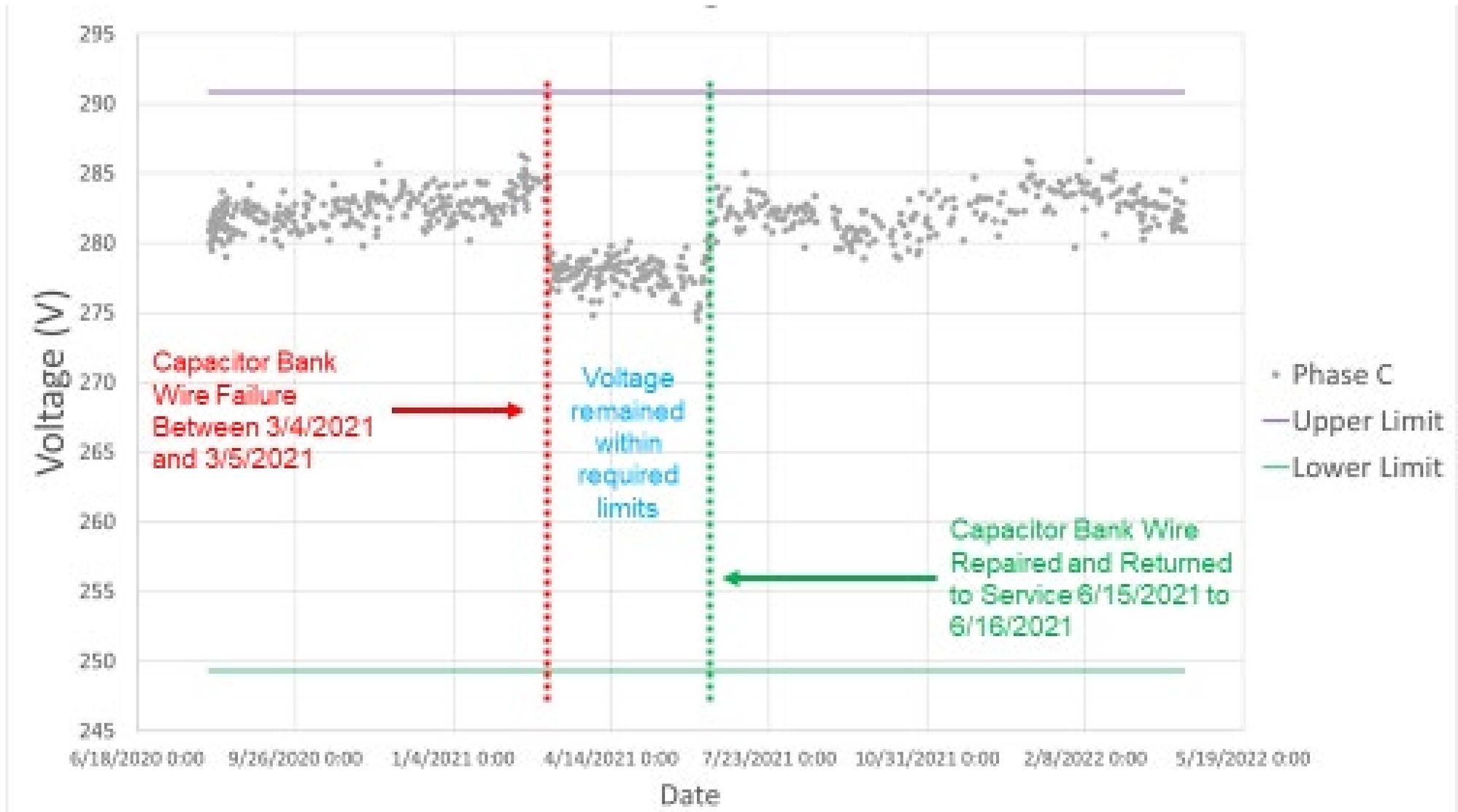
Oil switch tested



Meter Readings at Dairy



Meter Readings at Dairy



VLF Measurements Before/During/After Capacitor Bank Repair

Capacitor Bank

2016

2017

2018

2019

2020

2021

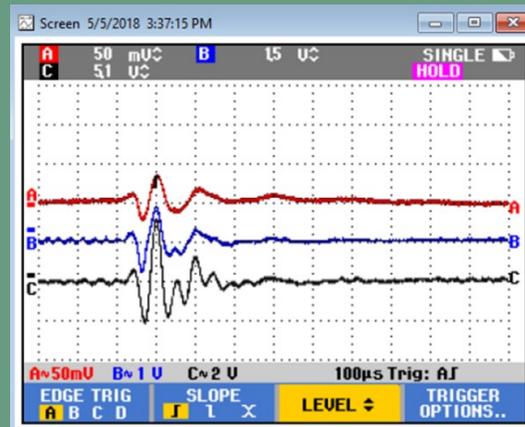
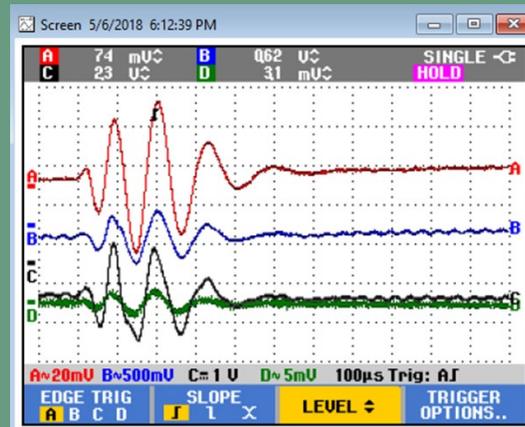
July

March 3

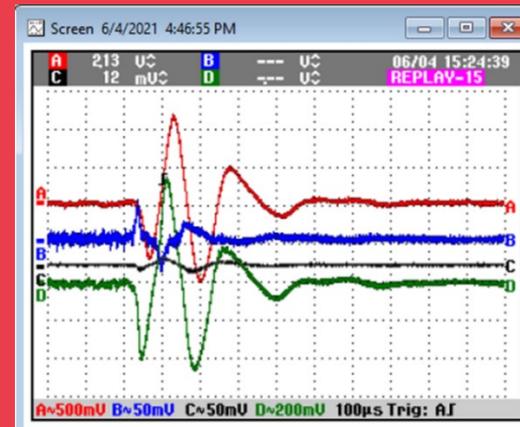
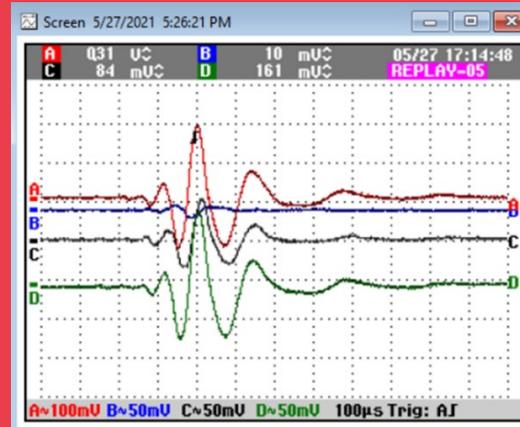
June 15

- While In Service
- Out of Service
- Back In Service

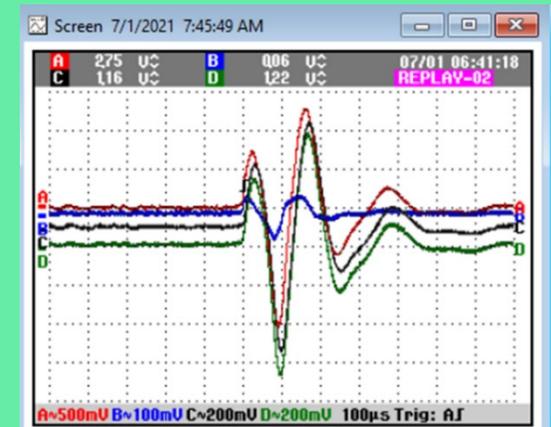
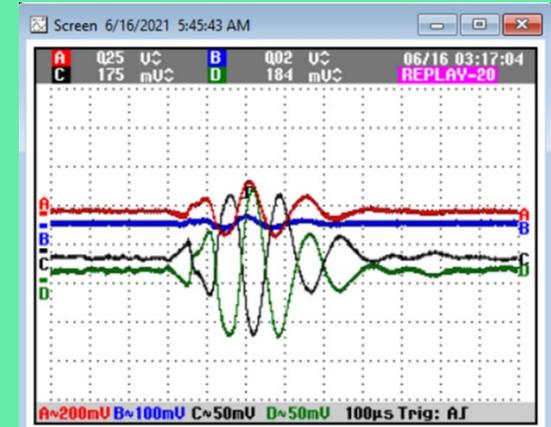
Before July 17, 2019



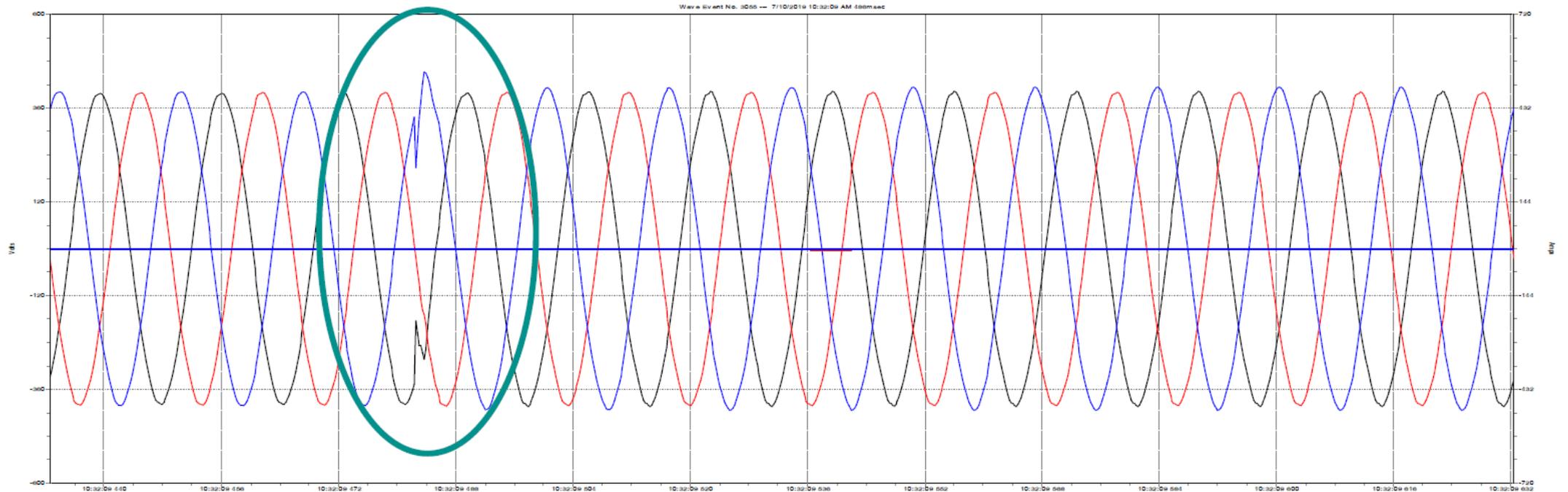
March 3 – June 15, 2021



After June 15, 2021



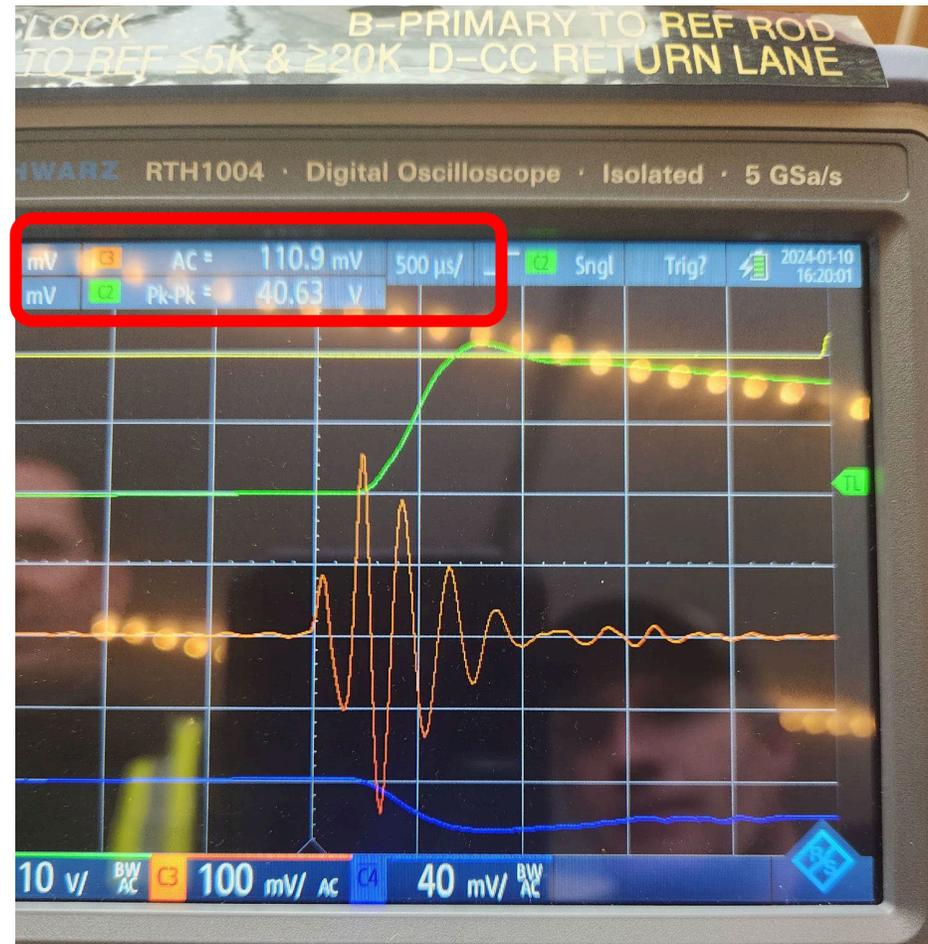
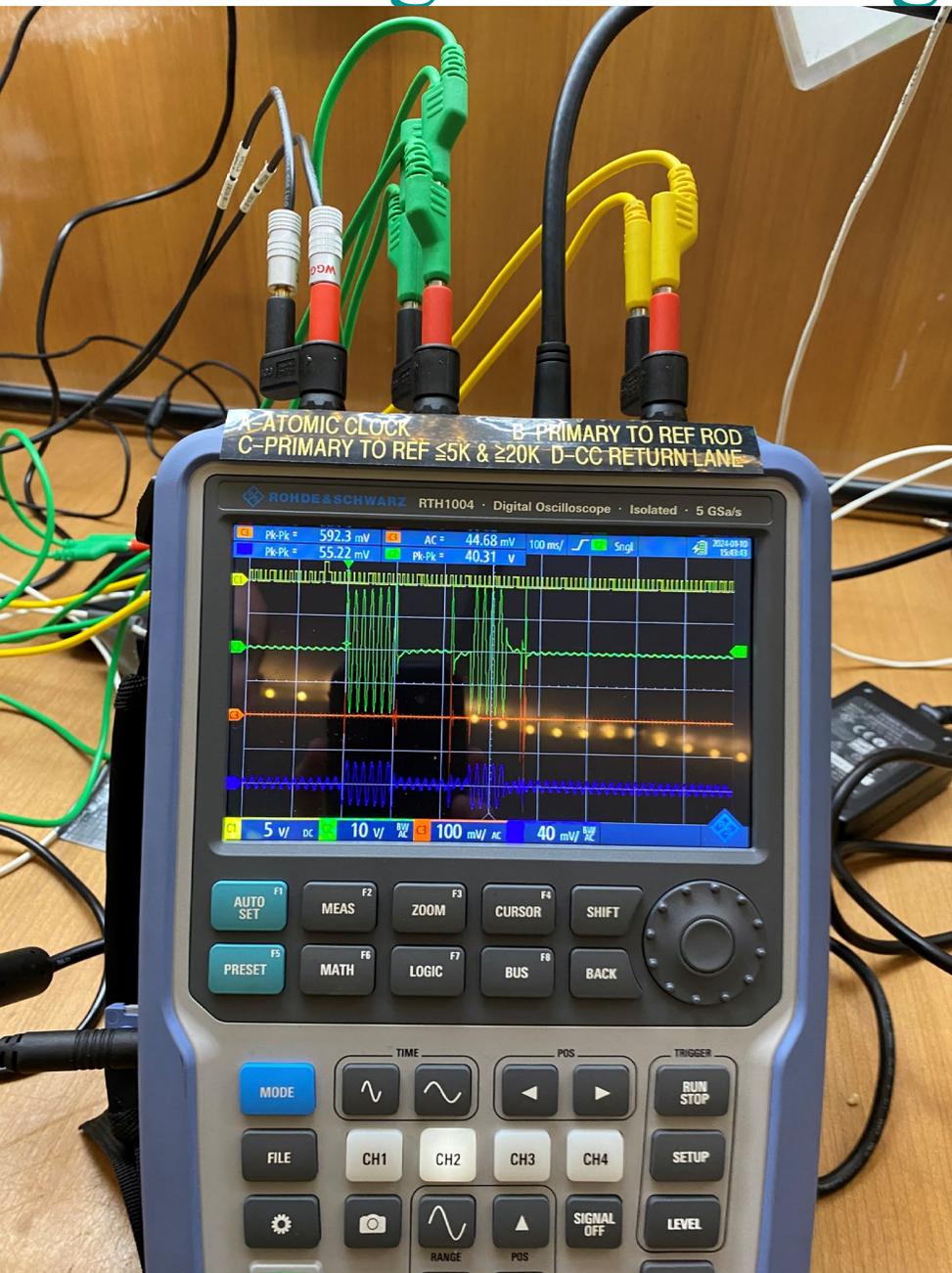
Switching Transients (Event #3055) – Phase A



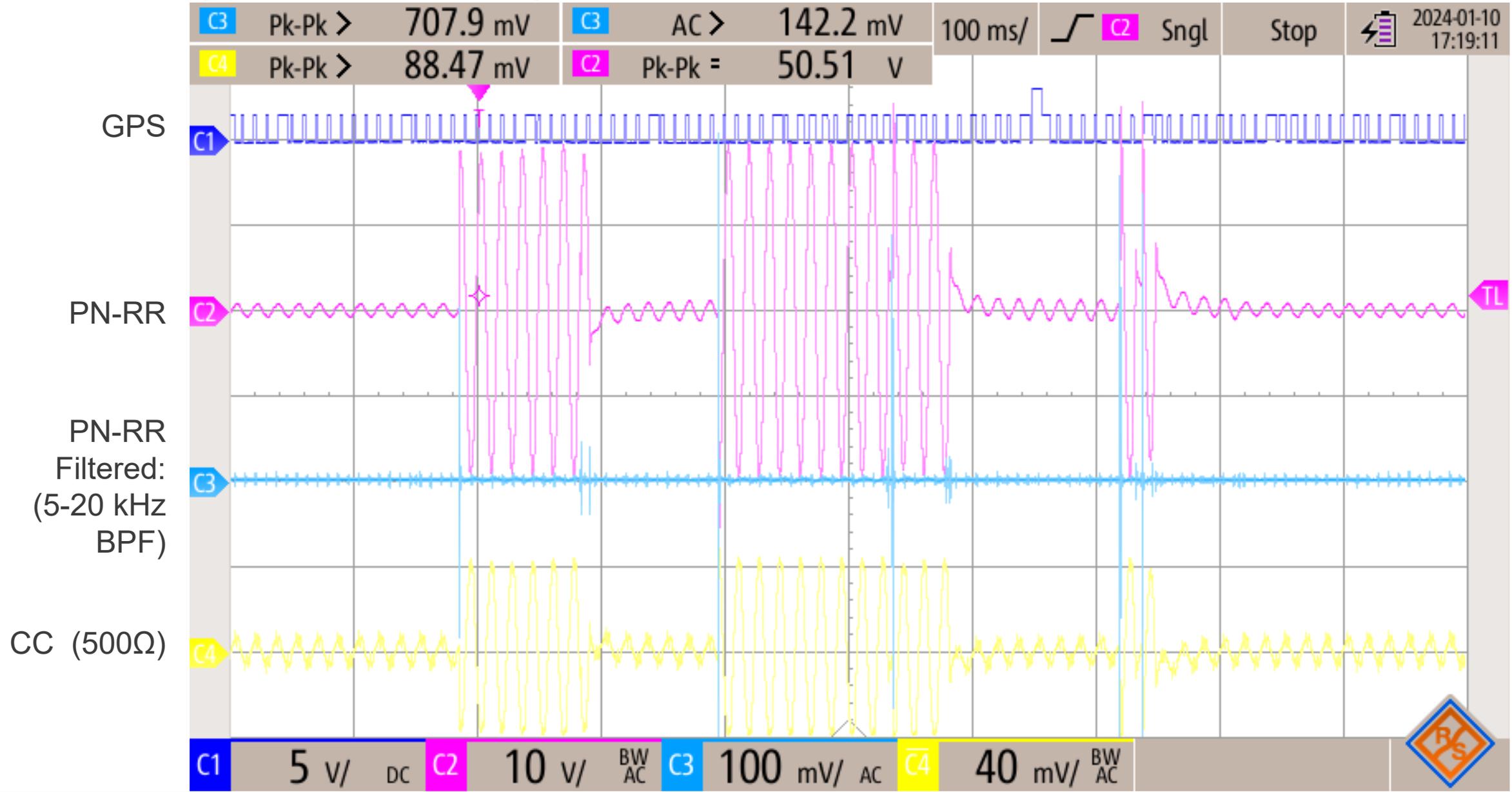
What Can Scientific Methodology Tell Us About Whether the Capacitor Bank is the Source?

- The capacitor bank does not automatically switch. Even if it did, capacitor switching does not cause VLF signals on the power line.
- Measurements made with the capacitor wire open. The wire failure did not cause VLF signals on the power line.
- VLF signals were continuous before the wire break, while the wire was broken and after the wire was repaired
- The Oil Switch withstood 15,000 volts (normal is 7,600 volts), did not break down internally and did not cause VLF signals on the power line
- The capacitor bank and failed wire are ruled out as a possible cause of VLF signals

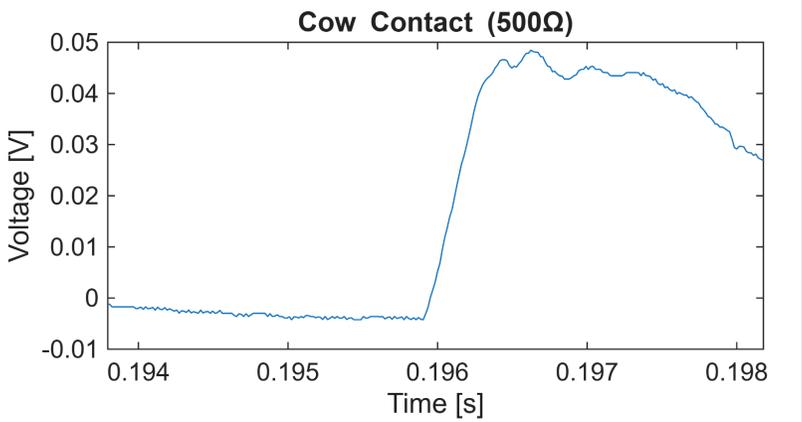
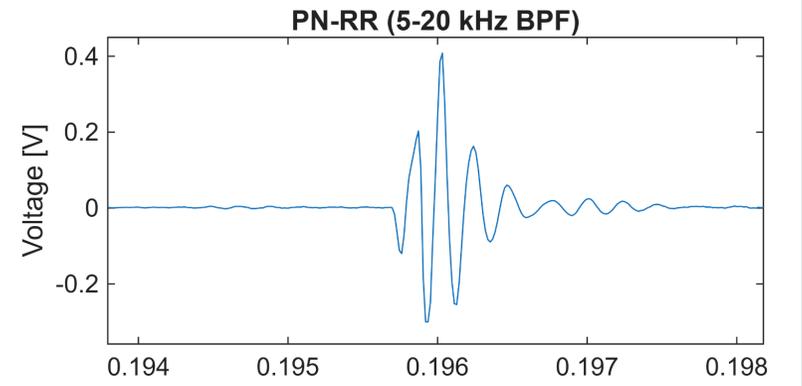
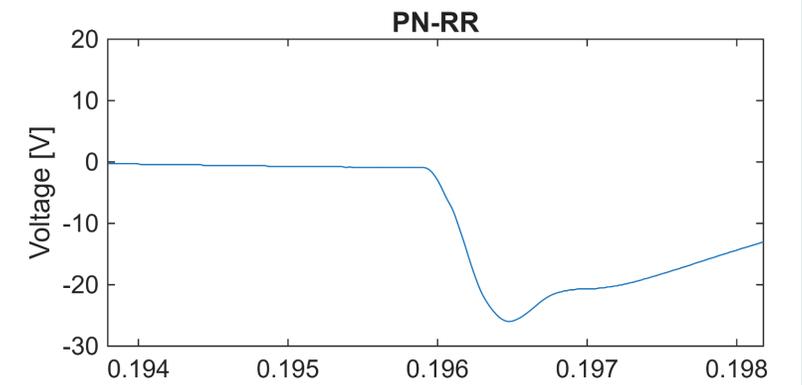
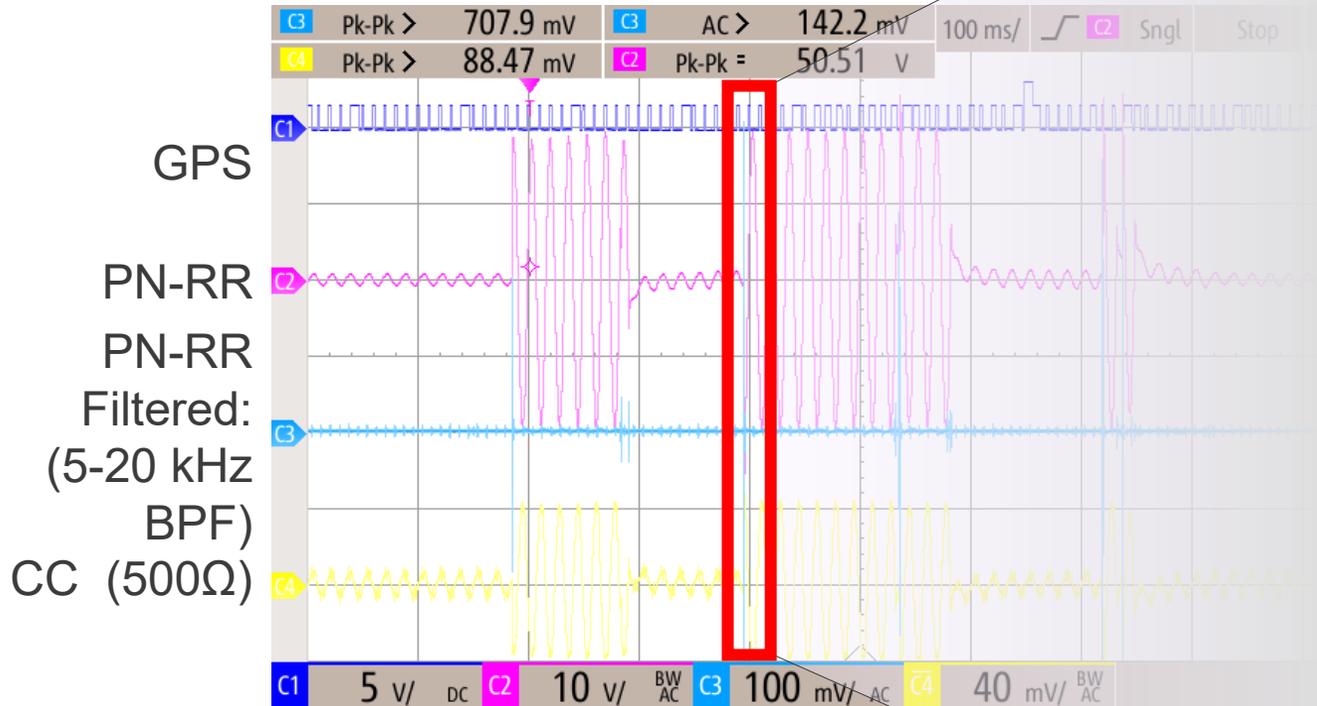
“Creating” a VLF Signal



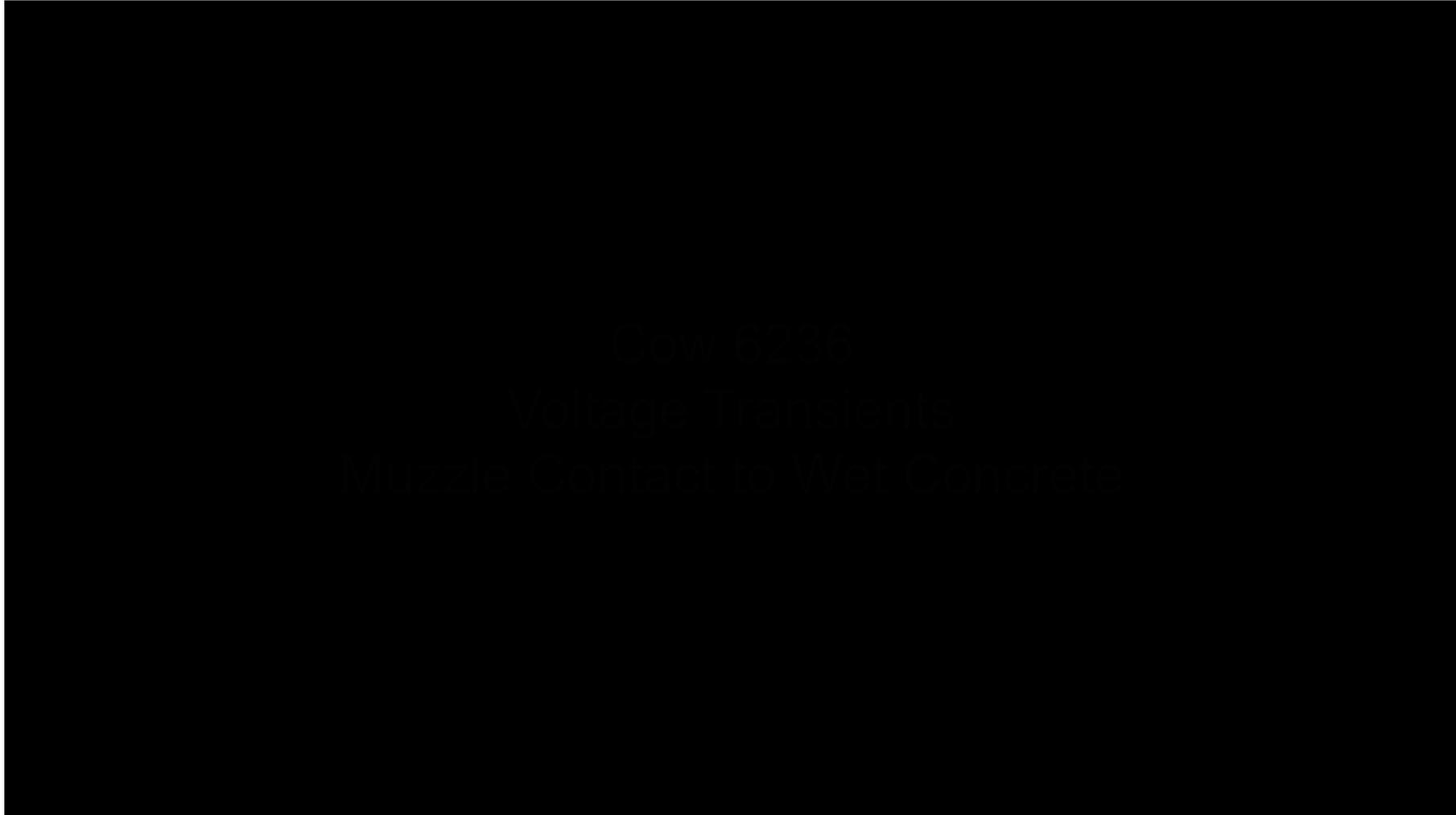
“Creating” a VLF Signal



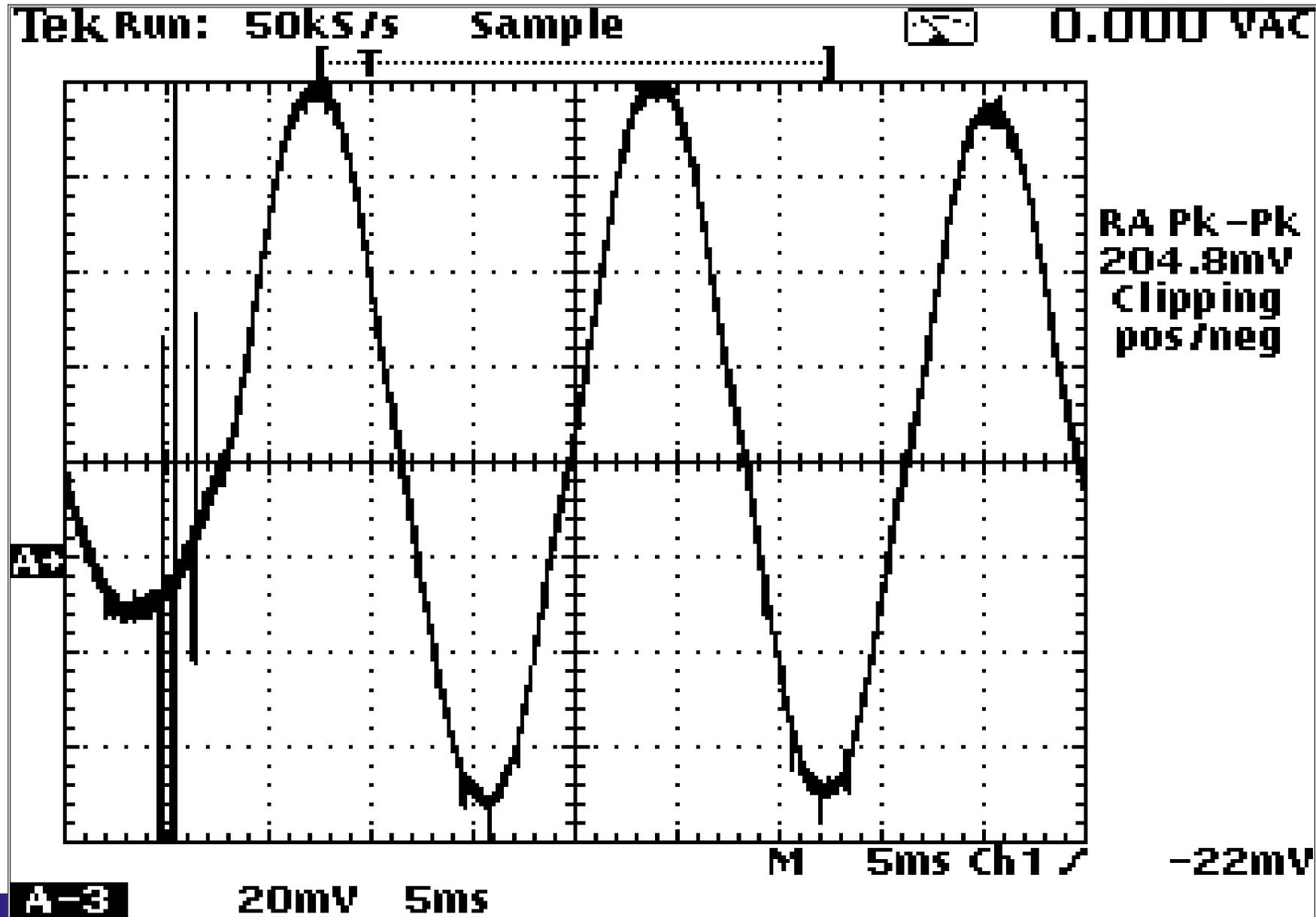
“Creating” a VLF Signal



Cow Exposed to VLF Signals



1999: Cow contact voltage measurement: Multiple VLF Transients in addition to 60 Hz Signal



Questions?

Thank You



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**Benjamin Cotts,
Ph.D., P.E.²**

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+1.303.578.0078

² CA, NY

Disclaimer

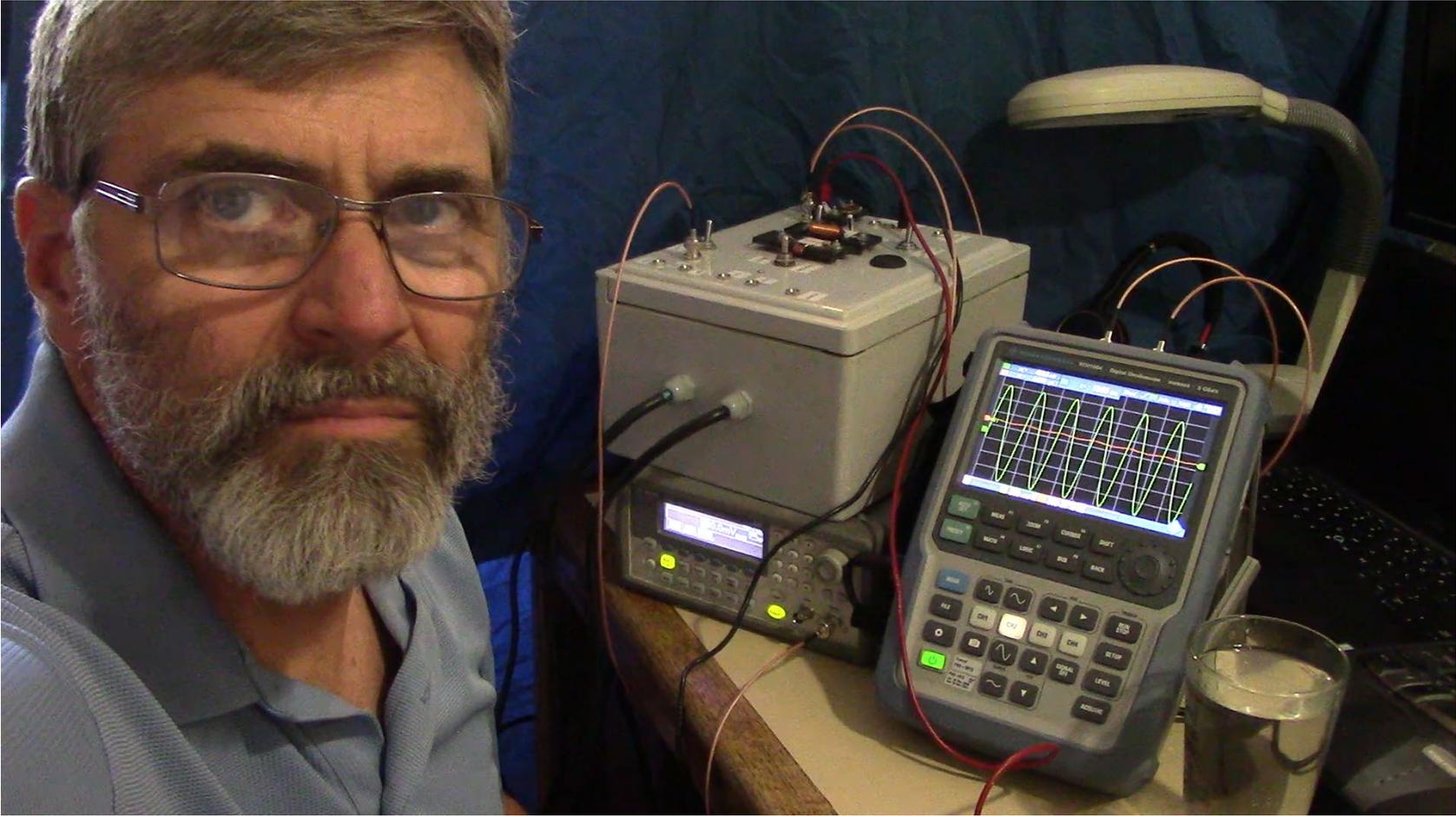
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Backup Slides

Human Sensitivity at 60 Hz



Human Sensitivity at 12,000 Hz



Obfuscation:

Long Test Wires

Burden Resistors

Trendplot / Phase Imbalance

Neutral Isolation

Disconnecting the Farm

Amplifiers

Changing the Vertical Scale

Filters (throwing away data)

Filters (creating VLF signals)

Concrete Rebar Rectification and DC

Stray Voltage Essentials

- Scientific Method
- Scientific Method
- Scientific Method
- Have the proper tools
- Know how to use the tools and understand their limitations