DOE/OE Transmission Reliability Program

Synchro-phasor Data Conditioning and Validation

Jim Thorp

Virginia Tech

jsthorp@vt.edu

27/28 June 2013

Washington, DC

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Project objective

- **Premise:** Each synchrophasors measurement, whether used for state estimation, control, or alarms, can be subjected to the same preprocessing as the linear estimator to be demonstrated in Aug'13 by Dominion Virginia Power. The proposed solution is in general a low cost solution. The open PDC is open source and freely distributed and Dominion already possesses a fully functional linear estimator in the openPDC platform. Even if a state estimator is not desired, the linear estimator can be thought of as part of the data conditioning algorithm in that it detects bad data, finds the best estimate, and increases the observability of the network.
- **Deliverable** C# openPDC software, recommendation, and functional specifications
- Dominion is planning on putting the linear estimator in the Grid Solutions open source applications library maintained by **GPA (Grid Protection Alliance)**

Major technical accomplishments that will be completed this year—stage in RD&D cycle

brief task statement list-details in proposal

Task

1. Prototype Development Recommendations on synchrophasor infrastructure
2. Commissioning process
3. Algorithms for online determination of Signal to Noise Ratio (SNR) of the PMU data
4. Recommendations for the central PDC architecture design and the ESOC architecture design (ESOC) Emergency System Operation Center
5. Optimized PMU placement scheme

Major technical accomplishments that will be completed this year—stage in RD&D cycle

6 Provide algorithms for:

a) Loss of data from one or several PMUs
b) Loss of signals in a PMU
c) Stale (non-refreshing) data
d) Inconsistent data, data rates and latencies
e) Off-sets in signal magnitude and phase
f) Corrupted and drifting signals in a PMU
g) Corrupted and drifting time reference in one or several PMUs
h) Combination of several issues described above
i) Combination of several issues described above
j) The failure of the topology processor and/or bad/incomplete topology information

j) A recommendation but implementation is not part of the proposed work.

Major technical accomplishments that will be completed this year—stage in RD&D cycle

- Task 2A: Demonstration at Dominion
- Test Algorithms on Dominion System
- Task 3: Develop Functional Specifications
- Deliverable C# Open PDC software, recommendation, and functional specifications
- Dominion is planning on putting the linear estimator in the Grid Solutions open source applications library maintained by GPA (Grid Protection Alliance)

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Deliverables and schedule for activities to be completed under FY13 funding

Task 1	Task Name	Deliverables (please name the reports and clarifly other deliverables)	Planned Start Date	Actual Start Date	Planned End Date	Actual End Date
1.1	Prototype Development Recommendations on synchrophasor infrastructure	Report #1	4/13	4/13	9/13	
1.2	Commissioning process	Report #2	4/13	4/13	9/13	
1.3	Signal to Noise Ratio(SNR) of the PMU data	Report #3	5/13		10/13	
1.4	Recommendations for the central design PDC architecture design and the ESOC architecture	Report #4	5/13		10/13	
1.5	Optimized PMU placement scheme	Report #5	9/13		2/14	
1.6	Algorithms	Report #6	4/13	4/13	11/13	
2A.	Demonstration at Dominion	Report #7	9/13		4/14	
3	Functional Specifications of the Data Validation System	Report #8	11/13		4/14	

Risk factors affecting timely completion of planned activities as well as movement through RD&D cycle

- Late start- solution two students at Dominion starting May 15th
- The unknown-during the Demonstration project PMU installation has been negatively effected by
  - A tornado -Dumpster thrown into a 500kV substation
  - An earthquake -Nuclear unit shut down
  - A hurricane - -large amounts of the service area flooded

And 30 Billion Cicadas are threatened for this summer

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Early thoughts on follow-on work that should be considered for funding in FY14

Task 2B: Demonstration elsewhere

- With or without a linear estimator
- The host utility would have to do some front end work for a linear estimator
- Does not assume open PDC but only measurements from a PDC at 30 per sec

How does this work?

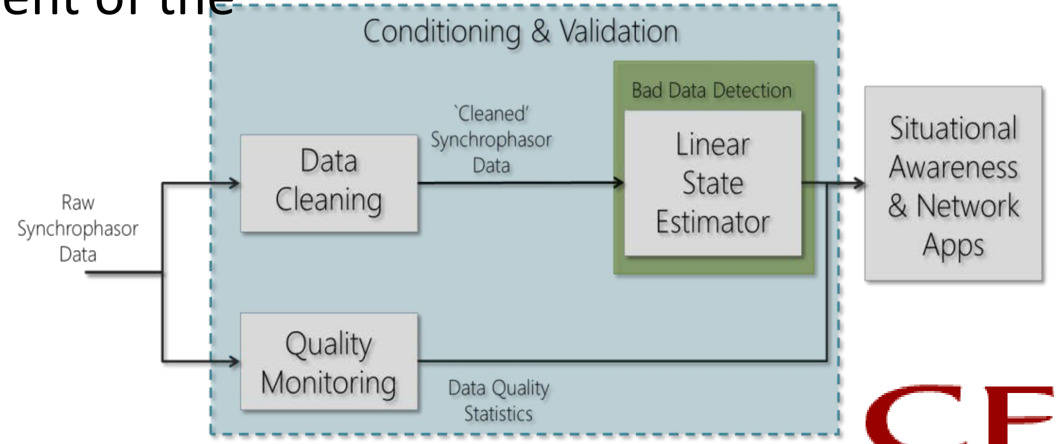
- A phasor only - three phase- state estimator is being installed on the Dominion Virginia Power 500kV system as part of a DOE demonstration project DE-0E0000118 led by Virginia Tech.
- By summer of 2013 a total of more than 600 measurements from twenty one 500kv stations, five 230kv stations, and one 115kv station will give an estimate at a rate of 30 times a second of the three phase complex voltages on the 500kV network. Both bus voltage and line currents are measured and communicated through a SONET network to the Control Center in Richmond. There is a PDC in each substation and a PDC in the control center. The application software was implemented in C# on an openPDC platform in the Dominion Control Center

Topology changes

In complex (or rectangular) form the measurements are linear functions of the complex bus voltages.

$$z = Hx, \quad \hat{x} = Mz$$

Where M is fixed and only changes as the network topology changes. The tripping of a line who's current is in the measurement set can be detected by the time tagged breaker status from the dual use line-relay/PMU or treated as missing data. Either way a front end is a required component of the estimator.



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Auto-Regressive Modeling

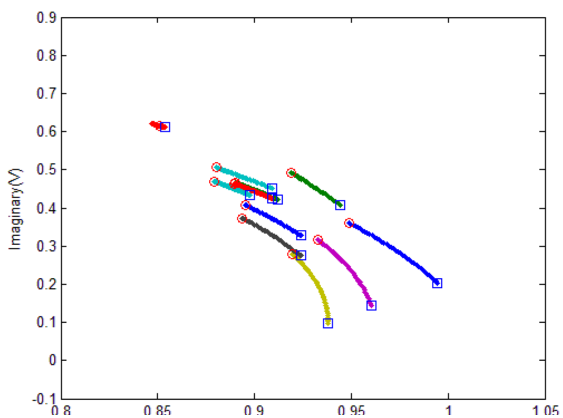
We are only looking at the 500kV subsystem essentially no injections are measured

- Try to predict next set of measurements based on prior measurements:

$$\hat{y}_t = \alpha_1 y_{t-1} + \alpha_2 y_{t-1} + \cdots \alpha_m y_{t-m} + \omega_t \quad t = m+1, \cdots n$$

- Morning load pickup: 60% increase in load in an hour

- :



These are load flow solutions every time step as load increases. (no approximation)
The trajectories are quadratic in the sense
a_k b_k and c_k are complex numbers
Quadratic fit is very close~10^{-5}

$$V_k(\lambda) = a_k + b_k\lambda + c_k\lambda^2 \; where \; Load_{new} = Load_{old} + \lambda\Delta L$$

Nose curve model

Coefficients used for Prediction Vandermonde matrix

- If $y(t)$ be an n^{th} order polynomial, sampled at time t,

$$y(t) = \alpha_n t^n + \alpha_{n-1} t^{n-1} + \alpha_{n-2} t^{n-2} + \ldots + \alpha_1 t + \alpha_0$$

- Then, for equally spaced samples

$$\begin{bmatrix} y(n) \\ y(n-1) \\ \vdots \\ y(1) \\ y(0) \end{bmatrix} = \begin{bmatrix} 1 & n & n^2 & \ldots & n^n \\ 1 & (n-1) & (n-1)^2 & \ldots & (n-1)^n \\ 1 & \vdots & \vdots & \ddots & \vdots \\ 1 & 2 & 2^2 & \ldots & 2^n \\ 1 & 1 & 1 & \ldots & 1 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_{n-1} \\ \alpha_n \end{bmatrix} = V\alpha$$

- The first row of V^{-1} gives the desired coefficients [3]:

$$b_n y(n) = -b_{n-1} y(n-1) - b_{n-2} y(n-2) \ldots - b_1 y(1) + y(0)$$

Where, $b^T = [b_n \quad b_{n-1} \quad \ldots \quad b_2 \quad b_1]$ *is the first row of* V^{-1}

$$y = V\alpha \quad V^{-1} y = \alpha \quad b^T y = \alpha_0 = y(0)$$

Detecting bad data and network switching

If x(n) is a complex 500kV voltage

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} w(n) \quad z(n+3) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x(n+3) \\ x(n+2) \\ x(n+1) \end{bmatrix} + r(n+3)$$

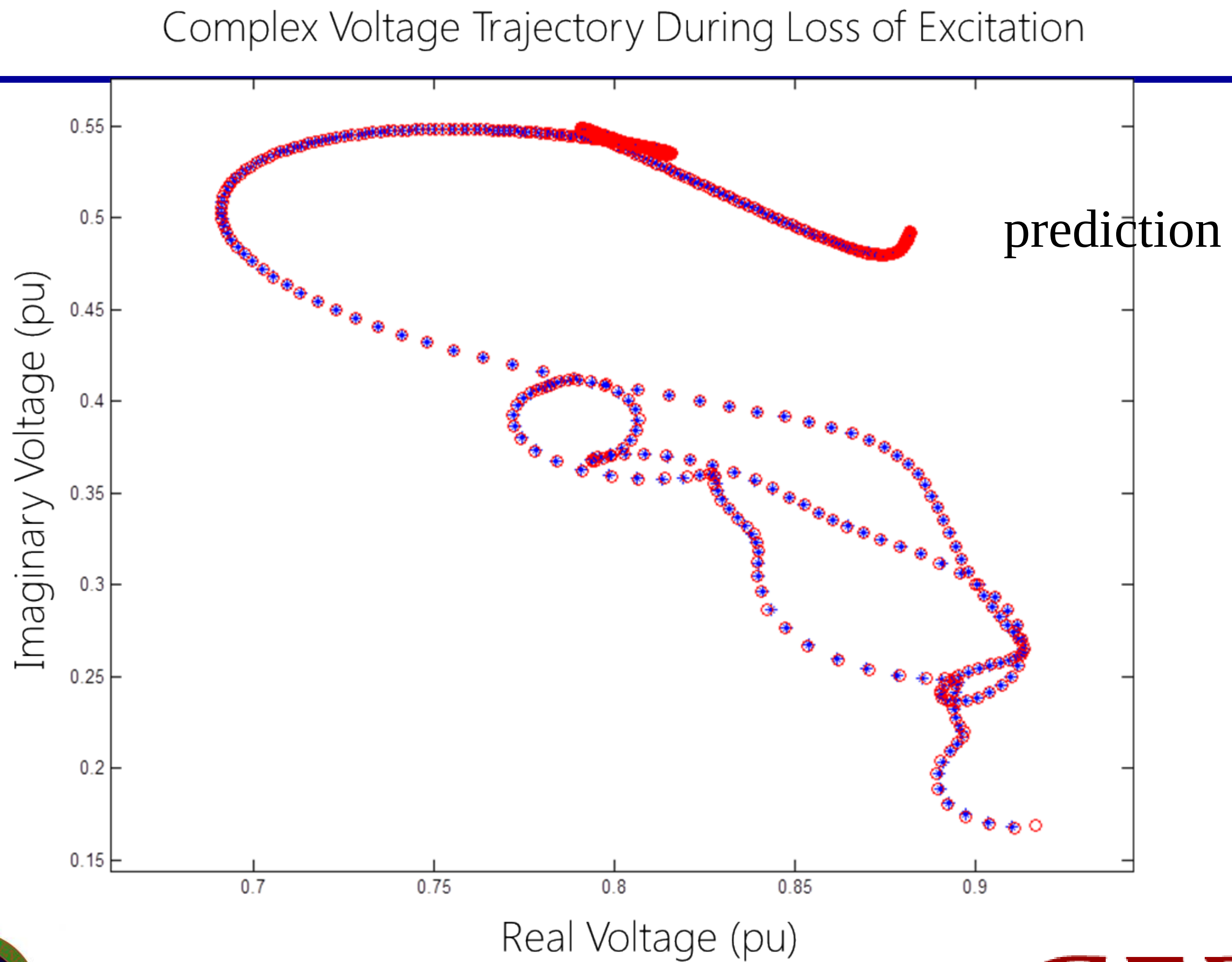
w ($\sigma_w = 10^{-5}$) and r ($\sigma_r = 10^{-3}$) random, white, and independent, can predict the state and the next measurement and form the observation residual. To make a state equation add and subtract

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 3 \\ 1 \\ 0 \end{bmatrix} \left[x(n-1) - \hat{x}(n-1) \right]$$

Observation residual

The added term is the "Kalman gain" multiplying the observation residual. This is the steady state Kalman gain for all covariance in w if the covariance of r is zero. For $\sigma_w = 10^{-1}$, $\sigma_v = 10^{-2}$ K=[2.8793 .9915 .0244]^{T}In general K depends on the ratio of the two covariances

Next slide –field data measurements + and estimate o formed by the last 3 values of this voltage using a Kalman Filter based on model on slide 15



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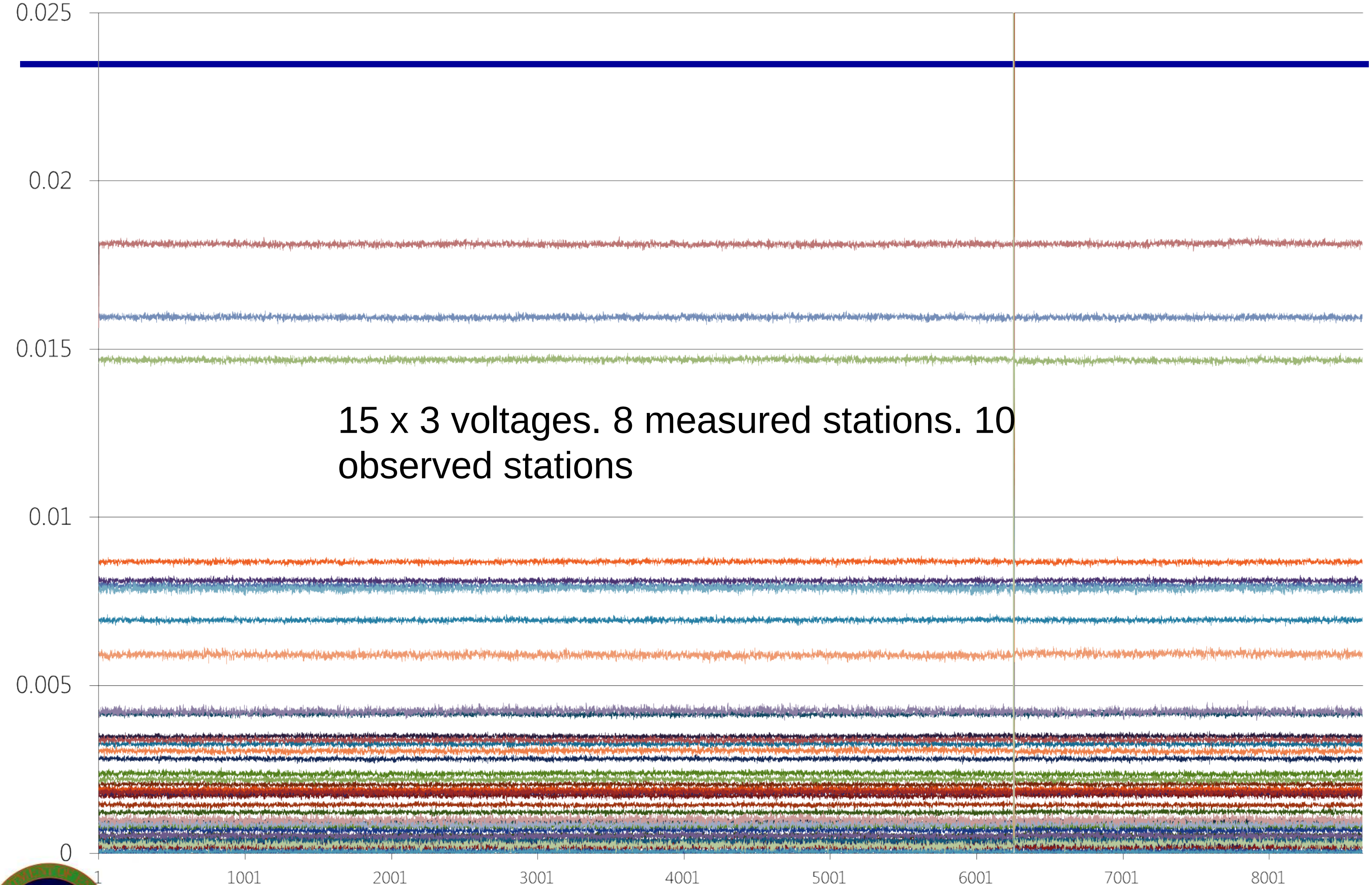
Observation Residuals for Voltage Magnitudes



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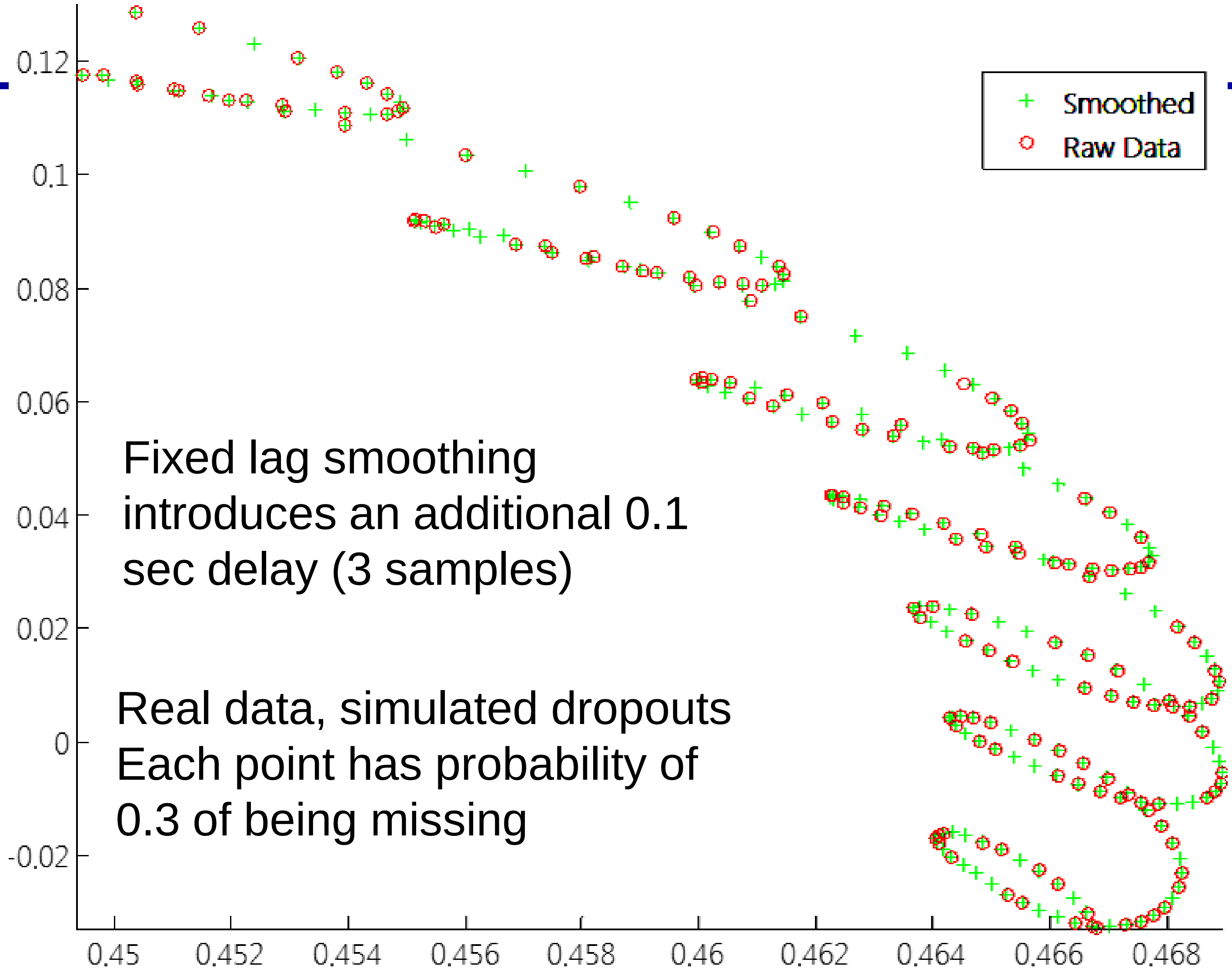
- Generally in Kalman Filters applications the observation residuals have zero mean. The means on the previous slide are because of uncorrected ratio errors in CCVTs and CTs.
- The assumed measurement matrix is H, the actual measurement matrix is H_r, the Kalman Filter steady state gain is K, The mean of x is $\bar{x}$ which is constant in the previous slide. The mean of the residual is then

$$\bar{z} = H_r \bar{x} \qquad \bar{\hat{z}} = H\bar{x} \qquad \overline{(z-\hat{z})} = (H_r - H)\bar{x}$$

- For example if measuring a voltage that row of H would be
- [0 0 1 0 . . . 0] but that row of H_r would be
- [0 0 α 0 . . . 0] $\alpha = 1.015e^{j\phi}$

Oscillation, Complex Voltage, 30% Dropouts



Fixed lag smoothing introduces an additional 0.1 sec delay (3 samples)

Real data, simulated dropouts
Each point has probability of 0.3 of being missing