Applications on openPDC platform at Washington State University

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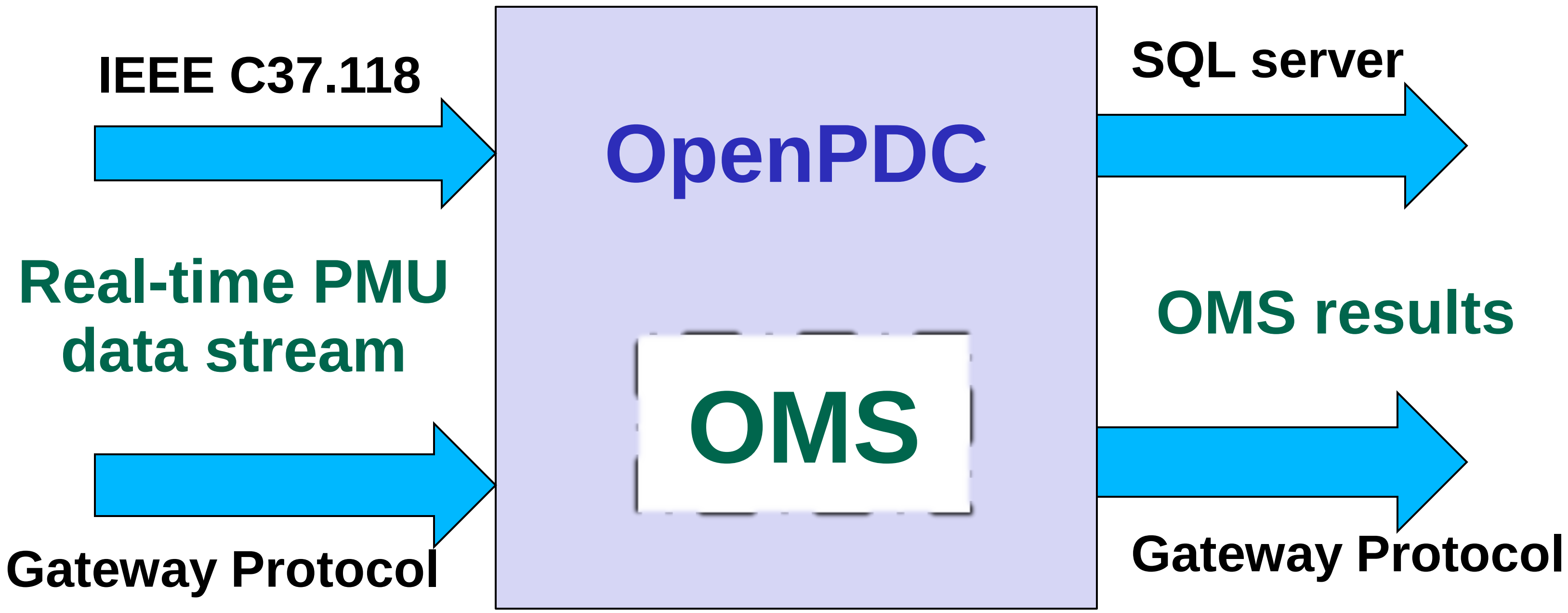
WSU projects

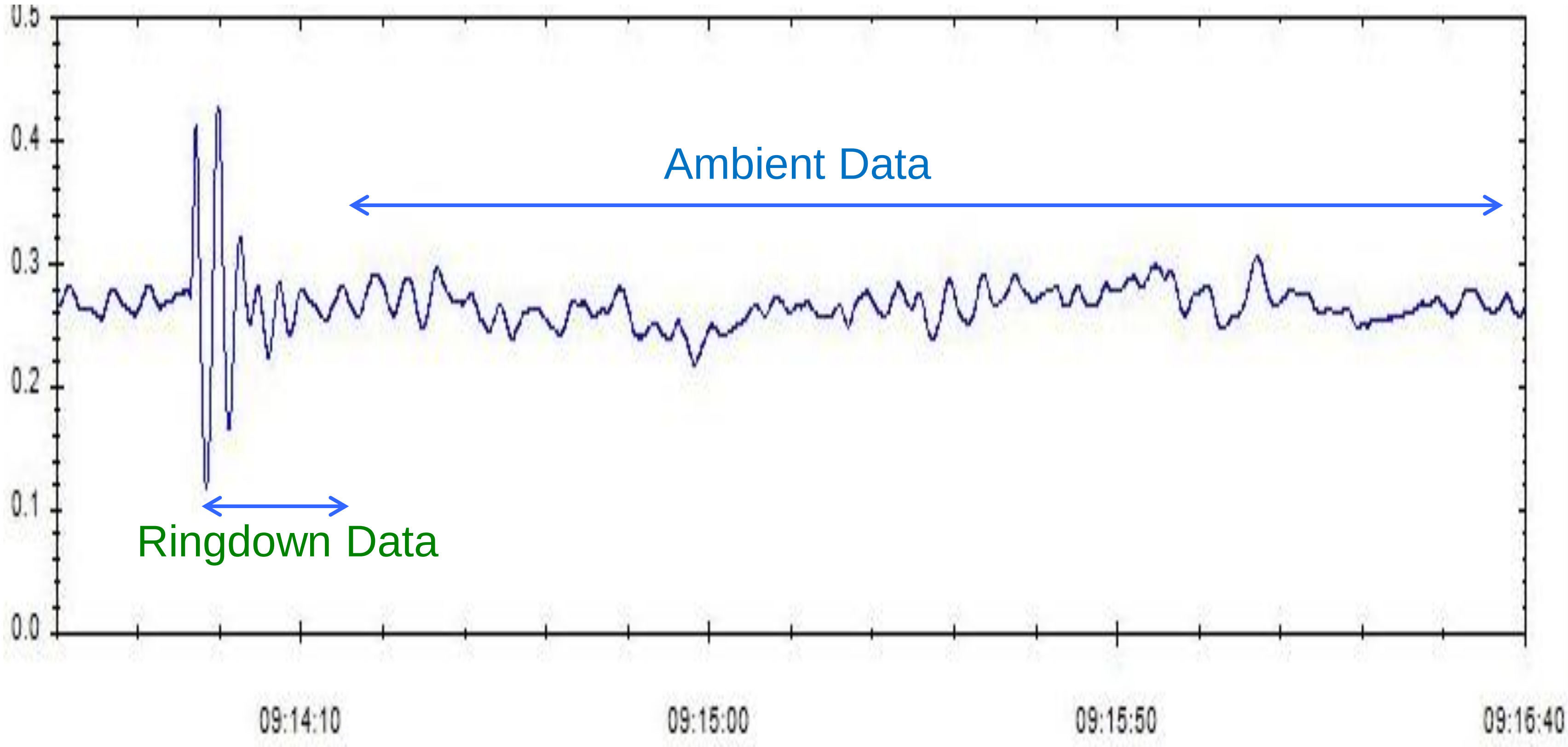
- "OMS" - Oscillation Monitoring System
  - Stand-alone system for oscillation detection and analysis using wide-area PMUs
- "VSMS" - Voltage Stability Monitoring System
  - Stand-alone system for voltage stability stress indicator using wide-area PMUs
- "GridSim" – Large-scale real-time power grid simulator
  - Powertech Labs new product "ePMU"

Oscillation Monitoring System

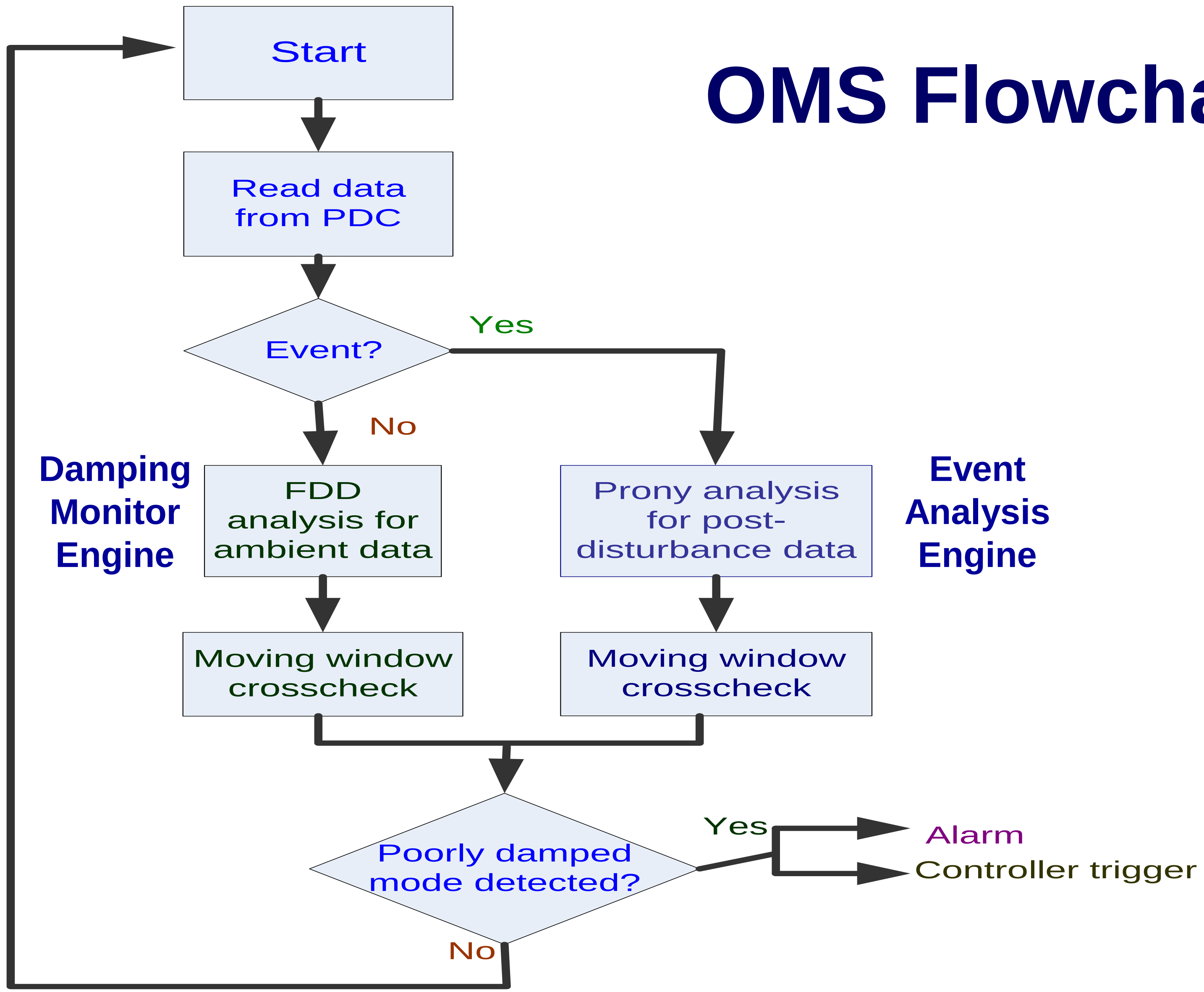


OMS action adapter built into OpenPDC 64 bit version 2.1.

Two Types of Data – Two Types of Engines



OMS Flowchart



Complementary Engines

- **Event Analysis Engine**
  - Four algorithms: Prony, Matrix Pencil and Hankel Total Least Square, ERA.
  - Aimed at events resulting in sudden changes in damping
- **Damping Monitor Engine**
  - Ambient noise based. Continuous.
  - Two algorithms: Fast Frequency Domain Decomposition, Fast Stochastic Subspace Identification
  - Provides early warning on poorly damped modes

Mathematical Model for Ringdown Data

- The response after small disturbances can be expressed in the sum of exponential terms

  - Transfer function

$$G_i(s) = \frac{\Delta y_i(s)}{\Delta u(s)} = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i}$$

where $R_i = c_i \phi_i \psi_i b$, ϕ_i and ψ_i are right eigenvector and left eigenvector

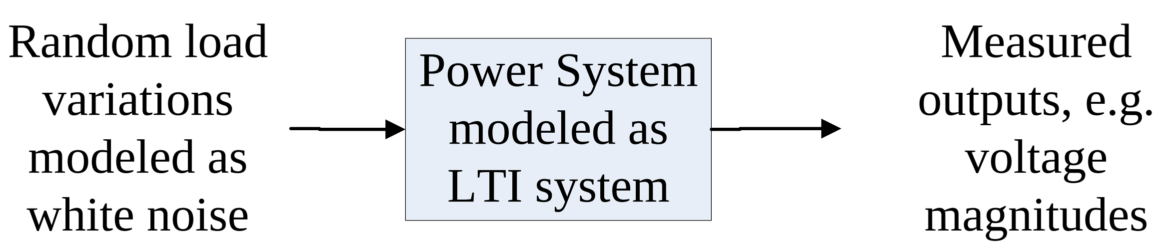
  - Impulse response $y_j(t) = \sum_{i=1}^{n} R_i \exp(\lambda_i t)$

  - Sampling at constant period $y(k) = \sum_{i=1}^{n} R_i z_i^k$ where $z_i = \exp(\lambda_i \Delta t)$

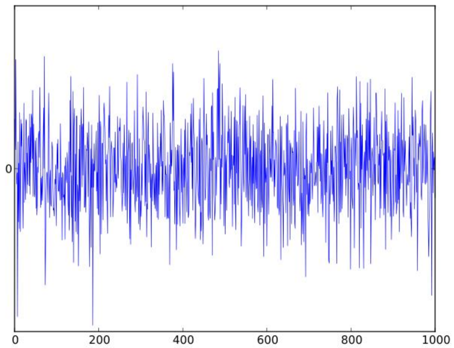
Mathematical Model for Ambient Data

- Power system is in fact a high-order nonlinear time-invariant system

- However, in normal operating state, power system can be modeled as an LTI system for a short period of time

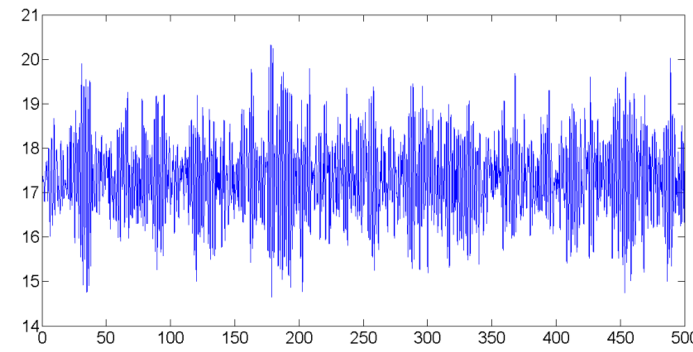


Frequency Domain Decomposition

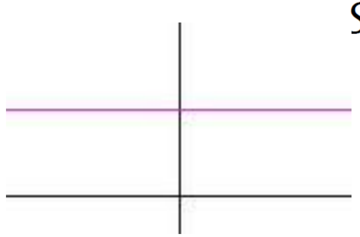


White noise

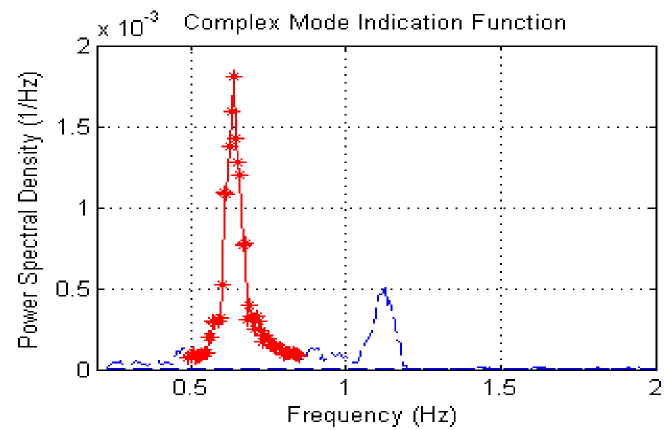
Power System

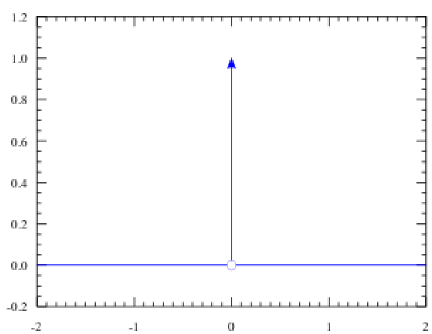


$$S_{yy}(j\omega) = H(j\omega).S_{uu}(j\omega).H(j\omega)^H$$

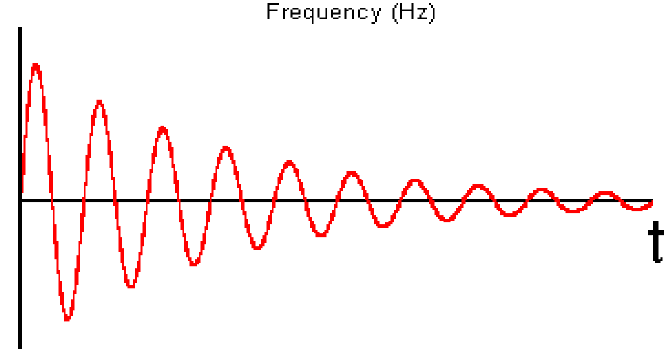


System





System



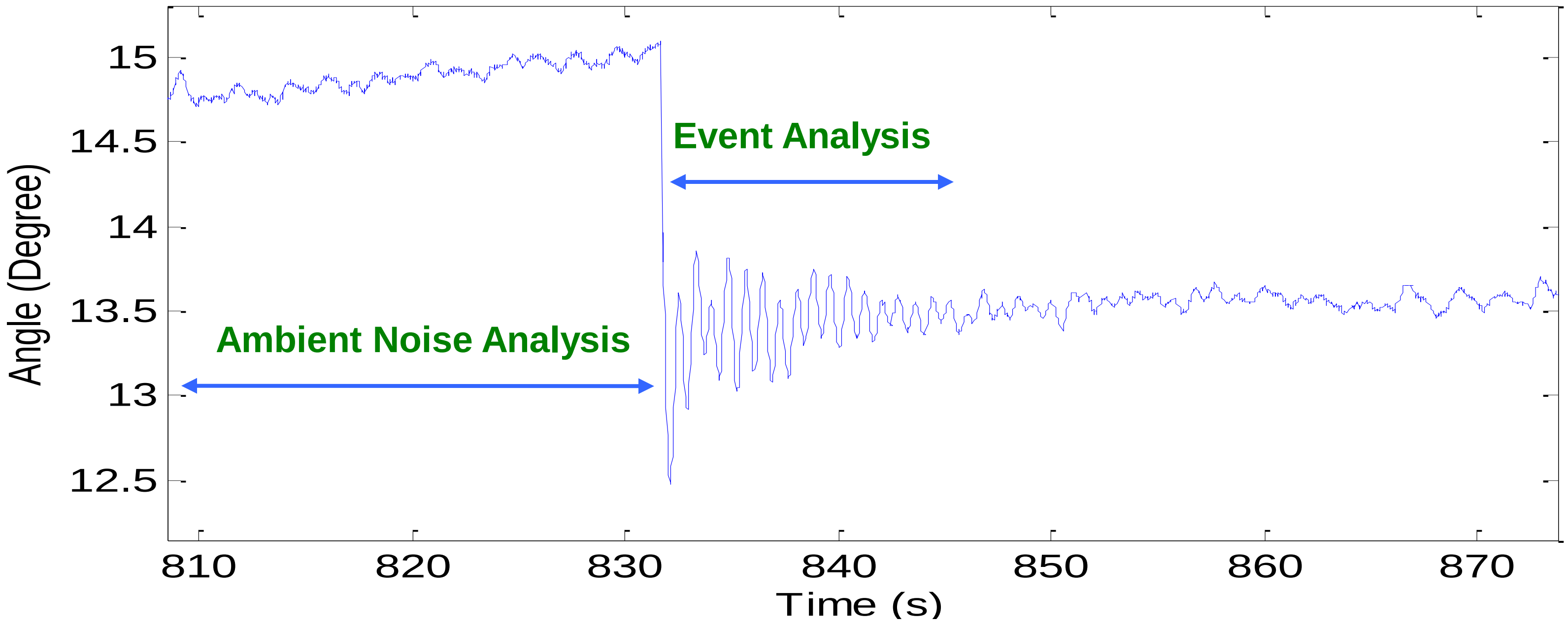
Procedure summary of FDD

- Form signal group from each PMU
- Power spectrum estimation by Multi-Taper Method
- Apply SVD on the power spectrum
- Apply inverse FFT on largest singular values
- Extract the pole frequency and damping ratio from the exponential form by ringdown analysis

OMS Engines

- Event Monitor Engine
  - Automated Prony type analysis of oscillatory ringdown responses
  - *Ten seconds* of PMU data analyzed every *one second*
- Damping Monitor Engine
  - Automated analysis of ambient noise data
  - *Four minutes* of PMU data analyzed every *ten seconds*

Results from Two Engines

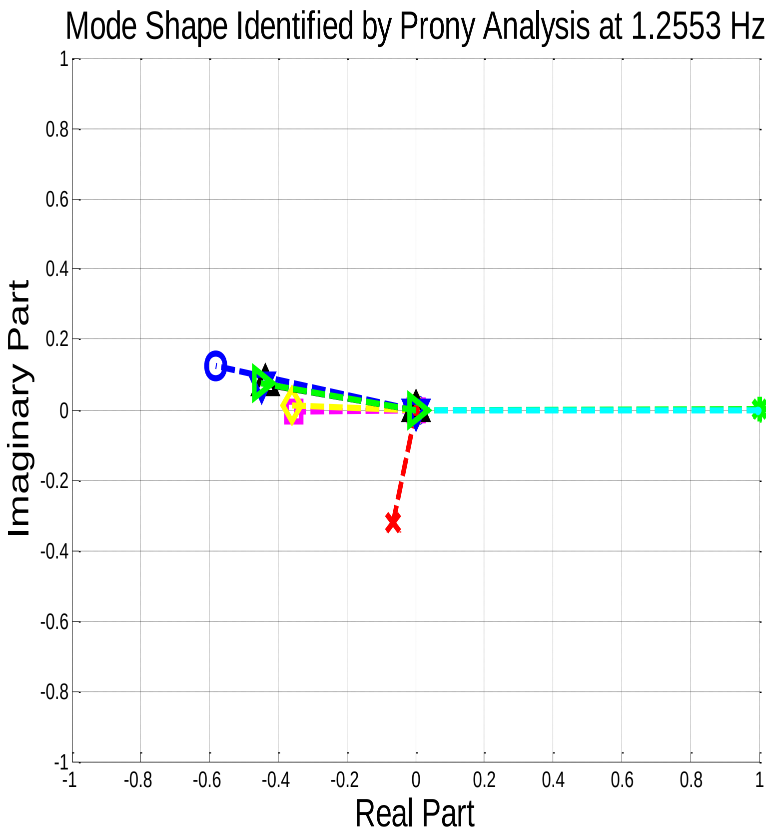


<u>Prony analysis:</u>
1.25 Hz Local Mode
@ 1.5% damping ratio

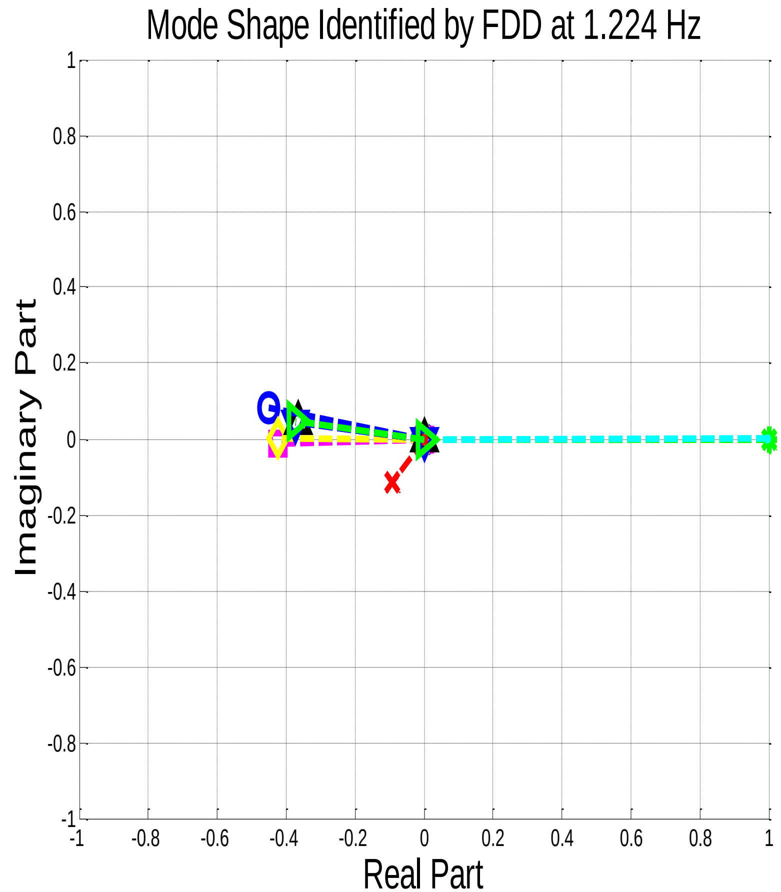
<u>FDD Analysis:</u>
1.224 Hz Local Mode
@ 1.17% damping ratio

Defective card found in Power System Stabilizer and fixed.

Mode Shape Estimation



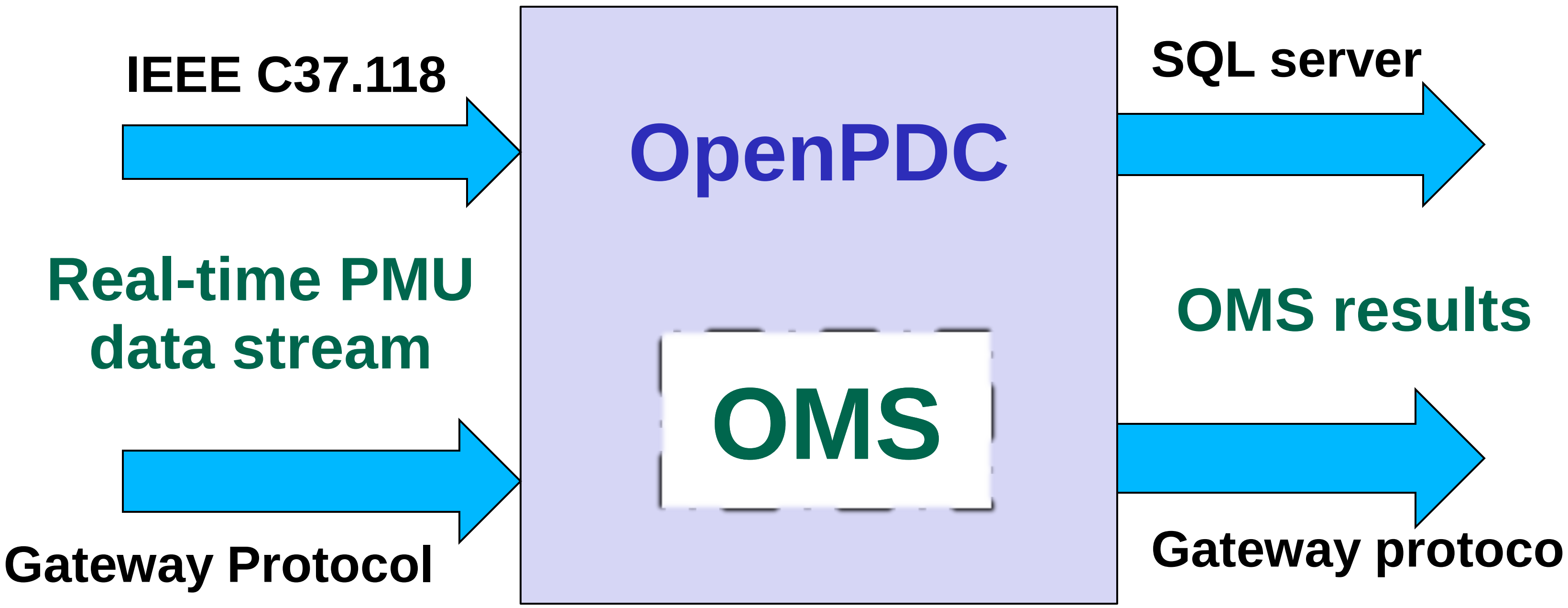
Prony Mode Shape



FDD Mode Shape

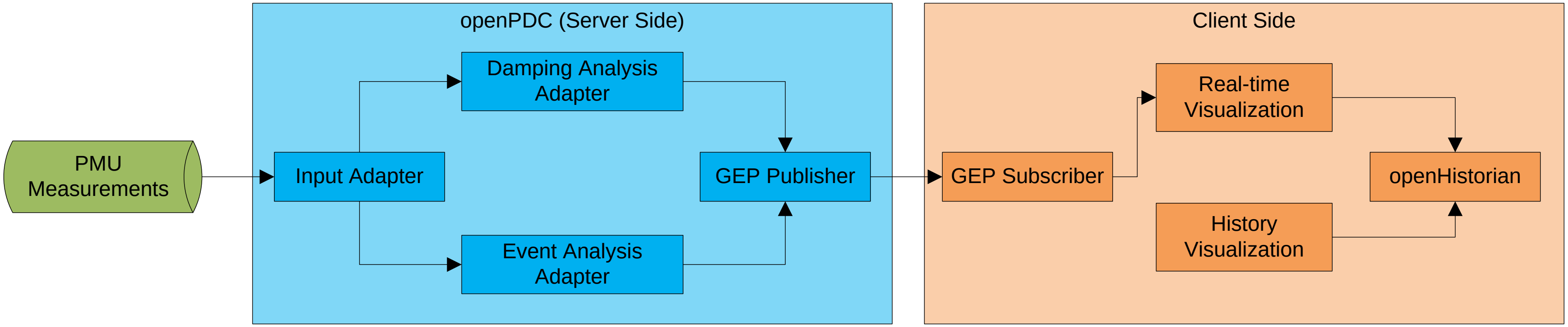
Mode shape helps pinpoint the root cause of oscillations.

Oscillation Monitoring System



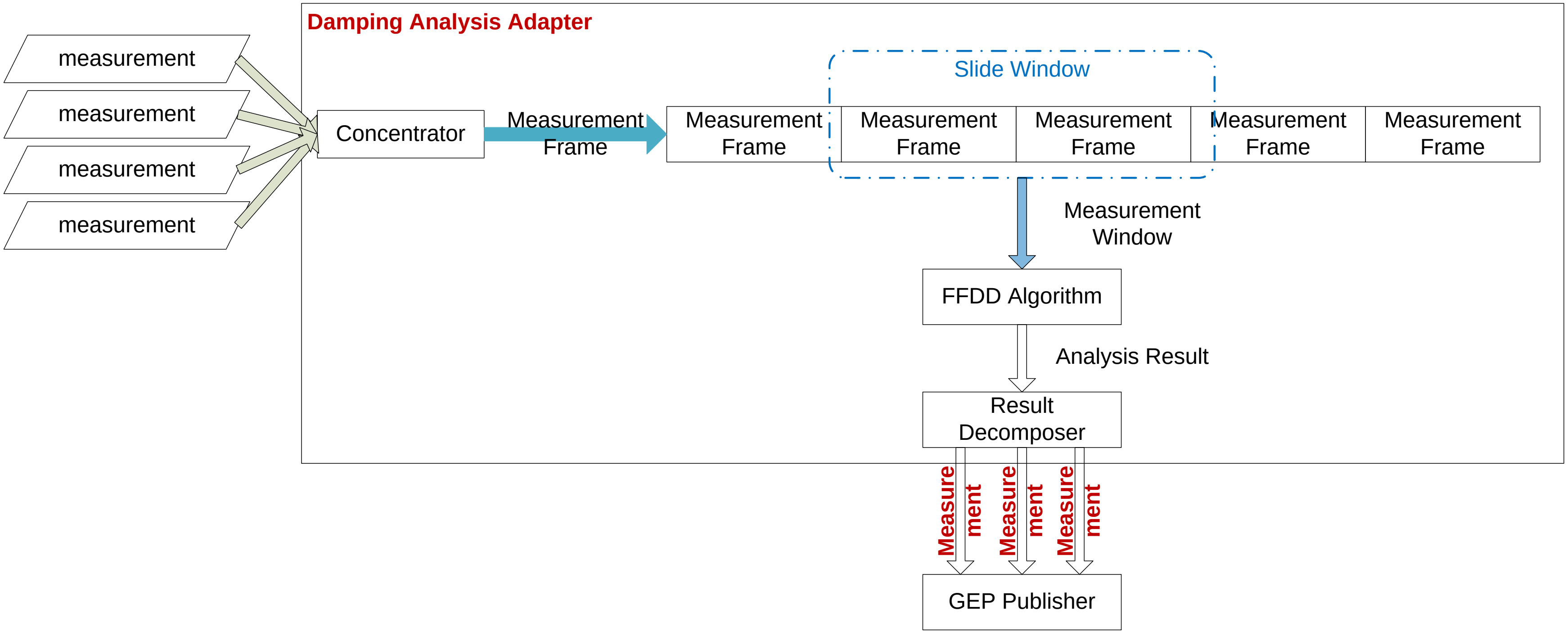
OMS action adapter built into OpenPDC 64 bit version 2.1. Tested at Entergy, TVA, Idaho Power, and WECC.

openPDC-based Architecture



- Server-side subsystem: two Action Adapters.
  - Damping Adapter
    - analyze ambient data to provide early-warning on poor-damped modes
  - Event Adapter
    - aims at events resulting in sudden changes in damping
- Client-side subsystem
  - Real-time visualization
    - receives updates from server, and presents them to user.
    - stores the received result into local openHistorian
  - History visualization
    - retrieve results from local openHistorian database
    - show the oscillation trend of the system in a specific period.

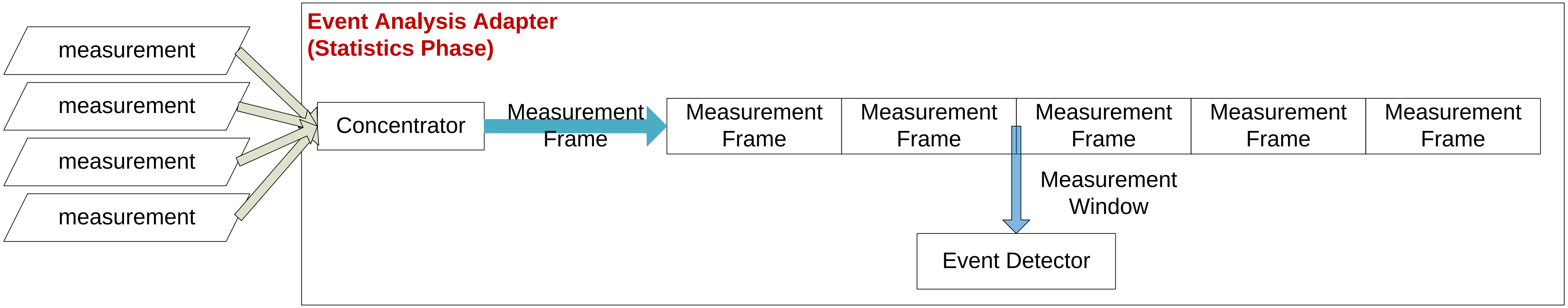
Monitor using ambient data



1. Measurements are concentrated into frame
2. Frames are inserted into a slide window.
3. A window of frames is fed into "FFDD Algorithm" to detect Oscillation
4. Detection result are decomposed into a batch of measurements.
5. Result measurements will be published using GEP

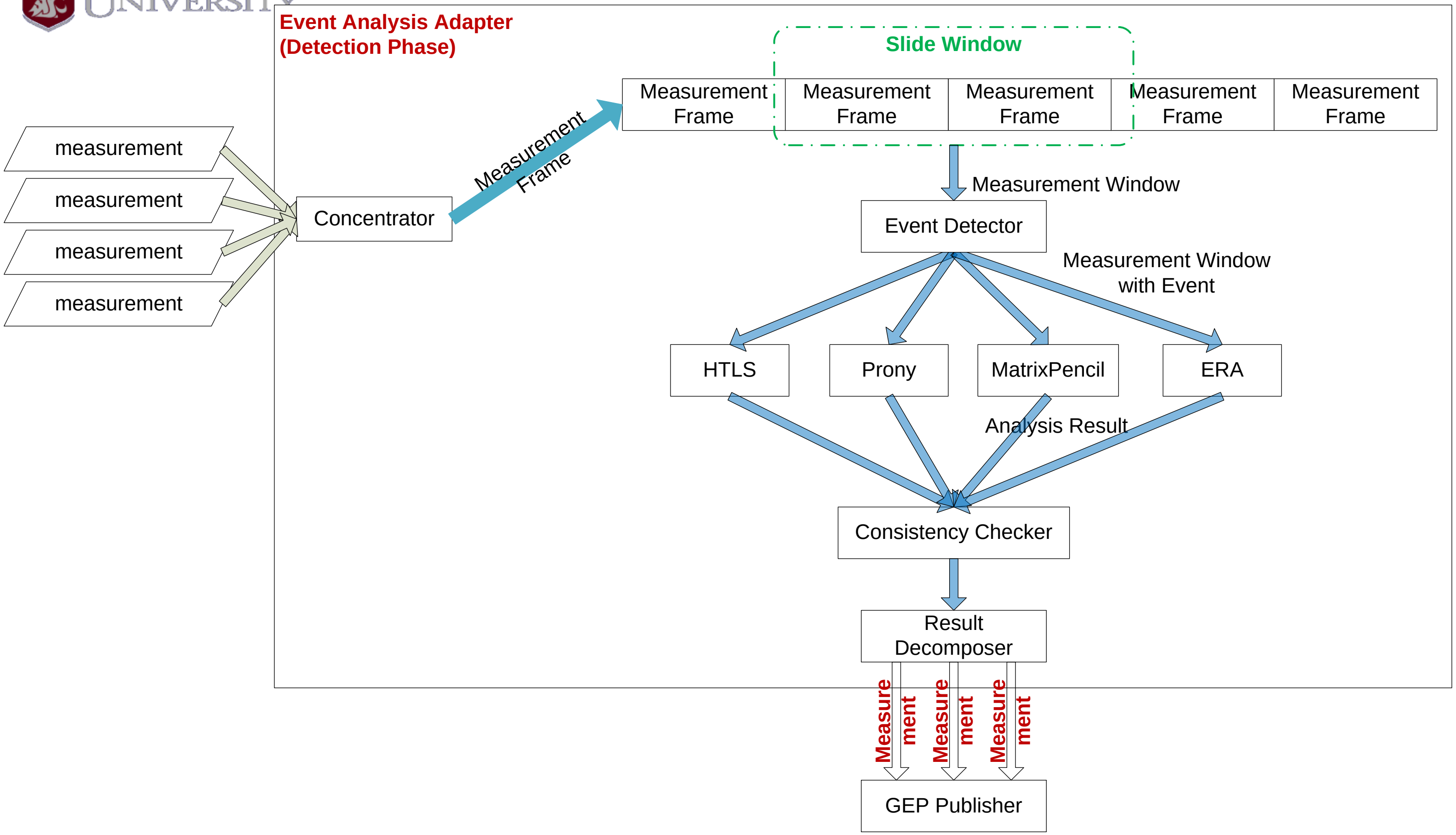
Monitor using event data

Phase I. Statistics Phase



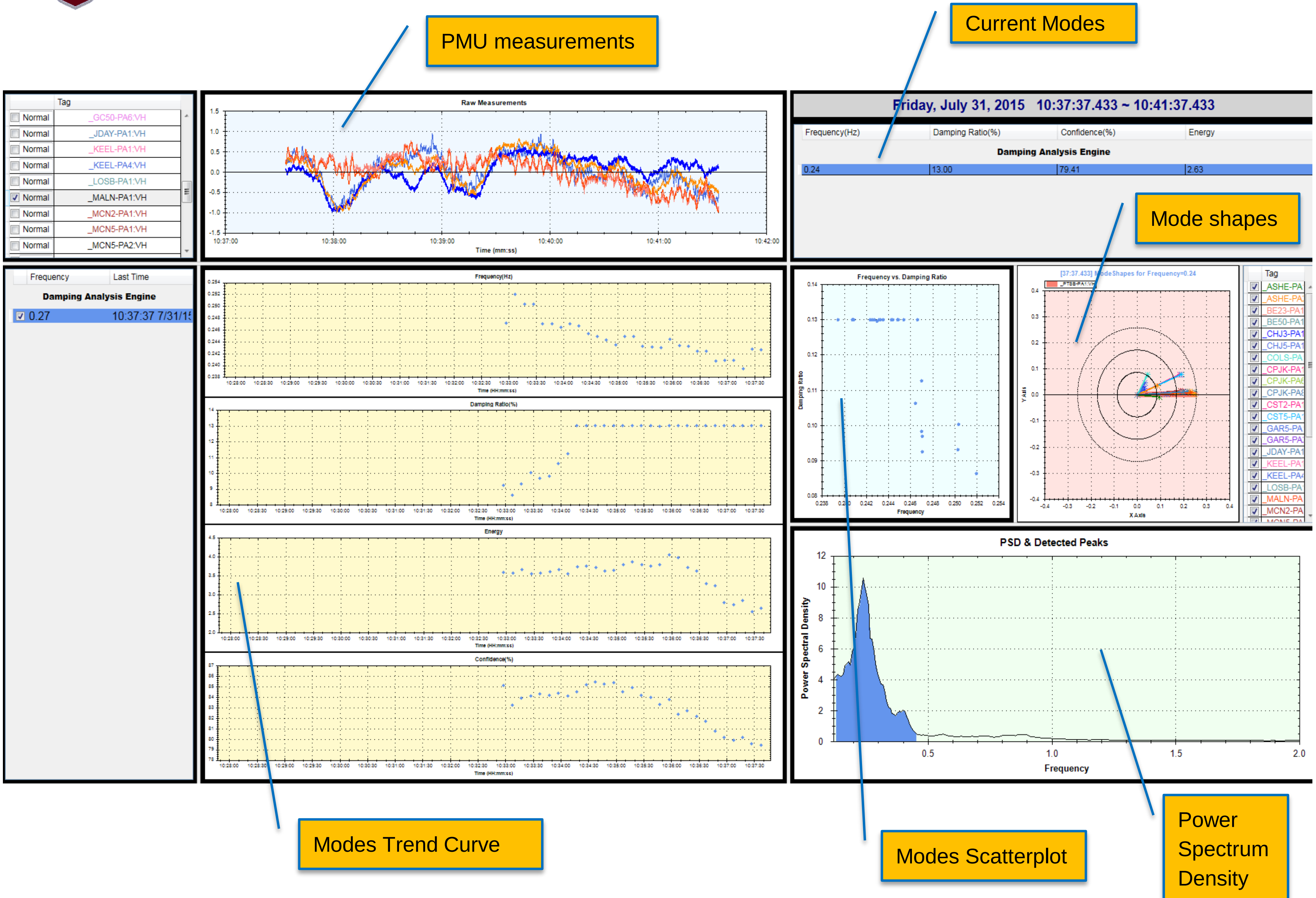
- accumulates a long period of measurements.
- calculate some statistics on this long period of data
- use these statistics as the thresholds to detect future event
- This phase will repeat periodically to update those event thresholds

Monitor using event data – Detect Phase

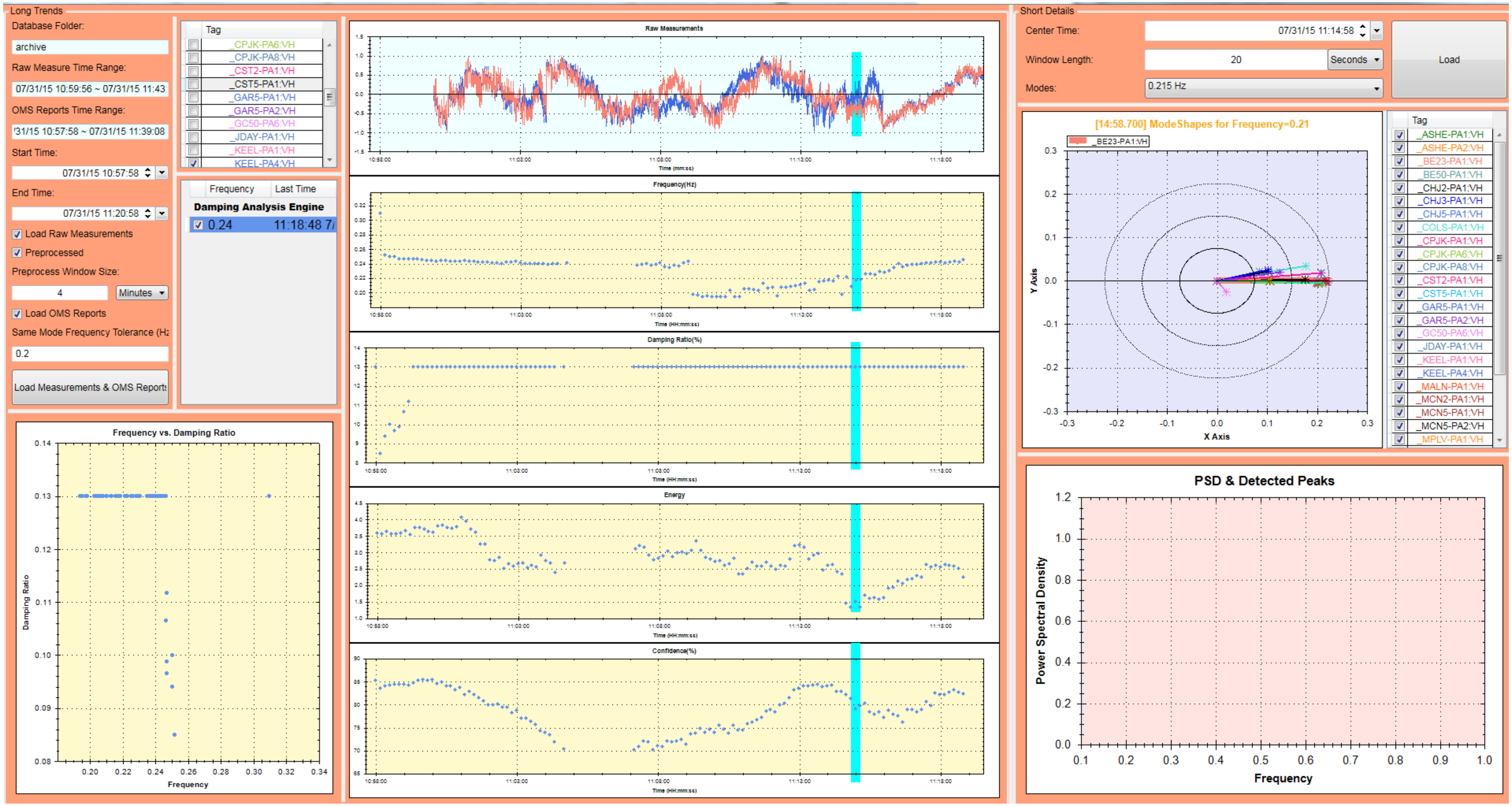


1. Measurements are concentrated and fed into slide window.
2. A window will go to Event Detector.
3. If continuous events are detected, further analysis starts.
4. Window with “real” event are analyzed by Prony, Matrix Pencil, HTLS and ERA in parallel
5. Analysis results need to go through “Consistency Check”.
6. Consistent result will be decomposed into measurements and published using GEP

Real-time visualization



History visualization



OpenPDC at WSU

- OpenPDC and openHistorian used extensively in several projects
- OpenPDC based PMU applications being installed at Entergy, TVA, and WECC
- Suggestions, Debugging, and WSU code contribution (openPDClite)
- Config tools, Visualization tools
- Commercialization…