Overview of Distribution Level Synchronous Measurement Applications

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FNET GridEye

Center for Ultra-wide-area Resilient Electric Energy Transmission Network (CURENT)

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Rensselaer Polytechnic Institute · Tuskegee University

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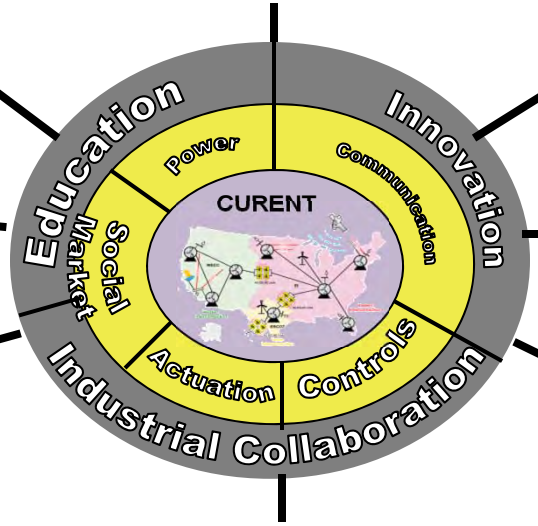

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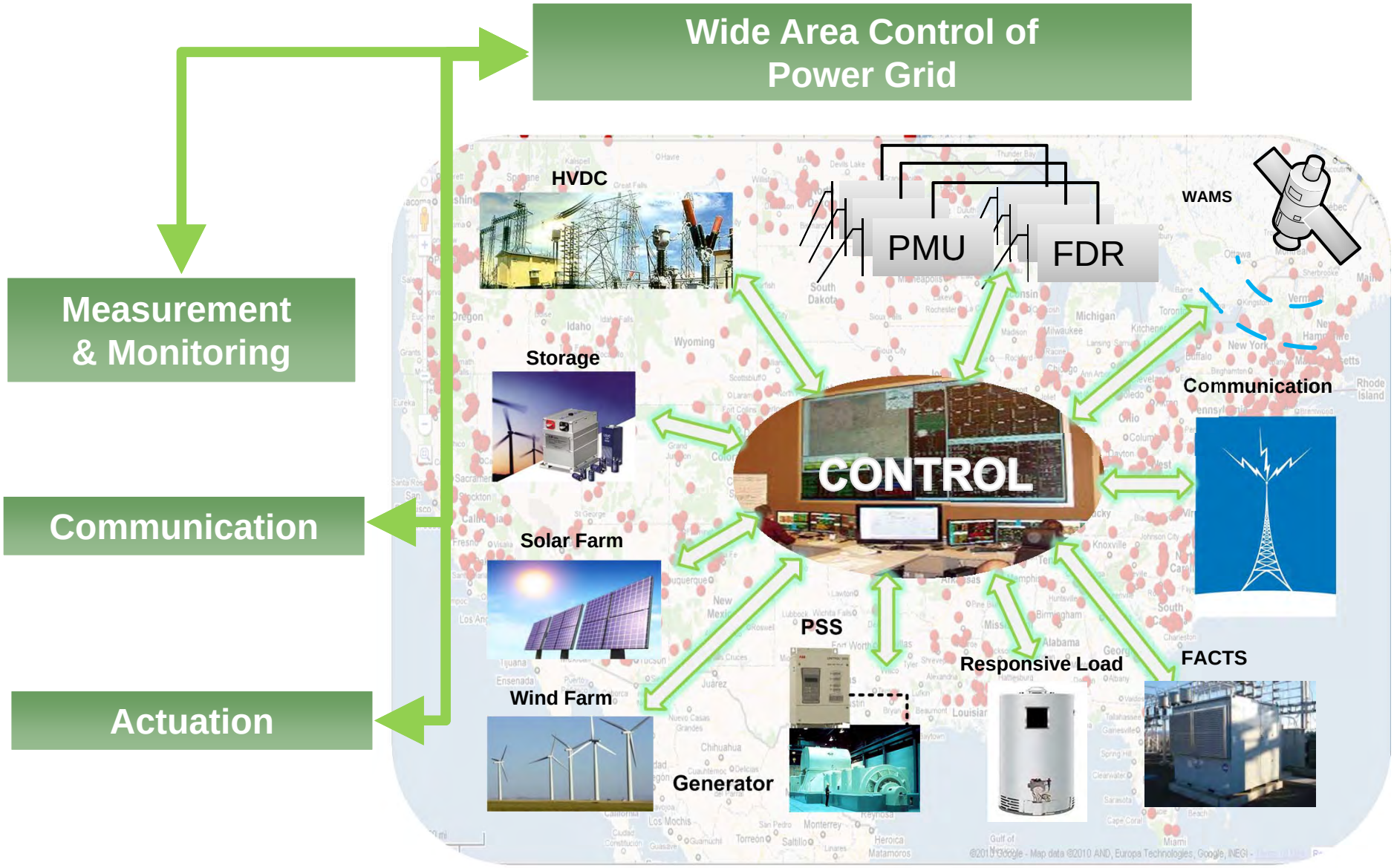
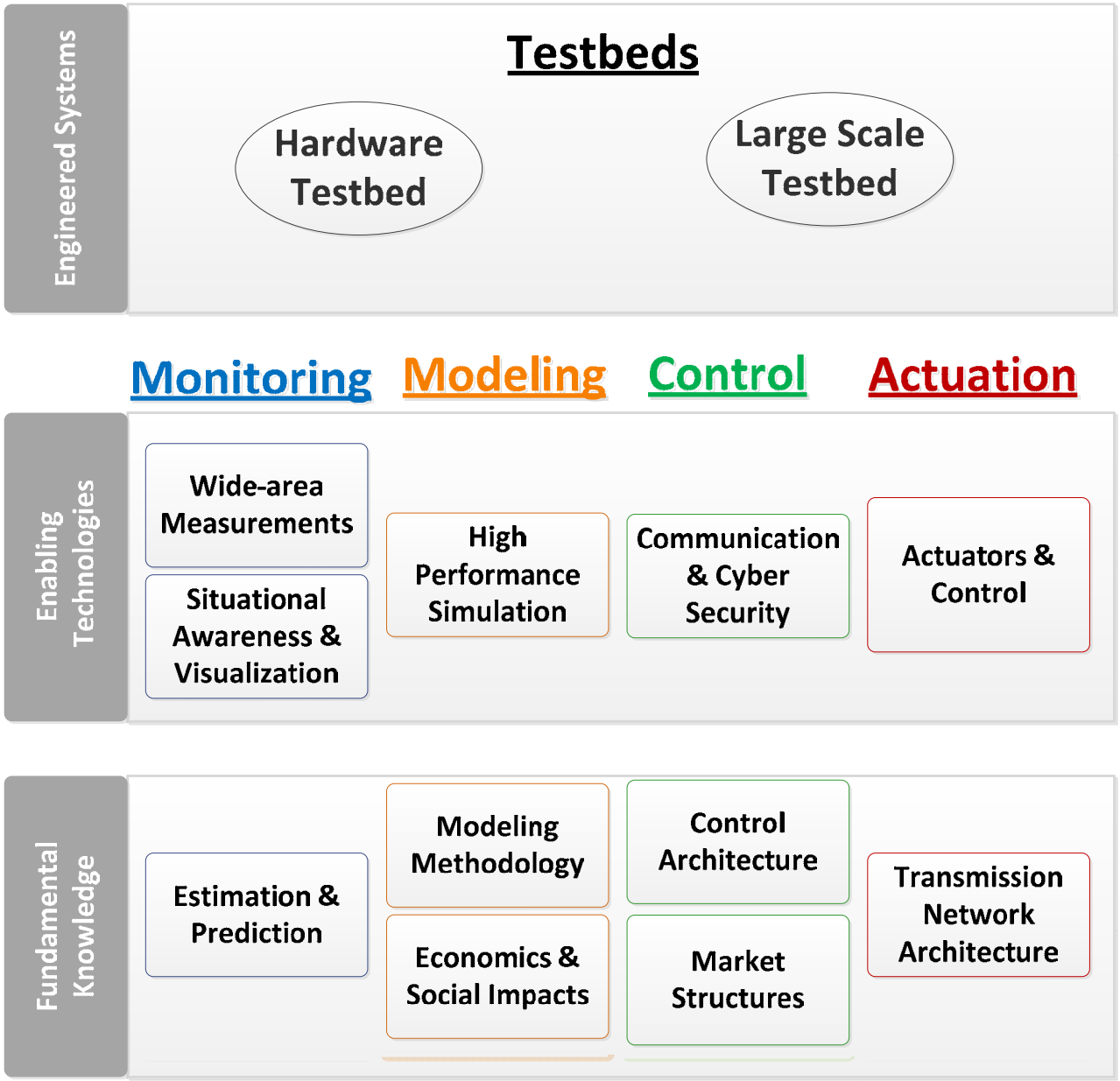
What is CURENT



ERC Three Plane Diagram



Barriers

- System complexity
- Model validity
- Multi-scale
- Inter-operability

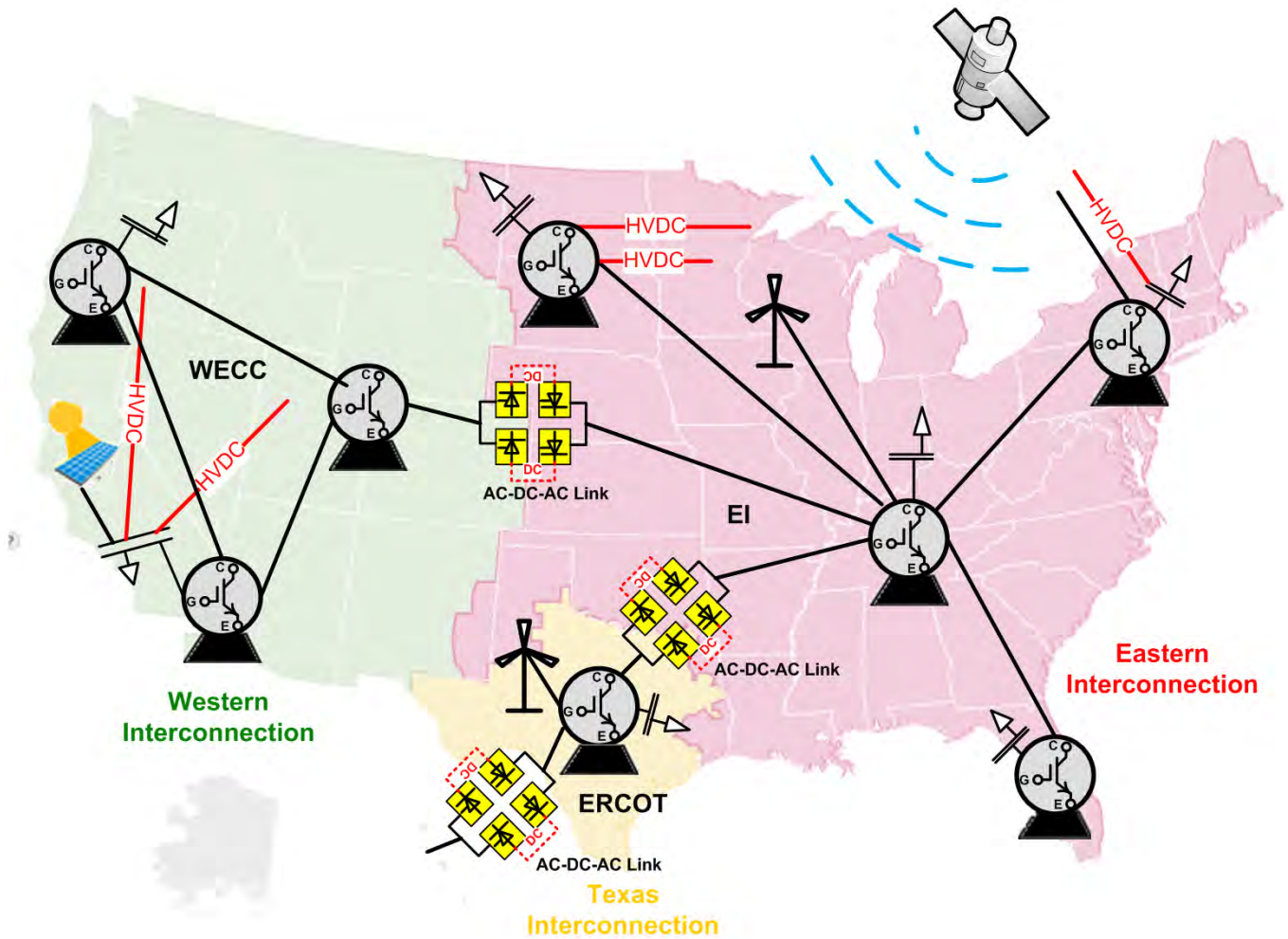
Barriers

- Dynamic measu. accuracy
- Cyber security
- Actuation & control limitation
- Poor system visibility

Barriers

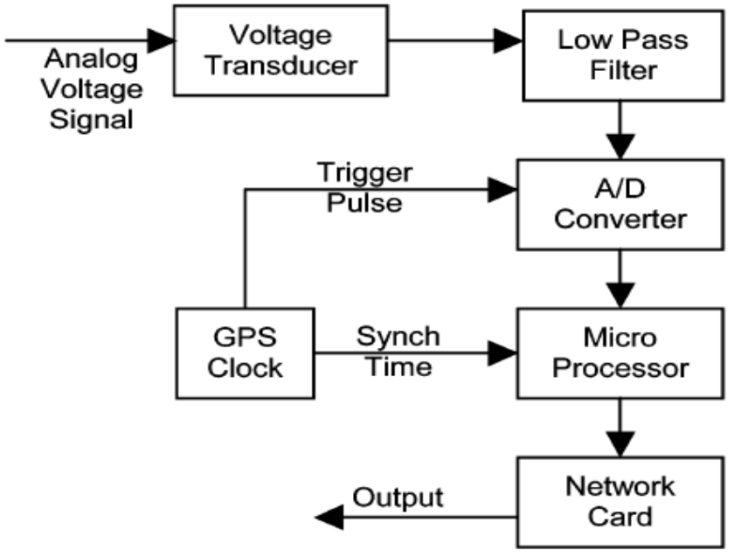
- Lack of wide-area control schemes
- Inflexible transmission systems
- Investment incentives
- Consumer participation

Testbeds to emulate wide-area grids



Hardware representation of dynamic cluster

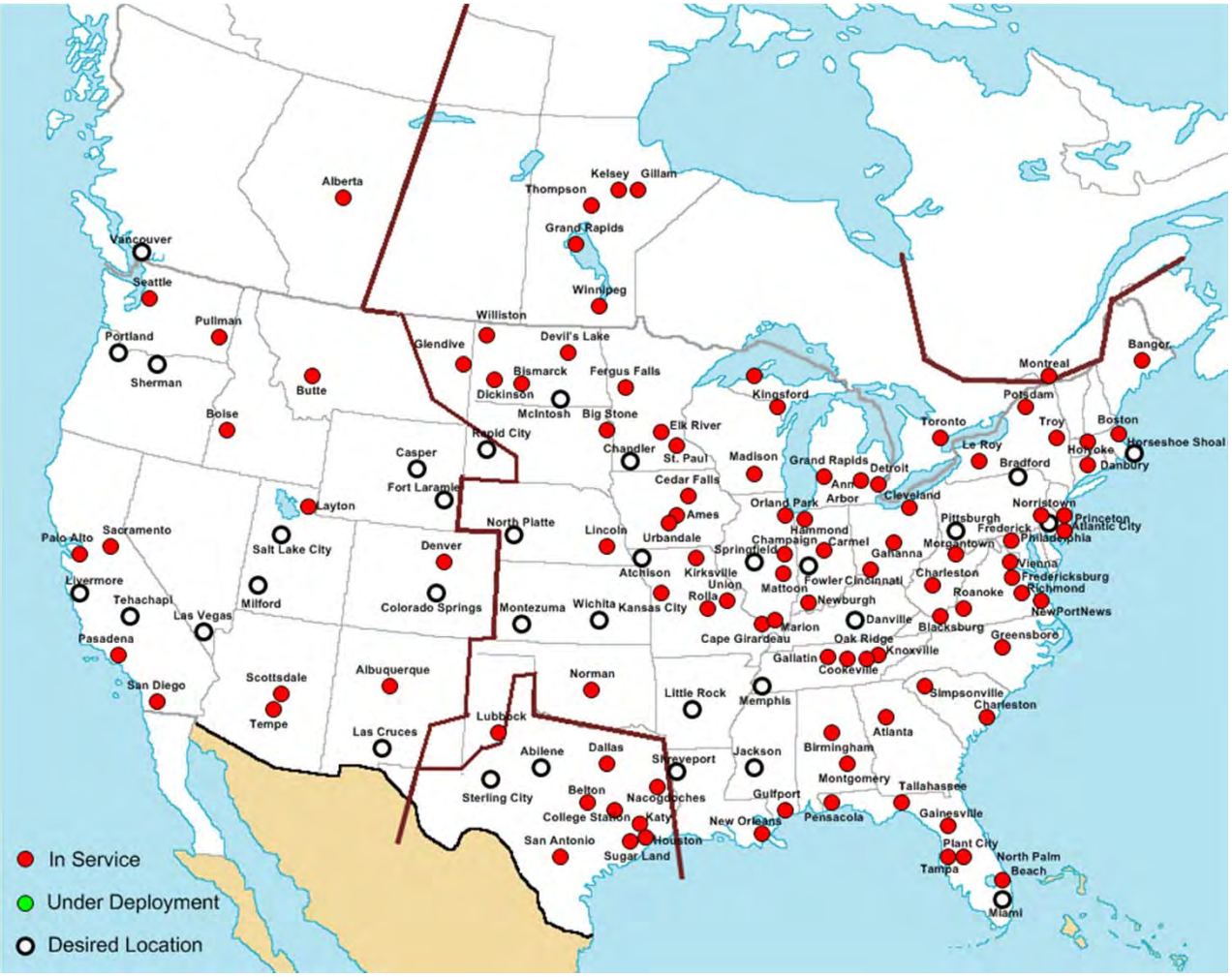
FDR Structure



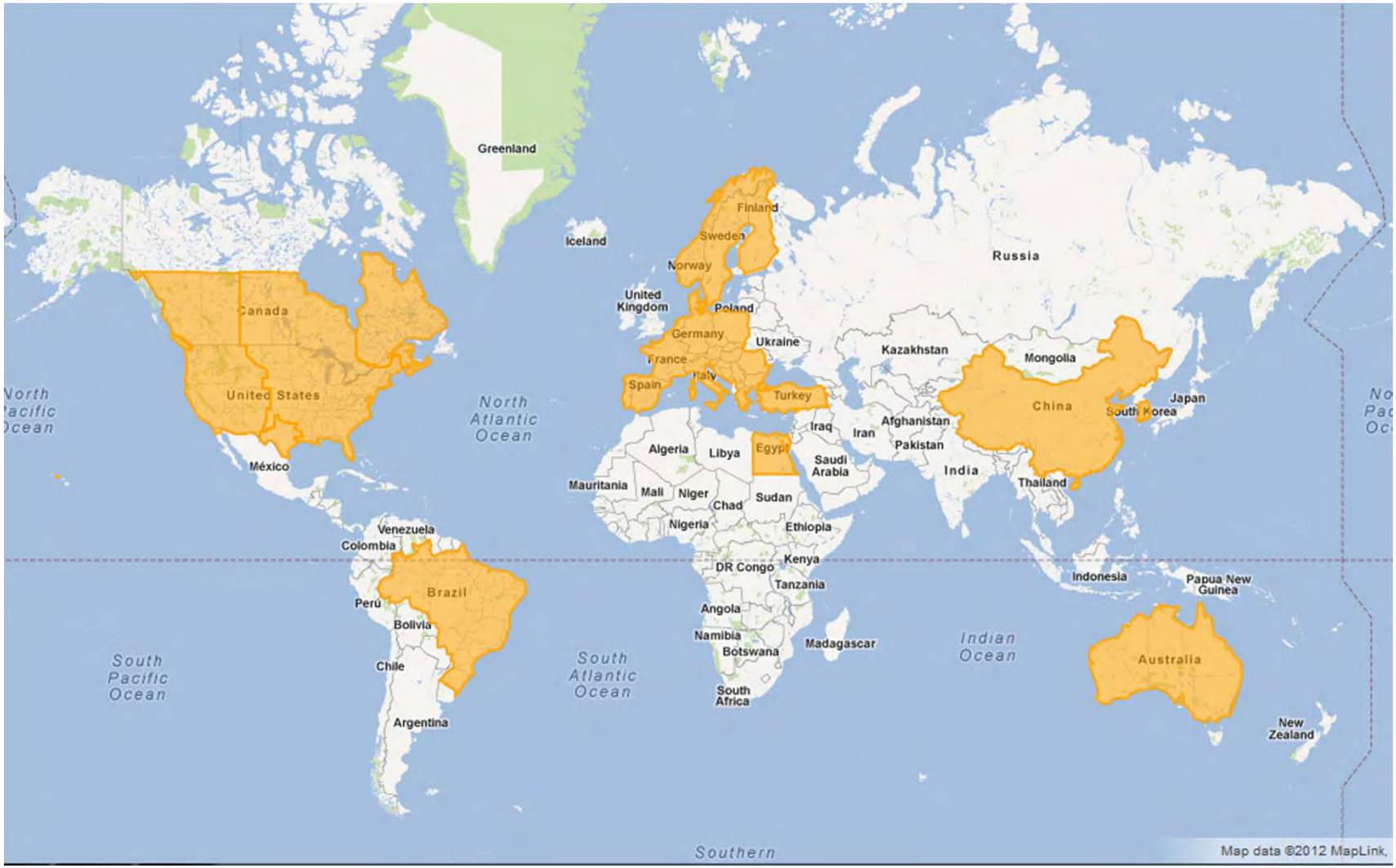
- The voltage transducer takes an analog voltage signal from an 110V wall outlet
- The voltage, angle, and frequency computed by each FDR is synchronized by the GPS time reference.
- Data transmitted to Servers at UTK and ORNL

FNET GridEye

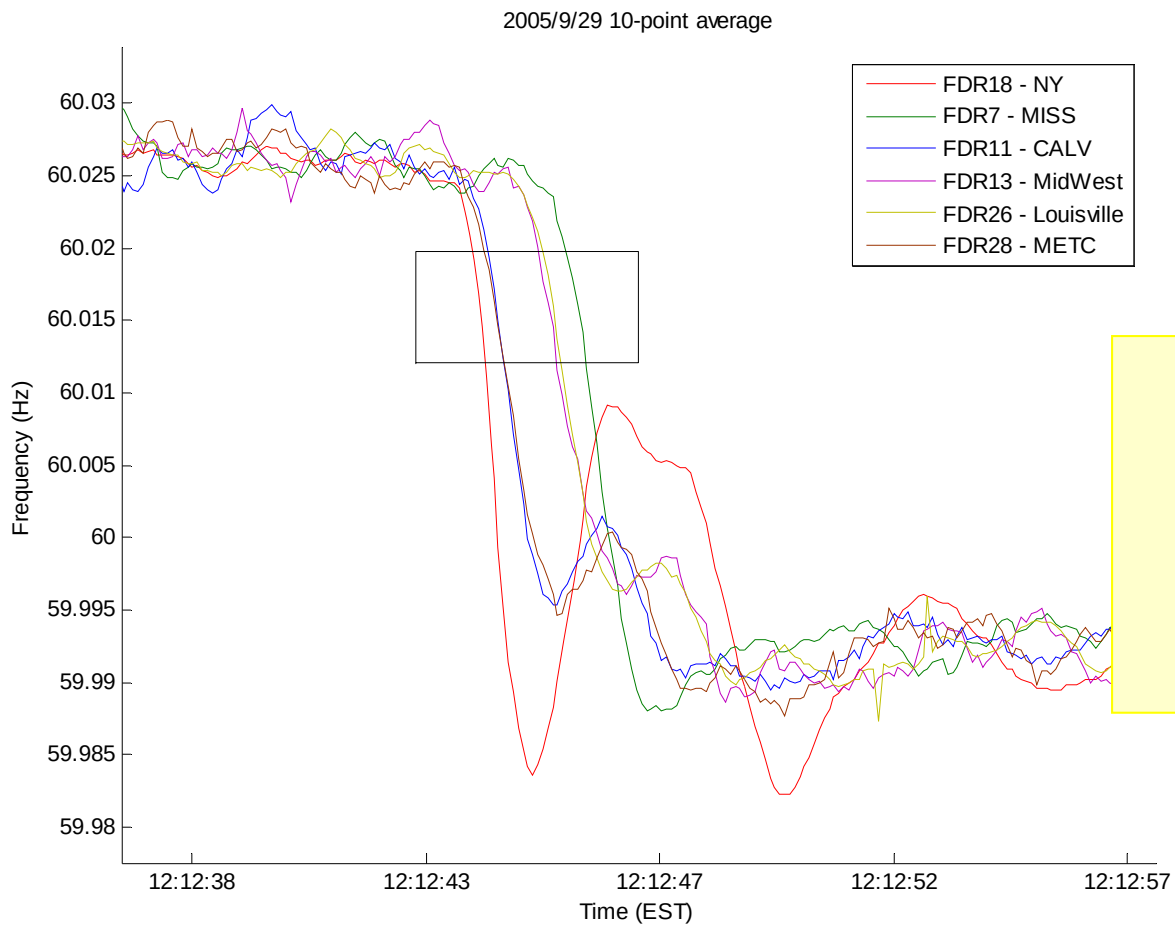
Partial list of frequency disturbance recorder (FDR) locations in US/Canada



Worldwide Deployment Map



On-line Event Location

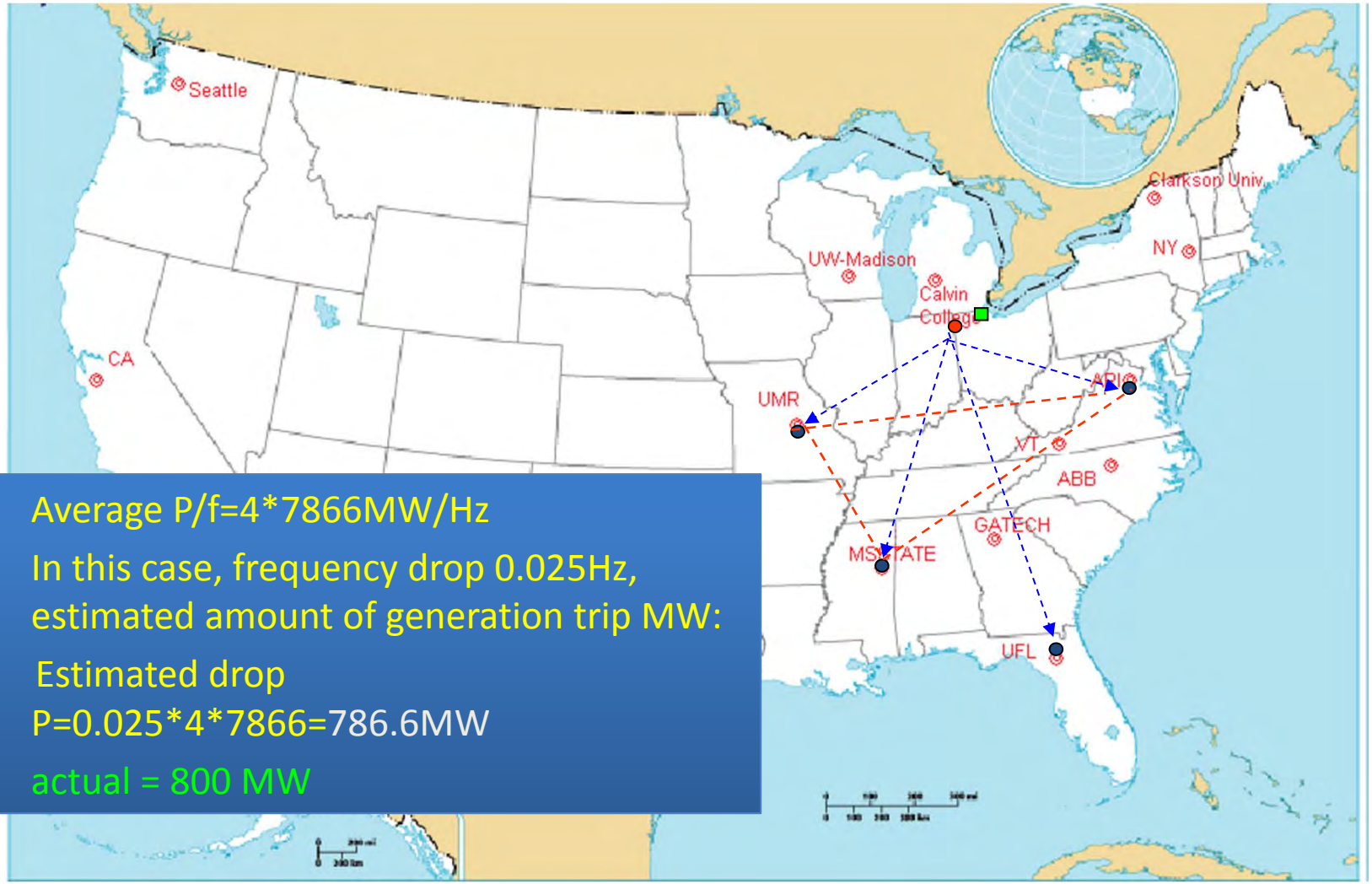


A US Patent has been issued for using frequency "time delay of arrival" in locating the source of power system disturbances

FNET GridEye

Triangulation of event location based on data from 4 of the FNET units

Red dot estimated location, Green square is actual location



- Average P/f=4*7866MW/Hz
- In this case, frequency drop 0.025Hz, estimated amount of generation trip MW:

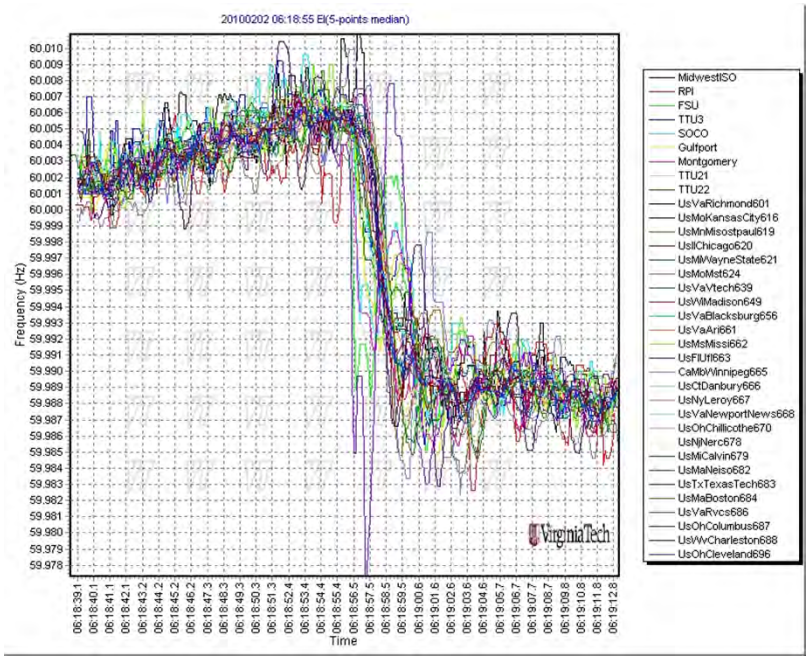
  Estimated drop P=0.025*4*7866=786.6MW
- actual = 800 MW

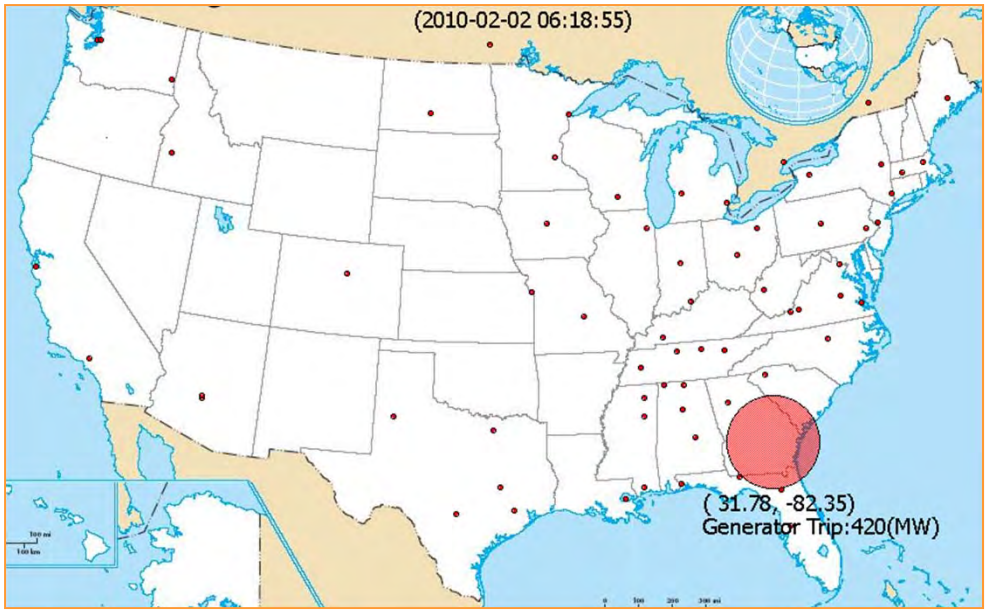
FNET GridEye

Sample automatic event alert

Event Estimation:
420MW EI Generator Trip at 06:18:55UTC, on 02/02/2010 near Edwin I Hatch power plant (SERC).
(Appling,GA 31513; Latitude: 31.7837, Longitude: -82.3486)

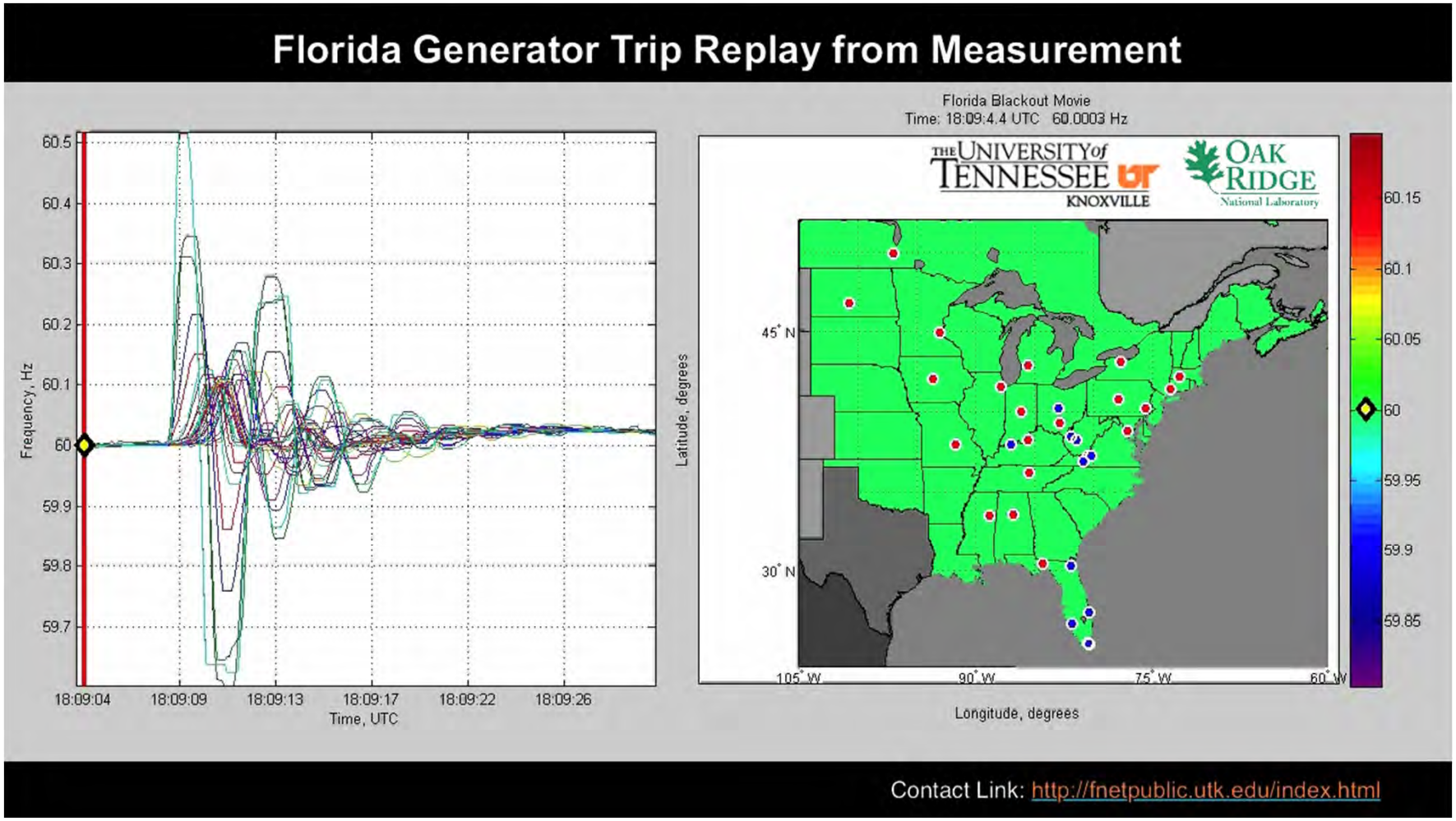
PLEASE KEEP THIS INFORMATION CONFIDENTIAL.





FNET GridEye

Disturbance Propagation Playback
FNET and PMU measurements 2-26-08

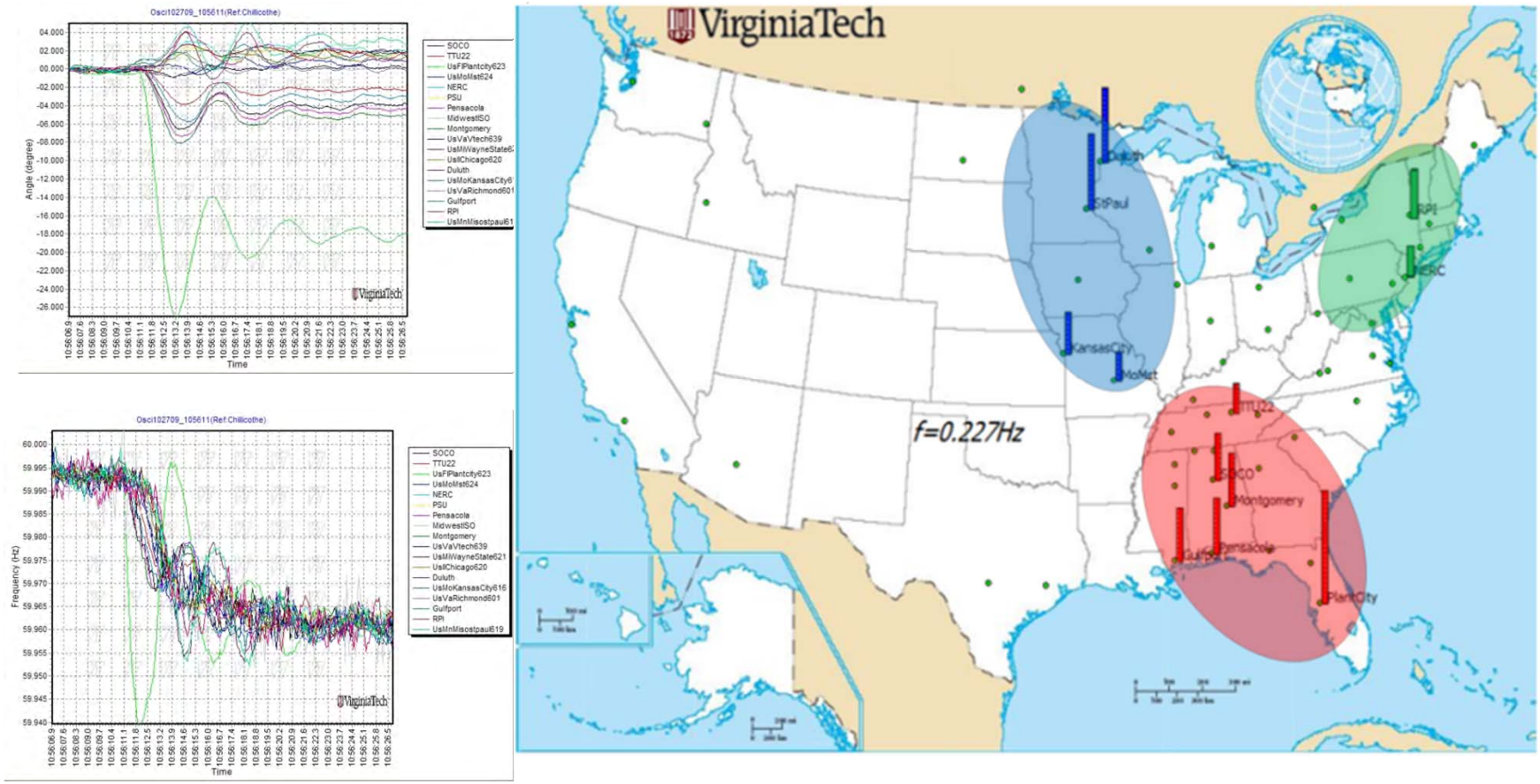


FNET GridEye

Wide area oscillation detection

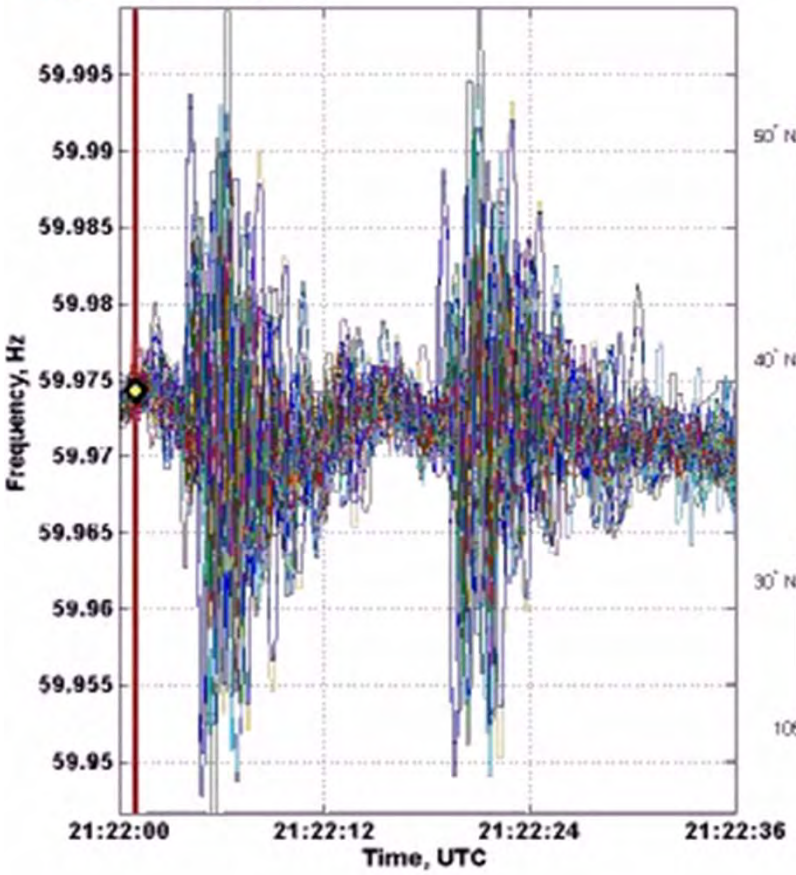
Three area oscillates

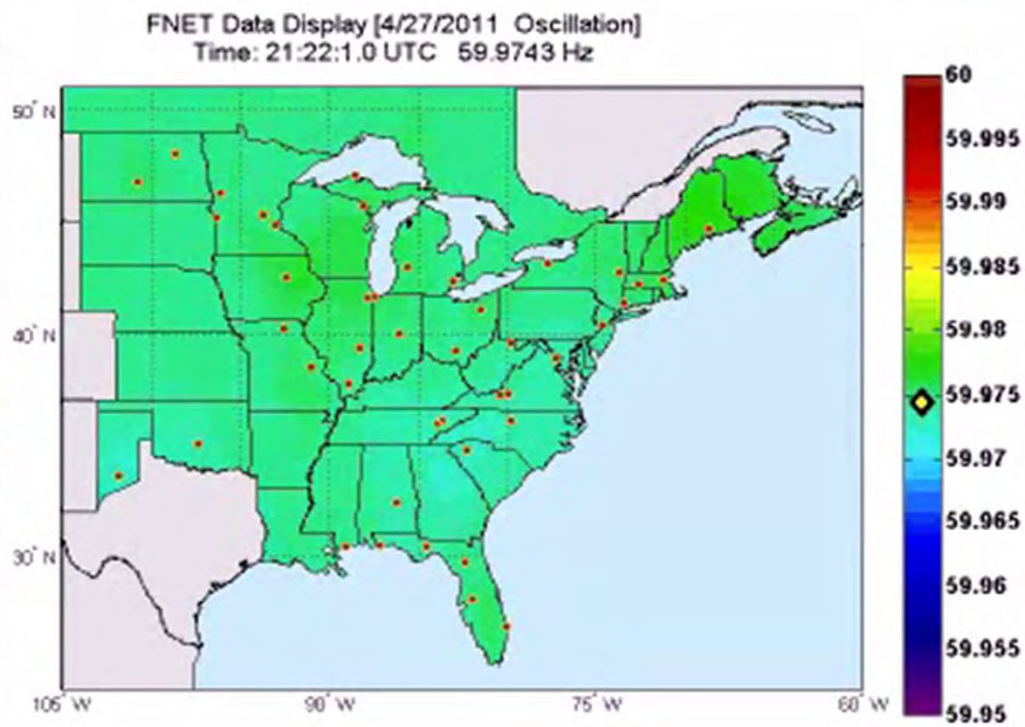
10/27/2009 10:56:11 UTC *Frequency: 0.227Hz*



FNET GridEye

Frequency Disturbance Propagation





Automatic FNET Oscillation Report

InterConnection: EI
Event Date&Time: 2012-01-10 20:27:49 UTC
Possible Event Type: Generation Trip

Basic Oscillation Magnitude information:

FDRs with Largest Negative Amplitude Oscillation

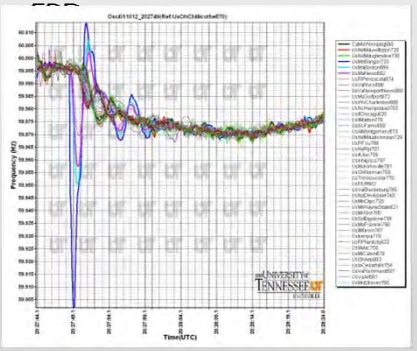
FDR Name	Mag (Deg)	Time(UTC)
UsMeBangor733	-37.1440	20:27:50.4
UsMaBoston684	-17.3893	20:27:50.7
UsMaNeiso682	-14.0546	20:27:50.8

FDRs with Largest Positive Amplitude Oscillation

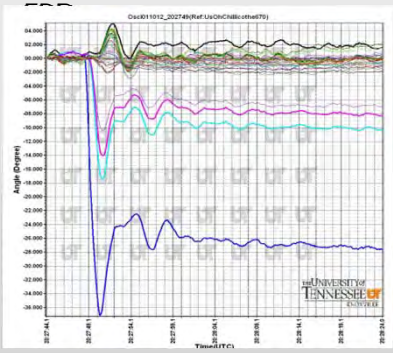
FDR Name	Mag (Deg)	Time(UTC)
CaMbWinnipeg665	-37.1440	20:27:50.4
UsNdMduwilliston726	-17.3893	20:27:50.7
UsNdMduglendive730	-14.0546	20:27:50.8

Event Data Plot:

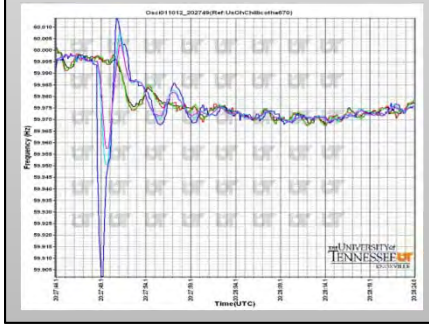
Frequency plot of All FDR



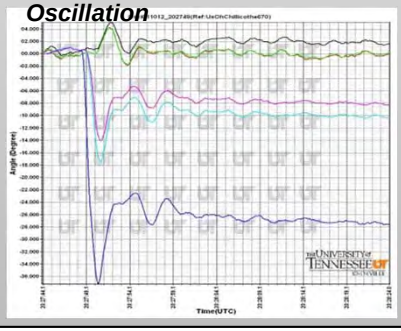
Relative Angle Plot of All FDR



Frequency Plot of FDRs with Largest Amplitude Oscillation



Relative Angle Plot of FDRs with Largest Amplitude Oscillation



Oscillation Mode Shapes (Using Matrix Pencil algorithm):

Dominant Frequency (Average): 0.2083 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsFlPensacola674	0.2040	15.518	159.0175	3.6646
UsMsGolfport672	0.2030	19.188	163.0663	4.8065
UsNcHampstead753	0.2240	3.332	113.0011	0.4082
UsAlMontgomery673	0.2035	10.737	159.6891	2.4108
UsFlFsu786	0.2047	13.560	162.7411	3.4397
UsIlUiuc755	0.2363	14.910	122.1164	1.0794
UsMoKirksville781	0.2049	19.227	-178.6252	2.8971
UsFlUfl663	0.2017	7.959	157.0381	2.6968
UsMnOtpc720	0.2134	31.448	165.1331	8.3357
UsSdBigstone739	0.2013	37.197	-170.4295	10.1426
UsMoFranklin756	0.1951	16.417	-161.1133	2.2910
UsIlMarion767	0.1938	17.718	-162.6550	2.0958
UsInImpa710	0.2363	9.562	119.6553	0.4169
CaMbWinnipeg665	0.2445	19.824	107.9509	4.1456
UsFlPlantcity623	0.2023	8.338	163.2294	3.4849
UsIaCedarfalls754	0.2230	36.554	161.3659	11.4422
UsVaNewportNews668	0.2027	29.723	9.0696	1.3100
UsNyRpi707	0.1933	20.371	26.0049	5.6132
UsMaNeiso682	0.1941	18.727	13.8098	6.6114
UsMeBangor733	0.1900	28.571	32.8401	17.5212
UsMiWayneState621	0.1956	20.373	14.2555	1.6029
UsMaBoston684	0.2018	20.823	-0.7596	9.3200
UsVaRichmond601	0.2163	39.935	21.2929	2.6054
UsVaAri661	0.2058	23.774	-6.2736	1.8780

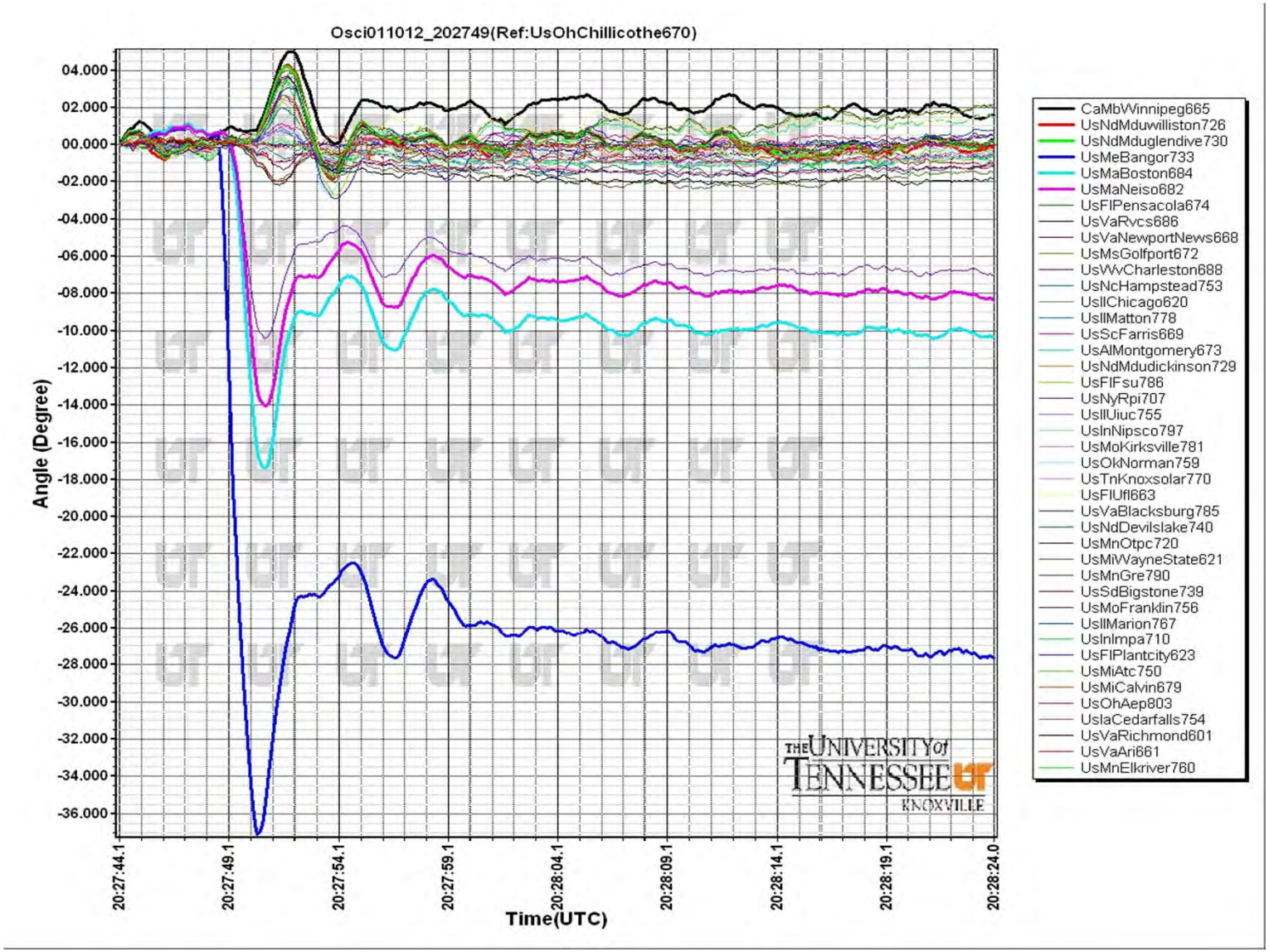
Dominant Frequency (Average): 0.1526 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsNdMduglendive730	0.1556	43.409	-116.7934	7.5853
UsNdMdudickinson729	0.1589	44.261	-118.1615	8.1313
UsNdDevilslake740	0.1575	46.382	-116.8440	8.5509
UsMiAtc750	0.1261	68.201	-84.5851	5.2765
UsNdMduwilliston726	0.1552	42.586	-120.4798	8.0104
UsMnElkriver760	0.1626	53.735	-107.2545	10.6236

Dominant Frequency (Average): 0.2775 Hz

FDR Name	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude (Degree)
UsVaBlacksburg785	0.2768	19.735	22.2481	0.9861
UsMnGre790	0.2678	30.274	76.5744	9.7172
UsOhAep803	0.3156	85.402	61.0457	0.6603
UsIlChicago620	0.2497	5.498	96.7982	0.3031

Automatic Oscillation Alert



Islanding Detection – Bulk & Micro Grid

- **Case 1 (EI 09/18/2007 10:21:23 UTC)**

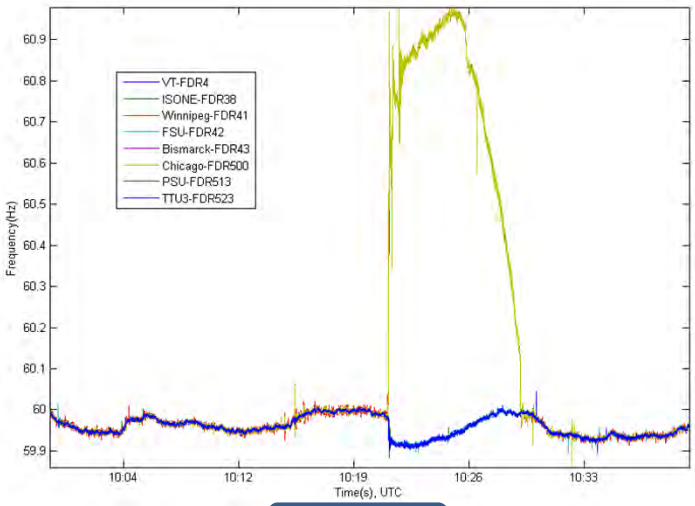


Fig. 1

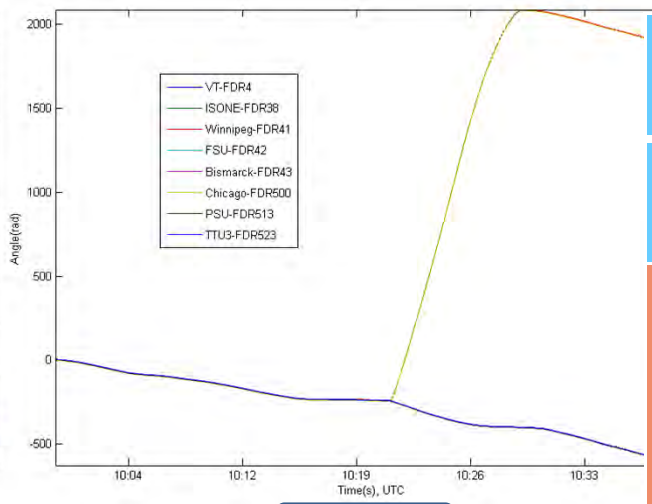


Fig. 2

$\lvert\Delta f_{\max}\rvert$	Winnipeg	1.0431Hz
	Bismarck	1.0577Hz
	Chicago	1.0577Hz
$(t_{\Delta f \geq f_{th}})_{\max}$	Winnipeg	498.2 s
	Bismarck	498.3 s
	Chicago	498.2 s
$\lvert\theta_{t+\Delta t_{tr}} - \theta_t\rvert_{\max}$	Winnipeg	19.4321 rad
$(t_{\Delta\theta \geq \theta_{th}})_{\max}$	Bismarck	19.4299 rad
	Chicago	19.4299 rad
	Winnipeg	495.8 s
	Bismarck	498.1 s
	Chicago	498.1 s

- **Case 2 (WECC 06/01/2010 23:37:32 UTC)**

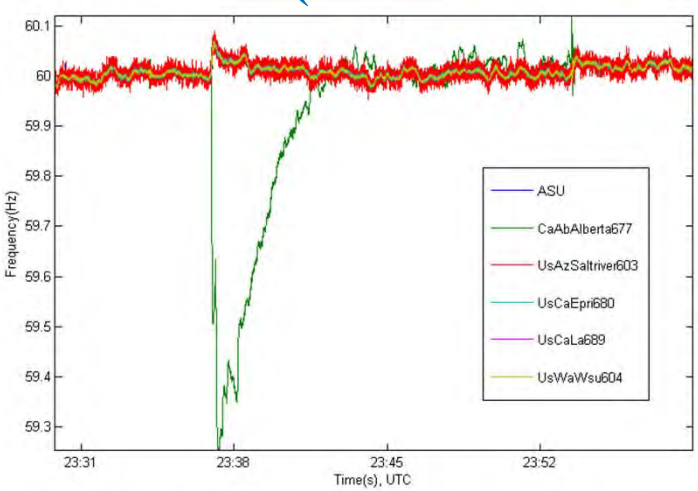


Fig. 3

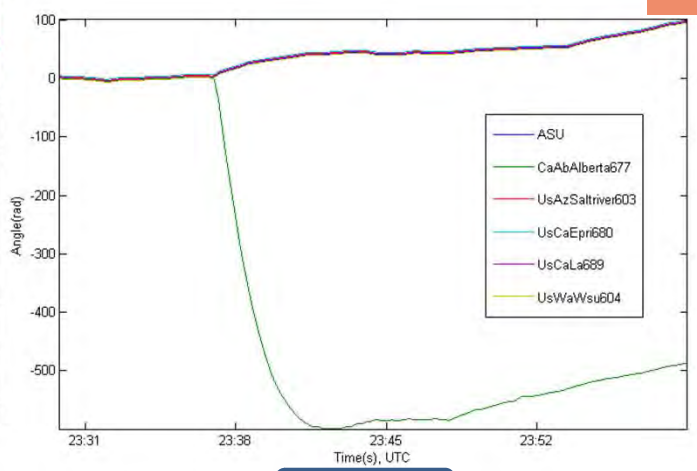
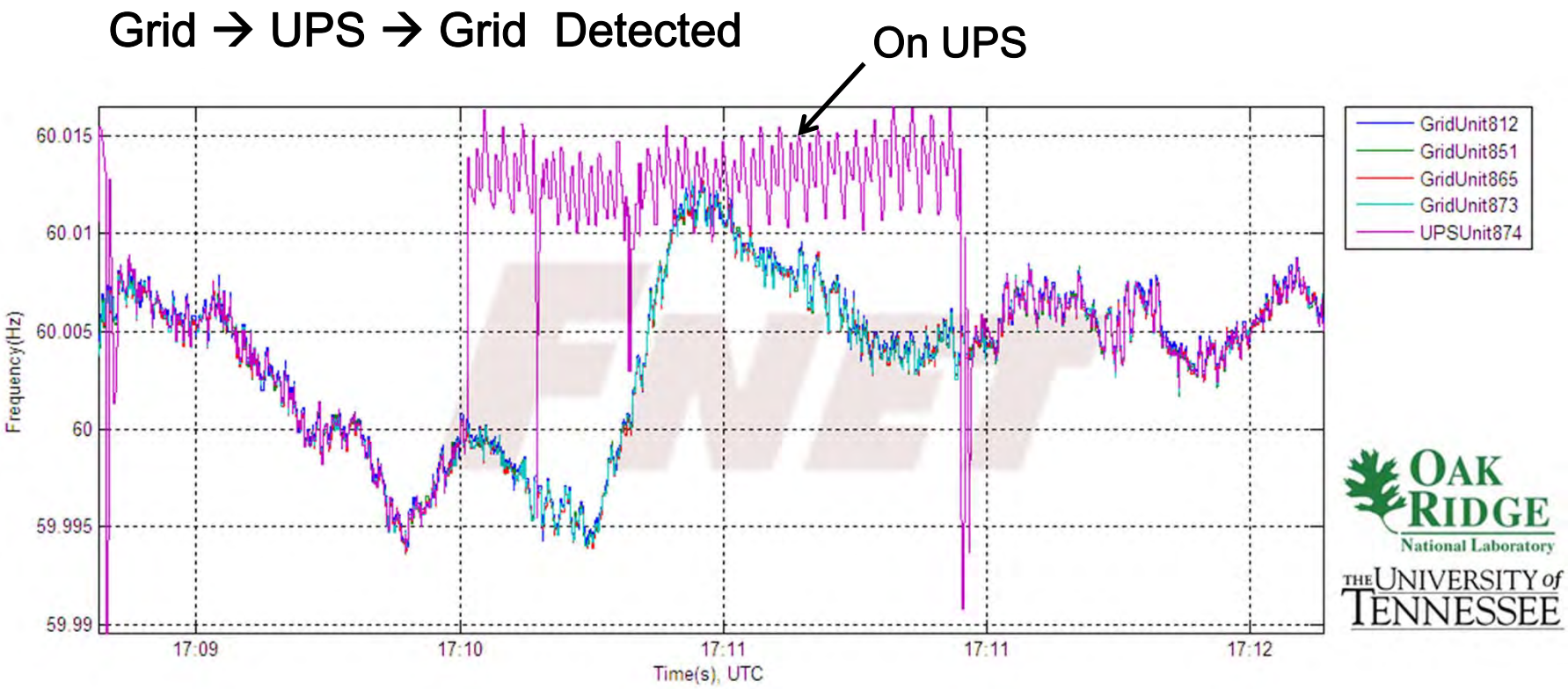


Fig. 4

Location	Alberta
$\lvert\Delta f_{\max}\rvert$	0.7925 Hz
$(t_{\Delta f \geq f_{th}})_{\max}$	281.1 s
$\lvert\theta_{t+\Delta t_{tr}} - \theta_t\rvert_{\max}$	14.8595 rad
$(t_{\Delta\theta \geq \theta_{th}})_{\max}$	280.9 s

Off Grid Detection for Hospitals and Data Centers



Central alarm system in operation

Sample Loss of Grid Power Alert System

ALERT - Backup Power Detected

U.S. DEPARTMENT OF ENERGY

A Backup Alert was just issued with the following details:

FDR Unit ID: 861
Location: Frederick, MD, US
Date: 6/7/2012 11:30:02 AM

Please login in to the EAGLE-I Dashboard to see additional details.

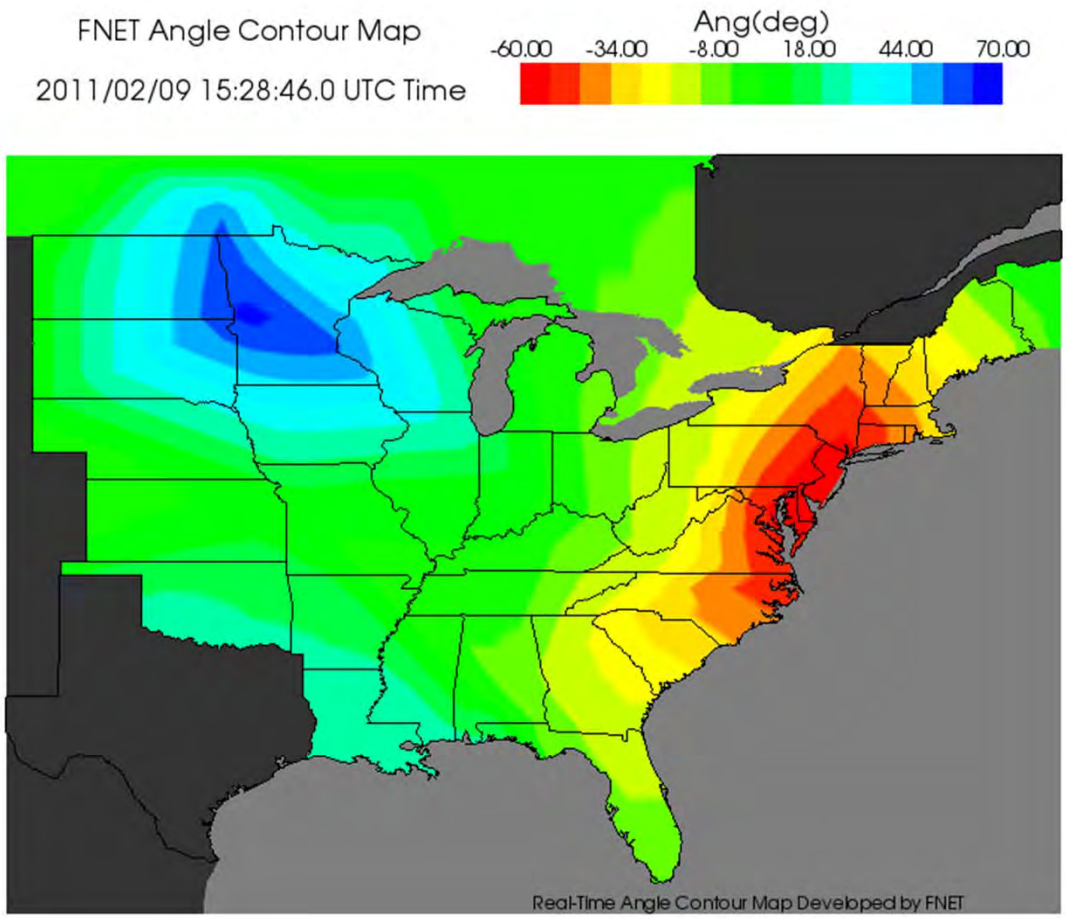
ALERT - Backup Power Update

U.S. DEPARTMENT OF ENERGY

ALERT - Backup Power Resolved

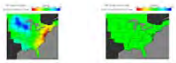
U.S. DEPARTMENT OF ENERGY

Real-time Angle Contour Display



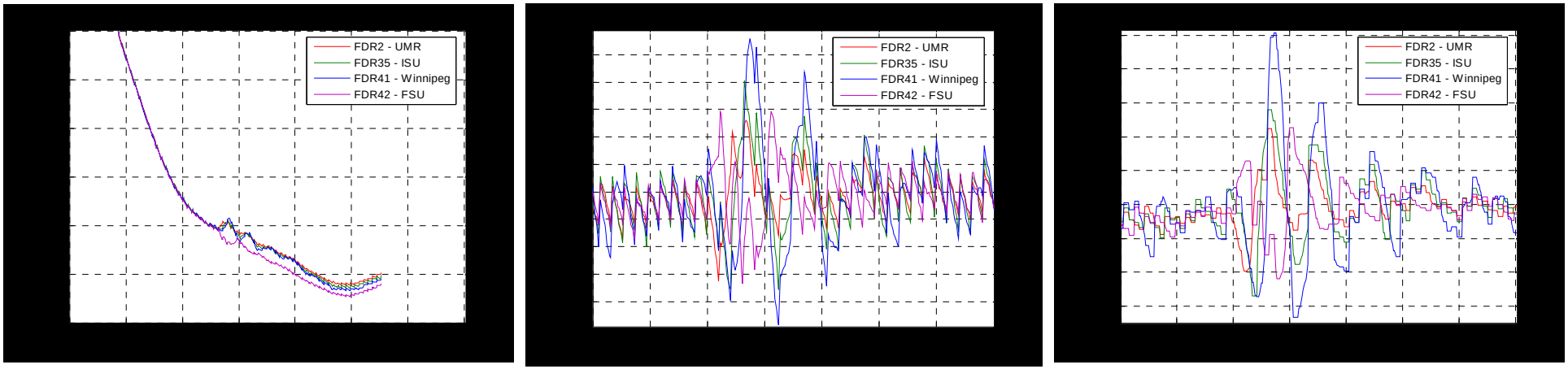
Click to show 24 hour video

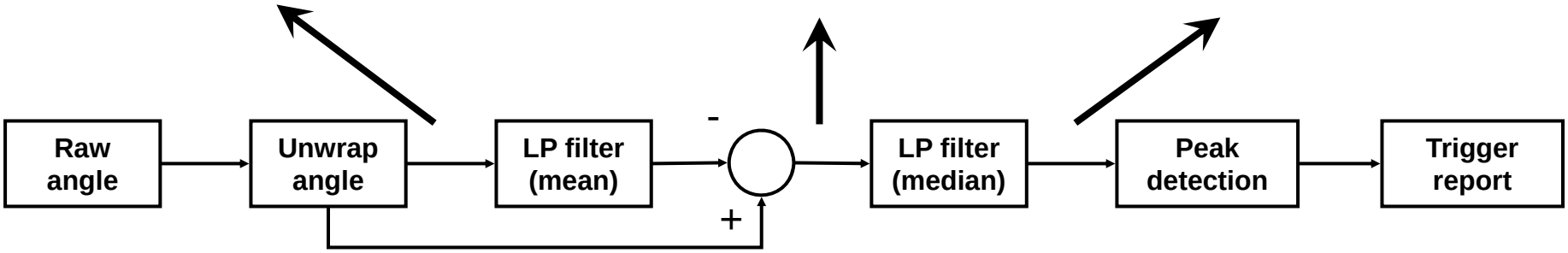
Angle change in gen trip



Angle change in HVDC event

Line Trip Trigger and Location Based on Relative Angle

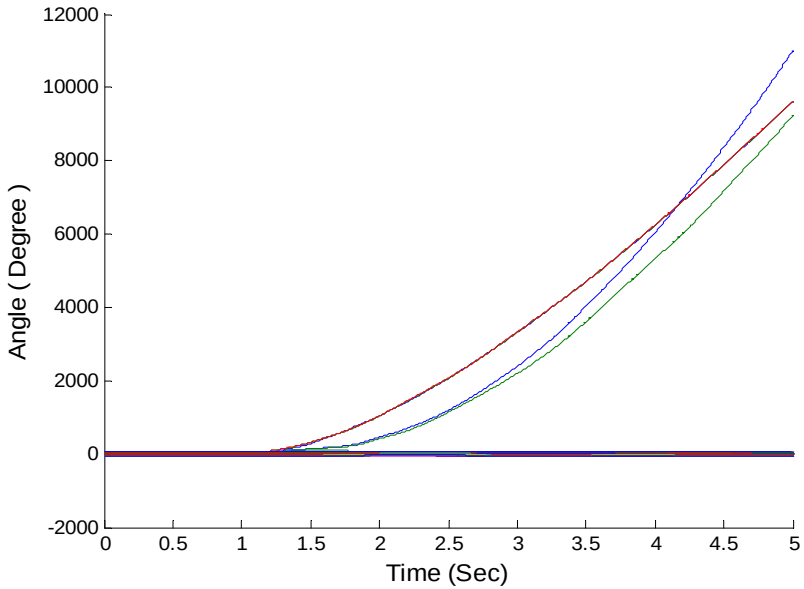


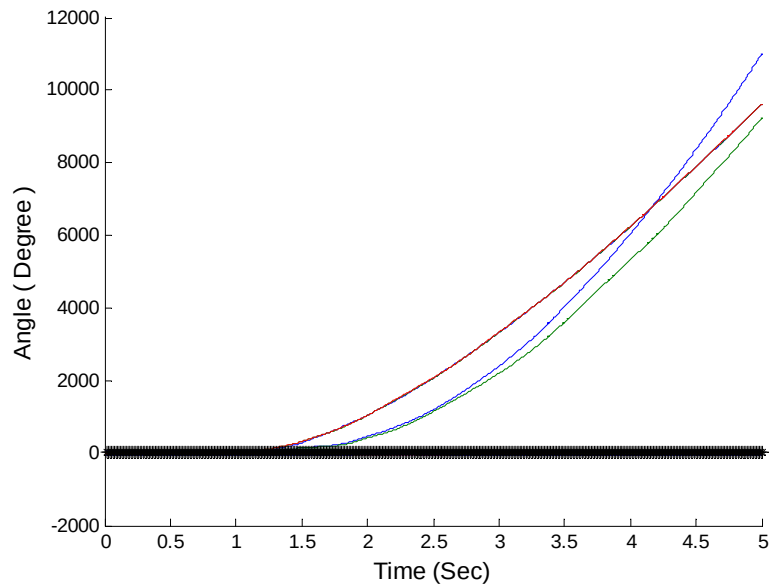


Stability Monitoring

Replace the rotor angles in Center-of-Inertia (COI) by the phasor angle of the high side bus voltage, and assume that the inertia is equally distributed to each of the generators in a bulk system.

$$\delta_{COI} = \frac{1}{H_T}\sum_{i=1}^{n} H_i \delta_i \quad \Rightarrow \quad \delta_{CBA} = \frac{1}{H_T}\sum_{i=1}^{n} H \delta_{bi} = \frac{H}{nH}\sum_{i=1}^{n} \delta_{bi} = \frac{\delta_{bT}}{n}$$





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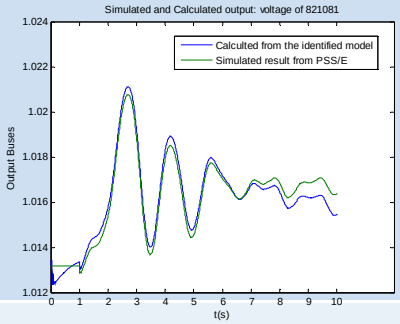
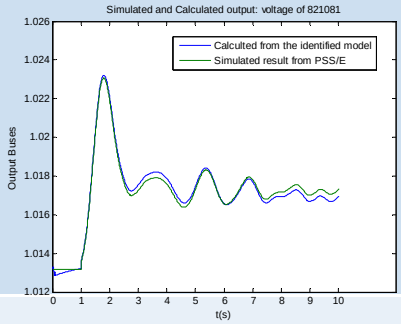
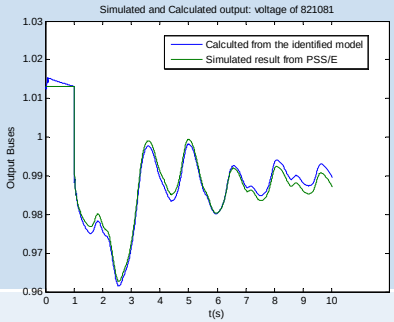
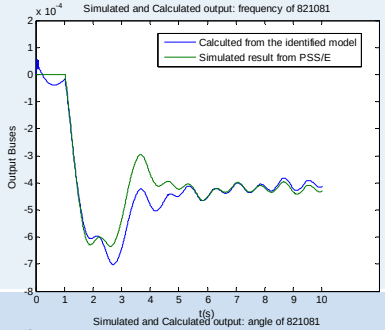
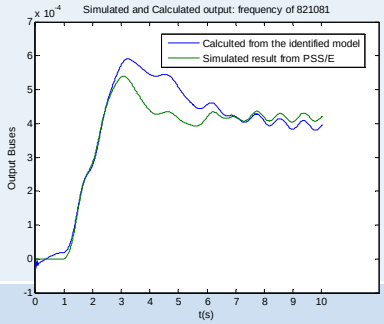
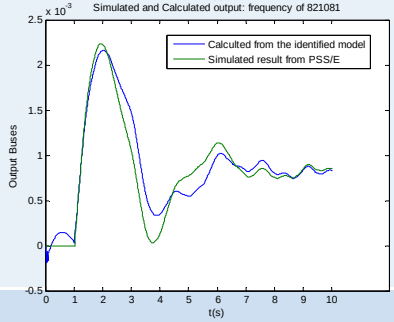
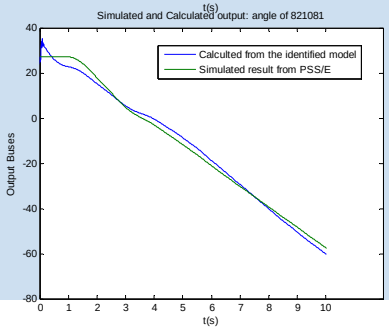
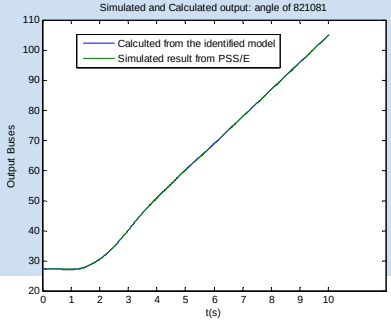
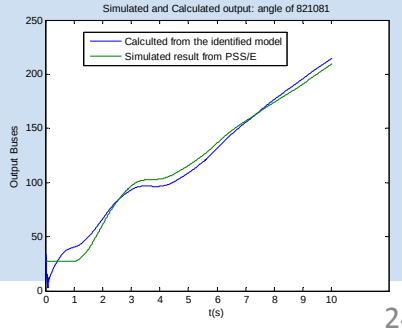
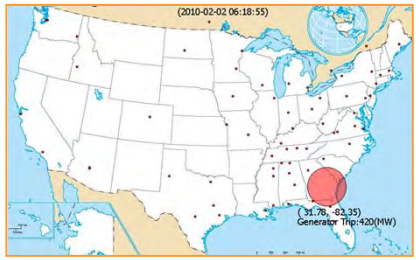
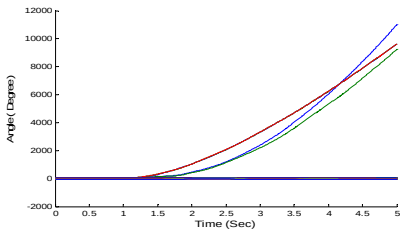
Dynamic Response Estimation

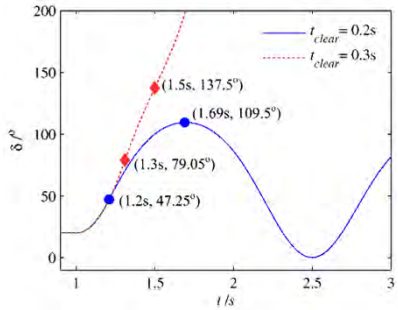
	Generation Trip Response	Load shedding Response	Line fault Response
Voltage			
Frequency			
Angle			

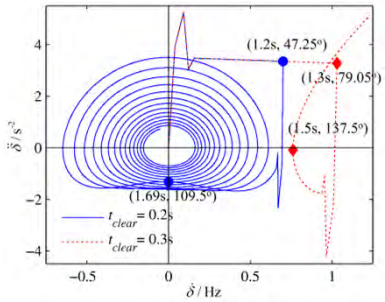
Measurement based On-line Grid Condition Assessment Toolbox

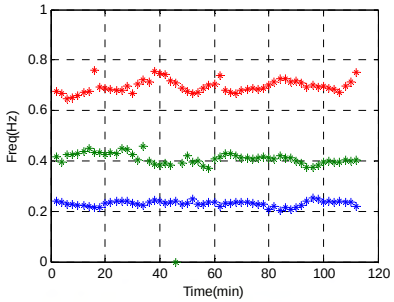
From top left: rotor angle stability prediction, transfer function
From middle left; oscillation mode estimation, damping, event location
From bottom left: Bus angle trending, islanding, line activities

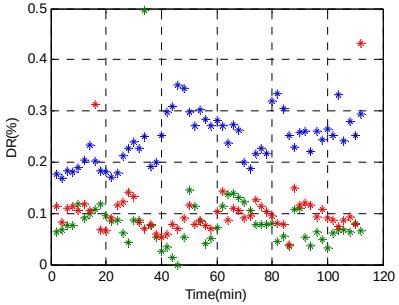


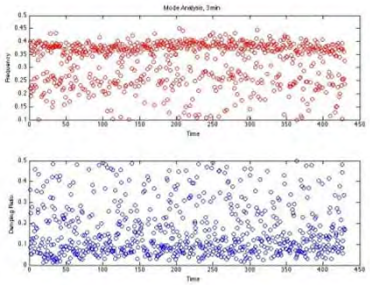


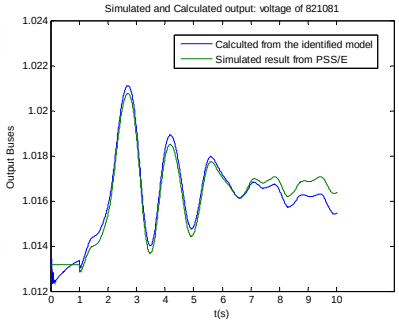


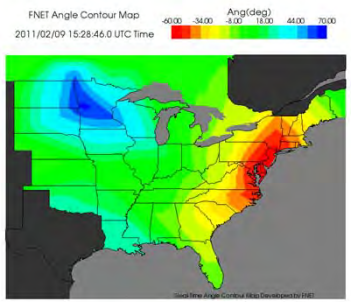


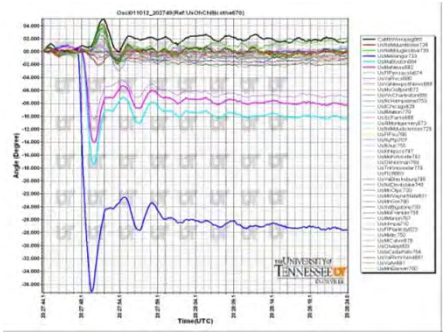


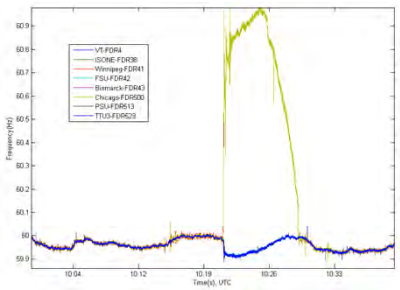


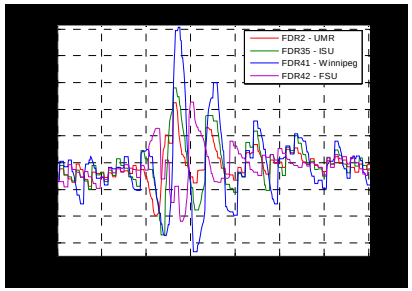






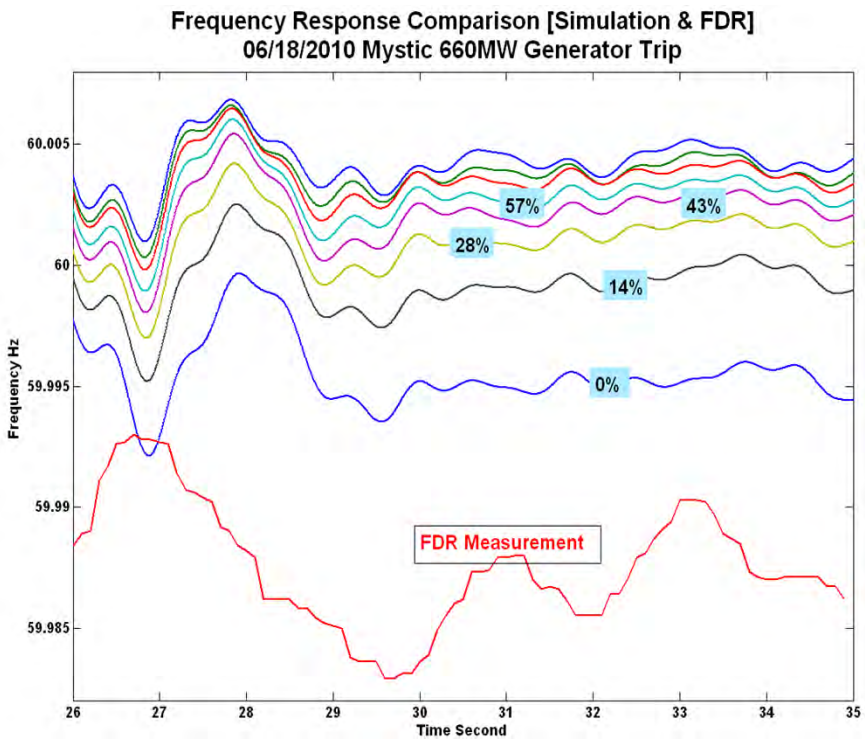


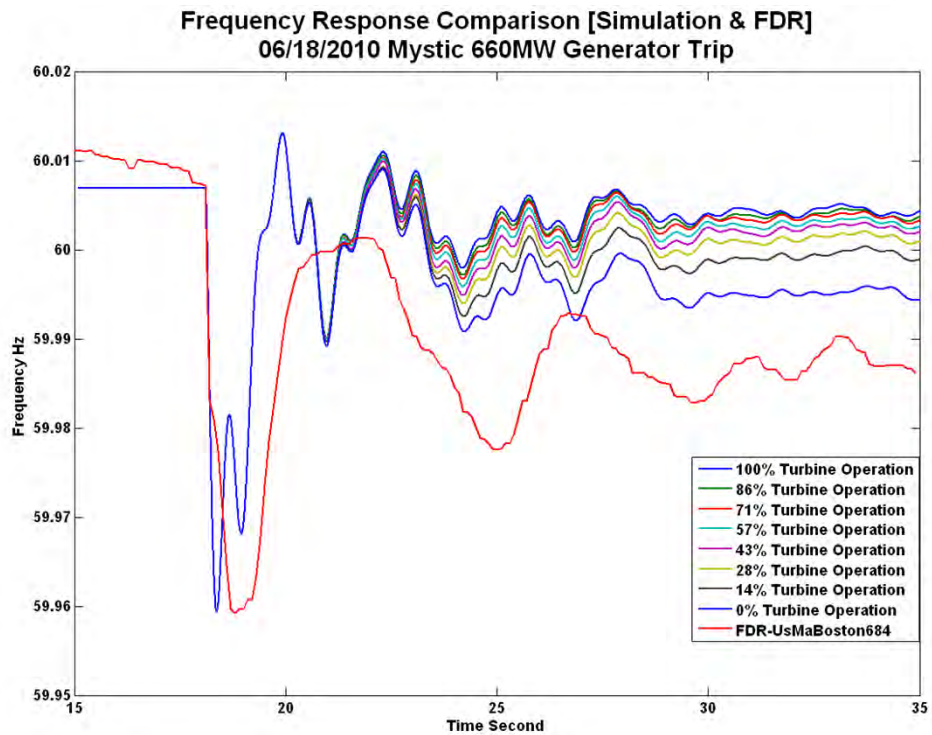




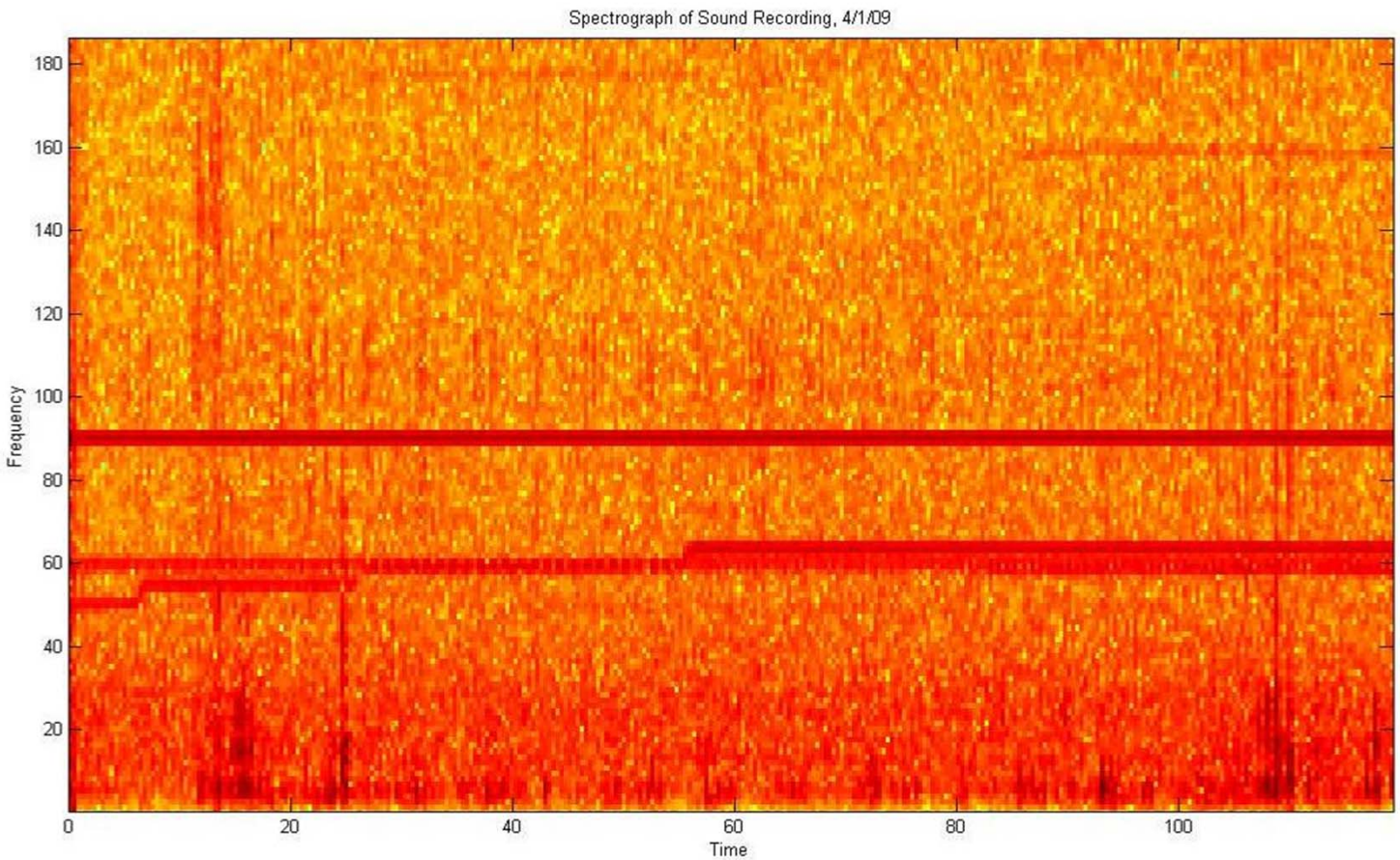
EI Model Validation

Partial Governor Operation



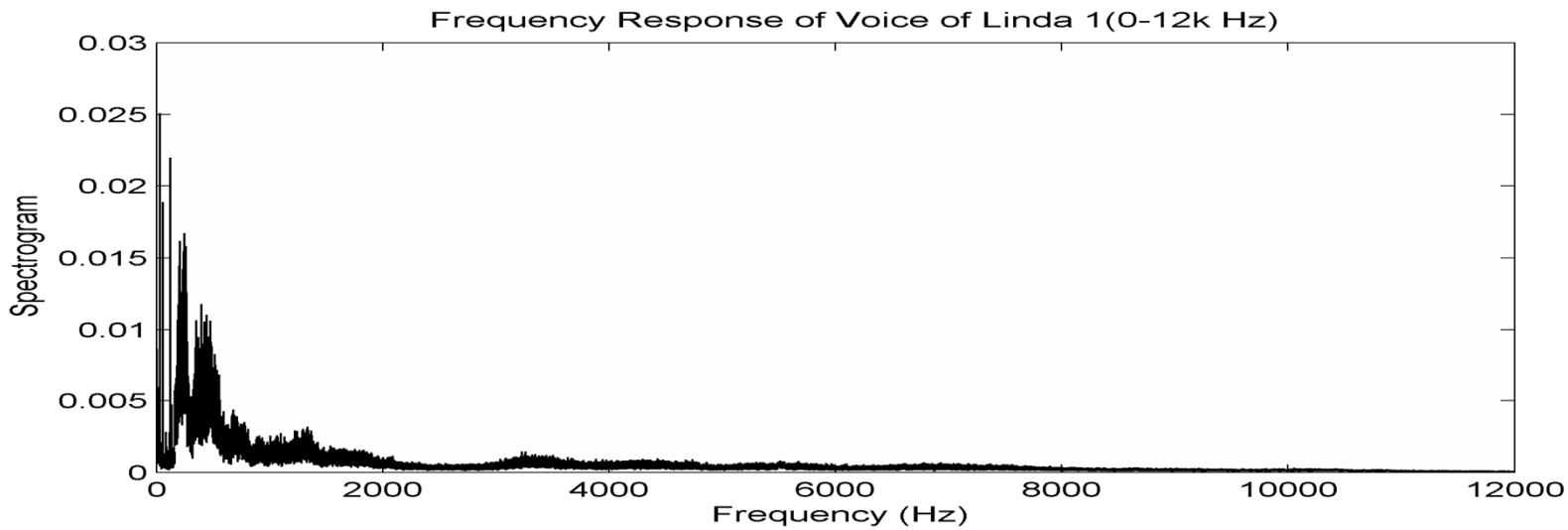


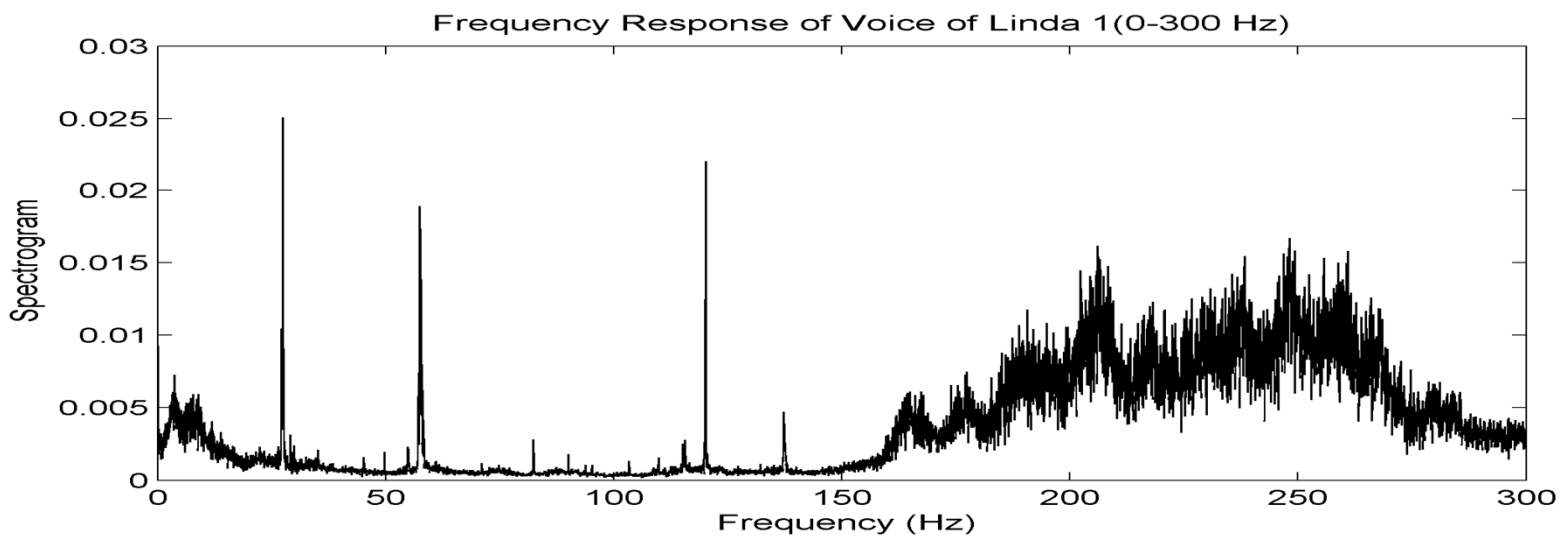
Audio Recording Spectrum



- Recorded by PC sound card (background)
- 60Hz component is visible

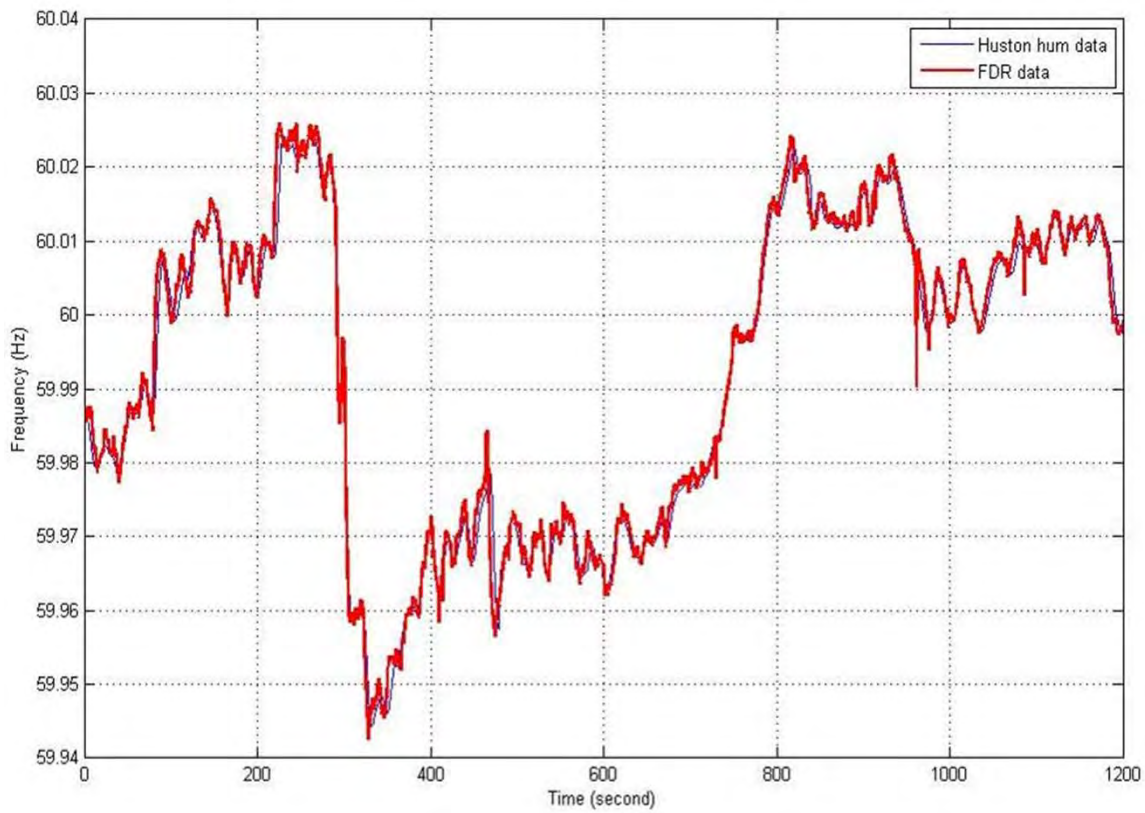
- **Frequency Response of Linda's Voice**





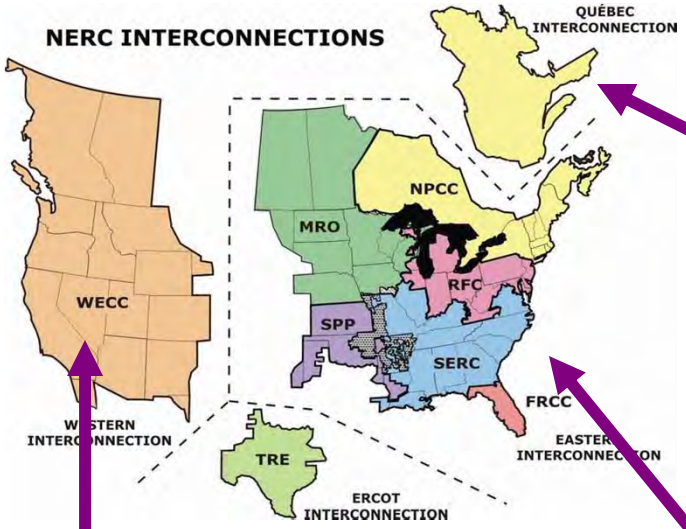
Case analysis – Houston police recording compared with FDR data collected in Huston, TX

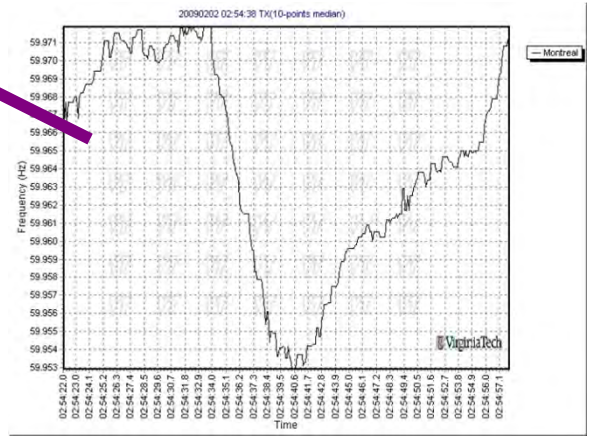
- Audio record: Houston police 05-07-2009,11:00-11:20 CDT
- Sample rate: 11kHz
- Recorded from equipment ground loop hum

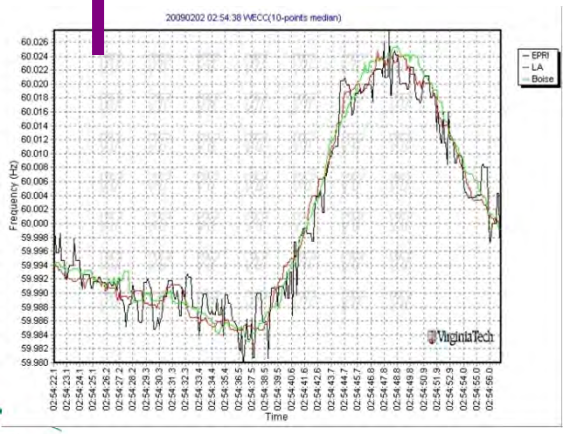


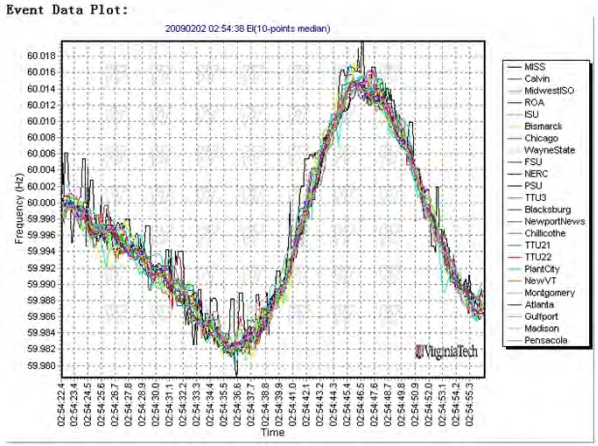
Power grid signature as authentication tool

Super Bowl
Frequency swings during comercials



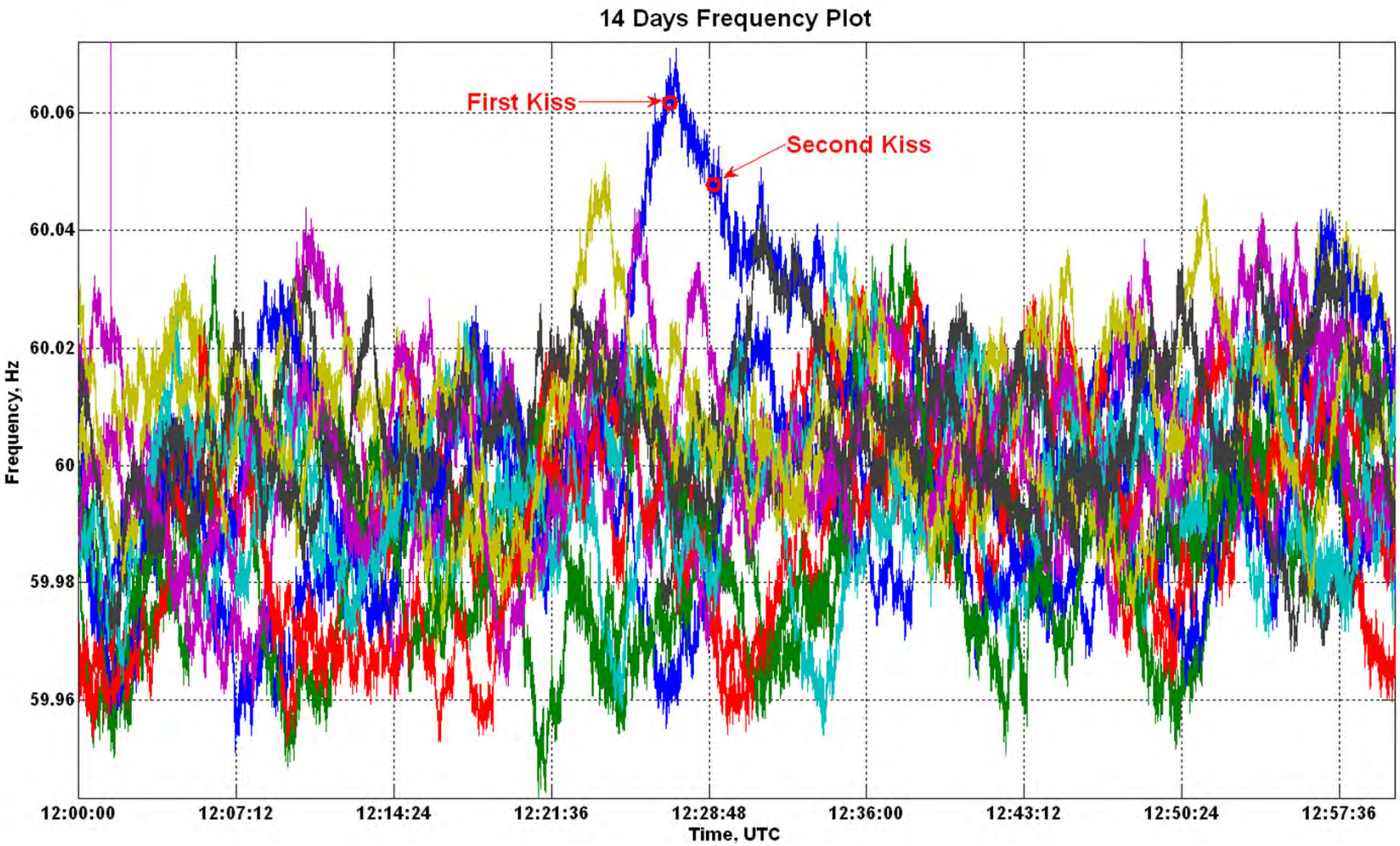






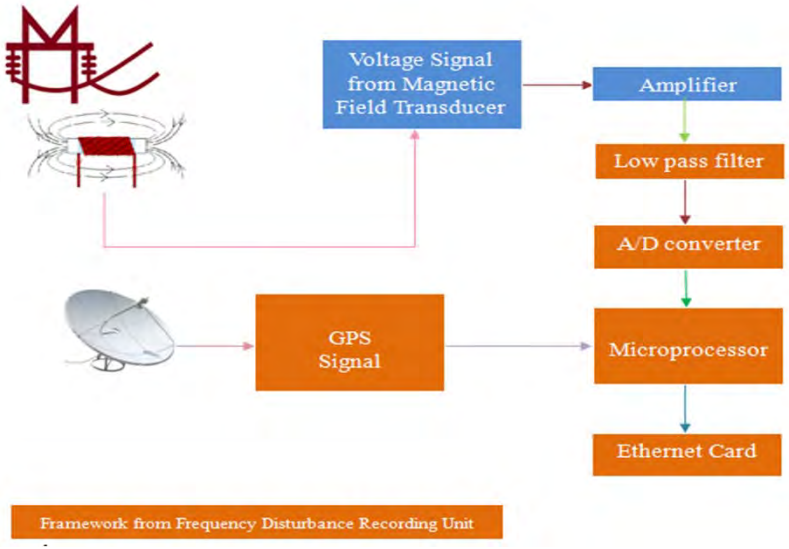
FNET GridEye

Royal Wedding



Contactless PMU Development

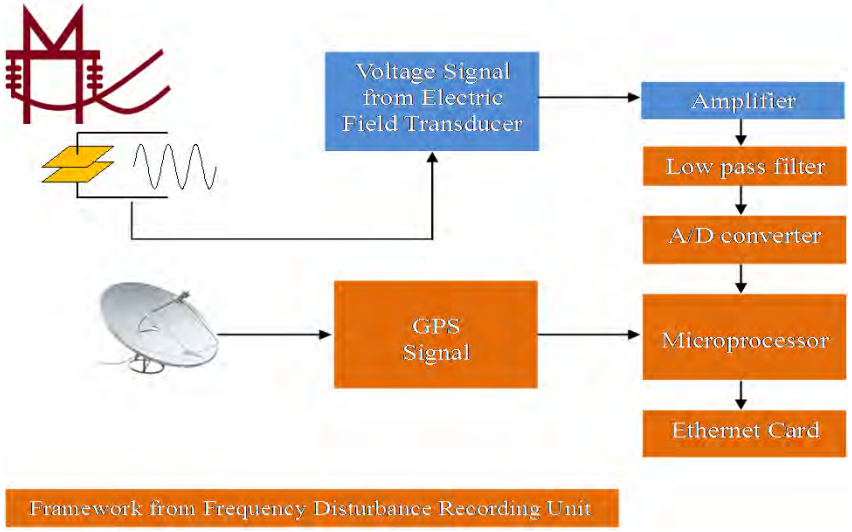
Magnetic Field Based PMU



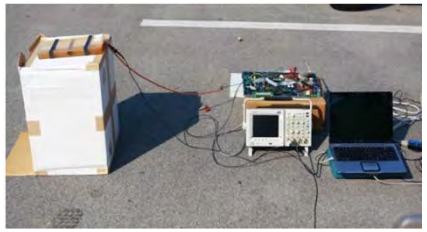
Lab Testing

Field Testing

Electric Field Based PMU



Lab Testing



Field Testing

FNET GridEye

Related web links:

FNET Live Display : http://fnetpublic.utk.edu/gradientmap.html

How to install FDR: http://www.youtube.com/watch?v=9Vt2OlVoBJc&NR=1

Sample oscillation alert:
http://fnetapp.eecs.utk.edu/FNETOsciEventReport/20120110_202749_EI_OsciSummary.html

FL Event Movie; http://www.youtube.com/watch?v=bdBB4byrZ6U&feature=related

CA Blackout Movie: http://www.youtube.com/watch?v=YsksUyeLu2Y

April 27 Storm TVA line trip Movie: http://www.youtube.com/watch?v=KmK2VMG57gw&feature=related

2011 Virginia Earthquake Movie: http://www.youtube.com/watch?v=XUN_h-k8kBg&feature=related

2003 blackout movie: http://www.youtube.com/watch?v=eBucg1tX2Q4&feature=related

Worldwide Measurement Map: http://powerit.utk.edu/worldmap/

UTK PowerIt Lab: http://powerit.utk.edu

NSF/DOE Center: http://curent.utk.edu

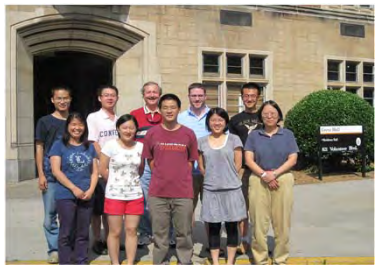
FNET GridEye

FNET Sponsors & Students

The FNET Team, 2006

2007

2009



2010

2011