Measurement Based Stability Assessment

DOE/OE Transmission Reliability R&D Internal Program Review Meeting

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Washington DC

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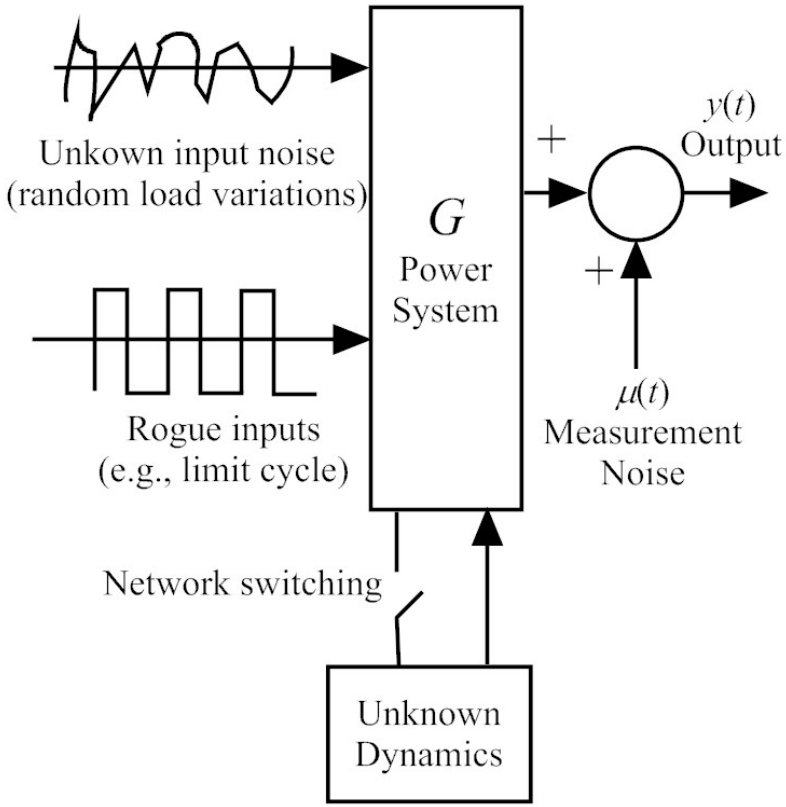
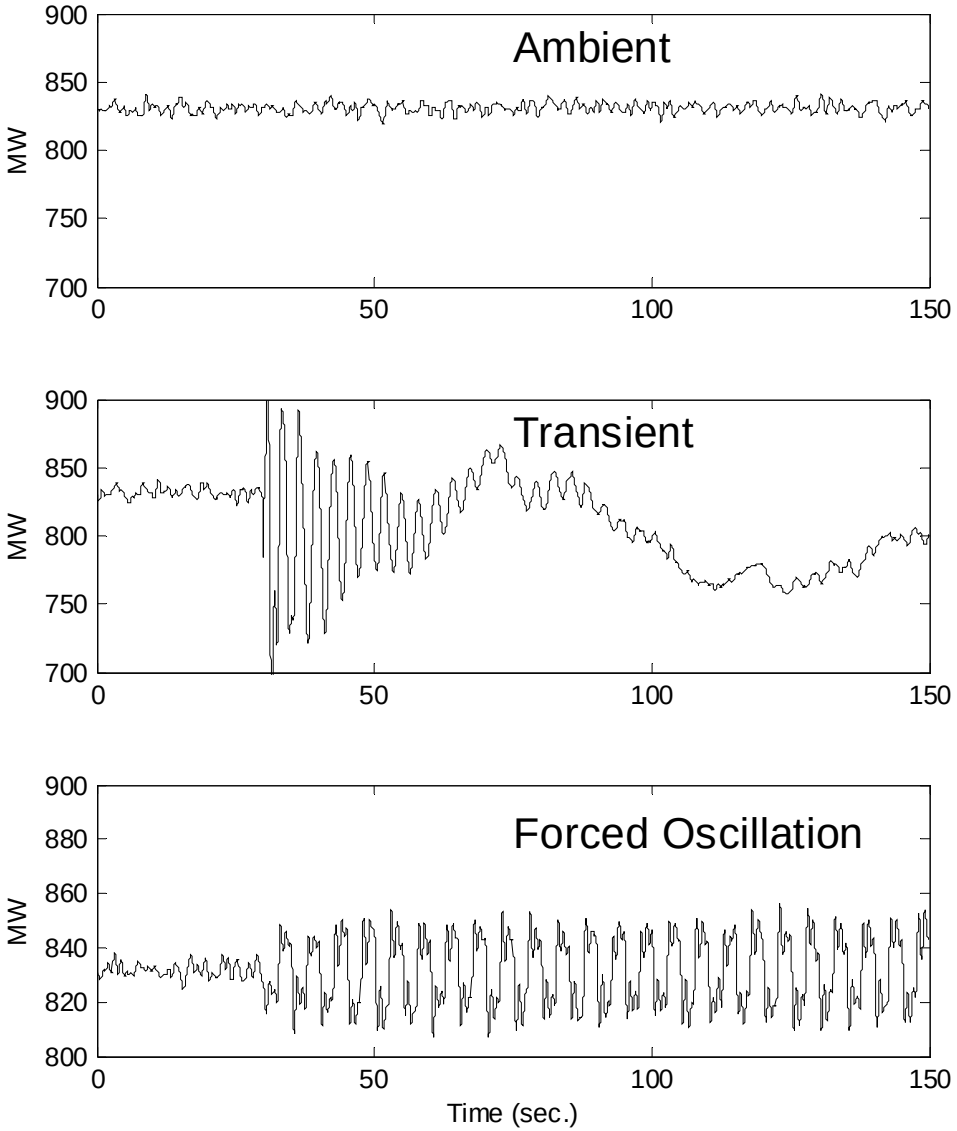
John Pierre, U of Wyoming

Project Overview

- Objective: 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
- Time line:
  - April 2006 thru April 2015
- Participants:
  - Dan Trudnowski, Montana Tech
  - John Pierre, University of Wyoming
  - Louis Scharf, Colorado State University (Retired)
  - Lots of graduate students
- Collaborators:
  - Ning Zhou, PNNL (funded independently)
  - Bonneville Power Administration
- Advisors
  - John Hauer, PNNL (Retired)
  - Bill Mittelstadt, BPA (Retired)

Dynamic Response Types

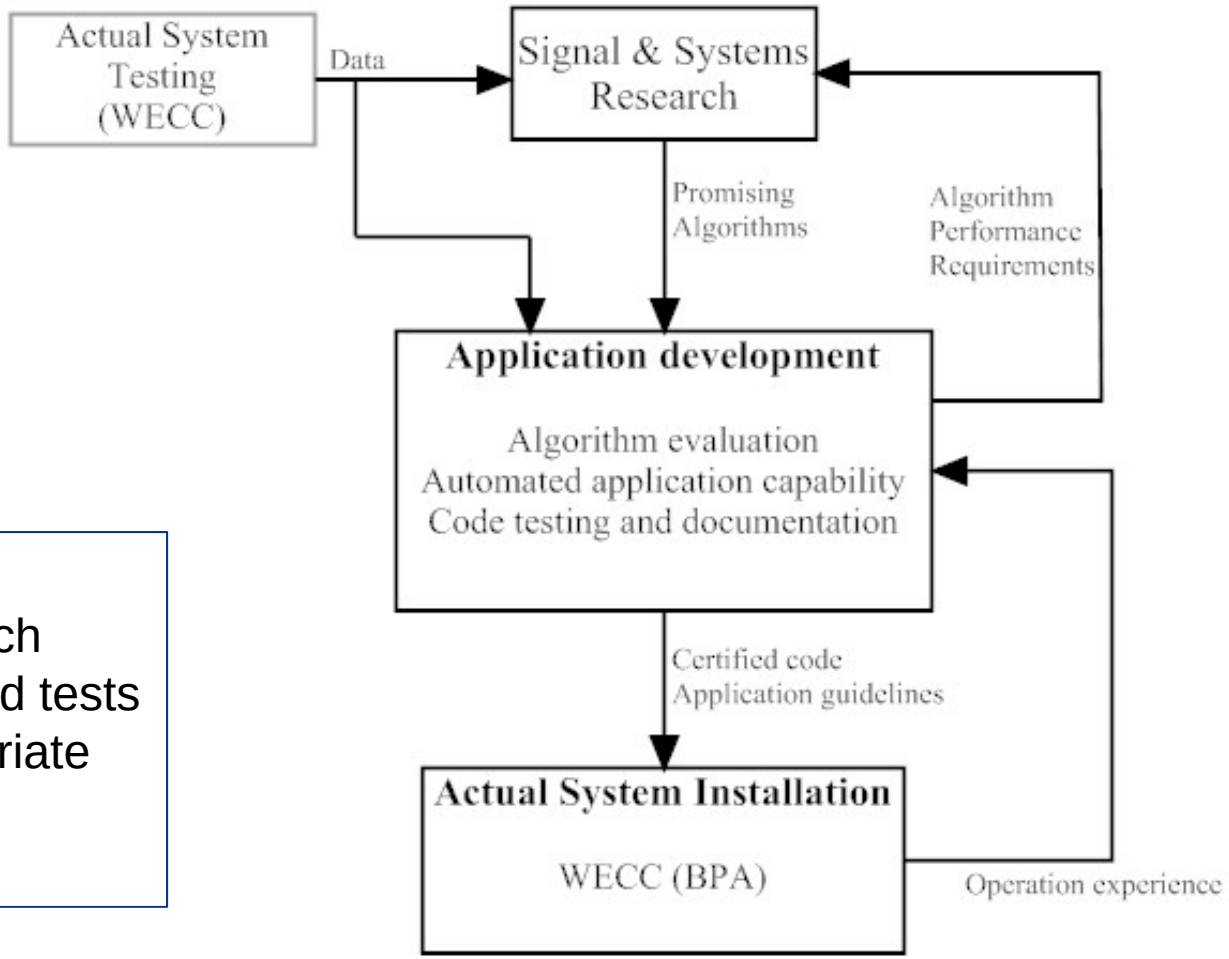




Algorithm Classes

- Oscillation Detector (OD): Immediately tells one that an oscillation is occurring with minimal quantification.
  - Very fast and robust
  - Distinguishes between forced oscillation and transient
  - If it is a FO, tells location of FO.
  - Operations and Engineering tool.
- Mode Meter (MM): Estimates a mode's frequency, damping, and shape.
  - Operates automatically
  - Ambient conditions (minutes)
  - Transient conditions (seconds)
  - Operations and Engineering tool
- Spectral Estimator (SE): Estimate the spectra of a signal.
  - Requires minutes of data for averaged spectra
  - Requires seconds of data for single window fft
  - Very robust
  - Operations and Engineering (Lots of data management and visualization)
- Ringdown Estimator (RE): Estimates a mode's frequency, damping, and shape.
  - Only works on transient data, requires seconds of data.
  - Not robust. Easy to fool (e.g., multiple switchings)
  - Engineering tool

Research Approach



Tasks:

1. Signal & systems research
2. Conduct and analyze field tests
3. Develop and test appropriate automated code

Accomplishments to Date
Signal & Systems Research

Red = Current or past year

- Mode-meter algorithms
  - YW = Yule Walker, YWS = Yule Walker Spectral, N4SID =Sub-space ID, R3LS = Regularized Robust Recursive Least Squares
  - Mode energy calculations for automated application
  - Tested Frequency Domain methods
  - R3ML = Regularized Robust Recursive Maximum Likelihood, MTF = Multi-Channel Transfer Func. – simultaneous mode and shape, Simultaneous mode and forced oscillation methods
- Performance and Validation Indices
  - Confidence bound estimation (Bootstrapping) for YW, YWS, and N4SID.
  - Direct Confidence bounds from RML
  - Whiteness testing

Accomplishments to Date

Signal & Systems Research

Red = Current or past year

- Ringdown Estimators
  - Compared BPA/PNNL Prony analysis with Matlab-based Prony
  - Algorithms to automatically detect a ringdown (Zhou)
- Mode Shape
  - Fundamental calculations for extracting mode-shape information.
  - 3 algorithms for estimating the mode-shapes.
- Forced Oscillations
  - Fundamental characteristics of forced oscillations.
  - Simultaneous mode and forced oscillation methods.
  - Effect of forced oscillations on mode-shape estimation algorithms
- Oscillation Detection
  - RMS Energy filtering
  - Self Coherency
- Spectral Estimation
  - Magnitude and Phase Response Estimates Standard Deviation
  - Fast recursive methods for estimating spectrum

Accomplishments to Date
Application Development & WECC Tests

Red = Current or past year

- Expert System for automated application of mode meter (Patent pending).
- Supported EPG's code implementation
- Installed prototype mode-meter and Ringdown estimator at BPA for 2010-13 operating season
- Modal Analysis Software (MAS).
- WECC System Tests
  - Designed methodology to construct multi-sine optimized PDCI probing signals
  - Supported and analyzed Aug. 2006, Aug. 2008 tests, 2009 season tests (14 tests), 2011 season tests (16 tests). 2012 season tests (26 tests)
  - Currently conducting 2013 season tests

Forced Oscillations (FOs)

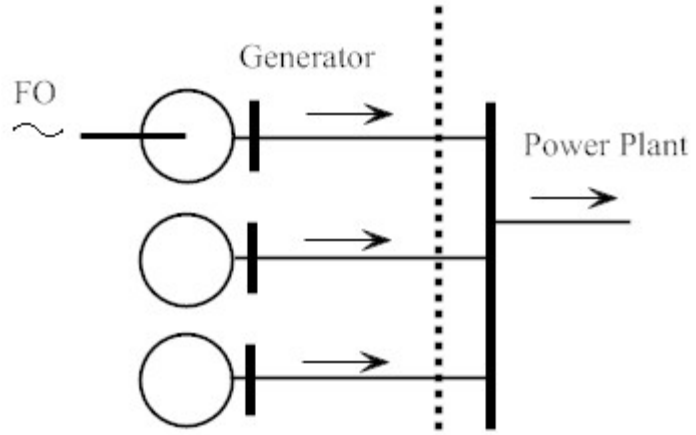
- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
  - NOT A SYSTEM INSTABILITY
- FOs very common
- Can be very severe: November 30, 2005
- Fundamental Goals: Develop signal processing algorithms that
  - Identify forced oscillations and distinguish them from system modes.
  - Identify the root location and cause of the forced oscillation.

FO Properties

- Research Questions
  - What are the fundamental causes?
    - Generator controls and loads.
    - Real power vs reactive power.
    - Pole slipping.
  - How do FOs propagate thru the system?
    - Voltage vs current.
    - Speed vs power.
  - What are the impacts of FOs on MM and Mode Shape algorithms?
- Study approach
  - Fundamental systems analysis.
  - miniWECC simulation and analysis.
- FOs are typically harmonic.

FO Properties

Propagation of real-power non-harmonic FOs



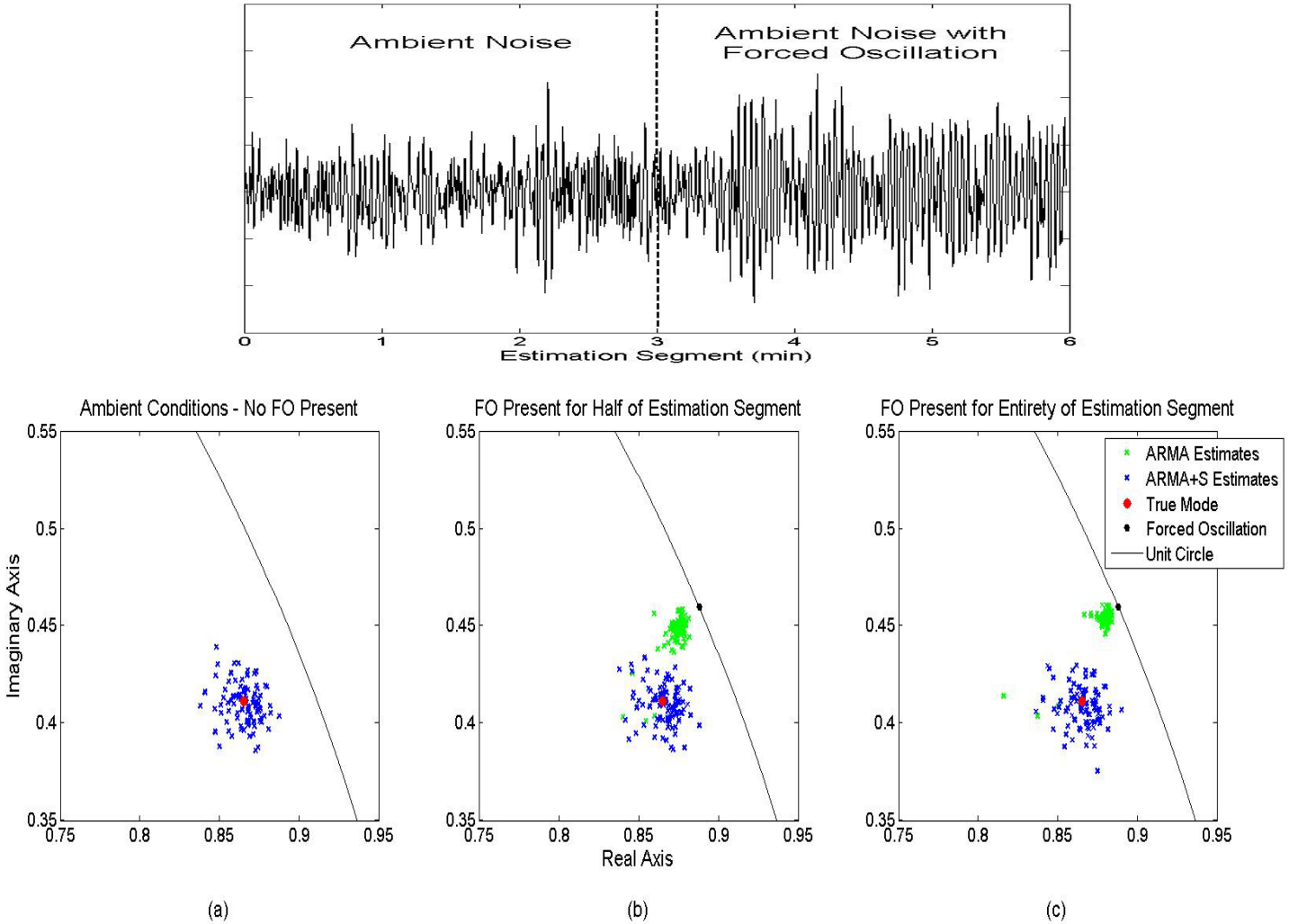
- If FO is not near a system mode, the real-power and current oscillations are largest at the FO power-plant.
- If FO is near a system mode, power-plant measurements DO NOT provide info on FO location.
  - FO tends to follow mode shape.
  - No pattern for voltage vs. current at the power plant.
  - Intra-plant measurements can reveal the location of the FO.
- What's next? – Harmonic FOs.

FO Impact on Mode-Shape Estimation

- Theoretical analysis and simulations have shown that FOs have minimal impact on spectral-based algorithms.
- What's next? - TF based mode-shape estimation.

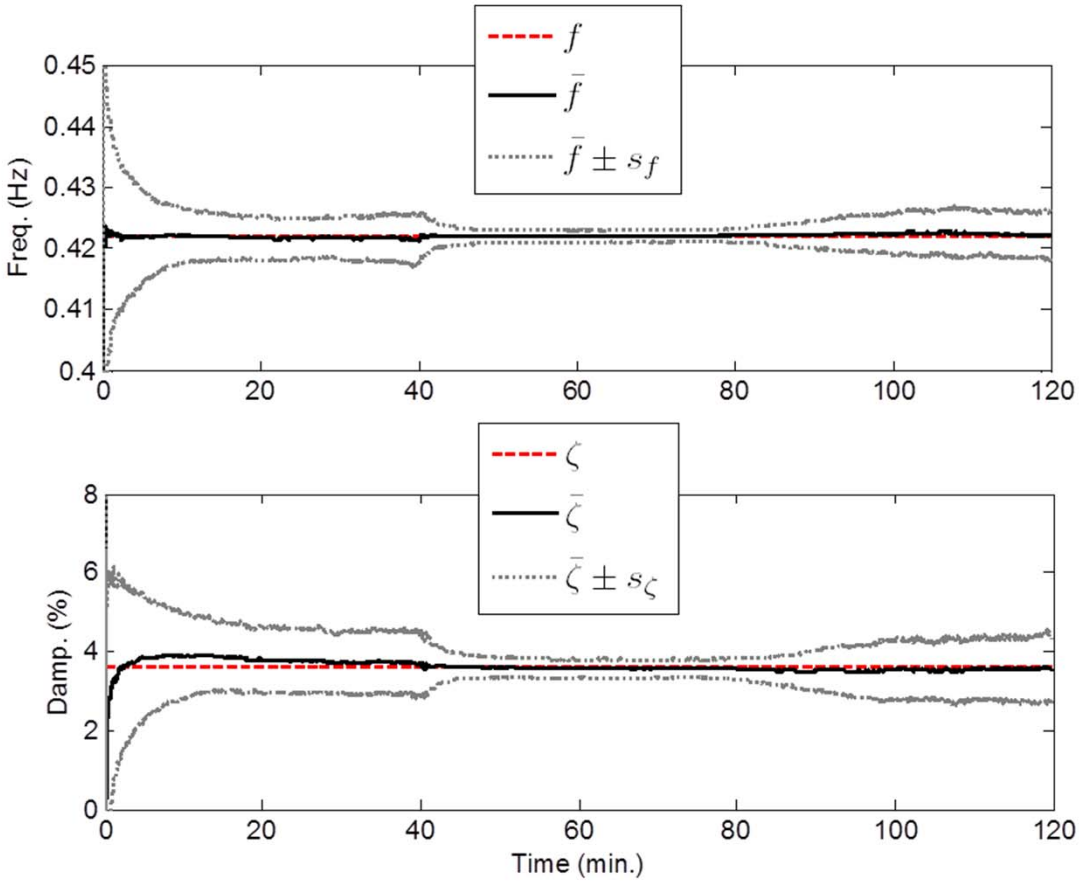
Simultaneous Mode and FO Estimation

Example Simulation

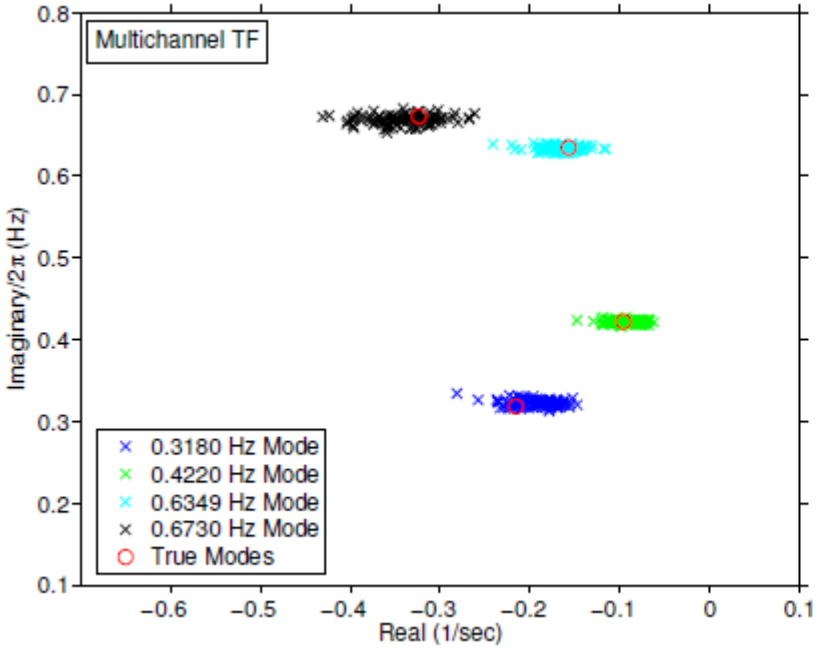


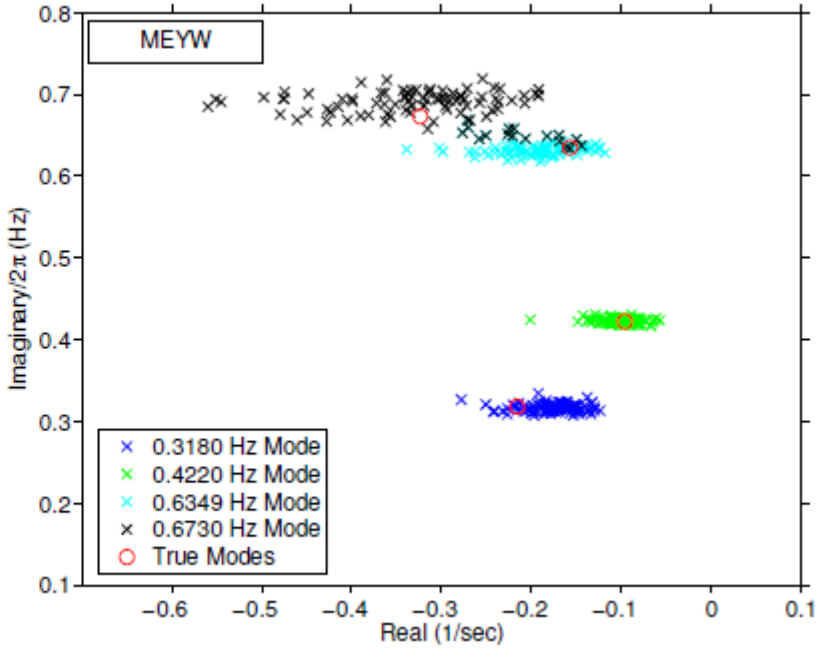
Mode Meter with Error Bounds RML

- 500 Monte Carlo Trials
- Probing from 40 to 70 minutes
- True values in RED
- Mean and region of one standard deviation given
- Mean lines up with true
- Standard deviation is low



Ambient Data Results
MCTF vs. MEYW





RD&D Stage

Components ranging from Theoretical Study to Pre-commercial.

- Theoretical Study:
  - Signal & systems research.
  - Forced oscillations research.
- Field Testing:
  - WECC system tests.
- Pre-commercial
  - MAS Software – Production-grade software engine for modal analysis in operations and control environment.
    - YW, R3LS, Mode-Meter Expert System
    - Auto-spectrum Estimation
    - Oscillation Detection via RMS Energy
  - Becoming operational at
    - BPA – Custom EMS software design.
    - WECC – Integrated into Alstom Grid application
    - CaISO – Integrated into RTDMS

FY13/14 Plans

- Continue fundamental signal & systems research
  - Continue mode-meter and mode-shape research
    - Improved accuracy
    - Impacts of forced oscillations
    - Performance indices (error bounds)
  - Fundamental nature of forced oscillations
  - Continue developing oscillation detection methods
    - Automated with little tuning
    - Distinguish between transients and forced oscillations
    - Identify root causes
- Continue to support WECC probing tests
- Integrate proven approaches into MAS

Testimonials

- ~45 publications in peer-reviewed journals and proceedings.
- Two patents pending.
- Helped organize/conduct IEEE Task Force (special publication).
- MAS production-grade software engine.
- MAS being used at WECC, BPA, and CaISO control centers

- **Questions?**