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Distributed Real-Time Electric Power Grid Event Detection and Dynamic Characterization

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UCSD Phasor Measurement System

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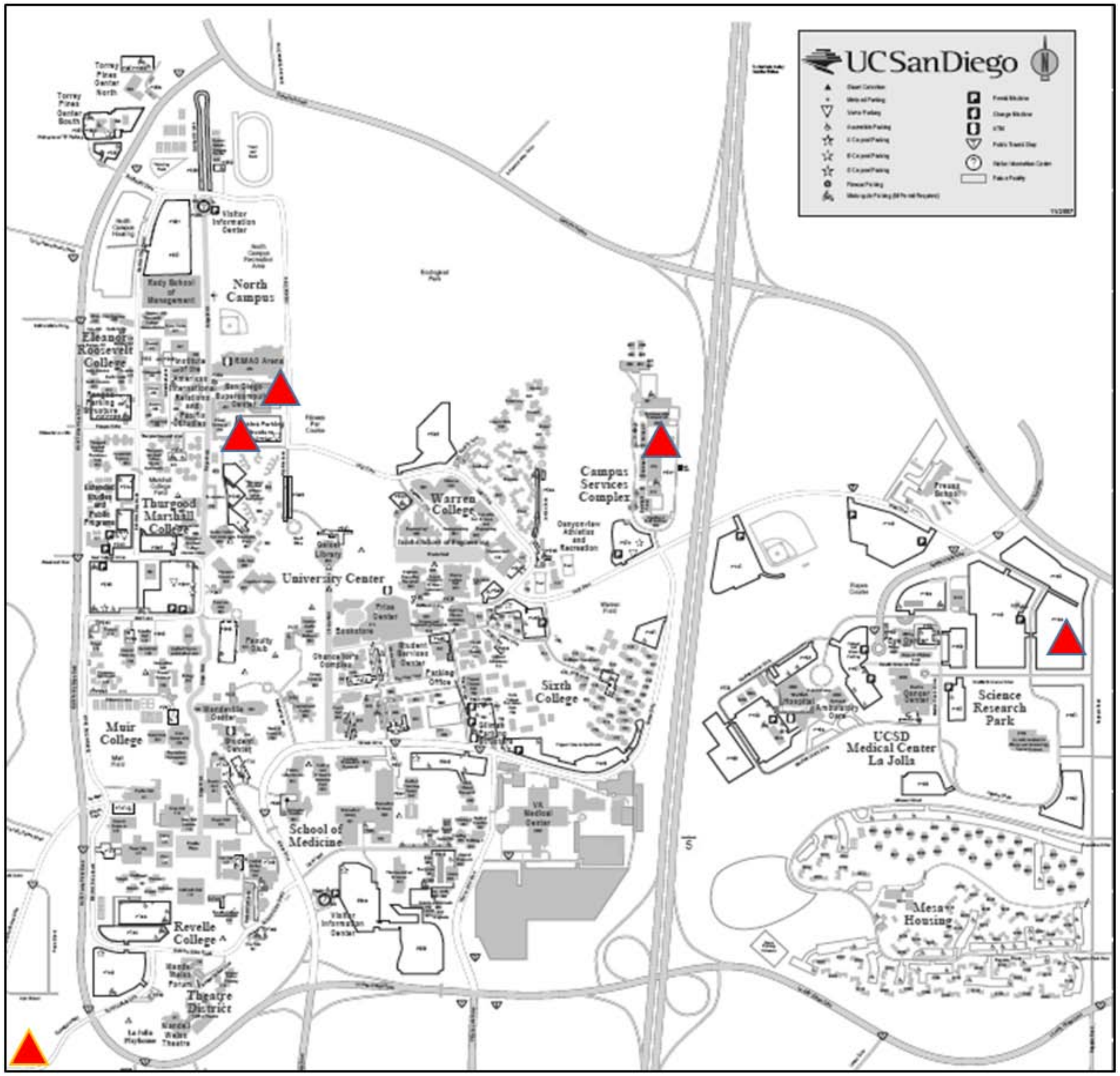
- Multiple PMUs currently on UCSD campus
- Installation of 20 additional microPMUs
- Lot of data being generated



Objectives:

- Automatically detect and mark events
- When event occurs, model dynamics

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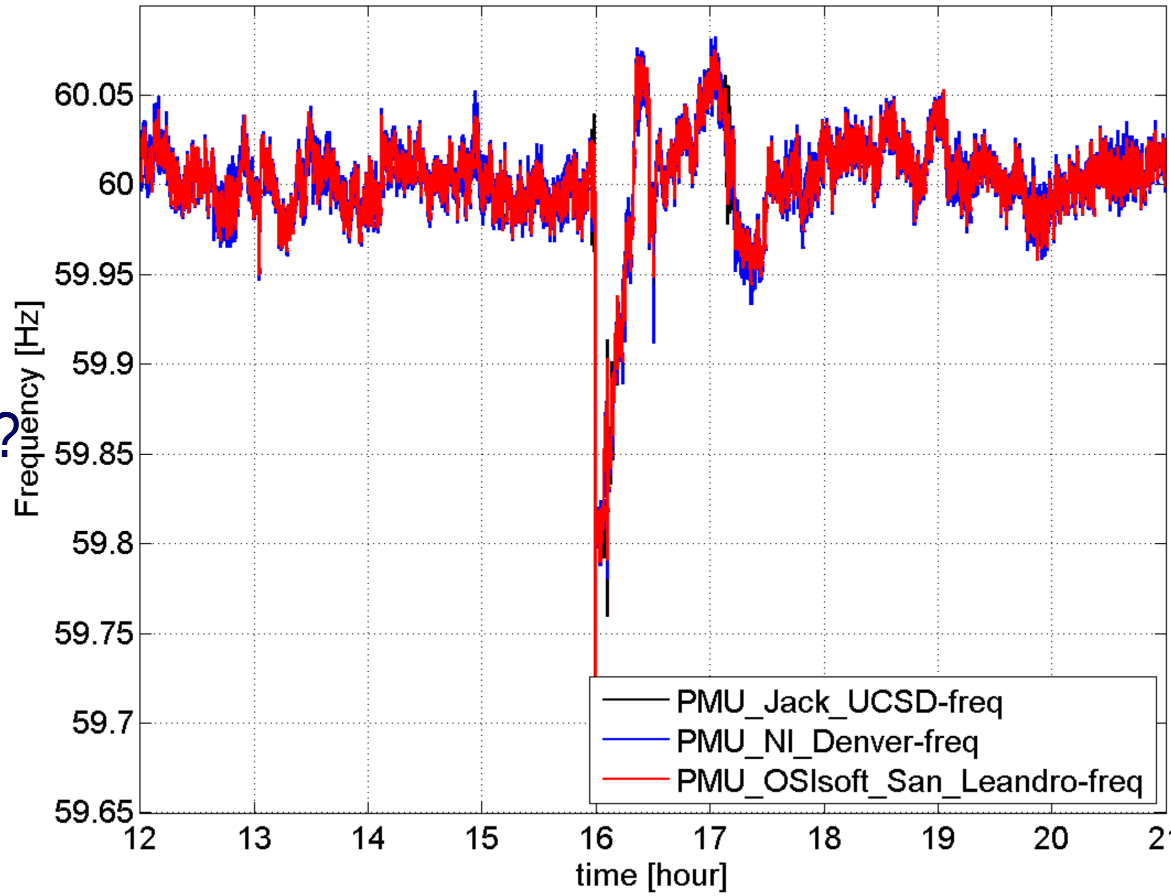
Motivation

Not only applicable for UCSD PMUs (example: WECC May 30 event)

- How do we detect individual events?
- Can event detection be distributed on each PMU?
- How can we dynamically quantify these events?

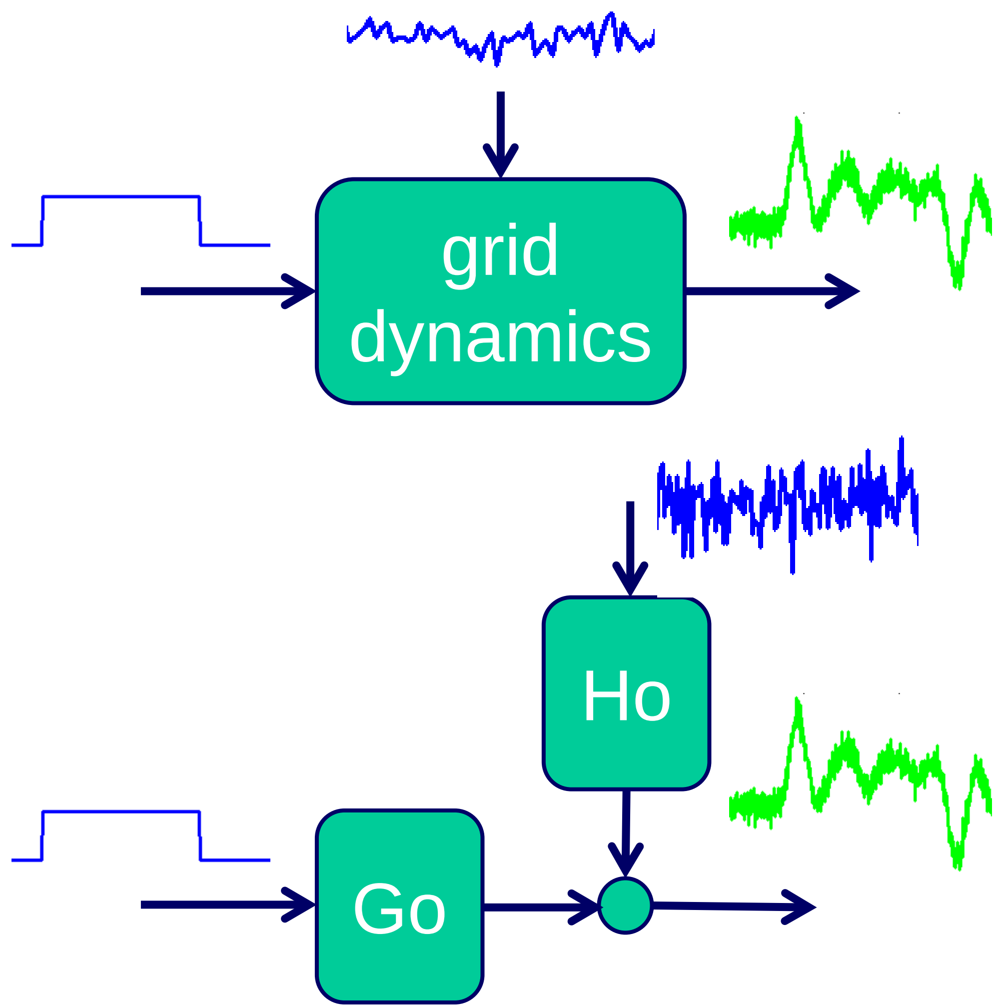


May 30 data: 972000 data points (30Hz sampling noon-9pm)

Event detection – Approach

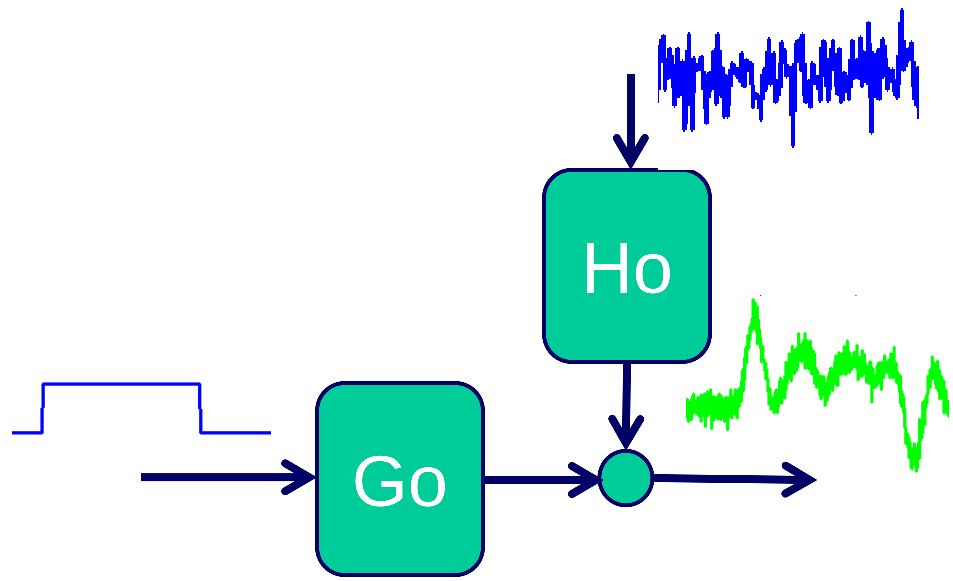
Approach is based on dynamic and statistical analysis of PMU data

- Assume PMU observation is linear combination of:
  - Main event signal filtered by grid dynamics
  - Small/random events filtered by grid dynamics
- What's new here:
  - Use knowledge on main modes (grid frequency and damping)
  - Compute optimal detection signal by reconstruction of (filtered) main event signal



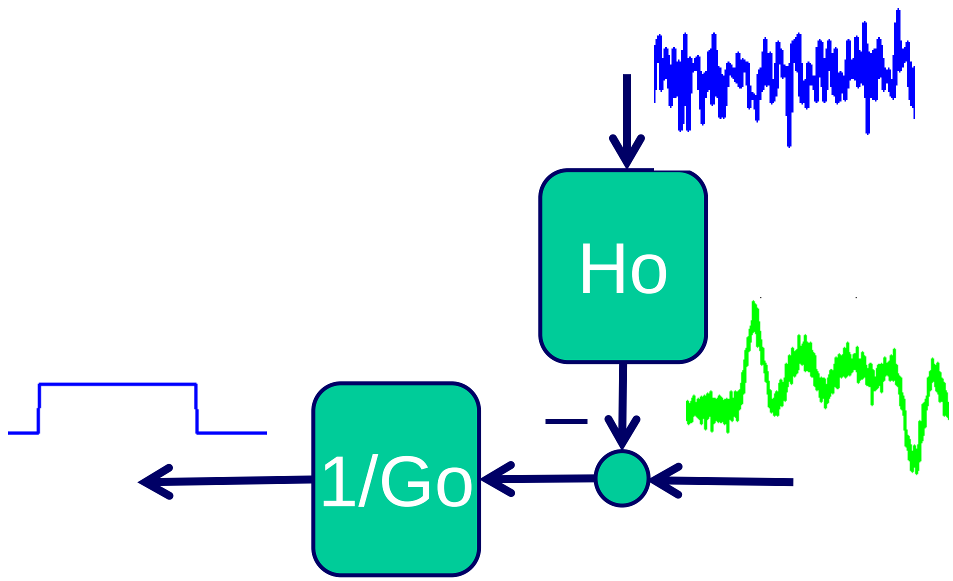
Event detection – Approach

- Starting from initial dynamics



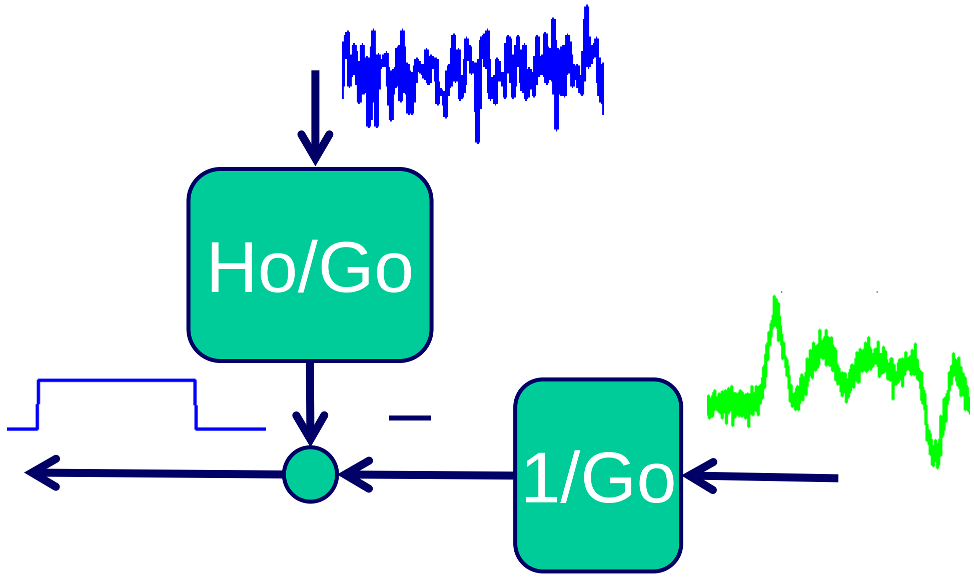
Event detection – Approach

- Starting from initial dynamics
  - Invert signal mapping



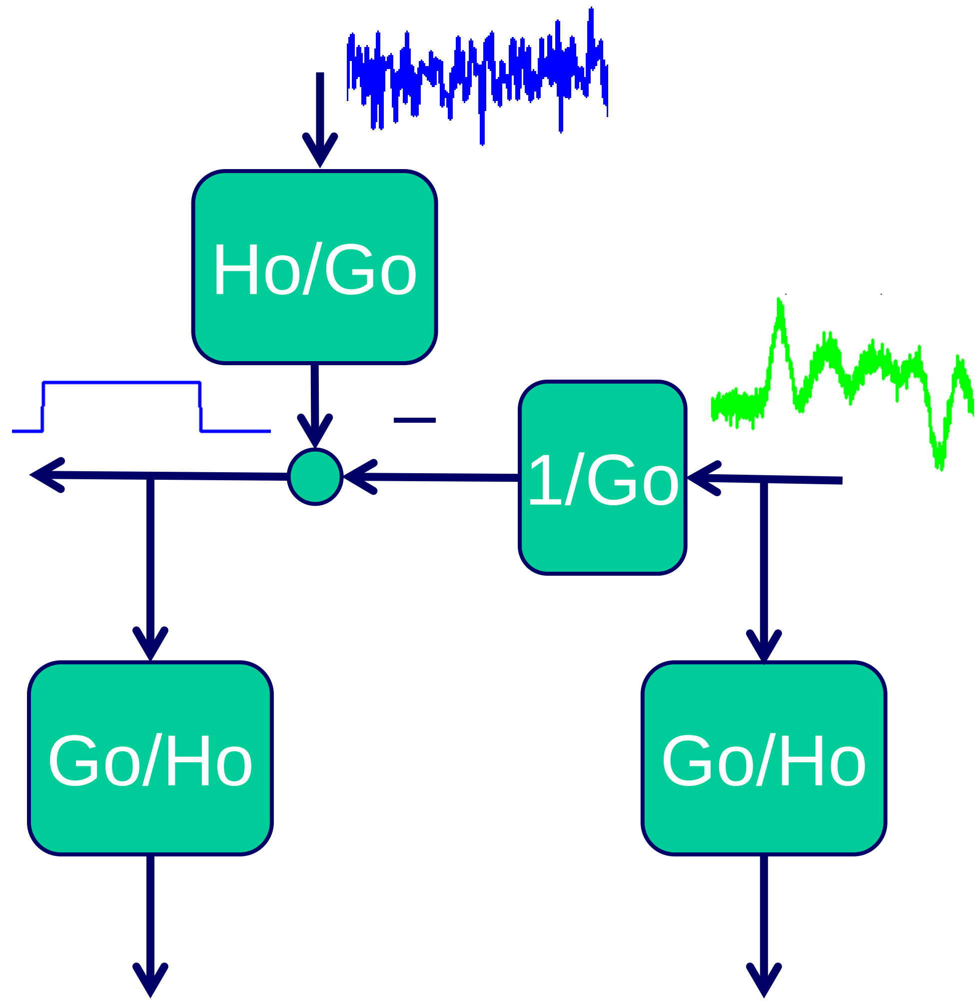
Event detection – Approach

- Starting from initial dynamics
  - Invert signal mapping
  - Model noise as output noise



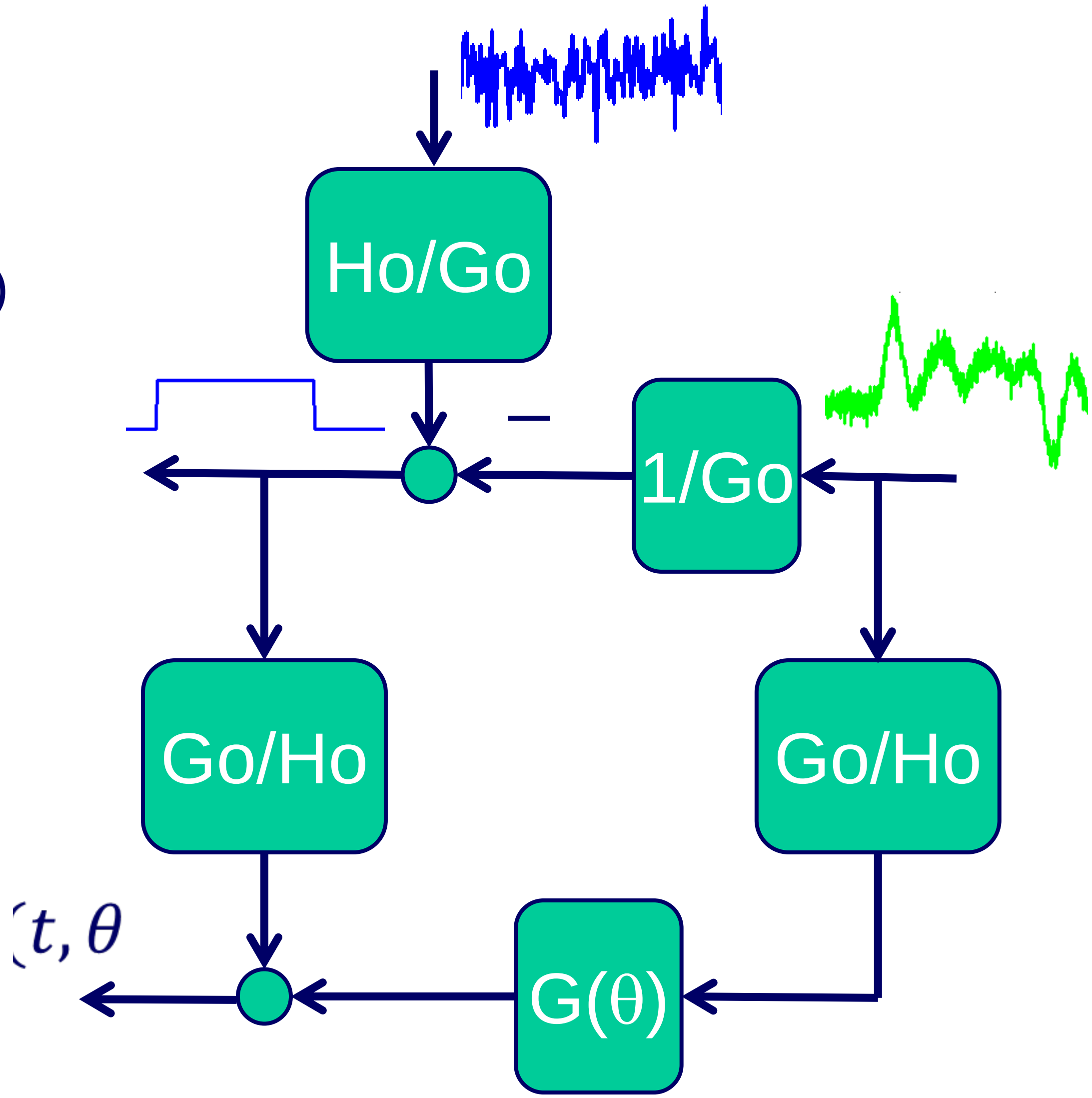
Event detection – Approach

- Starting from initial dynamics
  - Invert signal mapping
  - Model noise as output noise
  - Add fixed noise filter (low pass)



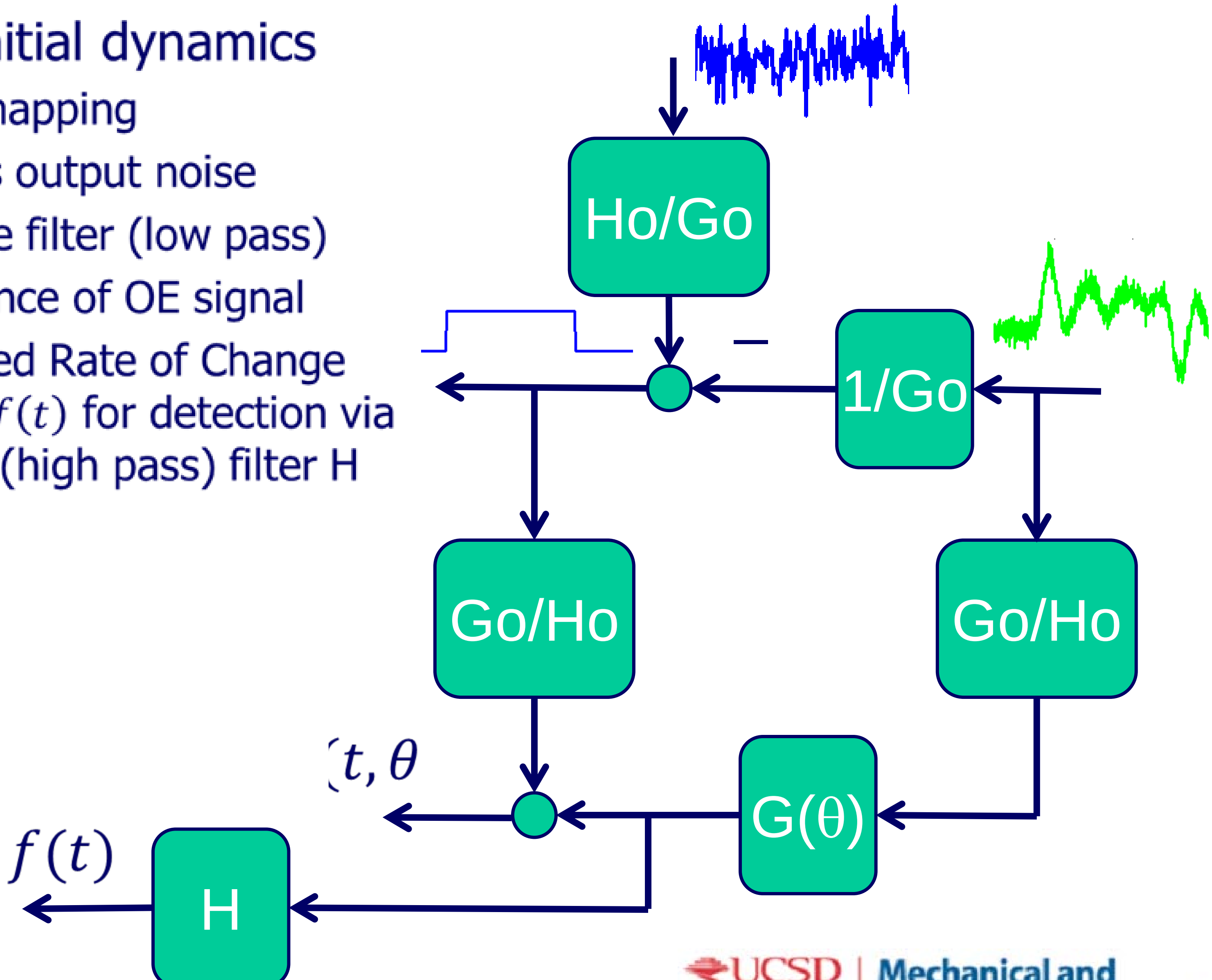
Event detection – Approach

- Starting from initial dynamics
  - Invert signal mapping
  - Model noise as output noise
  - Add fixed noise filter (low pass)
  - Minimize variance of OE signal



Event detection – Approach

- Starting from initial dynamics
  - Invert signal mapping
  - Model noise as output noise
  - Add fixed noise filter (low pass)
  - Minimize variance of OE signal
  - Define a Filtered Rate of Change (FRoC) signal $f(t)$ for detection via differentiation (high pass) filter H



Event detection – Approach

- Starting from initial dynamics
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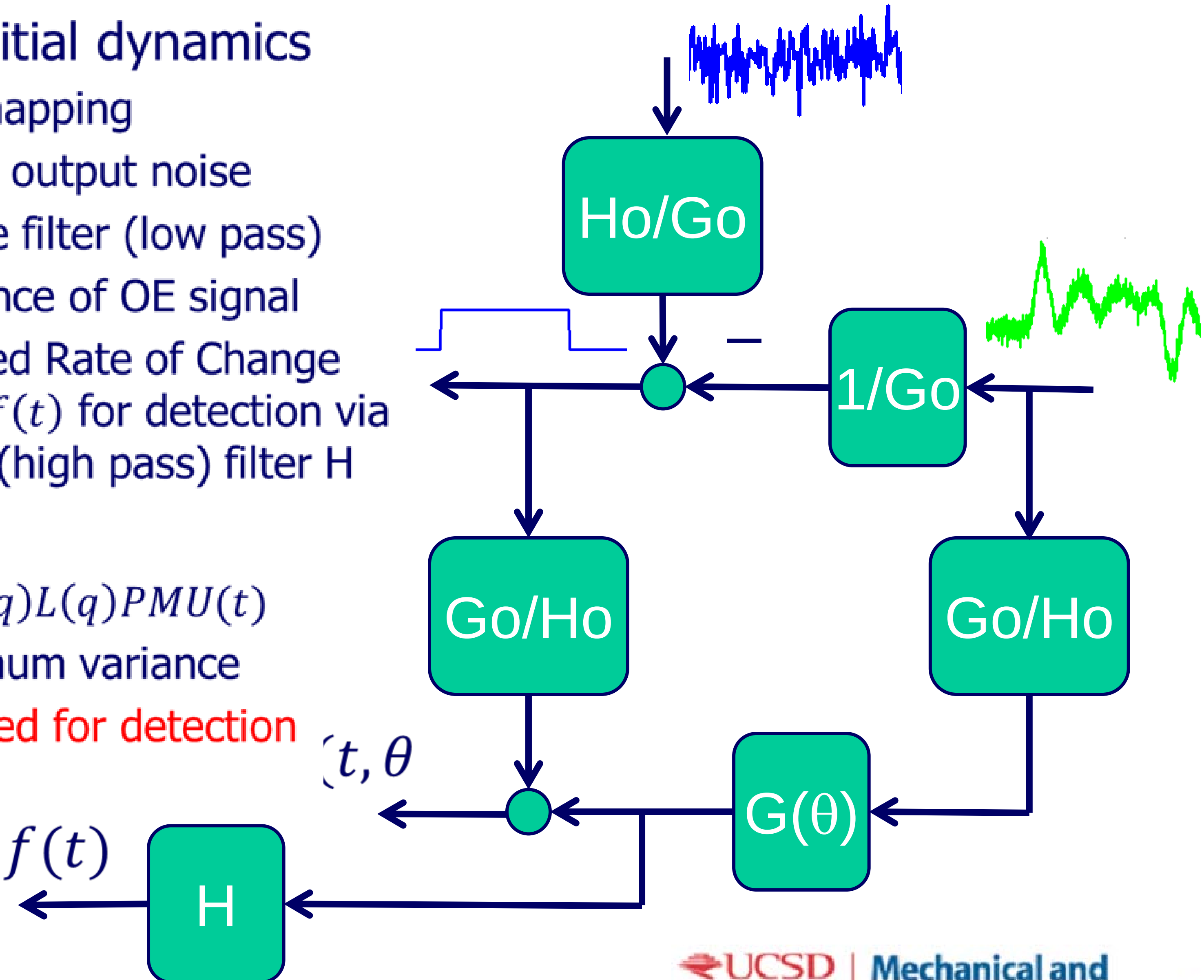
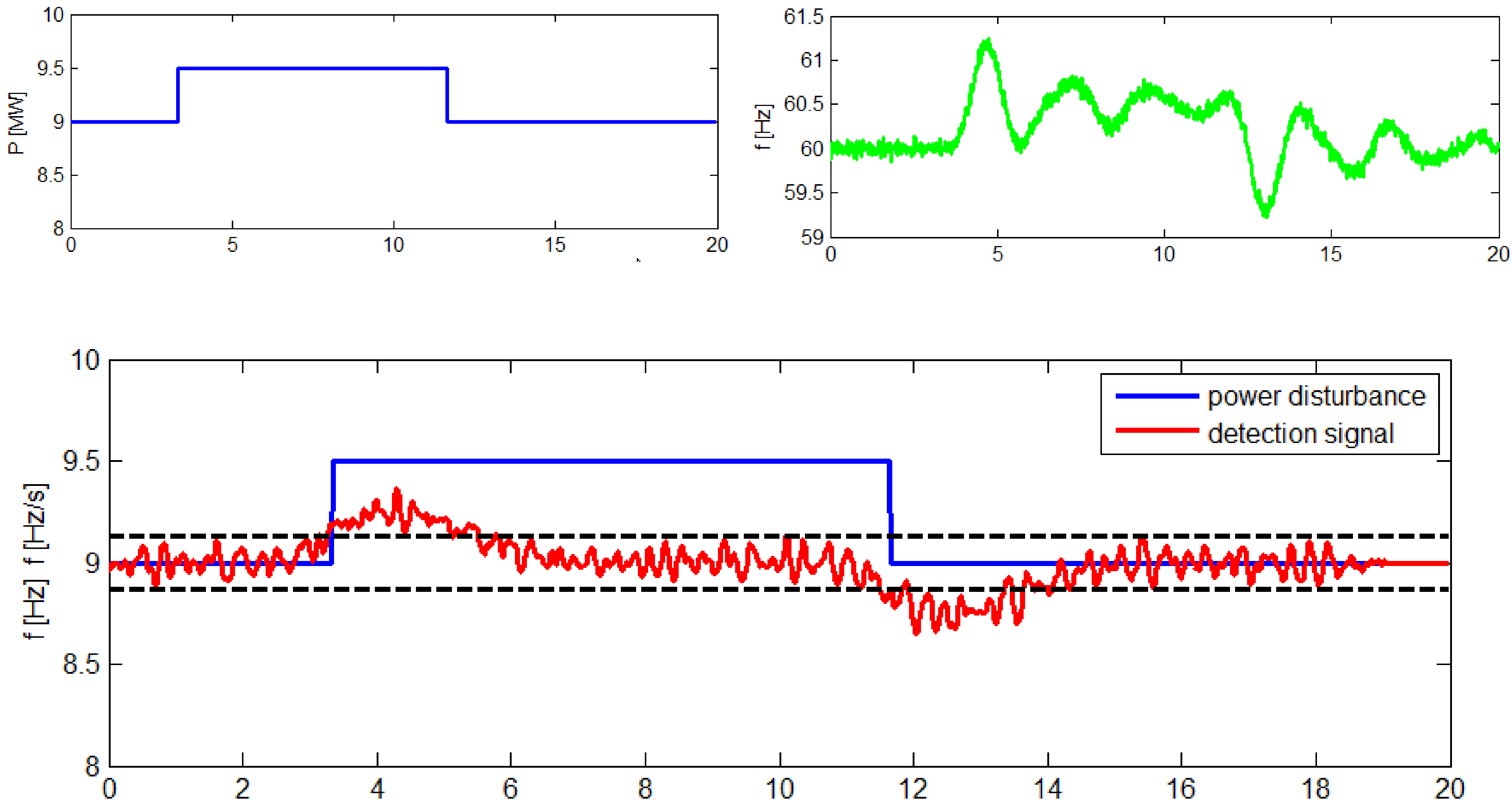
  - Model noise as output noise
  - Add fixed noise filter (low pass)
  - Minimize variance of OE signal
  - Define a Filtered Rate of Change (FRoC) signal $f(t)$ for detection via differentiation (high pass) filter H
- End Result:
  - $f(t) = H(q)G(q)L(q)PMU(t)$
  - $f(t)$ has minimum variance
  - $f(t)$ can be used for detection



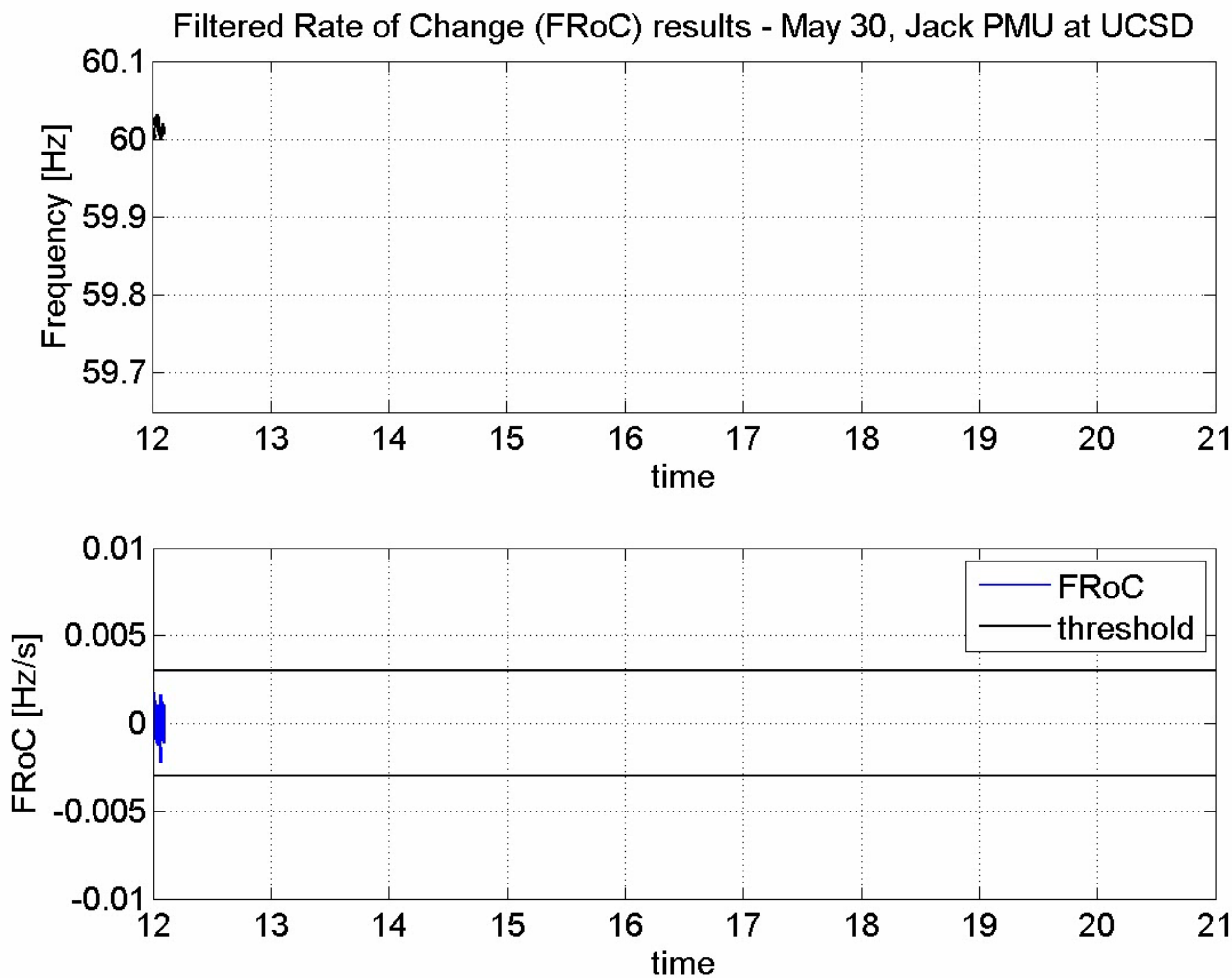
Event detection – Illustration



Event detection – Application to WECC

Automatic Event Detection

- Models Go and Ho estimate ("learned") from previously measured disturbance
- Minimization of prediction error via standard recursive optimization
- Event detection via threshold on Filtered Rate of Change signal



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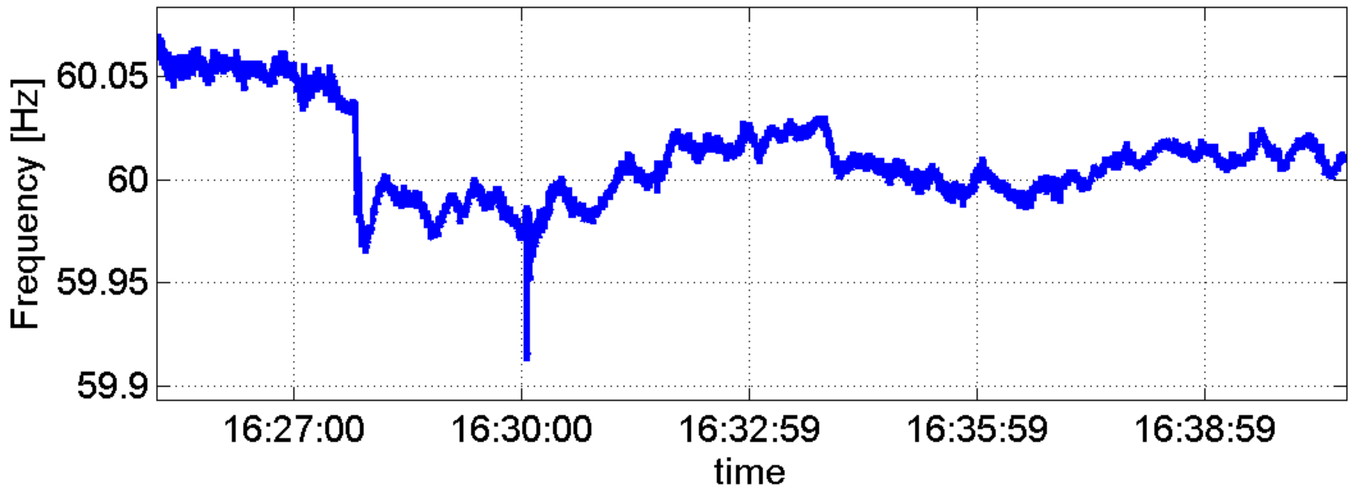
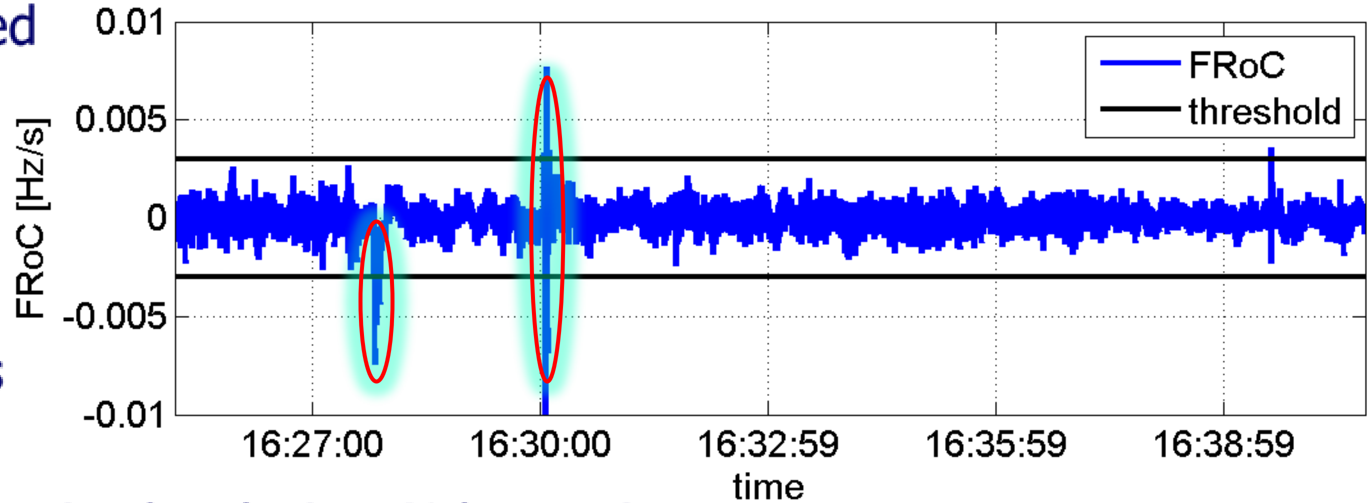
FRoC Signal – what's the big deal?

- Small thresholds with small $FRoC(k)$ during ambient behavior



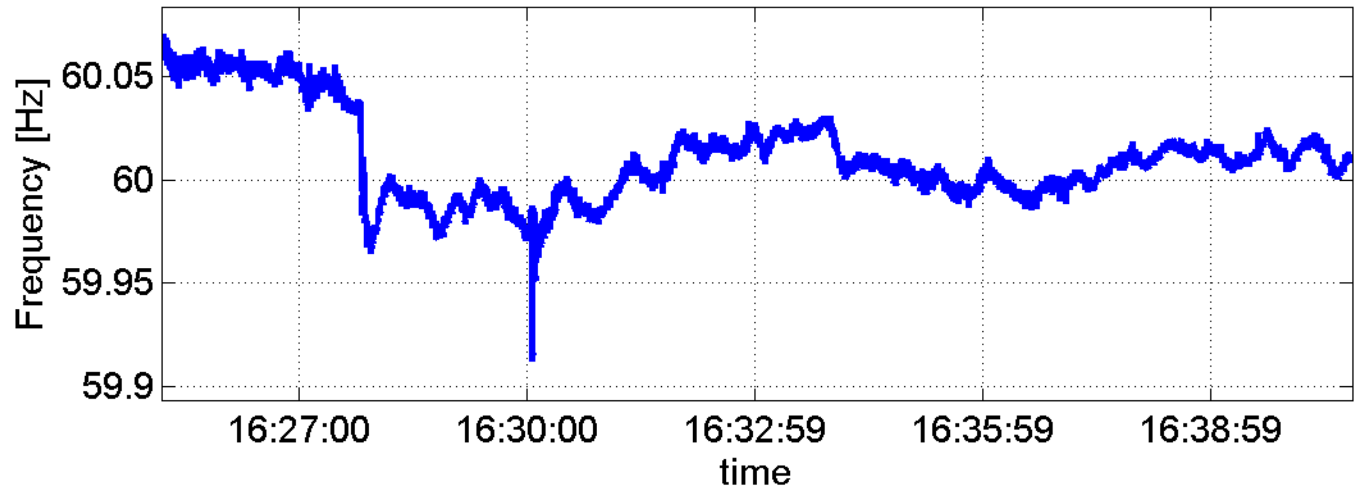
- Detection of events via:
  - Set threshold based on ambient data
  - $FRoC(k)$ outside threshold for m consecutive points
  - Classify event by saving/analyzing N data points

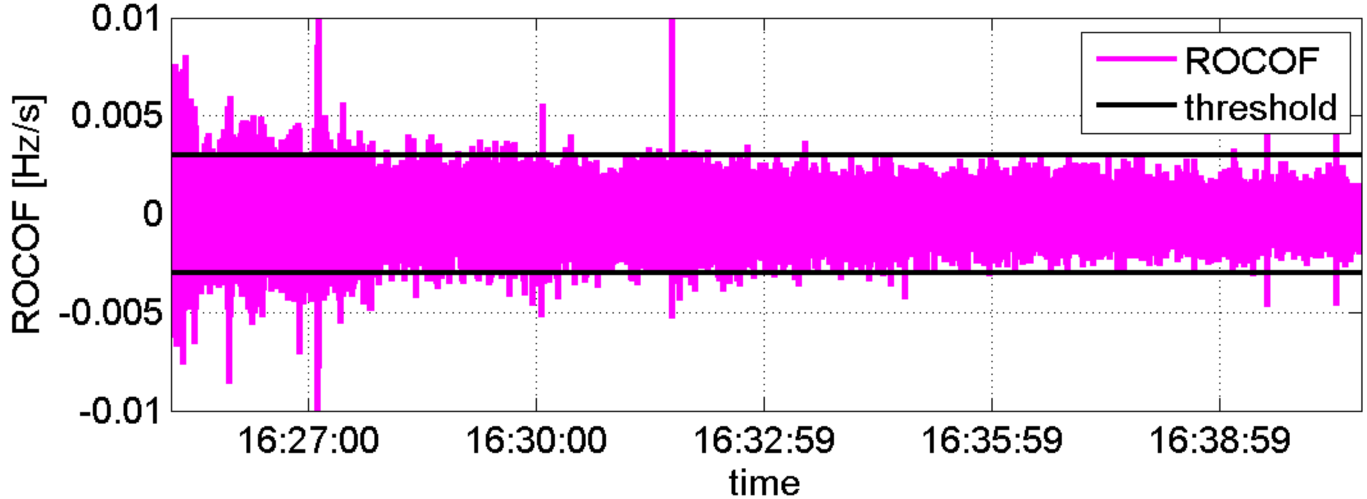


FRoC Signal – what's the big deal?

Compare with ROCOF

- Much larger than *FRoC(k)*
- More false alarms

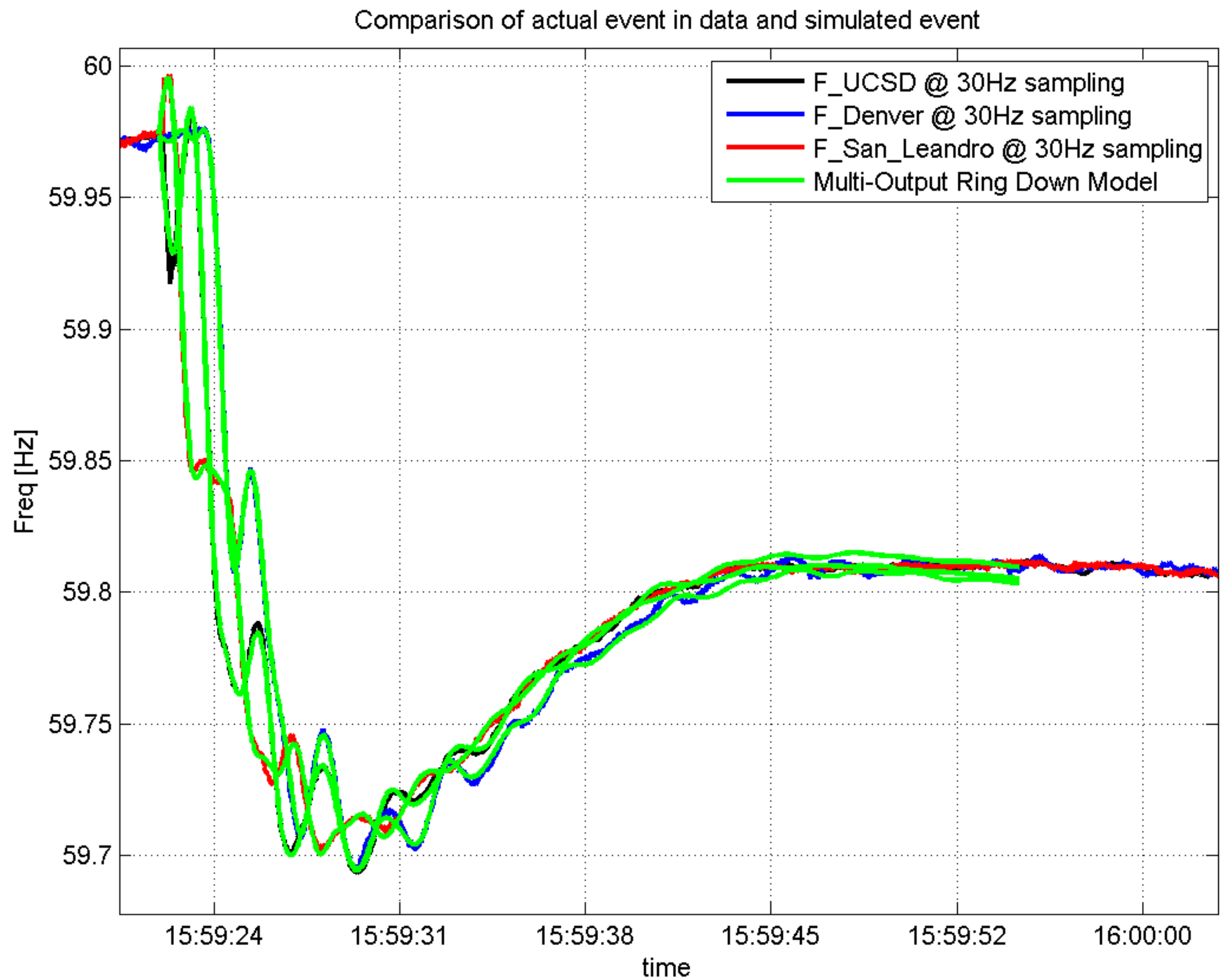




Once event has been detected: analysis

Automatically:

- Detect event.
  (via threshold on Filtered Rate of Change signal)
- Estimate parameters.
  Frequency, Damping, and Modal Participation from a Dynamic Model.
  (ring down analysis)



Approach:

- Assume observed event in frequency F(t) is due to a deterministic system

$$x(k+1) = Ax(k) + Bd(k)$$
$$F(k) = Cx(k)$$

Discrete-time model

where (unknown) input d(t) can be \`impulse' or \`step' or \`known shape'

- Store a finite number of data points of F(t) in a special data matrix **H**
- Inspect rank of (null projection on) **H** via SVD and determines # modes
- Compute matrices A, B and C via Realization Algorithm.
- Applicable to multiple time-synchronized measurements! (multiple PMUs)

End Result:

- Dynamic model (state space model) can be used for
  - Simulation: simulate the disturbance data
  - Analysis: Compute resonance modes and damping (from eigenvalues of A)

Realization Algorithm – SVD

- SVD can be computed by a numerically stable algorithm
- HOWEVER, SVD of Hankel matrix H will only be (ideally)

$$H = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix}, \quad \Sigma_1 = \mathrm{diag}(\sigma_1, \sigma_2, \cdots, \sigma_n), \quad \sigma_j > 0$$

  if there is NO noise on measurements $F(t)$
- In general:

$$H = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix}$$

$$\Sigma_1 = \mathrm{diag}(\sigma_1, \cdots, \sigma_n)$$

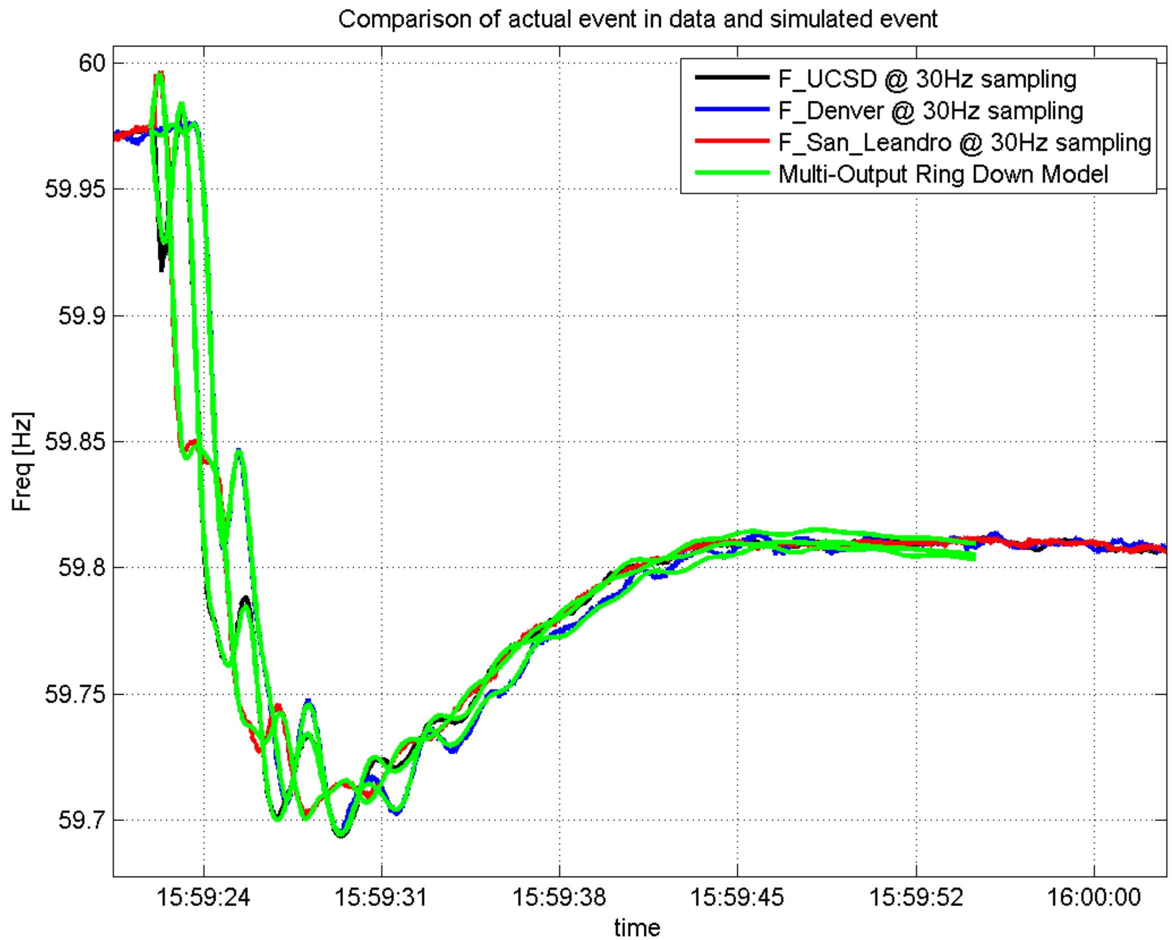
$$\Sigma_2 = \mathrm{diag}(\sigma_{n+1}, \cdots, \sigma_m)$$

$$\sigma_{n+1} << \sigma_n$$

- SOLUTION: decide on effective rank via threshold of singular values

More fun with May 30th event

- Use FRoC for automatic detection of event and begin of event
- Use all PMUs simultaneously to estimate a multiple output model
- Assume disturbance
  d(t) is step disturbance
- Use 900 data points (30sec)
- Compute SVD
- Compute dynamic model



Fn = 0.231811 Hz, D = 0.068505.
Fn = 0.392715 Hz, D = 0.082505.
Fn = 0.432960 Hz, D = 0.050235.
Fn = 0.663981 Hz, D = 0.083615.
Fn = 0.799182 Hz, D = 0.073641.

More fun with May 30th event

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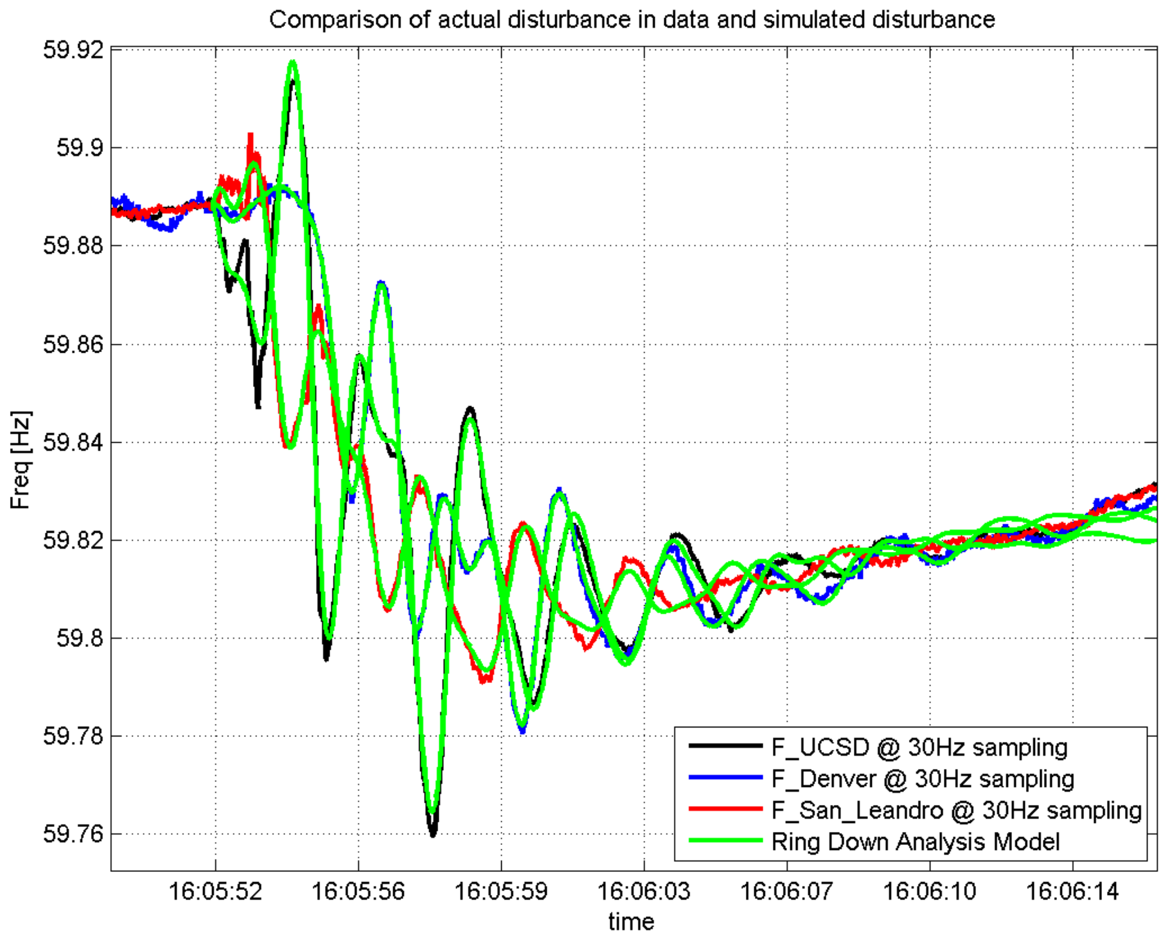

Fn = 0.242626 Hz, D = 0.097361.
Fn = 0.373111 Hz, D = 0.065633.
Fn = 0.433994 Hz, D = 0.092822.
Fn = 0.670271 Hz, D = 0.057847.
Fn = 0.759634 Hz, D = 0.043654.

Summary

- Automatically detect when a disturbance/transient event occurs
- Automatically estimate Frequency, Damping and Dynamic Model from disturbance event.

Main Features:

- Automatically detect event:
  - Predict ambient Frequency signal “one-sample” ahead
  - Observe when prediction deviates for event detection via FRoC signal
- Automatically estimate:
  - # of modes of oscillations in measured disturbance
  - Estimate frequency and damping of the modes
  - Put results in dynamic mode
- All done in real-time!

Software development