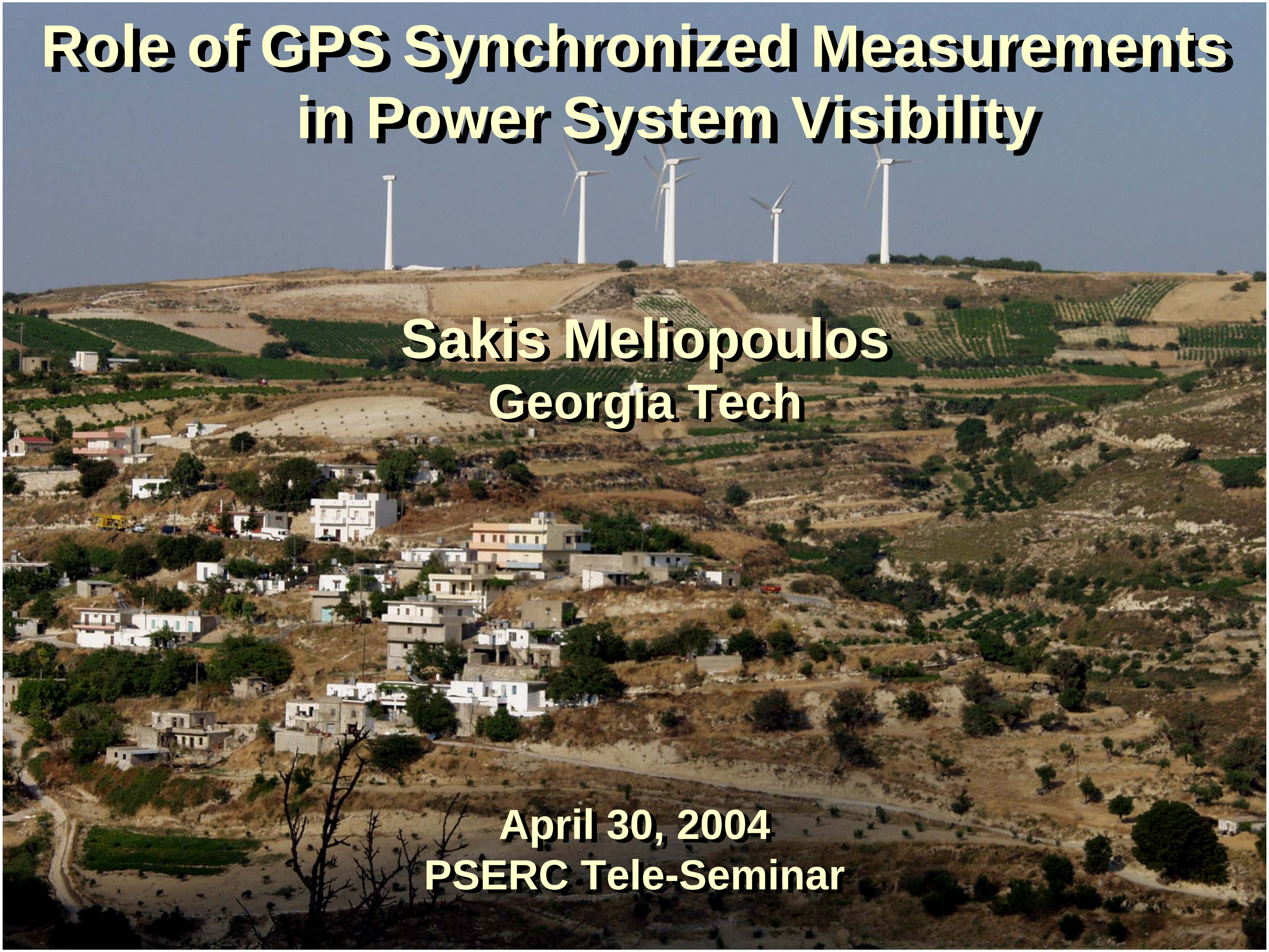


Role of GPS Synchronized Measurements in Power System Visibility

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

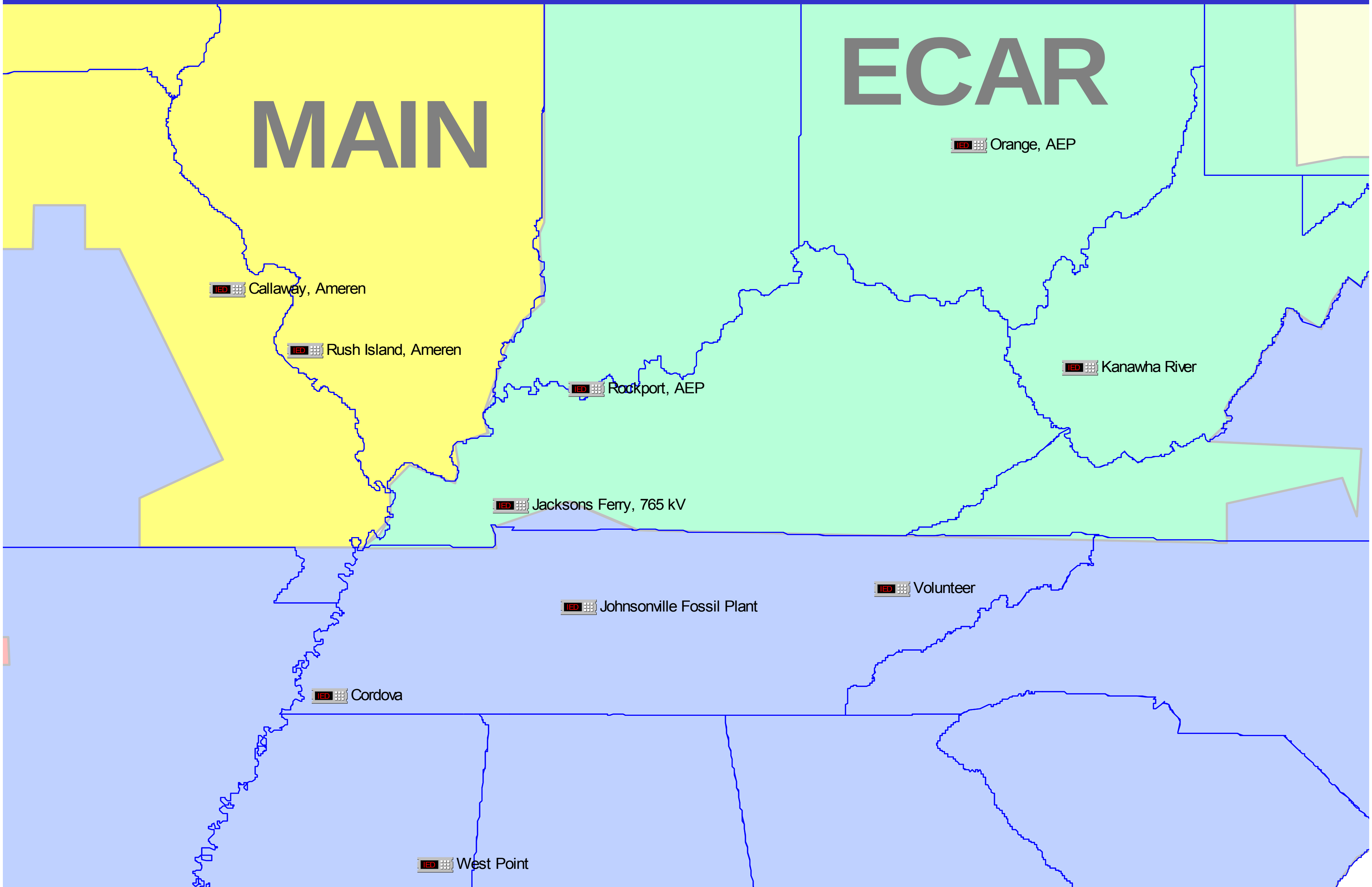
- **New Enhancement:**
  WAAS (Wide Area Augmentation System)
  Performance Much Better

- **Other Enhancements in the Works…**

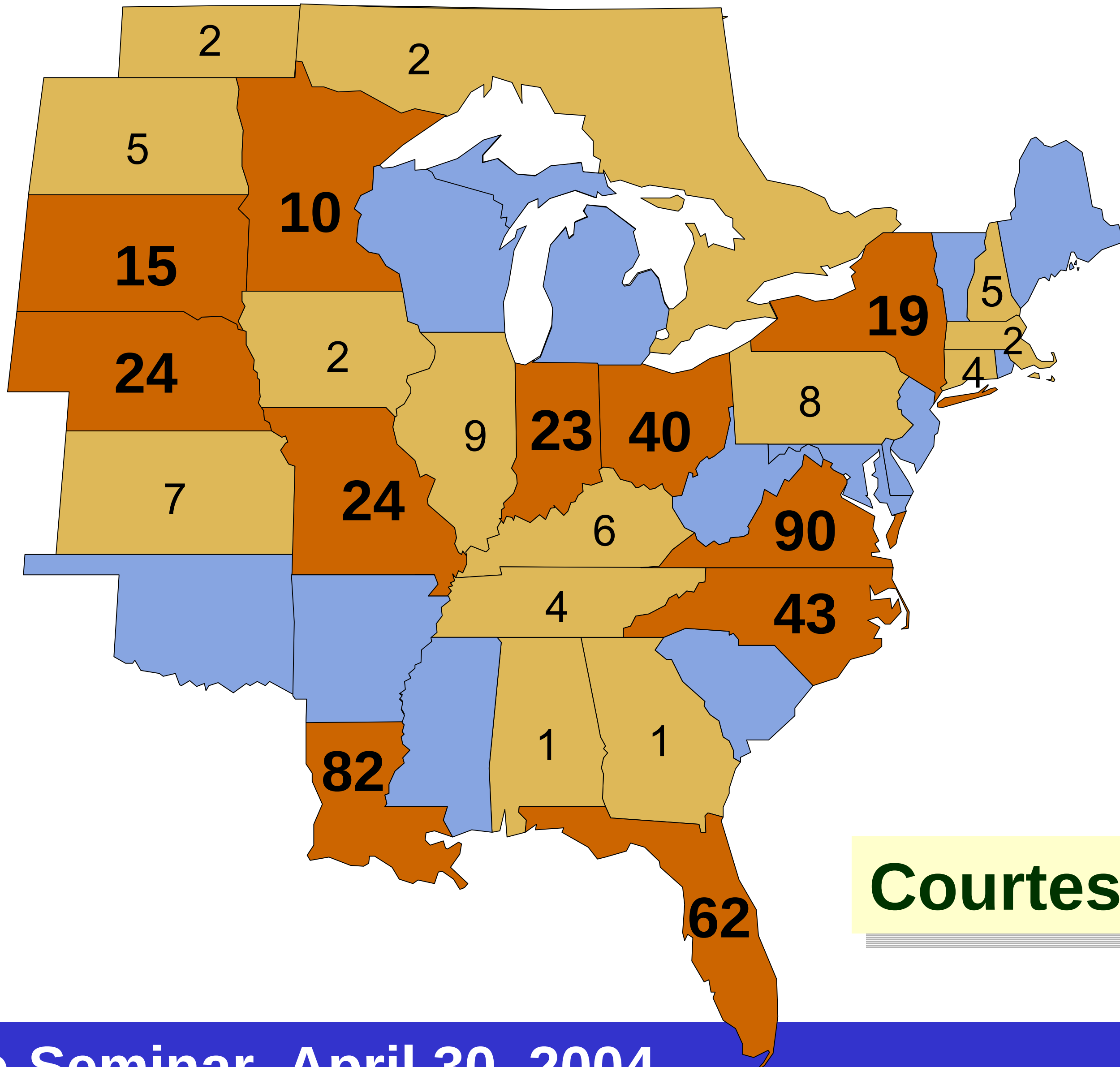
GPS-Synchronized Measurements

- 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



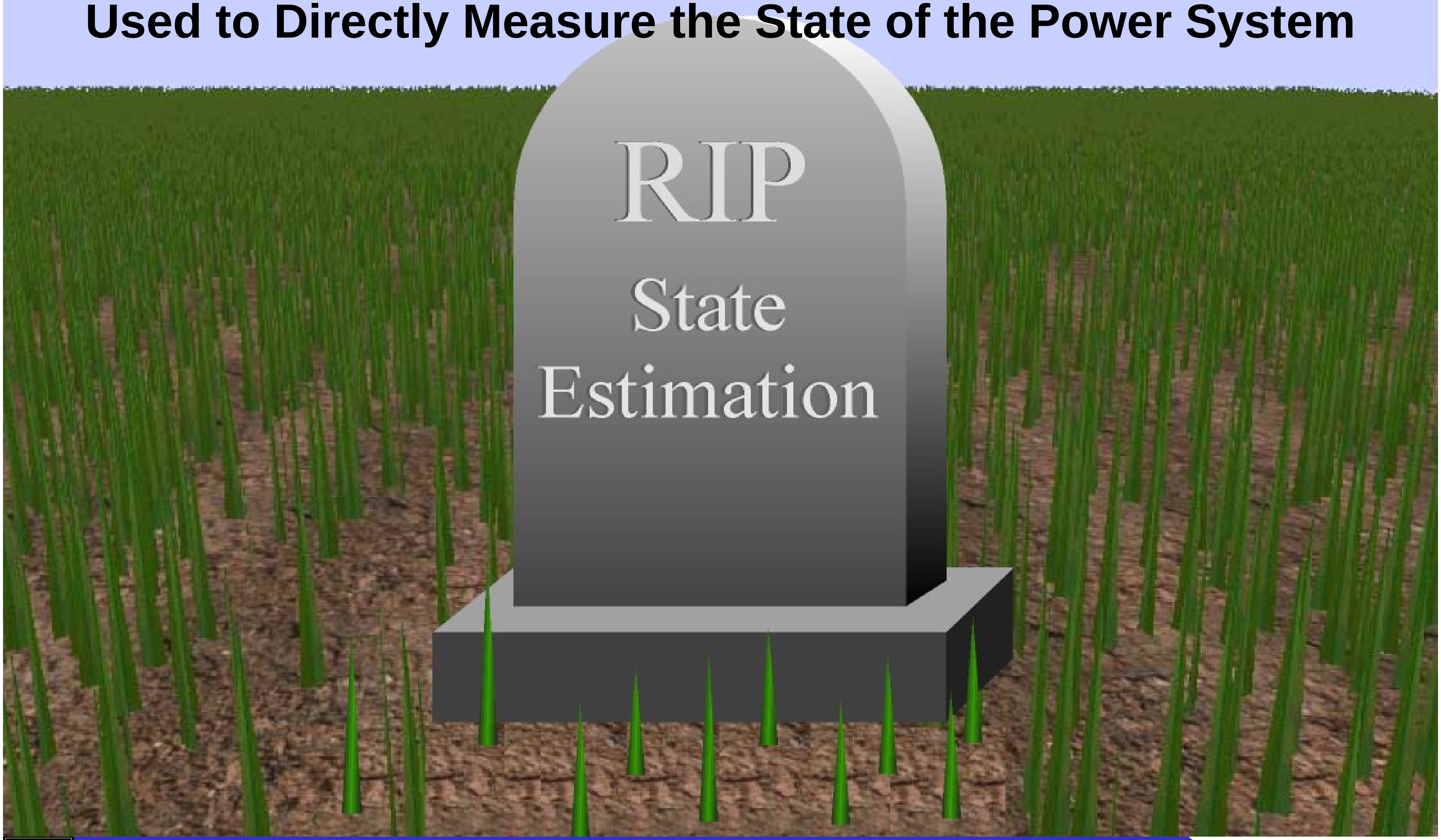
SEL-421 Deployment Eastern USA



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

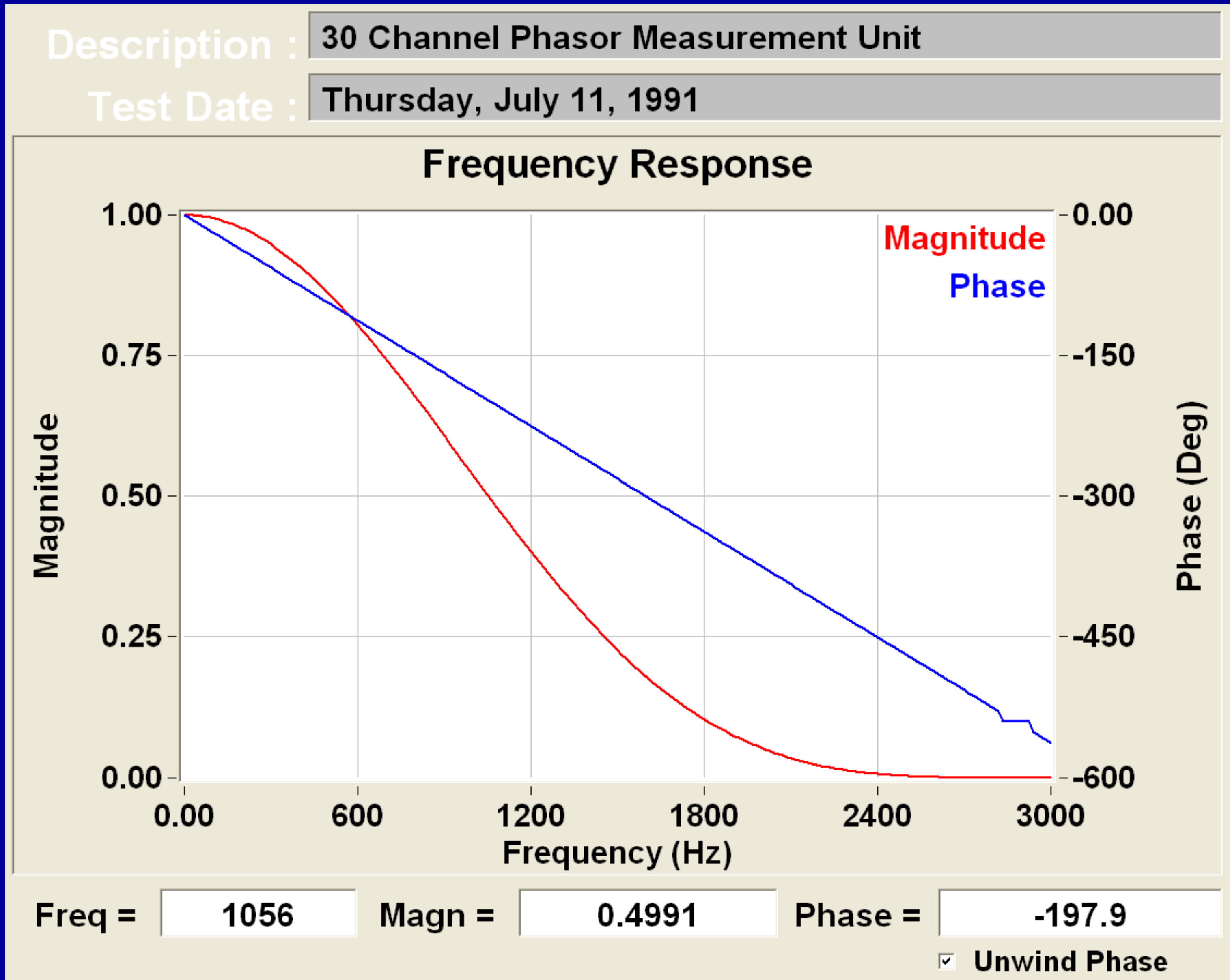
Solution

- Data Filtering via Estimation Methods → Validation

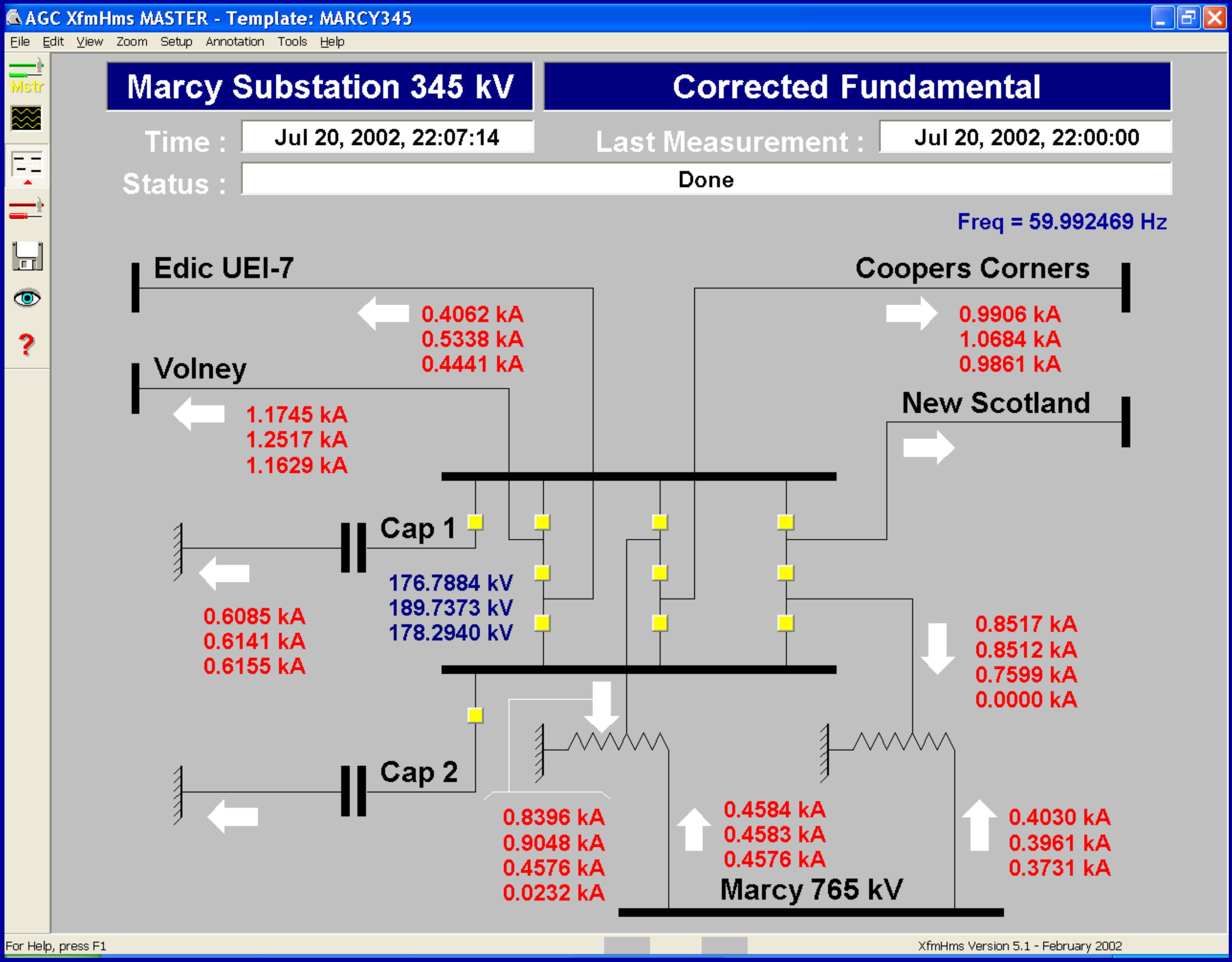
Example Specifications

	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



Errors from Imbalance and Asymmetry

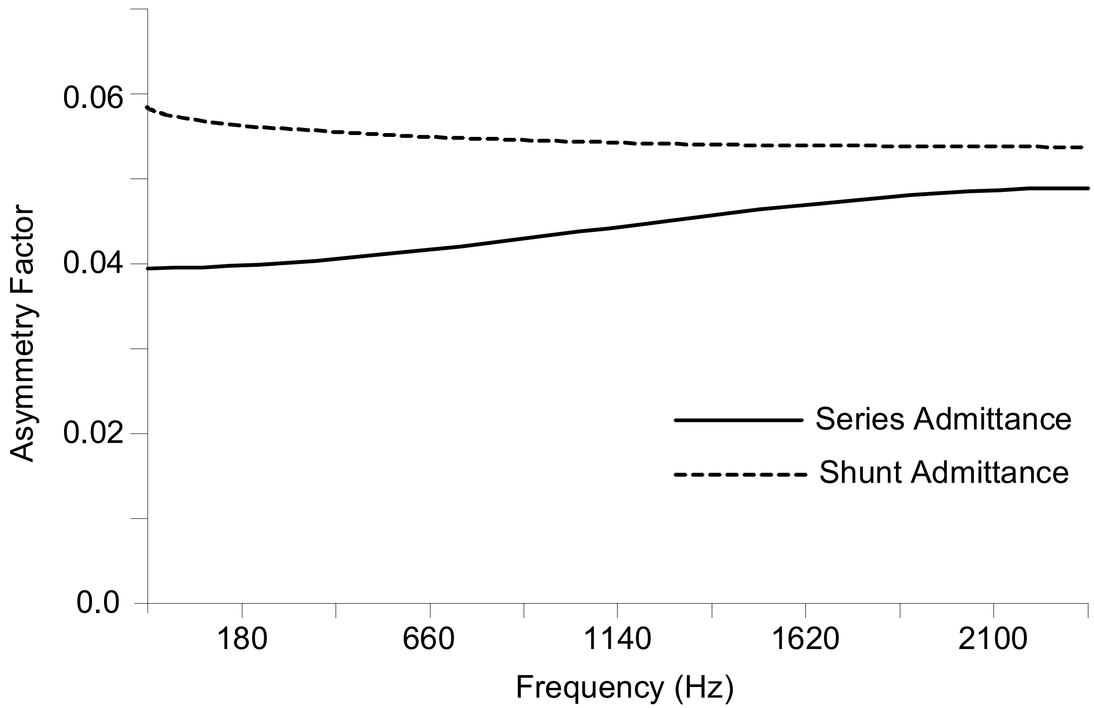


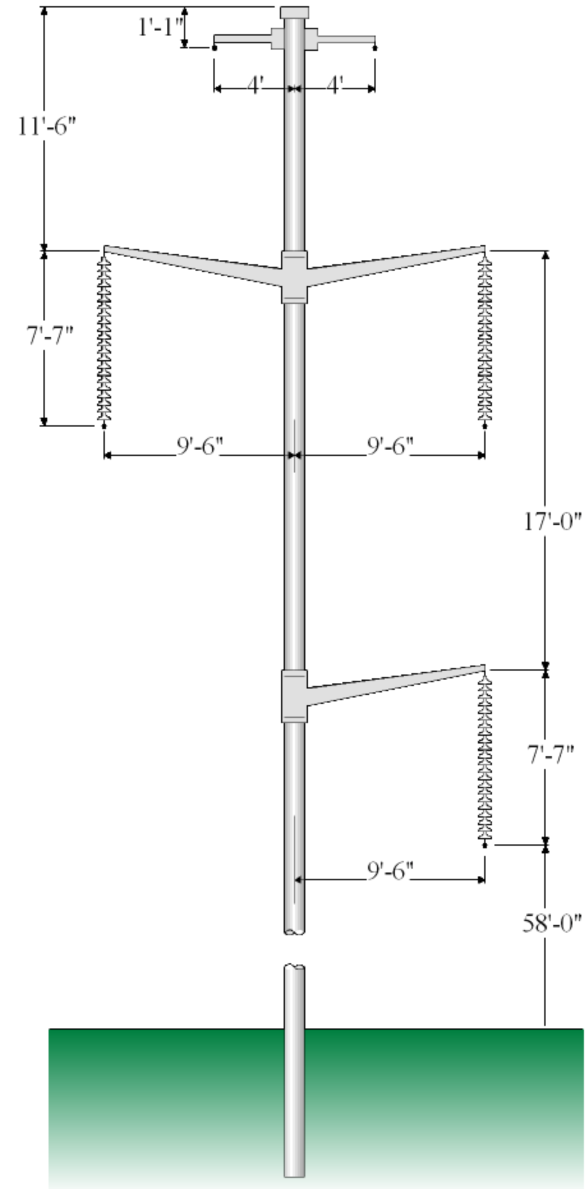
Validity of Power System Symmetry Assumption

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

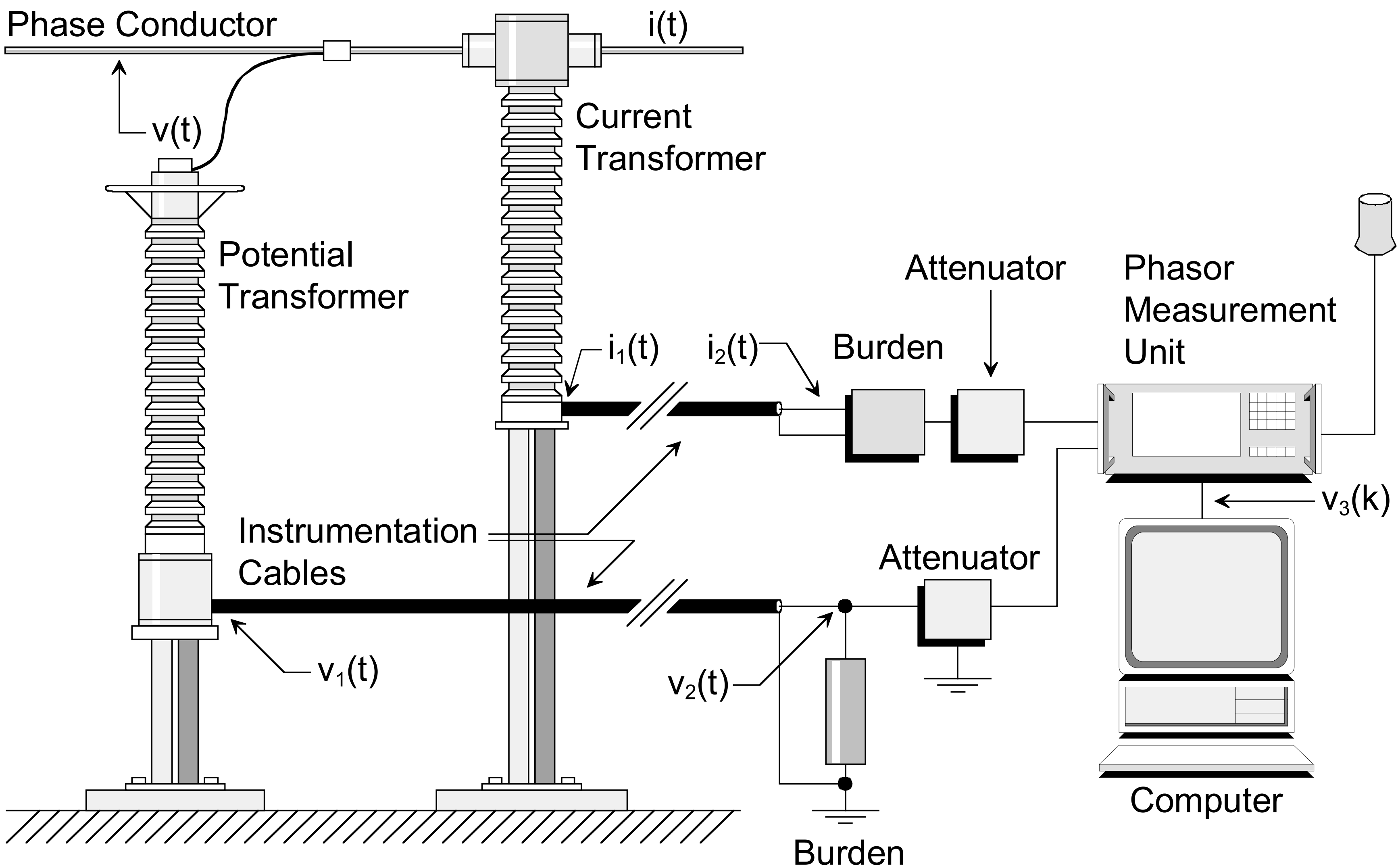
$$S_2 = \frac{1}{2}\frac{|y_{\max} - y_{\min}|}{|y_1|}$$

The Phase Impedances May Vary by 5% Among Phases



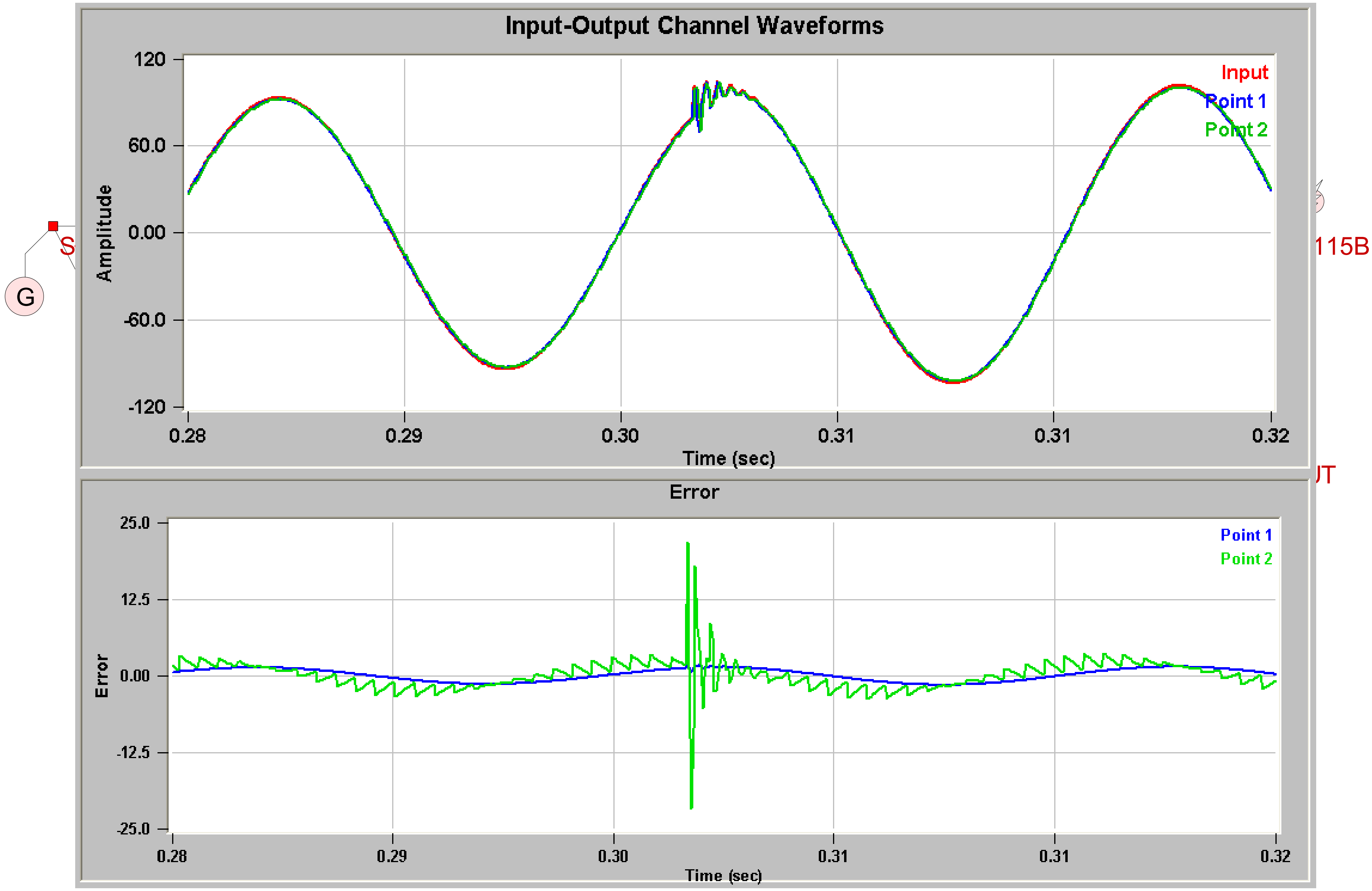


Instrumentation Errors



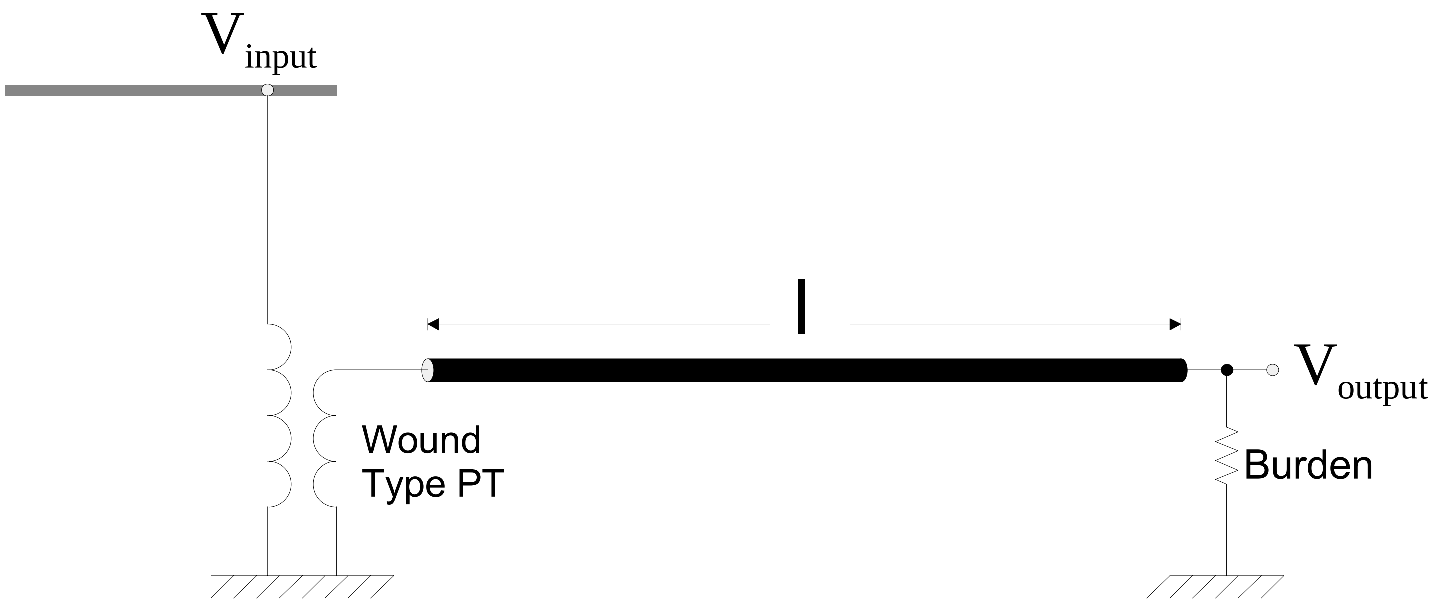
Instrumentation Errors

Voltage Measurement Error During Transients



Instrumentation Errors

Instrumentation Cable Phase Error



Cable Length (l)	Phase (V_{out} / V_{in})
75 m	0.04^0
150 m	0.07^0
225 m	0.11^0
300 m	0.14^0

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

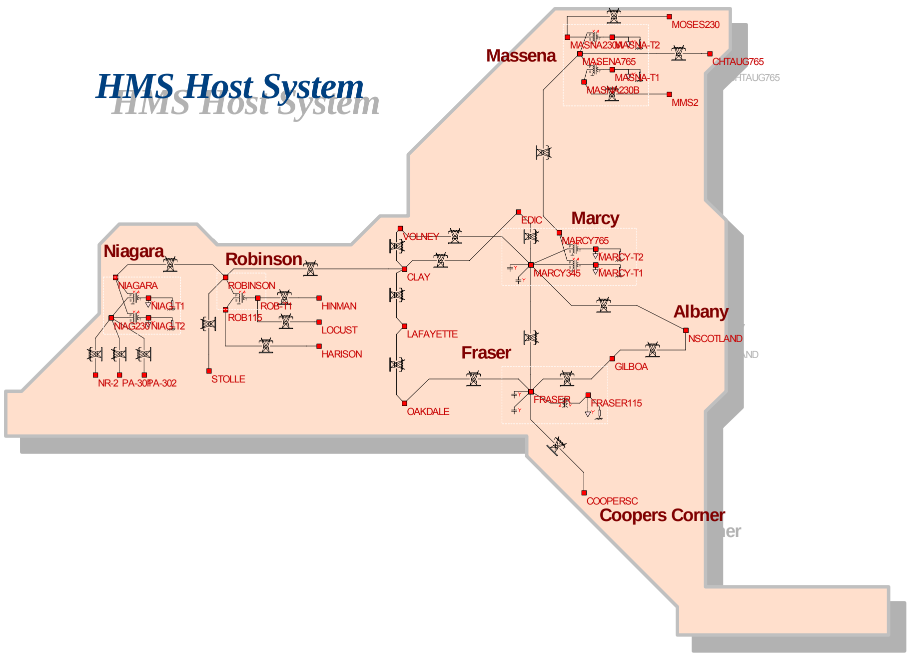
Implications:

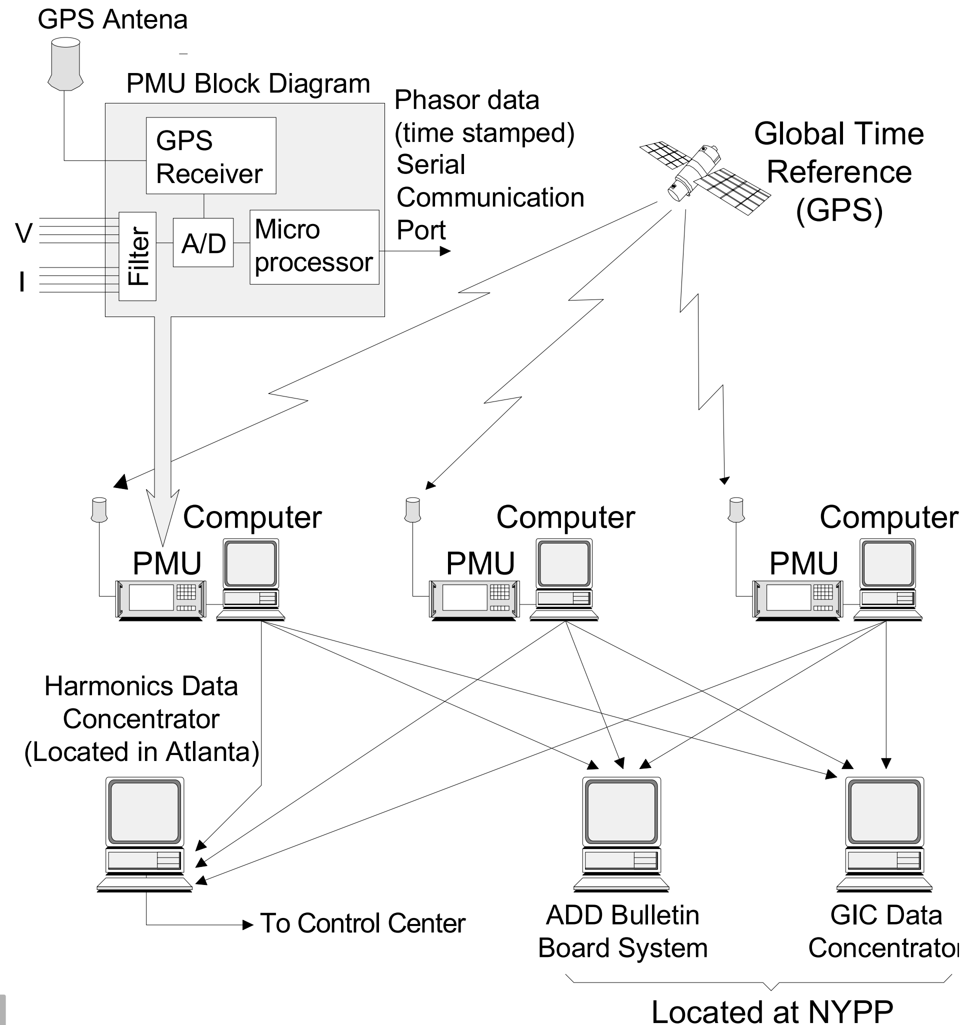
- Balanced Operation
- Symmetric Power System
- Biased SE
- Iterative Algorithm

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

Asymmetric Power System Model

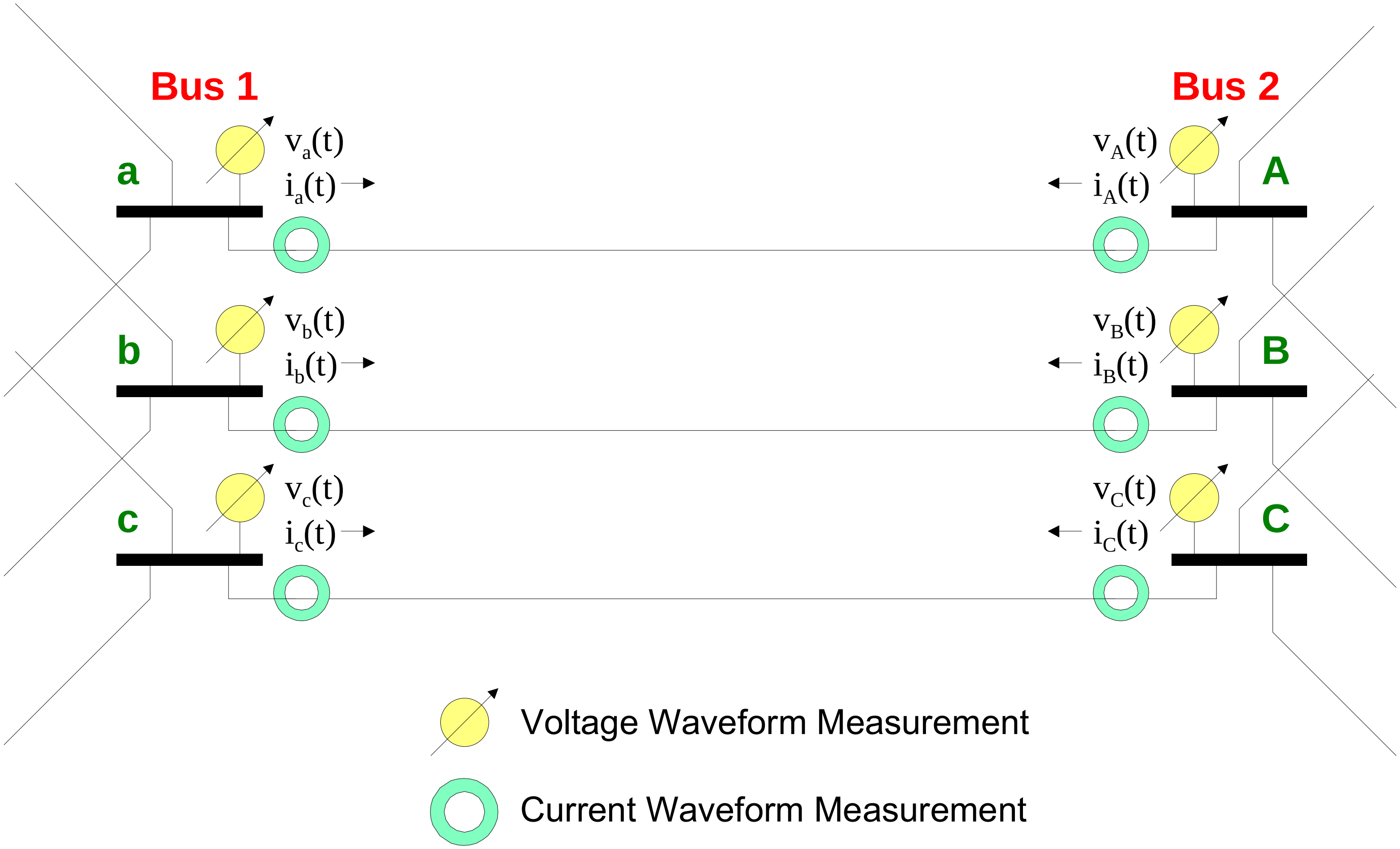
New York Power Authority





Synchronized Measurement Based SE
What is the Advantage

Phasor Measurements of Voltages and Currents



SE with Synchronized Measurements

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

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

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

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

$$r_{imag} = z_{imag} - H_{real} x_{imag} - H_{imag} x_{real}$$

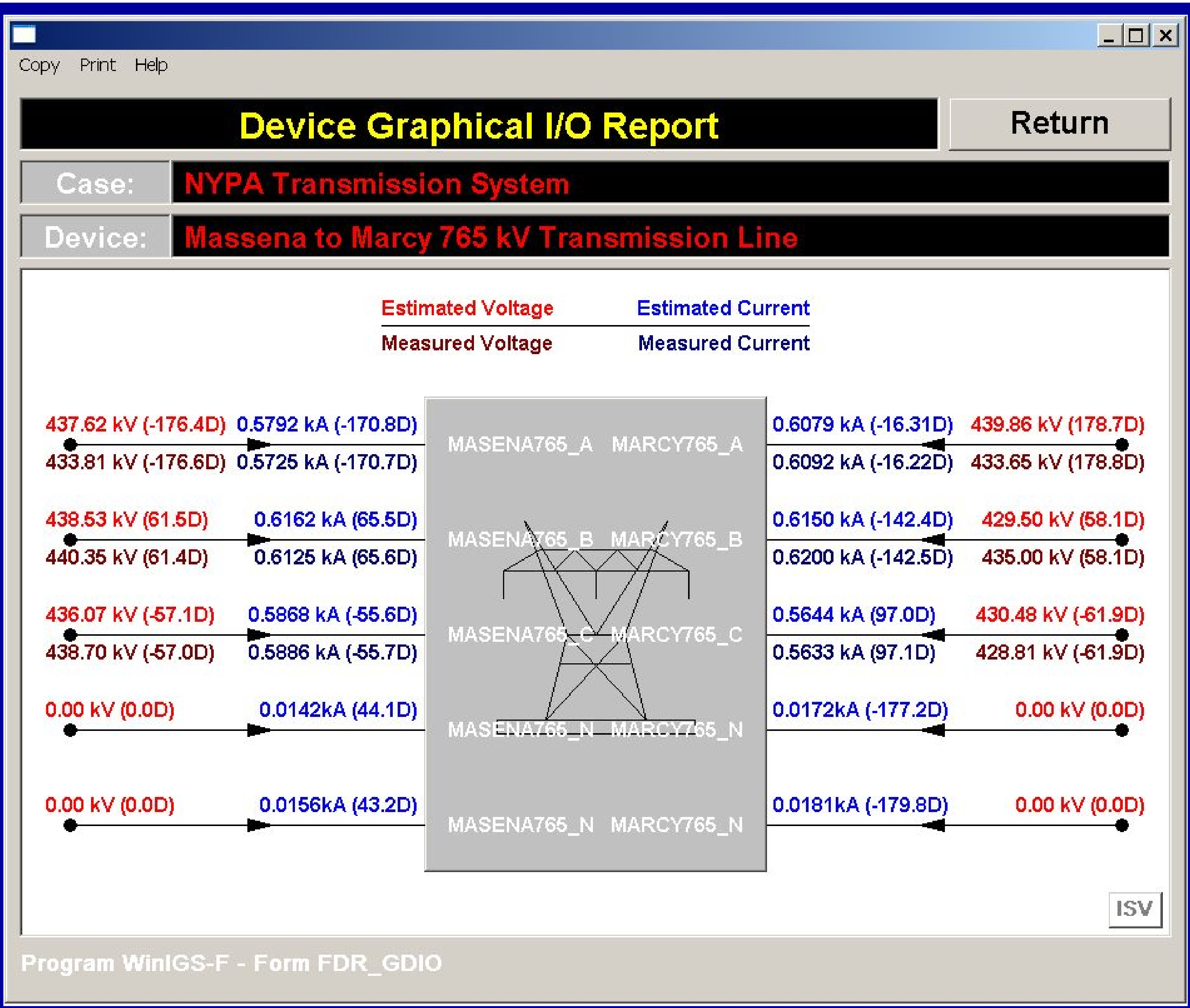
$$\begin{bmatrix} A & B \\ -B & A \end{bmatrix} \begin{bmatrix} x_{real} \\ x_{imag} \end{bmatrix} = \begin{bmatrix} H_{real}^{T} W z_{real} + H_{imag}^{T} W z_{imag} \\ H_{real}^{T} W z_{imag} - H_{imag}^{T} W z_{real} \end{bmatrix}$$

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

Observation

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

Big Advantage


Copy Print Help
Device Graphical I/O Report
Return
Case:
NYPA Transmission System
Device:
Massena to Marcy 765 kV Transmission Line
Estimated Voltage
Measured Voltage
Estimated Current
Measured Current
437.62 kV (-176.4D) 0.5792 kA (-170.8D)
433.81 kV (-176.6D) 0.5725 kA (-170.7D)
MASENA765_A MARCY765_A
0.6079 kA (-16.31D) 439.86 kV (178.7D)
0.6092 kA (-16.22D) 433.65 kV (178.8D)
438.53 kV (61.5D) 0.6162 kA (65.5D)
440.35 kV (61.4D) 0.6125 kA (65.6D)
MASENA765_B MARCY765_B
0.6150 kA (-142.4D) 429.50 kV (58.1D)
0.6200 kA (-142.5D) 435.00 kV (58.1D)
436.07 kV (-57.1D) 0.5868 kA (-55.6D)
438.70 kV (-57.0D) 0.5886 kA (-55.7D)
MASENA765_C MARCY765_C
0.5644 kA (97.0D) 430.48 kV (-61.9D)
0.5633 kA (97.1D) 428.81 kV (-61.9D)
0.00 kV (0.0D) 0.0142kA (44.1D)
MASENA765_N MARCY765_N
0.0172kA (-177.2D) 0.00 kV (0.0D)
0.00 kV (0.0D) 0.0156kA (43.2D)
MASENA765_N MARCY765_N
0.0181kA (-179.8D) 0.00 kV (0.0D)
ISV
Program WinIGS-F - Form FDR_GDIO

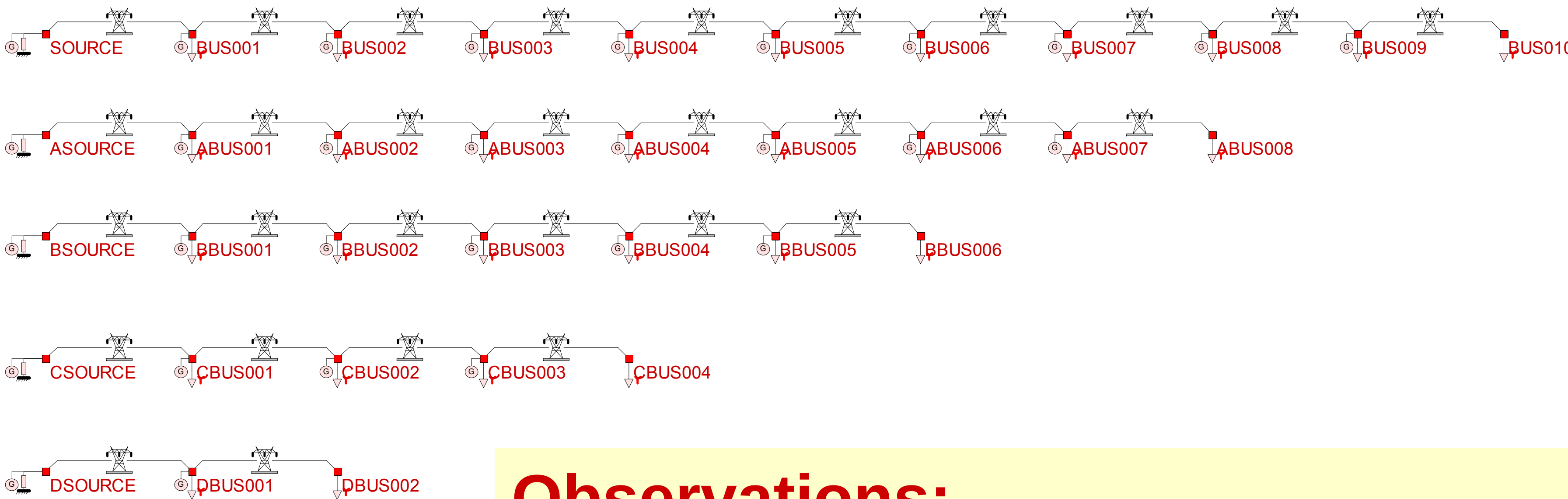
Detection of SE Bias

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



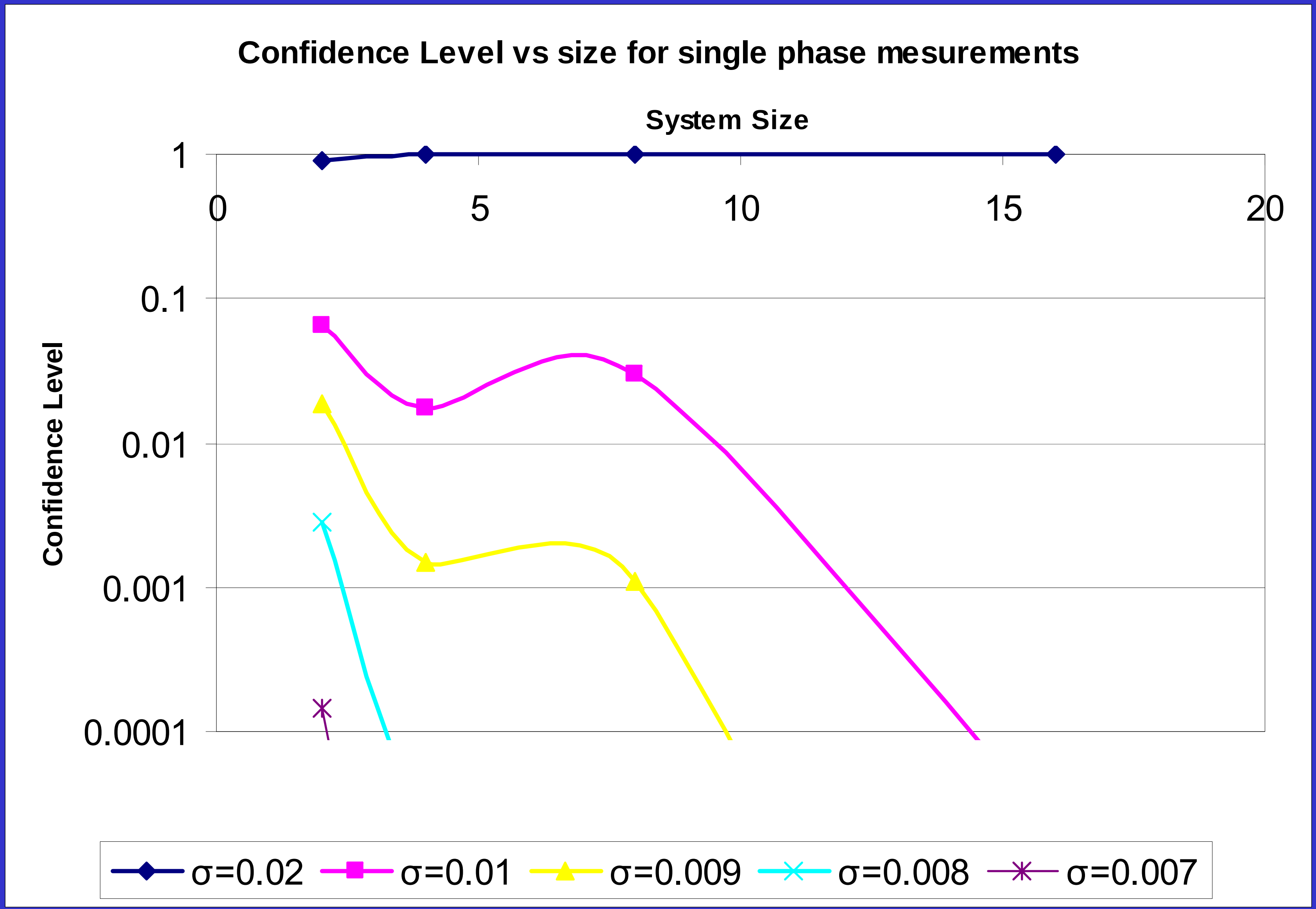
Observations:

System Imbalance Stabilizes

Phase with Max Voltage: Random

Effects on Mega RTO SE: Unknown

Confidence Level of Data Accuracy



Proposed Approach

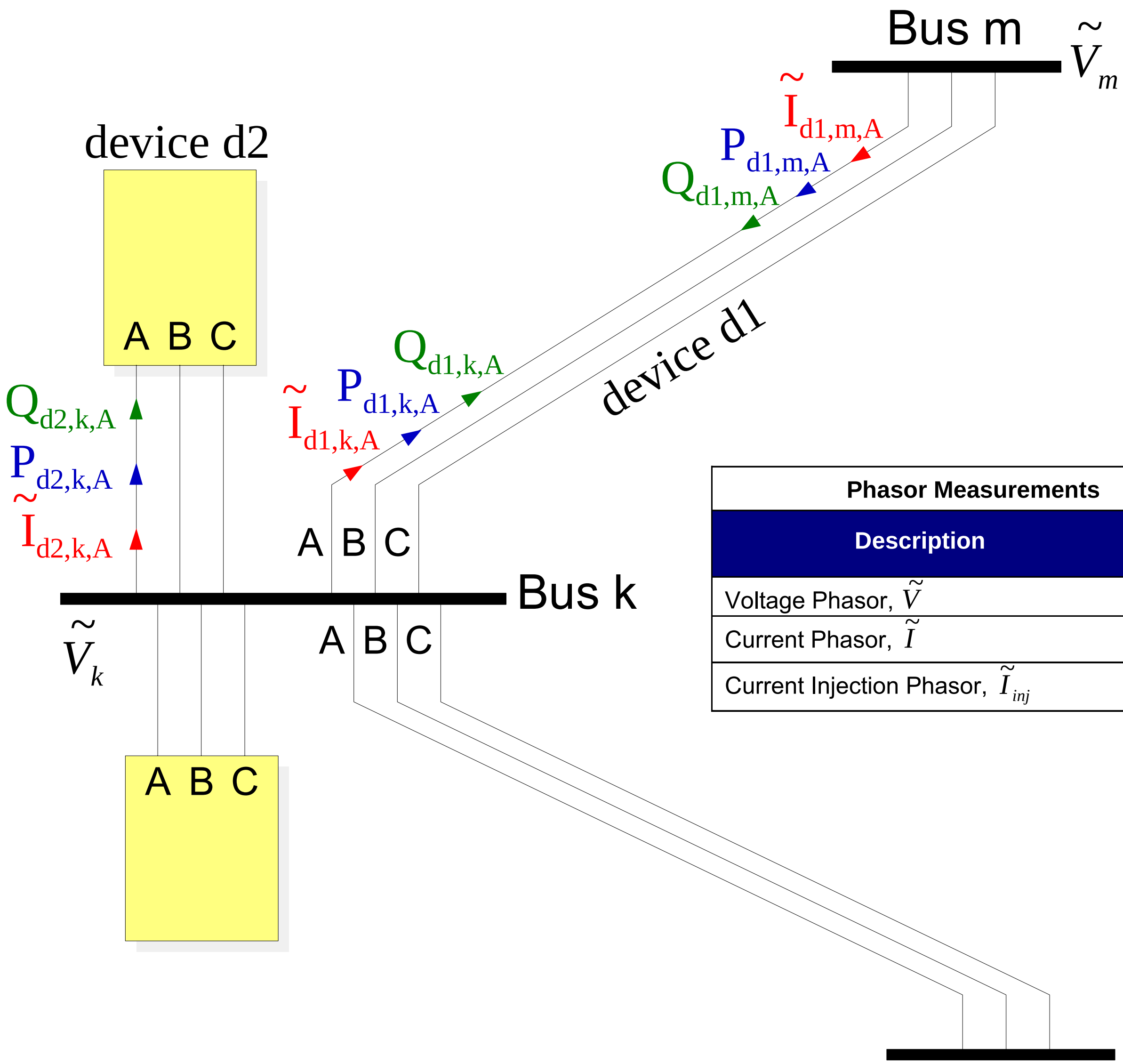
- GPS Synchronized Measurements are Imperfect – Errors are Present
- Other Useful Data Exist (SCADA, Relays, DFRs, etc.).

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

- Errors from Imbalance
- Errors from Asymmetry

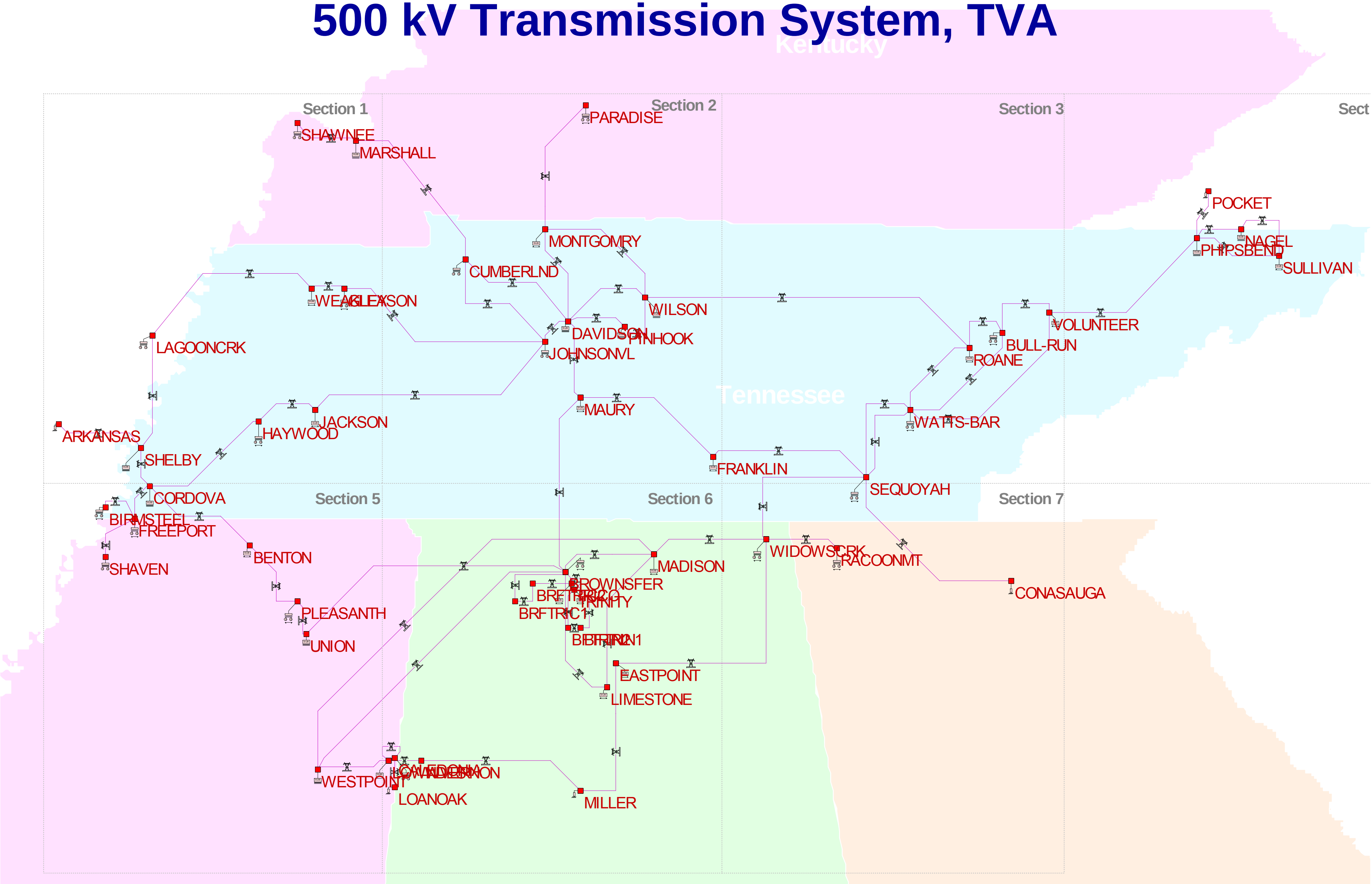
Proposed Approach: THREE PHASE MODEL. It Eliminates Model Biases

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 | Cancel

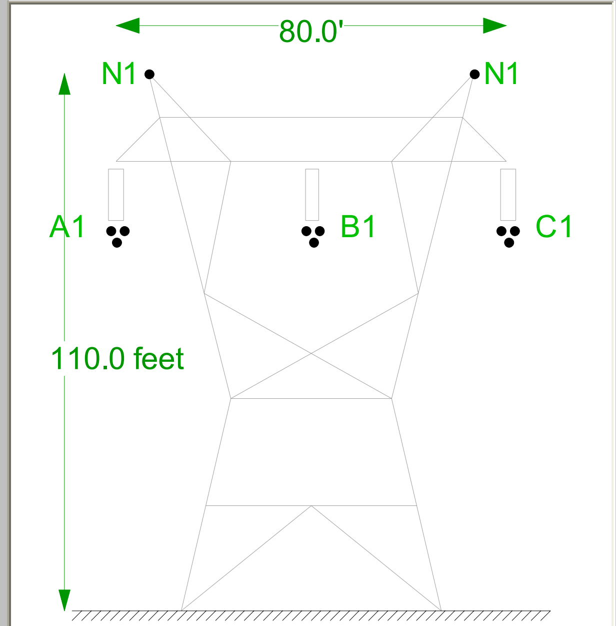
Franklin to Sequoyah 500 kV Line

Phase Conductors	Type	ACSR
	Size	RAIL
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



SINGLE TOWER 500 KV

Bus Name, Side 1	Circuit Number	Bus Name, Side 2
FRANKLIN	1	SEQUOYAH

Operating Voltage (kV)	500.0
Structure Name	N/A

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

$$Min \quad J = \sum_{\nu \in phasor} \frac{\tilde{\eta}_\nu^* \tilde{\eta}_\nu}{\sigma_\nu^2} + \sum_{\nu \in non-syn} \frac{\eta_\nu \eta_\nu}{\sigma_\nu^2}$$

GPS-Synchronized Measurements (Linear Model)

Voltage Phasor

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

Current Phasor

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

Non-Synchronized Measurements (Quadratic Model)

Voltage Magnitude

$$z_\nu = \left| \tilde{V}_{k,A} - \tilde{V}_{k,N} \right|^2 + 2\eta_\nu =$$

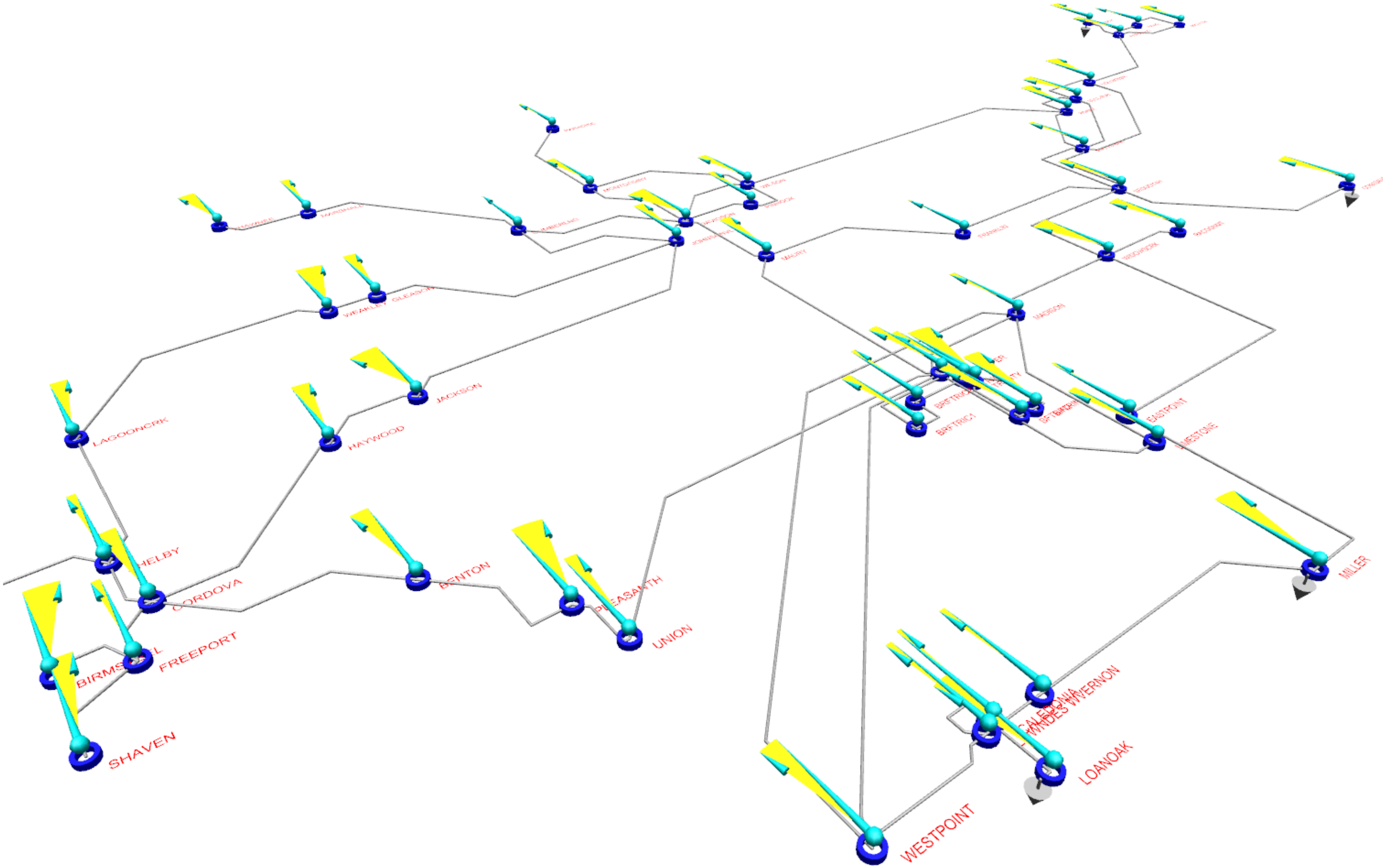
$$= \left(V_{k,A,r} - V_{k,N,r}\right)^2 + \left(V_{k,A,i} - V_{k,N,i}\right)^2 + 2\eta_\nu$$

Real Power

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

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

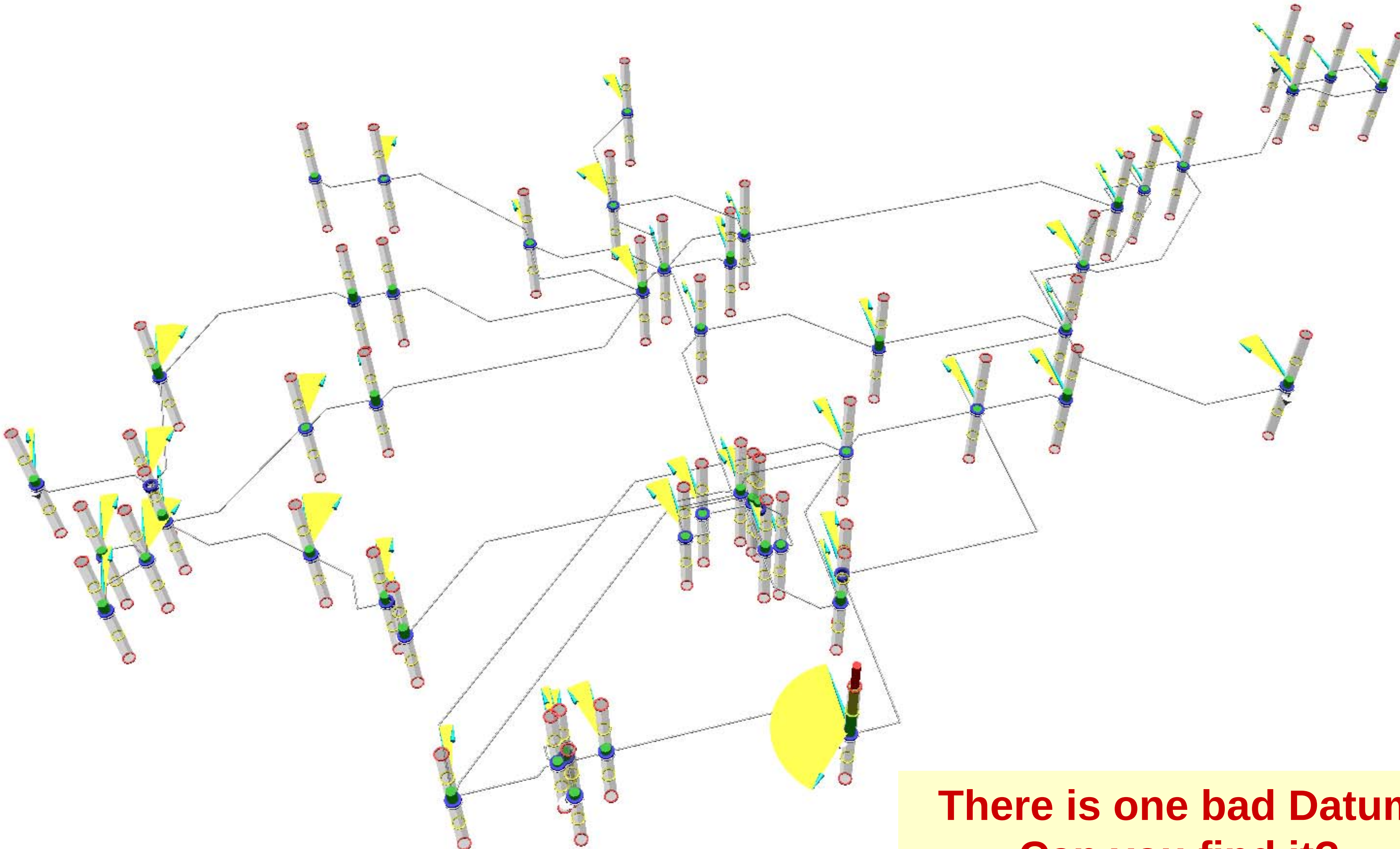
(b) Improved Bad Data Identification Process.

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)

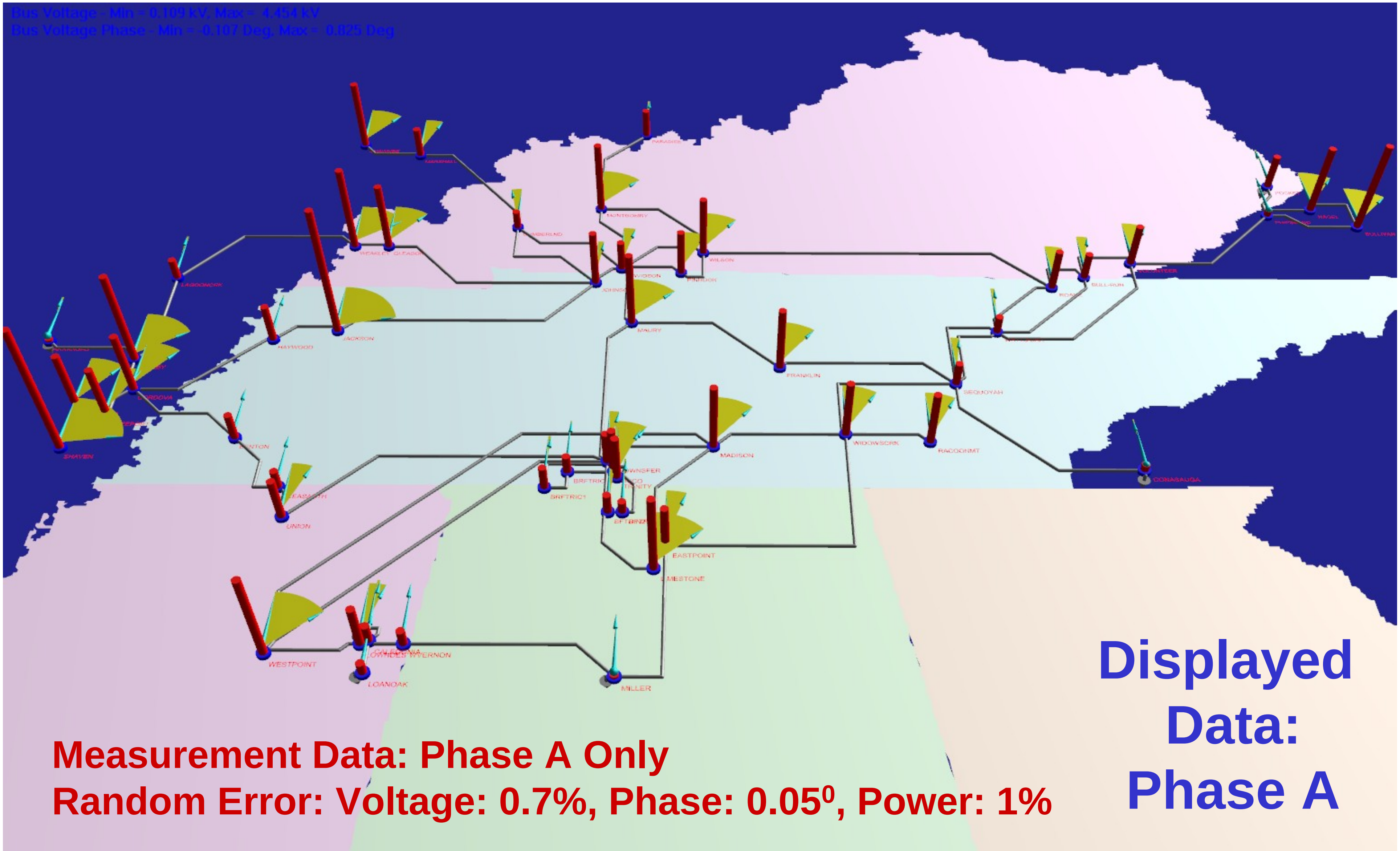


There is one bad Datum
Can you find it?

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

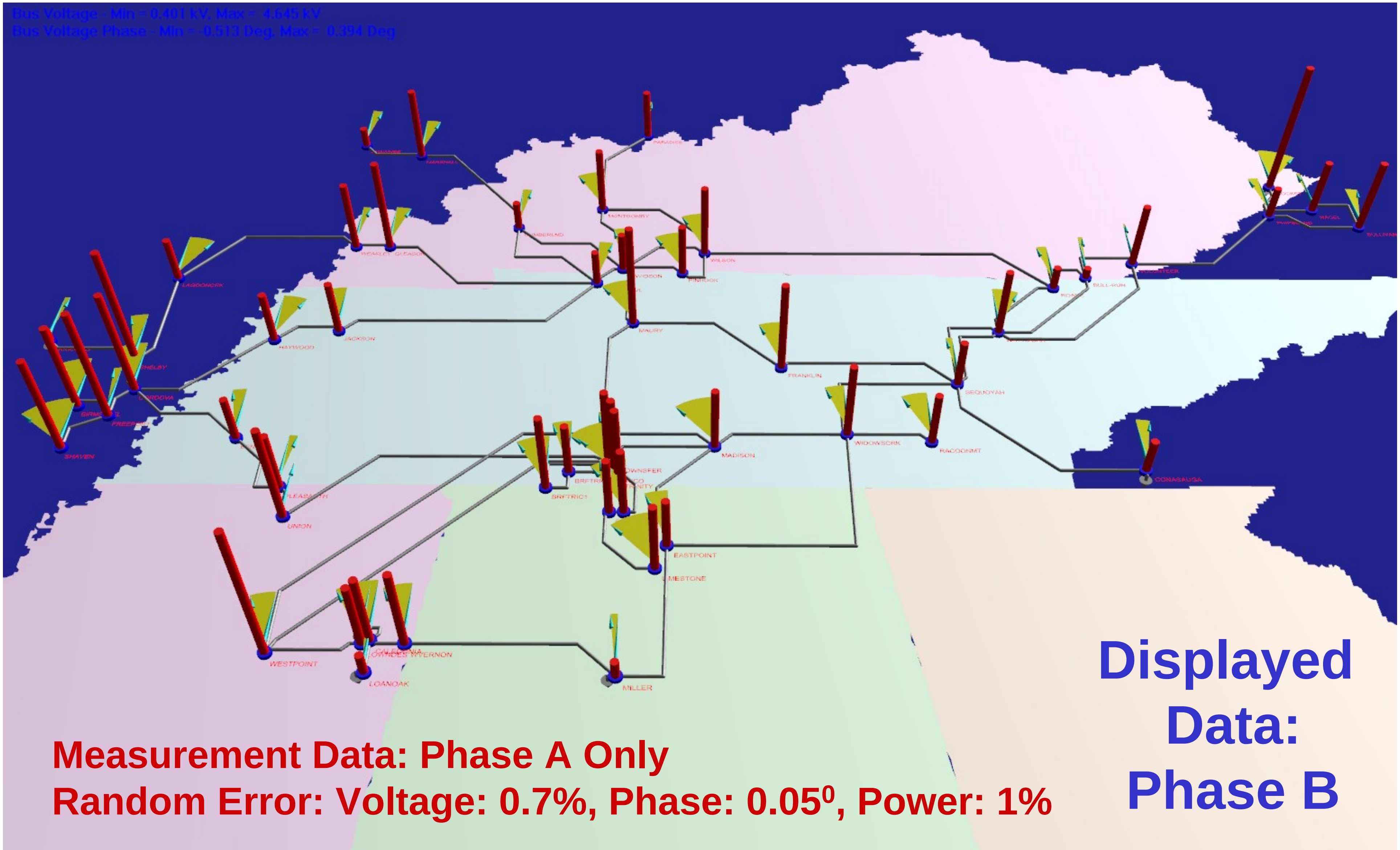
Magnitude Error Range: 0.1 to 4.4kV – Phase Error Range: -0.1 to 0.8 Degrees

(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)



Measurement Data: Phase A Only

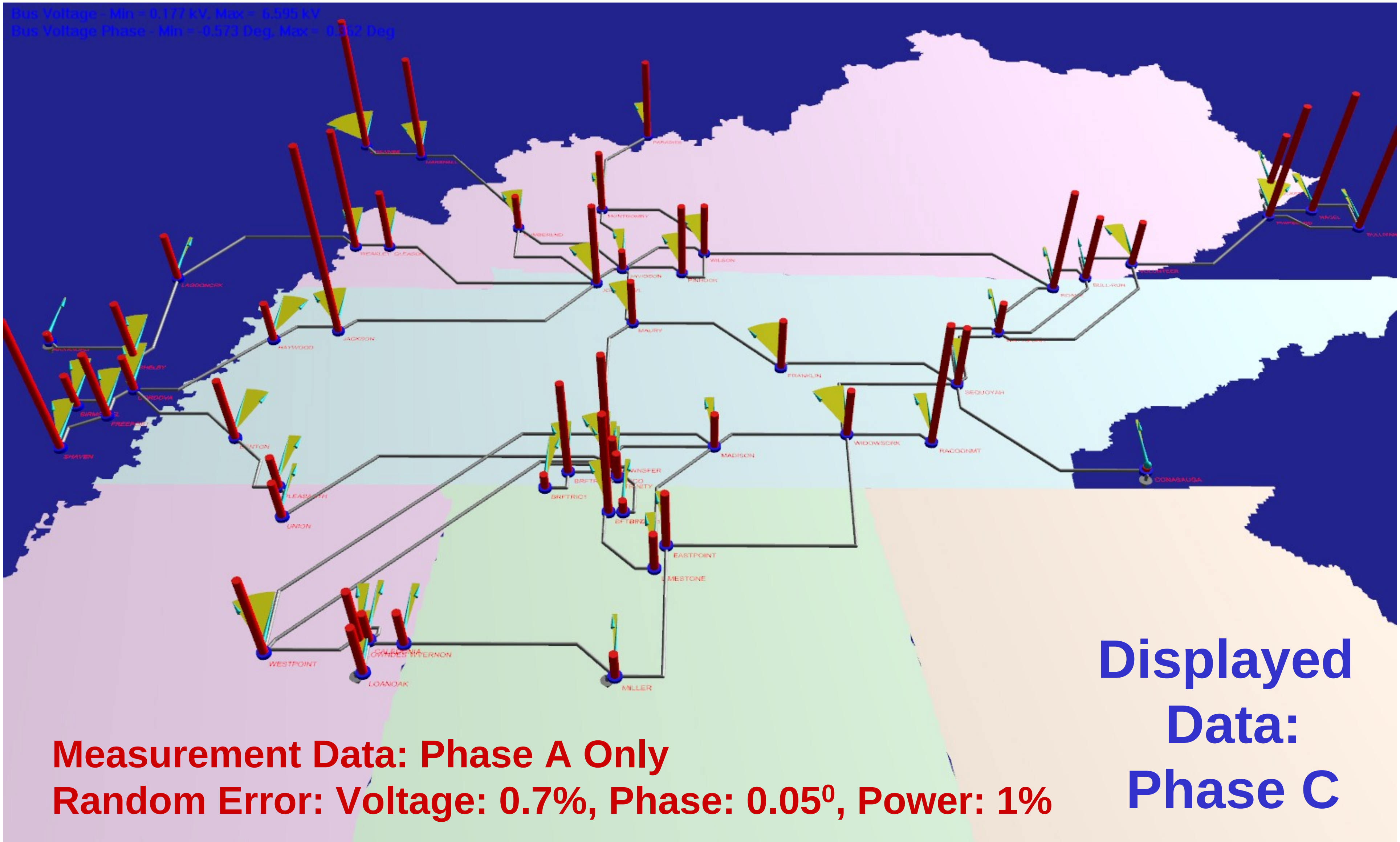
Random Error: Voltage: 0.7%, Phase: 0.05^{0}, Power: 1%

Displayed Data: Phase B

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)



Measurement Data: Phase A Only

Random Error: Voltage: 0.7%, Phase: 0.05^0, Power: 1%

Displayed Data: Phase C

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