Overview of Distribution Level Synchronous Measurement Applications
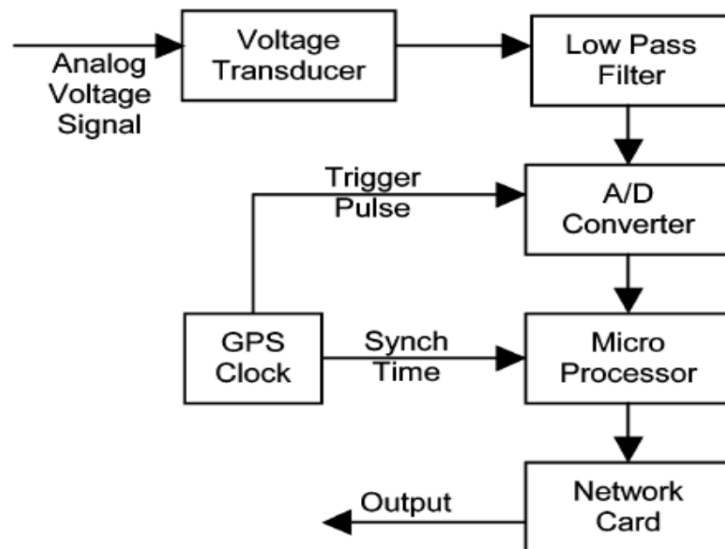
Dr. Yilu Liu
The University of Tennessee
Oak Ridge National Laboratory

Liu@utk.edu
865 266 3597

NASPI Orlando Meeting, Feb. 29, 2012
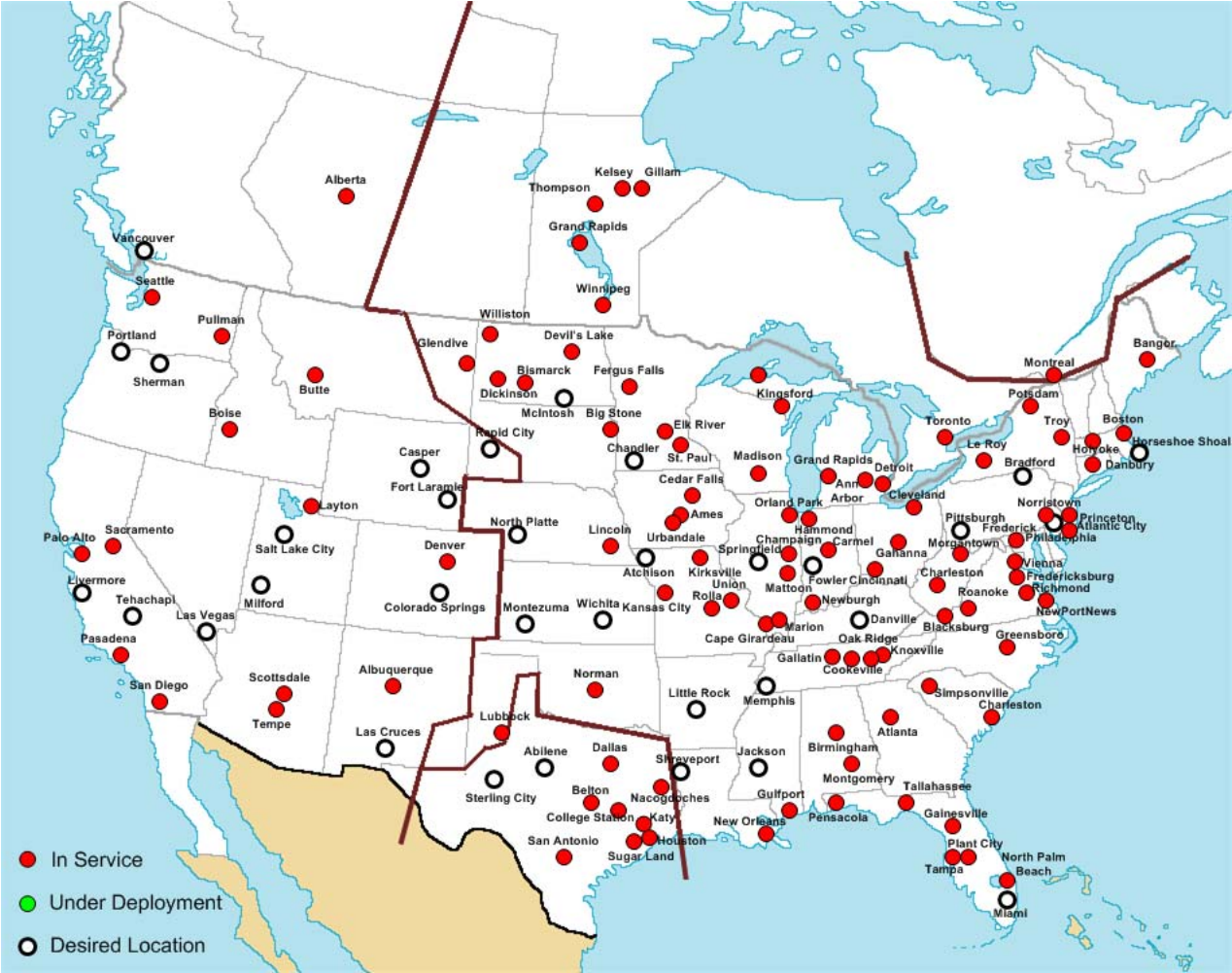
FNET GridEye

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.
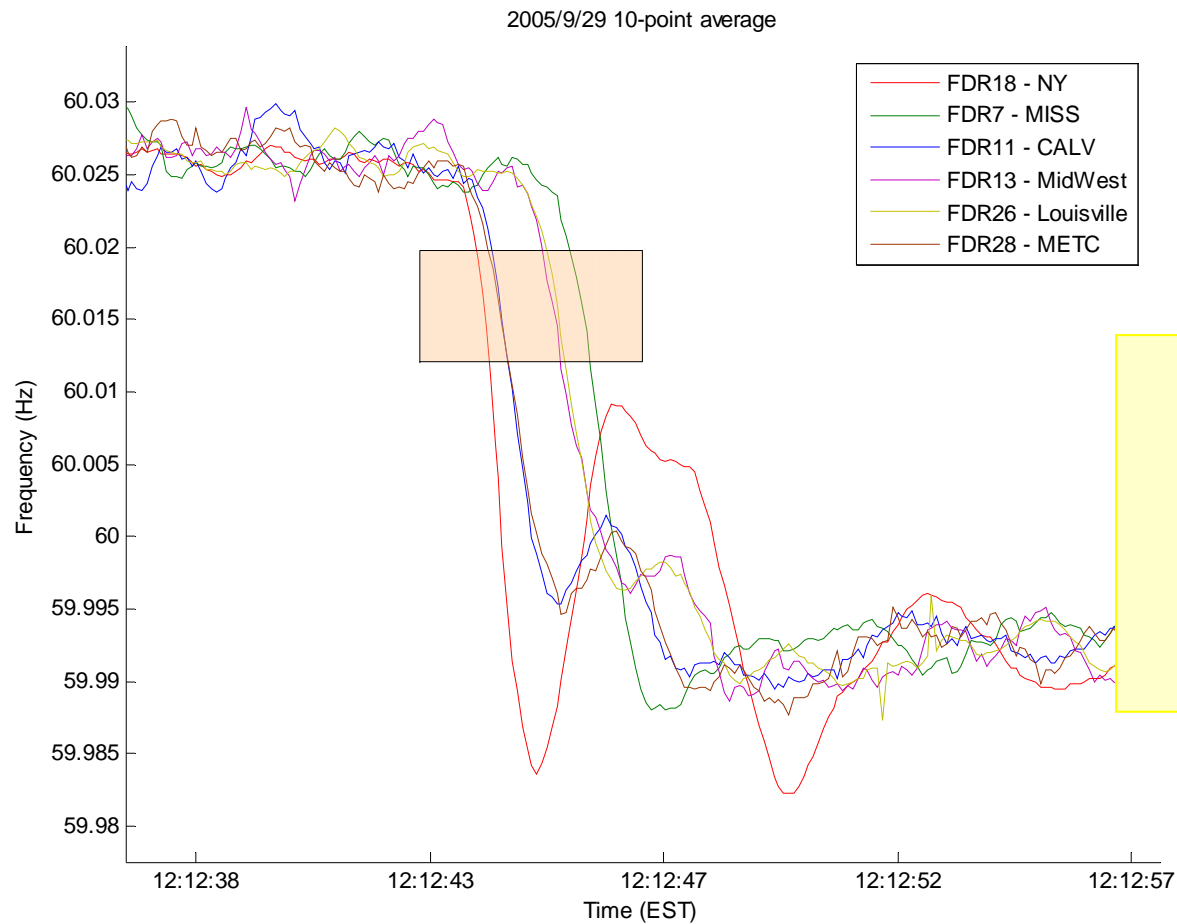- Data transmitted to Servers at UTK and ORNL

FNET GridEye

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

Worldwide Deployment Map

On-line Event Location

2005/9/29 10-point average
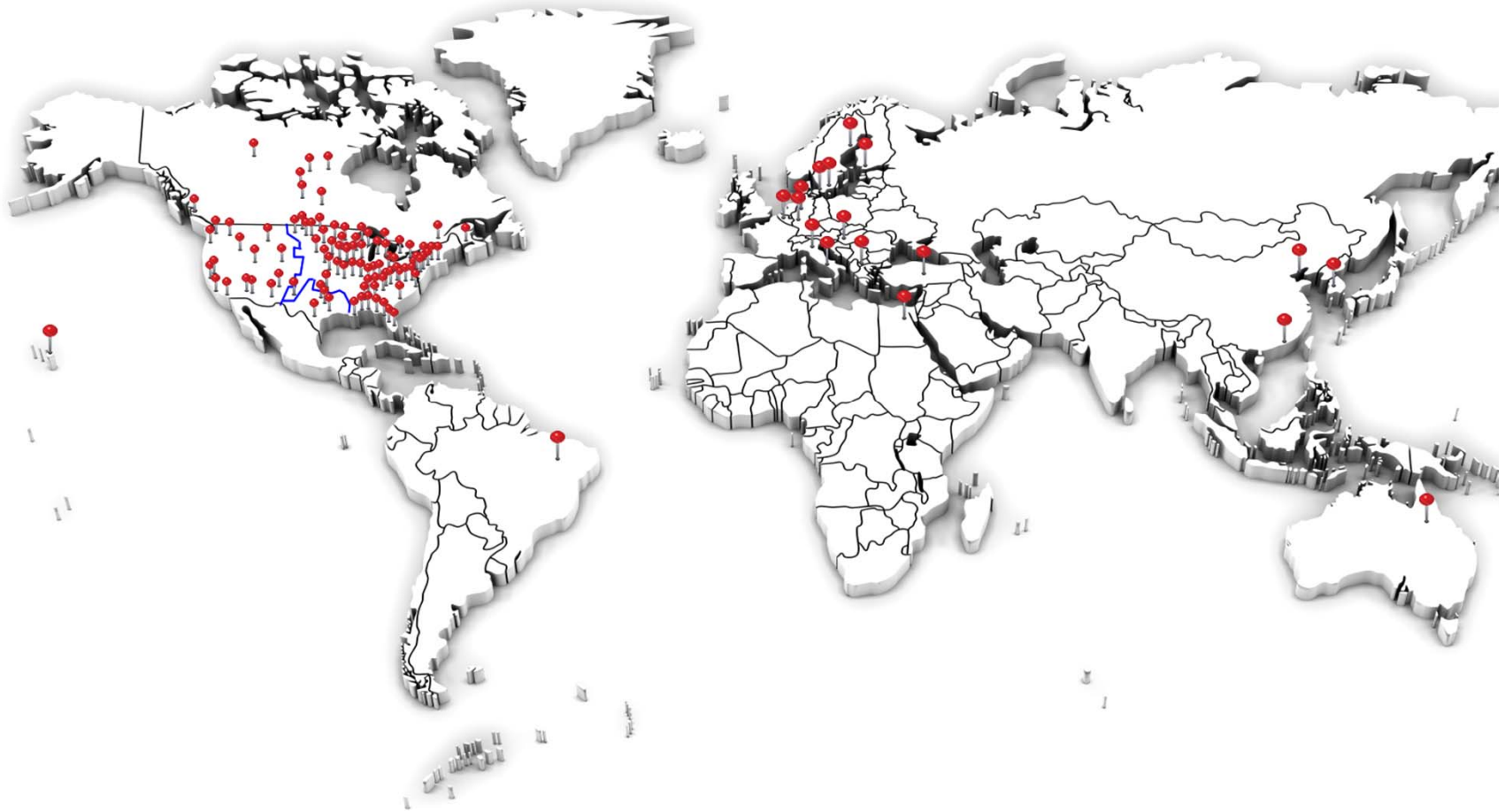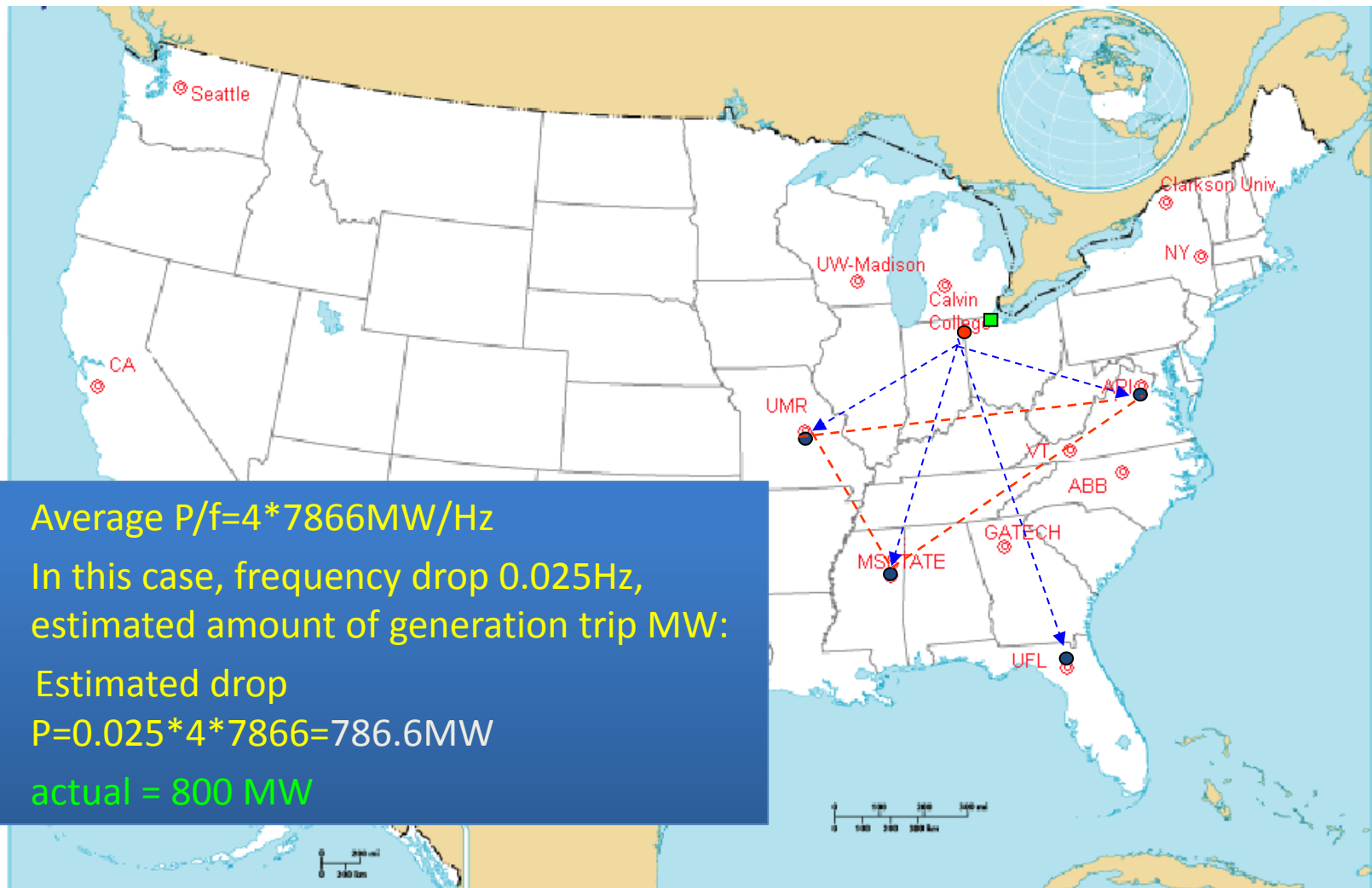
A US Patent has been issued for using frequency "time delay of arrival" in locating the source of power system disturbances

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

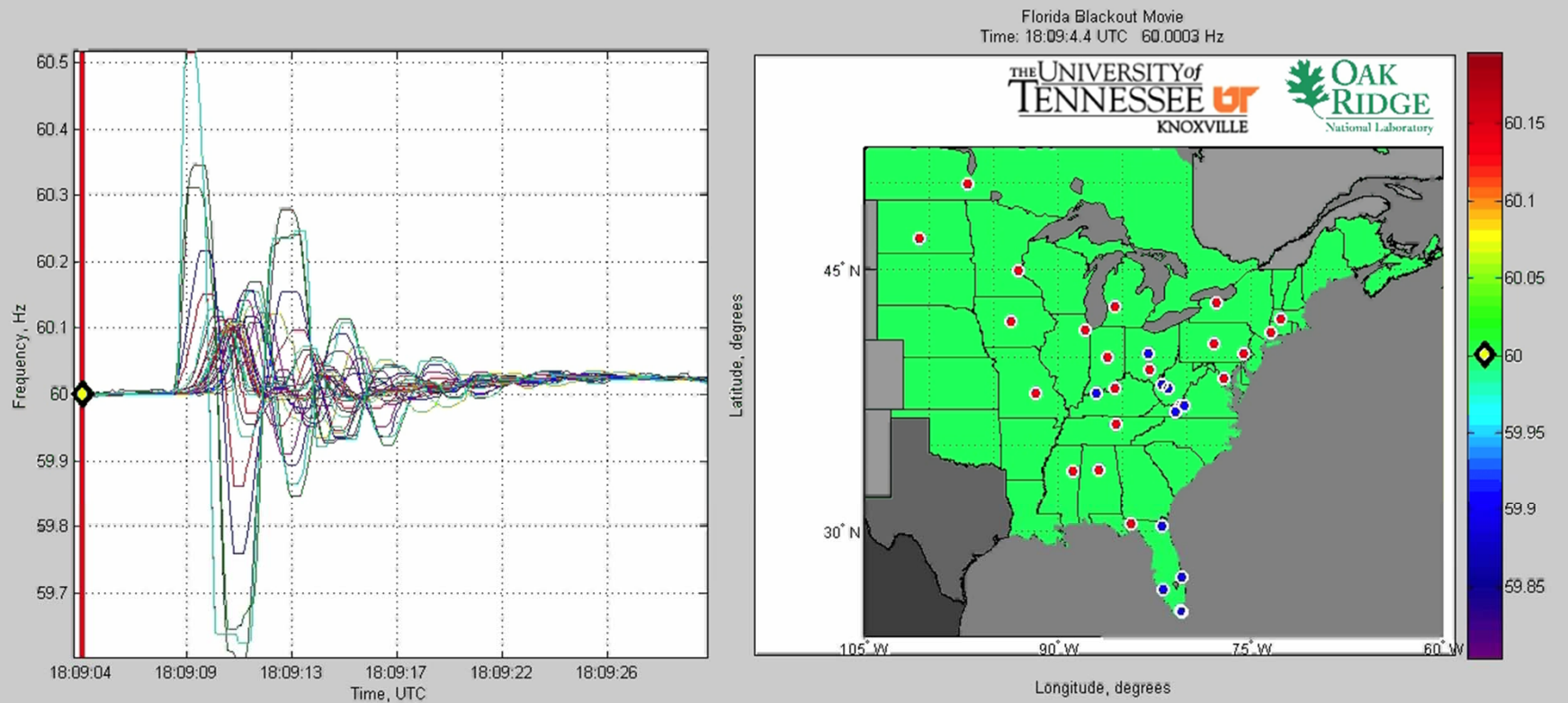# Sample automatic event alert

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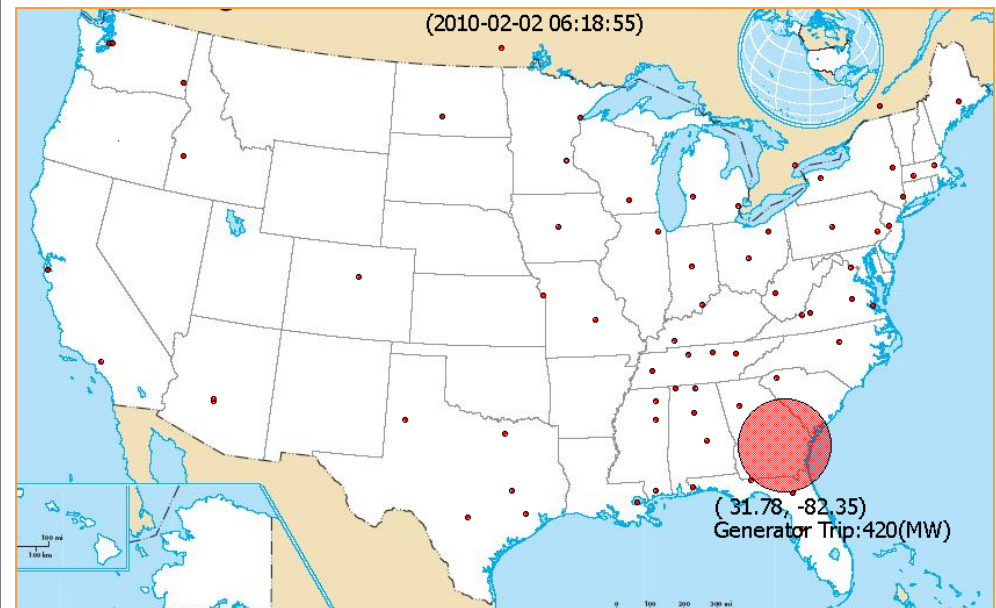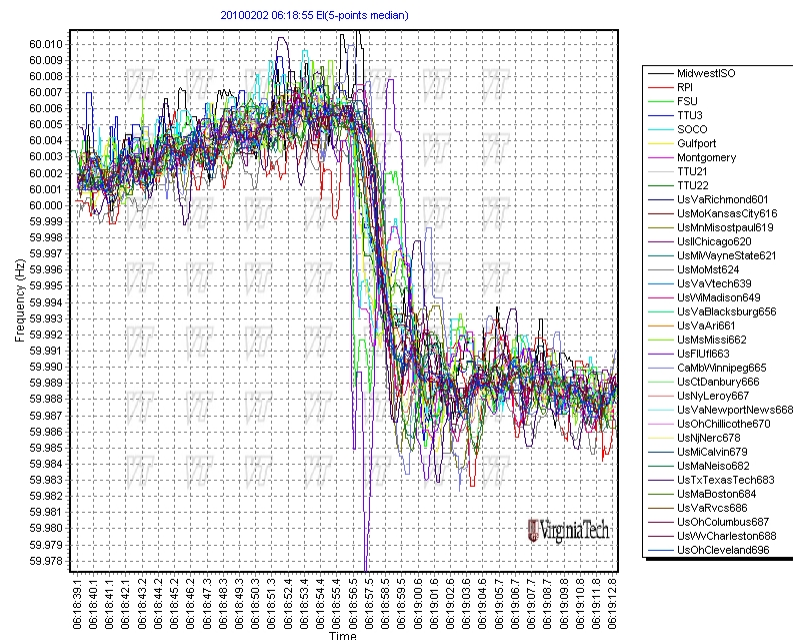
Disturbance Propagation Playback
FNET and PMU measurements 2-26-08

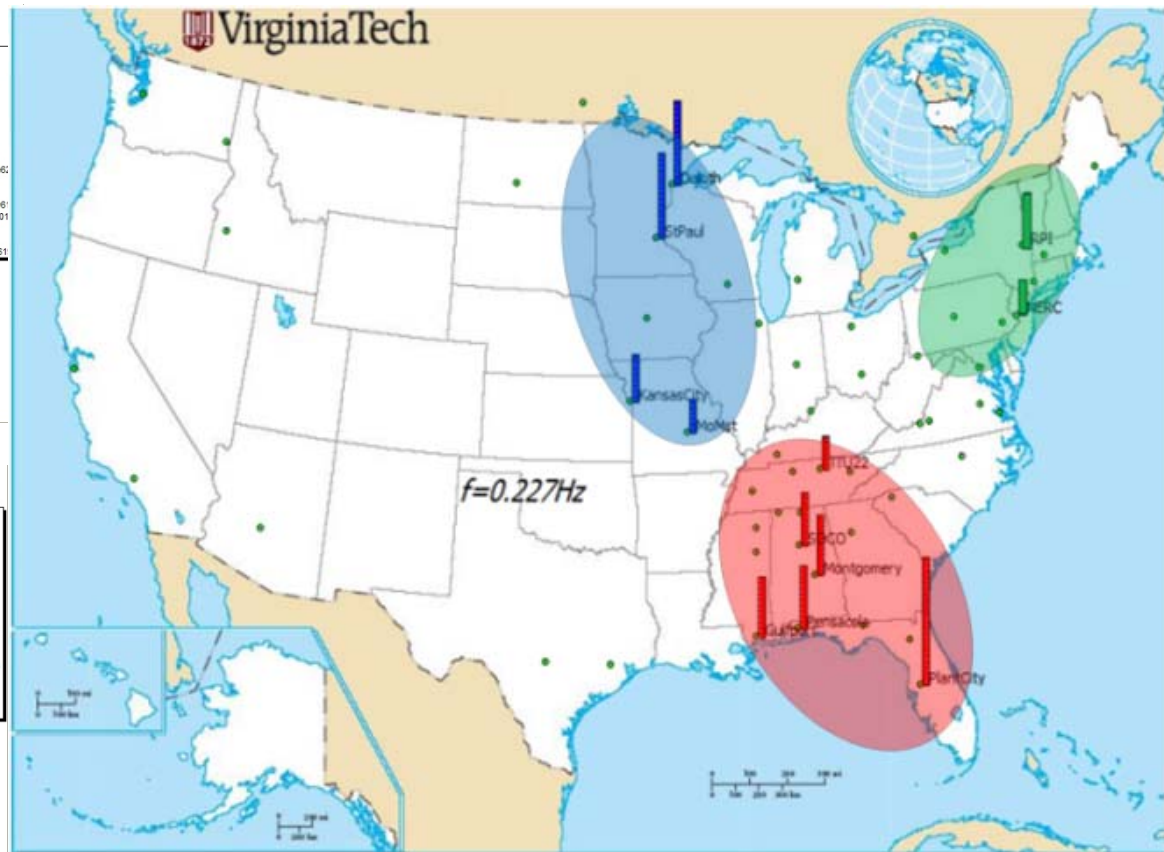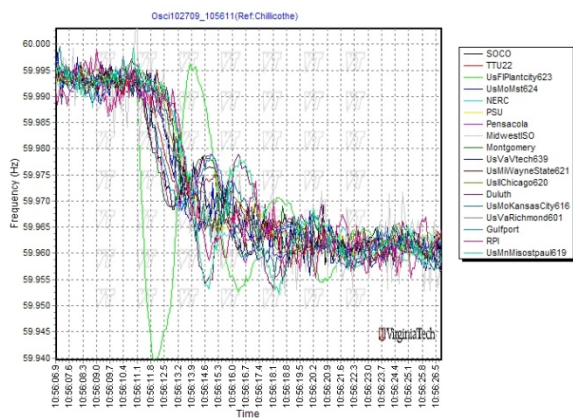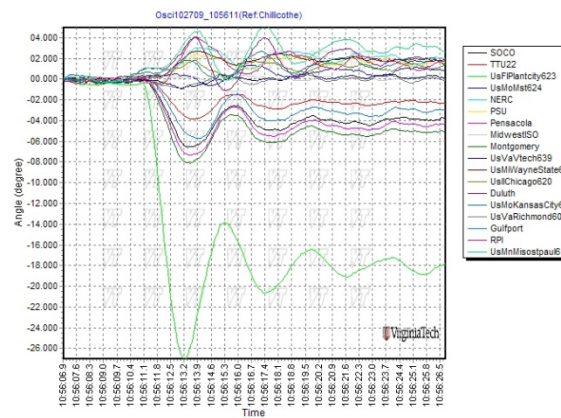Florida Generator Trip Replay from Measurement

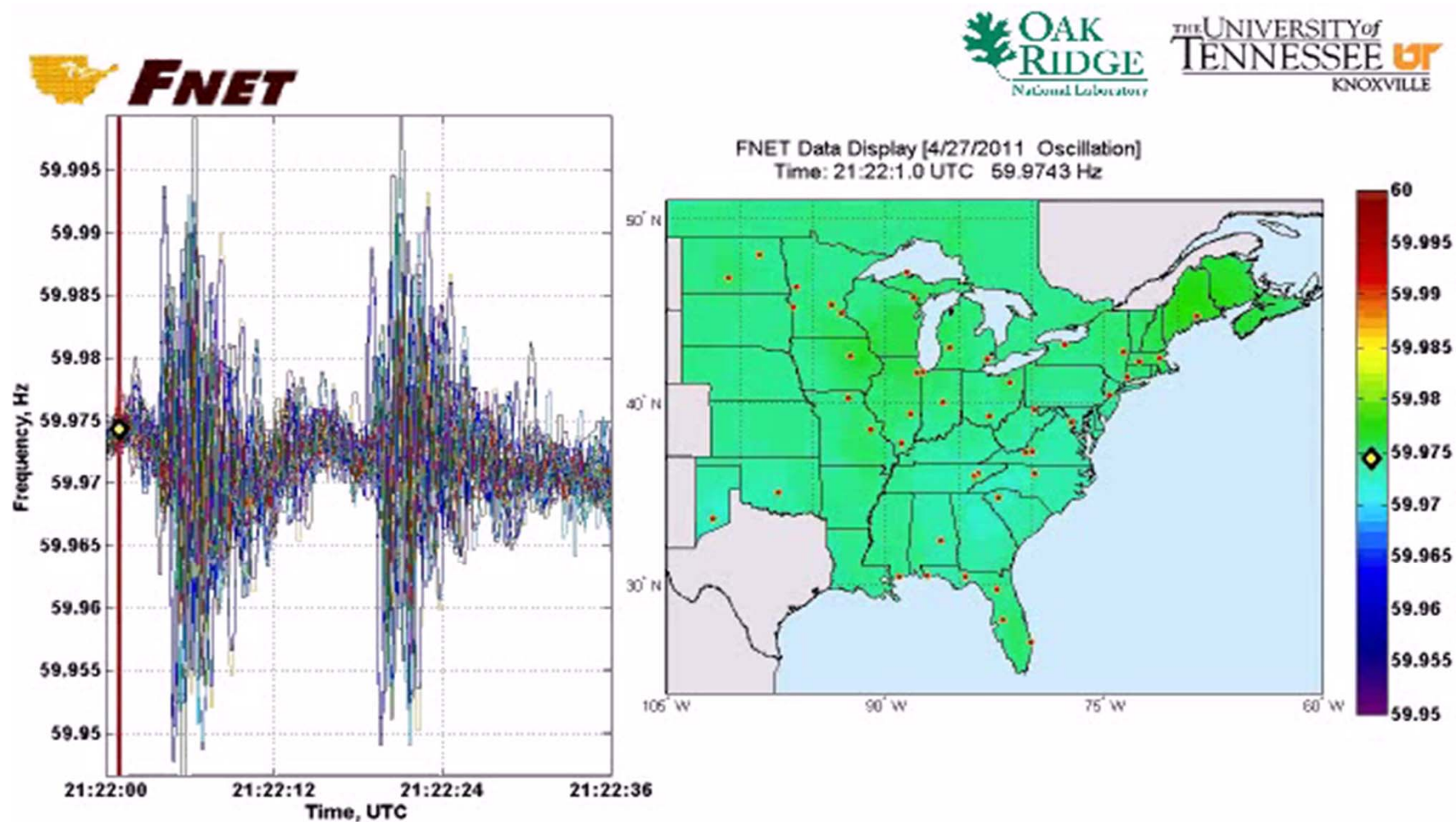# Wide area oscillation detection

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:

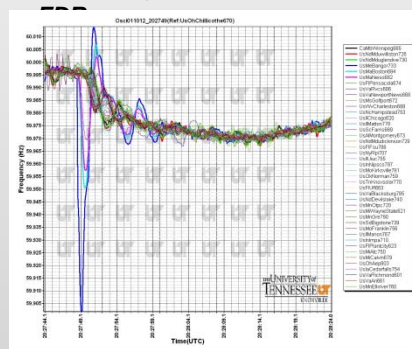### FDRs with Largest Negative Amplitude Oscillation

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

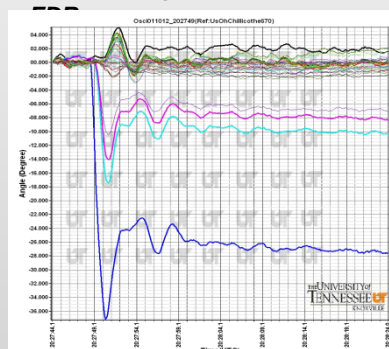### FDRs with Largest Positive Amplitude Oscillation

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:
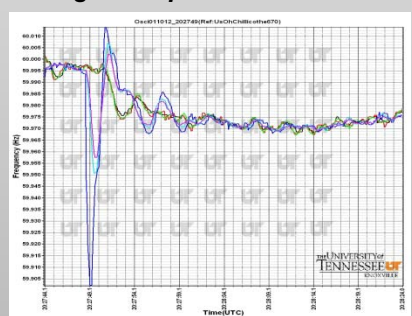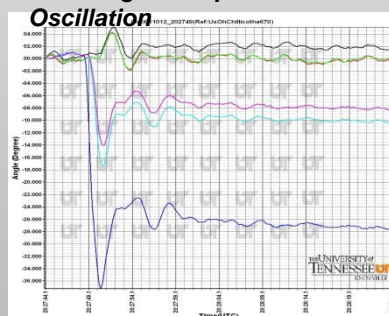
Frequency plot of All FDR

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

Osci011012_202749(Ref:UsOhChillicothe670)
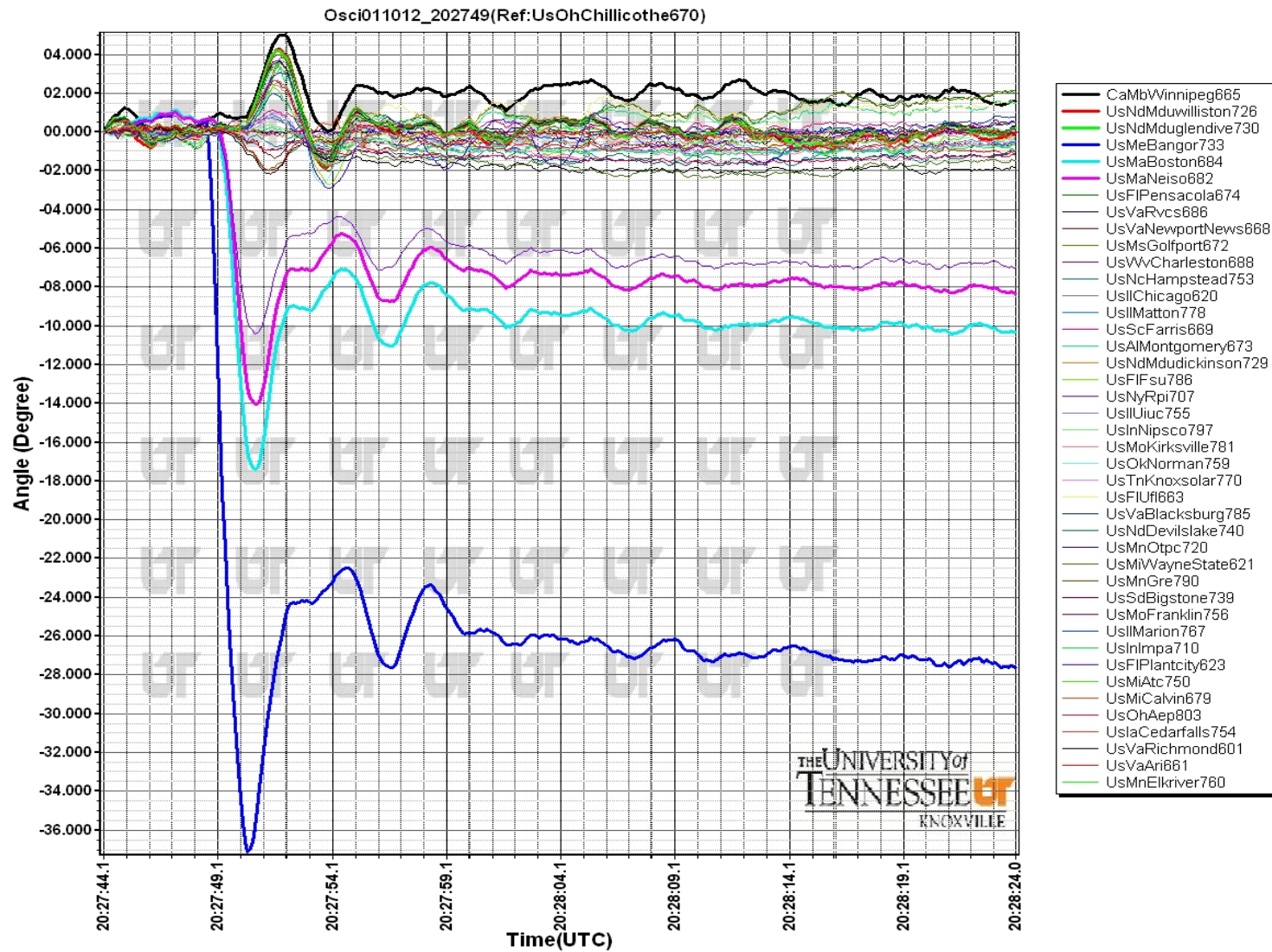
Islanding Detection – Bulk & Micro Grid

- ## Case 1 (EI   09/18/2007   10:21:23   UTC)
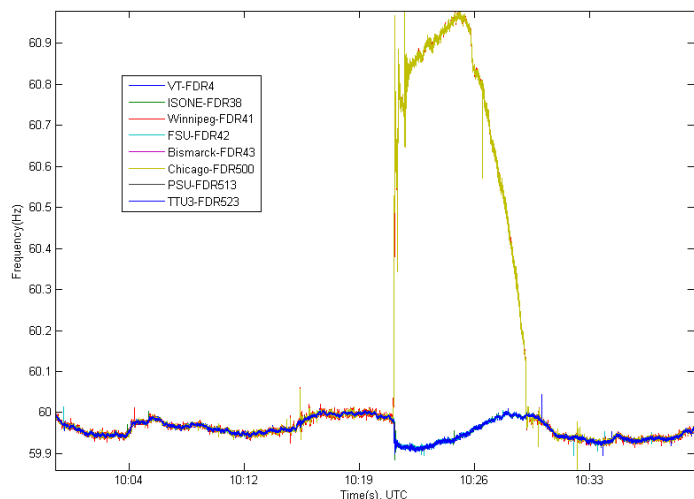
Fig. 1
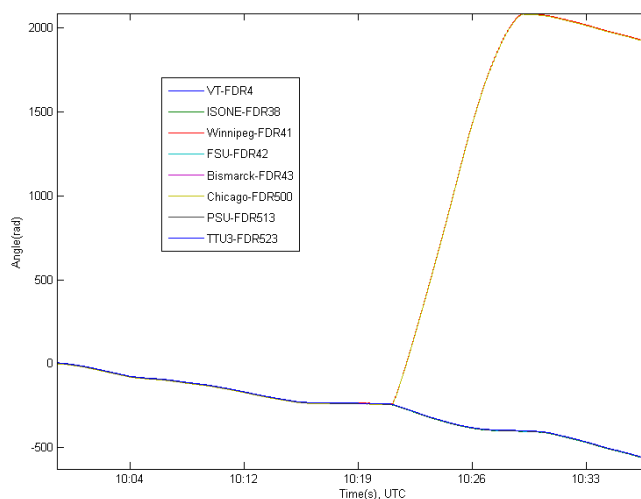
Fig. 2

$\left\| \Delta f_{max} \right\|$	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
$\left\| \theta_{t+\Delta t_{tr}} - \theta_t \right\|_{max}$	Winnipeg	19.4321 rad
	Bismarck	19.4299 rad
$(t_{\Delta \theta \geq \theta_{th}})_{max}$	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)
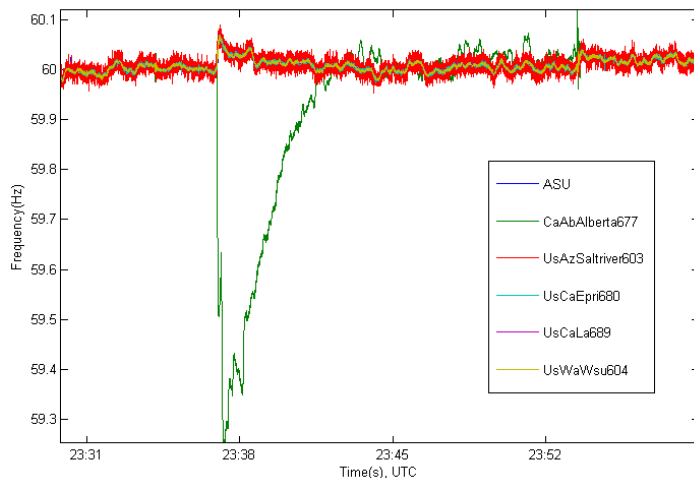
Fig. 3

Fig. 4

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

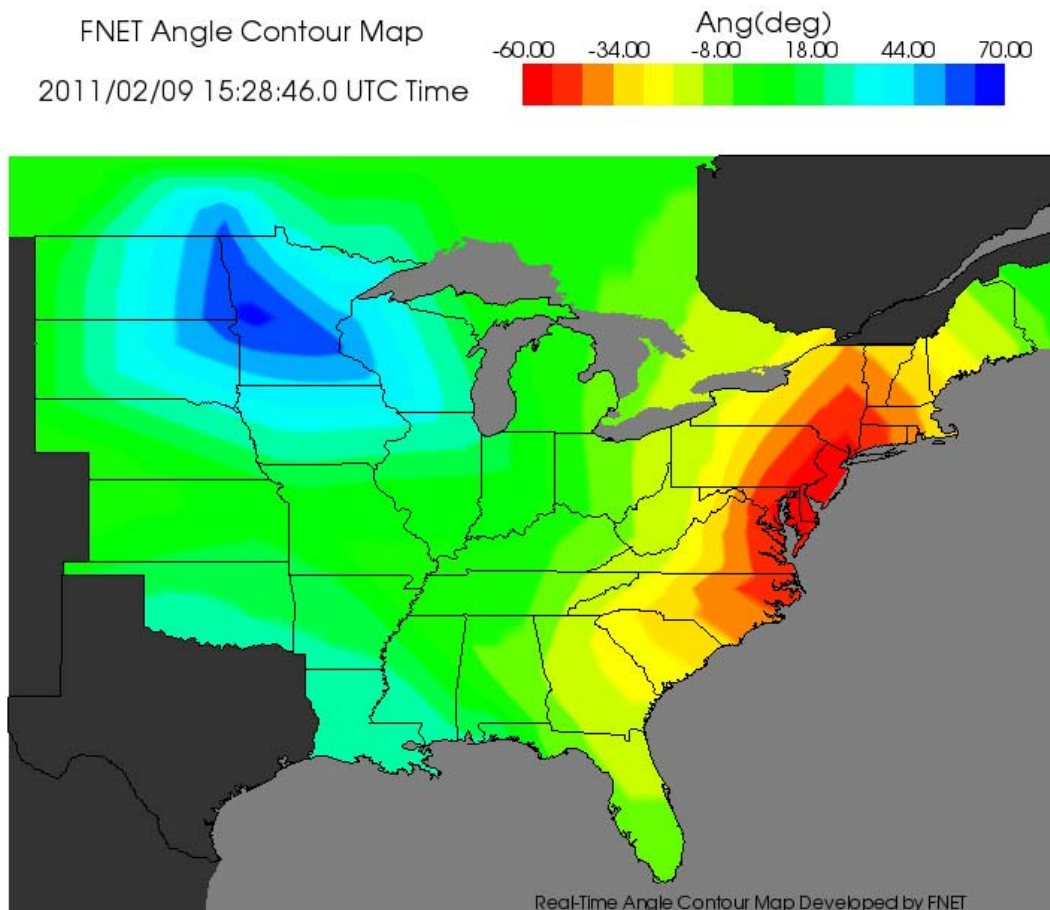FNET GridEye

FNET
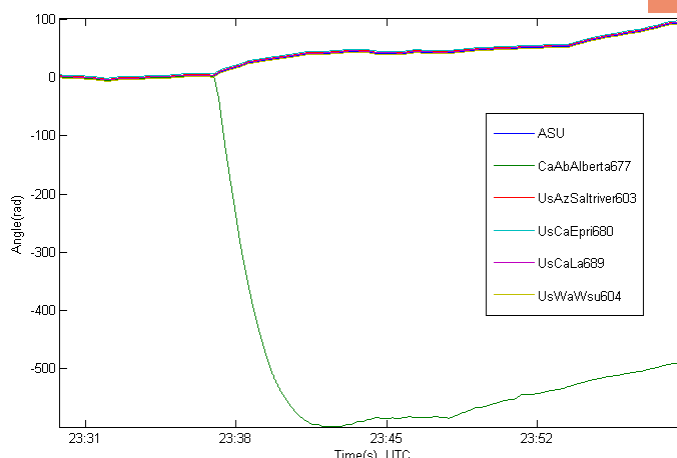
Off Grid Detection for Hospitals and Data Centers

Grid → UPS → Grid Detected

On UPS
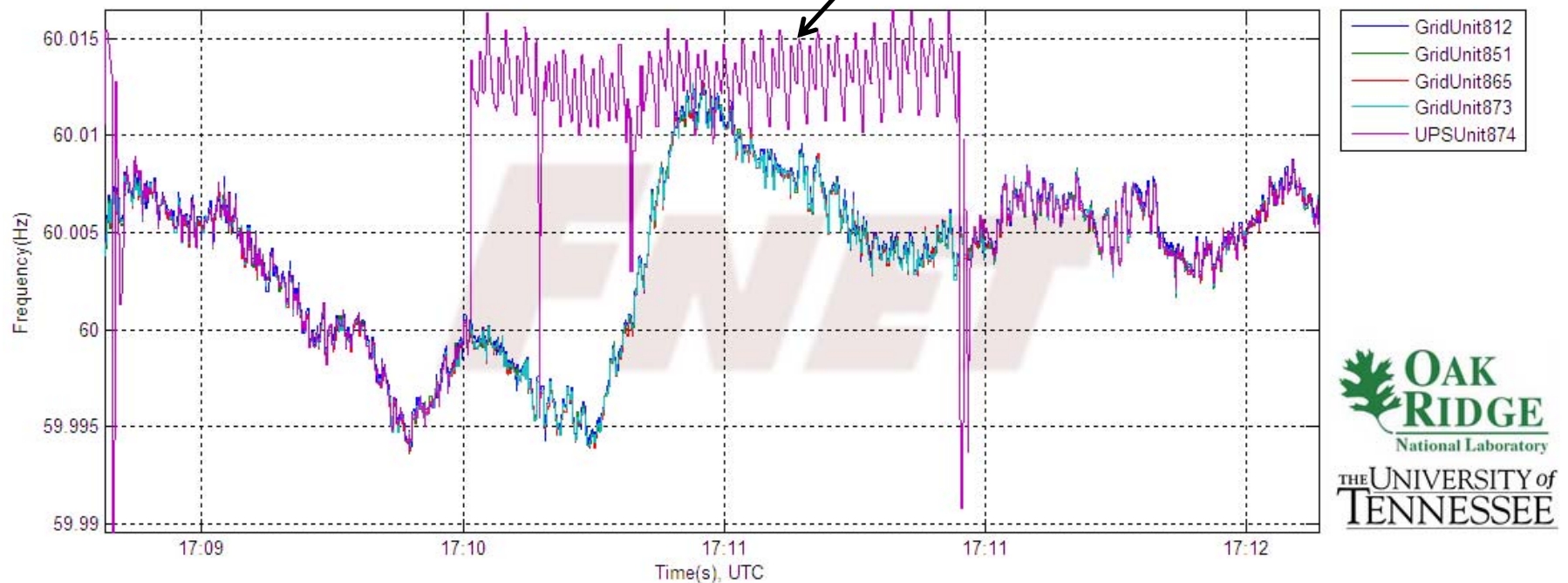
Central alarm system in operation

Real-time Angle Contour Display

FNET Angle Contour Map

Ang(deg)
-60.00 -34.00 -8.00 18.00 44.00 70.00

2011/02/09 15:28:46.0 UTC Time
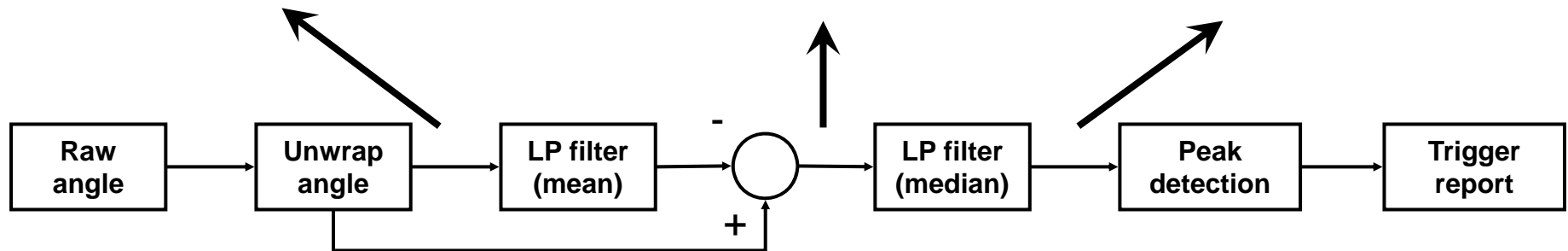
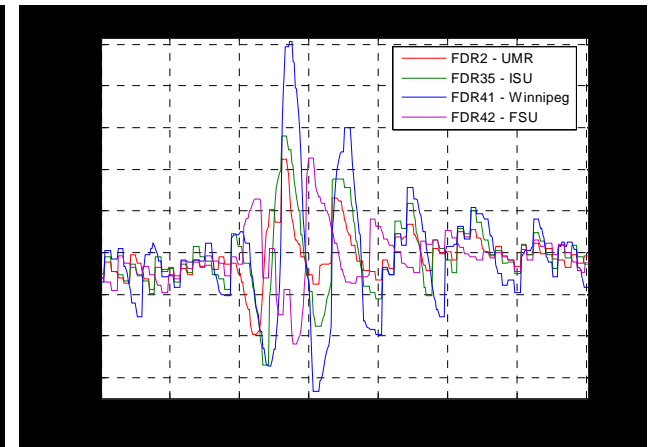Real-Time Angle Contour Map Developed by FNET
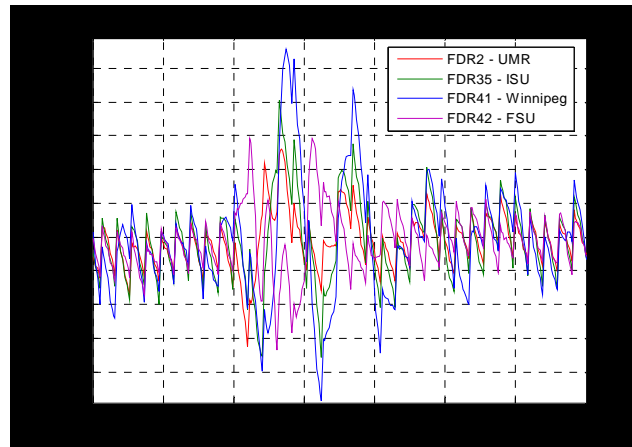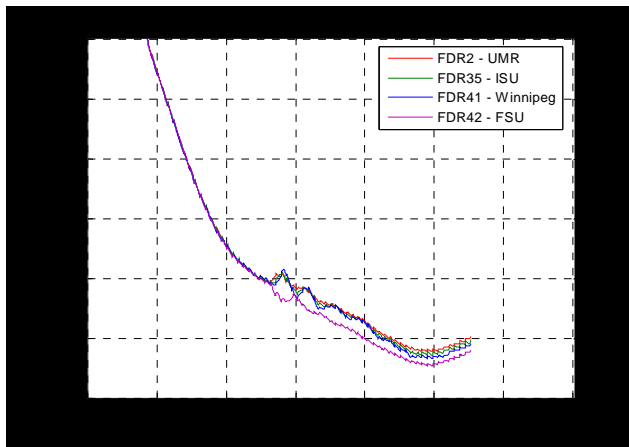
Click to show 24 hour video

Angle change in gen trip

Angle change in HVDC event

Line Trip Trigger and Location Based on Relative Angle

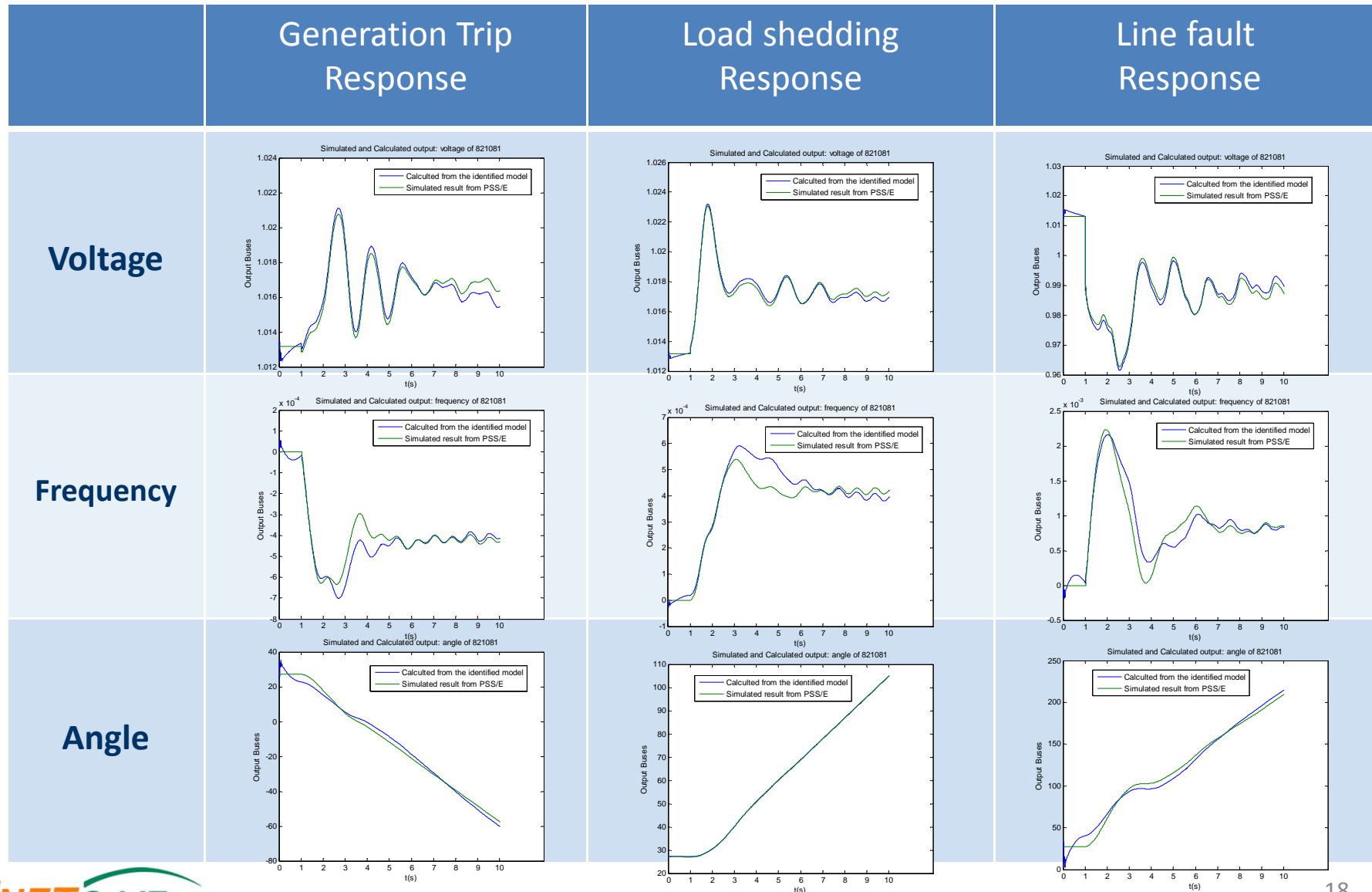| Raw angle | → | Unwrap angle | → | LP filter (mean) | → | ⊖ | → | LP filter (median) | → | Peak detection | → | Trigger report |

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.

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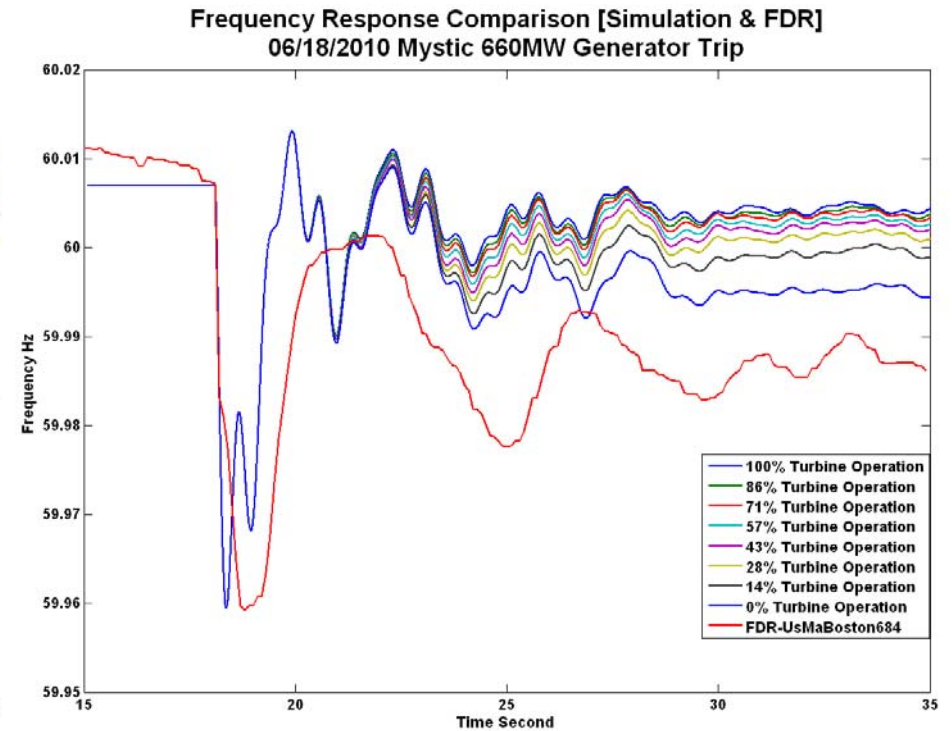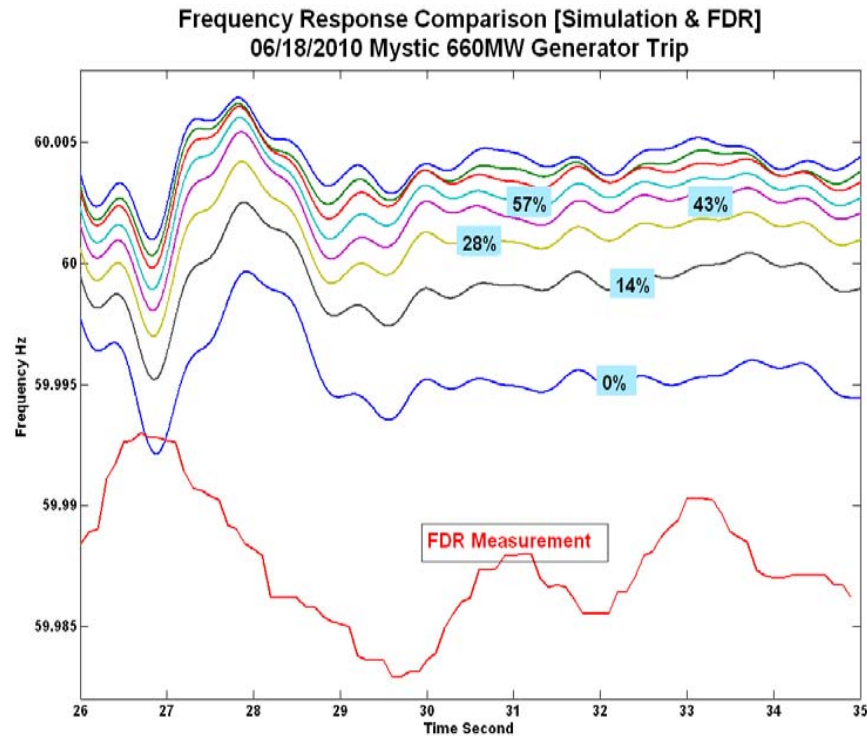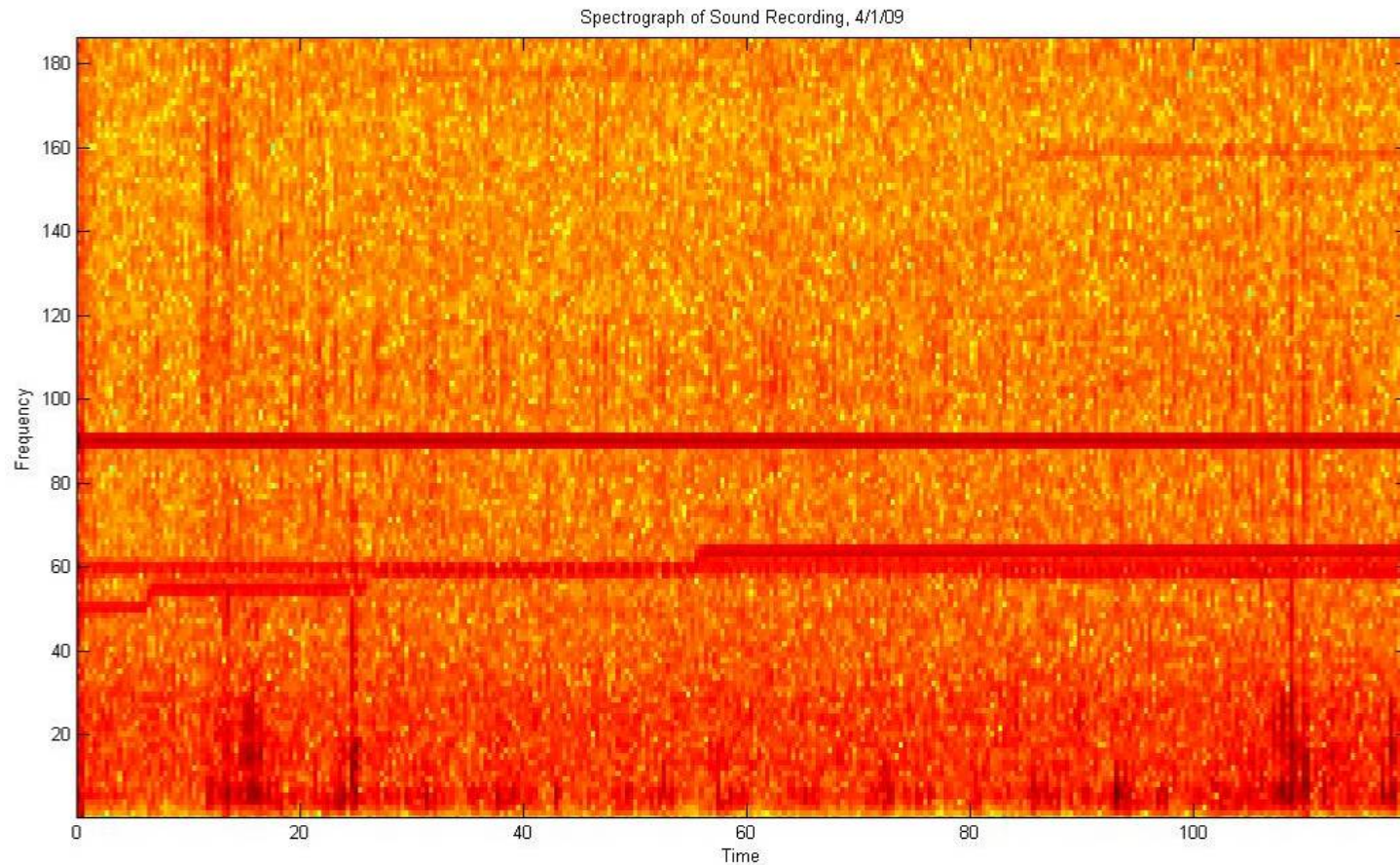

17
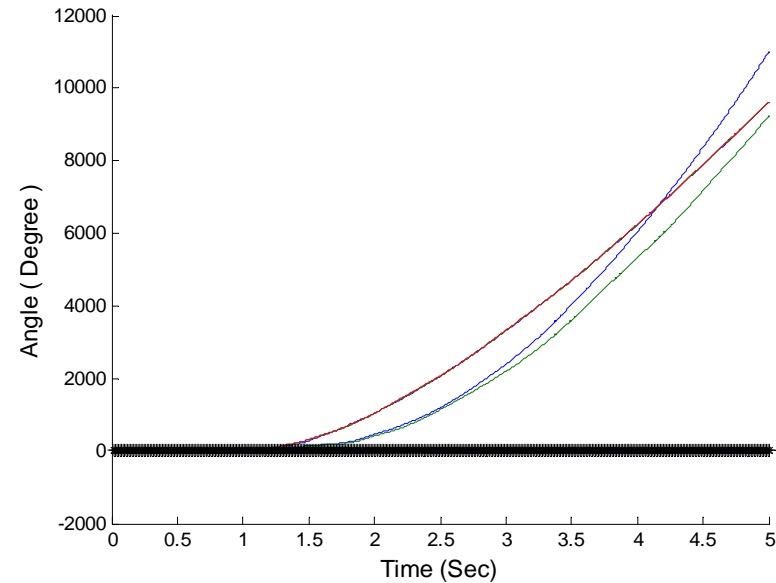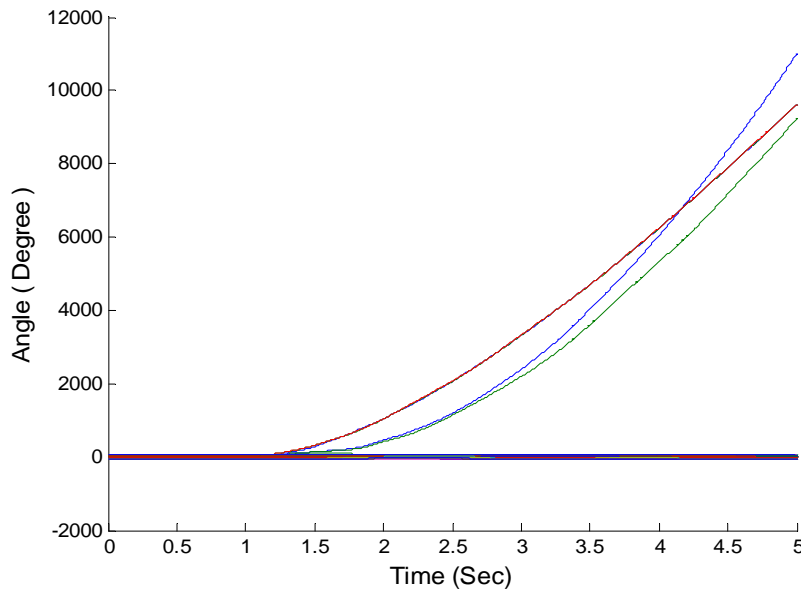
Dynamic Response Estimation

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

18

EI Model Validation
Partial Governor Operation

Frequency Response Comparison [Simulation & FDR]
06/18/2010 Mystic 660MW Generator Trip

Frequency Response Comparison [Simulation & FDR]
06/18/2010 Mystic 660MW Generator Trip

Audio Recording Spectrum

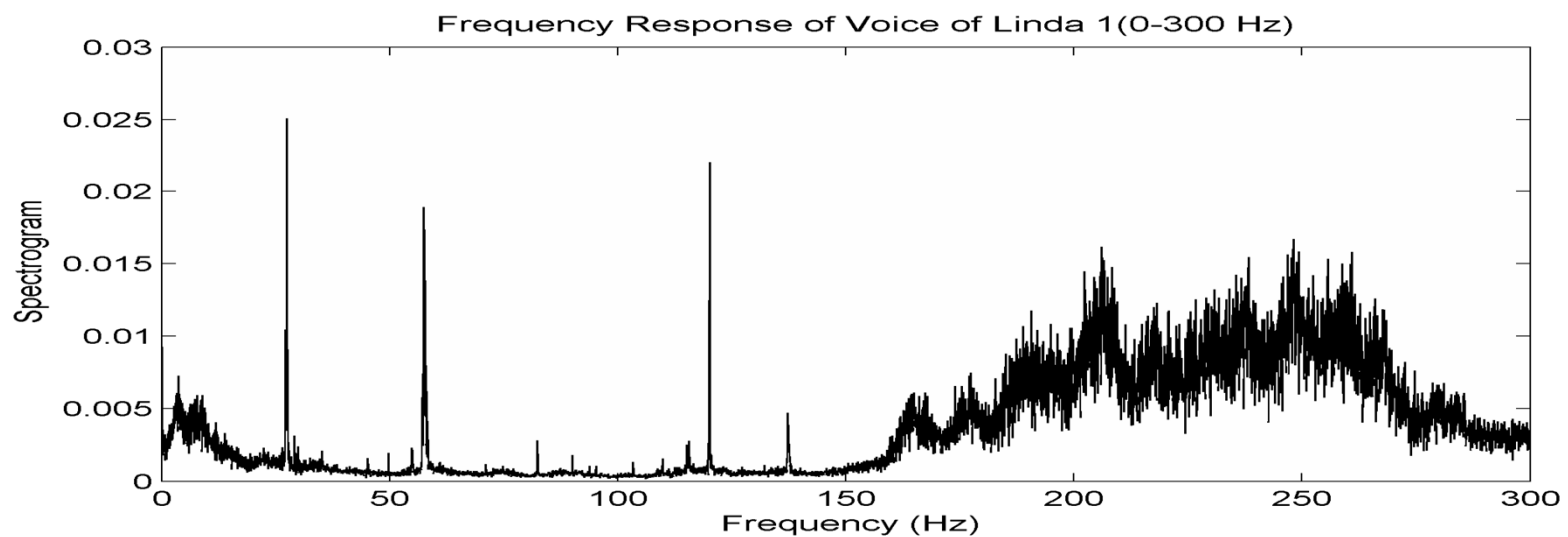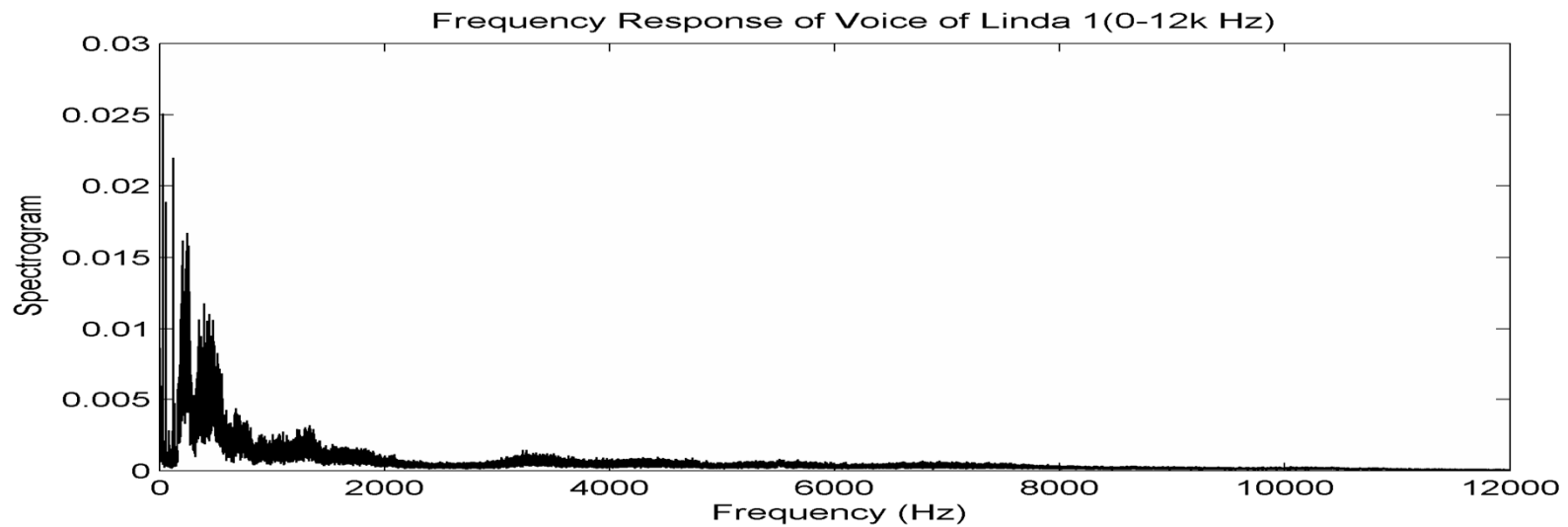Spectrograph of Sound Recording, 4/1/09

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

• Frequency Response of Linda's Voice

Frequency Response of Voice of Linda 1(0-12k Hz)
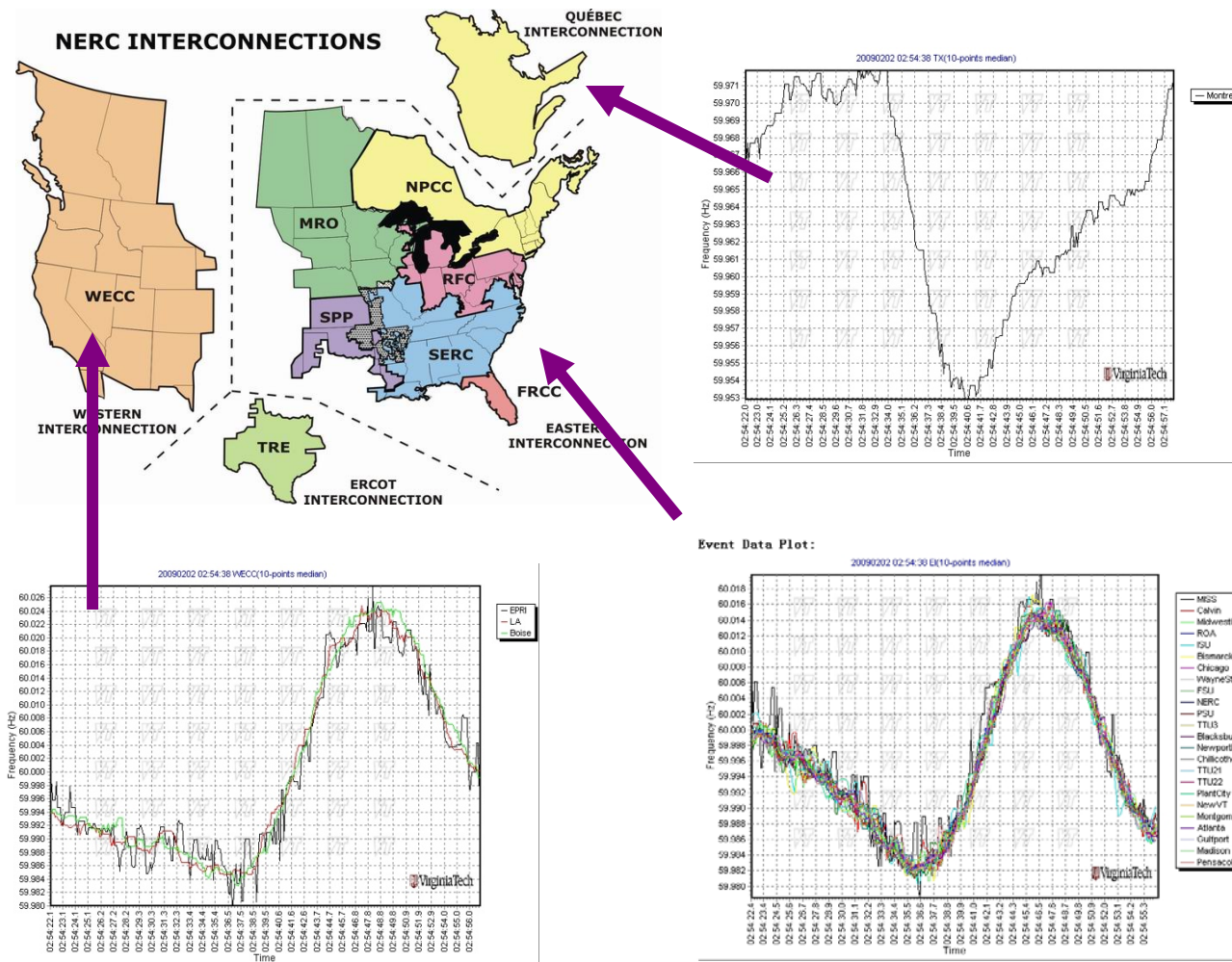

Frequency Response of Voice of Linda 1(0-300 Hz)

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
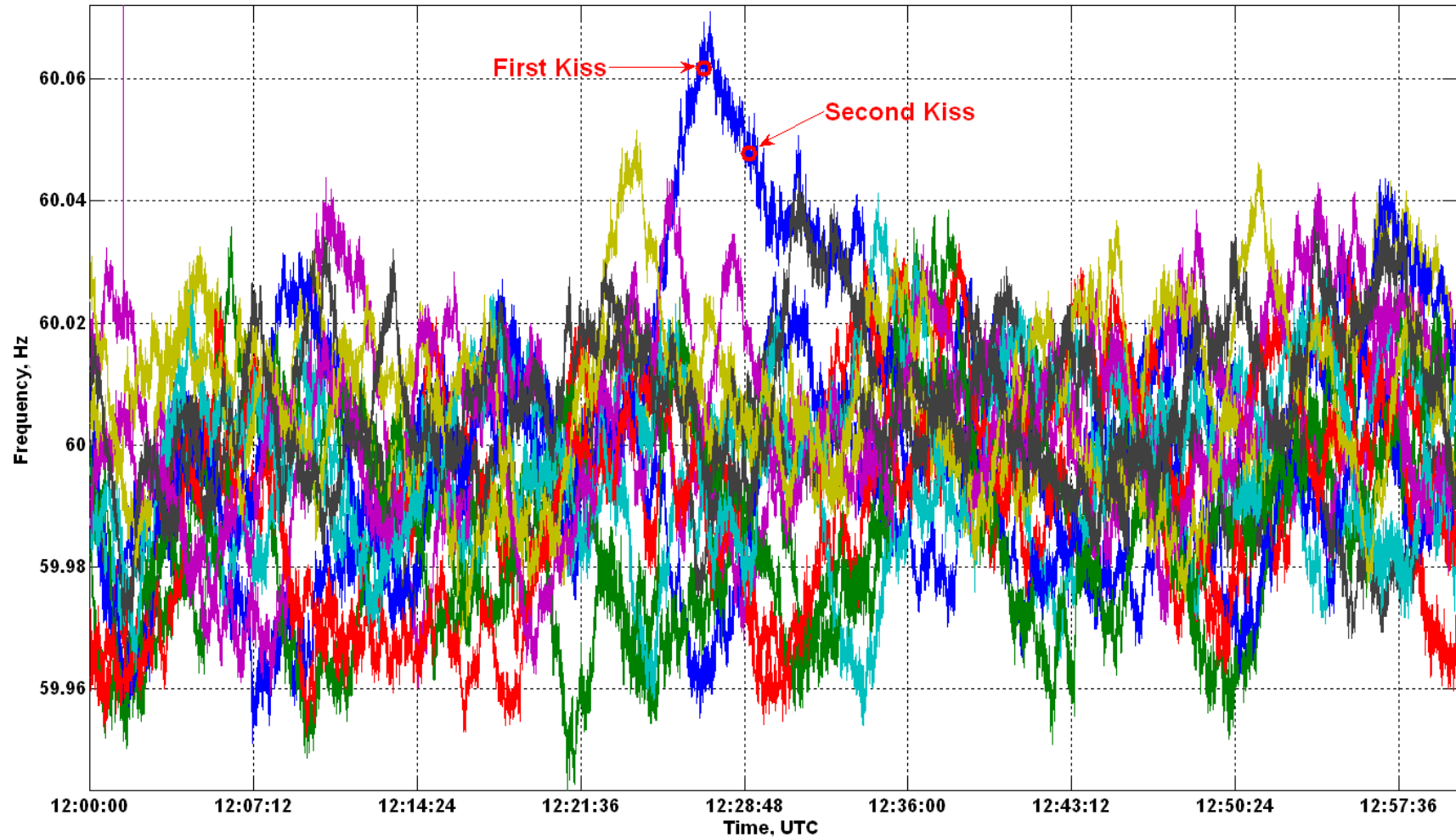- Sample rate: 11kHz
- Recorded from equipment ground loop hum
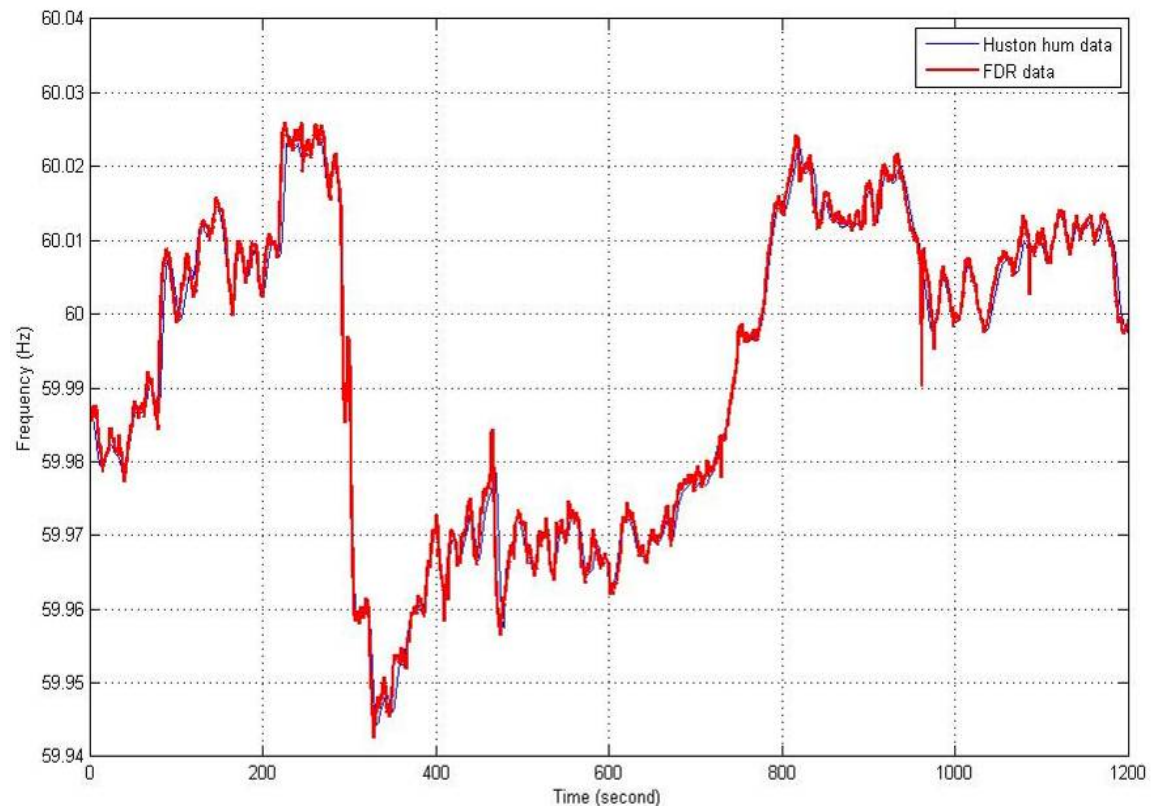
Power grid signature as authentication tool

Super Bowl
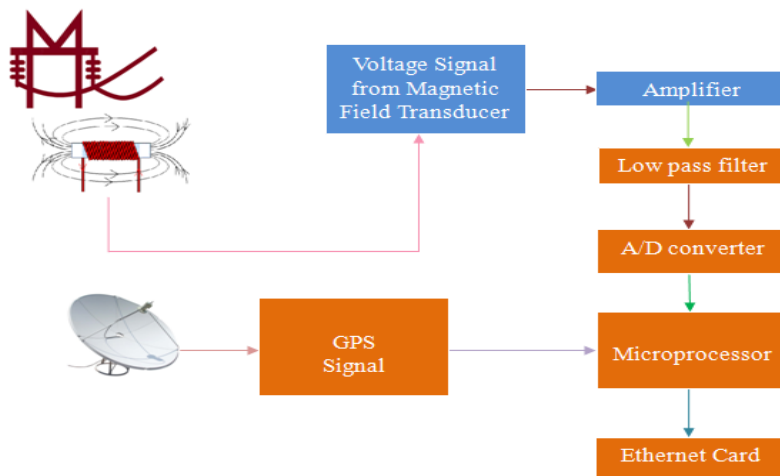# Frequency swings during comercials

FNET GridEye

Royal Wedding

14 Days Frequency Plot

Contactless PMU Development

❀ Magnetic Field Based PMU

Voltage Signal from Magnetic Field Transducer → Amplifier → Low pass filter → A/D converter → Microprocessor → Ethernet Card

GPS Signal → Microprocessor

Framework from Frequency Disturbance Recording Unit

Lab Testing   **Field Testing**

❀ Electric Field Based PMU
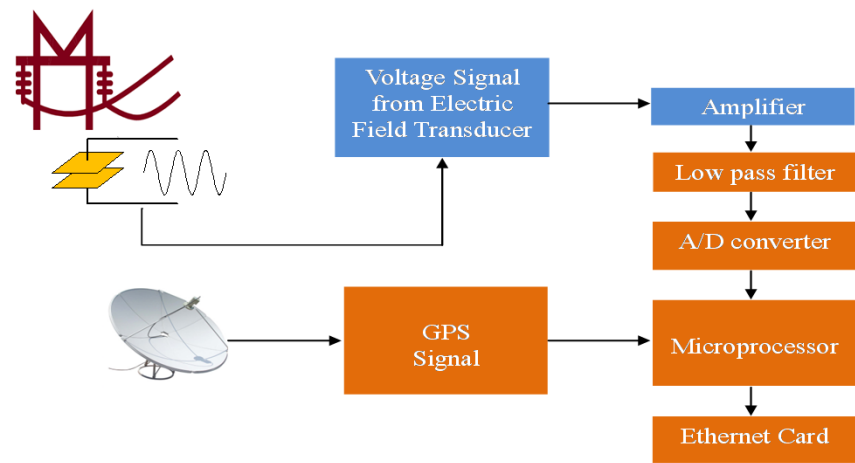
Voltage Signal from Electric Field Transducer → Amplifier → Low pass filter → A/D converter → Microprocessor → Ethernet Card

GPS Signal → Microprocessor

Framework from Frequency Disturbance Recording Unit

Lab Testing   **Field Testing**

FNET GridEye

25
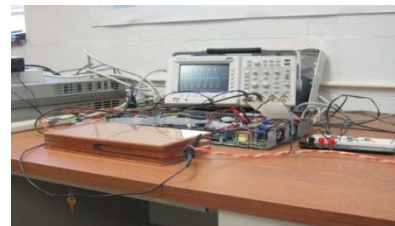
Related web links:

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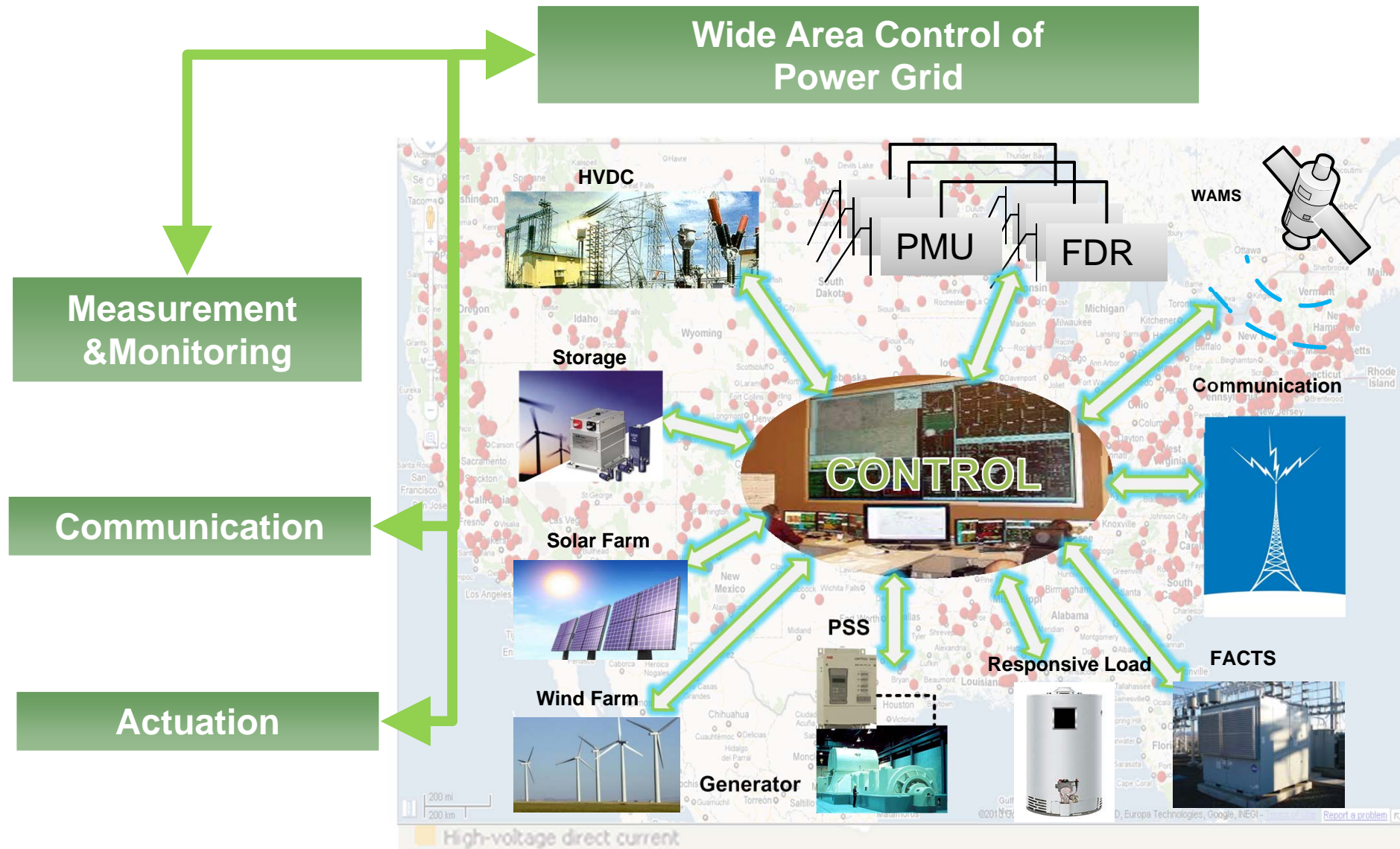
2003 blackout movie: http://www.youtube.com/watch?v=eBucg1tX2Q4&feature=related

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

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

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

FNET GridEye

NSF/DOE ERC for Wide-Area Control

CURENT

Hardware Testbed

Large-Scale System Testbed

Wide-area Control

Wide-area control algorithms, Communication delay, cyber security awareness

Wide-area Actuation

Wide-area actuation, transmission network architecture, Renewable as actuators

Wide-area Monitoring

High precision algorithms, time syn., none-contact measurement, state prediction, visualization

Wide-area ModSimAna

Wide-area dynamics, measurement based model, validation, model estimation, fast computation

Market effect and social impact
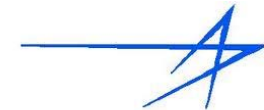
FNET Sponsors & Students
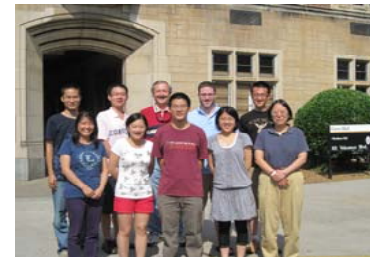

The FNET Team, 2006   2007   2009   2010   2011

FNET GridEye