DOE/OE Transmission Reliability Program

Measurement Based Stability Assessment

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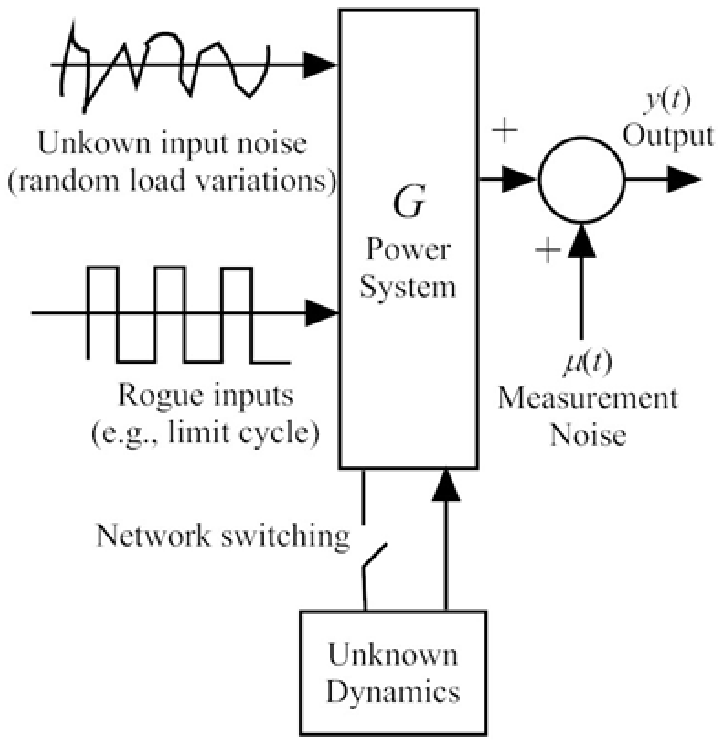
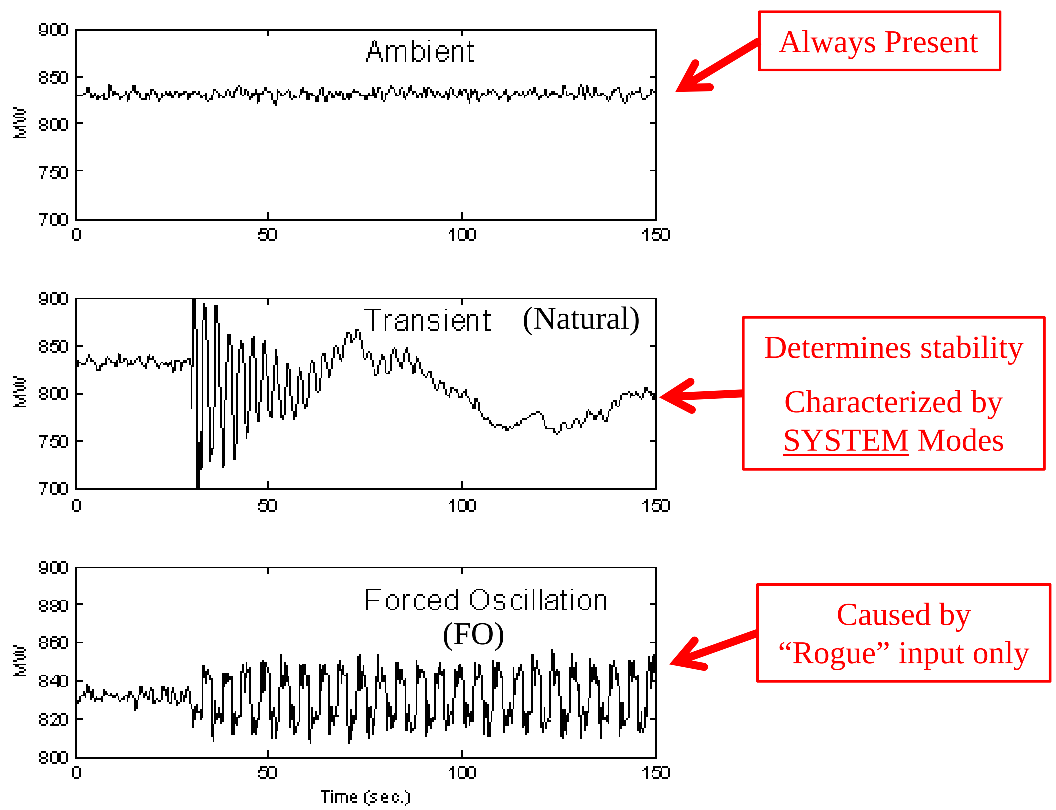
CERTS
Consortium for Electric Reliability Technology Solutions

Overview

- Develop, test, and refine algorithms to automatically estimate and quantify oscillations from PMUs in real time.
- Application
  - Real-Time Situational Awareness based upon actual system observations
- Participants:
  - Dan Trudnowski, Montana Tech
  - John Pierre, University of Wyoming
  - Lots of graduate students
- Collaborations (Past year)
  - PNNL (Jim Follum)
  - BPA (Nick Leitschuh, Dmitry Kosterev)
  - PEAK/WECC

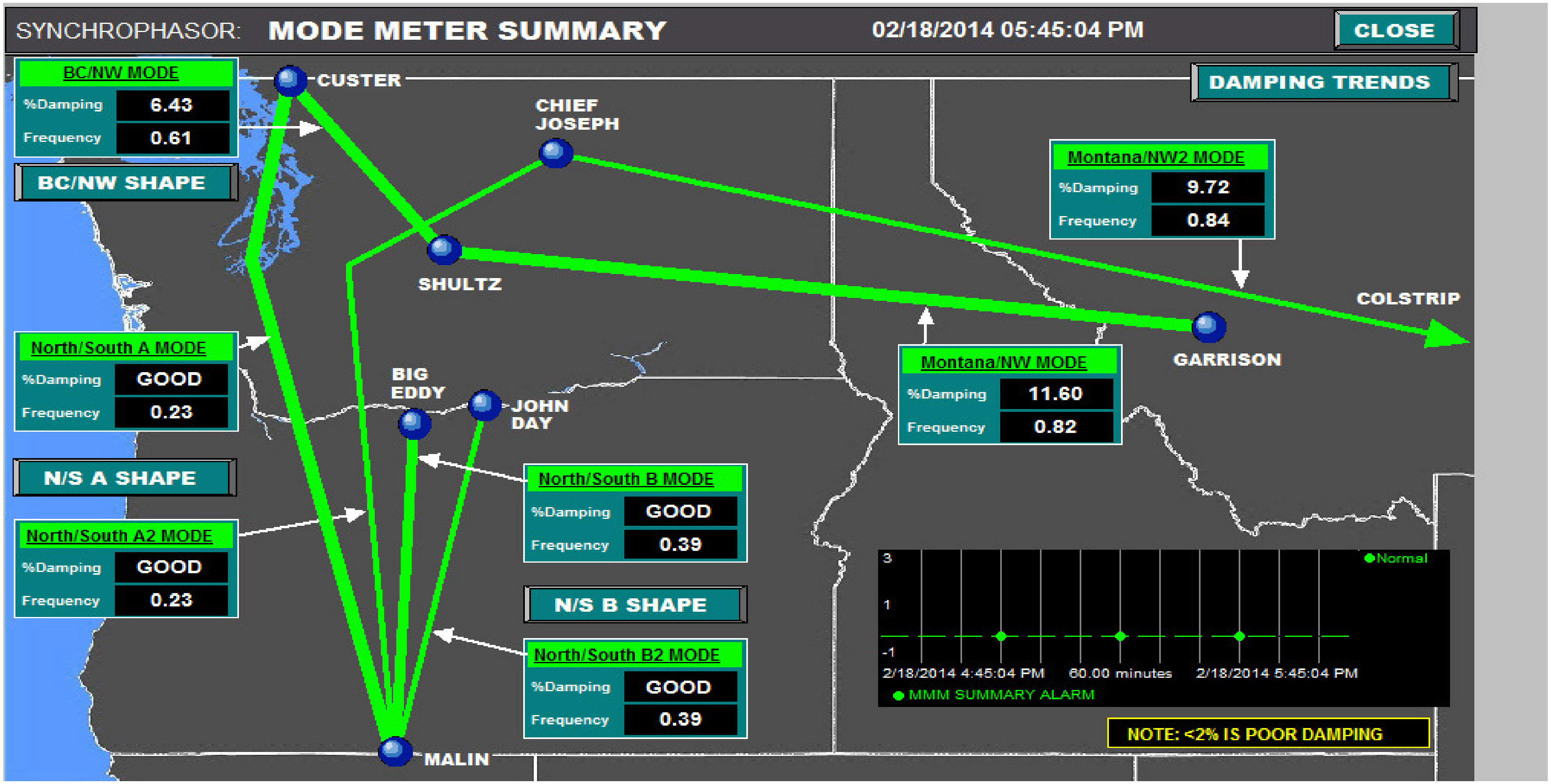
System Model





Screen Capture of BPA's Mode Meter

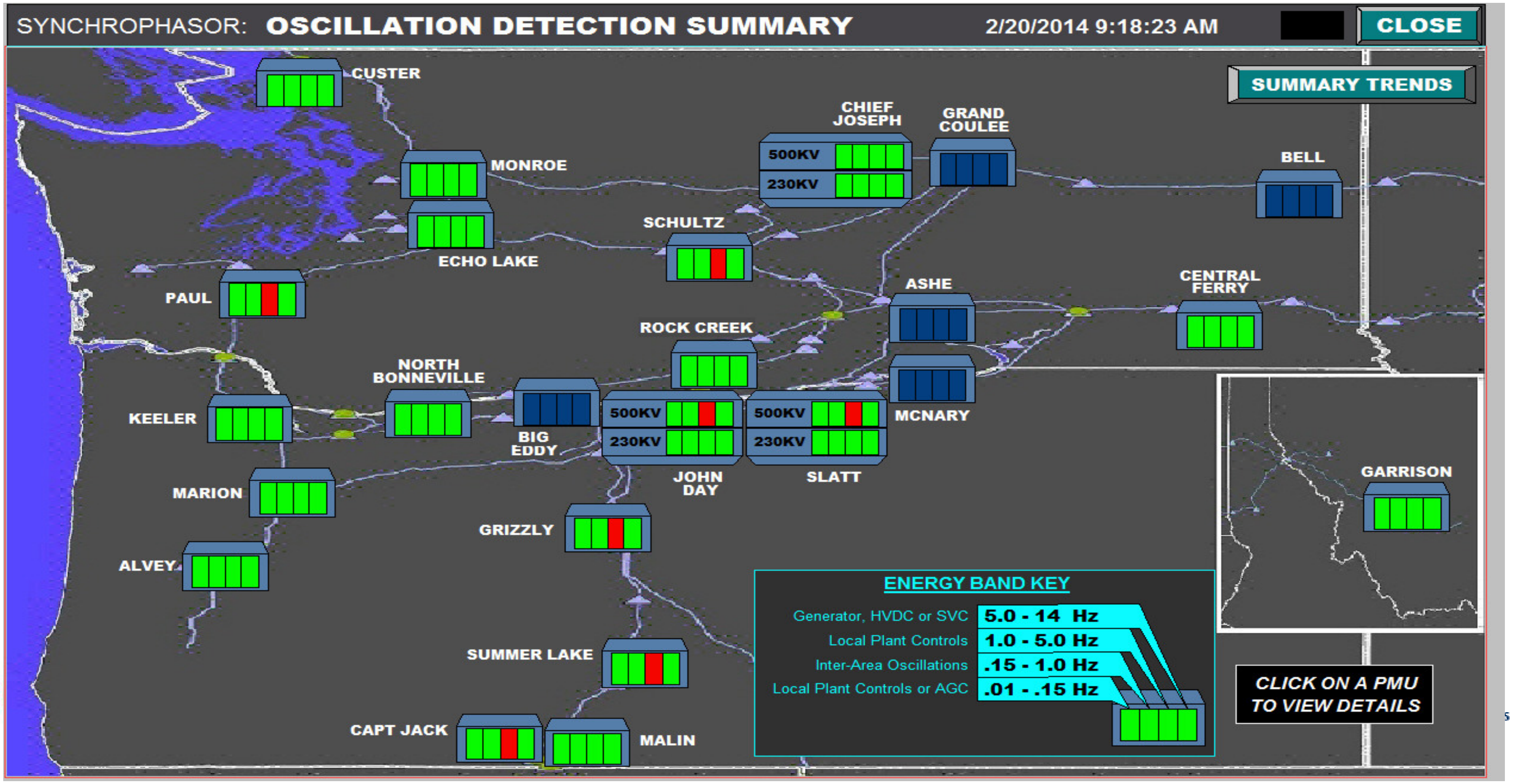
Tracks SYSTEM Modes
Assumes Ambient and/or Transient condition
FO biases results



Screen Capture of BPA's Oscillation Detector

Alarms based upon oscillation energy

Cannot distinguish between a Transient and FO



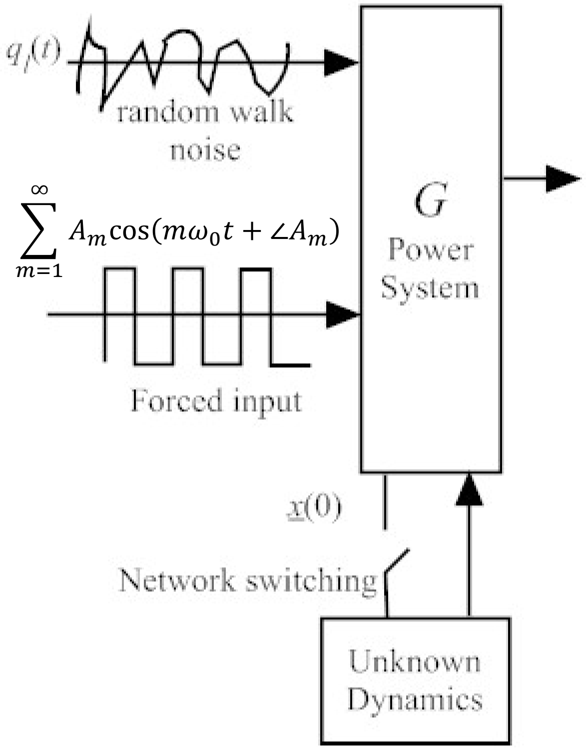
Project Objectives/Accomplishments

- Understand the fundamental nature and impact of FOs
  - FO harmonics, FO Shape, "Sinusoid" Noise in an undamped Transient
  - Most interesting (and difficult) case: FOs at system mode
- Develop Mode Meter algorithms that work in the presence of FOs
  - Several algorithms developed. Results presented at the 2014 review.
  - Methods require knowledge of the FO
  - WECC case: Sep 2014
- Develop Oscillation Detection Approaches
  - Goals:
    - Automated (no tuning, operations) – We're pretty good at this with Energy Methods
    - Determine if an oscillation is natural or forced - Very difficult
    - Identify the root cause (location) of a FO – Energy and shape typically point to the source
- Modal Analysis Software Development (BPA, PEAK, EPG)
  - Oscillation Detector and Mode Meter used at the BPA control center for alarming
  - Working with BPA to refine and define alarming – Setting alarm thresholds
  - Support PEAK/WECC in the implementation of MAS
- BPA/WECC Probing Tests Support
  - Help design tests, analyze data

Forced Oscillations (FOs)

- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
  - NOT A SYSTEM INSTABILITY
- FOs very common
  - Periodically detected in the BPA OD System
- Can be very severe: Nov. 2005, Feb. 2010, Feb. 2014
- Often bias Mode Meter algorithms (Sep. 2014)

FO Theory



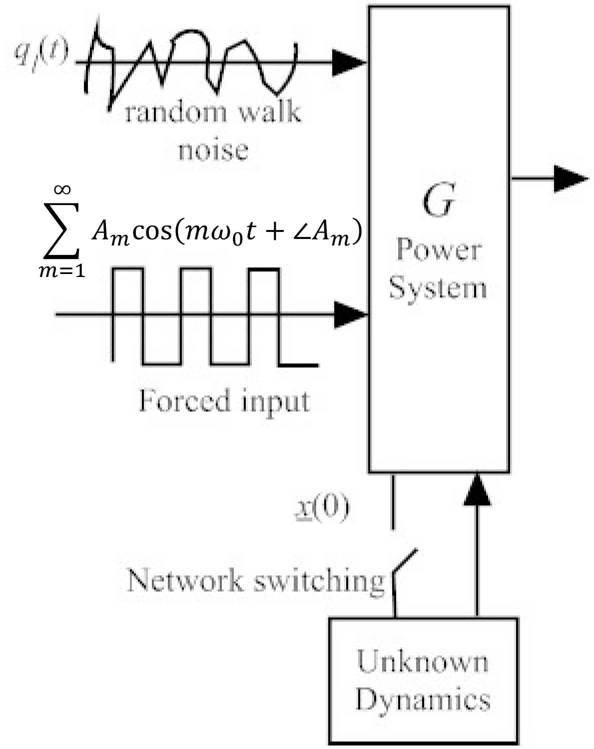
$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow \textbf{FO}$$

$$+\left[\sum_{i=0}^{N}2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Rightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

x_r = location r
$\lambda_i = \sigma_i + j\omega_i$ = ith system mode (eigenvalue)
v_i, u_i = ith left, right eigenvectors
b_1 = input vector for forced input
b_{2l} = input vector for lth random load

FO Theory



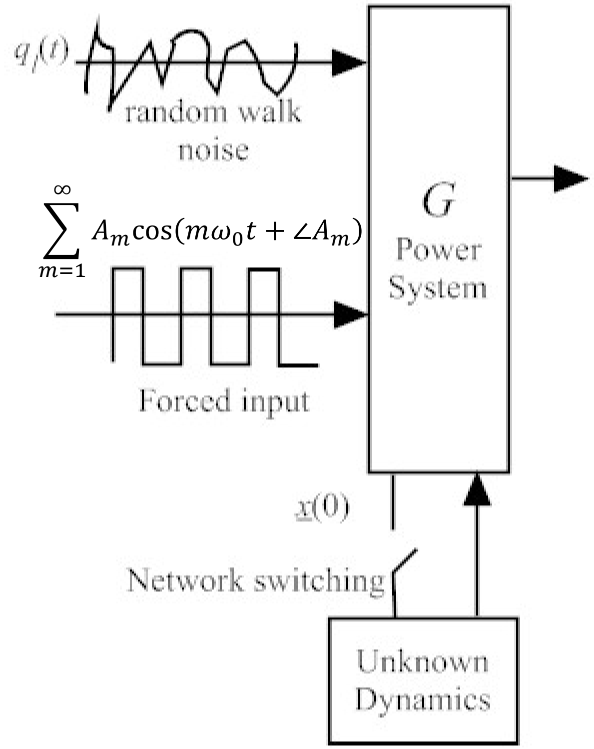
Harmonics

$$x_r(t) = \sum_{m=1}^{\infty} \left[\left| \sum_{i=1}^{N} \frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0 - \lambda_i} \right| |A_m| \cos\left(m\omega_0 t + \angle\left(A_m \sum_{i=1}^{N} \frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0 - \lambda_i} \right)\right)\right] \Rightarrow \textbf{FO}$$

$$+ \left[\sum_{i=0}^{N} 2 \left| \underline{u}_{ir}\underline{v}_i\underline{x}(0) \right| e^{\sigma_i t} \cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right) \right] \Rightarrow \textbf{Transient}$$

$$+ \sum_{l=1}^{M} \left[q_l(t) \circledast \left[\sum_{i=1}^{N} \left| \underline{u}_{ir}\underline{v}_i\underline{b}_{2l} \right| e^{\sigma_i t} \cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right) \right]\right] \Rightarrow \textbf{Colored Noise}$$

FO Theory



Harmonics

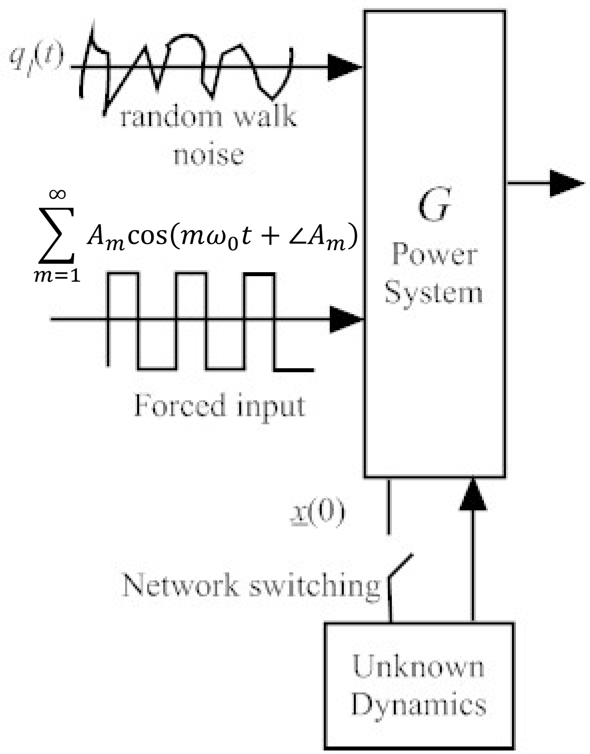
FO Shape (No Damping)

$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow \textbf{FO}$$

$$+\left[\sum_{i=0}^{N} 2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Rightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

FO Theory



FO Shape
(No Damping)

Harmonics

$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Longrightarrow \textbf{FO}$$

$$+\left[\sum_{i=0}^{N} 2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Longrightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

Colored by the **SYSTEM**

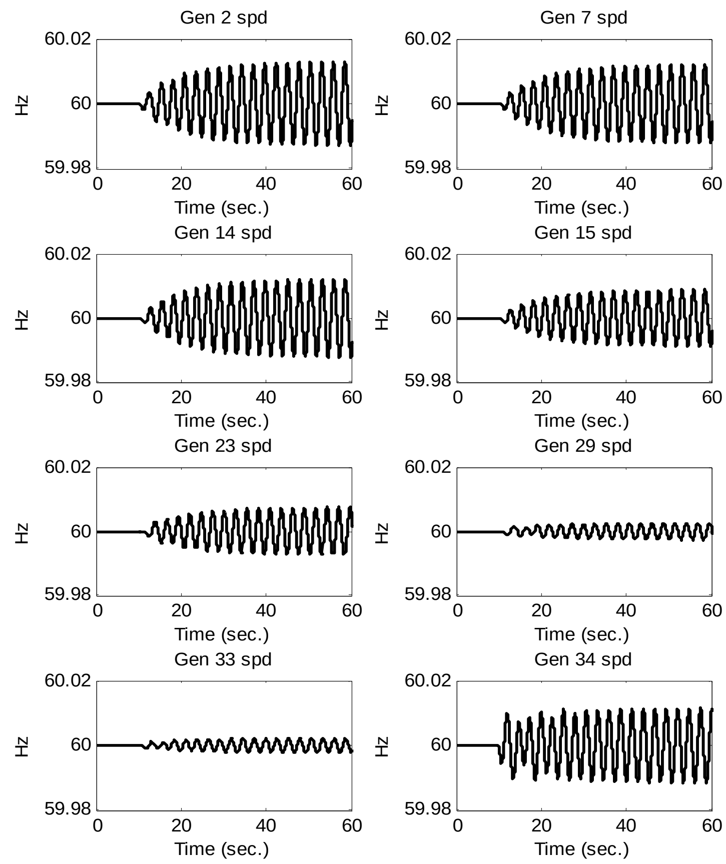
FO Theory – The “Shape”

$$\sum_{i=1}^{N} \frac{\underline{u_{ir}}\,\underline{v_i}\,\underline{b_1}}{jm\omega_0 - \lambda_i}$$

- FO shape is unique
- FO shape can be calculated from PMU measurements (amplitude and phase). – Spectral, filters, etc.
- If FO frequency is NOT at a system mode, FO shape typically points to the FO source (amplitude and phase).
  - Based upon simulations and real-world experiences.
  - Bases for current Oscillation Detection approaches.
  - System freq may be the best “locating” signal
- FO shape converges to SYSTEM MODE SHAPE if FO is at the mode freq. MOST DIFFICULT AND INTERESTING CASE.

FO at a System Mode

Gen #	Mode Shape		FO Shape	
	Mag	Angle (deg)	Mag	Angle (deg)
2	1.08	-1	1.07	4
7	1	0	1	0
14	1.04	-11	1.01	-12
15	0.73	1	0.73	0
23	0.64	-167	0.61	-164
29	0.21	-153	0.22	-141
33	0.15	-20	0.18	-31
34	0.85	-177	0.95	139



Transient vs Forced

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0 - \lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0 - \lambda_i}\right)\right)\right] \Longrightarrow \textbf{FO}$$

$$+\sum_{l=1}^{M}\left[q_l(t) \circledast \left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

Transient

$$\hat{x}_r(t) = 2\left|\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right|\cos\left(\omega_n t + \angle\left(\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right)\right) \Longrightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t) \circledast \left[\sum_{\substack{i=1\\ i\neq n}}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Longrightarrow \textbf{Colored Noise}$$

$$+\sum_{l=1}^{M}\left[q_l(t) \circledast \left[\left|\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right|\cos\left(\omega_n t + \angle\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right)\right]\right] \Longrightarrow \textbf{Sinusoid Noise}$$

Transient vs Forced

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{u_{ir}v_i b_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{u_{ir}v_i b_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Longrightarrow \textbf{FO}$$

Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}|e^{\sigma_i t}\cos(\omega_i t+\angle(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}))\right]\right] \Longrightarrow \textbf{Colored Noise}$$

Transient

$$\hat{x}_r(t) = 2|\underline{u}_{nr}\underline{v}_n\underline{x}(0)|\cos(\omega_n t+\angle(\underline{u}_{nr}\underline{v}_n\underline{x}(0))) \Longrightarrow \textbf{Transient}$$

No Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{\substack{i=1\\ i\neq n}}^{N}|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}|e^{\sigma_i t}\cos(\omega_i t+\angle(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}))\right]\right] \Longrightarrow \textbf{Colored Noise}$$

$$+\sum_{l=1}^{M}[q_l(t)\circledast[|\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}|\cos(\omega_n t+\angle\underline{u}_{nr}\underline{v}_n\underline{b}_{2l})]] \Longrightarrow \textbf{Sinusoid Noise}$$

Transient vs Forced

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow \textbf{FO}$$

Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

Transient

$$\hat{x}_r(t) = 2\left|\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right|\cos\left(\omega_n t+\angle\left(\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right)\right) \Rightarrow \textbf{Transient}$$

No Harmonics

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{\substack{i=1\\i\neq n}}^{N}\left|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}\right)\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

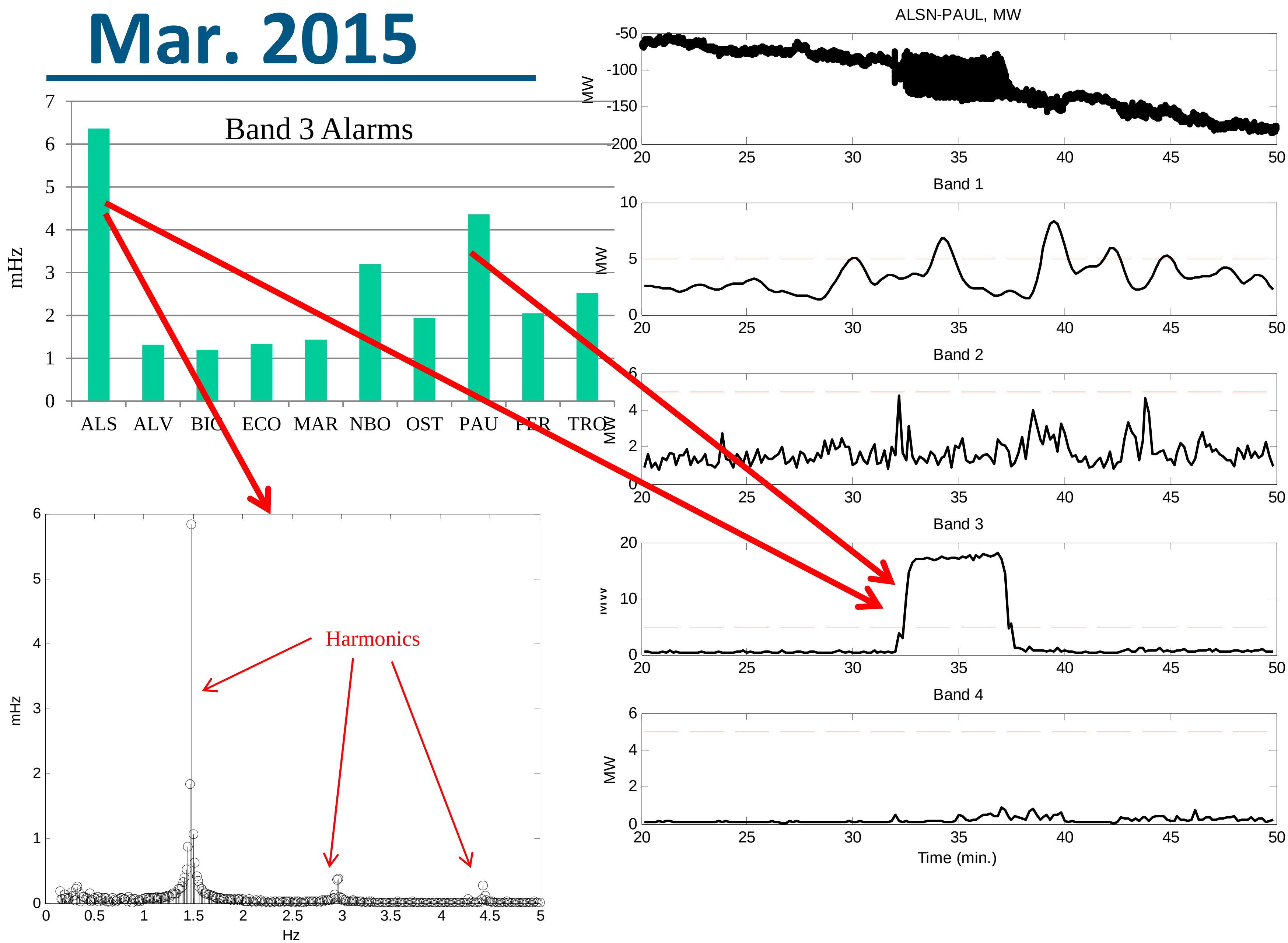
$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\left|\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right|\cos\left(\omega_n t+\angle\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}\right)\right]\right] \Rightarrow \textbf{Sinusoid Noise}$$

Unique to a Transient

Source Locating using System Freq

An Oscillation Detection Example

BPA
Mar. 2015



Band 3 Alarms
mHz
ALS ALV BIG ECO MAR NBO OST PAU PER TRO
Harmonics
Hz
ALSN-PAUL, MW
Band 1
Band 2
Band 3
Band 4
MW
Time (min.)

Publications (Past year)

- G. Pai and J.W. Pierre, “A Real-time Scheme for Validation of an Auto-regressive Time Series Model for Power System Ambient Inter-area Mode Estimation,” *Proceedings of HICSS-47*, Waikoloa, Hawaii, January 2014.
- J. Follum, Electromechanical Mode Estimation in the Presence of Forced Oscillations, Ph.D. Dissertation, Department of Electrical and Computer Engineering, University of Wyoming, June, 2014.
- J. Follum and J.Pierre, “Time-Localization of Forced Oscillations in Power Systems,” Proceedings of the IEEE Power & Energy Society General Meeting, July 2015. (accepted).
- R. Xie, D. Trudnowski, and I. West, “Shape Properties of Forced Oscillations,” *Presented at NASPI*, March 2015.
- R. Xie and D. Trudnowski, “Distinguishing Features of Natural and Forced Oscillations,” *Proceedings of the IEEE Power & Energy Society General Meeting*, July 2015 (accepted).
- M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, “RMS-Energy Filter Design for Real-Time Oscillation Detection,” *Proceedings of the IEEE Power & Energy Society General Meeting*, July 2015 (accepted).
- J. Follum and J.W. Pierre, “Detection of Forced Oscillations in Power Systems,” *IEEE Trans on Power Systems*, (under revision).
- “Modes of Inter-Area Power Oscillations in Western Interconnection,” Official document of the WECC, Joint Synchronized Information Subcommittee (authored by Oscillation Analysis Work Group - D. Trudnowski lead author), version 2014.1, May 2014.
- D. Trudnowski, “2014 PDCI Probing Tests,” Report to BPA, 2015.

Conclusions, Future Work, and Risk Factors

- Conclusions
  - Developing a fundamental understanding of the nature of FOs
    - FO harmonics, FO Shape, “Sinusoid” Noise in an undamped Transient
    - Most interesting (and difficult) case: FOs at system mode.
  - Develop Mode Meter algorithms that work in the presence of FOs
    - Several algorithms developed. Require knowledge of the FO freq.
  - Oscillation Detection
    - Energy methods appear to work very well
    - Source locating is mostly heuristic (system frequency signals)
  - MAS Support (BPA, PEAK, EPG)
- Future
  - Oscillation Detection
    - Are Energy methods the best for power systems?
    - Distinguishing between FOs and Transients (“Sinusoid” noise, other physics?)
    - Locating the source (can we be more scientific?)
  - Conduct detailed comparison of Mode Meter algorithms
    - Include FO cases
    - Luke Dosiek (Union College)
    - Collaboration: Bernie Lesieutre (UWiscon)
- Risk Factor
  - Access to real-life data

Extra Slides

Mode Meter Confidence Bounds

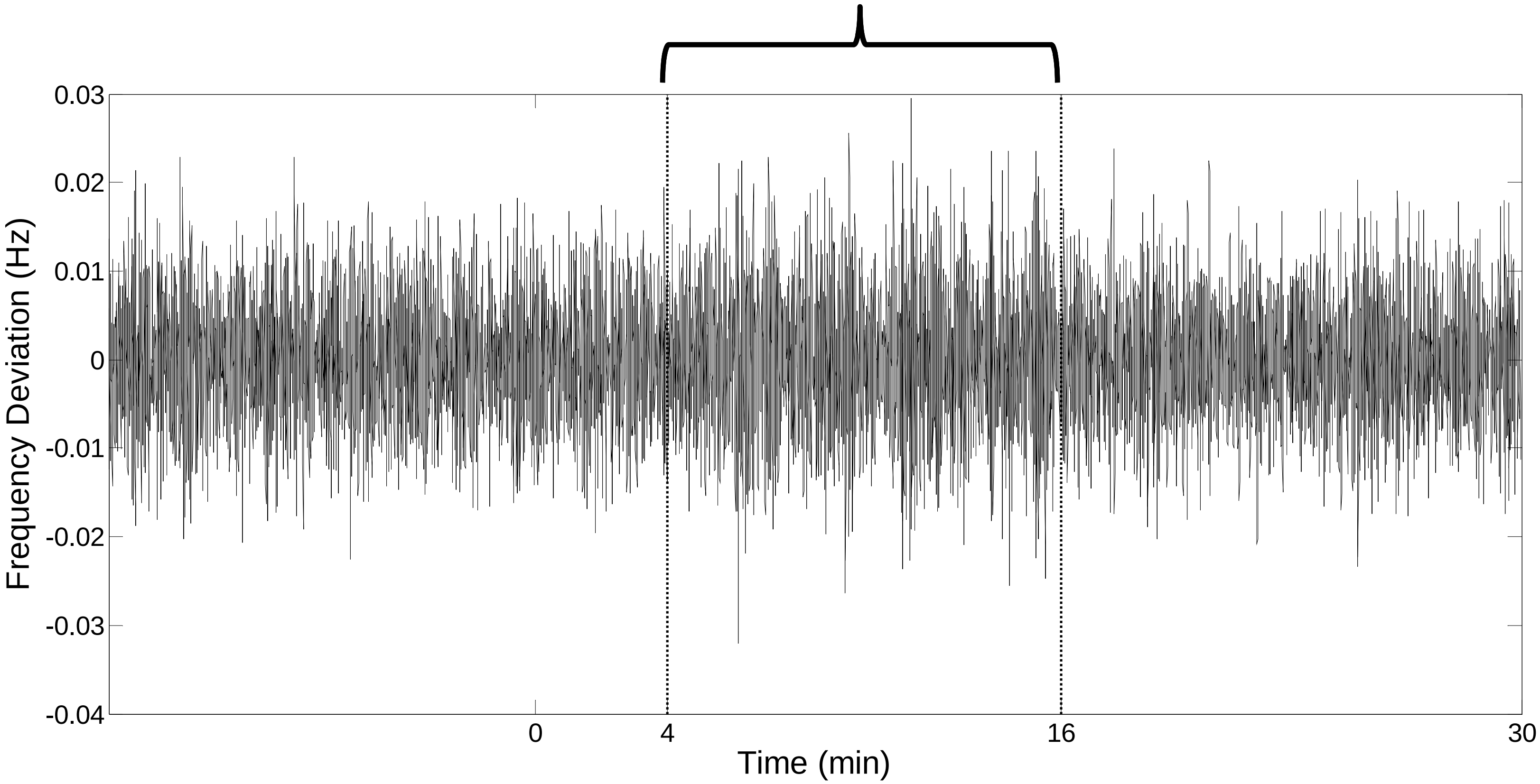
- Mode Meter Confidence Bounds: Indicator of the statistical performance (mean and variance) of a mode meter
- Confidence Bound Methods Investigated and Developed
  - Monte Carlo Simulations for Error Bounds
  - Bootstrap Methods for Error Bounds
  - Computationally Efficient Bootstrap Methods
  - Recursive Maximum Likelihood (RML) Method for Mode Estimation with Closed Form Expressions for Error Bounds (no bootstrapping or monte carlo!)

Development of Mode Meter Algorithms ~~that Work in Presence of Forced Oscillations~~

- Problem: Periodic Forced Oscillations (at frequencies close to modes) can fool traditional mode meters into thinking there is a lightly damped mode
- Solution: Incorporate possibility of FO into Mode Meter Algorithm
- Two New Algorithms
  - LS-ARMA+S (Least Squares Autoregressive Moving Average plus Sinusoid)
  - YW-ARMA+S (Yule Walker Autoregressive Moving Average plus Sinusoid)

Example: Small Forced Oscillation

Small FO starting at the 4 minute mark and extending to the 16 minute mark



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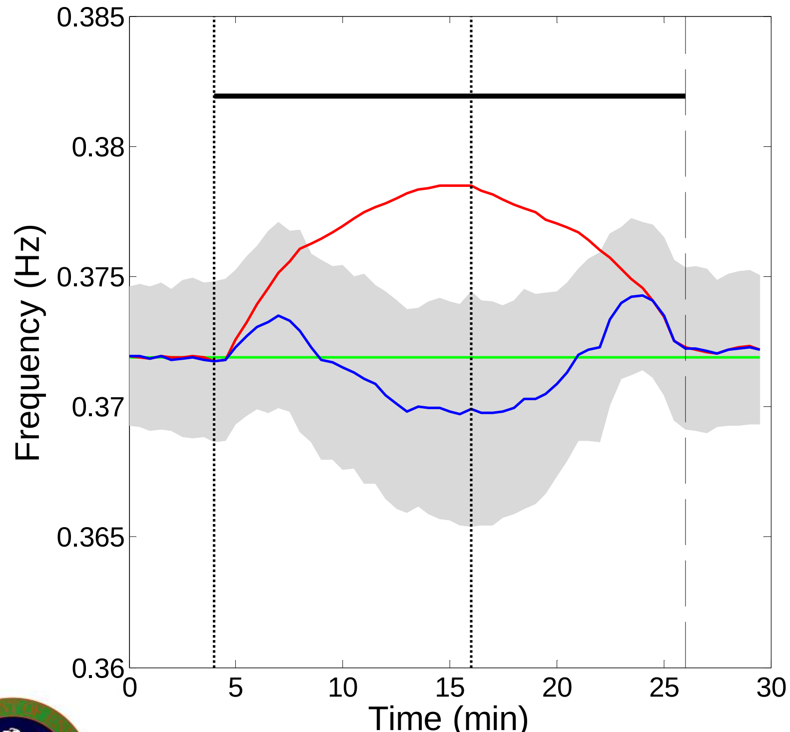
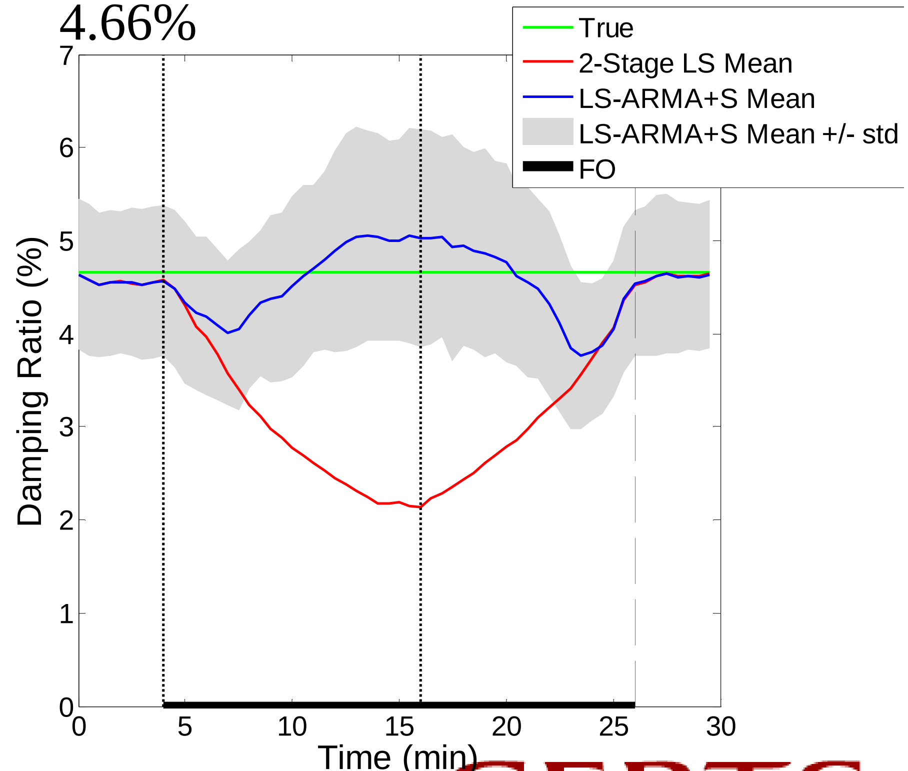
Mode Meter Results: Traditional (LS-ARMA) & One that Incorporates Detecting Forced Oscillations (LS-ARMA+S)

Frequency Estimate
True Mode Frequency 0.372
FO frequency 0.392 Hz



Damping Ratio Estimate
True Damping Ratio
4.66%



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