A Persistence Measure for use in PMU-based Ambient Data Monitoring

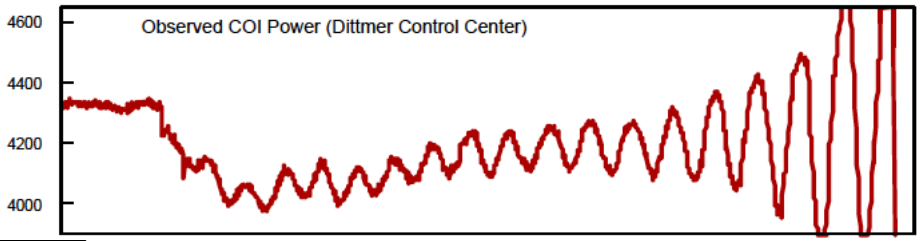
Bernie Lesieutre — University of Wisconsin-Madison
Sandip Roy — Washington State University

Publications

1. Lesieutre, Bernard C., and Sandip Roy, “Calculating and calibrating a persistence measure for use in monitoring power system vulnerability,” 55th Annual Allerton Conference on Communication, Control, and Computing, Allerton, IL, (2017)
2. Lesieutre, Bernard C., and Sandip Roy, “A system response persistence measure for use in ambient data monitoring,” North American Power Symposium, Morgantown, WV, (2017)
3. Roy, Sandip, and Bernard Lesieutre, “Frequency Band Decomposition of a Dynamic Persistence Measure Using Ambient Synchrophasor Data,” Power System Computation Conference (PSCC), Dublin, Ireland, 2018.

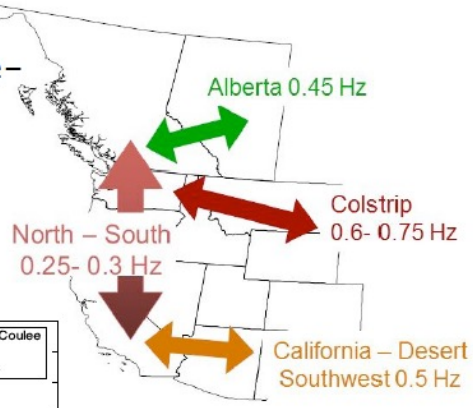
Background: Monitoring Damping

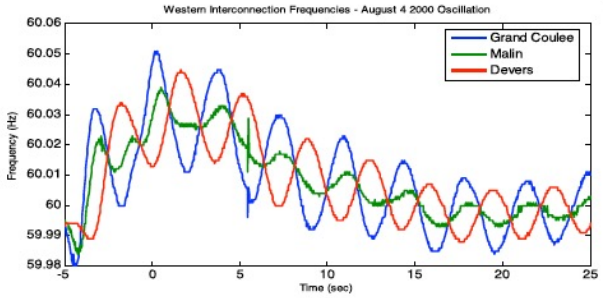
Sustained oscillations show lack of control in the grid, and can lead to blackouts.



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?



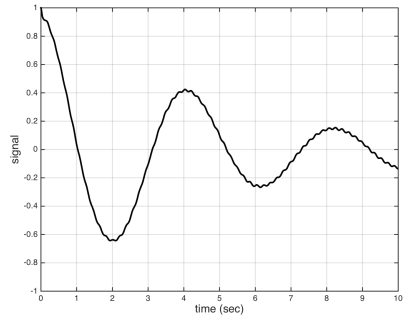


It would be useful to monitor system damping from ambient data, prior to a disturbance.

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

Background: Event Ringdown Analysis

Model fitting and Curve Fitting Techniques



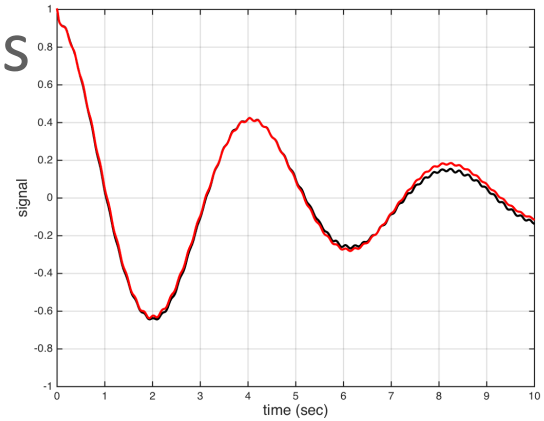
DATA

create system model

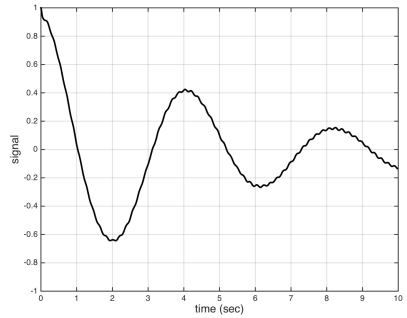
Prony, matrix pencil, ERA, etc.

then

Ping the model…

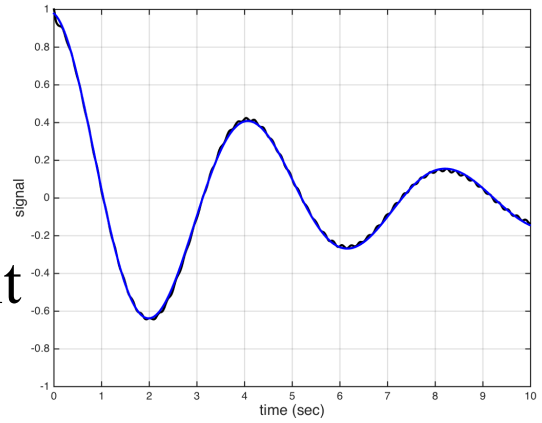


check result



Curve fit

VARPRO, etc



Results yield information about modes present in observed responses

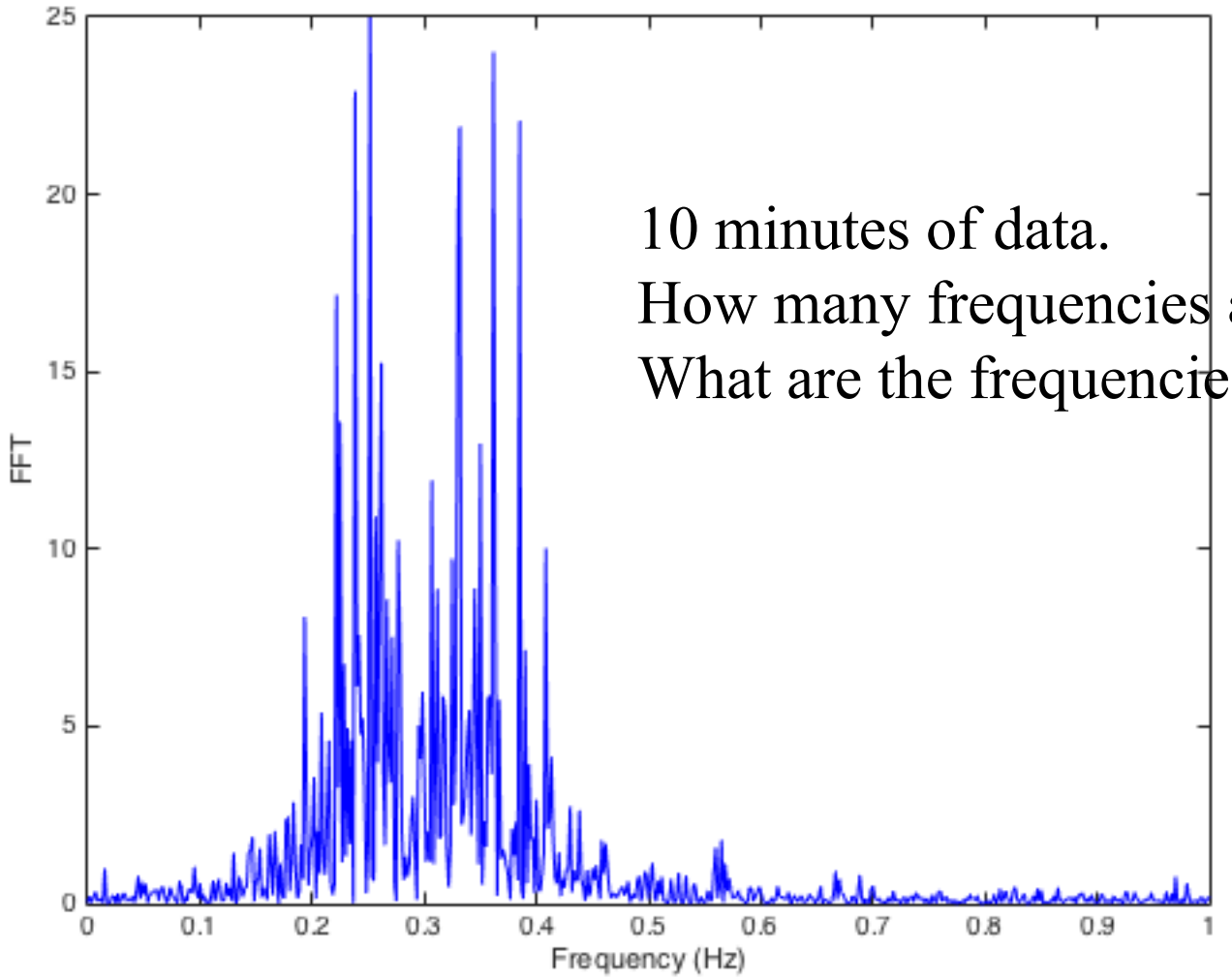
Events are infrequent.

How can we assess the system using ambient data?

Details: The Challenges

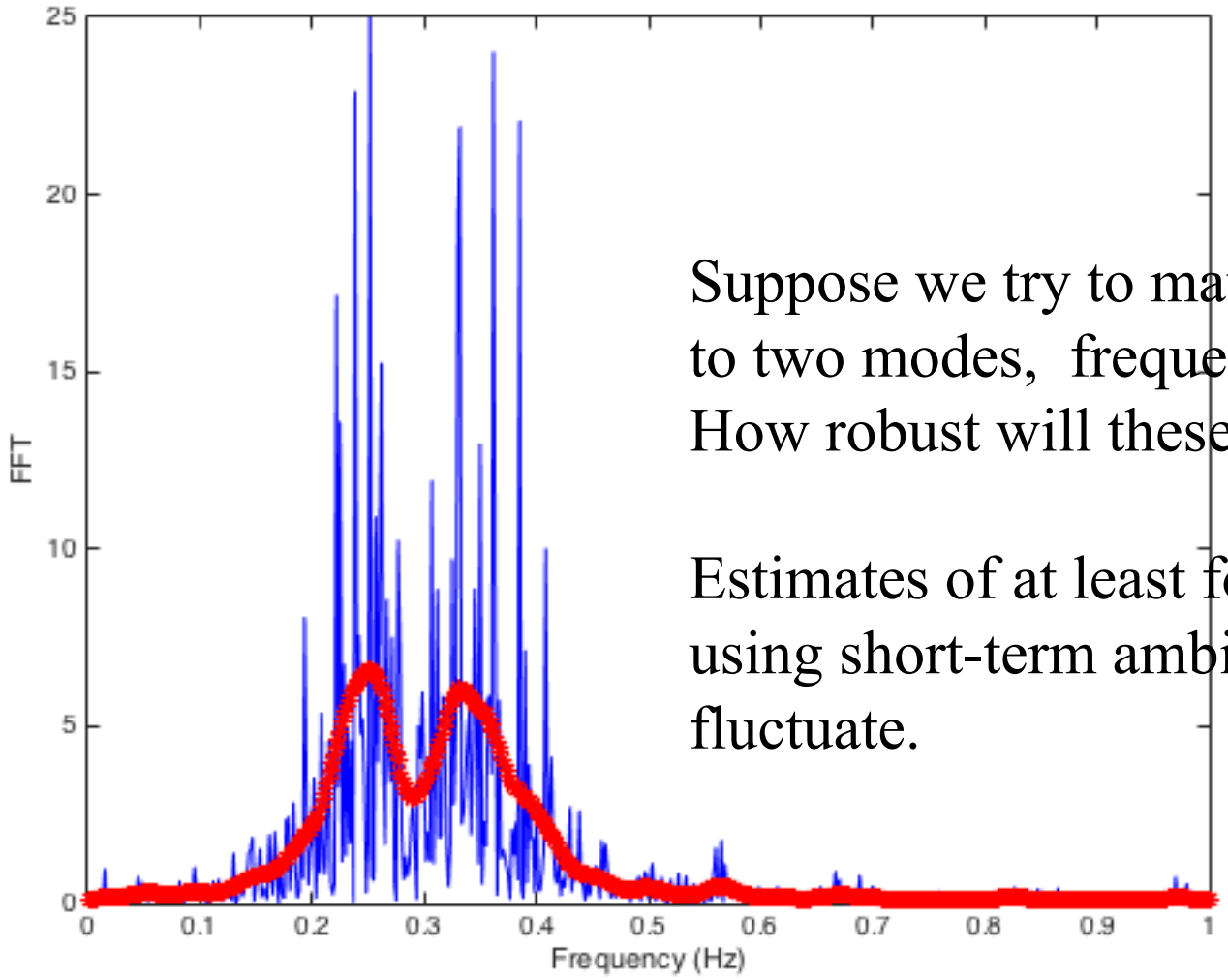
- Ambient data is noisy.
- Modal analysis is difficult with a short time windows.
- Estimating multiple mode frequencies and damping involves estimating many parameters using low SNR information. **Not robust**.

Challenges



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

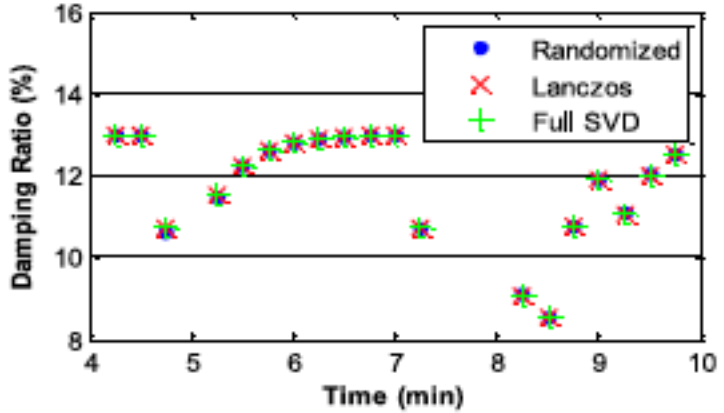
Challenges



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.

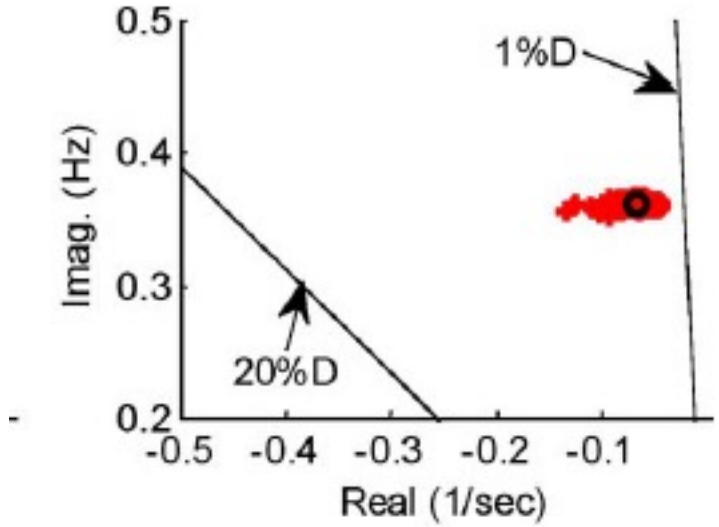
Background: Monitoring Damping



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

Subspace method

Accurately and consistently estimating damping is difficult using ambient data



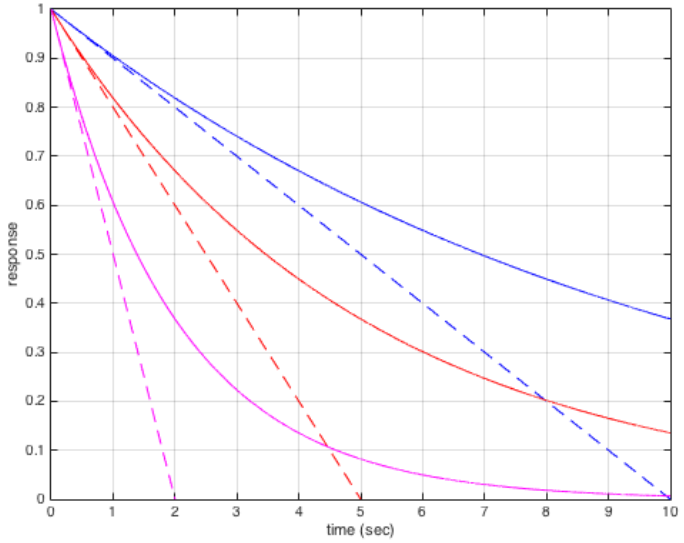
Trudnowski et al., IEEE Transactions on Power Systems, May 2008

Yule-Walker method

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.

Introduce a Persistence Measure

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

System Persistence Measure

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

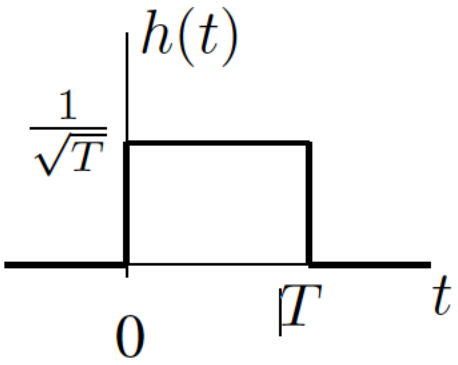
Important Properties:

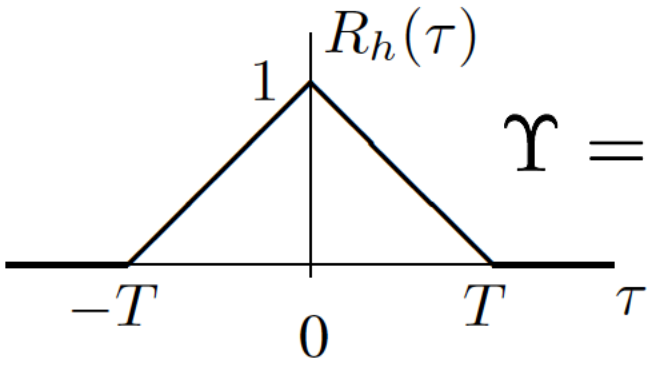
- **Scales linearly with "stretching" of impulse response, regardless of shape.**
- For exponentials, doubling the time constant, doubles the measure.
  - For single mode, non-oscillatory exponentially-decaying impulse response, **it equals the time constant**;
  - For single mode, oscillatory exponentially-decaying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

Calculable from the autocorrelation!

Example: Pulse, exponentials

Pulse





$$\Upsilon = \left\| \frac{R(\tau)}{R(0)} \right\|_2 = \frac{2}{3}T$$

Simple exponential

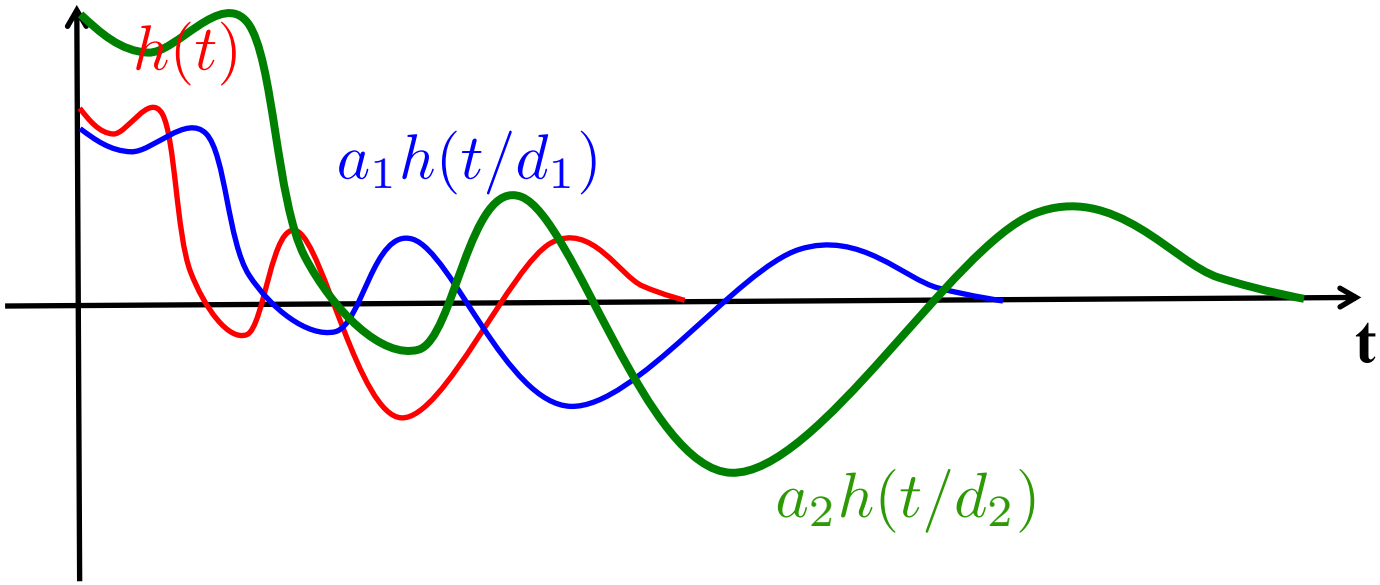
$$h(t) = e^{\sigma t} \rightarrow \Upsilon = -\frac{1}{\sigma} = T \quad \text{time constant}$$

Oscillatory response

$$h(t) = e^{\sigma t}\cos(\omega_o t) \rightarrow \Upsilon = \frac{-1}{2\sigma} + \frac{-2\sigma^6}{\sigma(\sigma^2+\omega_o^2)(2\sigma^2+\omega_o^2)^2}$$

Approximately one half the time constant

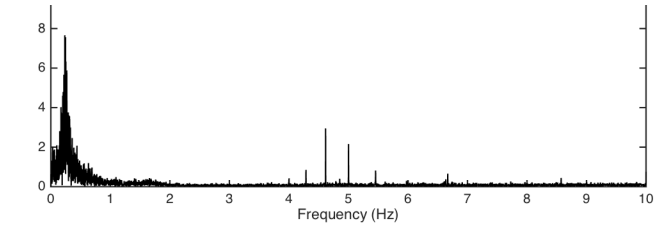
Stretching Property

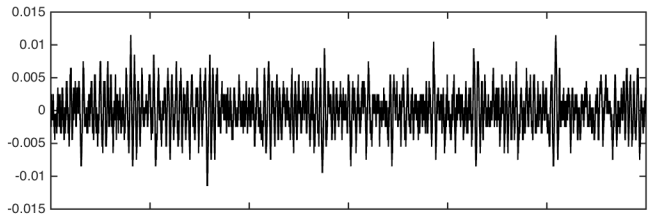


$$h(t) \rightarrow \Upsilon_0$$
$$a_1 h(t/d_1) \rightarrow d_1 \Upsilon_0$$
$$a_2 h(t/d_2) \rightarrow d_2 \Upsilon_0$$

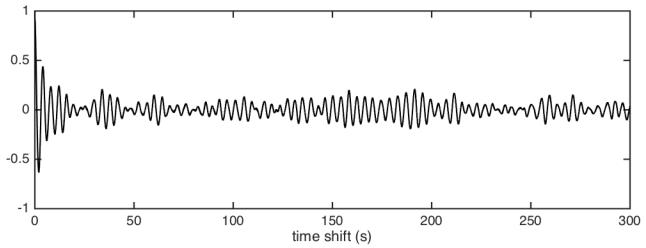
All these signals have the same shape. They differ in amplitude and stretching. The metric scales only with time-stretching. (Indifferent to amplitude.)

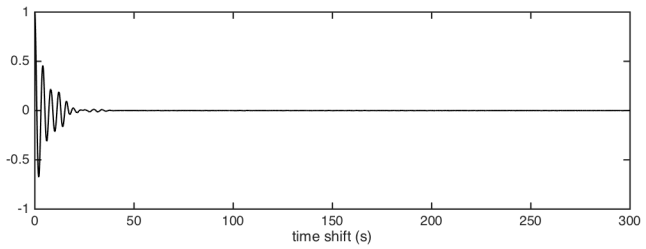
Example using real data





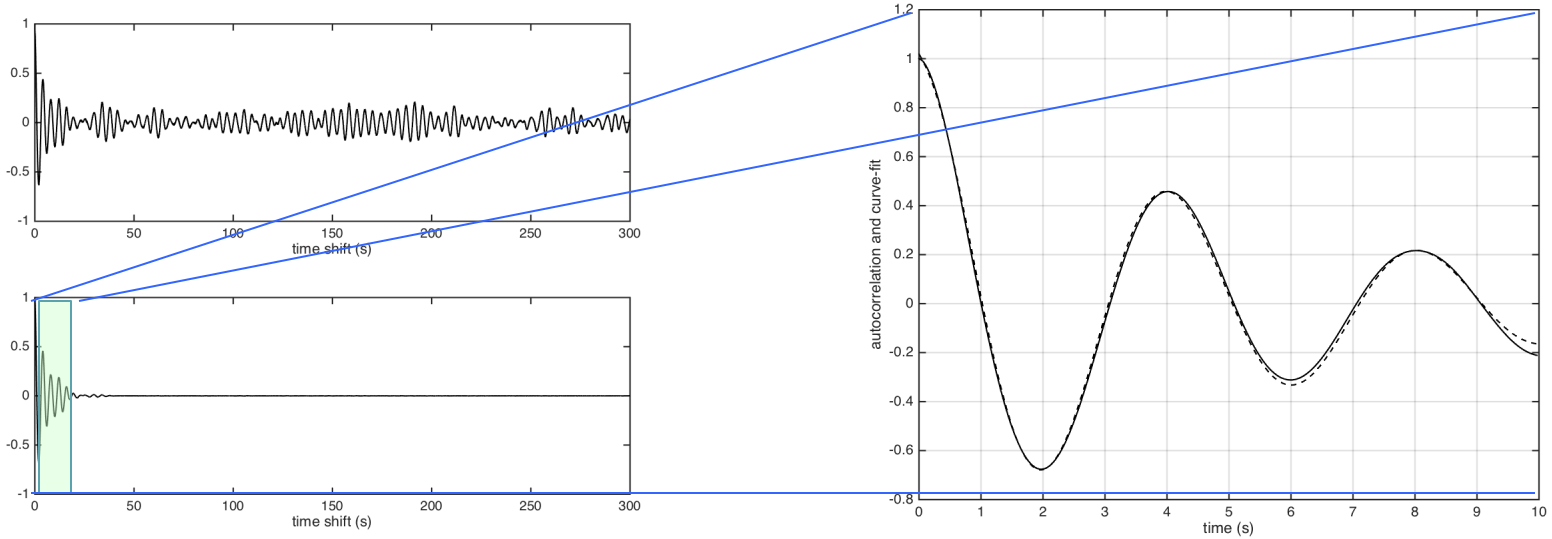
Spectrum and Raw Data, 10 minute window





Autocorrelation, straight and filtered.

Example using real data



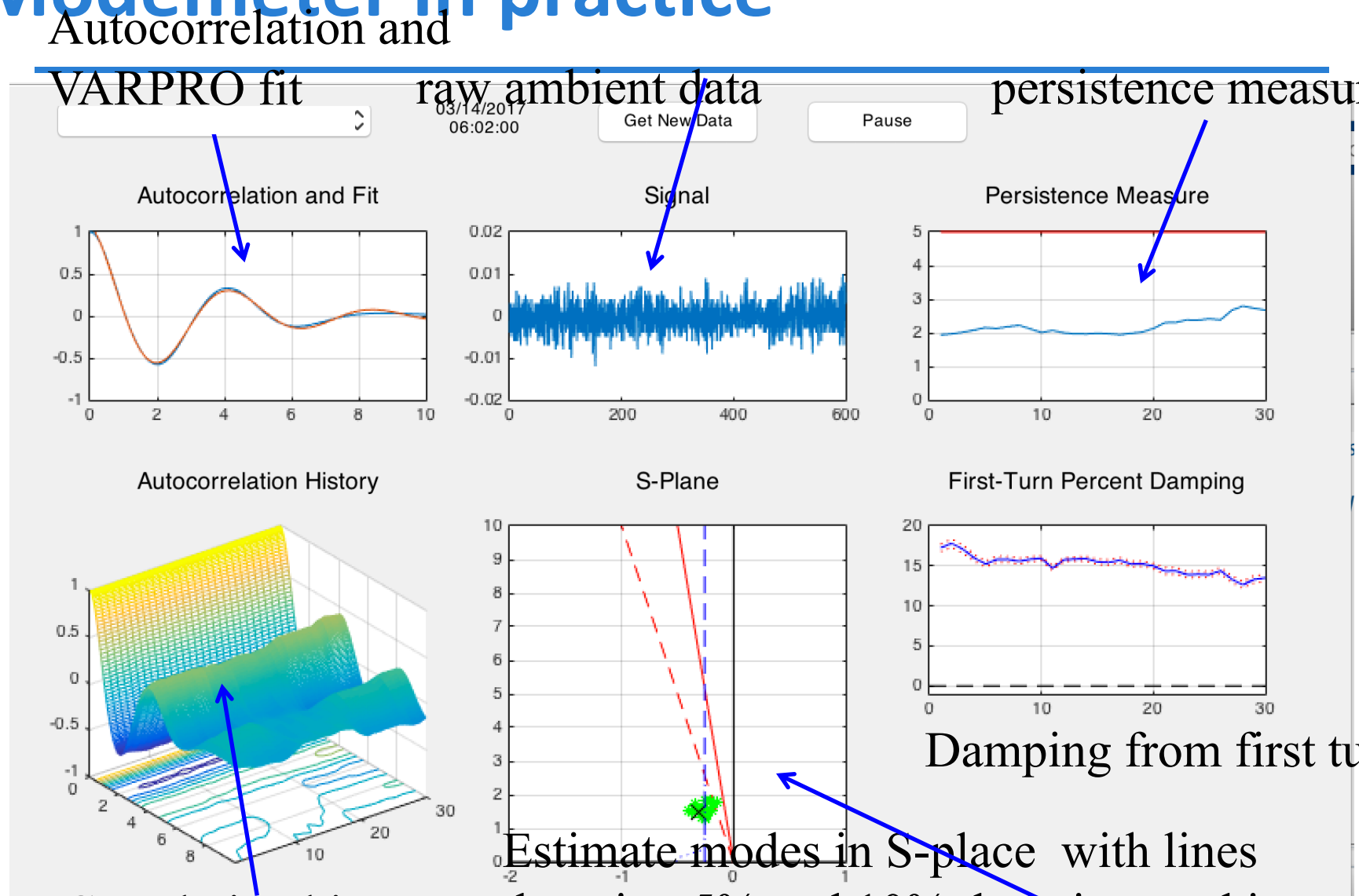
$$\Upsilon = 2.8031$$

$$\approx -\frac{1}{2 * 0.1784}$$

VARPRO curve fit yields mode

$$(\sigma + j\omega_o) = -0.1799 + j1.5556$$

Modemeter in practice



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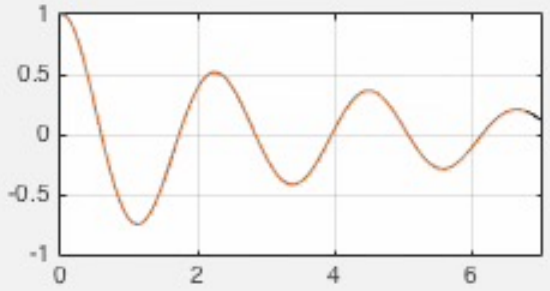
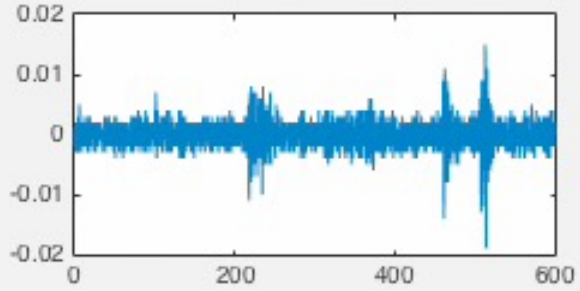
Get New Data

Pause

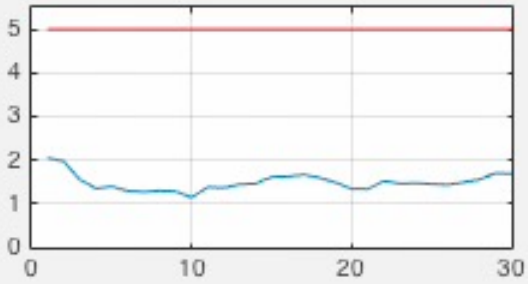
Autocorrelation and Fit



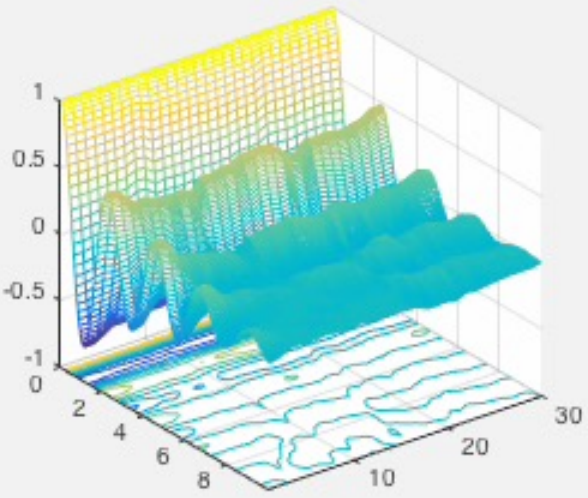
Signal



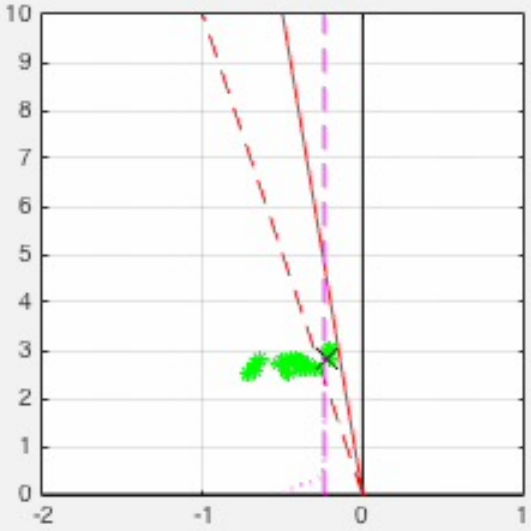
Persistence Measure



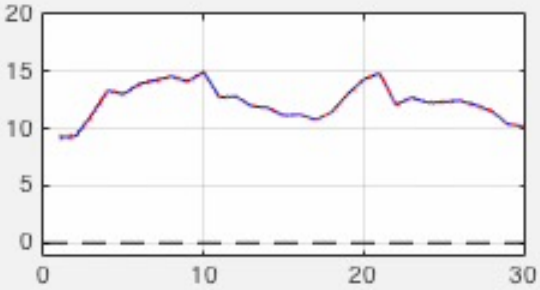
Autocorrelation History



S-Plane



First-Turn Percent Damping



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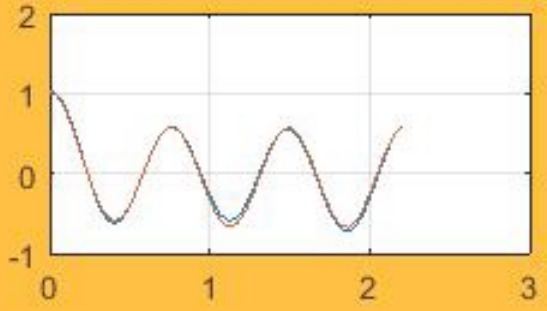
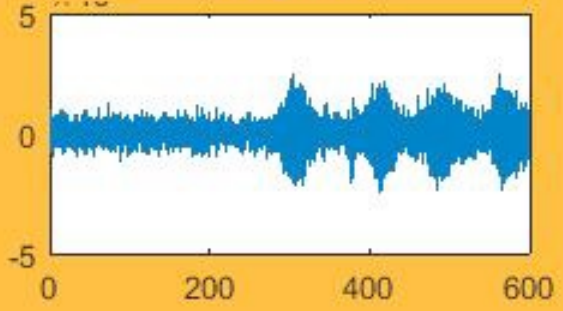
Autocorrelation and Fit

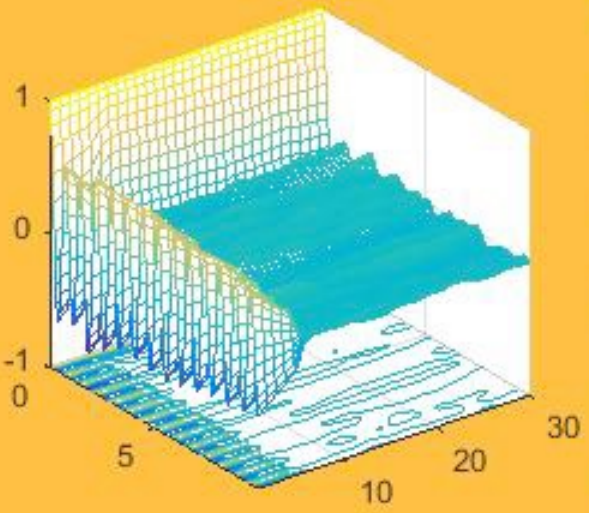


Signal



Persistence Measure

Autocorrelation History



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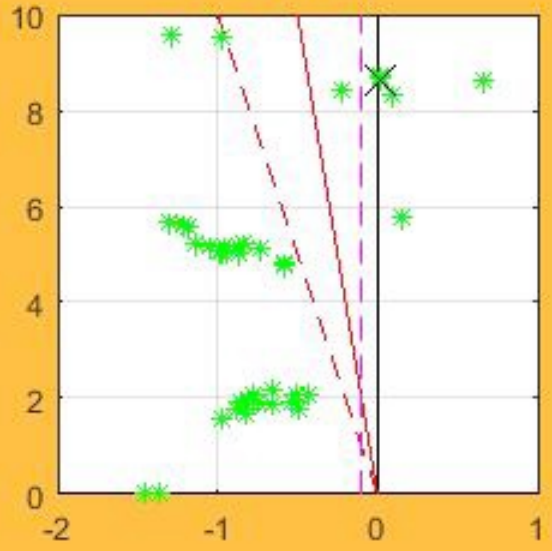
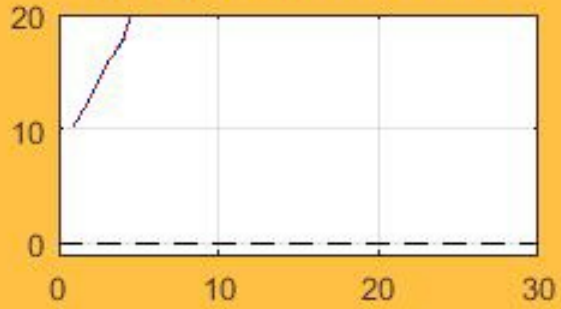


First-Turn Percent



Summary

- Challenge: quickly calculating modes using noisy ambient data is challenging and often inaccurate.
- The proposed scalar persistence measure is easily calculable from ambient data
- A prototype real-time monitoring system has been implemented and is running in real time