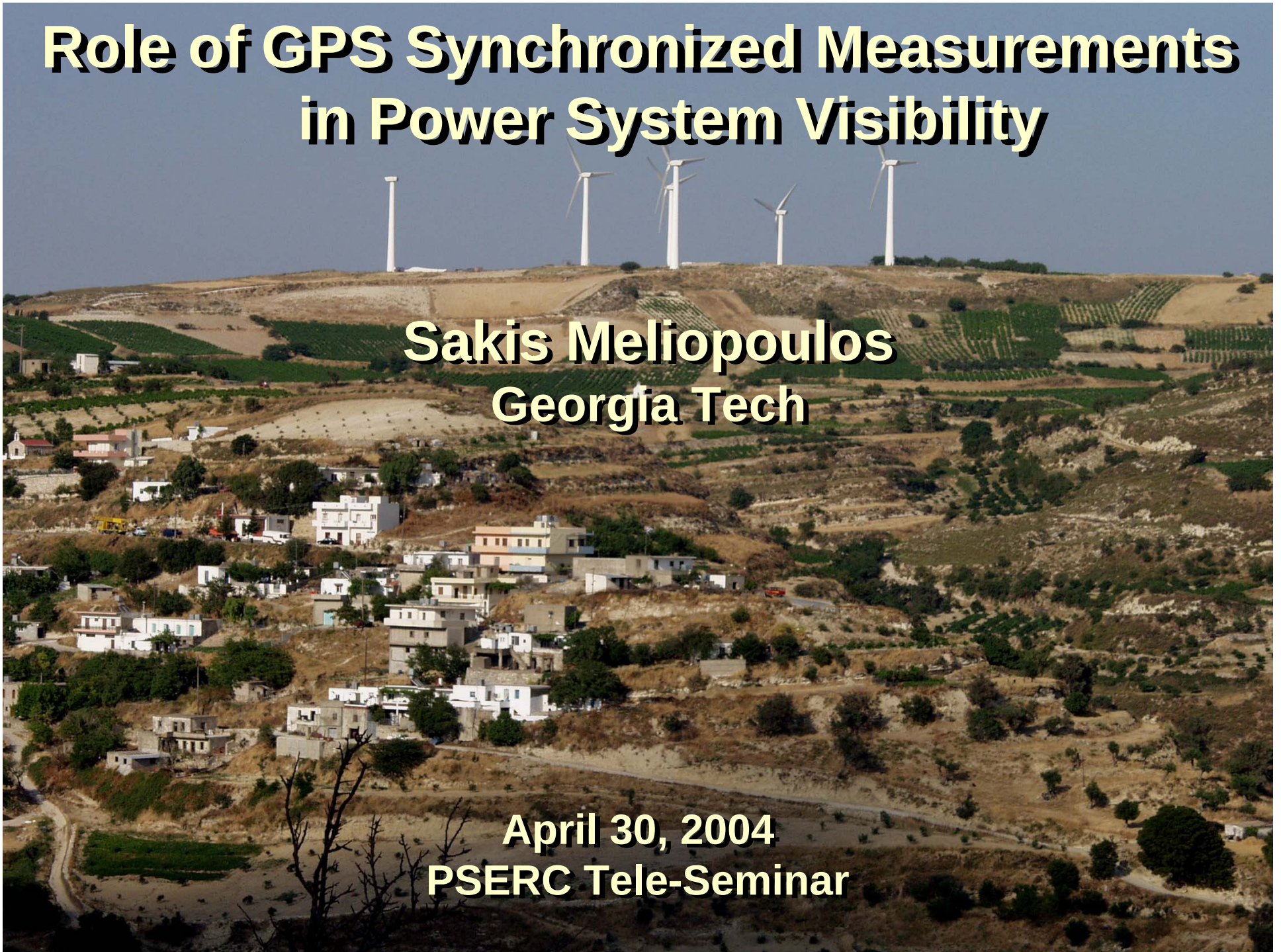


Role of GPS Synchronized Measurements in Power System Visibility

Sakis Meliopoulos
Georgia Tech

April 30, 2004
PSERC Tele-Seminar



Outline

- Power System Visibility (Real Time Model)
- GPS Synchronized Measurement Technology
- Data Validation – Issues
- NYPA's HMS
- Hybrid State Estimator
- Numerical Experiments

Bits & Pieces

From

US-Canada Power System Outage Task Force

Contributing Factors

Inadequate Situational Awareness

Recommendation 22

Evaluate and adopt better real-time tools for operators and reliability coordinators.

Observations

Basic Task in System Operation:

Obtain a Reliable and Accurate Real Time Model

Past and Present Practice:

SCADA + State Estimator → Real Time Model

Today's Reality:

SCADA, IEDs, DFRs, PMUs, Relays Collect an Enormous Amount of Data. Is There a Better Way to Validate and Utilize this Data?

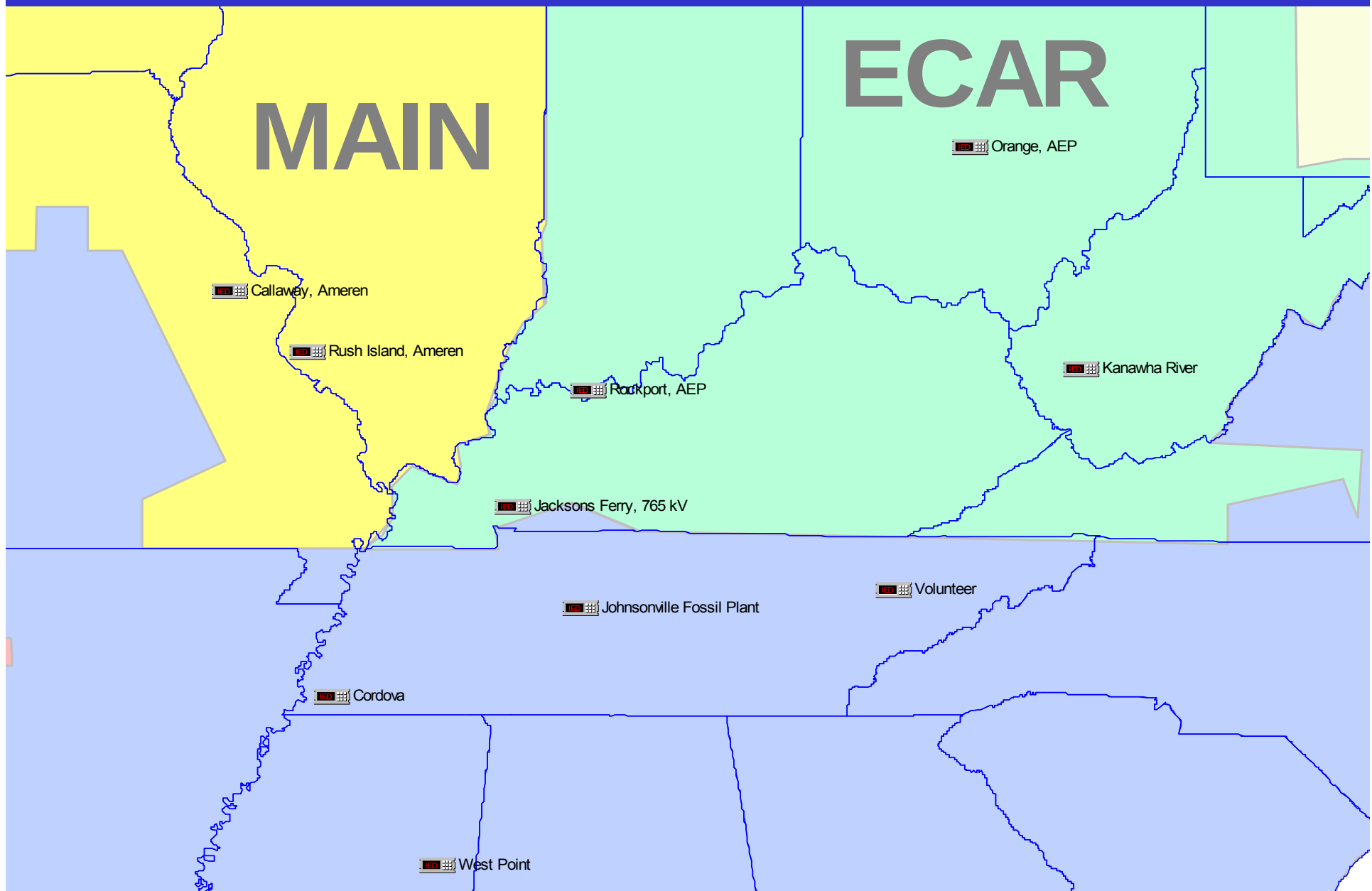
Basic Capabilities

- **GPS “Commercial” Accuracy (Time):**
0.5 Microseconds
Phase Error 0.01 Degrees at 60 Hz
- **GPS “Commercial” Accuracy (Location):**
7 meters
- **New Enhancement:**
WAAS (Wide Area Augmentation System)
Performance Much Better
- **Other Enhancements in the Works...**

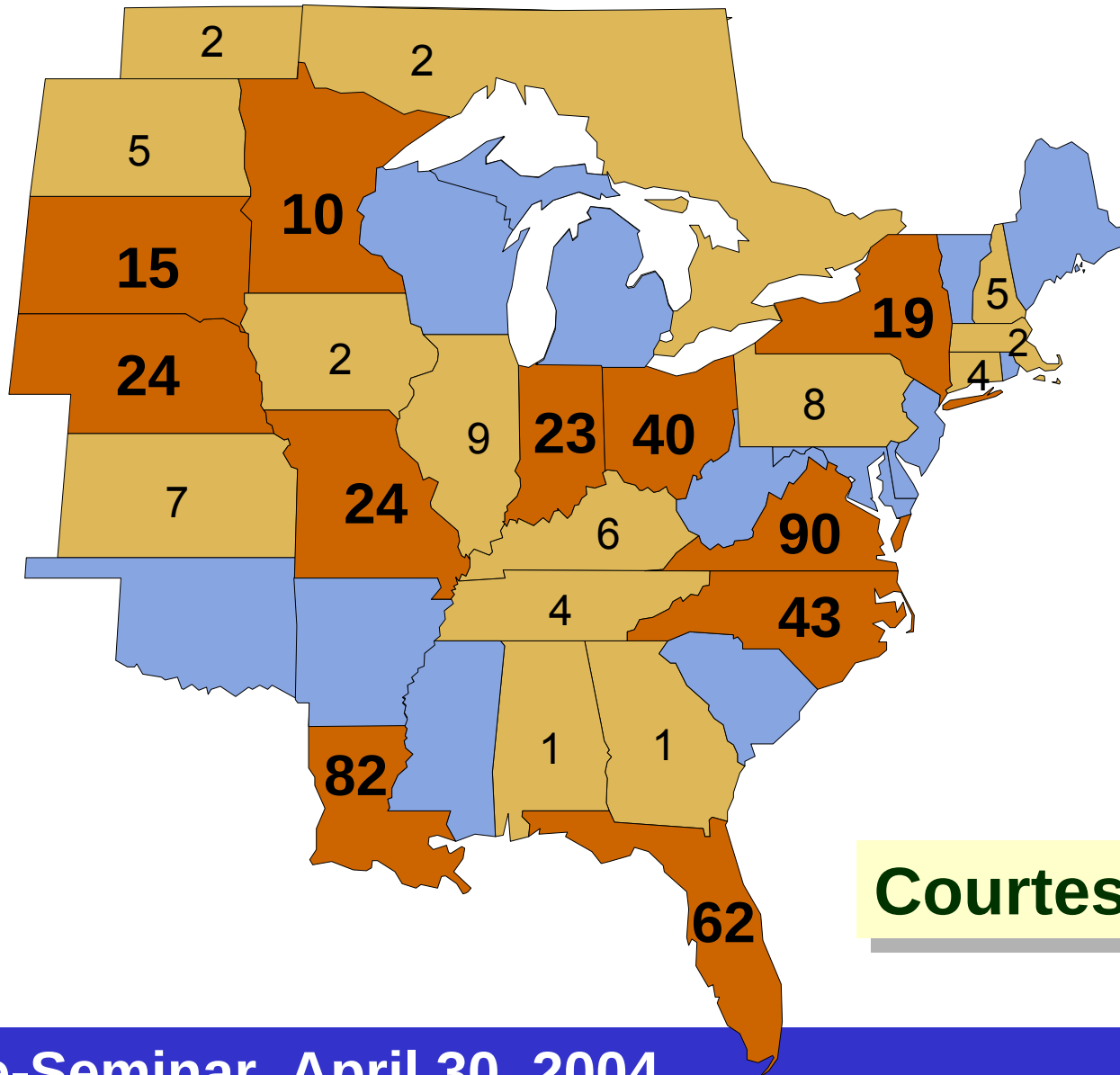
GPS-Synchronized Measurements

- Technology Became Available to Power Systems About 15 years ago
- Specialized Equipment
- Addition of GPS Synchronization in IDEs and Relays
- Cost is Rapidly Reducing (*Basic Receiver is \$30*)
- Technology is Under-Utilized

Planned GPS-Synchronized Measurements for the TVA System



SEL-421 Deployment Eastern USA



Courtesy of SEL

GPS-Synchronized Measurements

By Virtue of its Timing Accuracy the Technology Can Be Used to Directly Measure the State of the Power System



Important Observations

Measurement Errors

- GPS Synchronized Measurements are More Accurate than Sensors but still Imperfect – Errors are Present
- Sensorless SCADA Have Accuracy Comparable to GPS Synchronized Measurements

System Exhibits “Internal” Errors

- Errors from Instrumentation
- Errors from Imbalance
- Errors from Asymmetry

Solution

- Data Filtering via Estimation Methods → Validation

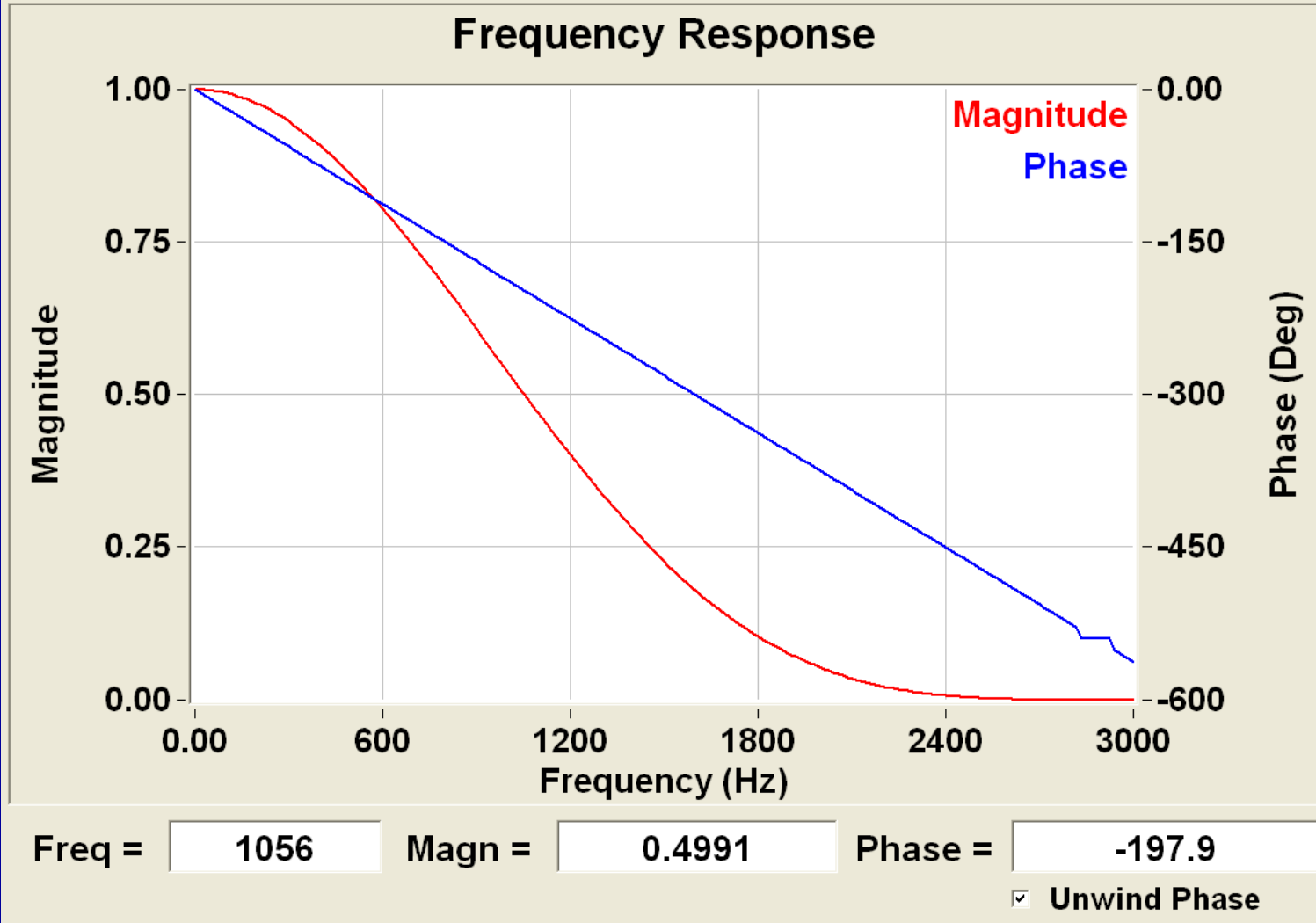
Example Specifications

	Arbiter 1133A	Macrodyne 1620
A/D Converter Technology	Successive Approximation	Sigma-Delta Modulation
A/D Converter Word Length	14 bits	16 bits
Sampling Rate (samples per second per channel)	10240	2880
Automatic Calibration	yes	no
GPS Time Tagging	yes	yes
Simultaneous Sampling	no	yes
GPS synchronized sampling	no	yes
Voltage Input Isolation	differential amplifier	optical
Current Input Isolation	transformer	optical
Anti-Aliasing Filters	no	Digital (built in A/D Converter)
Phase Measurement Error at 60 Hz	0.01 Degrees	0.01 Degrees
Communications	Ethernet and RS232	RS232

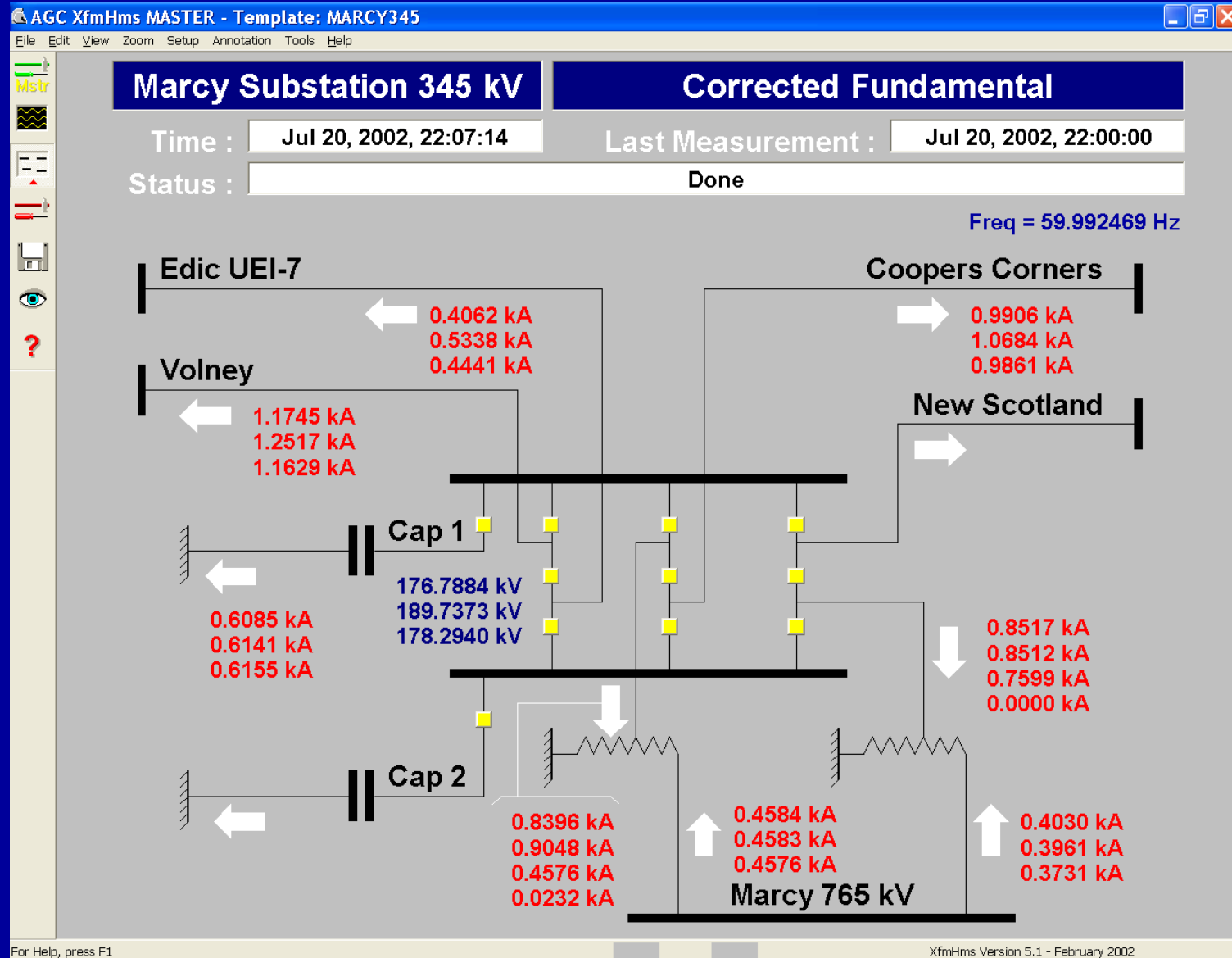
Example Characteristics of a PMU

Description : 30 Channel Phasor Measurement Unit

Test Date : Thursday, July 11, 1991



Errors from Imbalance and Asymmetry

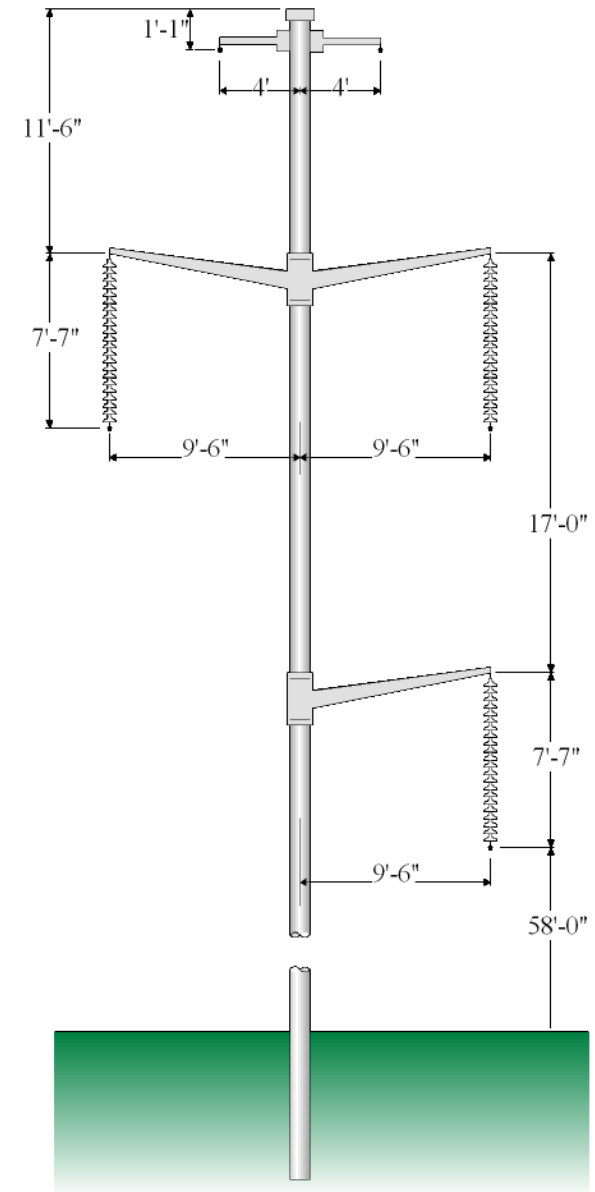
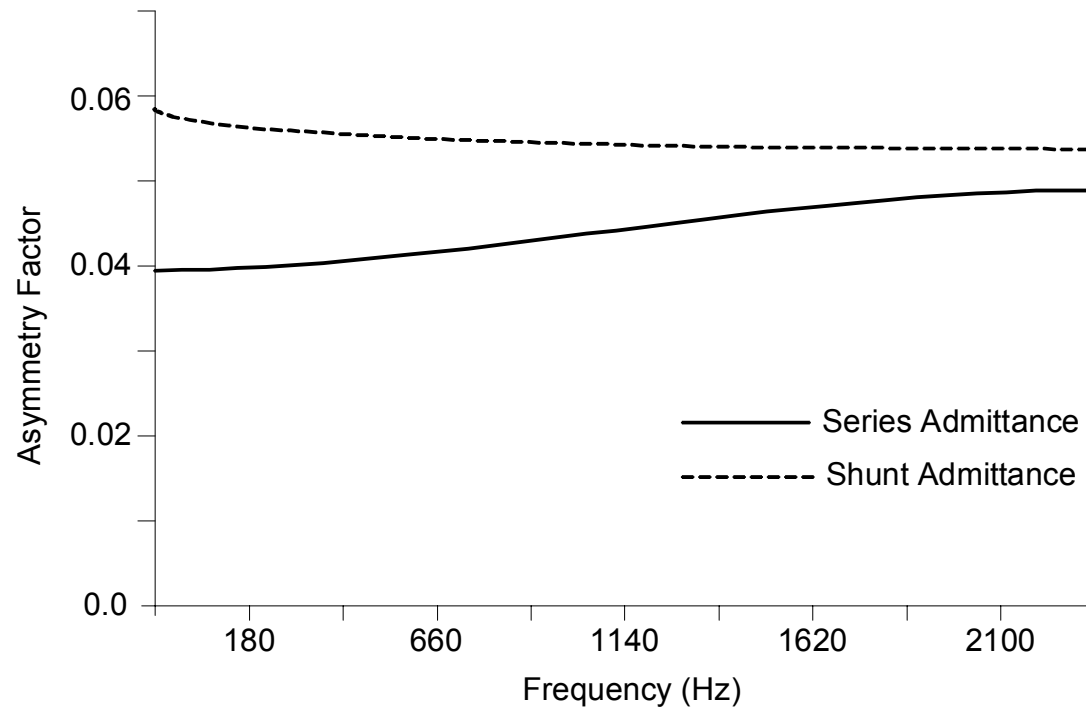


Validity of Power System Symmetry Assumption

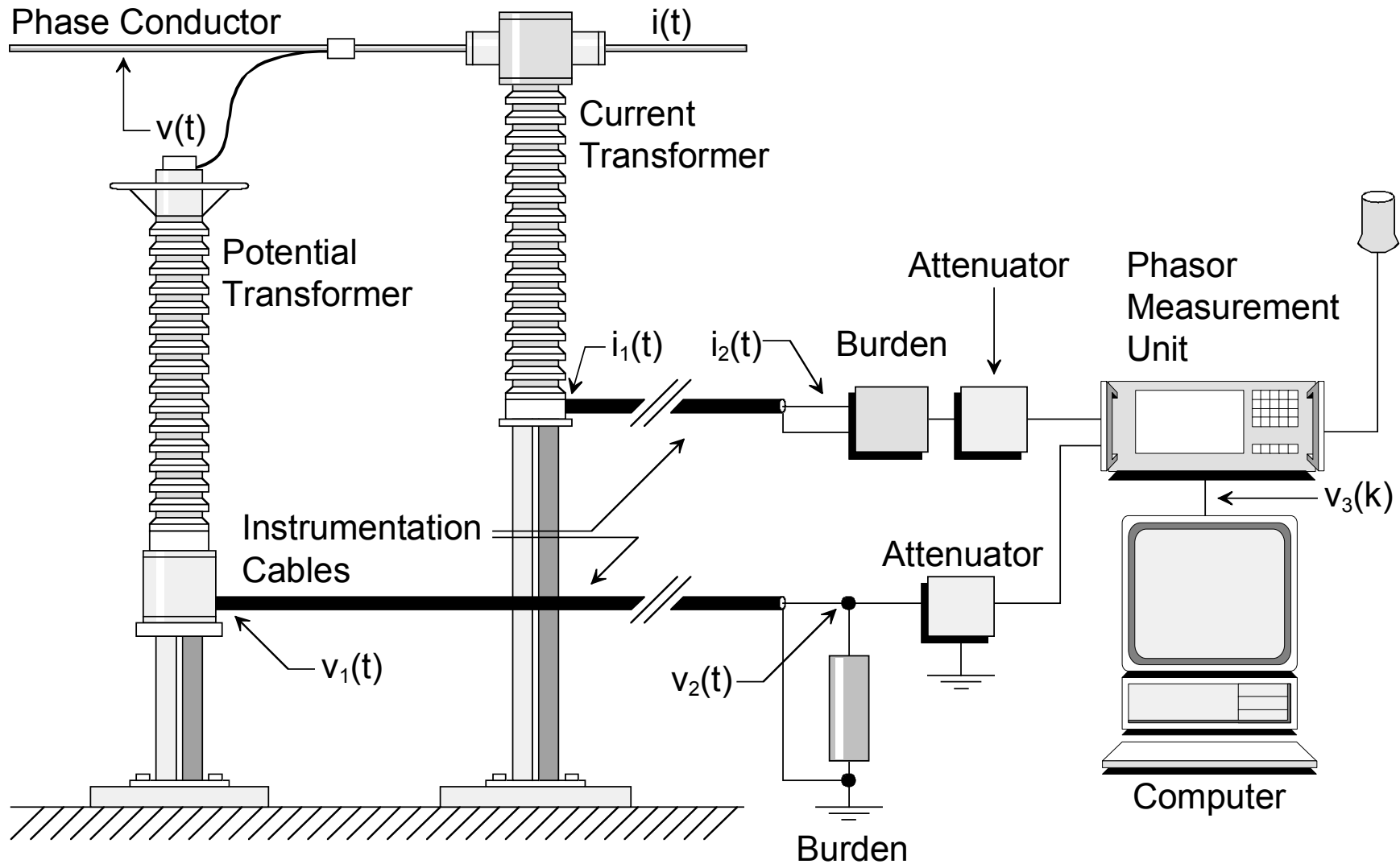
$$S_1 = \frac{1}{2} \frac{|z_{\max} - z_{\min}|}{|z_1|}$$

$$S_2 = \frac{1}{2} \frac{|y_{\max} - y_{\min}|}{|y_1|}$$

The Phase Impedances May Vary by 5% Among Phases

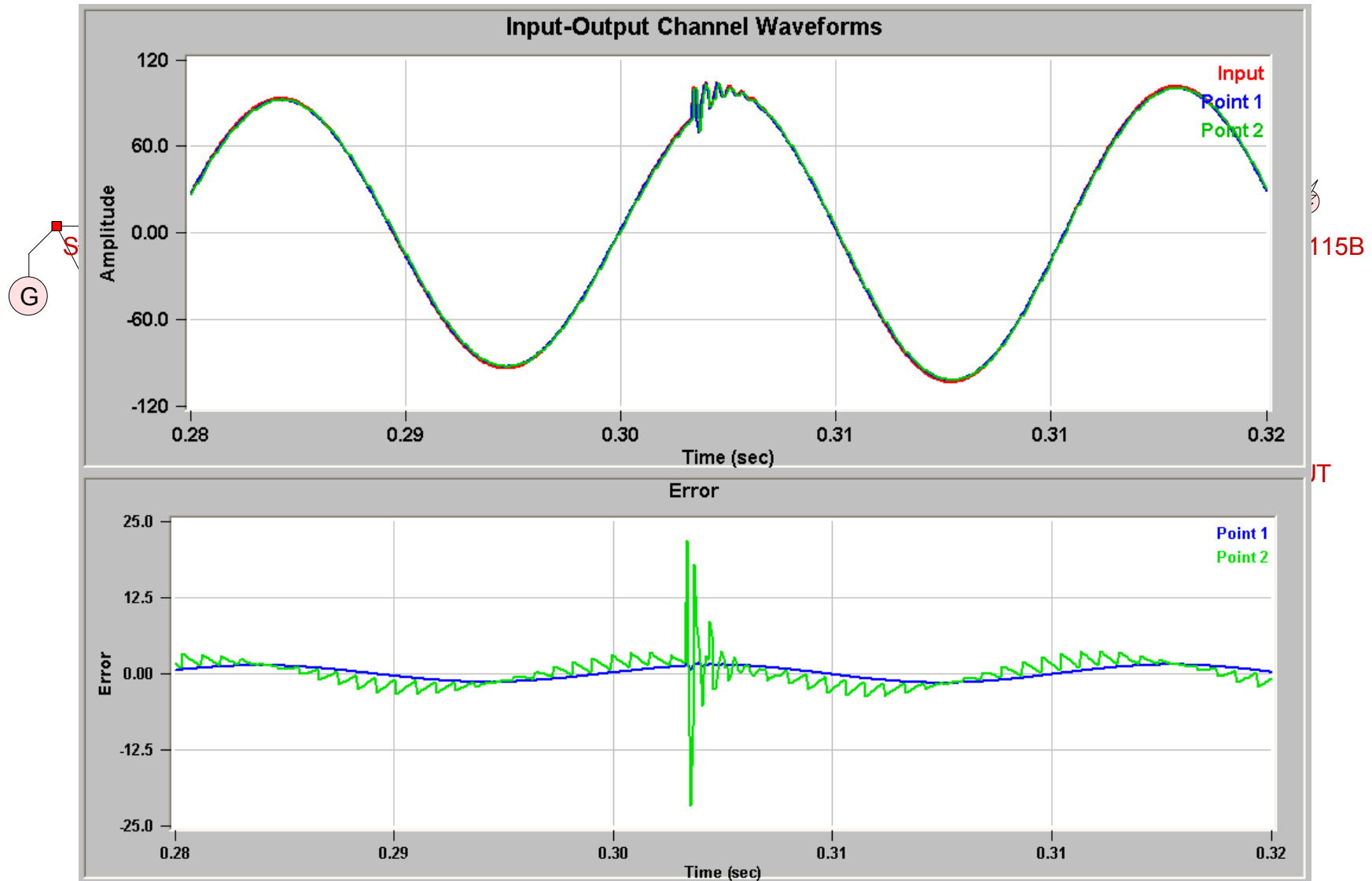


Instrumentation Errors



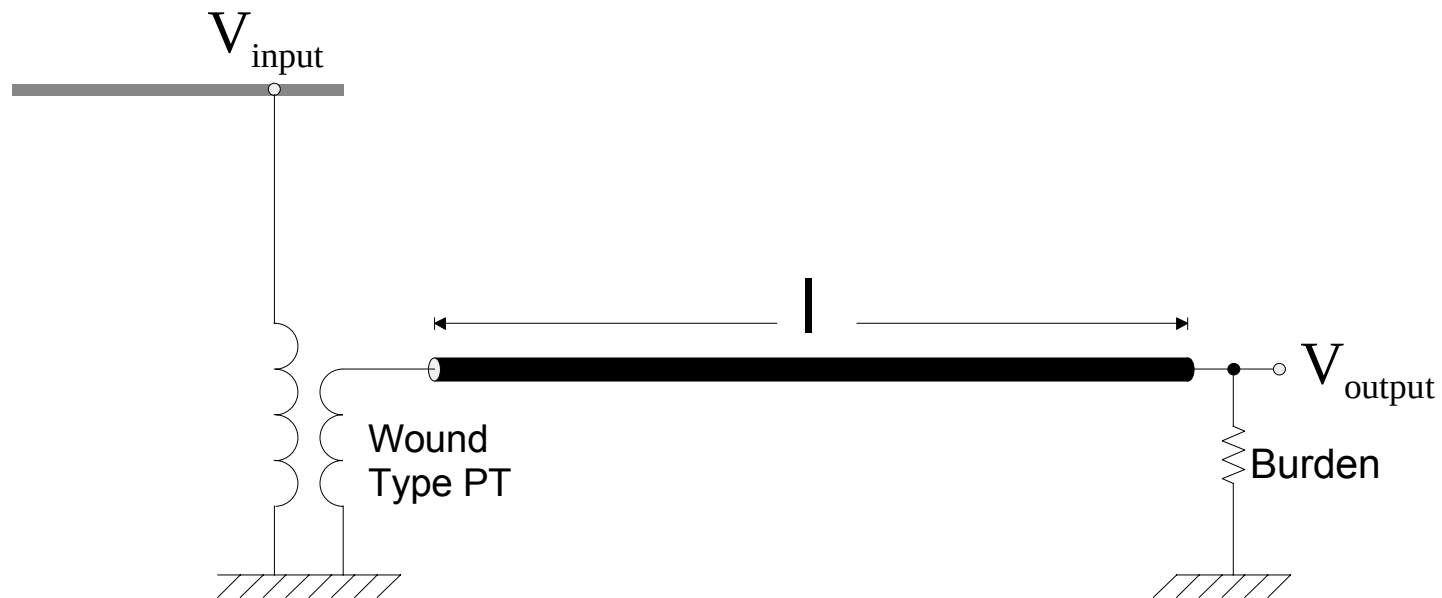
Instrumentation Errors

Voltage Measurement Error During Transients



Instrumentation Errors

Instrumentation Cable Phase Error



Cable Length (l)	Phase (V_{out} / V_{in})
75 m	0.04°
150 m	0.07°
225 m	0.11°
300 m	0.14°

**PMU Phase
Accuracy is
0.01 degrees**

Traditional State Estimation

Power System SE: Basic Assumptions

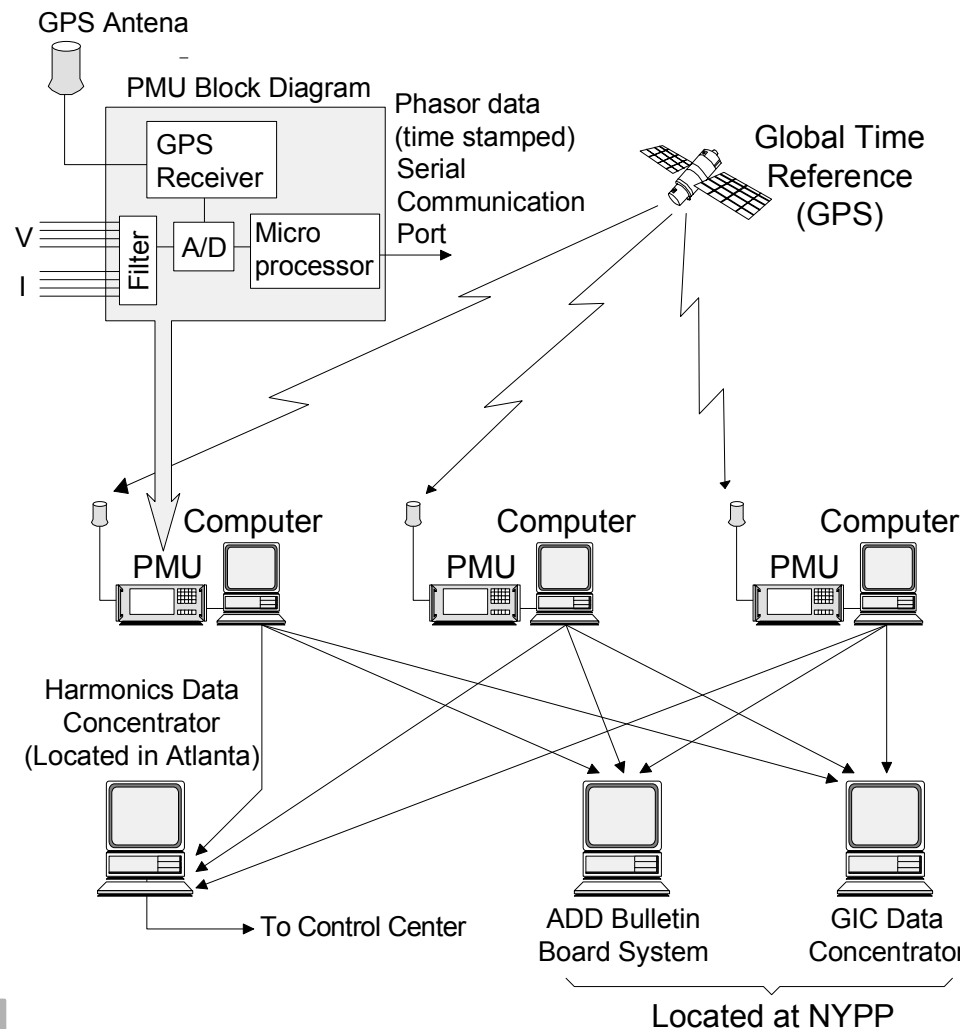
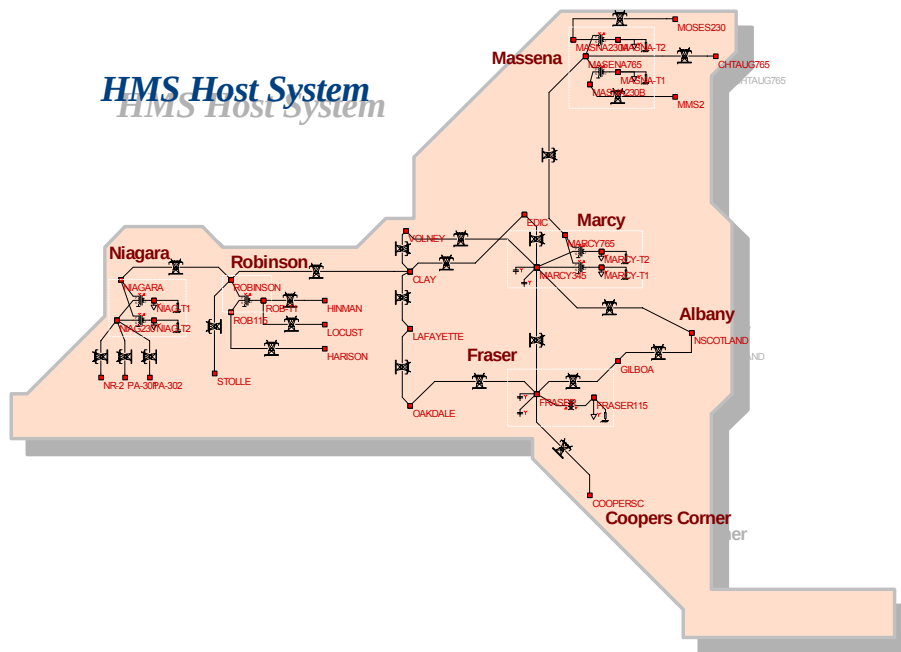
- Positive Sequence Model
- P, Q, V measurement set
- Instrumentation Errors Part of Meas Data
- Near-Simultaneous Measurements
- Single Frequency

Implications:

- Balanced Operation
- Symmetric Power System
- Biased SE
- Iterative Algorithm

NYPA's Harmonic Measurement System Using GPS Synchronized Measurements (Macrodyne's PMUs)

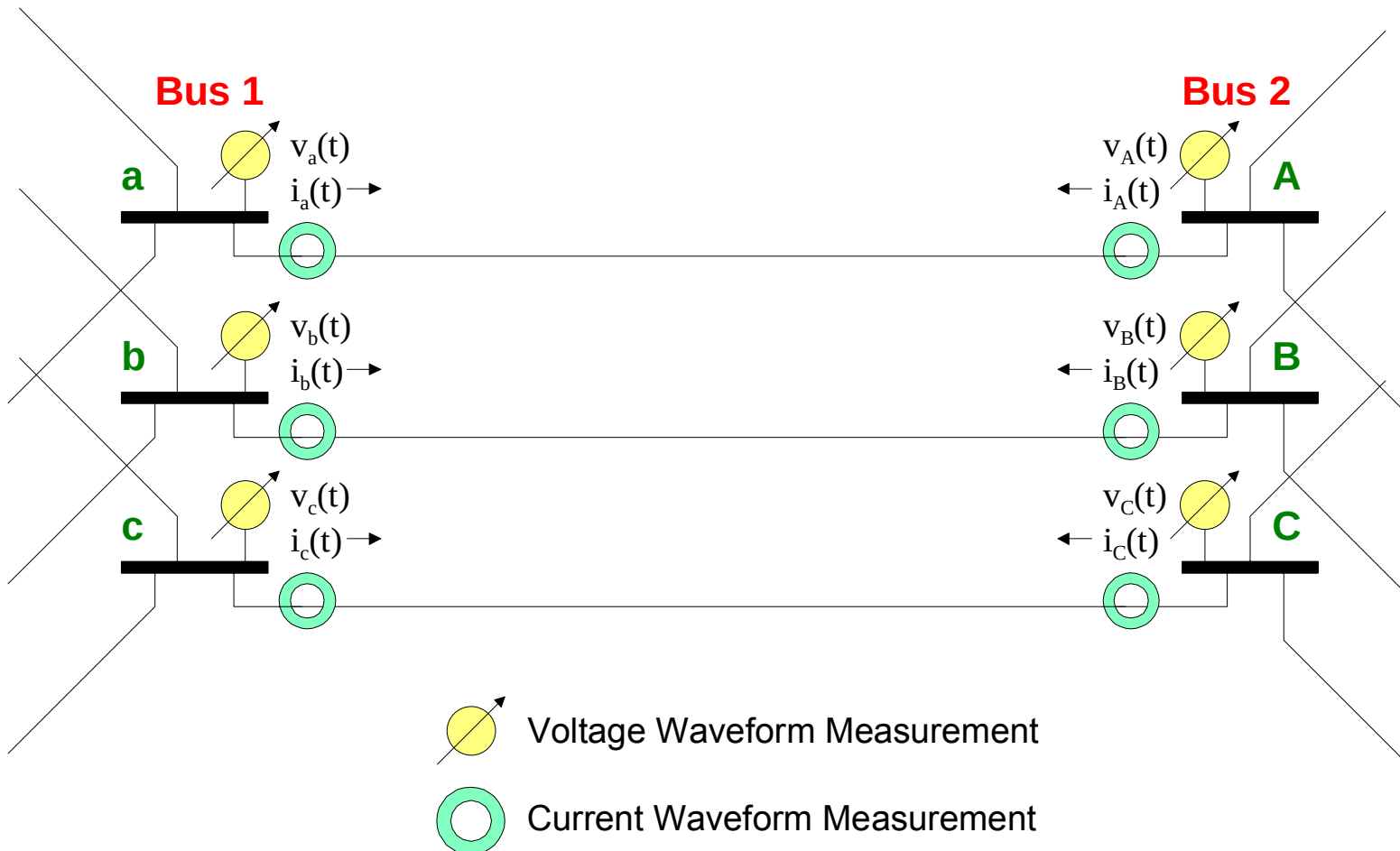
Asymmetric Power System Model New York Power Authority



Synchronized Measurement Based SE

What is the Advantage

Phasor Measurements of Voltages and Currents



SE with Synchronized Measurements

$$\text{Min} \quad \tilde{r}^H W \tilde{r}$$

$$\text{Subject to:} \quad \tilde{r} = \tilde{z} - \tilde{H} \tilde{x}$$

$$\text{Min} \quad r_{real}^T W r_{real} + r_{imag}^T W r_{imag}$$

$$\text{Subject to:} \quad r_{real} = z_{real} - H_{real} x_{real} - H_{imag} x_{imag}$$
$$r_{imag} = z_{imag} - H_{real} x_{imag} - H_{imag} x_{real}$$

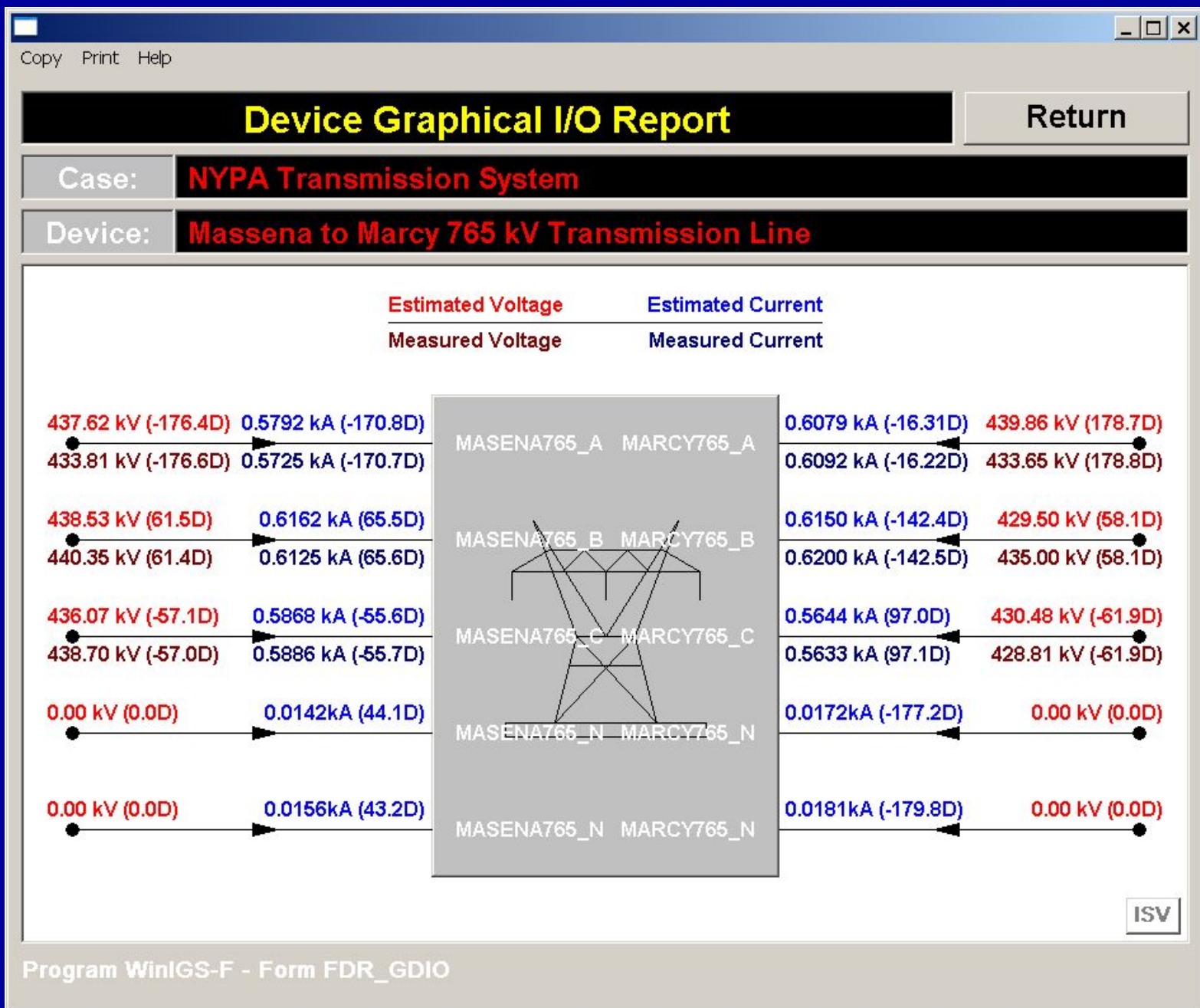
$$\begin{bmatrix} A & B \\ -B & A \end{bmatrix} \begin{bmatrix} x_{real} \\ x_{imag} \end{bmatrix} = \begin{bmatrix} H_{real}^T W z_{real} + H_{imag}^T W z_{imag} \\ H_{real}^T W z_{imag} - H_{imag}^T W z_{real} \end{bmatrix}$$

***** Direct Solution *****

Observation

In Case that All Data are GPS
Synchronized Measurements the
State Estimator is DIRECT

Big Advantage



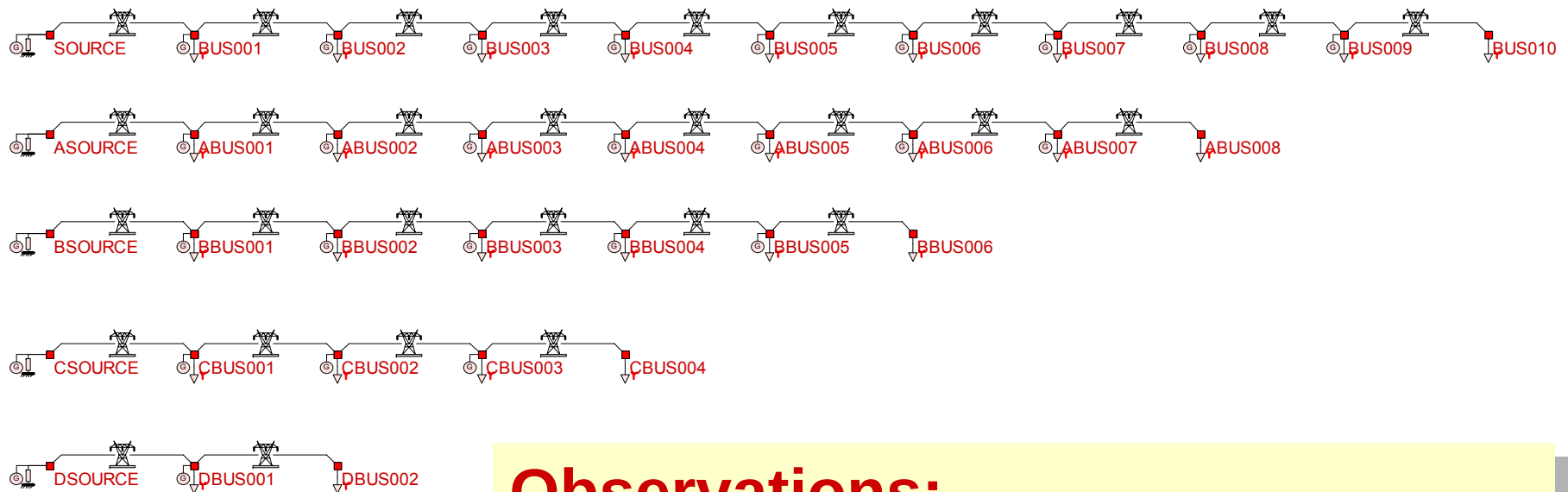
Detection of SE Bias

Numerical Experiments on the MSU-1 Line (765 kV)

Case Description	Confidence Level (Chi-Square Test)
Three Phase Asymmetric Model, Three Phase Measurements	100.00
Three Phase Symmetric Model, Three Phase Measurements	13.02
Three Phase Asymmetric Model, Single Phase (A) Measurements	0.0

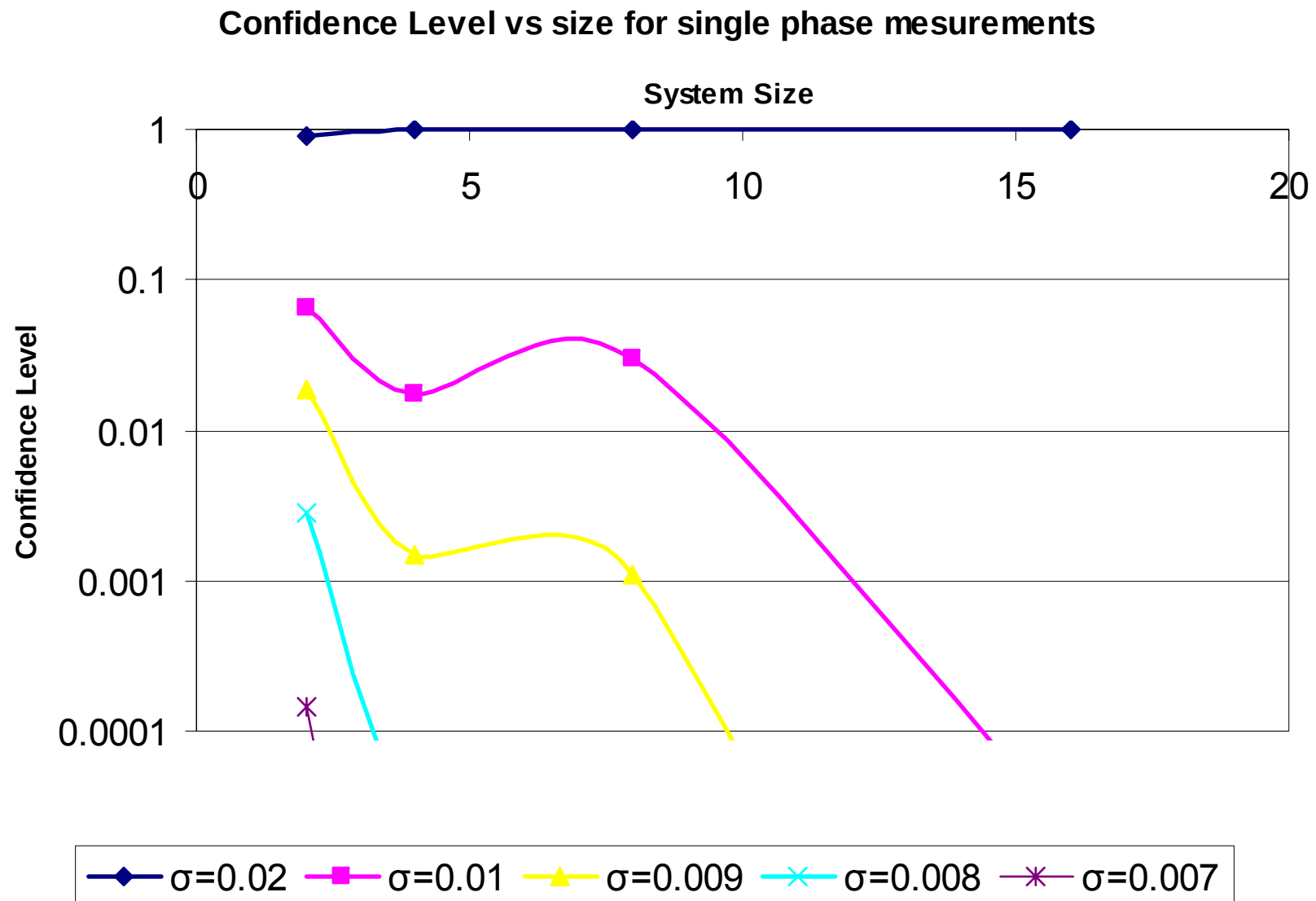
Investigation of SE Biases via Numerical Experiments

Approach: Systems of Variable Size



Observations:
System Imbalance Stabilizes
Phase with Max Voltage: Random
Effects on Mega RTO SE: Unknown

Confidence Level of Data Accuracy



Proposed Approach

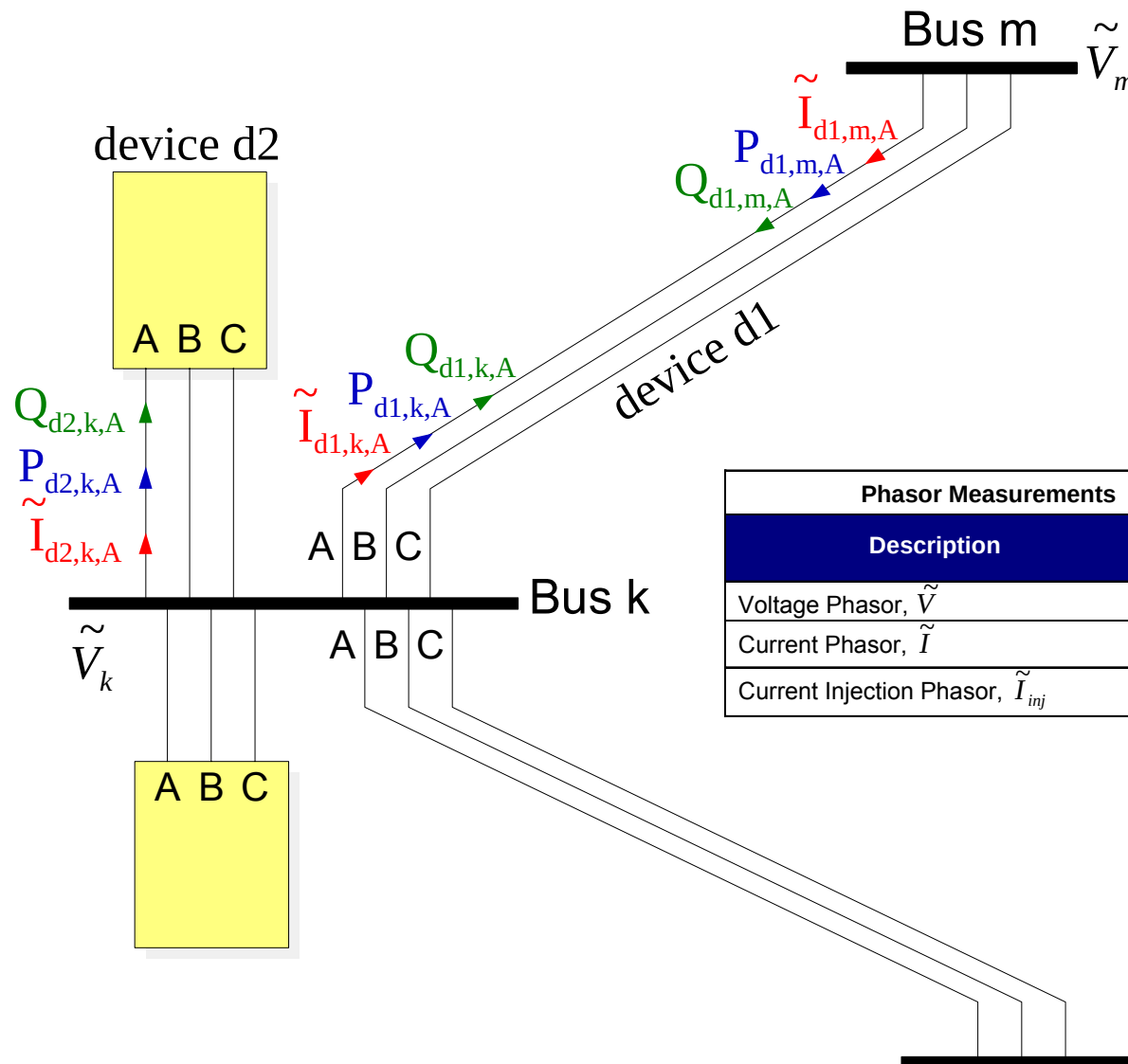
- GPS Synchronized Measurements are Imperfect – Errors are Present
- Other Useful Data Exist (SCADA, Relays, DFRs, etc.).

Proposed Approach: **HYBRID STATE ESTIMATOR**. It Utilizes all Available Data

- Errors from Imbalance
- Errors from Asymmetry

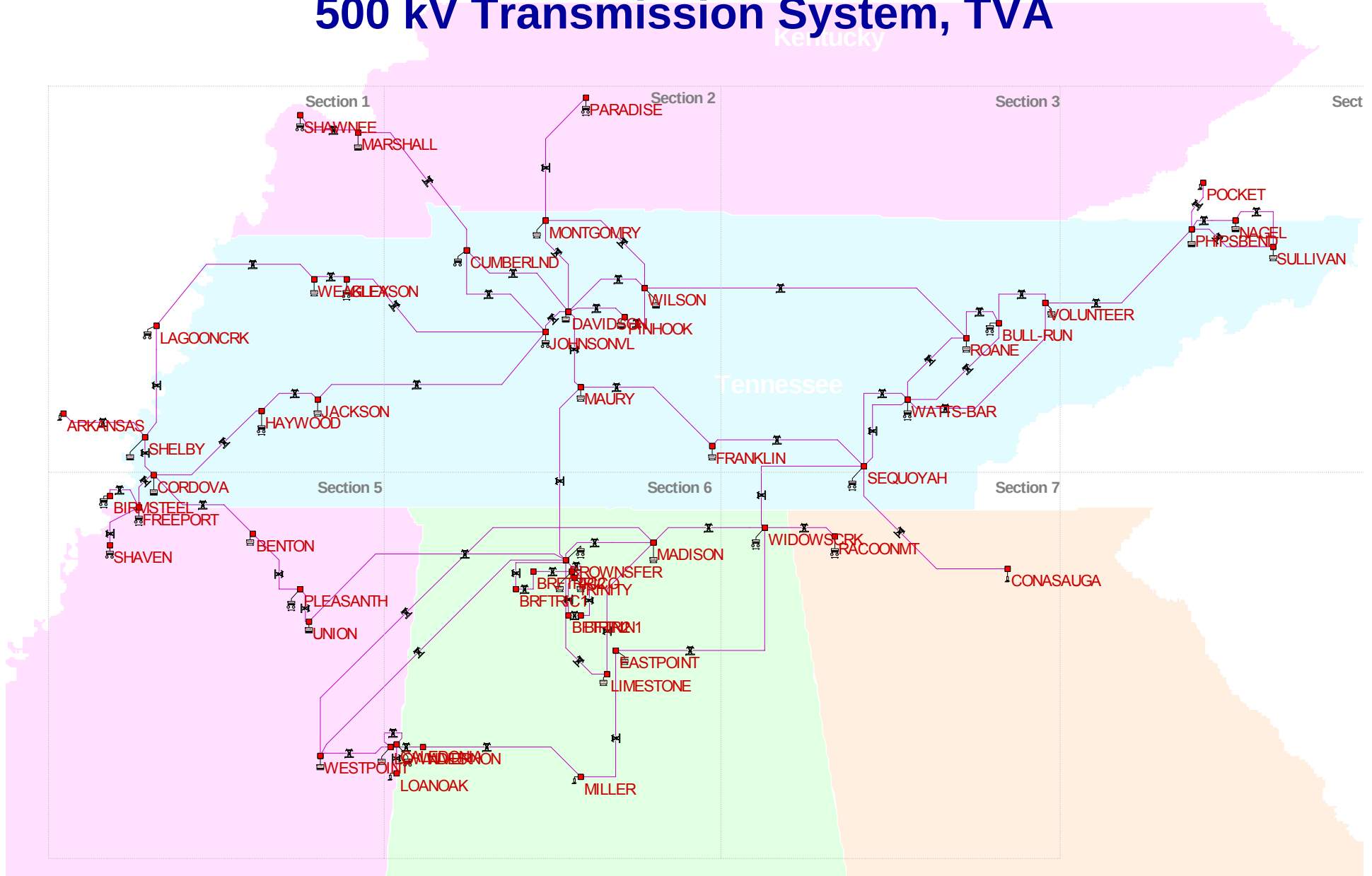
Proposed Approach: **THREE PHASE MODEL**. It Eliminates Model Biases

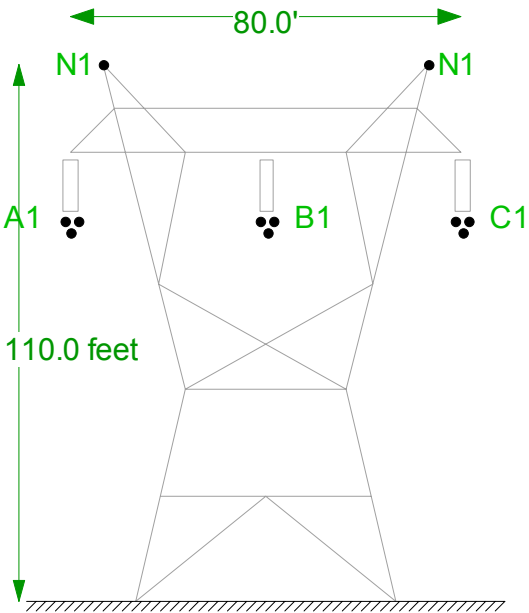
QPF-SE Approach: Available Data



Phasor Measurements		Non-Synchronized Measurements	
Description	Type Code	Description	Type Code
Voltage Phasor, $\tilde{V}$	1	Voltage Magnitude, V	4
Current Phasor, $\tilde{I}$	2	Real Power Flow, P_f	5
Current Injection Phasor, $\tilde{I}_{inj}$	3	Reactive Power Flow, Q_f	6
		Real Power Injection, P_{inj}	7
		Reactive Power Injection, Q_{inj}	8

QPF-SE Approach: Three Phase Model of the 500 kV Transmission System, TVA



3-Phase Overhead Transmission Line		Accept	
Franklin to Sequoyah 500 kV Line		Cancel	
Phase Conductors	Type ACSR Size RAIL	 SINGLE TOWER 500 KV	
Shields/Neutrals	Type HS Size 5/16HS		
Tower/Pole	Type TVA-SA-23R1 Circuit Number 1		
Tower/Pole Ground Impedance (Ohms)			
R = 25.0 X = 0.0			
Line Length (miles) 62.77 Line Span Length (miles) 0.1 Soil Resistivity (Ohm-Meters) 100.0			
Bus Name, Side 1	Circuit Number	Bus Name, Side 2	
FRANKLIN	1	SEQUOYAH	
Operating Voltage (kV) 500.0 Structure Name NA		Insulation Level (kV) FOW (Front of Wave) 2300.0 BIL (Basic Insulation Level) 1650.0 AC (AC Withstand) 1050.0	
☐ Insulated Shields ☐ Transposed Phases ☐ Transposed Shields			

Program WinIGS-F - Form IGS_M102

QPF-SE Approach: Hybrid SE Formulation

$$\text{Min } J = \sum_{v \in \text{phasor}} \frac{\tilde{\eta}_v^* \tilde{\eta}_v}{\sigma_v^2} + \sum_{v \in \text{non-syn}} \frac{\eta_v \eta_v}{\sigma_v^2}$$

GPS-Synchronized Measurements (Linear Model)

Voltage Phasor

$$\tilde{z}_v = \tilde{V}_{k,A} - \tilde{V}_{k,N} + \tilde{\eta}_v$$

Current Phasor

$$\tilde{z}_v = \tilde{I}_{d1,k,A} + \eta_v = C_{d1,k,A}^T \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} + \tilde{\eta}_v$$

Non-Synchronized Measurements (Quadratic Model)

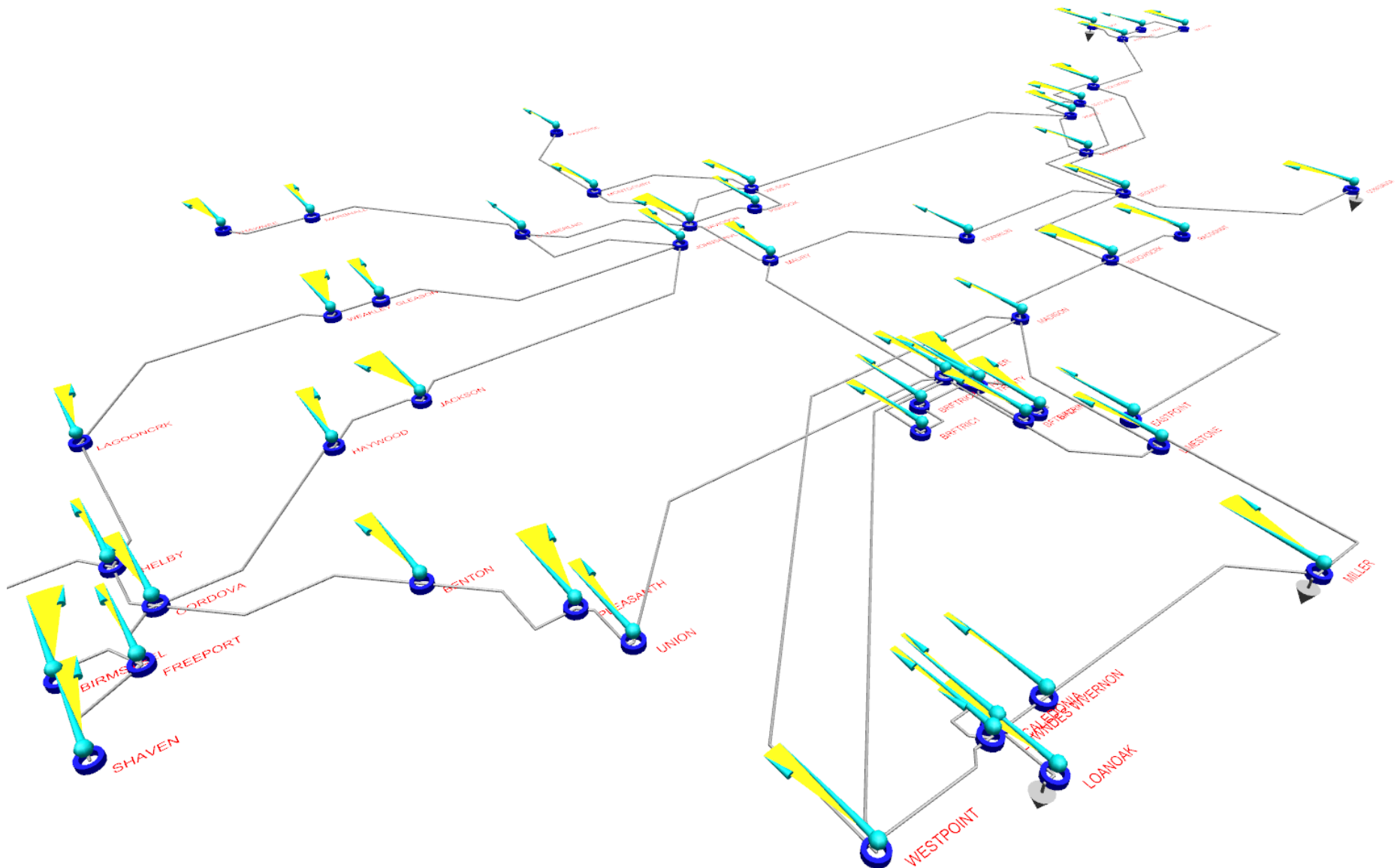
Voltage Magnitude

$$\begin{aligned} z_v &= |\tilde{V}_{k,A} - \tilde{V}_{k,N}|^2 + 2\eta_v = \\ &= (V_{k,A,r} - V_{k,N,r})^2 + (V_{k,A,i} - V_{k,N,i})^2 + 2\eta_v \end{aligned}$$

Real Power

$$z_v = P_{d1,k,A} + \eta_v = \text{Re} \left\{ \tilde{V}_{k,A} \left(C_{d1,k,A}^T \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} \right)^* \right\} + \eta_v$$

Error of Bus Voltage Phase – Estimated minus Measured Value Magnified 200 times (min error: -0.144, max error: 0.147 degrees)



Bad Data Detection & Identification

This is an Important Issue:

- Current Approaches are Computationally Demanding.
- Leverage Points Are Especially Troublesome.

Utilizing All Available Data Increases Redundancy.

The implications are:

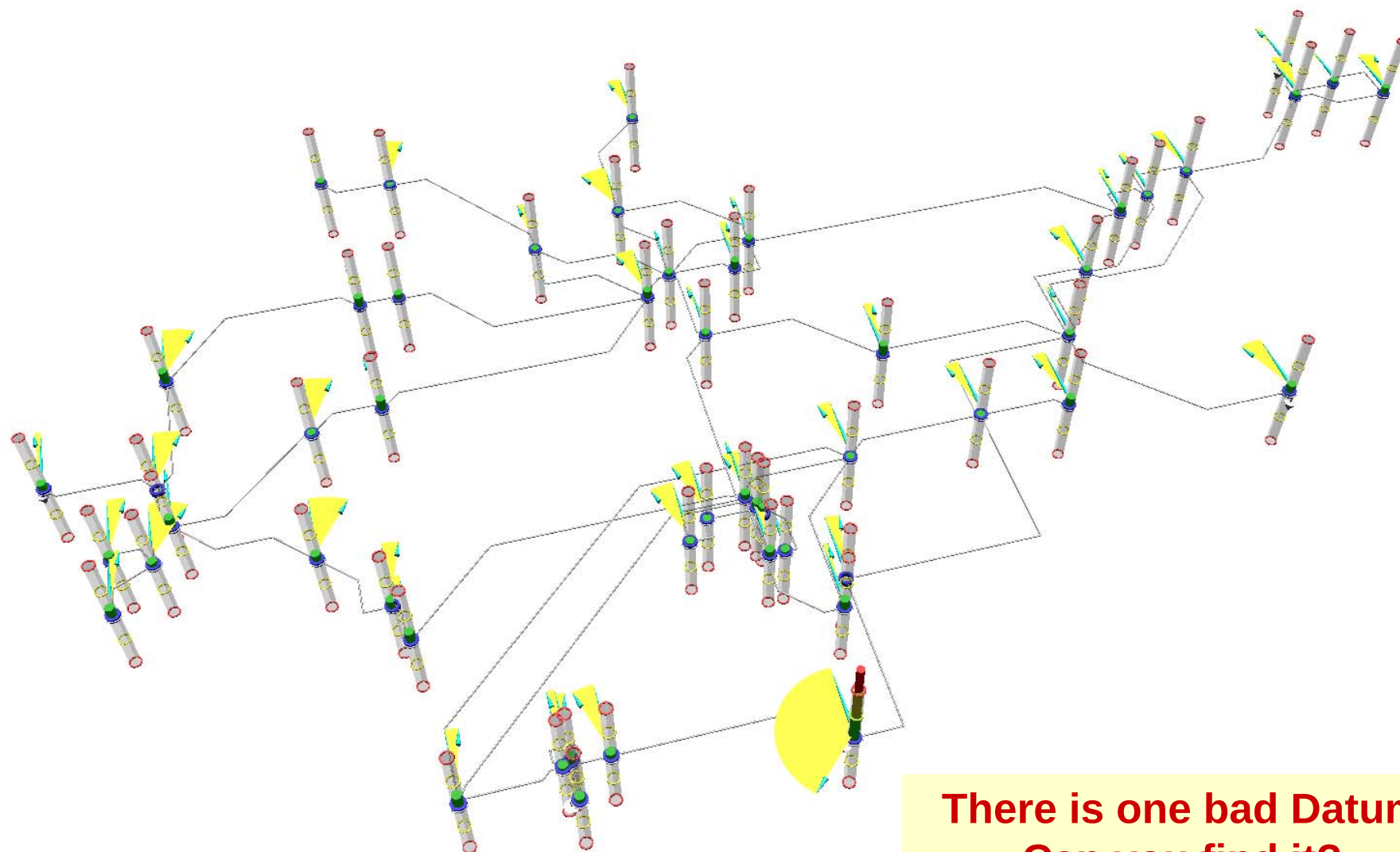
- (a) Increased Effort for System Initial Calibration, and
- (b) Improved Bad Data Identification Process.

Visualization Methods Also Help

Error of Bus Voltage Magnitude and Phase – Estimated minus Measured Value

Magnitude is Normalized (min magnitude error: 0, max magnitude error: 0.141)

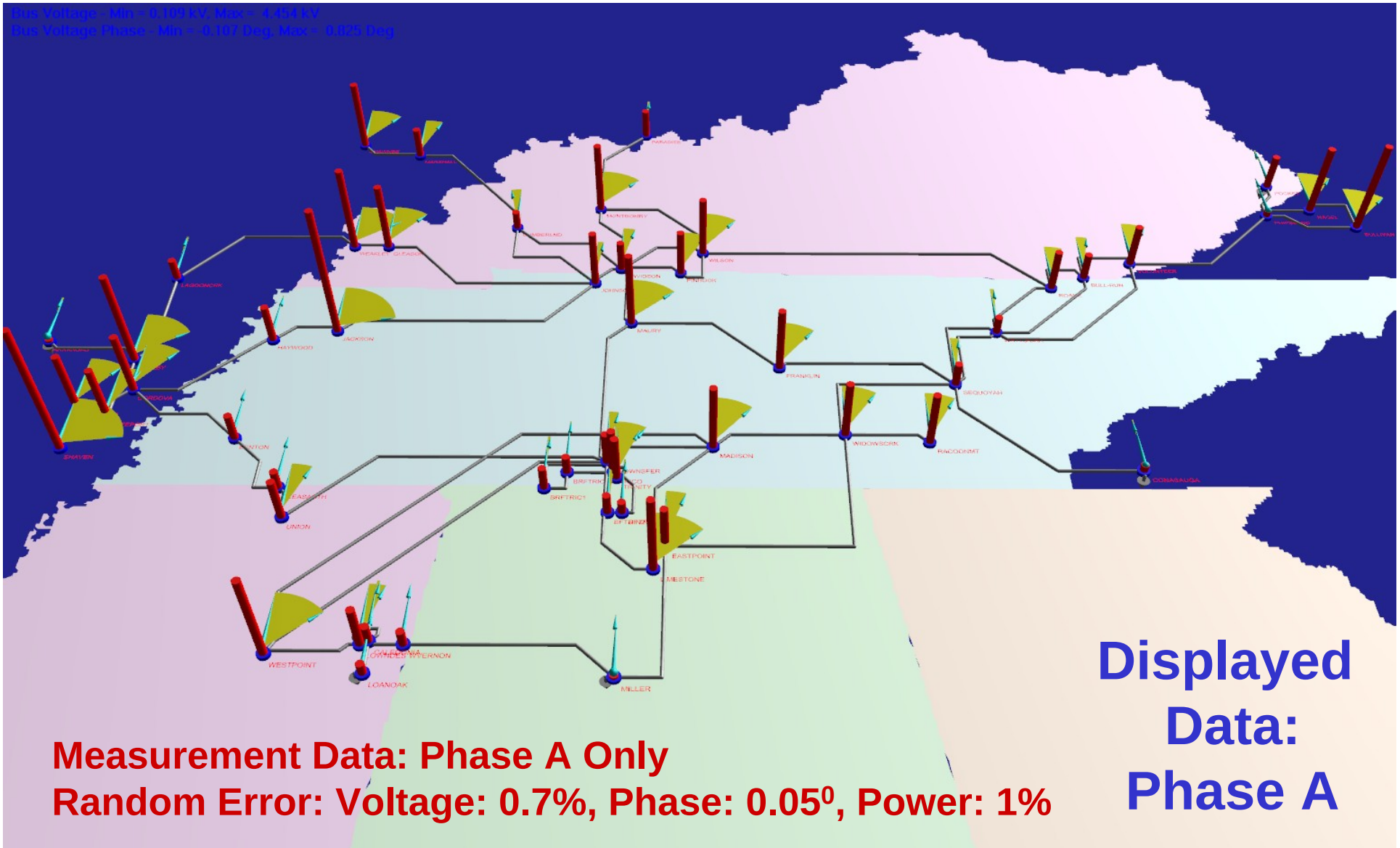
Phase is Magnified 200 times (min phase error: -0.672, max phase error: 0.165)



**There is one bad Datum
Can you find it?**

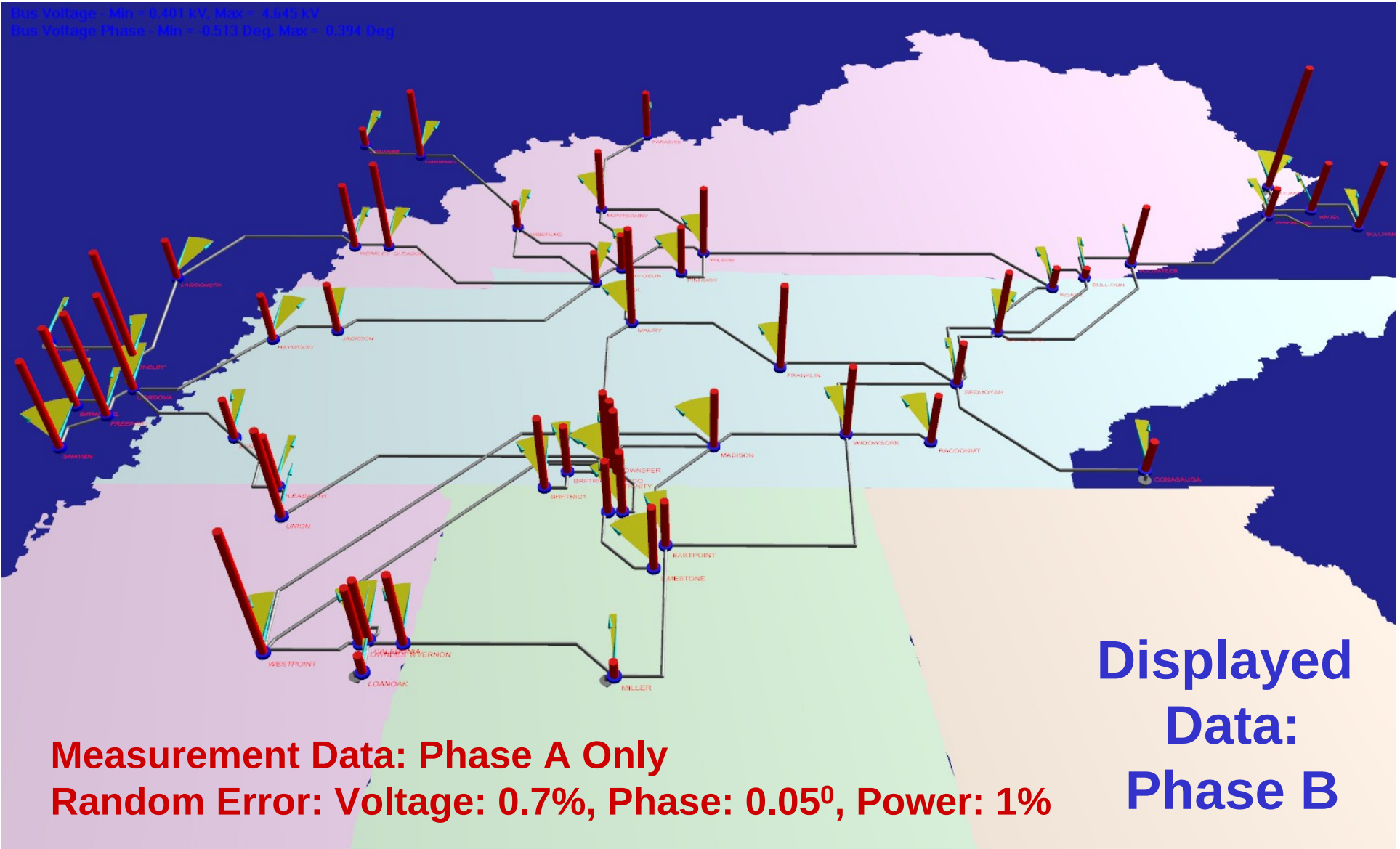
Error of Bus Voltage Magnitude and Phase – Estimated minus Measured Value

Magnitude Error Range: 0.1 to 4.4kV – Phase Error Range: -0.1 to 0.8 Degrees
(Phase Error is Magnified 100 times)



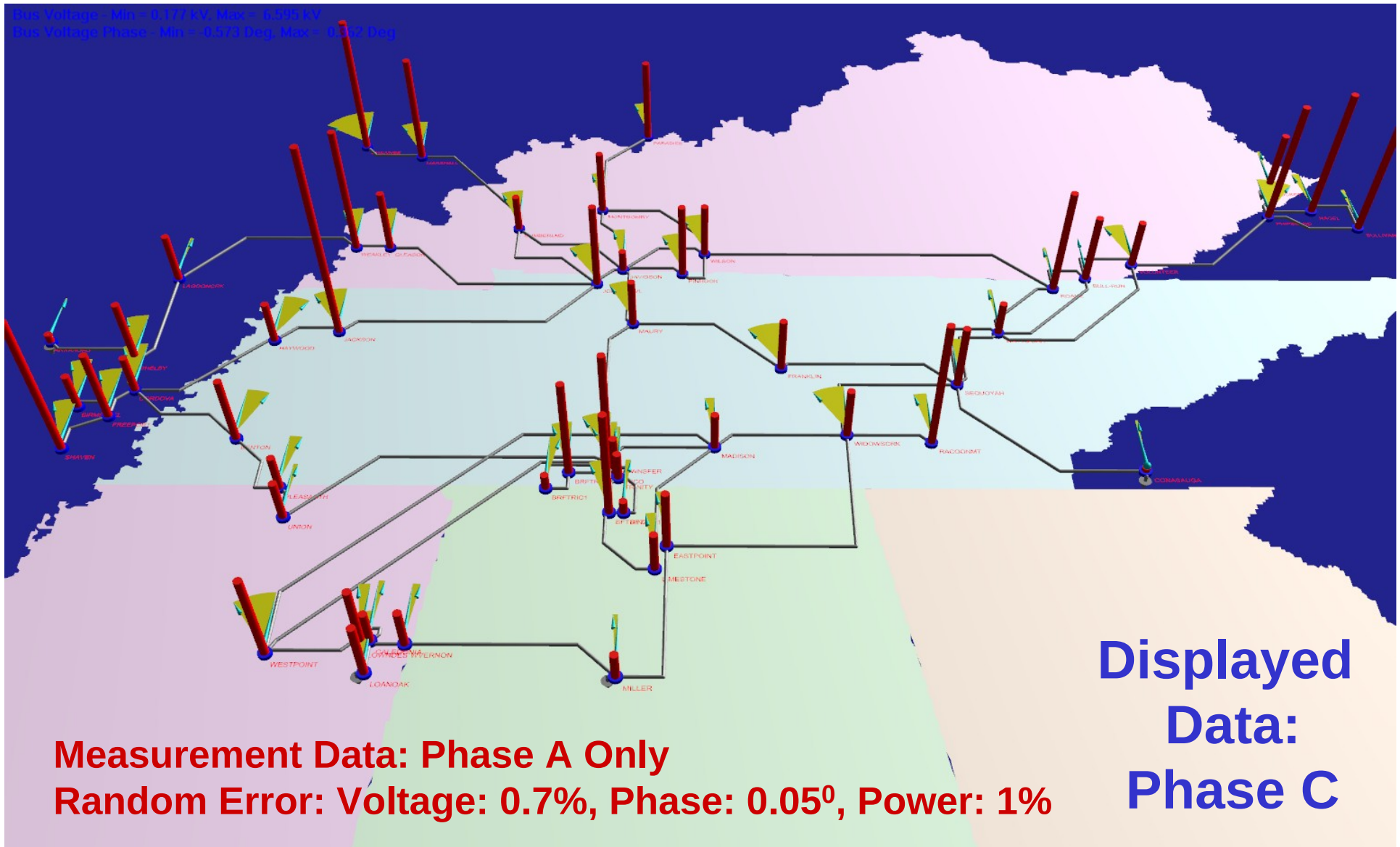
Error of Bus Voltage Magnitude and Phase – Estimated minus Measured Value

Magnitude Error Range: 0.4 to 4.6kV – Phase Error Range: -0.5 to 0.4 Degrees
(Phase Error is Magnified 100 times)



Error of Bus Voltage Magnitude and Phase – Estimated minus Measured Value

Magnitude Error Range: 0.2 to 6.6kV – Phase Error Range: -0.6 to 0.4 Degrees
(Phase Error is Magnified 100 times)



Proposed Utilization of the QPF-SE

- Assume There Are Sufficient GPS Synchronized Measurements for Complete State Observability from These Measurements Alone
- Exercise QPF-SE Once Each Hour
- Use Results of QPF-SE to Calibrate GPS Synchronized Measurements.
- Use the GPS Synchronized Measurements Directly as the Real Time Model.

Summary and Conclusions

Present Implementation of State Estimators
Biased Estimator

Synchronized Measurements
Direct State Estimation

Synchronized Measurements + Multiphase Model
Unbiased State Estimation

Synchronized Measurements+SCADA+IEDs
+ Multiphase Model
Hybrid, Unbiased State Estimation

Τελος