GridSweep: Active Measurements of Electric Distribution Systems

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U.S. Department of Energy

Alex McEachern, McEachern Laboratories

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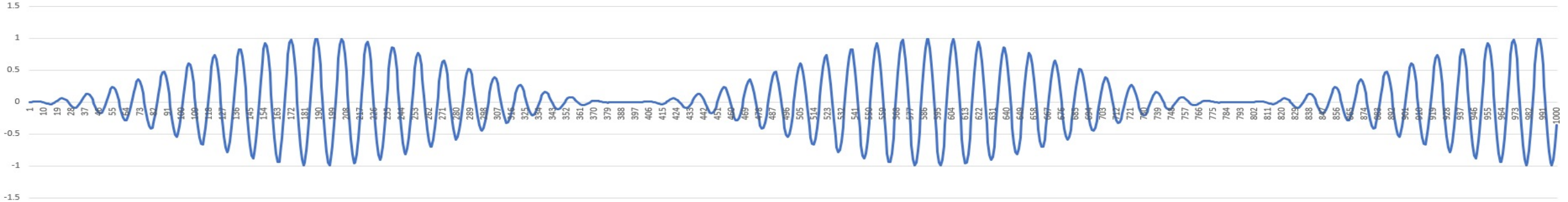
Lawrence Berkeley National Laboratory



GridSweep: Active Measurements of Electric Distribution Systems

The Idea:

- GridSweep forces a tiny, low-frequency (1 Hz to 40 Hz) signal onto the grid by amplitude modulating a 1-kW resistive load plugged into any 120-V outlet.
- GridSweep then measures the grid's voltage response at another 120-V outlet, then extracts the parts-per-billion signal from the background noise.
- The goal is to create a novel, low-cost method for revealing and quantifying grid stability.
- The project will help identify vulnerabilities specific to sub-synchronous disturbance frequency and control loop parameters, informing grid operators where nascent instabilities need to be curbed or monitored.

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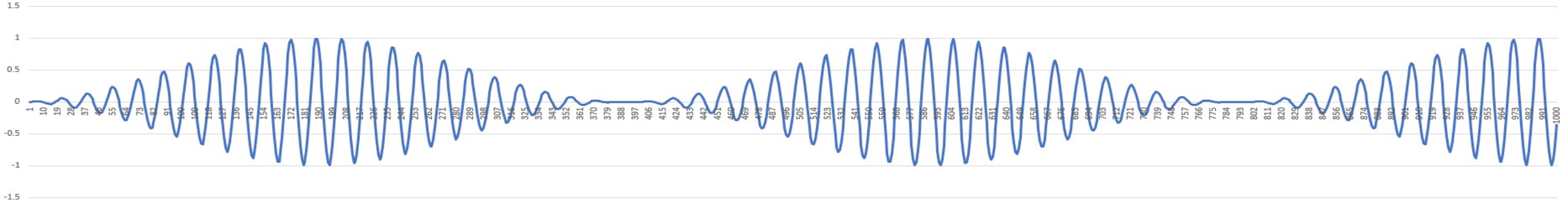

GridSweep: Active Measurements of Electric Distribution Systems

Project Objectives:

- Create a completely new class of active grid instrumentation for situational awareness.
- Apply data techniques for ambient noise analysis and small-signal extraction.
- Characterize bulk grid inertia, generator control loop parameters, frequency-specific grid response and location-specific load dynamics live *in situ*.
- Demonstrate a synchronized GridSweep network with geographic correlation.
- Support rapid adoption and deployment with open source tools.

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BERKELEY LAB
Lawrence Berkeley National Laboratory

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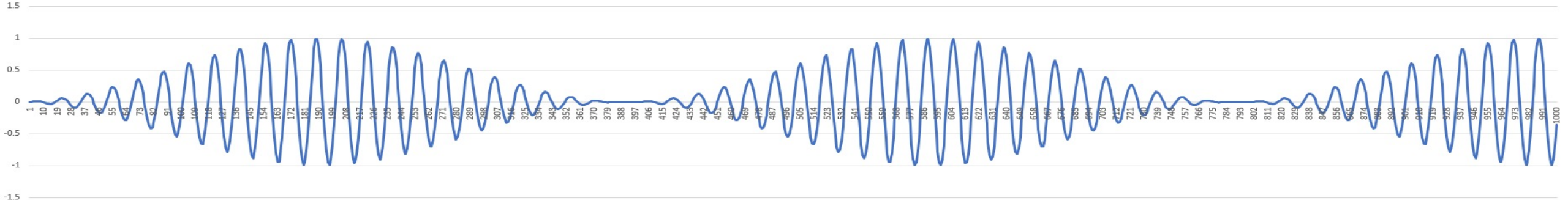
Lawrence Livermore National Laboratory

IDAHO POWER
An IDACORP Company

CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

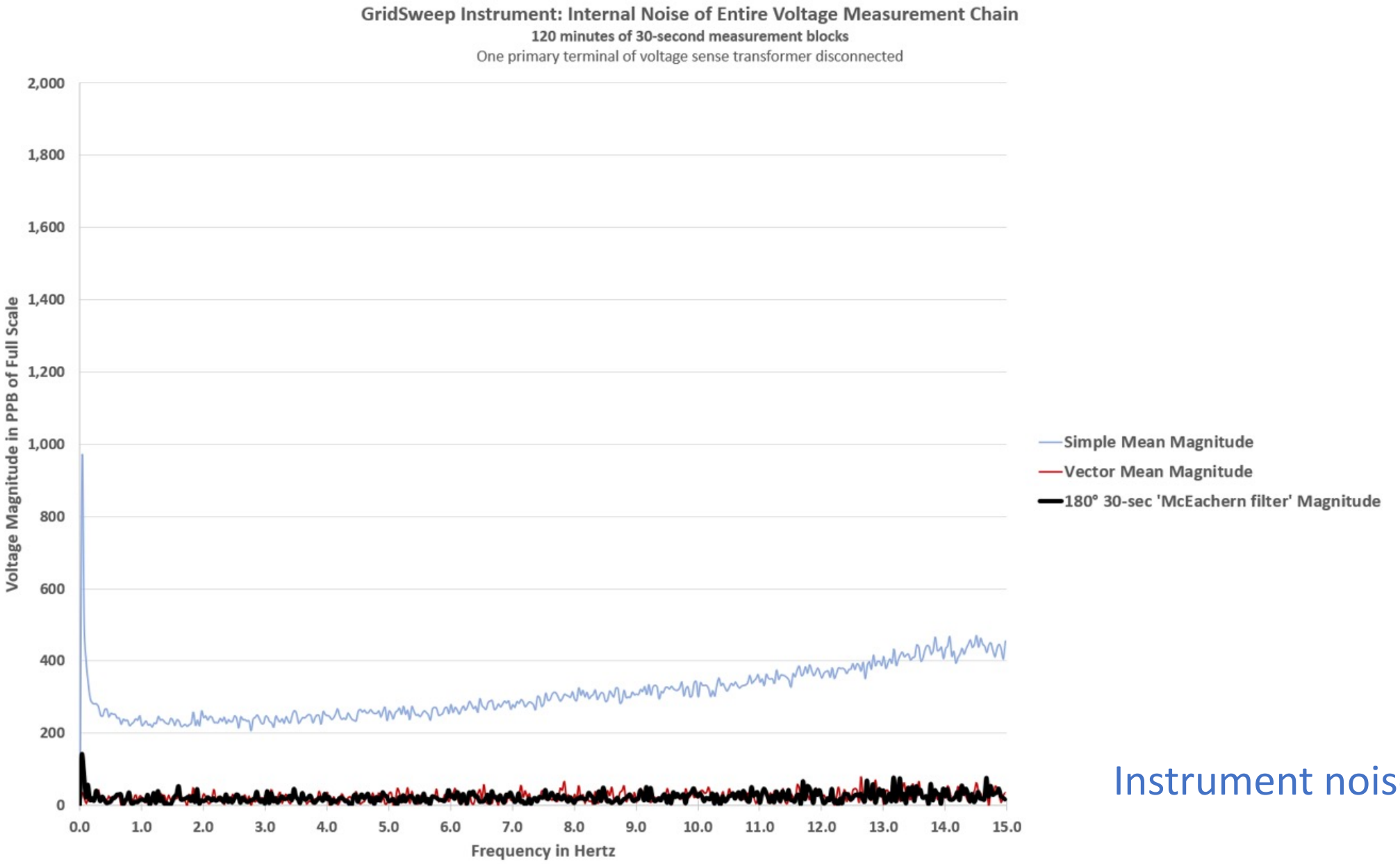
Hawaiian Electric



Comparison of active grid probing methods

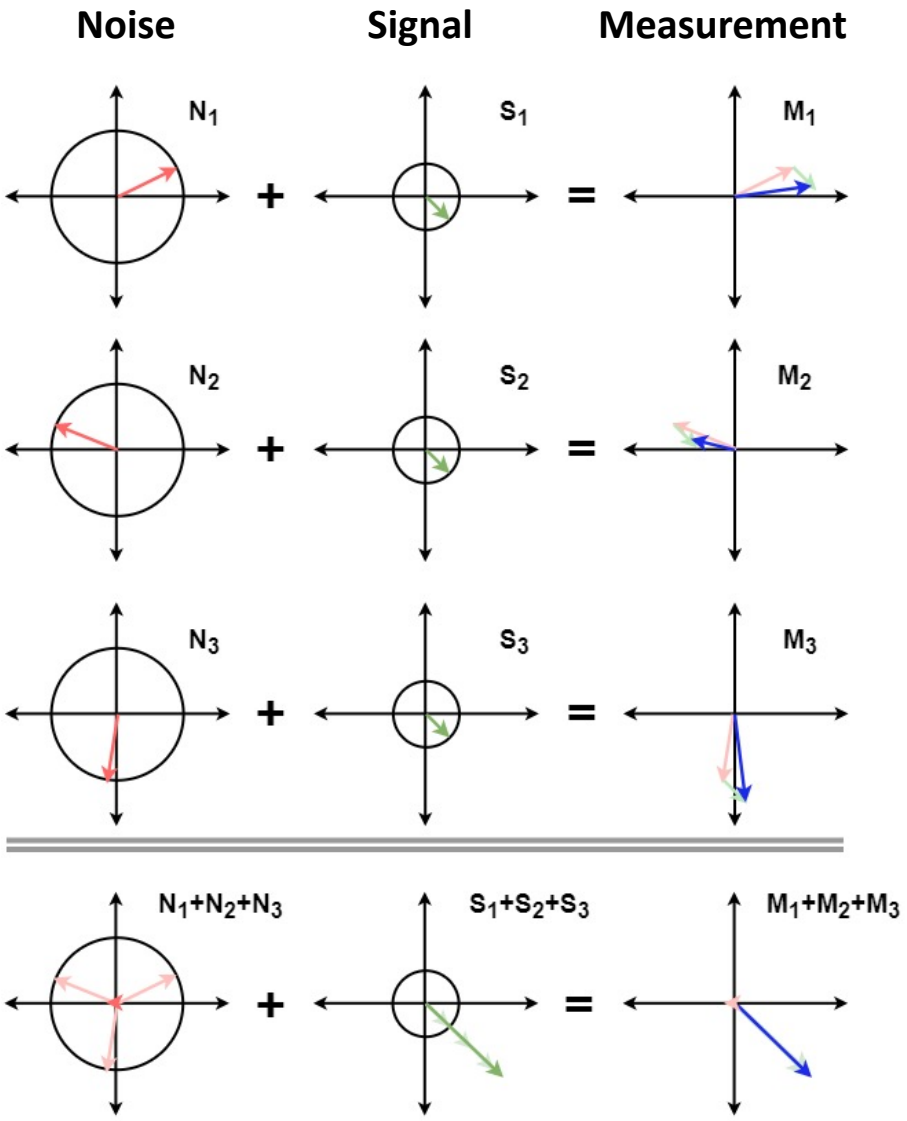
		Source	Stimulus	Measurement devices	Measurement resolution	Noise extraction method
1980s-		Chief Joseph Brake	1 GW impulse	Fault recorders	1000 ppm 0.1%	None
2015-		Grid Thumper	1 MW impulse	microPMUs	10 ppm 0.001%	Time-synchronous demodulation
2022-		**GridSweep**	**1 kW swept sine**	**GridSweep**	**100 ppb 0.00001%**	**Single frequency vector-synchronous demodulation**

120-minute block of GridSweep entire-voltage-measurement-chain noise (2,000 PPB full scale)



Instrument noise floor, ppb

Extracting GridSweep signal from noise: Vector Synchronous Demodulation



GridSweep uses signal averaging to increase signal-to-noise ratio (SNR)

Instead of real-value average, we use phasor average

In GridSweep we control:
- signal frequency *and*
- signal phase, relative to GPS

Measurements are also locked to GPS

"Constant phase angle" of signal enables phasor average to extract signal at parts-per-billion (ppb) levels

Illustration by Mohini Bariya

Can you really see probing on the grid? Grid Thumper signal propagation, 2019 data

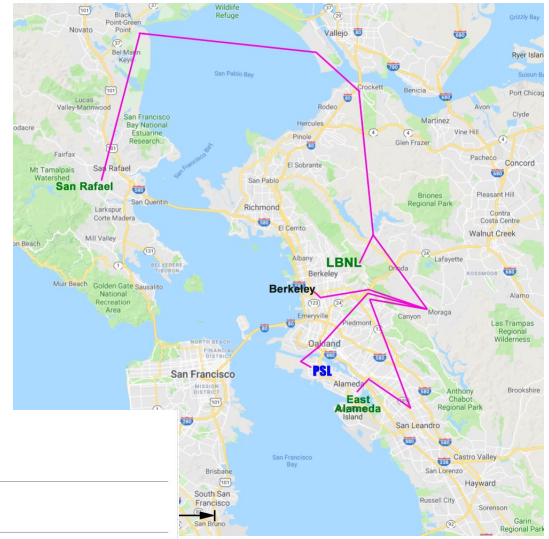
Experiment demonstrates that small signals can be propagated through the bulk grid:

Impulsive 1-MW Grid Thumper "thumps" at source, 1.2-second intervals

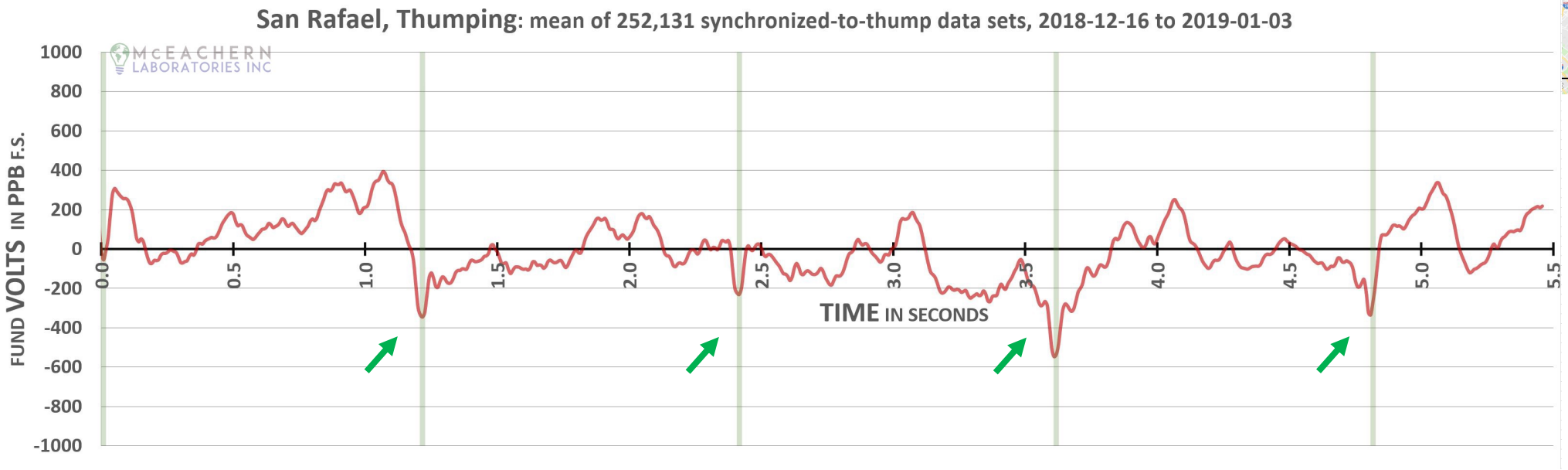
Path from source to sensor: approx. 80 km (50 mi), of which 30 km is on bulk grid

480V → 6kV → 120kV → 230kV → 115kV → 24kV → 120V

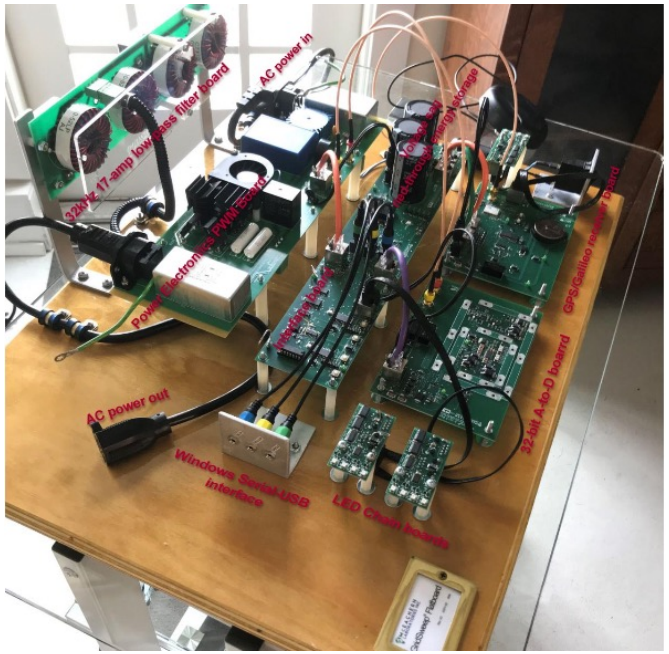
Just a demonstration: Thumps are broad-spectrum, i.e. low energy at any one frequency, and sensor is microPMU, not designed for low-noise use



Measured result at sensor:



2021: GridSweep instrument design & construction completed



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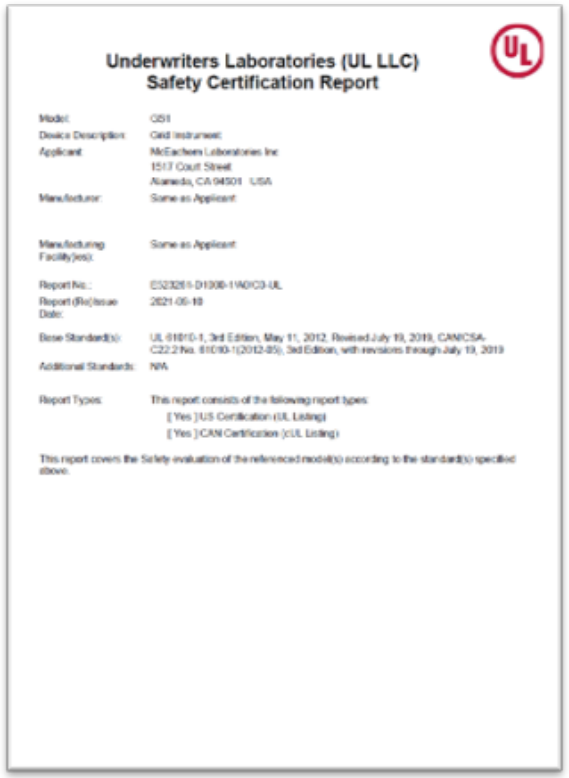
Functional firmware, software complete
(continuing development on user interface)

UL Certification complete!



Underwriters Laboratories (UL LLC)
Safety Certification Report

Model: GS1
Device Description: Grid Instrument
Applicant: McEachern Laboratories Inc
1517 Court Street
Alameda, CA 94501 USA
Manufacturer: Same as Applicant

Manufacturing Facility(ies): Same as Applicant

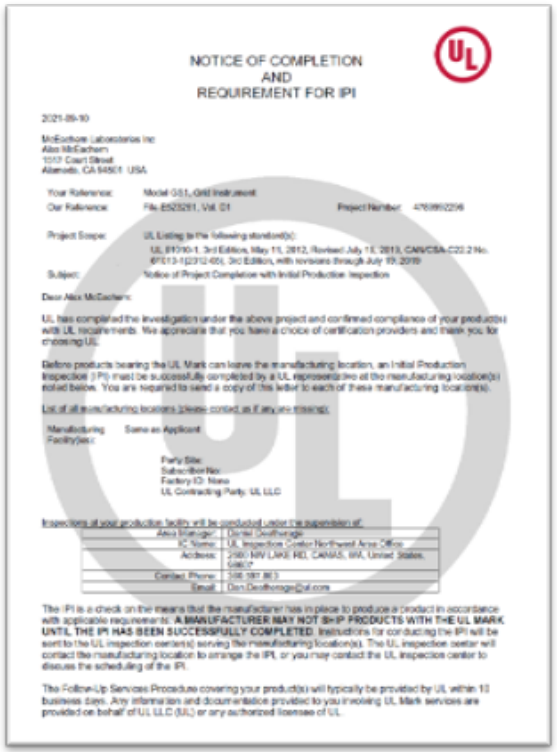
Report No.: E523261-D1000-11A0IC0-UL
Report (Re)Issue Date: 2021-09-10

Base Standard(s): UL 61010-1, 3rd Edition, May 11, 2012, Revised July 19, 2019, CAN/CSA-C22.2 No. 61010-1(2012-05), 3rd Edition, with revisions through July 19, 2019

Additional Standards: N/A

Report Types: This report consists of the following report types:
[Yes] US Certification (UL Listing)
[Yes] CAN Certification (cUL Listing)

This report covers the Safety evaluation of the referenced model(s) according to the standard(s) specified above.



NOTICE OF COMPLETION
AND
REQUIREMENT FOR IPI

2021-09-10

McEachern Laboratories Inc
Alex McEachern
1517 Court Street
Alameda, CA 94501 USA

Your Reference: Model GS1, Grid Instrument
Our Reference: File E523261, Vol. 01 Project Number: 4769992256

Project Scope: UL Listing to the following standard(s):
UL 61010-1, 3rd Edition, May 11, 2012, Revised July 19, 2019, CAN/CSA-C22.2 No. 61010-1(2012-05), 3rd Edition, with revisions through July 19, 2019

Subject: Notice of Project Completion with Initial Production Inspection

Dear Alex McEachern:

UL has completed the investigation under the above project and confirmed compliance of your product(s) with UL requirements. We appreciate that you have a choice of certification providers and thank you for choosing UL.

Before products bearing the UL Mark can leave the manufacturing location, an Initial Production Inspection (IPI) must be successfully completed by a UL representative at the manufacturing location(s) noted below. You are required to send a copy of this letter to each of these manufacturing location(s).

List of all manufacturing locations (please contact us if any are missing):

Manufacturing Facility(ies): Same as Applicant

Party Site:
Subscriber No:
Factory ID: None
UL Contracting Party: UL LLC

Inspections at your production facility will be conducted under the supervision of:

Area Manager:	Daniel Deatherage
IC Name:	UL Inspection Center Northwest Area Office
Address:	2800 NW Lake Rd, Camas, WA, United States, 98607
Contact Phone:	360 397 8613
Email:	Dan.Deatherage@ul.com

The IPI is a check on the means that the manufacturer has in place to produce a product in accordance with applicable requirements. **A MANUFACTURER MAY NOT SHIP PRODUCTS WITH THE UL MARK UNTIL THE IPI HAS BEEN SUCCESSFULLY COMPLETED.** Instructions for conducting the IPI will be sent to the UL inspection center(s) serving the manufacturing location(s). The UL inspection center will contact the manufacturing location to arrange the IPI, or you may contact the UL inspection center to discuss the scheduling of the IPI.

The Follow-Up Services Procedure covering your product(s) will typically be provided by UL within 10 business days. Any information and documentation provided to you involving UL Mark services are provided on behalf of UL LLC (UL) or any authorized licensee of UL.

Certification includes both the GridSweep instrument and the manufacturing facility.

Follow-up Service Inspection Report
E523261D1211001155801

INSPECTION DETAILS

Date:	2021-10-01	File Number.:	E523261
Responsible Office:	Northbrook	Volume:	01
Inspection Center:	909	CCN:	PICQ
Product Type:	Laboratory-use Electrical Equipment	UL Rep Name:	Donte Anderson
Deliverable Type:	Listed	UL Rep ID:	23581
Party Site Number:	2656952	Subscriber Factory No.:	
Manufacturer Name:	McEachern Laboratories Inc	Factory Rep Name	1 - Alex McEachern
Manufacturer Address:	1517 Court St Alameda, CA 94501	Factory Rep Phone:	510-295-8264
		Factory Rep Email:	alex@mceachern.com
Nature of visit:	Initial Production Inspection	Sample Status:	Samples not required
UL Marks Used?	Yes	UL Marks Removed?	No
Variation Notice Issued?	No	Inspection Conducted Remotely?	Yes
Comments After Submission:			

PRODUCT DOCUMENTS/PRODUCTION READY VISIT

Model	Product	Section	Multiple Listed
GS1	GridSweep	D1000	No

SAMPLE DOCUMENTS

If samples are required to be sent to UL, indicate below. If required samples are not sent, explain in the Comments area.

No Samples			
Additional Comments			

In addition to the requirements specified in the applicable UL Services agreement and Follow-Up Service Procedure, UL further defines responsibilities, duties and requirements for both manufacturers and UL representatives in the document titled "UL Mark Surveillance Requirements" that can be located at www.ul.com/fus, and in accordance with the applicable terms and conditions of the document at www.ul.com/responsibilities. Manufacturers without Internet access may obtain the current versions of these documents from their local UL customer service representative or UL field representative.

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Ready for manufacturing and safe deployment

UL listed – reasonable and prudent regard for safety

- GridSweep instrument itself
- GridSweep documentation
- GridSweep manufacturing location

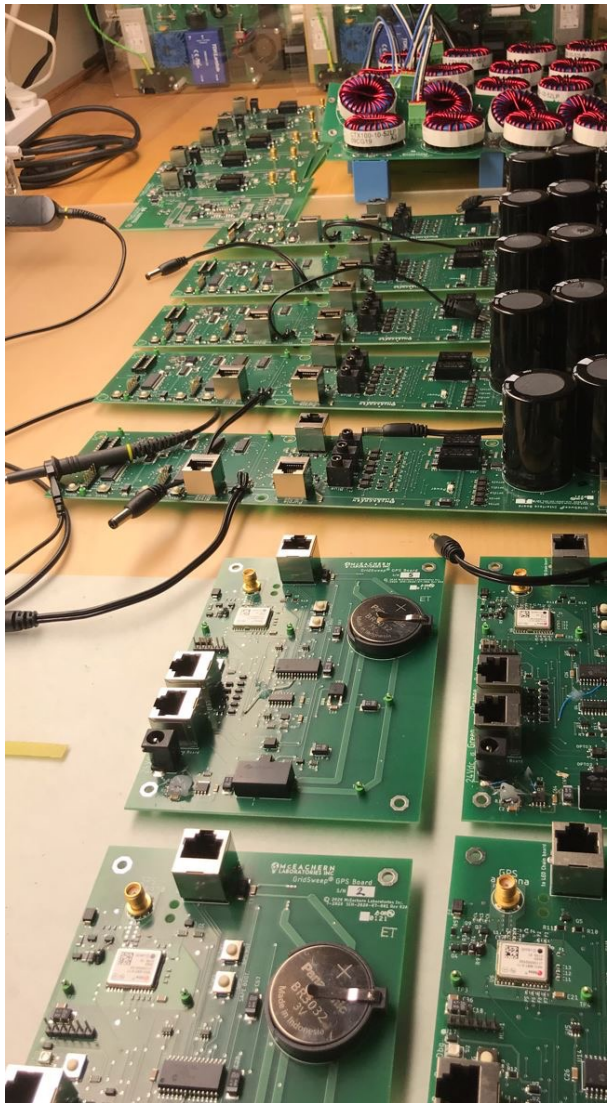
FCC – complies with U.S. emissions and immunity requirements

CE – certified for deployment in European community

- Safety regulations
- Emission and immunity regulations
- Documentation regulations
- End-of-life disposal regulations

GridSweep® instrument design is now ready for legitimate deployment in offices, warehouses, etc.

2022: Production of 10 GridSweep instruments complete



10 GridSweep instruments – production complete

McEACHERN LABORATORIES INC

Manufacturing Certificate 2022-01-31

Laboratory temperature and humidity: 16.5°C 62%RH

Procedures used:

- "GridSweep® Safety Test Procedures" Revision 02, issued 2022-01-13
- "GridSweep Final Test and Cal Procedure" Revision 02, issued 2022-01-13

NIST-Trace Equipment Used for this Certificate:

Manufacturer	*Model*	*Serial Number*	*NIST-trace Certificate Number*	*Cal Due Date*
Fluke	8846A Lab Bench Multimeter	3960004	ANMAR 91646097	24-Jun-2022
GW Instek	GPT-9803 HiPot Tester	GES150213	NT0004	14-Sep-2022
McE Labs	ECT1 40-amp Earth Current Tester	100001	NT0003	14-Sep-2022

Test settings and limits:

1. Hi-pot test: 2.4kV DC, 5 second ramp, 10 second hold, 2.00mA pass/fail limit.
   Applied from L-N joined together, to chassis earth & GPS & serial jacks joined together.
2. Earth current: 30 amps @ 60 Hz. 4.00V rms limit.
   Applied from earth conductor input, to earth conductor output and chassis joined together.

Results:

Model	*Serial Number*	*HiPot Result at 2.4kV*	*Earth current Result at 30A*	*Voltage gain*	*Voltage offset*	*Current gain*	*Current offset*
GridSweep GS1	0001	PASS (.00mA)	PASS (0.91Vrms)	0.96366	-0.0050	0.98080	-0.0030
GridSweep GS1	0002	PASS (.00mA)	PASS (0.82Vrms)	0.96344	+0.0079	0.98467	-0.0010
GridSweep GS1	0003	(sampled to UL)	(sampled to UL)				
GridSweep GS1	0004	PASS (.01mA)	PASS (0.35Vrms)	0.96393	+0.0049	0.98557	+0.0042
GridSweep GS1	0005	PASS (.00mA)	PASS (0.75Vrms)	0.96449	+0.0031	0.98926	-0.0041
GridSweep GS1	0006	PASS (.01mA)	PASS (0.91Vrms)	0.96460	+0.0055	0.98708	+0.0000
GridSweep GS1	0007	PASS (.00mA)	PASS (0.94Vrms)	0.95786	+0.0028	0.98752	+0.0003
GridSweep GS1	0008	PASS (.00mA)	PASS (0.79Vrms)	0.95771	+0.0056	0.98470	+0.0008
GridSweep GS1	0009	PASS (.01mA)	PASS (0.77Vrms)	0.98170	+0.0052	0.98379	-0.0025
GridSweep GS1	0010	PASS (.01mA)	PASS (0.32Vrms)	0.95991	+0.0054	0.99016	-0.0038
GridSweep GS1	0011	PASS (.01mA)	PASS (0.78Vrms)	0.95876	+0.0036	0.98613	-0.0016
GridSweep GS1	0012	(sampled to UL)	(sampled to UL)				

for McEachern Laboratories Inc. https://McELabs.com

Alex McEachern 31 January 2022

McEACHERN LABORATORIES INC

NIST-Trace Calibration Certificate

Certificate Number: GS1-0005-22 Date/Time: 2022-01-31 14:35

Cal Due Date: 2023-01-31

Equipment Under Test: McEachern Laboratories Inc. GridSweep Model GS1 S/N 0005
Laboratory temperature and humidity: 21.3°C 47%RH

NIST-Trace Equipment Used for this Certificate:

Manufacturer	*Model*	*Serial Number*	*NIST-trace Certificate Number*	*Cal Due Date*
Fluke	8846A	3960004	ANMAR 91646097	24-Jun-2022

Reference meter was configured for AC voltage measurements, 3 Hz filter. Reference meter was connected L-N to output of AC source. EUT reading was the mean of 30 consecutive readings.

Other Equipment Used for this Certificate (NIST Trace not required):

Manufacturer	*Model*	*Serial Number*
BK Precision	9803 AC Power Source	462B18109

Pass/Fail NIST-trace Tests Performed:

Nominal setting	*Ref Meter Reading*	*EUT reading: Voltage*	*EUT accuracy specification: % of reading*	*EUT-Reference difference: % of reading*	*Pass / Fail*
120VAC 60.0Hz	119.838 Vrms	119.834 Vrms	±0.100%	-0.003%	PASS

Indicative NIST-trace Tests Performed:

Nominal setting	*Indicative Meter Reading*	*EUT reading: Current*	*EUT indicative specification: % of reading*	*EUT-Reference difference: % of reading*	*Indicative result*
2.0 Arms 60.0Hz	2.053 Arms	2.053 Arms	±0.500%	+0.000%	OK

As of this date, the Equipment Under Test meets the specified accuracy levels stated above.

The accuracy levels are traceable through one or more of the following: an unbroken chain of certified measurement standards to the United States National Institute of Standards and Technology (NIST) or other National Measurement Institutes (NMIs), or through the use of natural physical constants, intrinsic standards, or ratio calibration techniques.

for McEachern Laboratories Inc. https://McELabs.com

Alex McEachern 31 January 2022

Probing with GridSweep

Amplitude modulation of a load with precisely known frequency and phase allows synchronized probing with multiple instruments, different locations

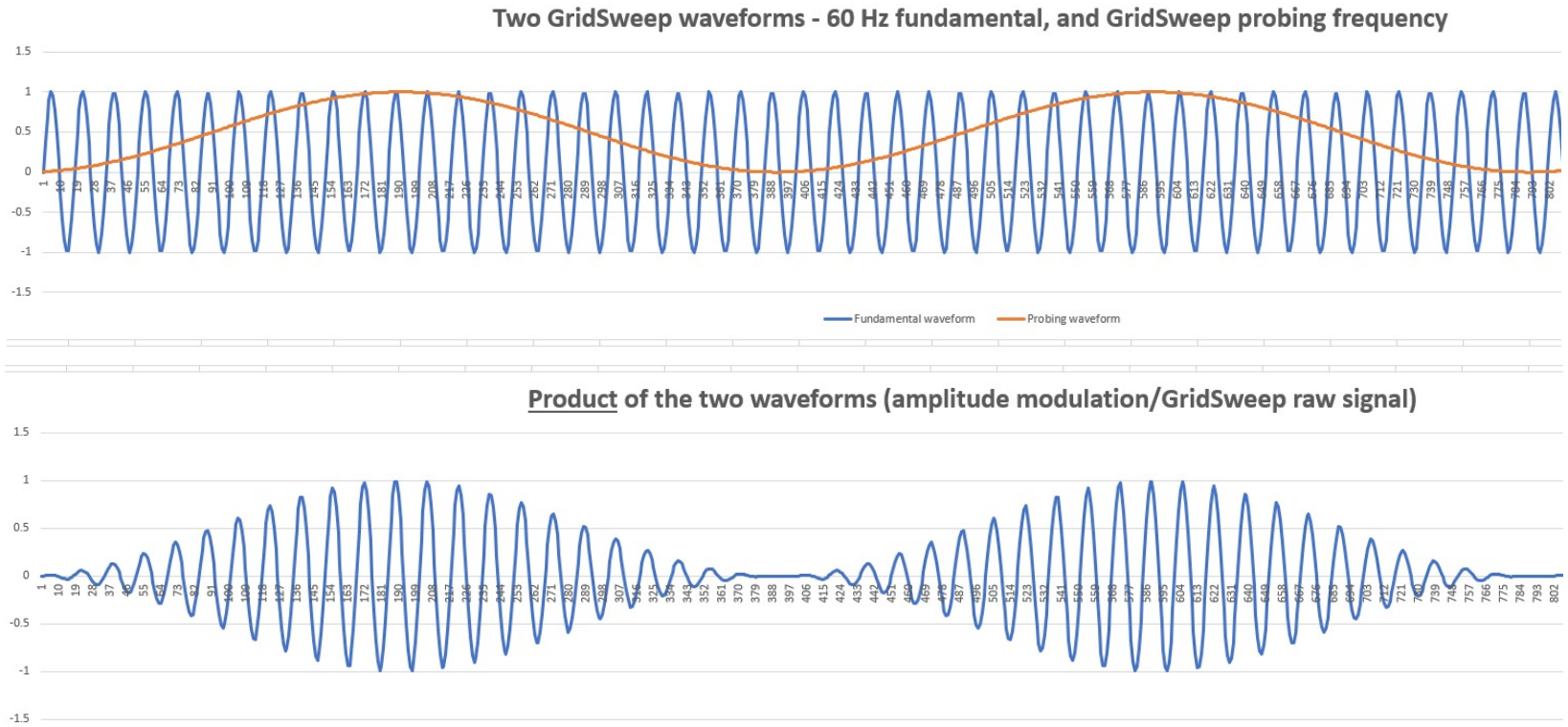
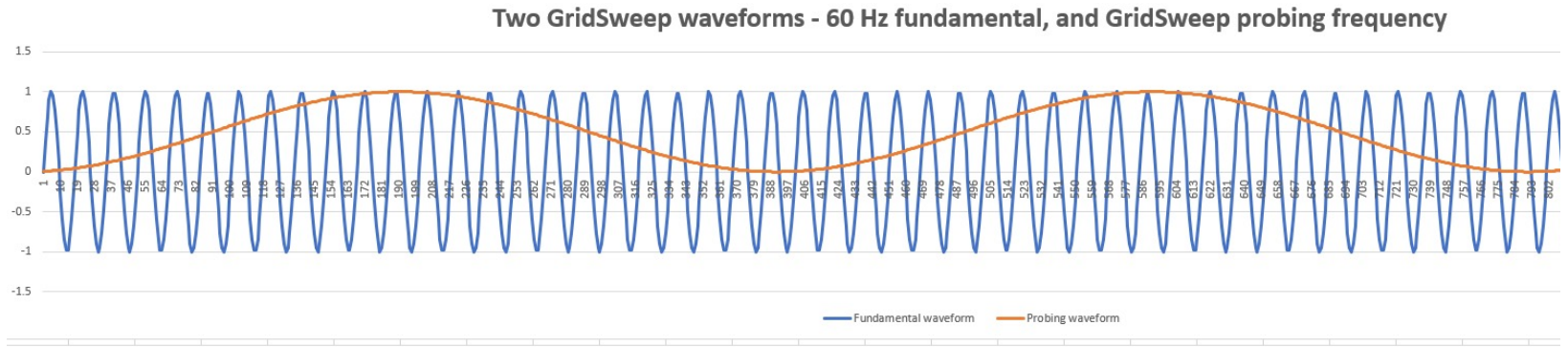
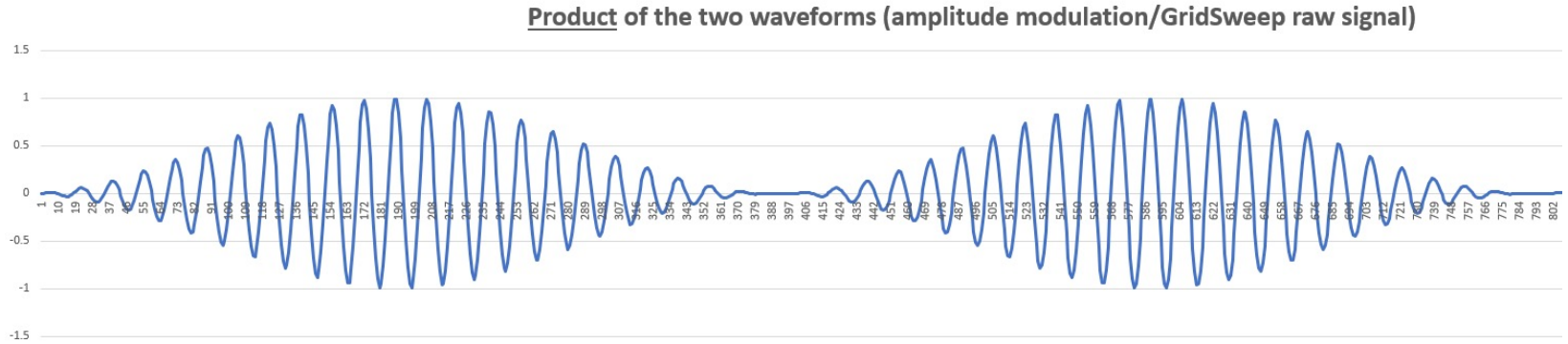


Photo: Paul Ortmann, Idaho Power

Probing with GridSweep

Amplitude modulation of a load with precisely known frequency and phase allows synchronized probing with multiple instruments, different locations





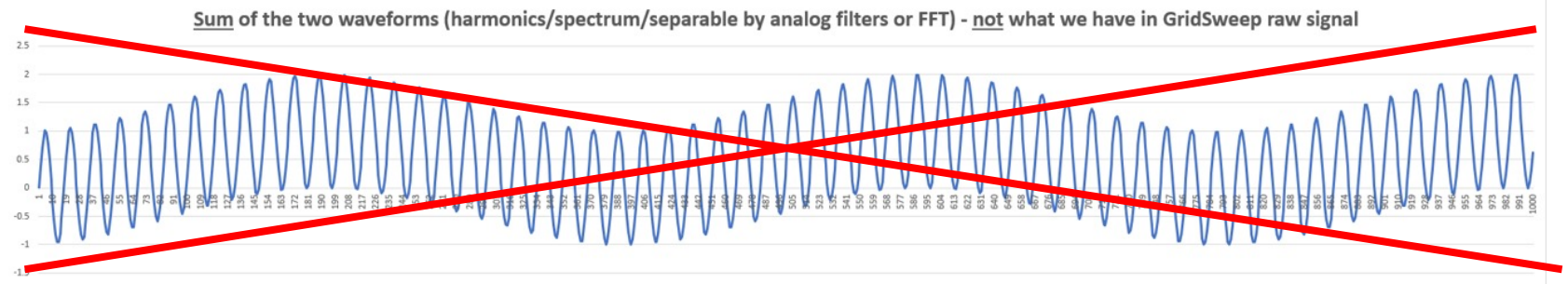
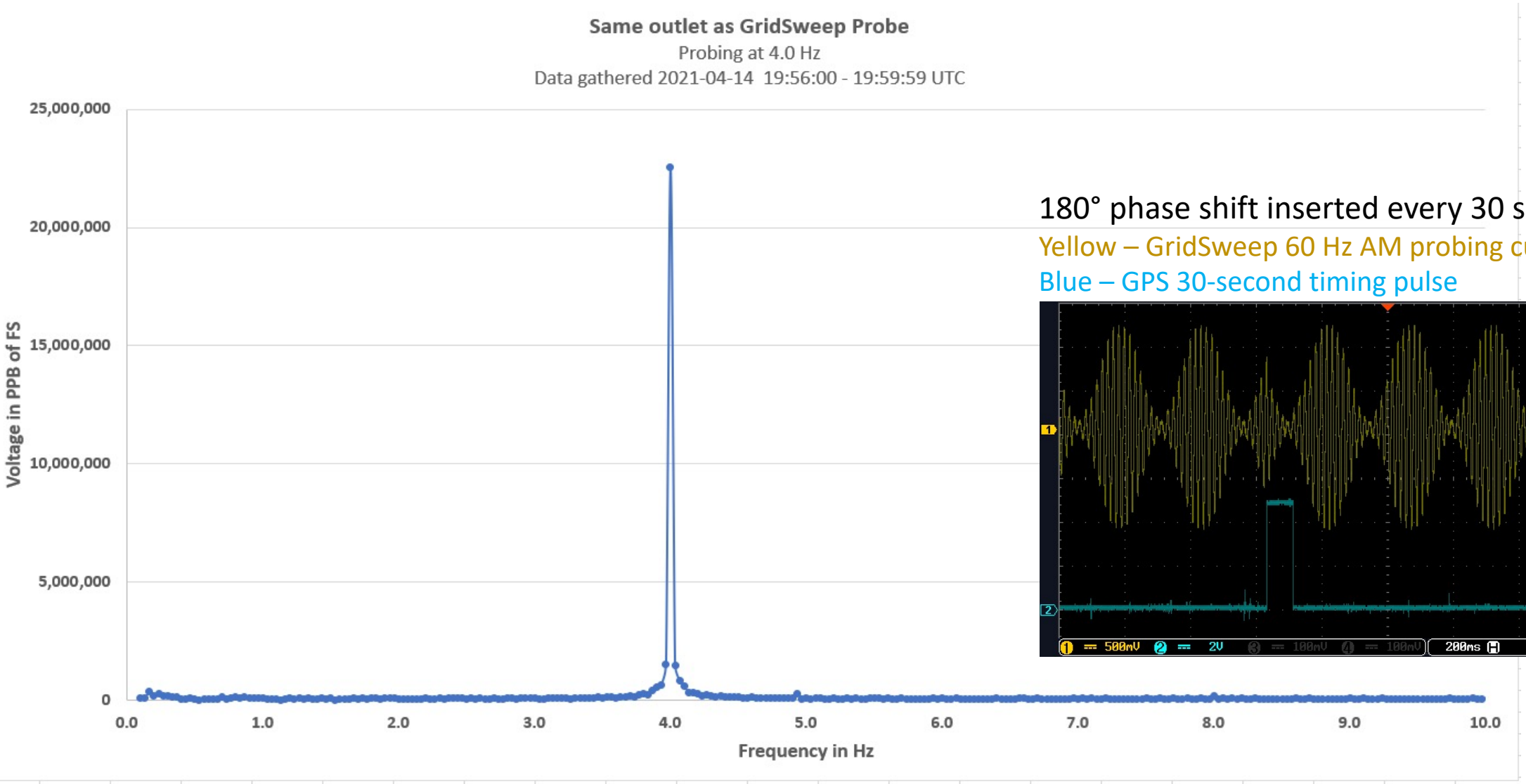


Photo: Paul Ortmann, Idaho Power

Early validation: Detect probing signal at the same outlet

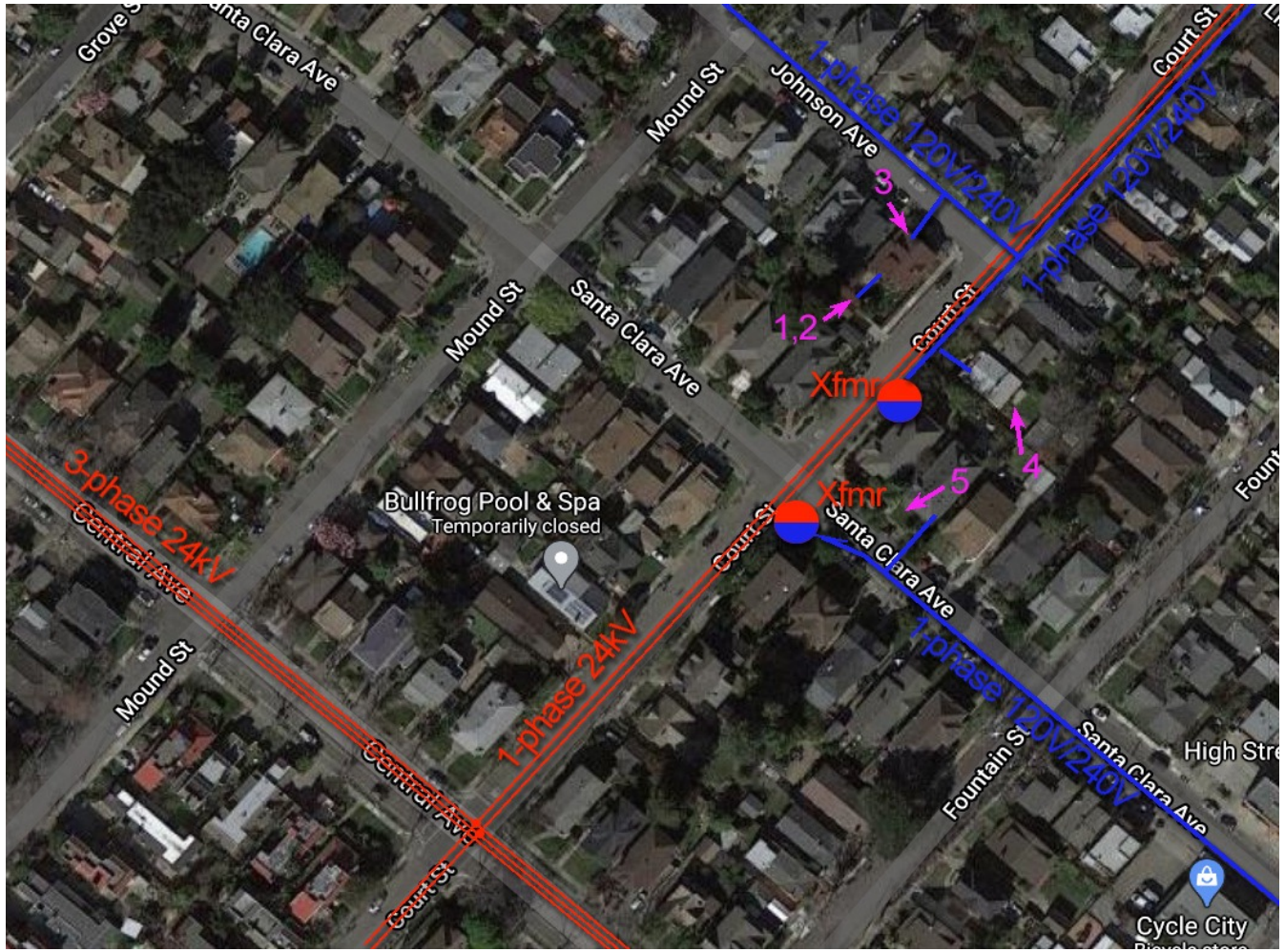


180° phase shift inserted every 30 seconds:

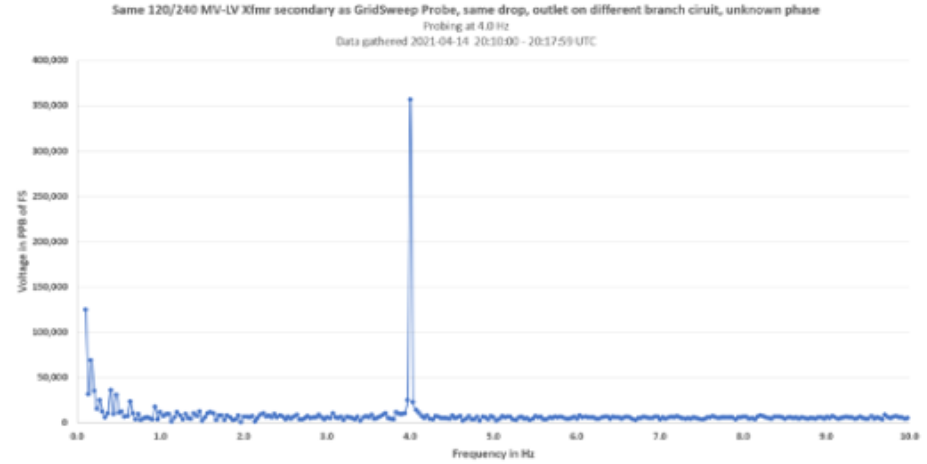
Yellow – GridSweep 60 Hz AM probing current

Blue – GPS 30-second timing pulse

Detect probing signal at different house, same transformer

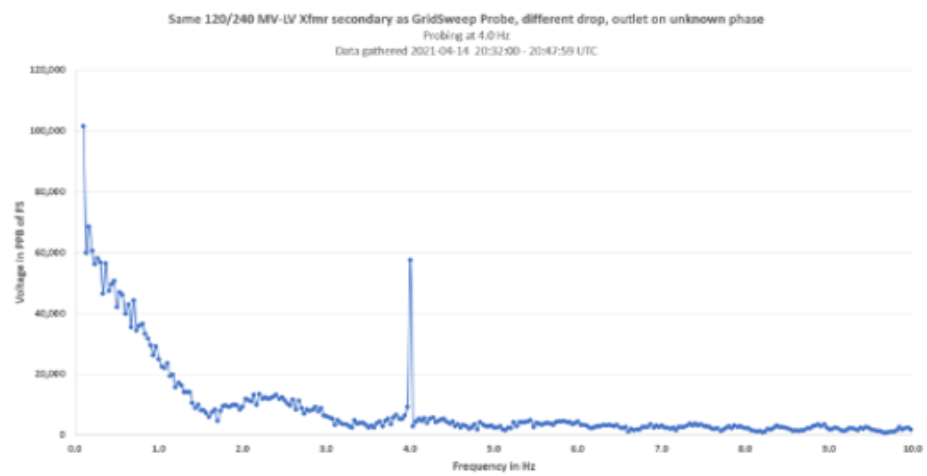


Data set 3



Recorded at a 120-volt outlet on the same service drop as the probing signal, but on a different branch circuit.

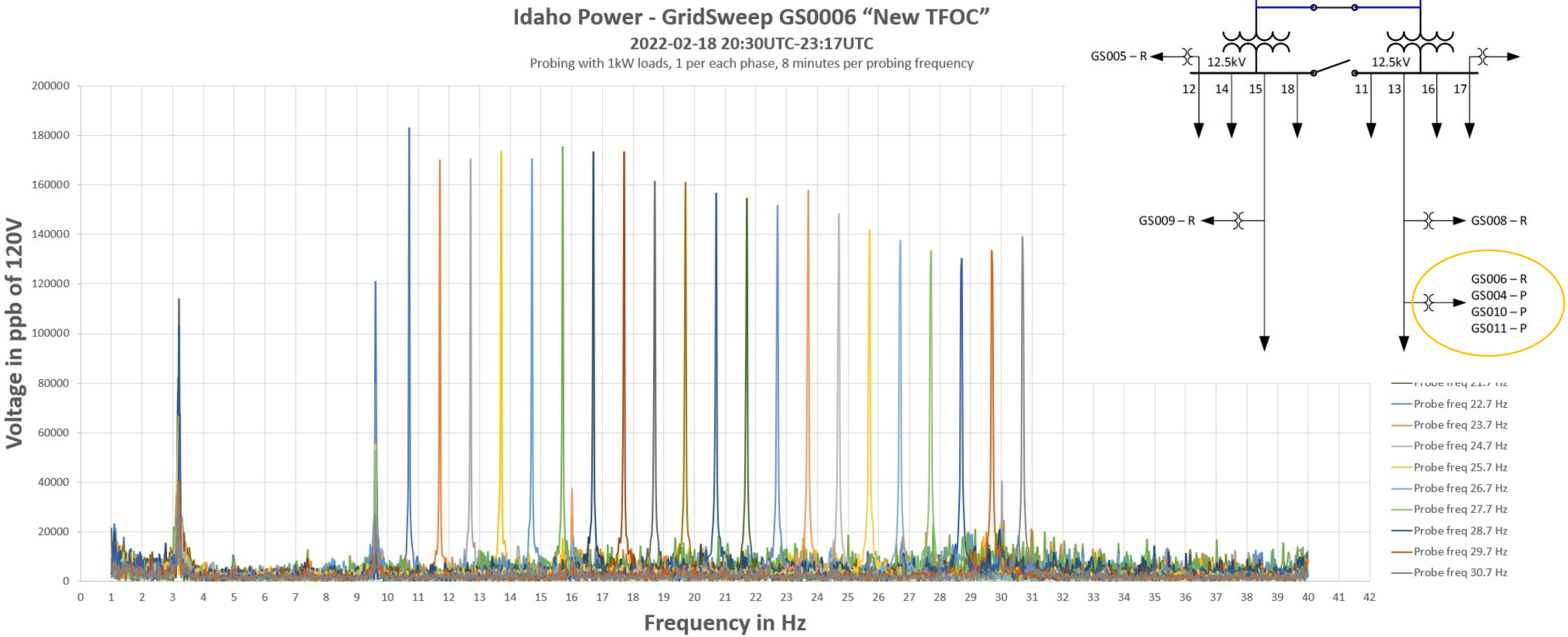
Data set 4



Recorded at a 120-volt outlet on the same MV transformer as the probing signal, but a different service drop.

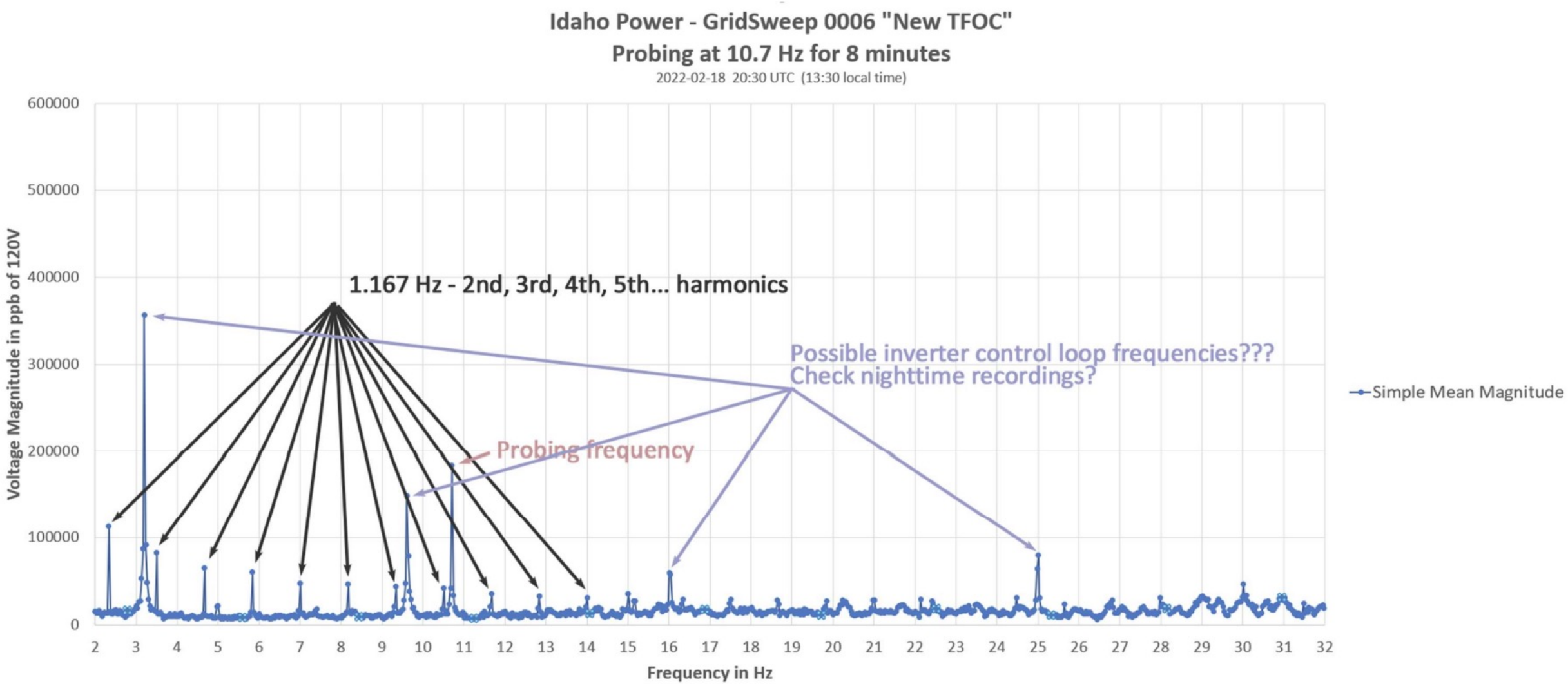
Feb 2022: 8 GridSweep instruments deployed at Idaho Power

3 instruments deployed as probes (1kW on each phase), probing at 9.7 to 30.7 Hz
5 instruments deployed as sensors at various distances



Feb 2022: 8 GridSweep instruments deployed at Idaho Power

Many puzzles in 81 GB of data...



GridSweep Experiments at Idaho Power, March-April 2022

Range	Compare ability to detect signal versus electrical separation between probe and receiver
Sweeping	Compare signal strength at different frequencies, 8 min each
Probing duration	See how detection algorithms perform when given different lengths of probing episodes, which informs how long we need to probe for
Baseline	Observe waveform for 24-hour continuous point-on-wave (CPOW) data without probing
Targeted probing	Explore distinct peak near 25 Hz from earlier sweeping experiment
Frequency alternation	Compare signal strength at different frequencies correcting for changing noise environment
Inverter test	Probing at constant frequency while turning 50-kW solar inverter on and off at hourly intervals

Coming soon: GridSweep probing in Hawai’i

How will the CPOW and probing data look different on an island grid with very high-penetration solar?

Image: RevoluSun

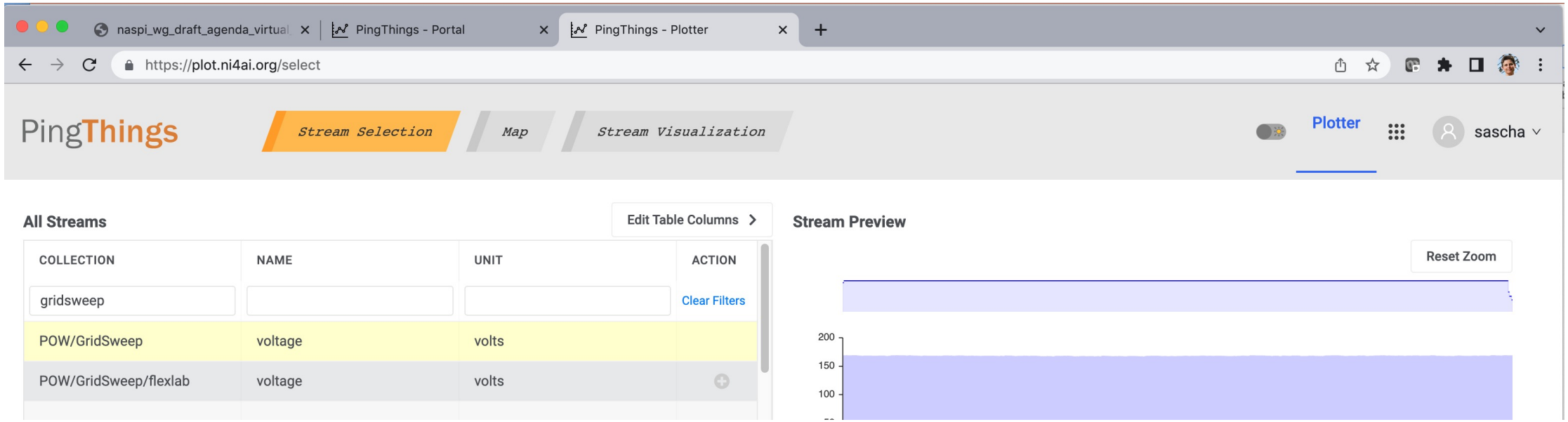
GridSweep data on ni4ai

Ask us about accessing and studying GridSweep data

Early test data accessible on PingThings' PredictiveGrid via the National Infrastructure for Artificial Intelligence on the Grid [ni4ai.org](ni4ai.org)

Coming soon: CPOW and probing data from 5 GridSweep receivers in Idaho experiments

For more information, please contact Sascha von Meier: vonmeier@berkeley.edu



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https://plot.ni4ai.org/visualize

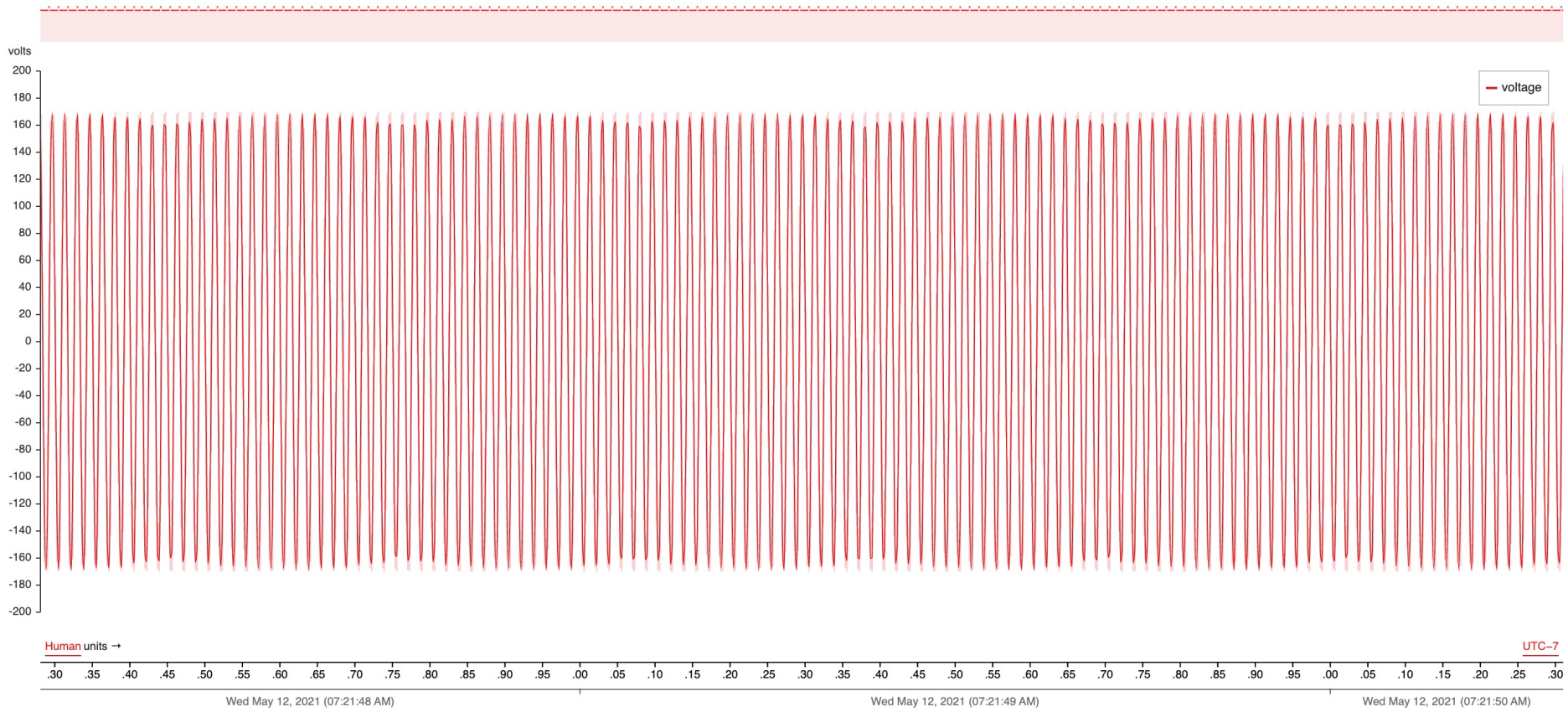
PingThings

Stream Selection | Map | Stream Visualization

Plotter

sascha

Reset Zoom



Show Legend ☑ | Save chart as image | Export to Jupyter | Export to CSV | Generate Permalink

Streams

Edit Table Columns >

COLOR	LEGEND	COLLECTION	NAME	UNIT	AXIS	ZOOM	FOCUS	SHOW / HIDE
	voltage	POW/GridSweep	voltage	volts	volts	↔		Stream: ☑ Axis: ☑

naspi_wg_draft_agenda_virtual | PingThings - Portal | PingThings - Plotter

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PingThings

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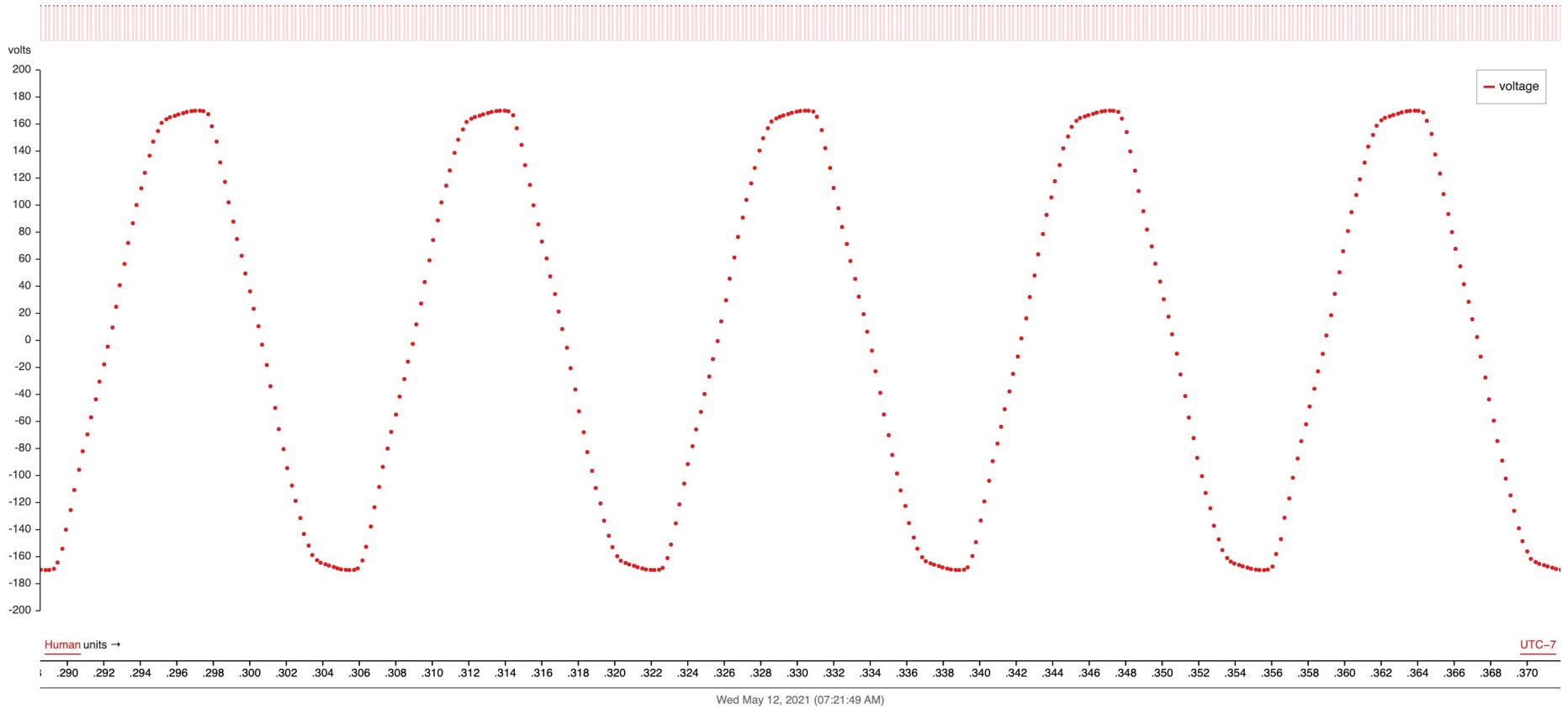

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Streams

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COLOR	LEGEND	COLLECTION	NAME	UNIT	AXIS	ZOOM	FOCUS	SHOW / HIDE
	voltage	POW/GridSweep	voltage	volts	volts	↔		Stream: ☑ Axis: ☑

Possible future applications of GridSweep

Ask us about using GridSweep in your research project

Bulk Grid Stability and Security

- Determine appropriate response to low damping ratios
- Inform dynamic transfer capability limits for bulk transmission; remedial action schemes
- Prepare to actively mitigate threatening oscillations, while recognizing benign ones
- Perform certain classes of white-hat cyber-physical attacks, and prototype defenses against them

System and Device Models

- Confirm/correct grid stability models with empirical measurements
- Calibrate the response curves of in-situ PT's and CT's to increasing harmonics
- Measure and validate synthetic inertia; provide observability of inverter-based generation

Control

- Improve interactions between traditional generator droop controls, and modern inverter controls
- Measure hidden control-loop parameters of inverters, individually or in aggregate
- Inform inverter control settings to prevent inadvertent common-mode failures and loss of generation
- Inform management strategy for controllable loads, such as EV chargers
- Provide hard-data rationale for inverter interconnection limits if and when necessary

Questions?

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