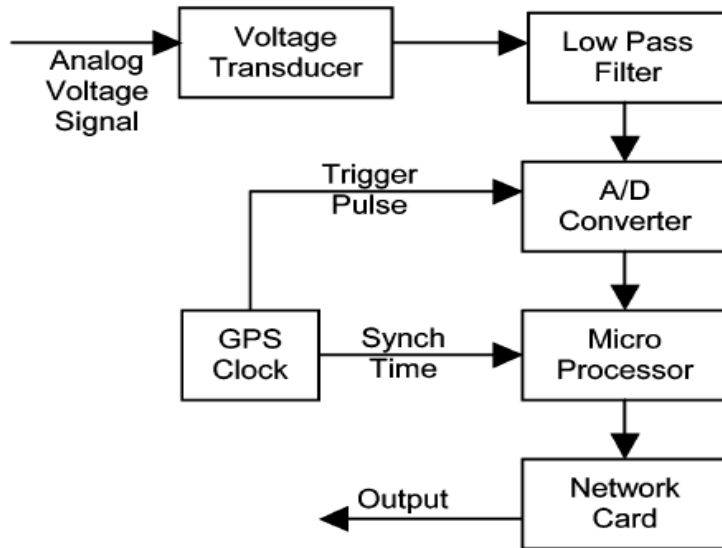


Distribution Level Synchronous Measurement and Its Applications

Dr. Yilu Liu
Governor's Chair Professor
The University of Tennessee, Oak Ridge National Laboratory

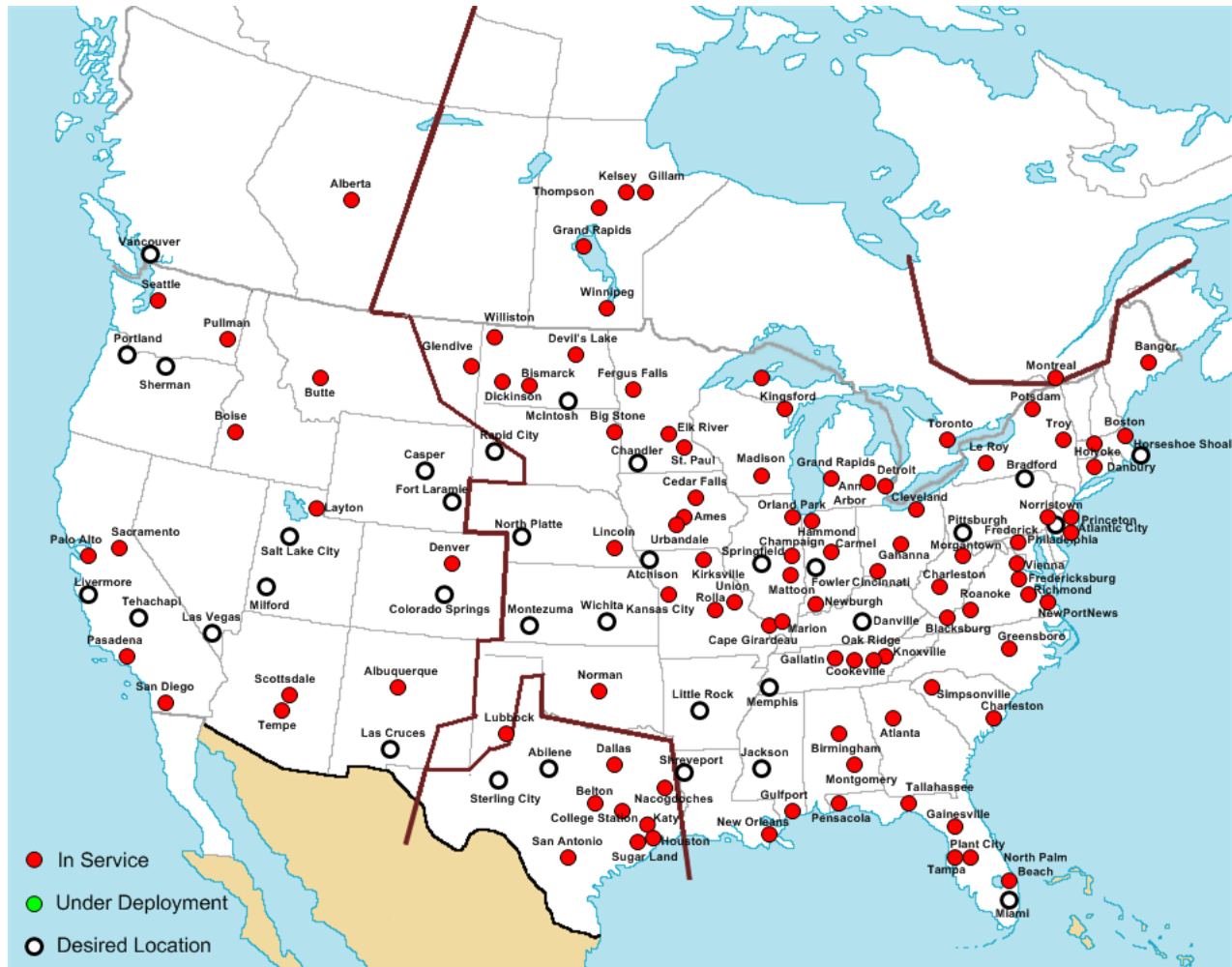
Liu@utk.edu
865 266 3597

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

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

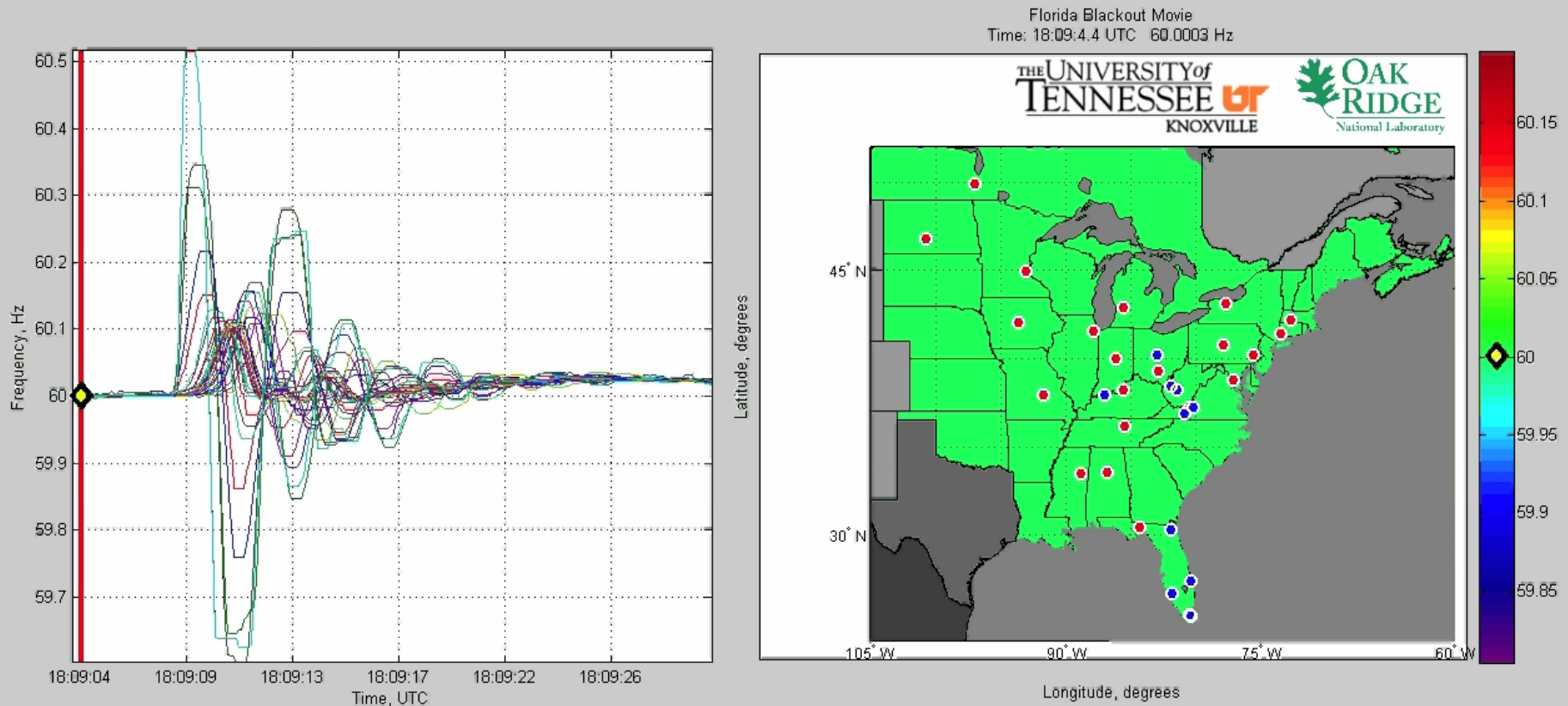


Worldwide Deployment Map

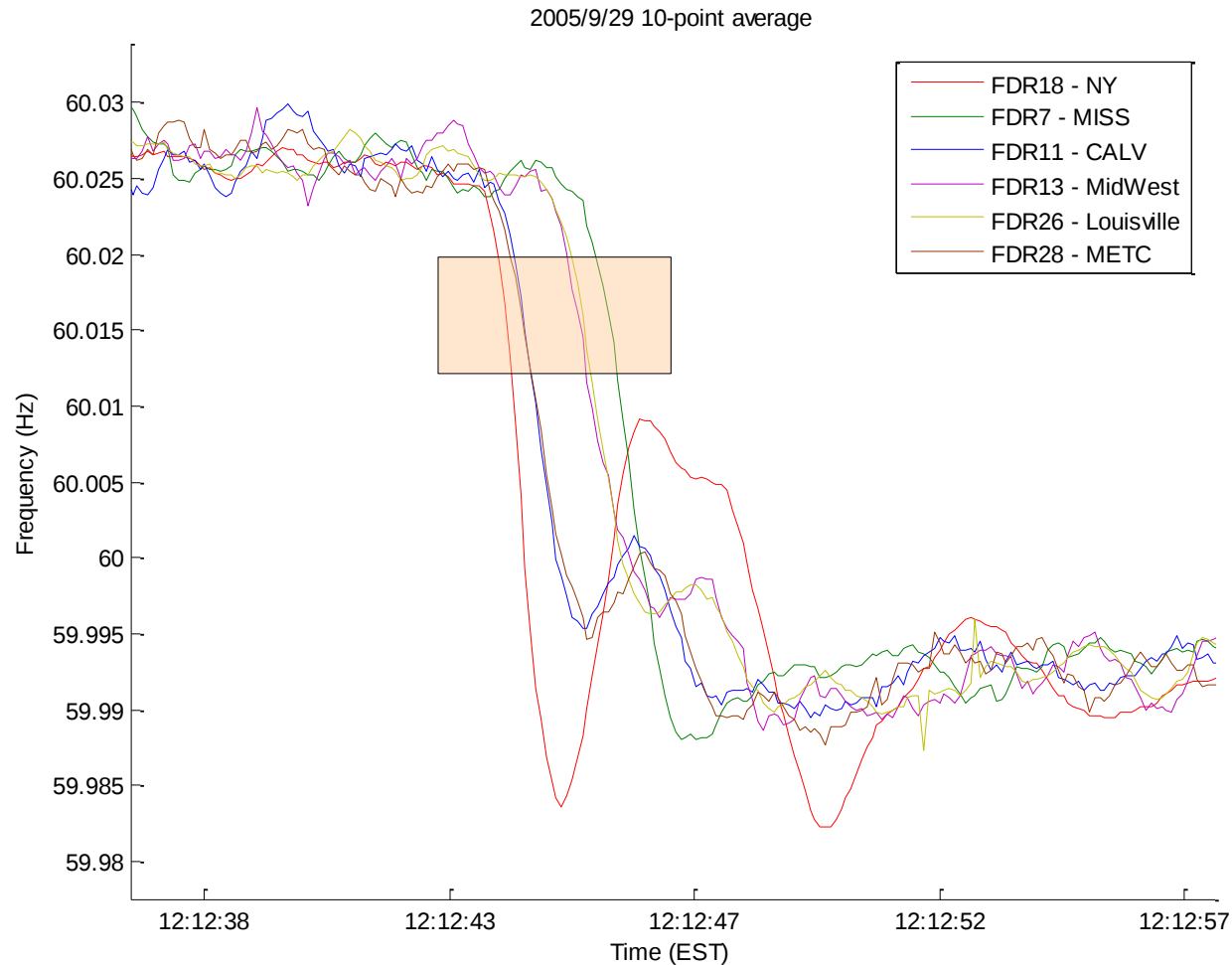


Disturbance Propagation Playback FNET and PMU measurements 2-26-08

Florida Generator Trip Replay from Measurement



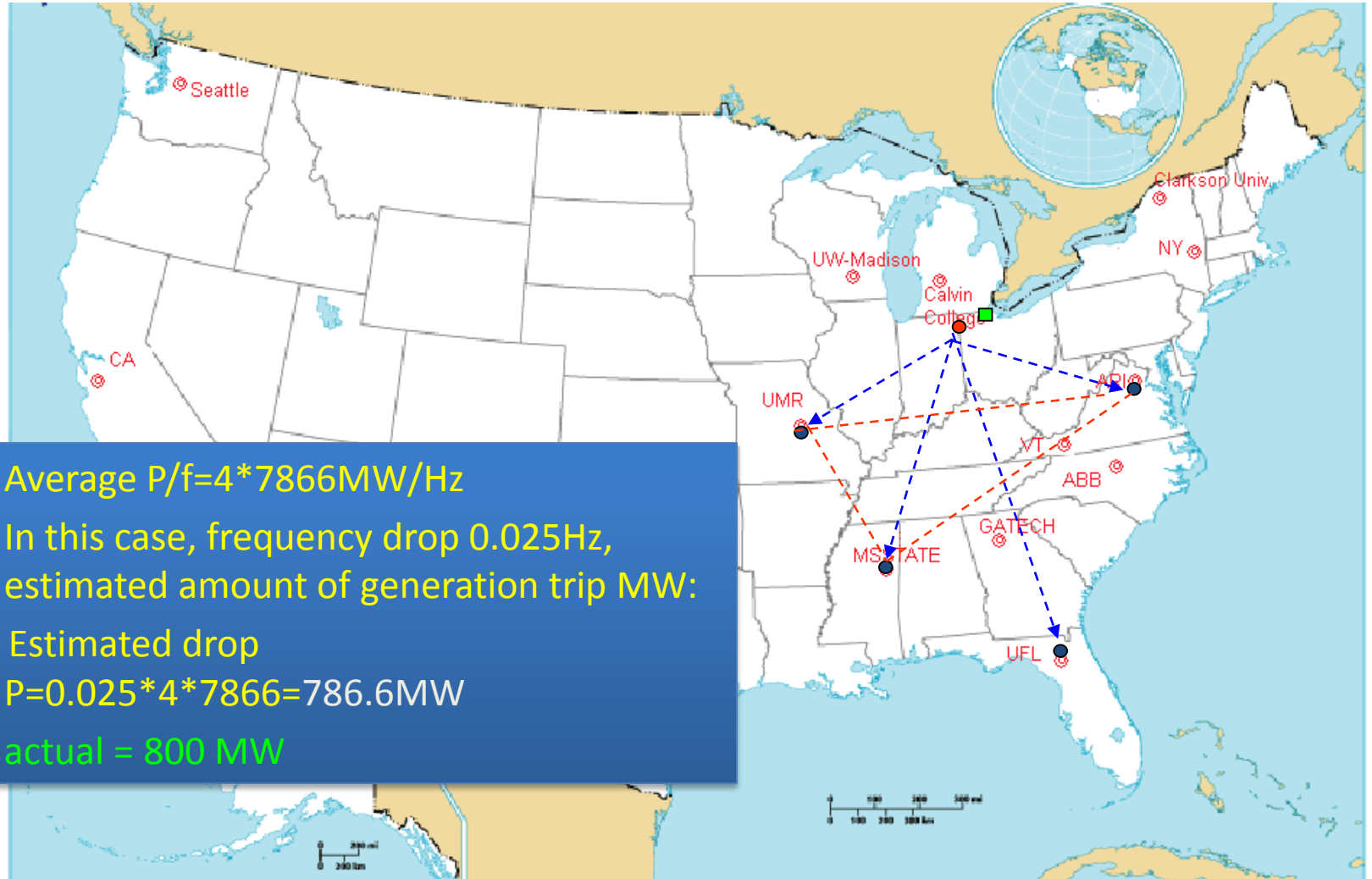
On-line Event Location



US Patent: 7519454,7765034

Triangulation of event location

Red dot estimated location, Green square is actual location



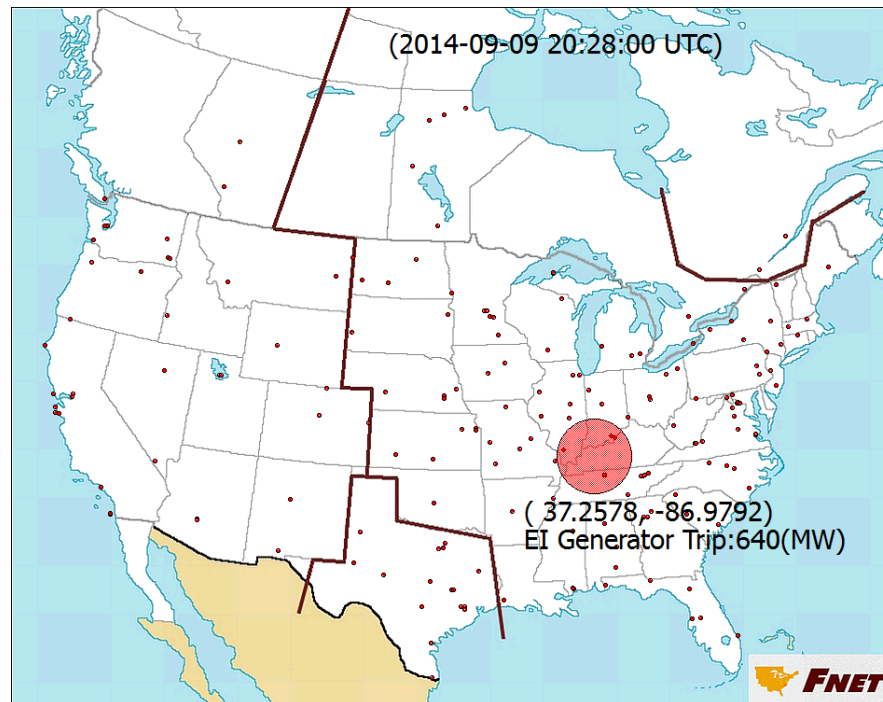
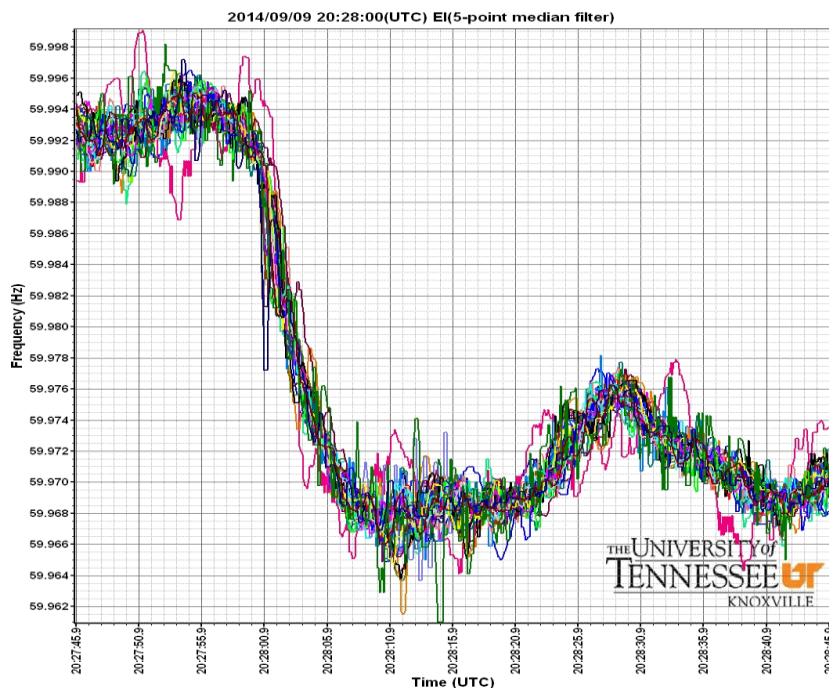
- Average $P/f = 4 * 7866 \text{ MW/Hz}$
- In this case, frequency drop 0.025 Hz ,
estimated amount of generation trip MW:
Estimated drop
 $P = 0.025 * 4 * 7866 = 786.6 \text{ MW}$
- actual = 800 MW

Sample automatic event alert

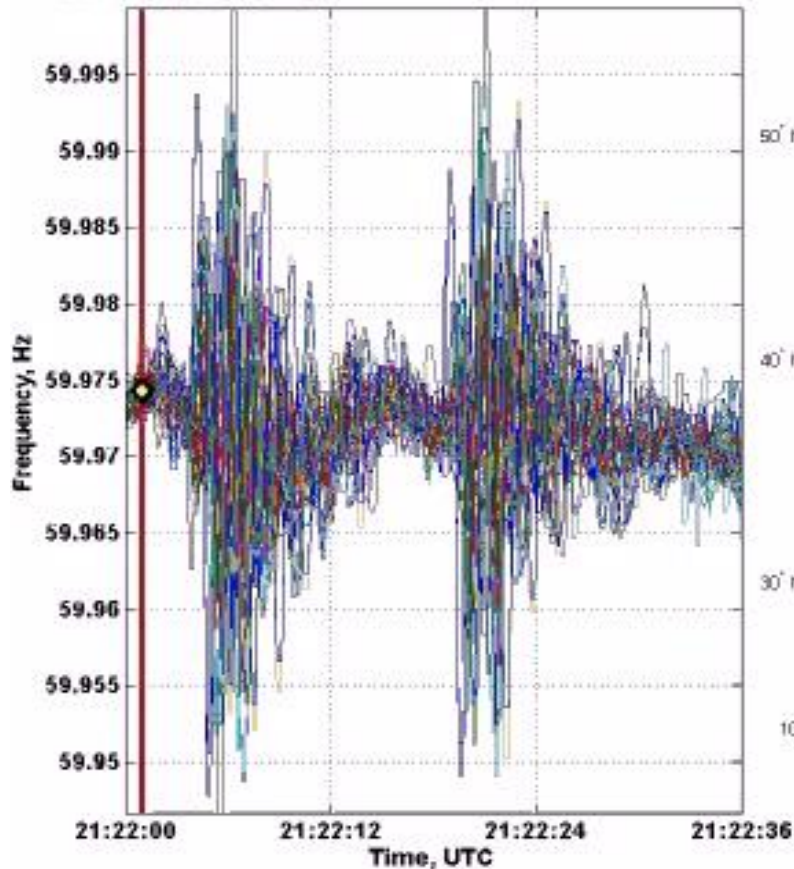
Event Estimation:

640MW EI Generator Trip at 20:28:00UTC, on 09/09/2014 near Paradise power plant (SERC)
((Muhlenberg,KY,42337; Latitude: 37.2578, Longitude: -86.9792)

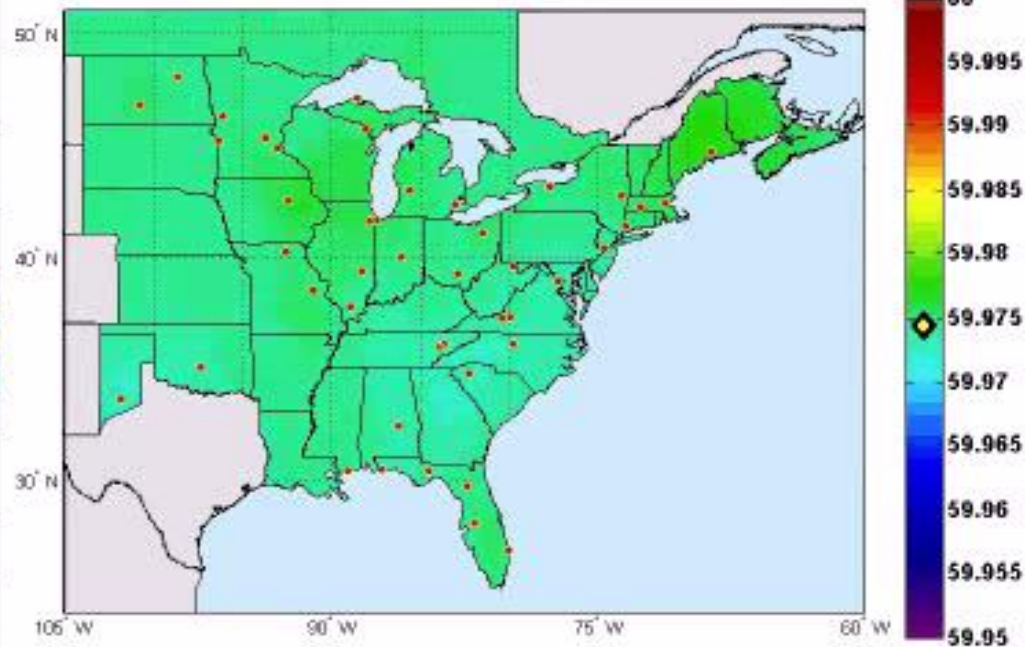
PLEASE KEEP THIS INFORMATION CONFIDENTIAL.



Frequency Disturbance Propagation

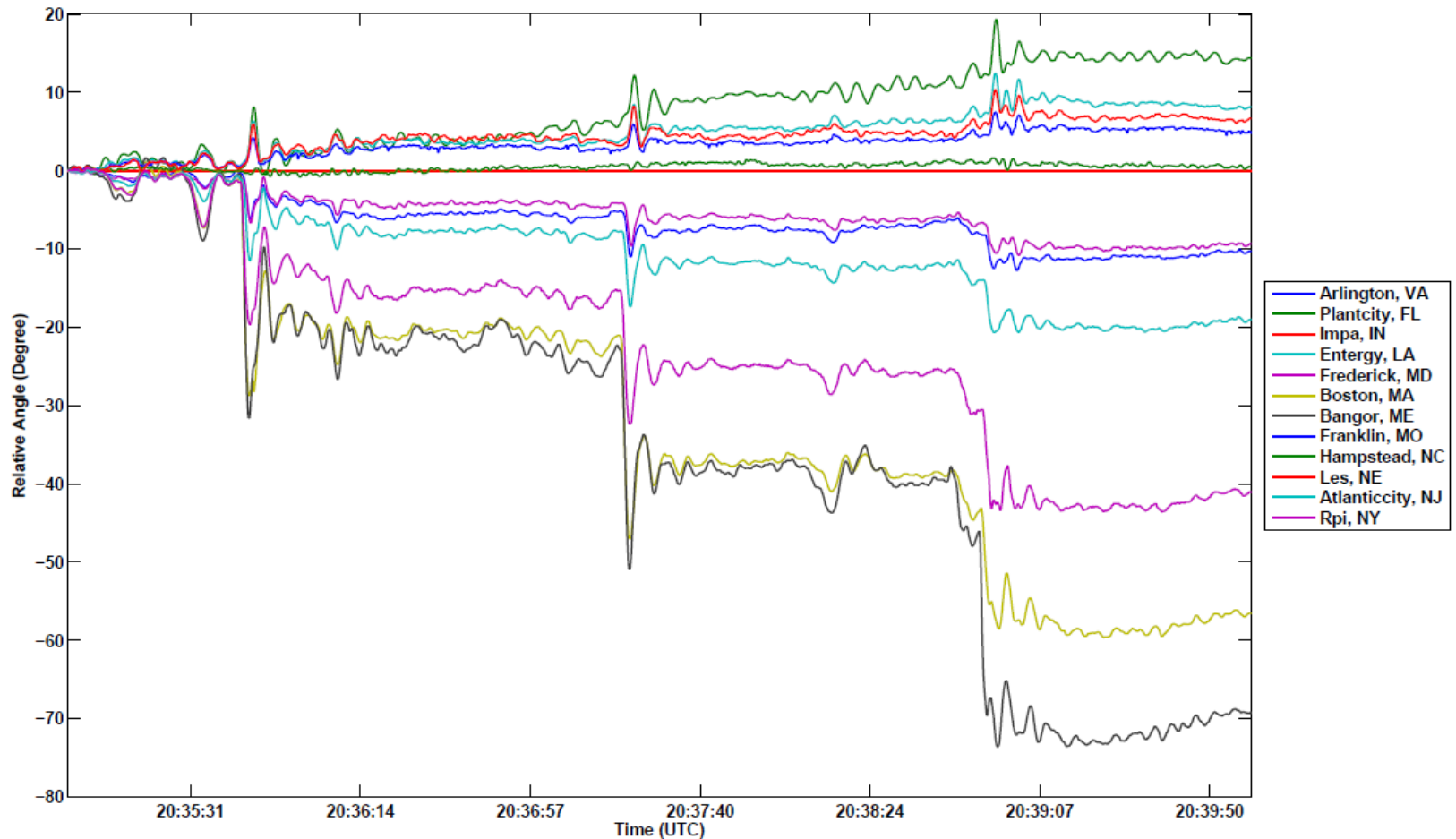


FNET Data Display [4/27/2011 Oscillation]
Time: 21:22:1.0 UTC 59.9743 Hz

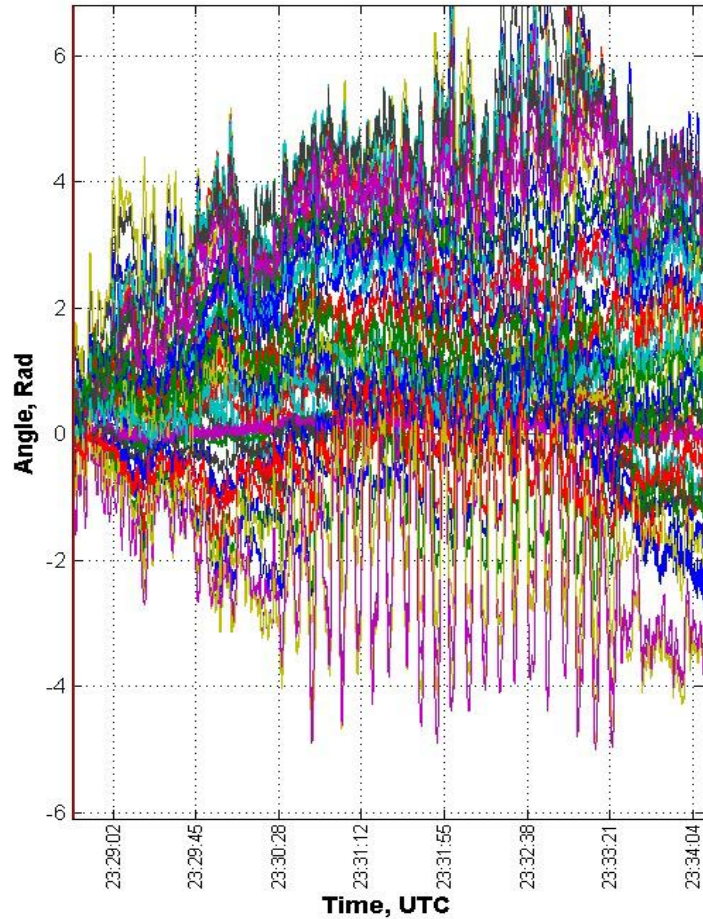


III. Case Study:

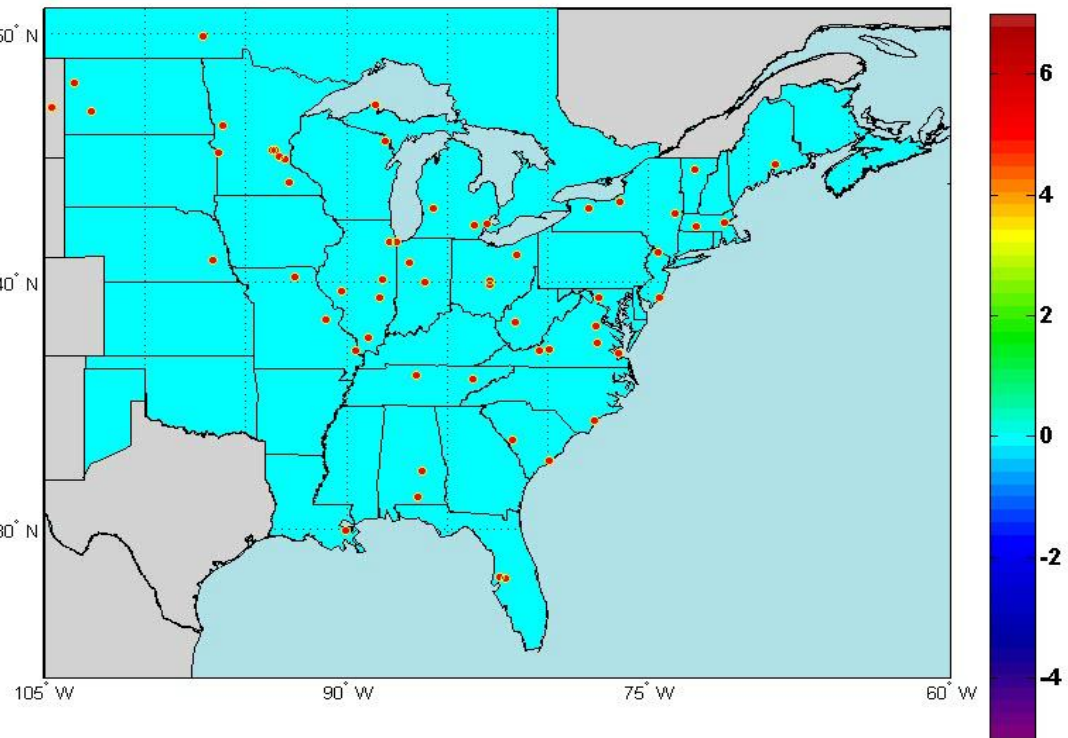
Relative phase angle in EI



Forced Oscillation Playback



FNET Angle Data Display [4/5/2013 Oscillation]
Time: 23:28:41.0 UTC

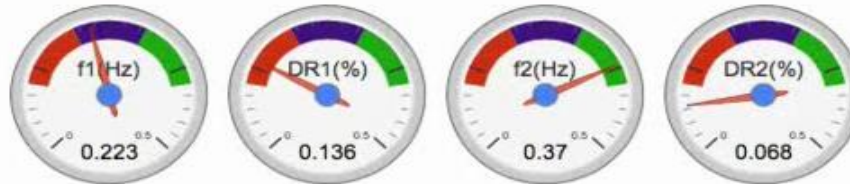


Ambient Online Oscillation Mode Monitor

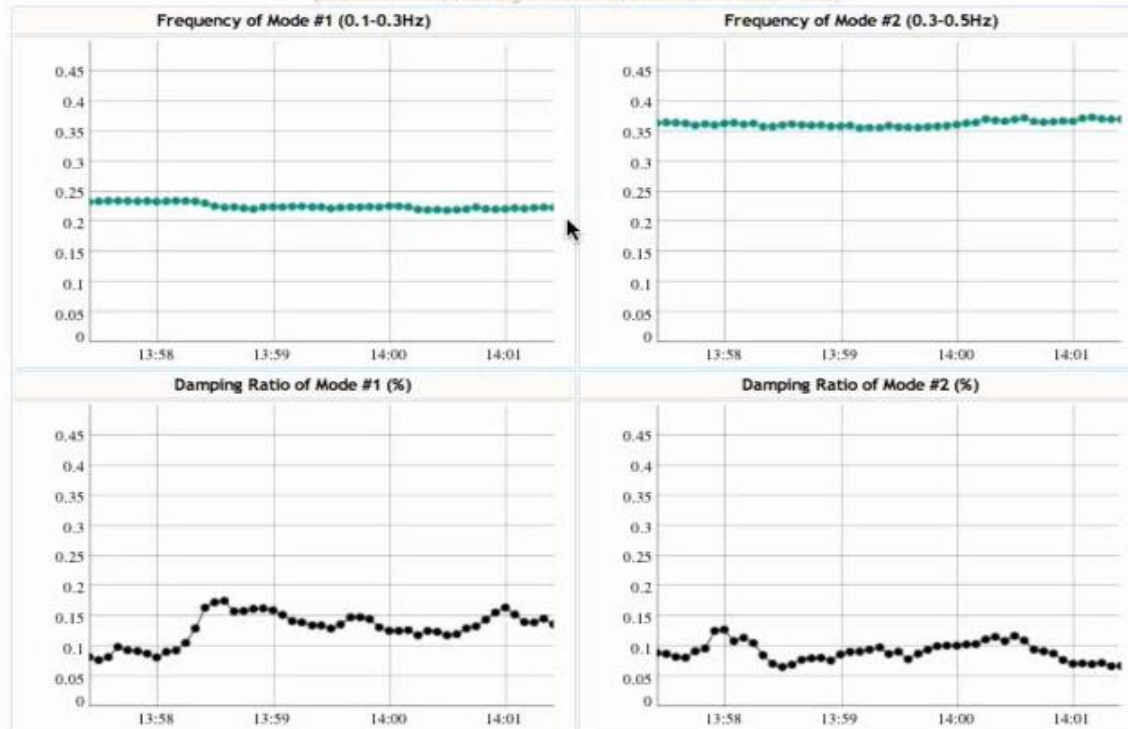
fnettest.eecs.utk.edu

FNET Mode Estimation Result

INTERCONNECTION: FDR:



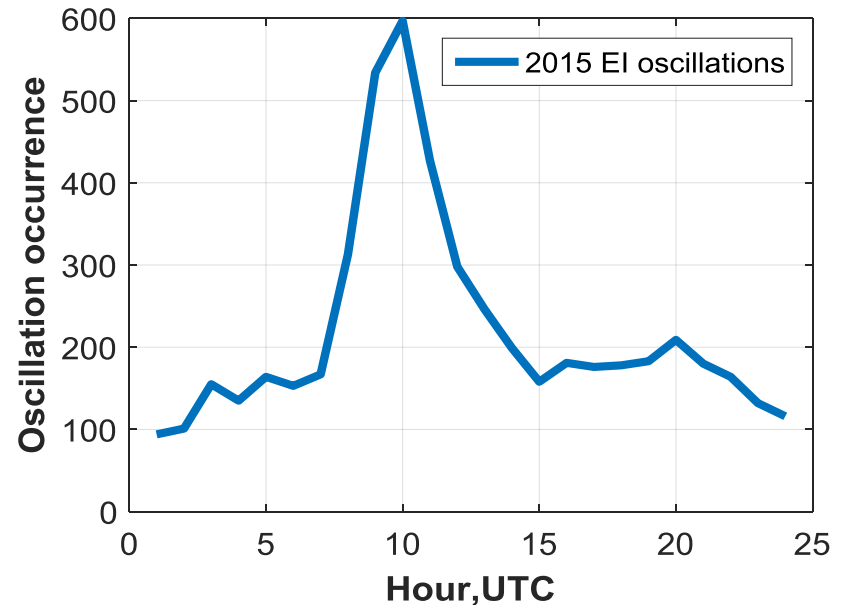
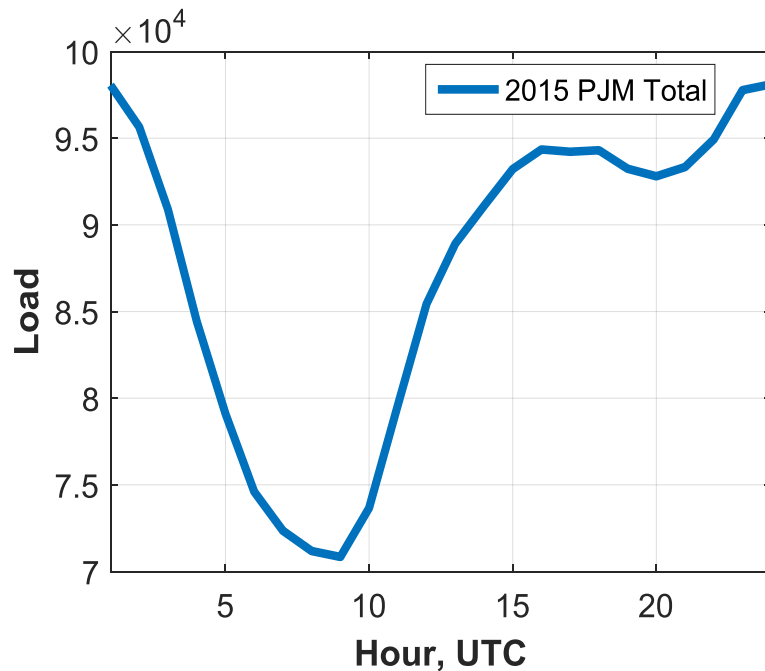
(Duration for 5mins; Select Region to Zoom In, Double Click to Return Normal)



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Hourly Analysis – Oscillation Occurrence



It can be observed that the detected oscillation numbers are highly associated with the daily load profile, which may be explained by the fact that a disturbance can potentially cause more severe frequency deviations under light-loaded conditions. So more oscillations can be detected during that time.

Islanding Detection – Bulk & Micro Grid

• Case 1 (EI 09/18/2007 10:21:23 UTC)

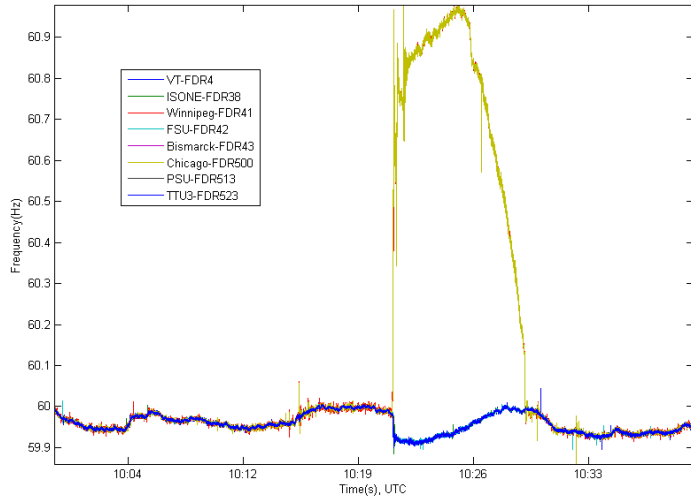


Fig. 1

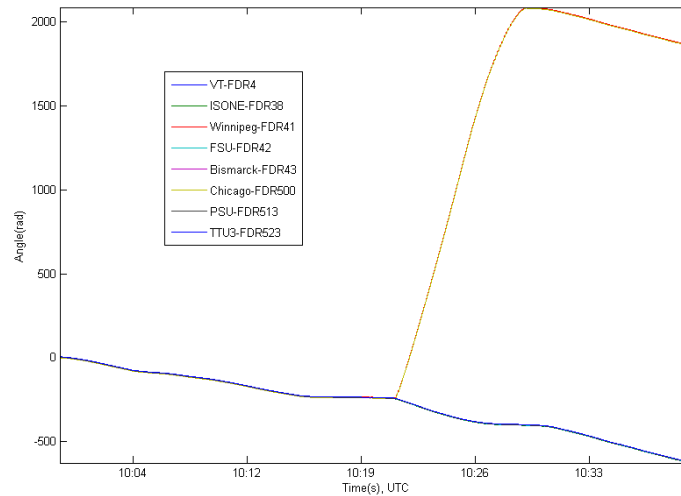


Fig. 2

$ \Delta f_{\max} $	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
$ \theta_{t+\Delta t_{tr}} - \theta_t _{\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)

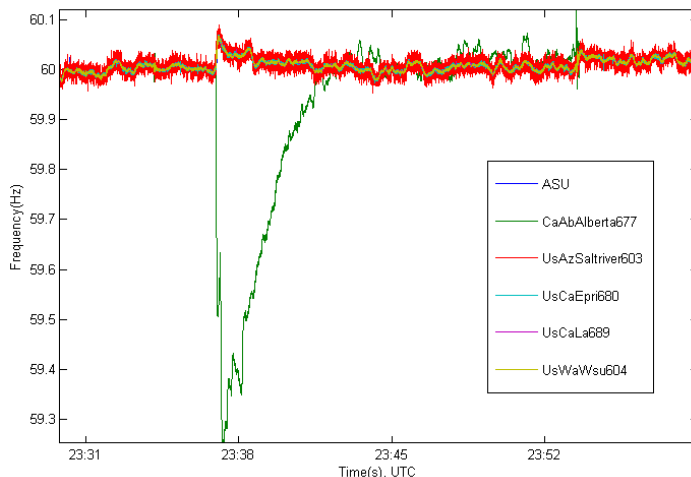


Fig. 3

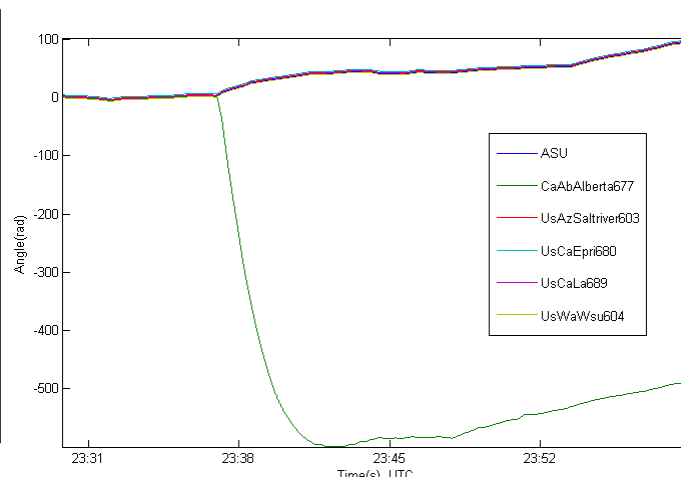


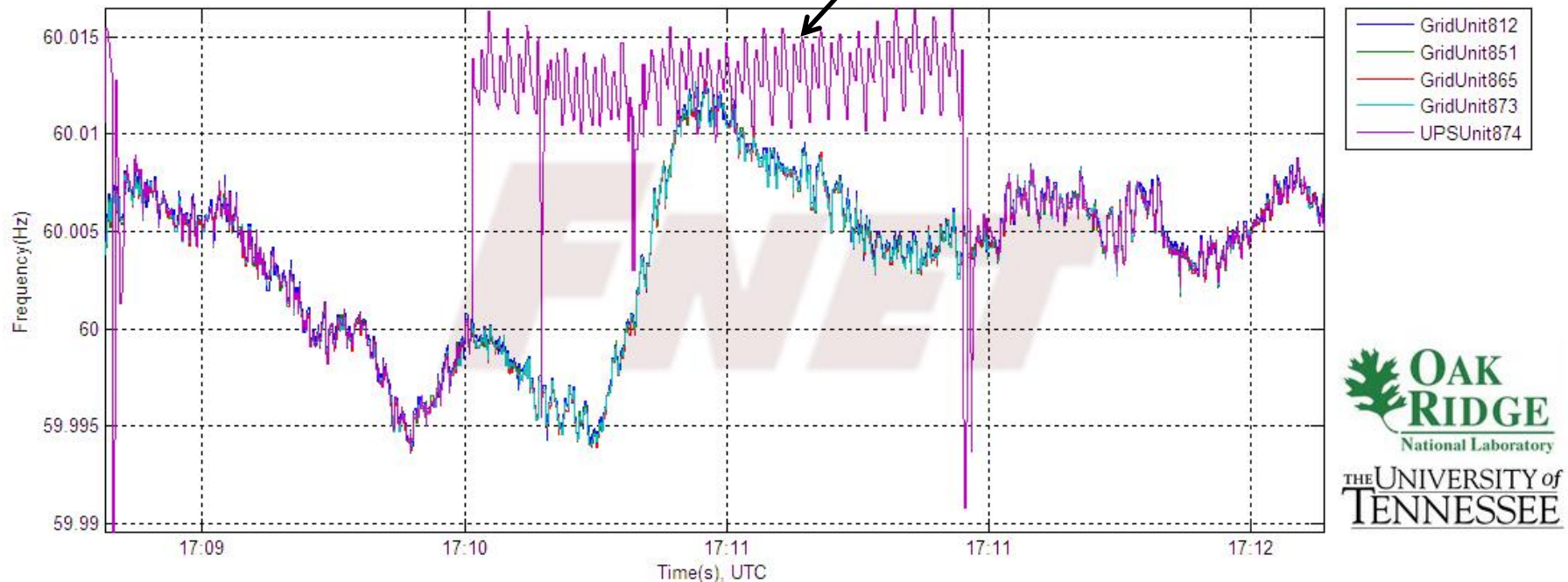
Fig. 4

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

Off Grid Detection for Hospitals and Data Centers

Grid → UPS → Grid Detected

On UPS



Central alarm system

Sample Loss of Grid Power Alert System



A Backup Alert was just issued with the following details:

FDR Unit ID: 861

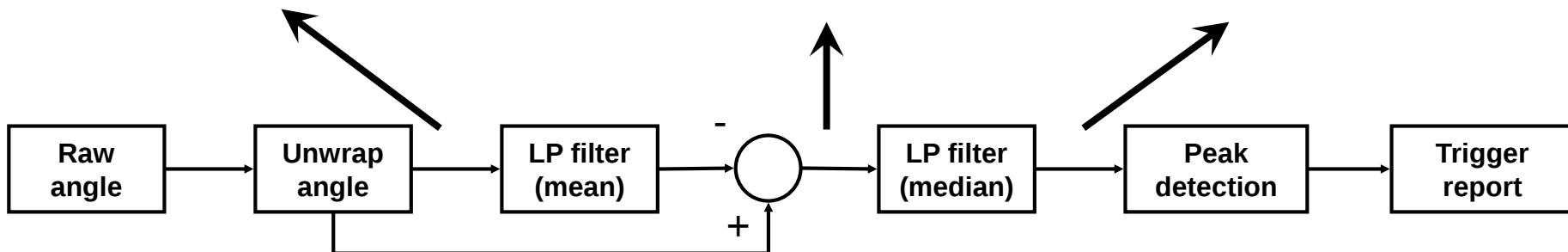
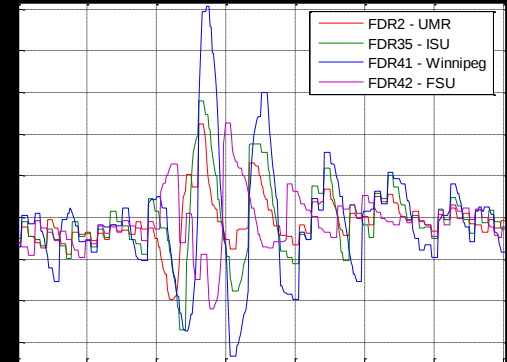
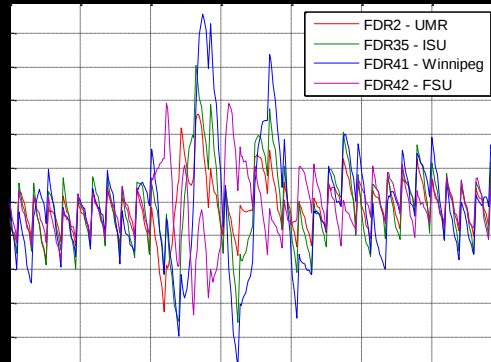
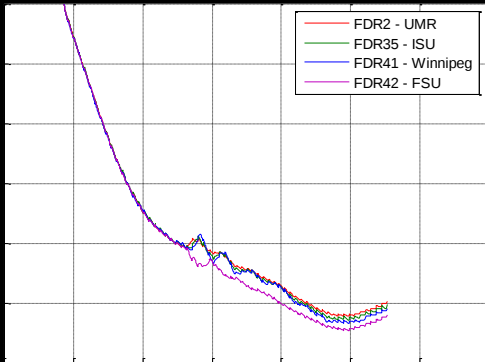
Location: Frederick, MD, US

Date: 6/7/2012 11:30:02 AM

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

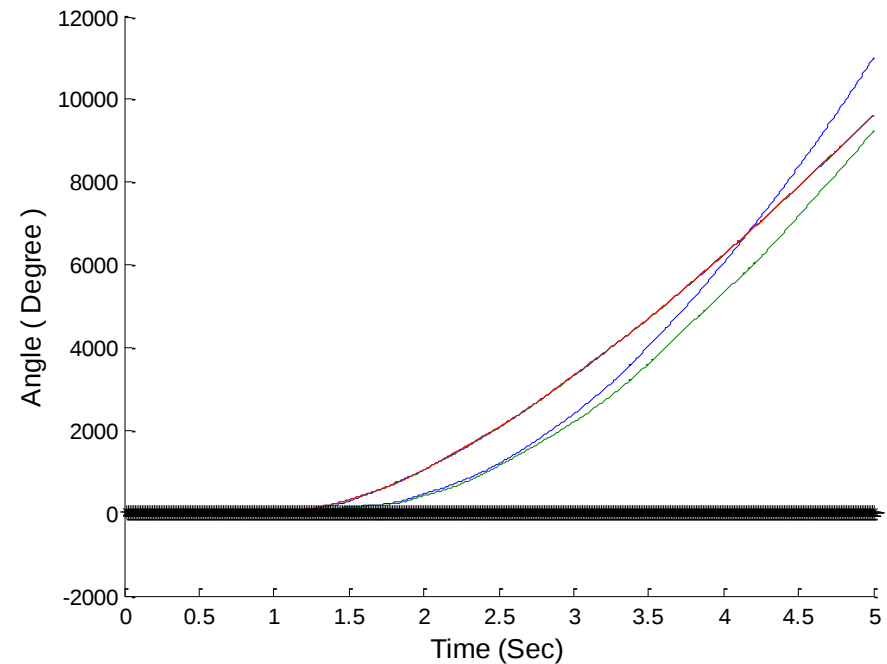
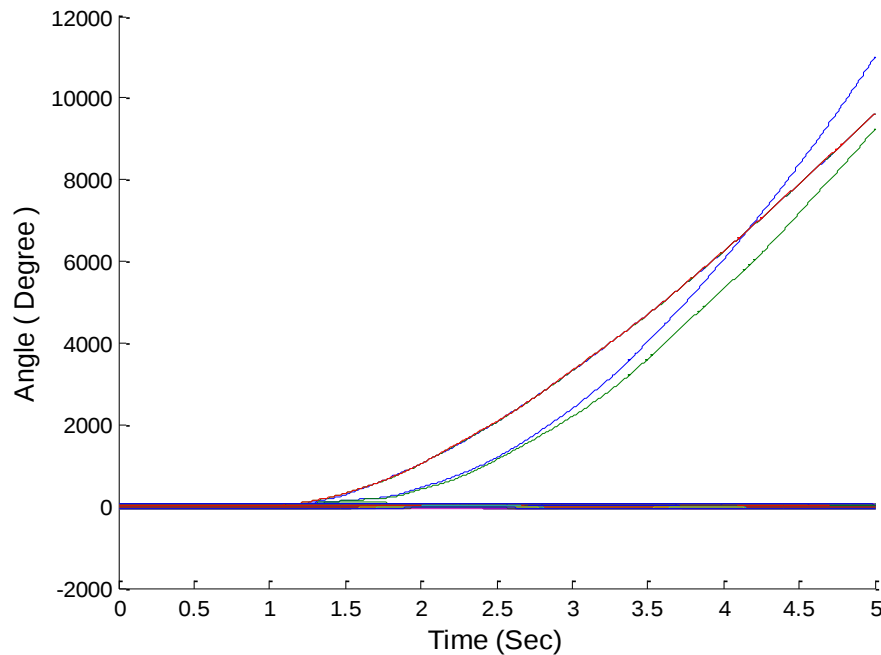


Line Trip Detection and Location Based on Relative Angle



Stability Monitoring

Incremental Center-of-Inertia (COI) angle vs. individual machine bus angle difference as indicator of stability



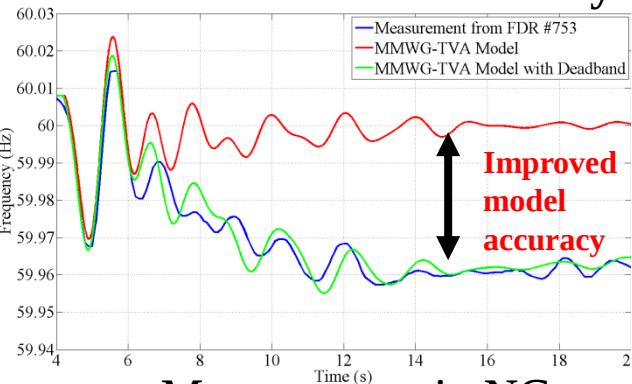
Online Event Alert Summary

- **Generator trip report with MW and location estimate**
- **Oscillation alerts and reports**
- **Islanding or off-grid detection and alert**
- **Line trip detection and alert**
- **Low inertial alert**
- **Forced oscillation detection and alert**
- **FIDVR alert**

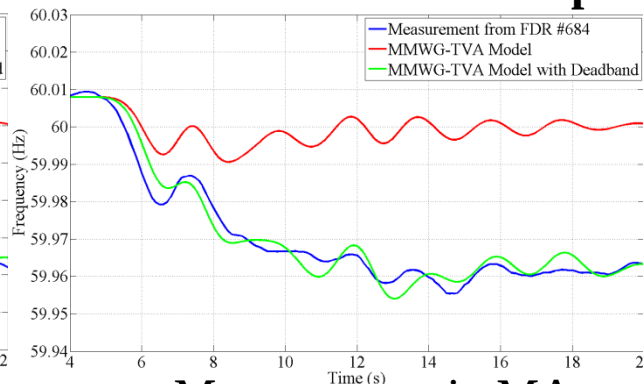
Synchrophasor-based Dynamic Model Validation on the Eastern Interconnection with Governor Deadband

- Synchrophasor measurement collected by FNET/GridEye is used to calibrate the simulated frequency response.
- Governor deadband is adjusted by measurements to reflect the actual system performance.

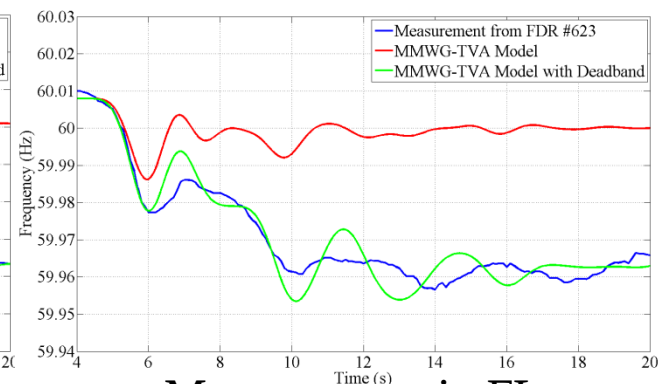
Case Study: a 1100 MW Generation Trip in North Carolina



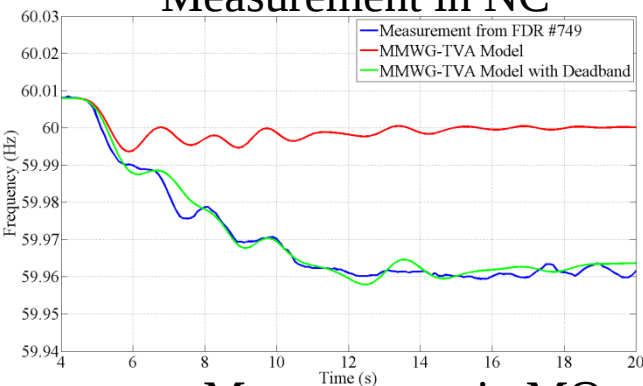
Measurement in NC



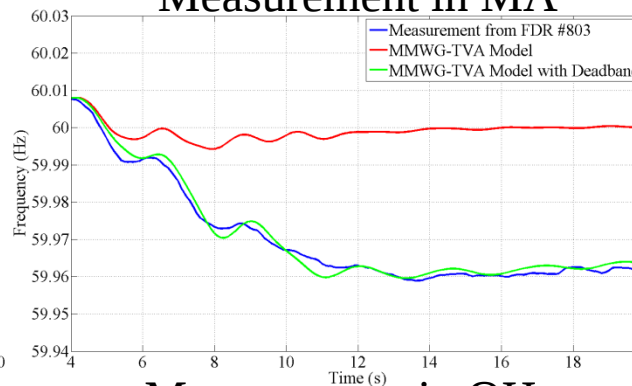
Measurement in MA



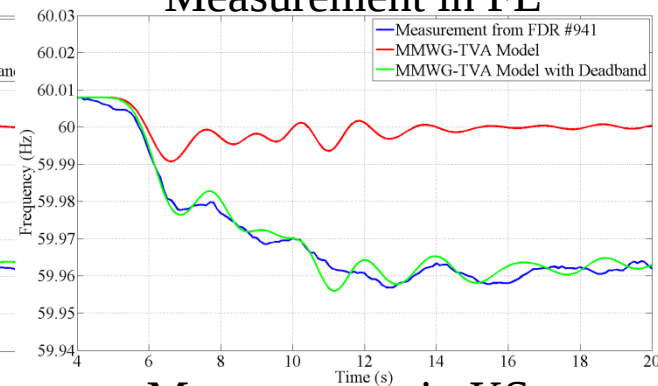
Measurement in FL



Measurement in MO



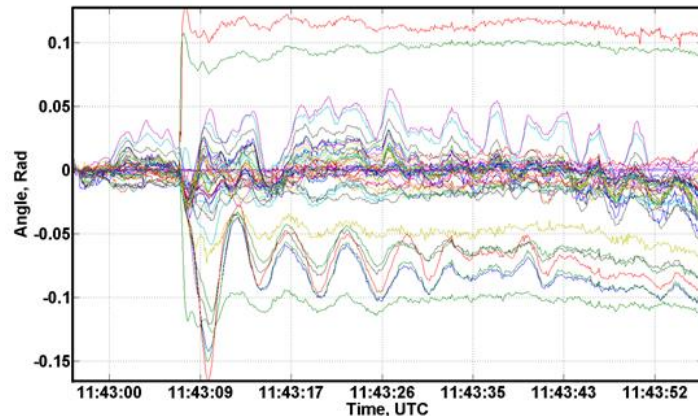
Measurement in OH



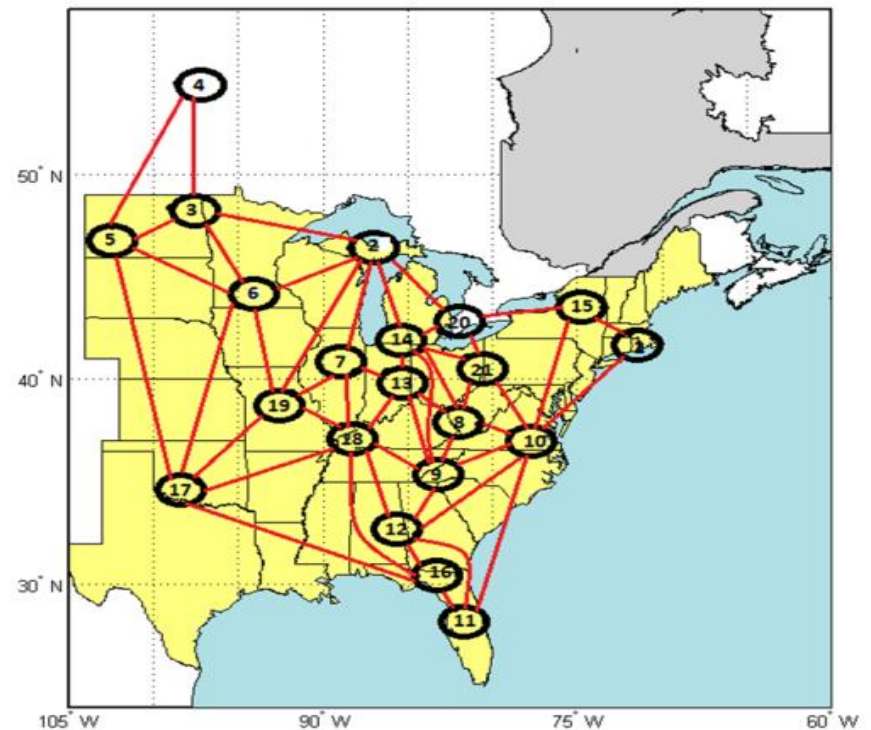
Measurement in KS

Dynamic Model Reduction Based on Phasor Measurements

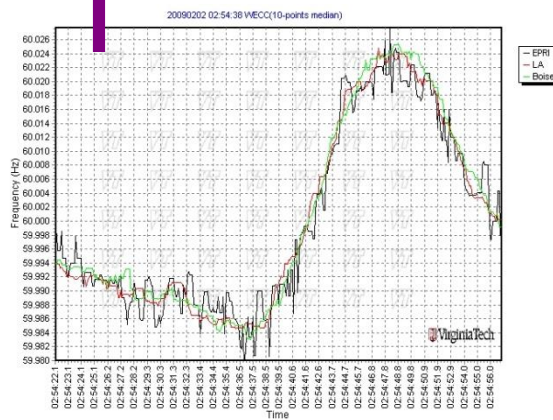
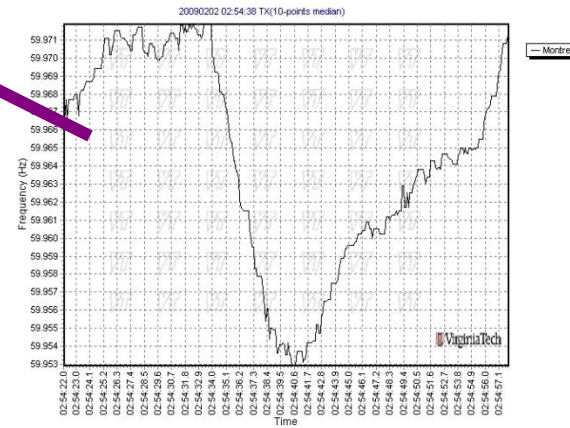
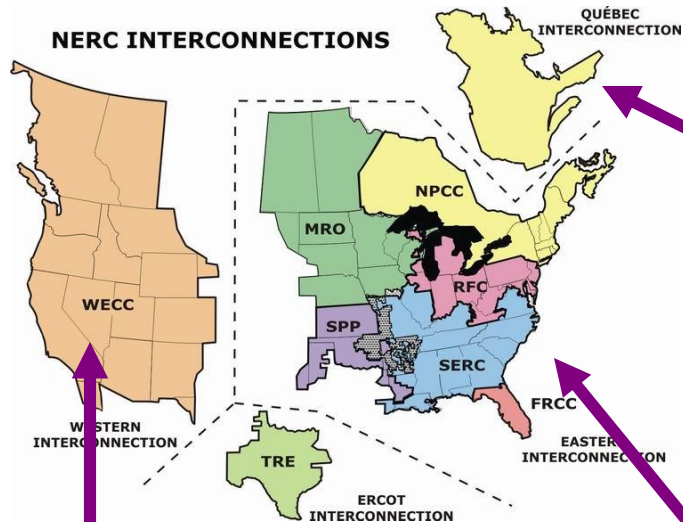
Coherency Determination



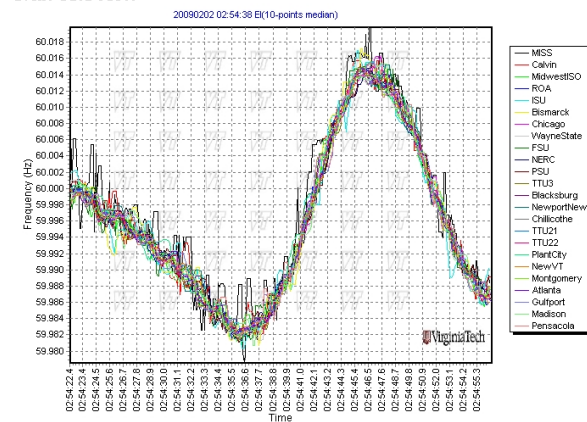
Network Reduction



Super Bowl Frequency swings during commercials

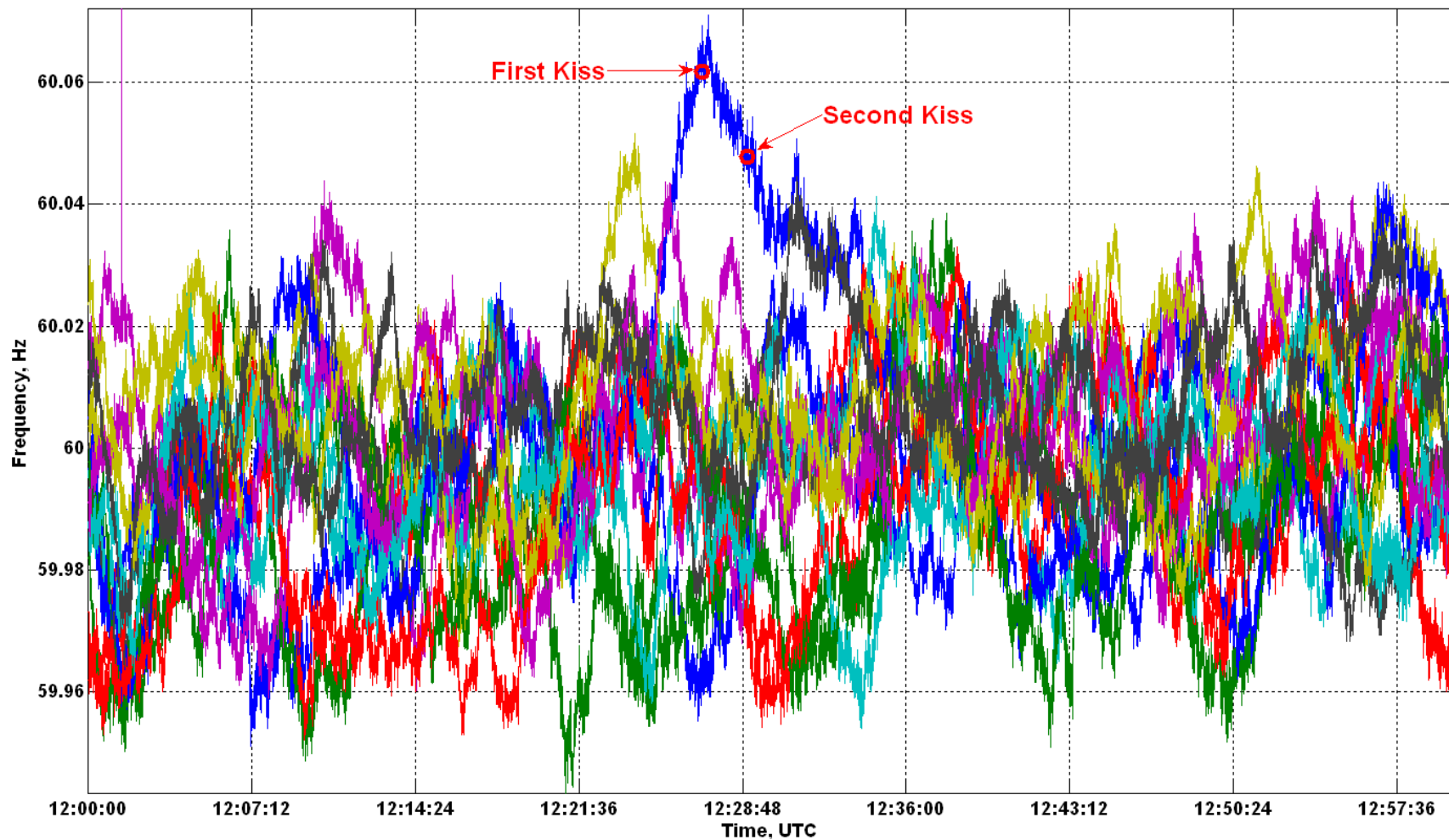


Event Data Plot:



Royal Wedding

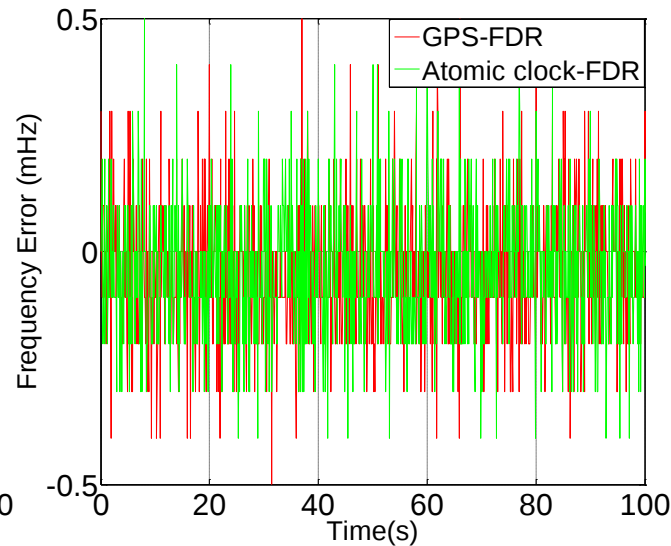
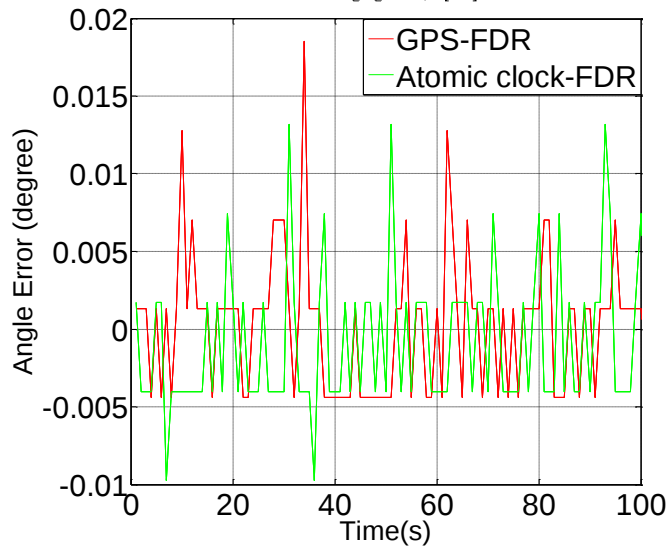
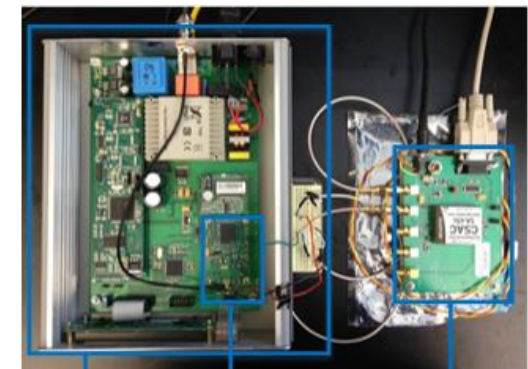
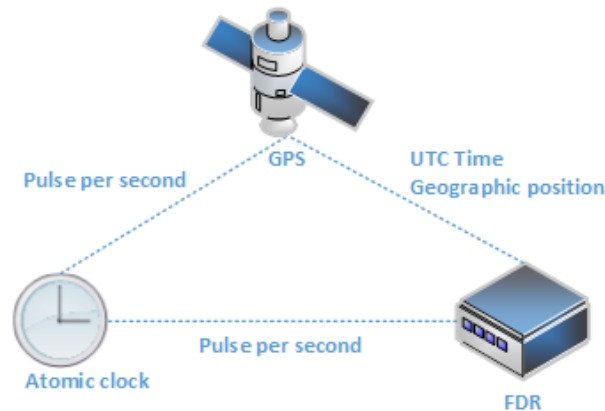
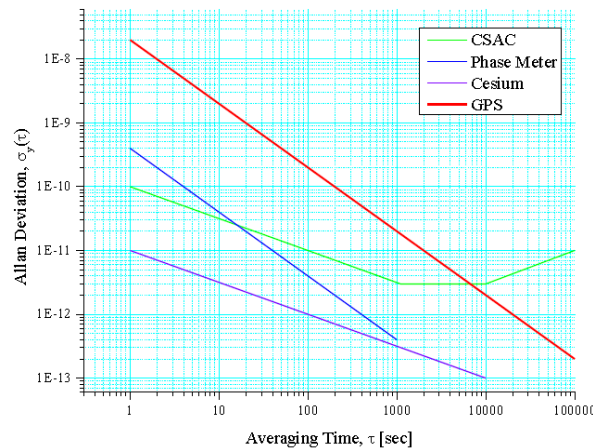
14 Days Frequency Plot



PMU with Chip Scale Atomic Clock

SA. 45s Chip-Scale Atomic Clock

- World's first commercially available chip scale atomic clock
- GPS is noisier than CSAC for averaging time < 5000 seconds

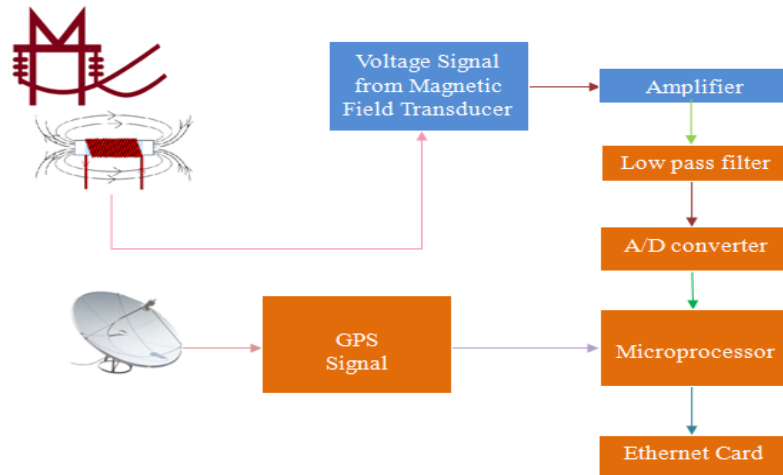


Stand deviation of frequency and angle errors

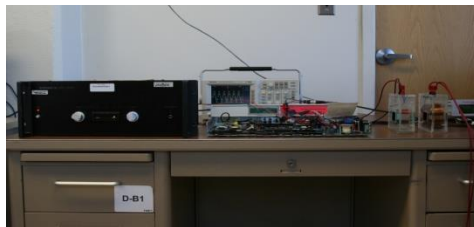
	GPS-FDR	Atomic clock-FDR
Angle	0.0041	0.0046
Frequency	1.45e-4	1.42e-4

Contactless PMU Prototypes

⚙️ Magnetic Field Based PMU



Framework from Frequency Disturbance Recording Unit

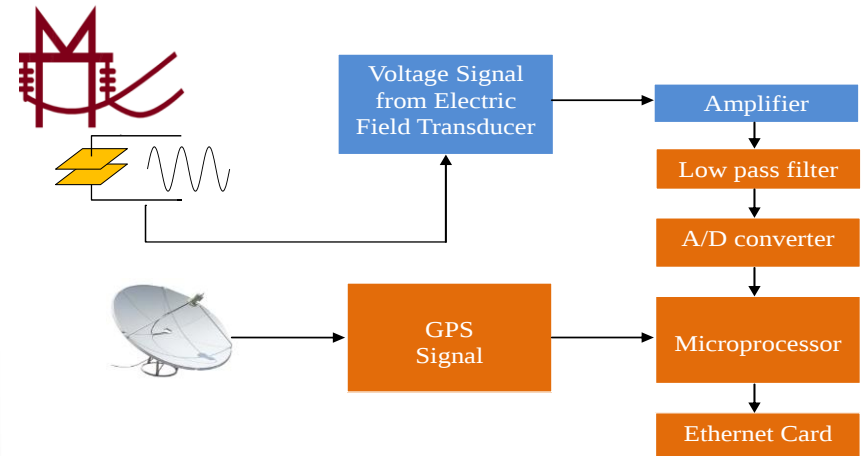


Lab Testing



Field Testing

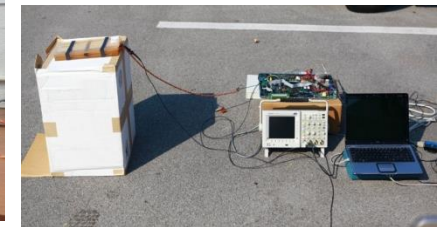
⚙️ Electric Field Based PMU



Framework from Frequency Disturbance Recording Unit



Lab Testing



Field Testing

Universal Grid Analyzer (UGA)



Power quality measurement

- Harmonics and THD: 15th harmonics; reporting rate: 1 Hz
- Voltage sag/swell detection: IEC Standard compliant; reporting rate*: 10 Hz
(* Every data frame has 12 flags, equivalent reporting rate is 120 Hz)

Best PES paper award

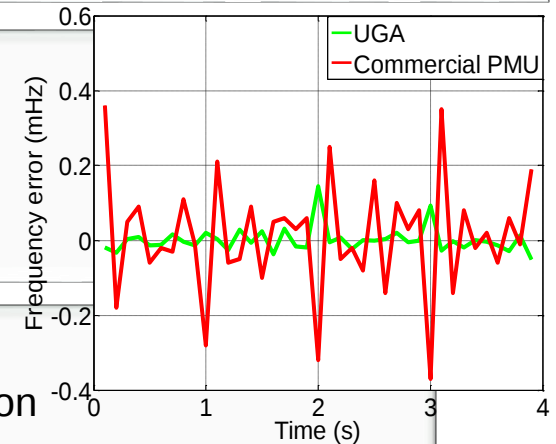


Phasor measurement

- Frequency error: 0.06 mHz
- Phase angle error: 0.003 degree

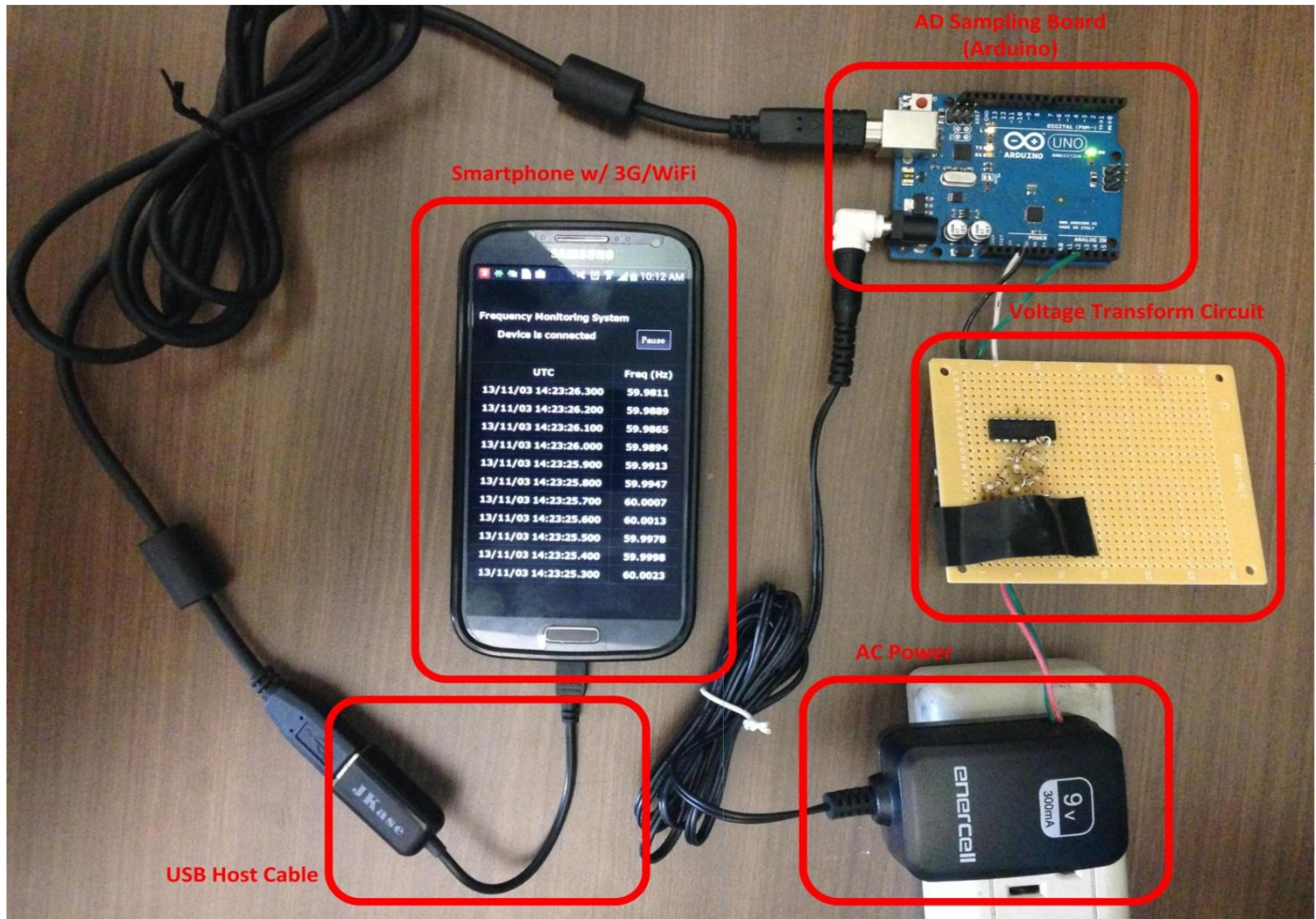
White noise analysis

- Signal-to-noise ratio (SNR) estimation
 - Estimation rate: 1 Hz



Patent Pending

Smart Phone Based Grid Monitor



Information Links:

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

How to install FDR: <http://www.youtube.com/watch?v=9Vt2OIVoBJc&NR=1>

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

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

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

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-k8kBq&feature=related

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

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Invent the Future



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PROTECTION
ALLIANCE



NERC

NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION



Desired New Locations

- Arizona: Flagstaff, Tucson
- California: Redding, Fresno, Bakersfield
- Colorado: Colorado Springs, Grand Junction
- Florida: Jacksonville, Orlando
- Idaho: Idaho Falls, Twin Falls
- Iowa: Sioux City
- Minnesota: Duluth
- Michigan: Grand Rapids
- Mississippi: Tupelo, Hattiesburg
- Missouri: St Louis
- Montana: Billings
- Nebraska: Omaha
- Maine
- Nevada
- New Mexico: Santa Fe
- New York: Ithaca, New York City
- Ohio: Cincinnati
- Oregon: Bend
- Atlantic City,
- Harrisburg
- South Dakota: Sioux Falls
- Nashville
- Texas: Lubbock, Dallas, Abilene, Austin, Amarillo
- Utah: Provo
- Washington: Yakima
- Wisconsin: Wausau
- Wyoming: Jackson, Casper
- New Brunswick, Nova Scotia
- **France, Argentina, UK, and Italy.**

Contact Information

- If you would like to host a FDR unit
- IF you would like to receive FNET/GridEye Alerts
- If you have questions

Dr. Yilu Liu, Liu@utk.edu, 865 266 3597

University of Tennessee and Oak Ridge National Lab

