DOE/OE Transmission Reliability Program

A persistence Measure and VARPRO-Based Modal Analysis of Ambient Sychrophasor Data

Bernie Lesieutre
Lawrence Berkeley National Laboratory/
University of Wisconsin-Madison
lesieutre@wisc.eud

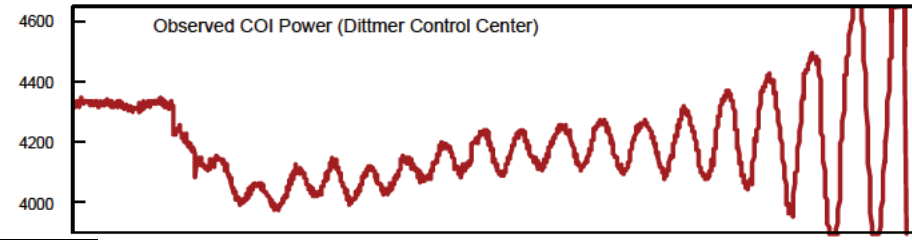
Sandip Roy
Washington State University
sroy@eecs.wsu.edu

CERTS Review: June 13, 2017, Washington, DC

CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

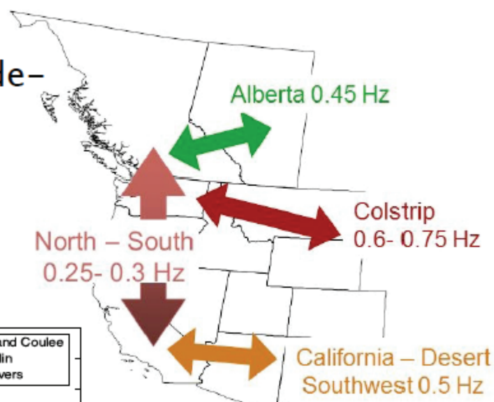
Background: Monitoring Damping

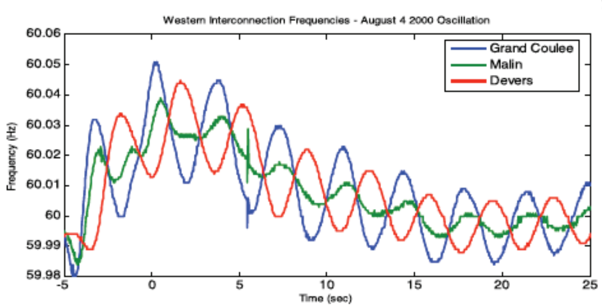
Sustained oscillations show lack of control in the grid, and can lead to blackouts.



Wide-Area View of Oscillations with Synchrophasors

Synchro-phasors provide wide-area geographic visibility of power oscillations:
– Is it a local or inter-area oscillation?





It would be useful to monitor system damping from ambient data, prior to a disturbance.

D. Kosterev, J. Undrill, “Oscillations in Power Systems,” NASPI Jun. 3, 2011

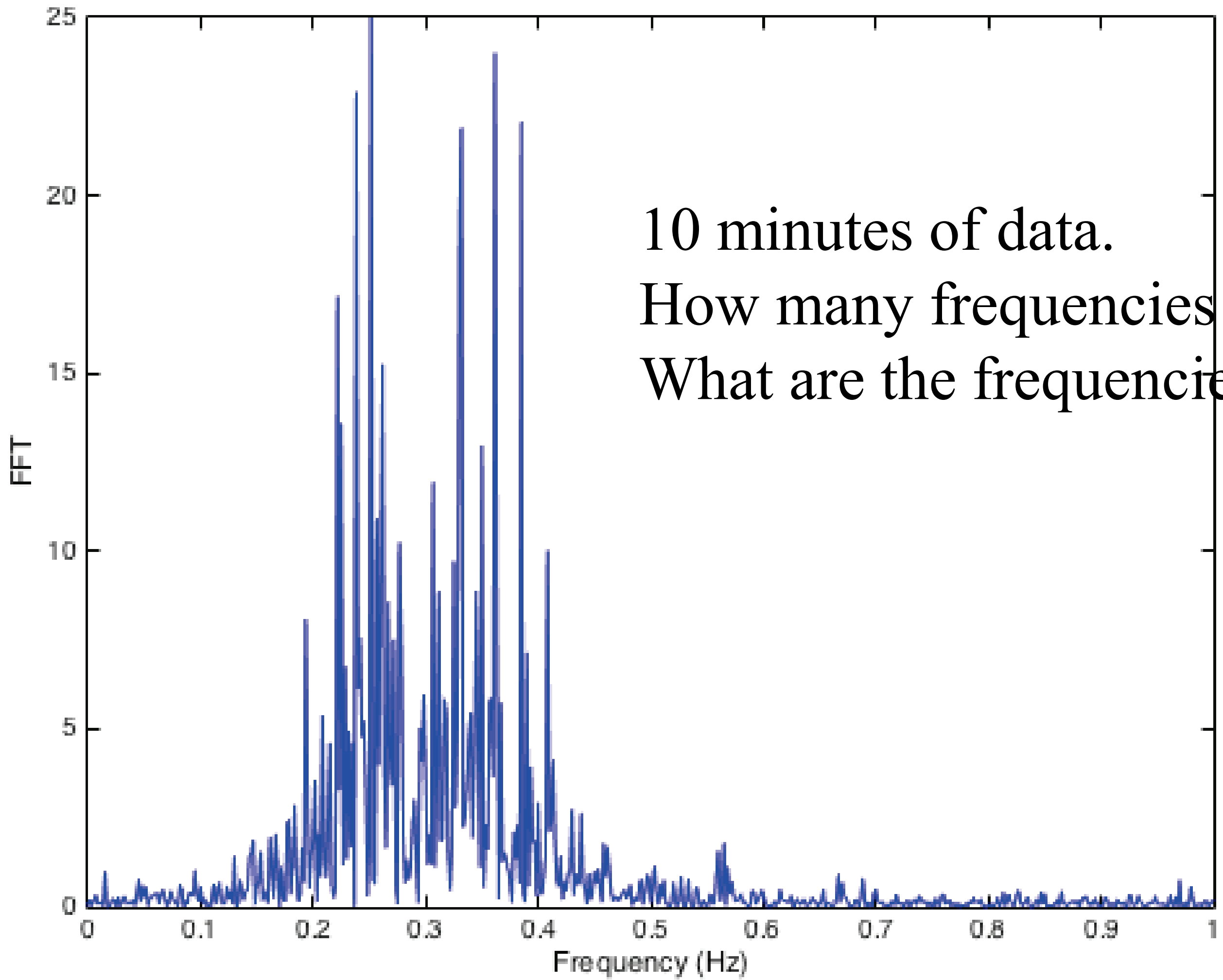
CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Details: The Challenges

- Ambient data is noisy.
- Modal analysis is difficult with a short time windows.
- Estimating multiple mode frequencies and damping involves estimating many parameters using low SNR information. Not robust.

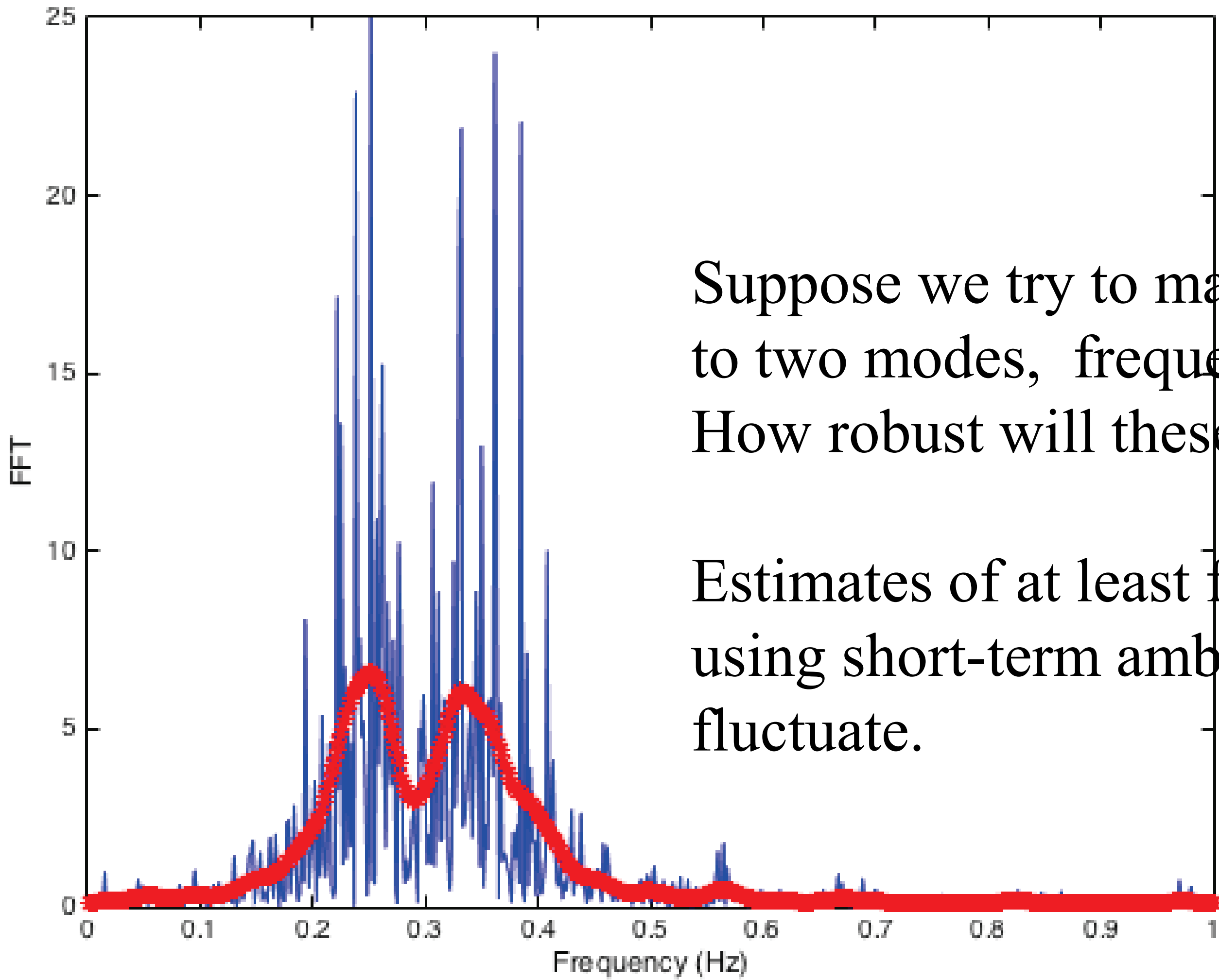
CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Challenges



10 minutes of data.
How many frequencies are present?
What are the frequencies and damping?

Challenges



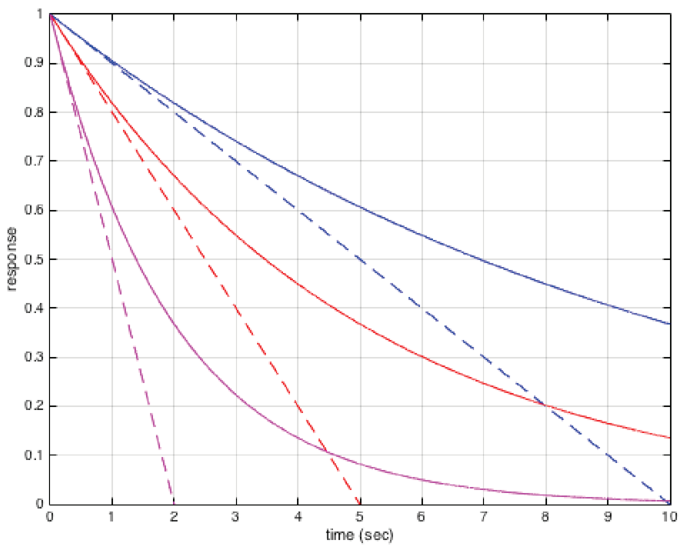
Suppose we try to match data to two modes, frequency and damping. How robust will these estimates be?

Estimates of at least four parameters using short-term ambient data will fluctuate.

Introduce a *persistence* measure !

- Instead of a modal decomposition (or in addition to), calculate a single persistence measure of the duration/decay of a natural response.

The most obvious example is an exponential time-constant.



$$h(t) = e^{-\frac{t}{T}}\ u(t)$$

The larger the time constant, the longer the ”duration” or “persistence” of the response.

CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Introduce a Persistence Measure

$$\Upsilon = \left\| \frac{R(\tau)}{R(0)} \right\|_2$$

System Persistence Measure

$$\Upsilon = \frac{\int_{w=-\infty}^{\infty} S(w)^2 dw}{\left(\int_{w=-\infty}^{\infty} S(w) dw\right)^2}$$

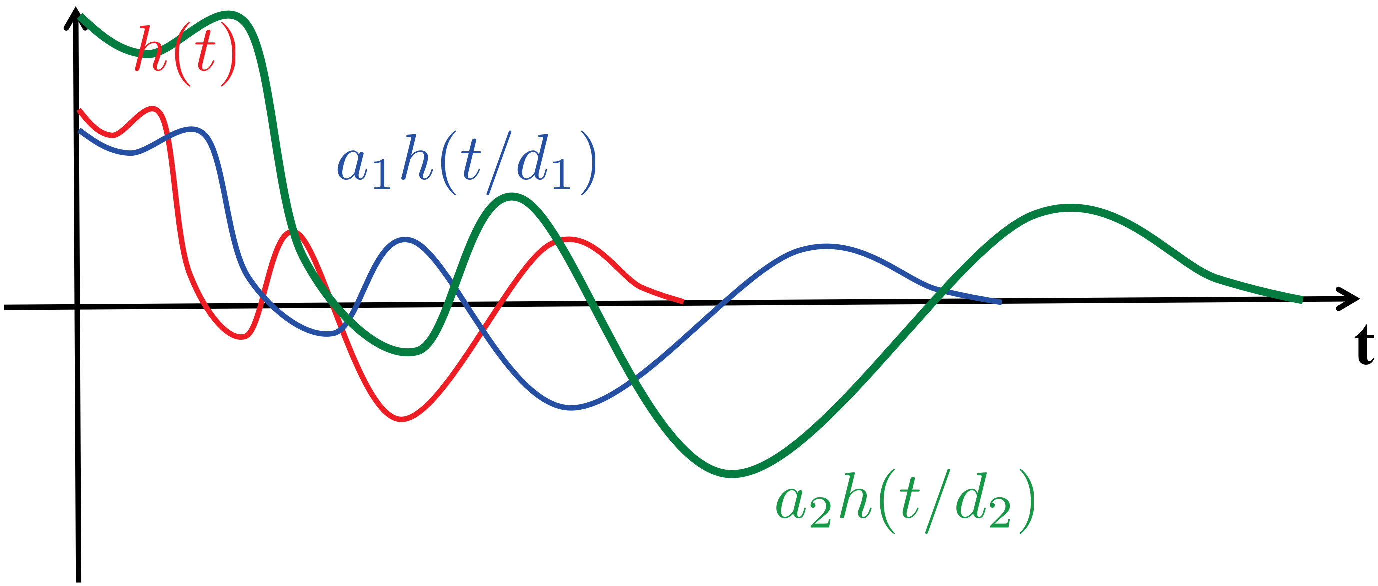
Important Properties:

- **Scales linearly with "stretching" of impulse response, regardless of shape.**
- For exponentials, doubling the time constant, doubles the measure.
  - For single mode, non-oscillatory exponentially-decaying impulse response, **it equals the time constant**;
  - For single mode, oscillatory exponentially-decaying impulse response **it is half the time constant**.

Calculable from the autocorrelation!

CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Stretching Property

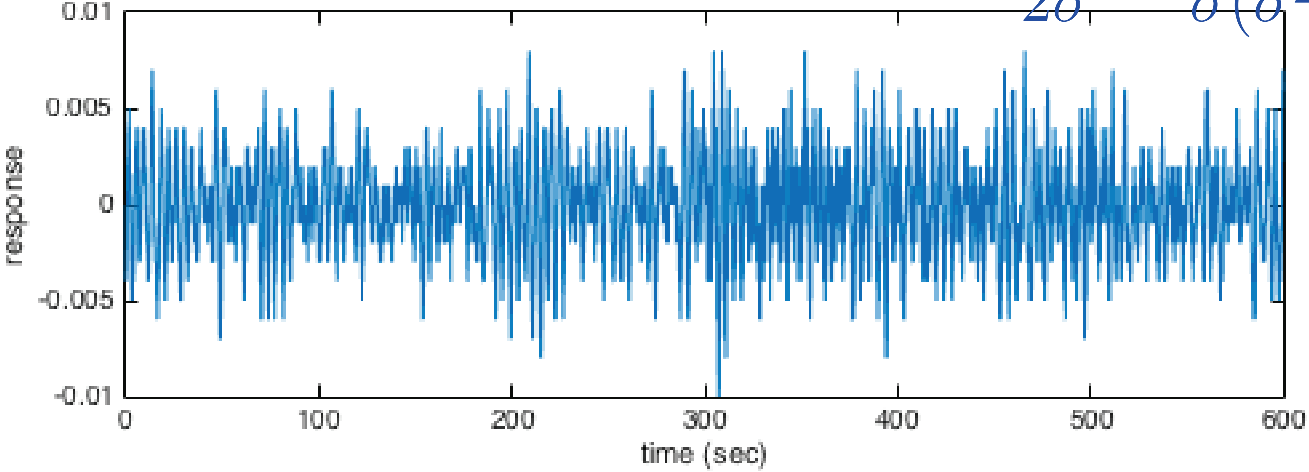


$$h(t) \rightarrow \Upsilon_0$$
$$a_1 h(t/d_1) \rightarrow d_1 \Upsilon_0$$
$$a_2 h(t/d_2) \rightarrow d_2 \Upsilon_0$$

All these signals have the same shape. They differ in amplitude and stretching. The metric scales only with time-stretching. (Indifferent to amplitude.)

Example (real data)

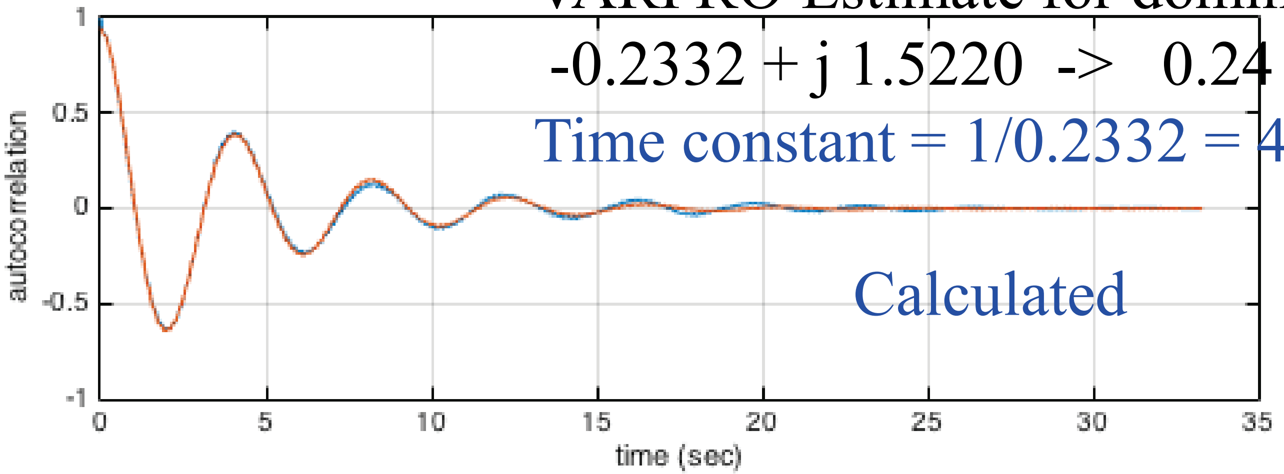
$$\Upsilon = \frac{-1}{2\sigma} + \frac{-2\sigma^6}{\sigma(\sigma^2 + \omega_o^2)(2\sigma^2 + \omega_o^2)^2}$$



VARPRO Estimate for dominant mode exponent

-0.2332 + j 1.5220 -> 0.24 Hz at 15% damping

Time constant = 1/0.2332 = 4.29 seconds



Calculated

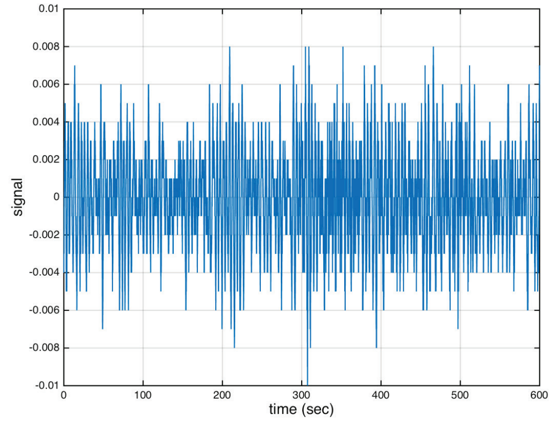
$$\Upsilon = 2.20$$

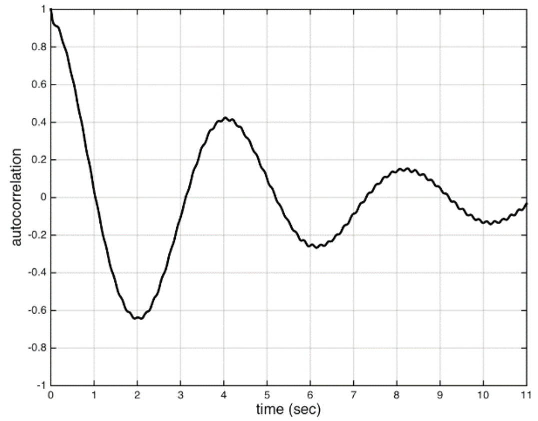
$$2\Upsilon = 4.40$$

CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Mode Estimation via Curve Fitting

- Apply VARPRO curve-fitting technique to modal analysis of ambient data.





The "easy" curve is the autocorrelation of the random-looking signal.

This auto correlation may be analyzed using model-fitting (Yule-Walker, subspace methods, etc.) or curve fitting techniques.

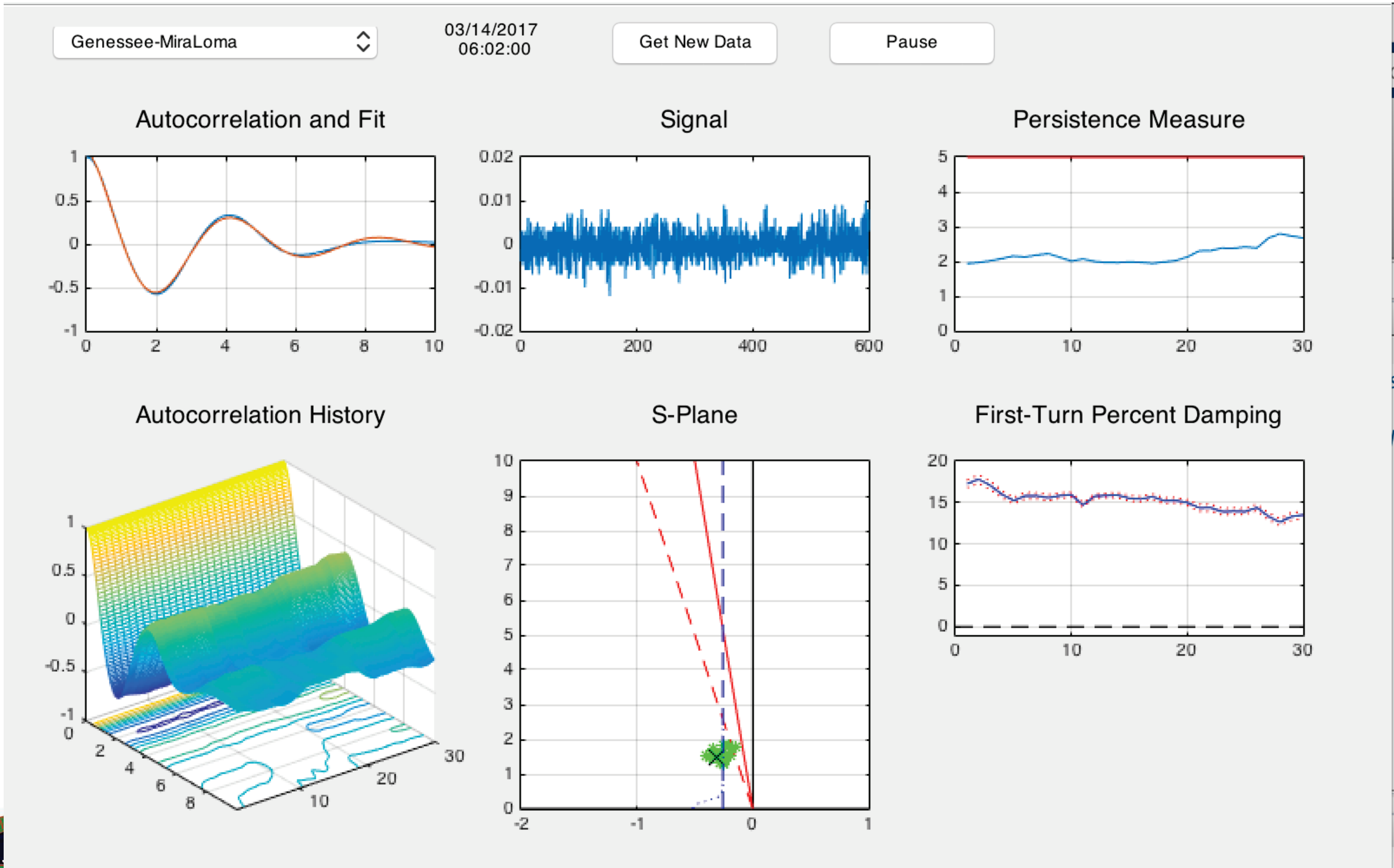
Our approach uses curve-fitting.

CERTS CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Summary: Results for past year

- **Added Persistence Measure to real-time monitoring.**
- **Added First-turn relative damping estimate.**
- **Under-the-hood improvements to algorithms (calibrating finite window-based calculations)**
- **Implemented in BPA real-time phasor measurement laboratory.**
- **Produced initial papers on our methods**
  - Lesieutre, B.C. and S. Roy, "A System Response Persistence Measure for use in Ambient Data Monitoring," to be presented at the 2017 North American Power Symposium.
  - Roy, S, and B.C. Lesieutre, "A Sample-Autocorrelation-Based Approach for Monitoring Power-System Damping from Ambient Synchrophasor Data," to be presented at the 2017 North American Power Symposium

Modemeter



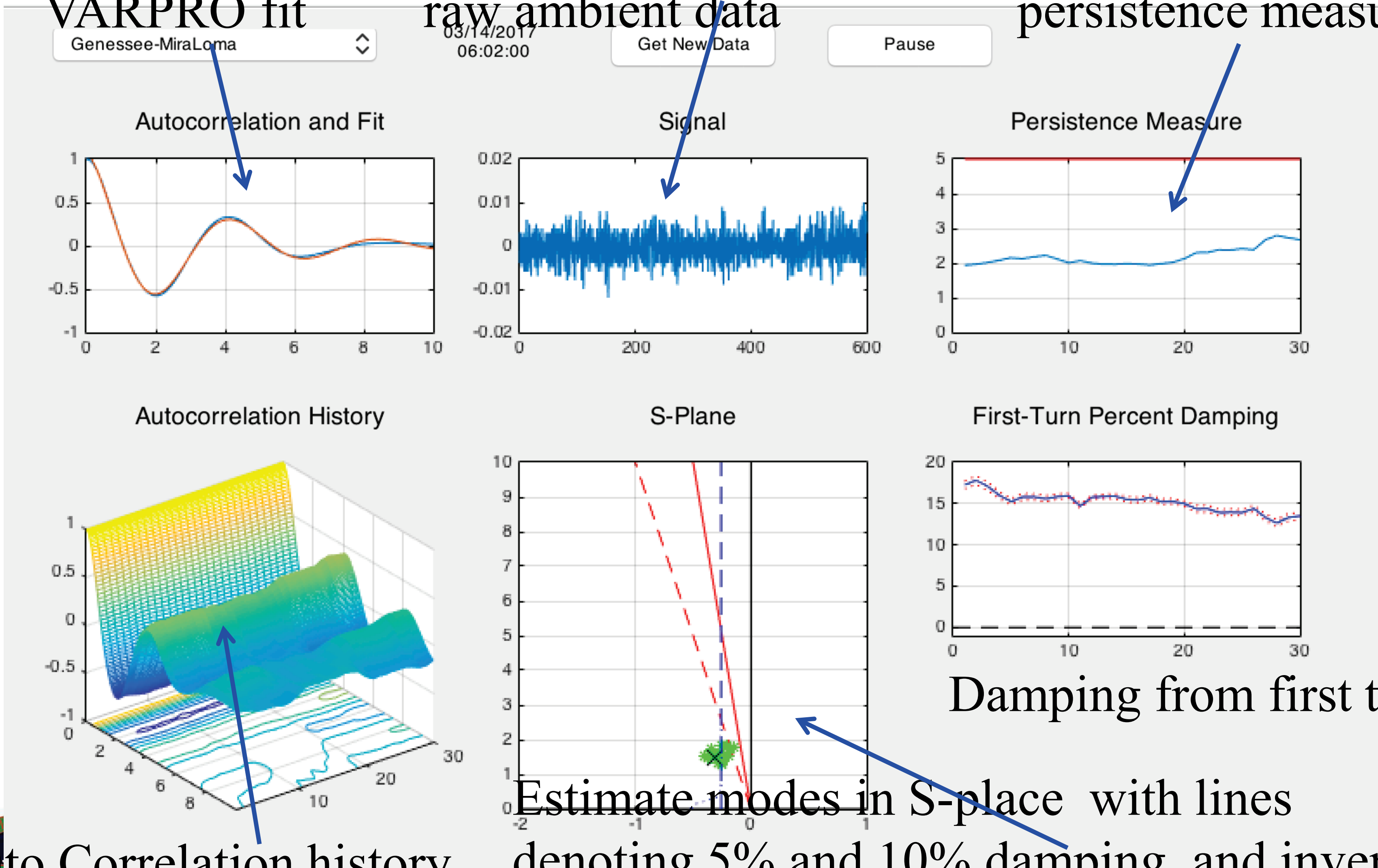
ELECTRIC RELIABILITY
TECHNOLOGY SOLUTIONS

Modemeter

Autocorrelation and VARPRO fit

raw ambient data

persistence measure.



Damping from first turn

Auto Correlation history

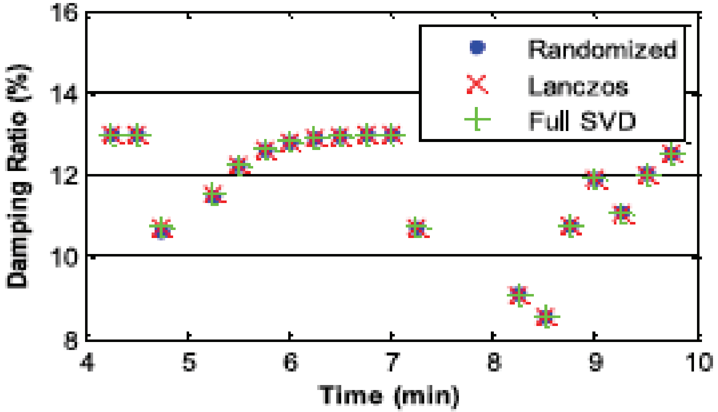
Estimate modes in S-place with lines denoting 5% and 10% damping, and inverse persistence measure.

Looking Forward

Some technical things

- Frequency-domain form of metric, and variants.
- Multiple signals
- More testing
- More publishing
- **Technology Transfer**

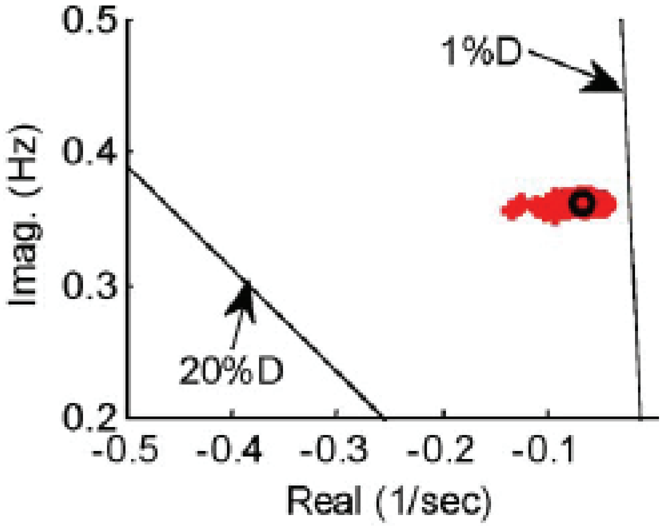
Background: Monitoring Damping



Wu et al. IEEE Transactions on Smart Grid, May 2017

Subspace method

Accurately and consistently estimating damping is difficult using ambient data



Yule-Walker method

Trudnowski et al., IEEE Transactions on Power Systems, May 2008

CONSORTIUM *for* ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS