

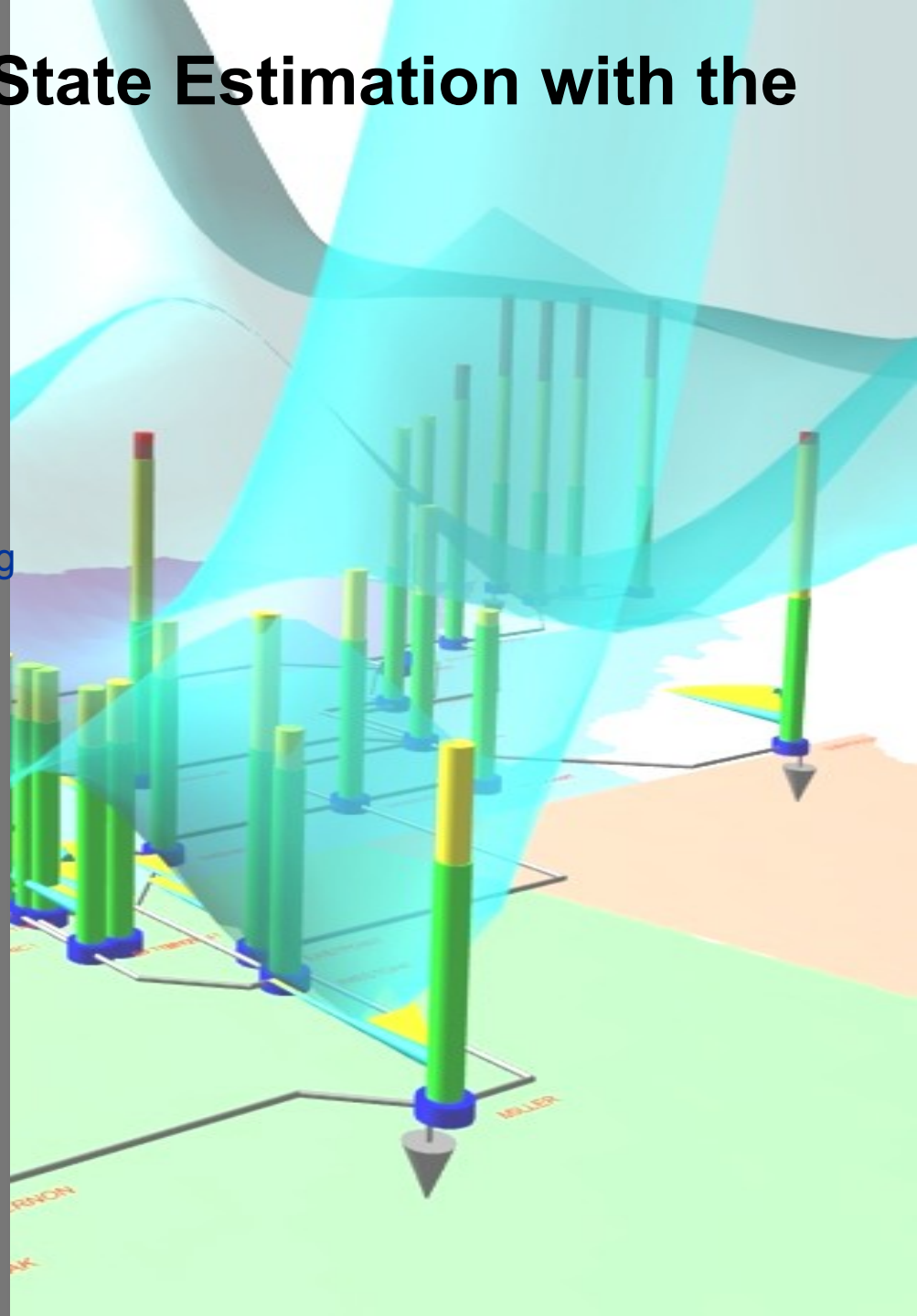
# PMU-Based Distributed State Estimation with the SuperCalibrator

PSERC Seminar

June 17, 2008

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School of Electrical and Computer Engineering  
Georgia Institute of Technology



# Presentation Outline

The Need for State Estimation

Evolution of State Estimation Technology

GPS Synchronized Measurement Technology

The SuperCalibrator Approach

Implementation and Demonstration (VIWAPA,  
May 5-6, 2008)

Future Directions



# The Need for State Estimation

## 1965 Blackout

Edward Teller (member blue ribbon committee) compared the electric power system with a dinosaur: Big Body – Small Brain, reflecting on the fact that at the time the communications infrastructure and information transmittal was in its infancy.



# Development of the State Estimator – ca 1968

## Basic Assumptions:

- Positive Sequence Model
- P, Q, V Measurement set
- Near-Simultaneous Measurements
- Single Frequency



## Implications:

- Balanced Operation
- Symmetric Power System
- Biased State Estimator
- Iterative Algorithm

## Hardware:

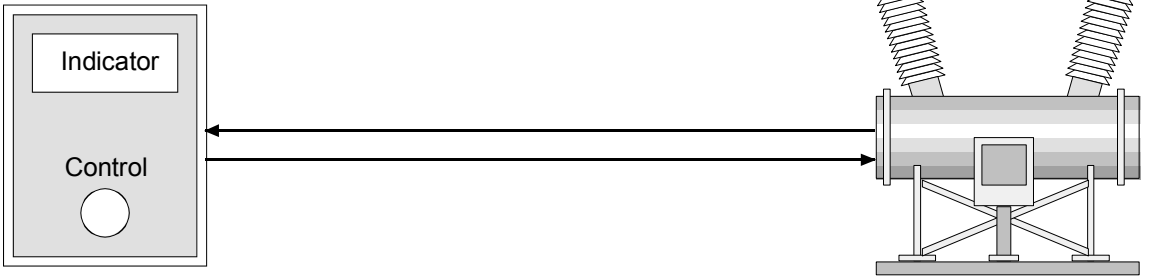
- Sensors for P, Q and V
- Accuracy: 1 to 3%
- Communications – mostly dedicated
- → SCADA



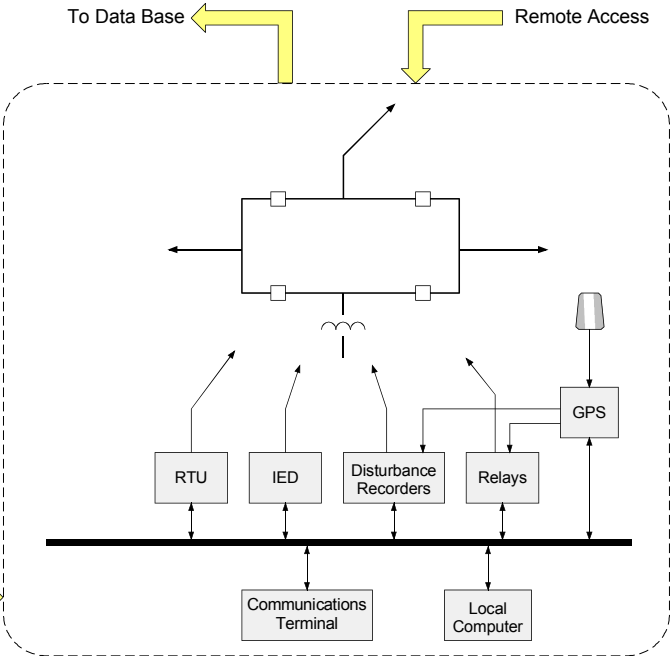
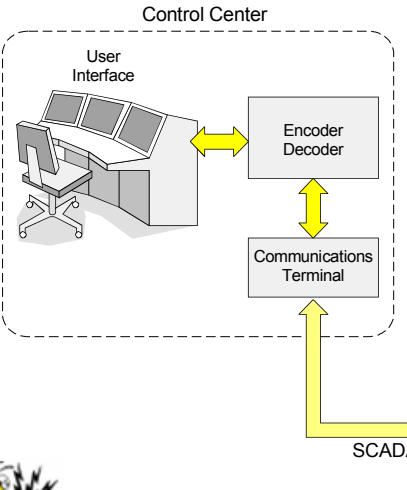
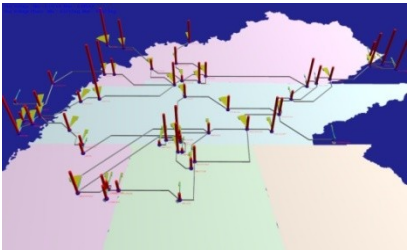
# Evolution of Supervisory Control – State Estimation in Power Systems



# SCADA Evolution



SCADA circa 1923



SCADA circa 2003



# Forward to August 2003

From  
US-Canada Power System Outage Task Force

## Contributing Factors

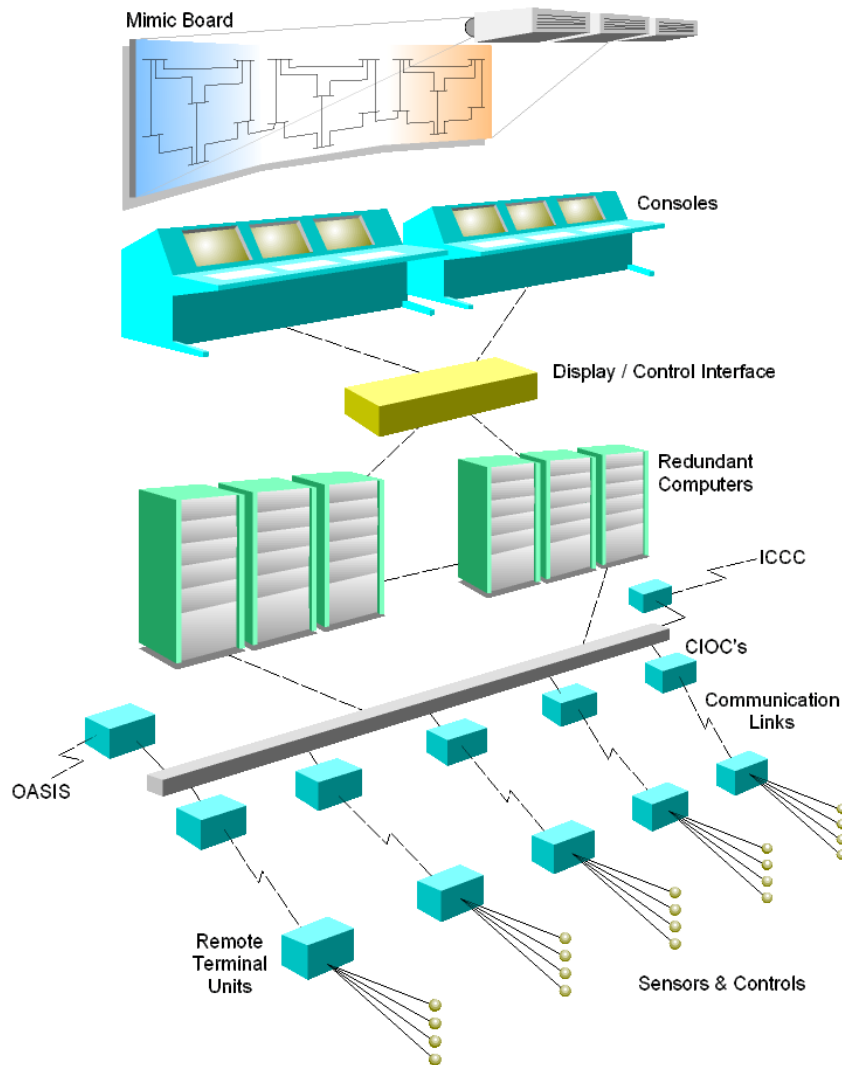
Inadequate Situational Awareness

## Recommendation 22

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



# Present Operating Model



## Real Time Model

State Estimation

## Applications

Load Forecasting

Optimization (ED, OPF)

VAR Control

Available Transfer capability

Security Assessment

Congestion management

Dynamic Line Rating

Transient Stability

EM Transients, etc.

Visualizations

## Markets:

Day Ahead, Power Balance,  
Spot Pricing, Transmission Pricing  
(FTR, FGR), Ancillary Services



# Two Major Issues

(a) Data Reliability/Accuracy and (b) Automation

Basic Tools for Grid Visibility:

**SCADA** (unfiltered) and **SE** (filtered)

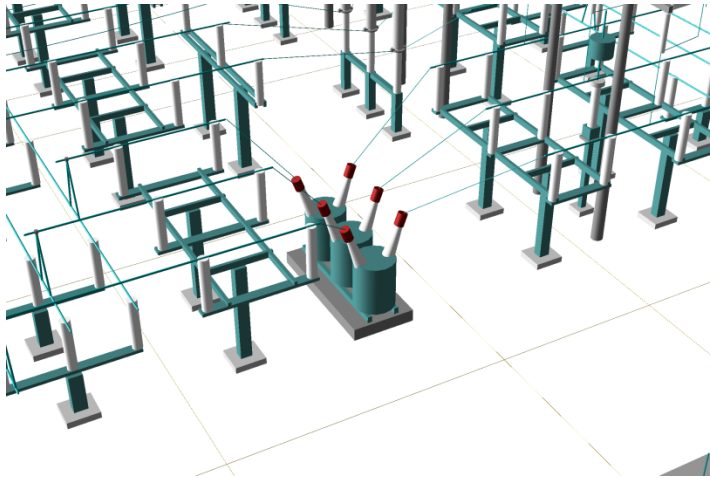
The objective of **SE** is to provide a **reliable real time model**

**How Well is it Done, What is the Accuracy**

Can We Make All Information Available to All  
Constituent Part of the Electric Grid Enterprise?  
(The Promise of Automation)

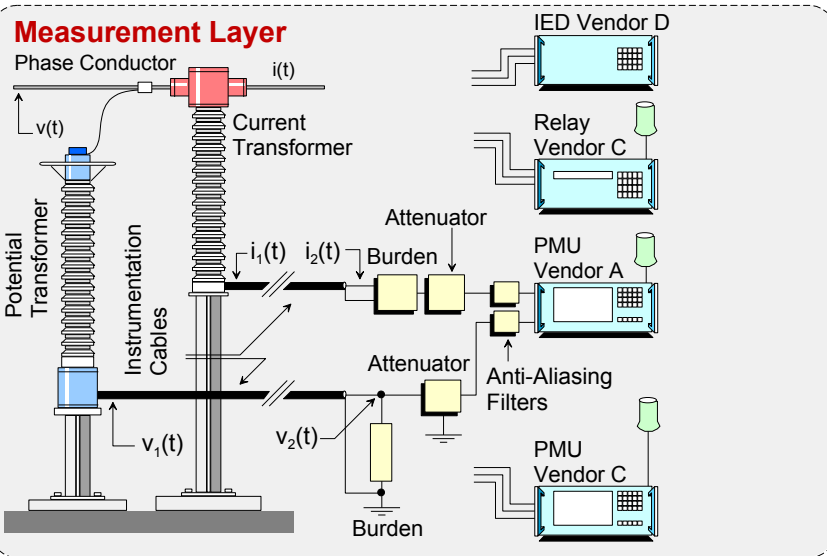


# Present State of the Art



- (a) SCADA Transducers: 1 to 3%
- (b) Modern Relays: 0.1 to 1%
- (c) GPS-Synchronized Equipment:  
Magnitude 0.1% to 1%, Phase: 0.01 to 0.05 Degrees at 60 Hz.  
(Systematic Errors Can Be Easily Accounted for)

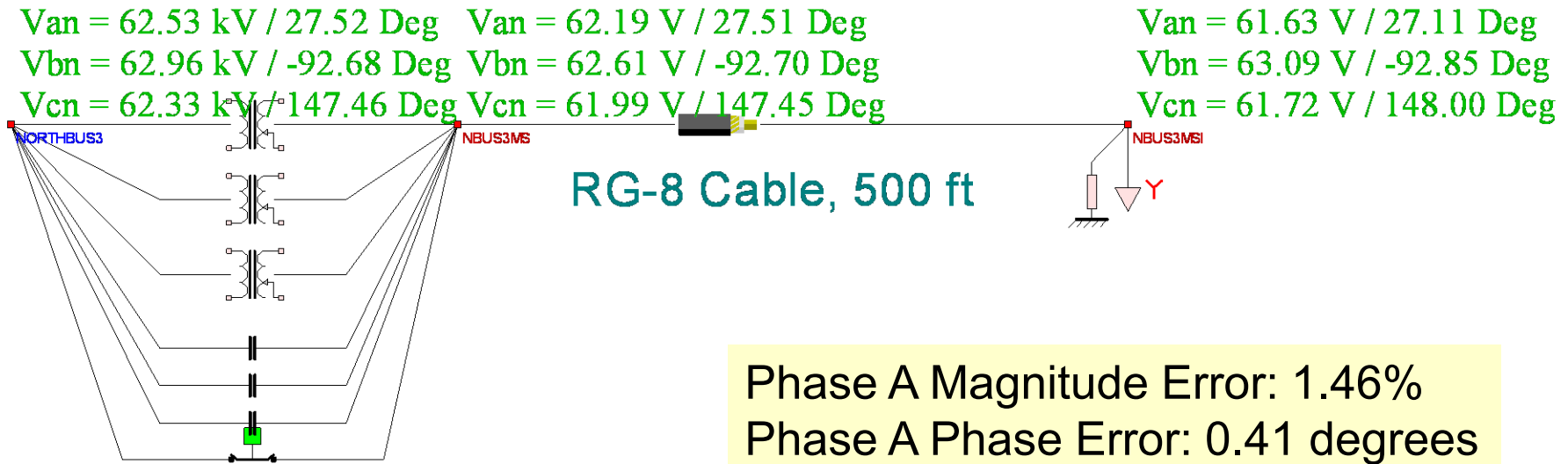
- (b) System Asymmetries (4 to 6% differences among phases)
- (c) System Imbalance (0 to 12% among phases – based on personal observations)
- (d) Instrumentation Channel Errors (0.02 to 3%)



# Instrumentation Errors:

## Voltage Measurement Example

### Voltage Measurement IC Substation A, 115 kV Bus



69kV:69V Wound Type VT



# Why Do We Need High Accuracy?

If we consider a 50 mile long 230 kV line, rated 400 MVA and evaluate the required accuracy in voltage magnitude and phase angle measurements to achieve a 1% accuracy in power flow then we have the following pairs:

Voltage Magnitude: 0.5%, Phase Angle: 0 degrees

Voltage magnitude: 0.4%, Phase Angle: 0.03 degrees

Voltage magnitude: 0.3%, Phase Angle: 0.05 degrees

Voltage magnitude: 0.2%, Phase Angle: 0.09 degrees

**Use of raw data for various monitoring, prediction and control may lead to large errors**



# Traditional State Estimator

## Basic Assumptions:

- Positive Sequence Model
- P, Q, V Measurement set
- Near-Simultaneous Measurements
- Single Frequency



## Implications:

- Balanced Operation
- Symmetric Power System
- Biased State Estimator
- Iterative Algorithm

## Sources of Error:

- GPS-Synchronized Equipment: Magnitude 0.1% to 1%, Phase: 0.01 to 0.05 Degrees at 60 Hz
- SCADA: 1 to 3%
- System Asymmetries (4-6% differences among phases)
- System Imbalance (0-12% among phases)
- Instrumentation Channel Errors (0.02-3%)



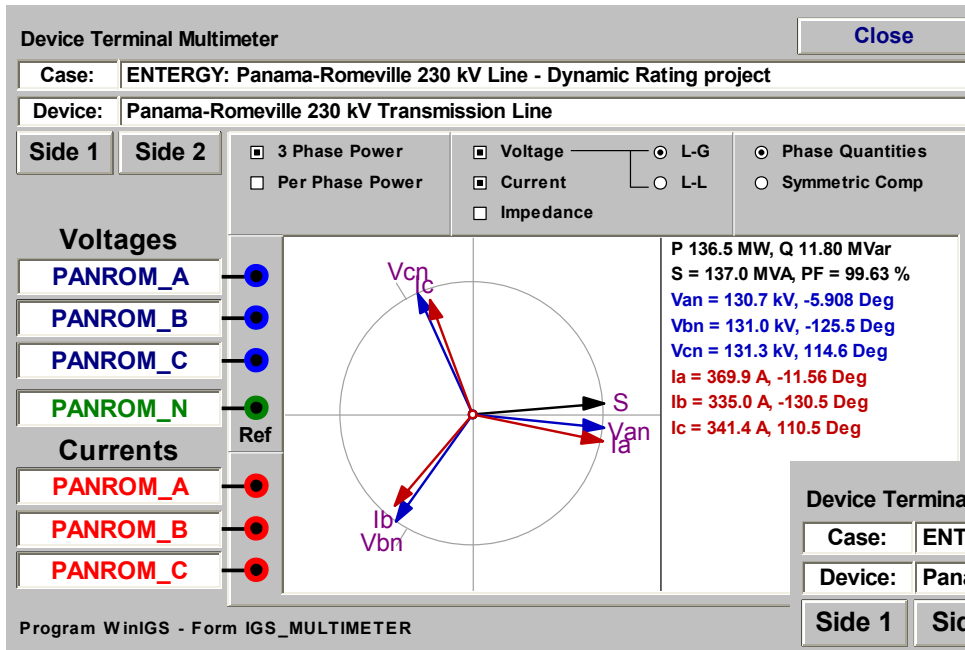
## Time Response:

- Centralized State Estimator Response (minutes)



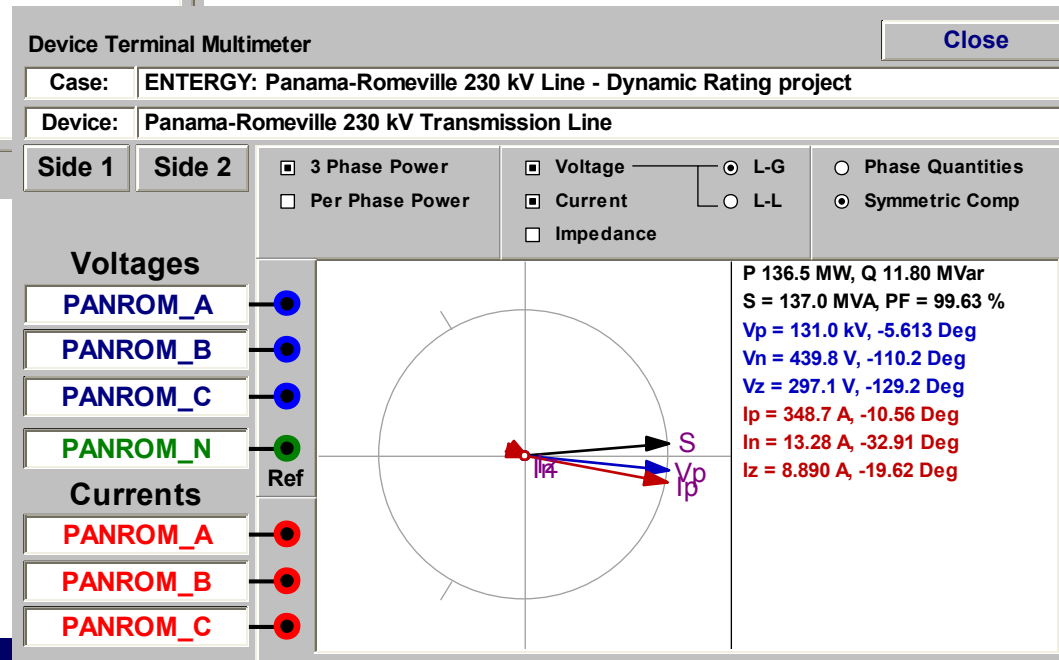
# Important Example

## What Are the Limits of Traditional State Estimation?



$$\tilde{V}_{an} = 30.7e^{-j5.908^0} \text{ kV}$$

$$\tilde{V}_{pos} = 31.0e^{-j5.613^0} \text{ kV}$$



$$\tilde{I}_a = 369.9e^{-j11.56^0} \text{ A}$$

$$\tilde{I}_{pos} = 348.7e^{-j10.56^0} \text{ kV}$$



# GPS Synchronized Measurements Enable Distributed State Estimation



# History of GPS-Synchronized Measurements

Efforts to Develop Technologies with Accurate Time Synchronization Started in the Early 80's. Examples:

Missout & Girard, 1980

Bonanomi, 1981

Phadke, 1989-90

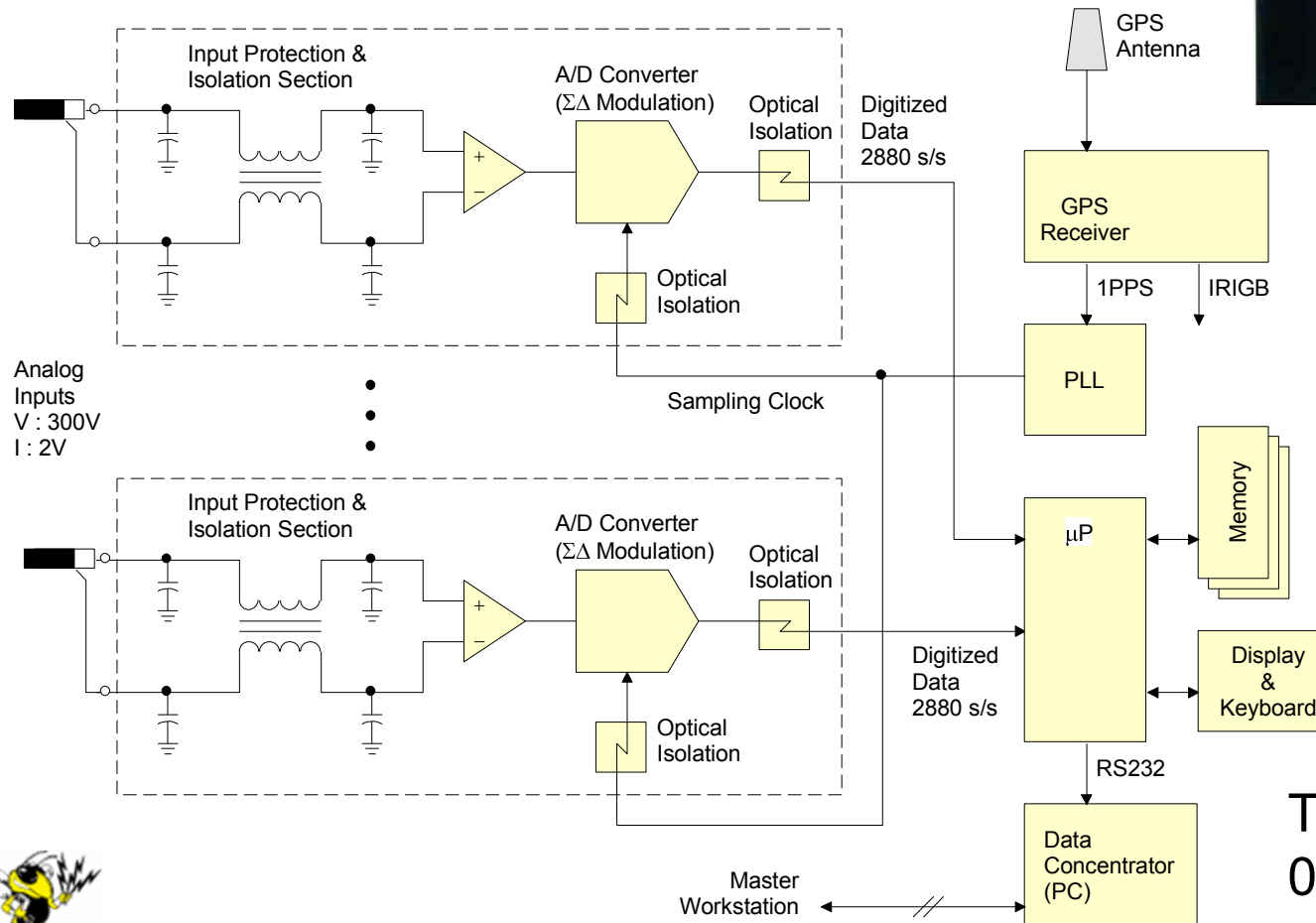
These efforts resulted in technologies with time synchronization accuracy that was several tens of microseconds.

In 1992, Macrodyne (Jay Murphy) introduced the first PMU (Phasor Measurement Unit) capable of taking measurements with synchronization comparable to GPS clock accuracy (microsecond accuracy)



# Macrodyne 1620 PMU

Released to Market January 1992



## CHARACTERISTICS

Individual Channel  
GPS Sync

Common Mode  
Rejection Filter with  
Optical Isolation

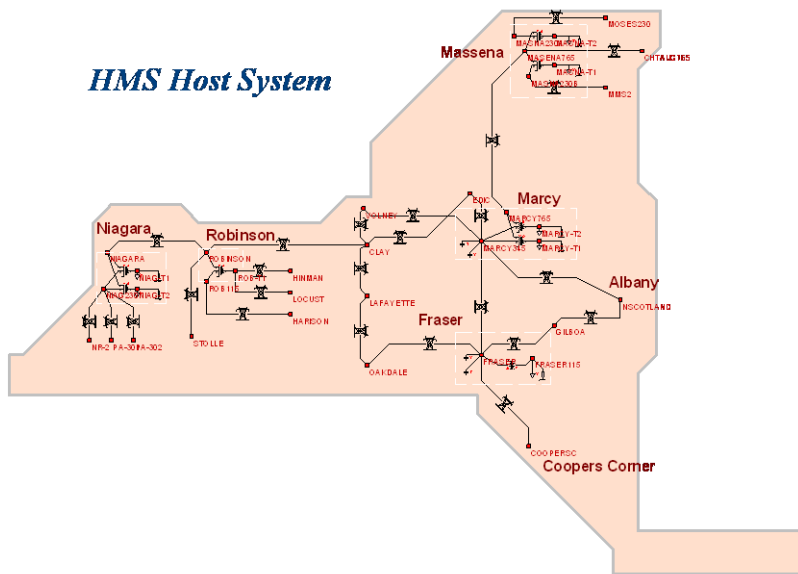
16 bit A/D  $\Sigma\Delta$  Modul.

Time Precision 1  $\mu s$   
0.02 Degrees at 60 Hz

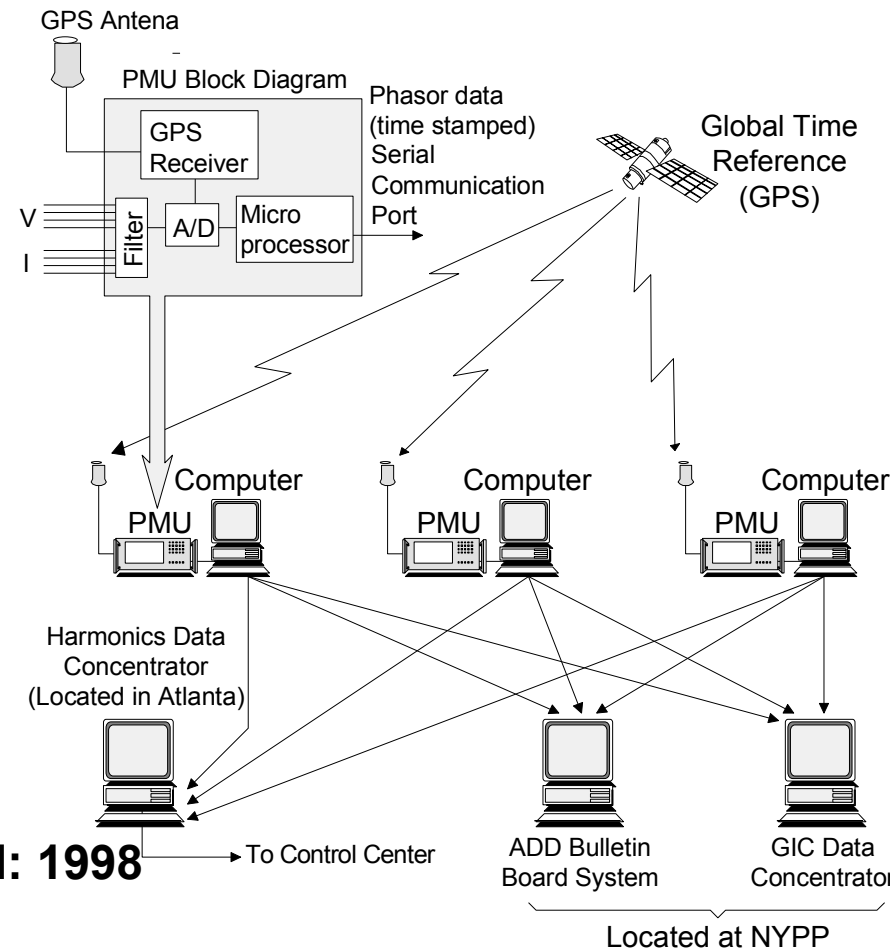


# NYPA's Harmonic Measurement System Using GPS Synchronized Measurements (Macrodyne's PMUs)

## Asymmetric Power System Model New York Power Authority



## First Wide Area Monitoring System In Eastern Interconnection



**NYPA Project Launched: 1993, Completed: 1998**

**NYPA: Shalom Zelingher, Bruce Fardanesh**

**GaTech: Meliopoulos & Cokkinides**



# The SuperCalibrator Concept...

Develop a State Estimator that Addresses all of the Above Issues

## **IMPORTANT FEATURE:**

The presence of GPS Synchronized Measurements Allows Full Decentralization of the State Estimation Process

## **IMPLEMENTATION:**

Formulate the State Estimation Problem for Each Substation. Transport the Substation State Estimates to Control Center and Synthesize the System State



# The SuperCalibrator is a Substation Based State Estimator with the Following Features:

## **Eliminates Model Biases**

(Full Three-Phase Model with Neutrals, etc.)

## **Eliminates Imbalance Biases**

(Single Phase or Three Phase Measurements)

## **Eliminates Biases From Instrumentation Channel Errors**

(Model is Augmented with Instrumentation)

## **Robustness**

(Model Quadratrization)

# The SuperCalibrator Concept

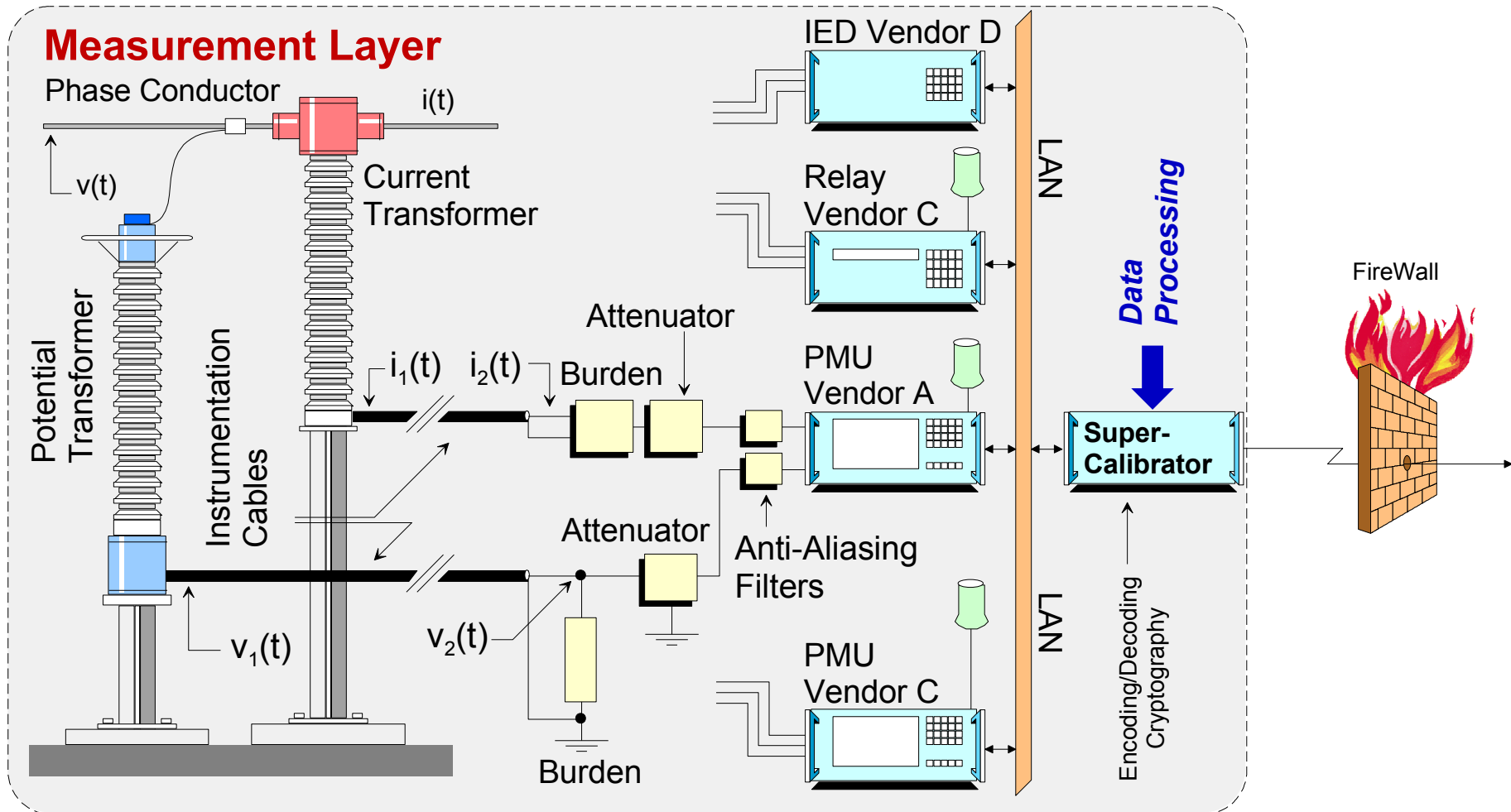
The SuperCalibrator is conceptually very simple. The basic idea is to provide a model based error correction of substation data and in particular RELAY DATA. The basic idea is to utilize a **high fidelity** model of the substation, (three-phase, breaker-oriented model, instrumentation channel inclusive and data acquisition model inclusive). Then all substation data obtained with any device, PMU, meter, relay, SCADA, etc. is expressed as a function of the state of the **high fidelity** substation model.

The SuperCalibrator uses (a) a static state estimator algorithm, and (b) a dynamic state estimator algorithm.

**GPS Synchronized Relays Make the Process Robust and the Results Globally Valid**



# SuperCalibrator Schematic Representation



Model Based Data Validation and Information Extraction  
(Redundancy, Bad Data Rejection, Statistical Estimation, etc.)

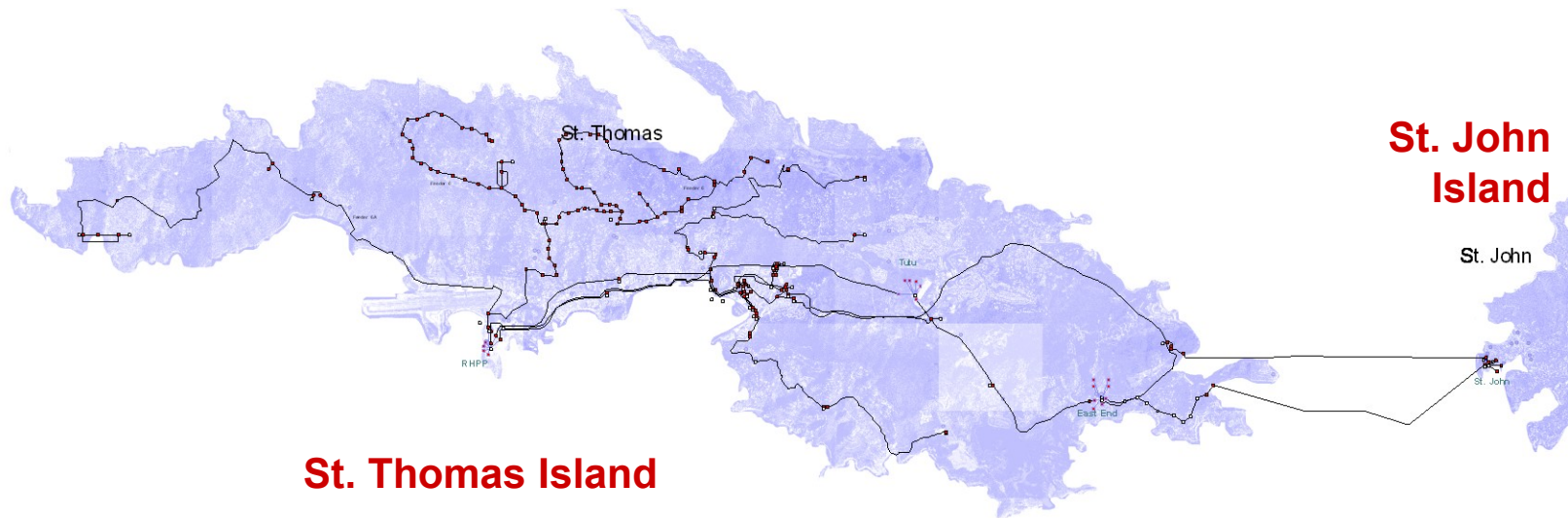


# SuperCalibrator Implementation on the VIWAPA System



# Demonstration (Pilot) Project

Pilot project for demonstrating the application of the SuperCalibrator concept for distributed state estimation on the US Virgin Islands power network.



- ◆ US Virgin Islands consist of the main islands of St. Croix, St. John and St. Thomas, along with many other surrounding minor islands.
- ◆ The network is a stand-alone power system and is not connected to the US national power grid.
- ◆ The SuperCalibrator is implemented on the St. Thomas and St. John Islands power system – the system has five substations and a generating plant.
- ◆ Each substation has at least one SEL 421 relay or SEL 734 with GPS-synchronized measurement capability.



# Implementation

Substation Model  
Substation State

Measurements  
Pseudo-measurements

Estimation Method



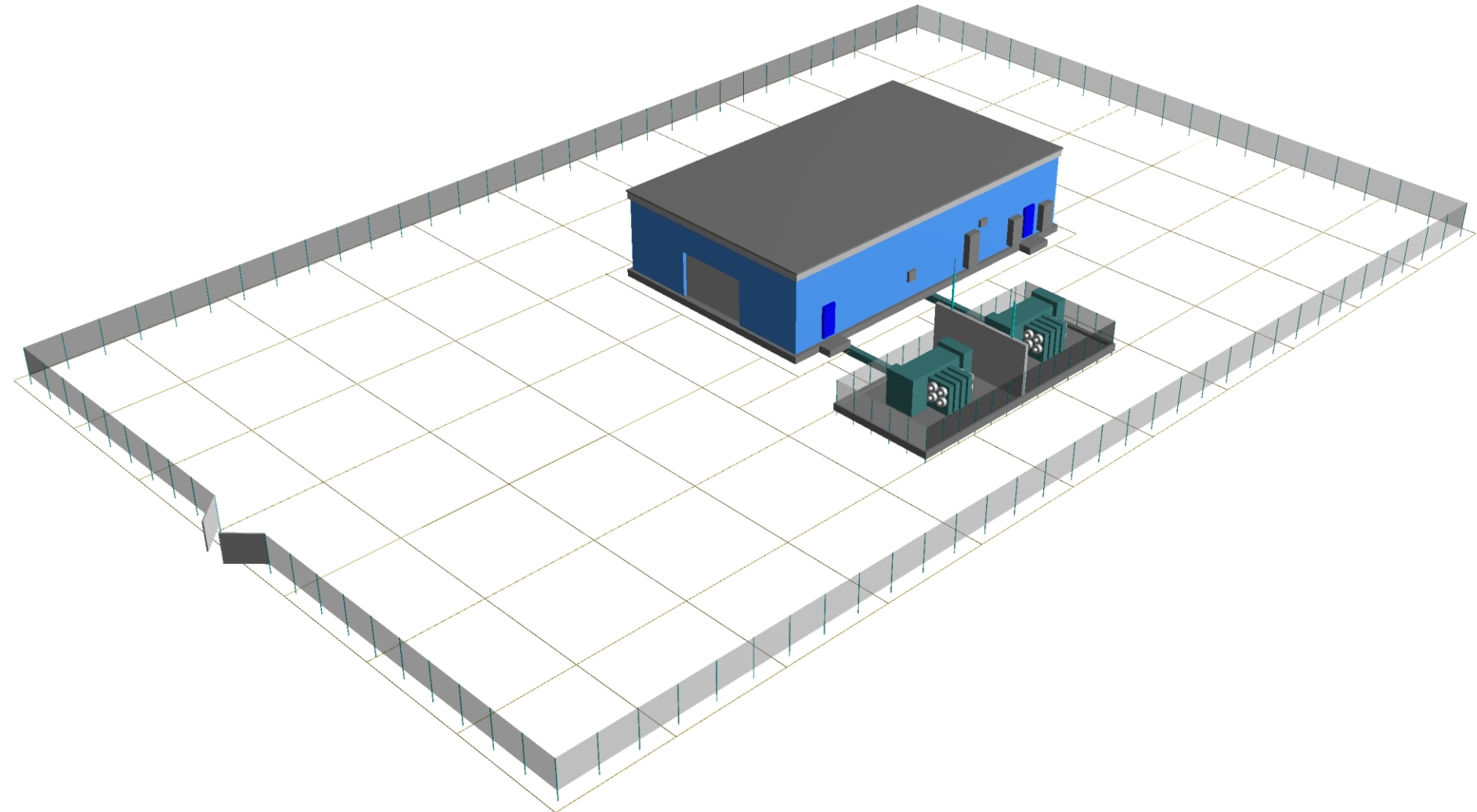
# Substation Model

- Physically Based Component Modeling
- Explicit Representation of Phase Conductors, Neutrals, Ground Conductors and Grounding – accounts for ground potential rise
- Explicit Representation of Breakers, Switches
- Explicit Representation of Instrumentation and Relay Inputs Integrated with the Power System



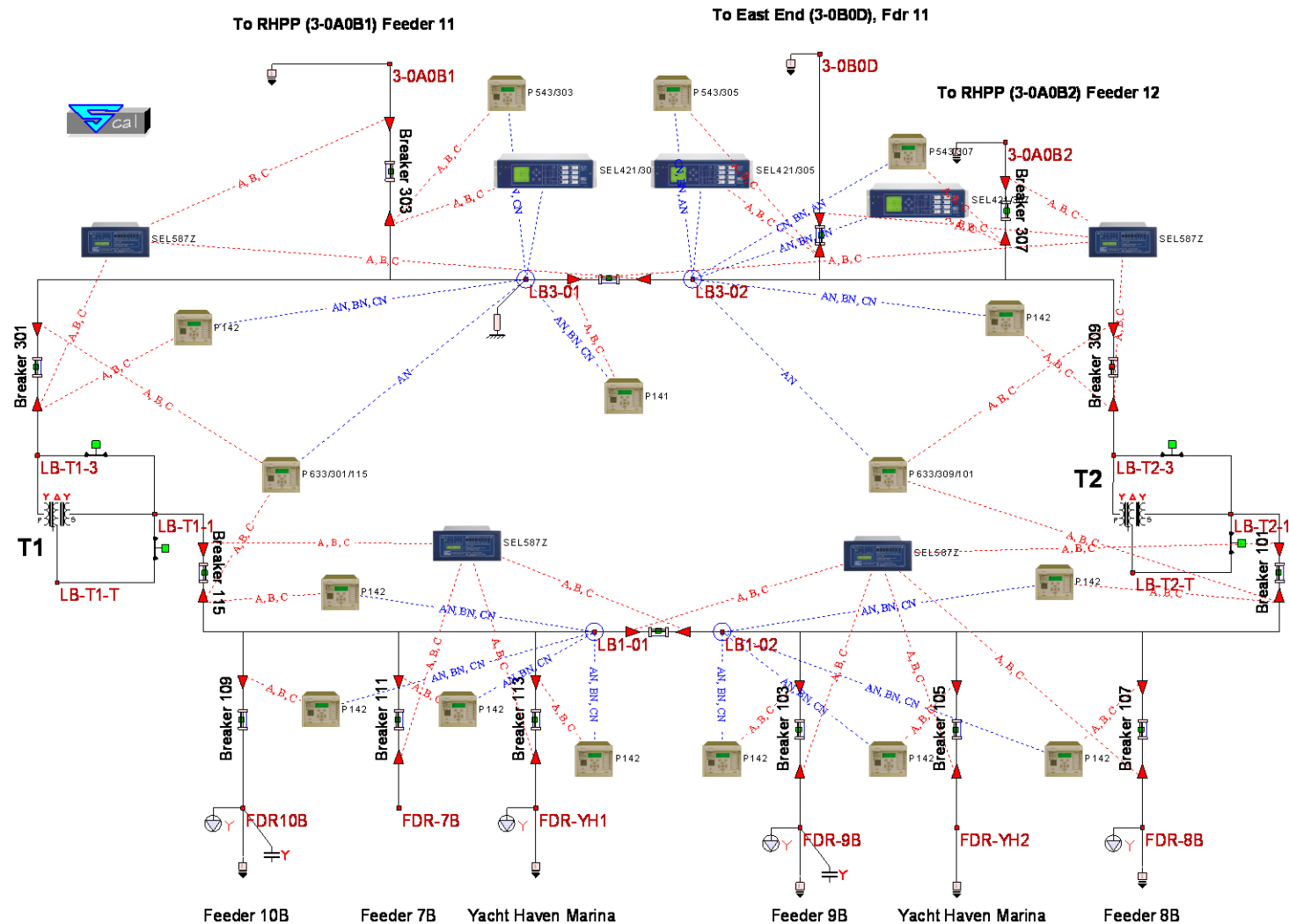
# SuperCalibrator Implementation

## Substation Configuration – Long Bay – 3D Model



# SuperCalibrator Implementation

## Substation Configuration – Long Bay



# SuperCalibrator Implementation

## Substation Configuration – Long Bay

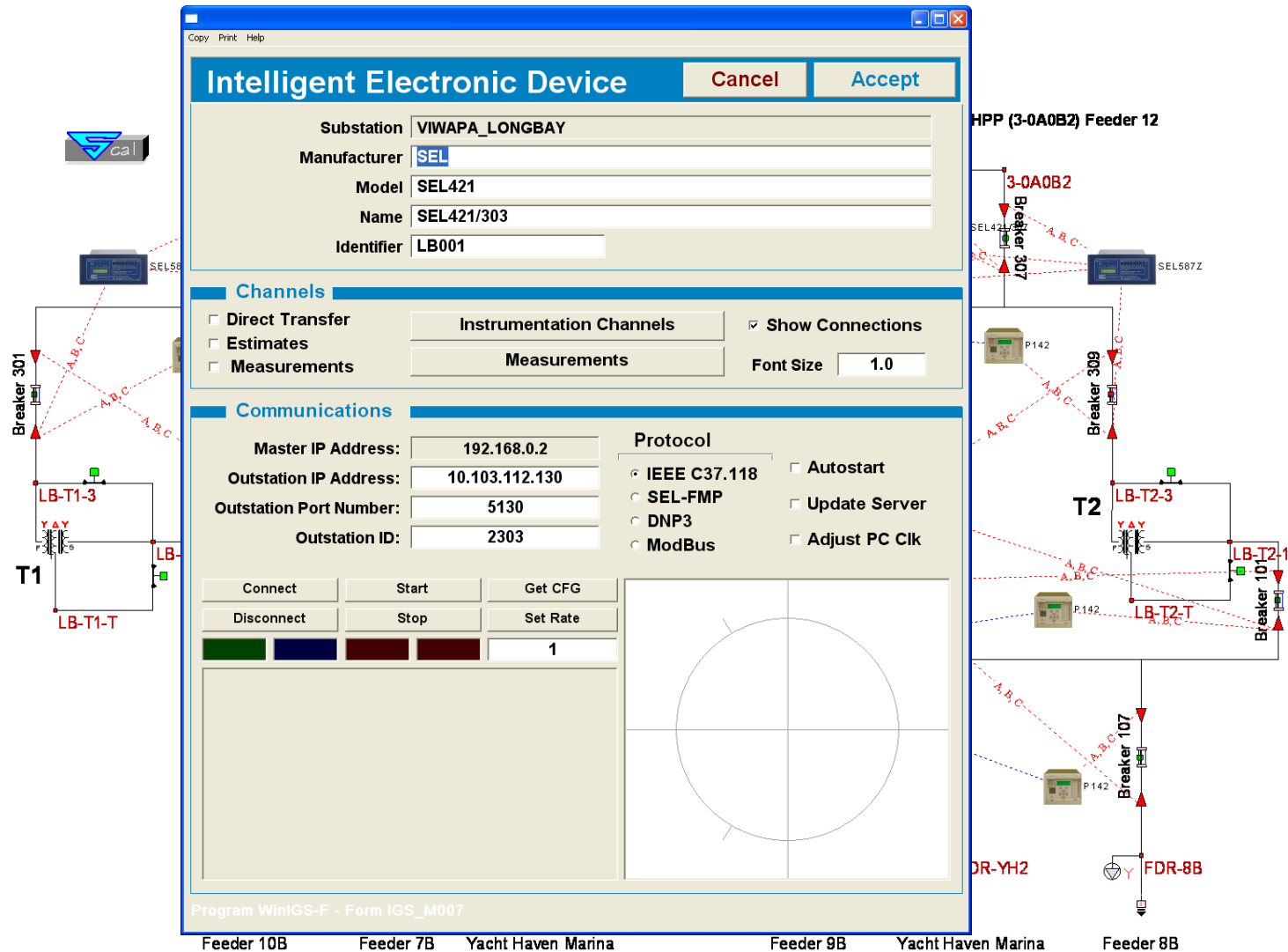




Diagram showing the connection of the IGS\_M007 program to the IGS network. The program is connected to Feeder 10B, Feeder 7B, Yacht Haven Marina, Feeder 9B, and Yacht Haven Marina. The network is labeled DR-YH2 and FDR-8B.

# SuperCalibrator Implementation

## Substation Configuration – Long Bay

Copy Print Help

|   | Item  | Name |
|---|-------|------|
| 1 | C_303 |      |
| 2 | C_303 |      |
| 3 | C_303 |      |
| 4 | V_VT1 |      |
| 5 | V_VT1 |      |
| 6 | V_VT1 |      |

New

Program

**Instrumentation Channel Parameters**

Cancel
Accept

|                                  |                      |                    |                                                                                 |                   |
|----------------------------------|----------------------|--------------------|---------------------------------------------------------------------------------|-------------------|
| IED                              | VIWAPA_LONGBAY_LB001 | Local              | 282                                                                             | Transfer Function |
| Channel Name                     | V_VT1_AN             | Remote             | 1                                                                               | Update            |
| Data Type                        | Voltage Phasor       | Phase (A,B,C...)   | AN                                                                              |                   |
| Bus Name                         | LB3-01               | Current Direction: | <input checked="" type="radio"/> Into Device <input type="radio"/> Outof Device |                   |
| Power Device                     | Breaker 303          |                    |                                                                                 |                   |
| Standard Deviation               | 25.00                | Weight             | 1.00000                                                                         |                   |
| Overall Nominal Ratio and Offset |                      | 175.00             | 0.00                                                                            |                   |

**Instrument Transformer**

Instr. Transformer Code

VT1

Type

PT\_20K

Tap

X1-X3

Ratio

20125.0/115.0 V

Nominal Primary Voltage (kV)

34.50

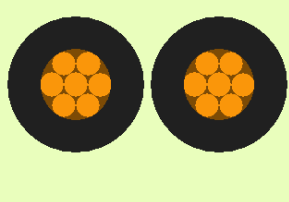
**Instrumentation Cable**

Length (ft)

61.50

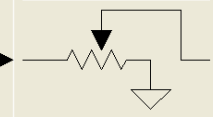
Cable Type

COP-PAIR-10



**Attenuator**

1.00



**Burden**

R (Ohms)

1000.00

X (Ohms)

0.00

**DAU**

IDEAL16BIT

Peak Voltage(V)

300.00

Calibr Factor

1.00

Calibr Offset

0.00

Time Skew (us)

0.00

↓

Data Concentrator

Copy Print Help

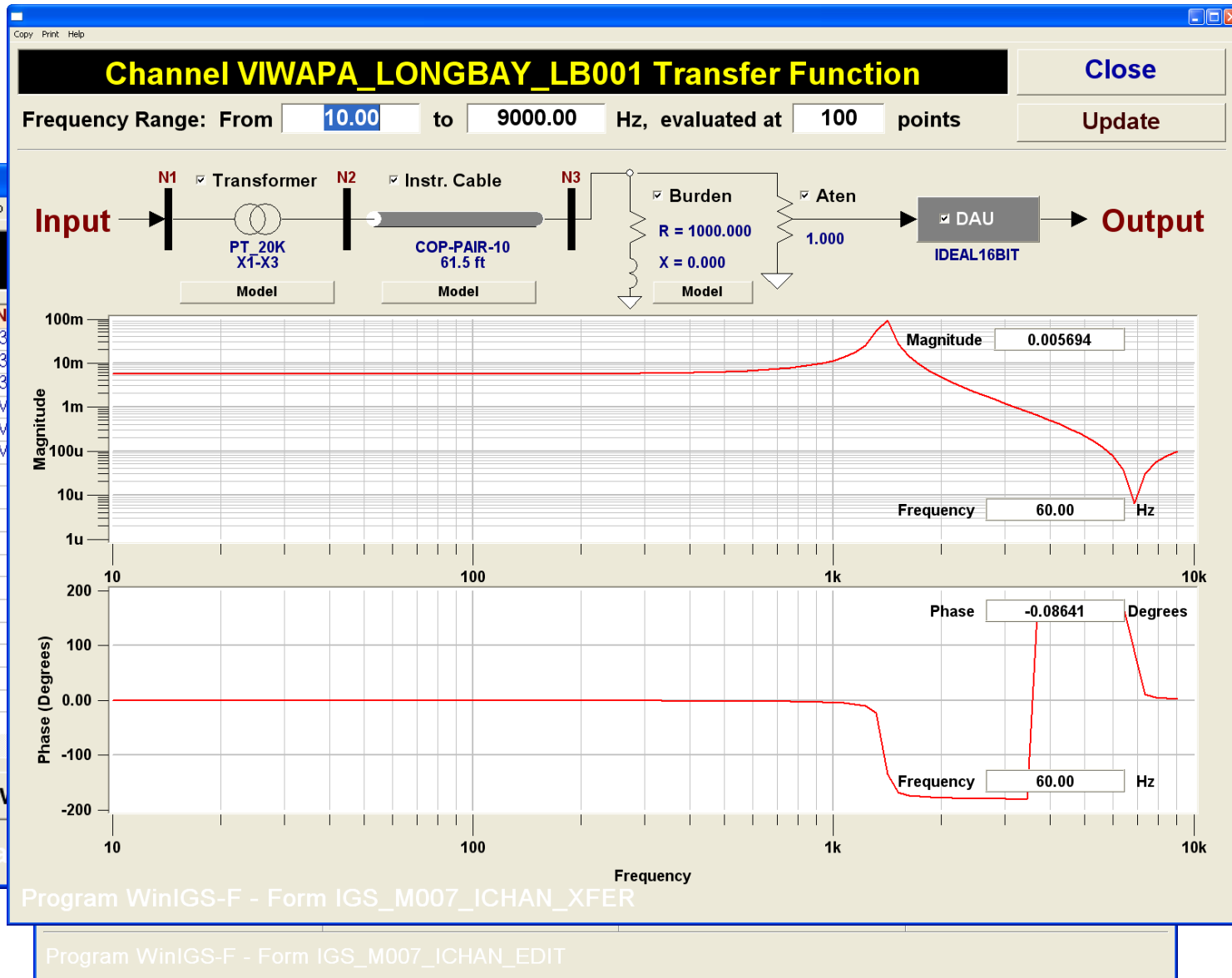
| Length | IED   |
|--------|-------|
| 50     | LB001 |
| 50     | LB001 |
| 50     | LB001 |
| 50     | LB001 |
| 50     | LB001 |
| 50     | LB001 |

Accept

Program WinIGS-F - Form IGS\_M007\_ICHAN\_EDIT



# SuperCalibrator Implementation



# SuperCalibrator Implementation

## State Estimation Configuration – Long Bay

Copy Print Help

**Cal** **SuperCalibrator Master** Cancel Accept

Substation: **VIWAPA\_LONGBAY**

Description: **Substation State Estimation Setup**

**Global Standard Deviations**

**Start** **Stop** ☐ Autostart

Voltages: **0.00**

Currents: **0.00**

**Update**

**State**

**Measurements**

**Pseudomeasurements**

**Server Setup**

Host IP Address: **192.168.0.2**

Port Number: **1000**

Name: **LongBay**

Outstation ID: **1**

Transmission Rate: **4** p / s

☐ Autostart

**Transmit**

☒ State Estimate

☐ Measurements

**Start Server** **Stop Server**

Server Status: **Off**

Connections: **0**

Transmit: **Off**

Receive: **Off**

Data Available: **Off**

Conf: **10** K: **100**

Program WinIGS-F - Form IGS\_M010

Feeder 10B Feeder 7B Yacht Haven Marina Feeder 9B Yacht Haven Marina Feeder 8B

Breaker 101-T2-1



# SuperCalibrator Implementation

## State Estimation Configuration – Long Bay

Copy Print Help



Ca

Substation

Description

Start

Stop

Autostart

Host IP Address:

Port Number

Name:

Outstation ID:

Transmission Rate:

Autostart

Transmit

State Estimate

Measurements

Start Server

Stop Server

Program Window

Copy Print Help

State Estimation State Definition

Cancel

Accept

Substation

LongBay

State Vector Nodes

(Bus Voltage Phasors)

|    | Bus      | Ref.Node |
|----|----------|----------|
| 1  | LB3-01_A | LB3-01_N |
| 2  | LB3-01_B | LB3-01_N |
| 3  | LB3-01_C | LB3-01_N |
| 4  | FDR11_A  | FDR11_N  |
| 5  | FDR11_B  | FDR11_N  |
| 6  | FDR11_C  | FDR11_N  |
| 7  | FDR12_A  | FDR12_N  |
| 8  | FDR12_B  | FDR12_N  |
| 9  | FDR12_C  | FDR12_N  |
| 10 | OH295_A  | OH295_N  |
| 11 | OH295_B  | OH295_N  |
| 12 | OH295_C  | OH295_N  |

Add

Remove

Edit

Clear

Add

Check

Substation Buses

|    | Bus     |
|----|---------|
| 1  | 3-0A0B1 |
| 2  | 3-0A0B2 |
| 3  | 3-0B0D  |
| 4  | FDR-7B  |
| 5  | FDR-8B  |
| 6  | FDR-9B  |
| 7  | FDR-YH1 |
| 8  | FDR-YH2 |
| 9  | FDR10B  |
| 10 | LB-T1-1 |
| 11 | LB-T1-3 |
| 12 | LB-T1-T |
| 13 | LB-T2-1 |
| 14 | LB-T2-3 |
| 15 | LB-T2-T |
| 16 | LB1-01  |
| 17 | LB1-02  |

Next Buses

|    | Bus       |
|----|-----------|
| 1  | 1-BX10-13 |
| 2  | 1-BX11-13 |
| 3  | 1-BX13A13 |
| 4  | 1-BX13B13 |
| 5  | 1-BX7-13  |
| 6  | 1-BX8-13  |
| 7  | 1-BX8910  |
| 8  | 1-BX9-13  |
| 9  | B13E      |
| 10 | B13W      |
| 11 | B34-1     |
| 12 | B34-1B    |
| 13 | B34-2     |
| 14 | B34-3     |
| 15 | B34-4     |

Breaker 101-T2-1

100

eder 8B

Program WinIGS-F - Form IGS\_M010\_STATE

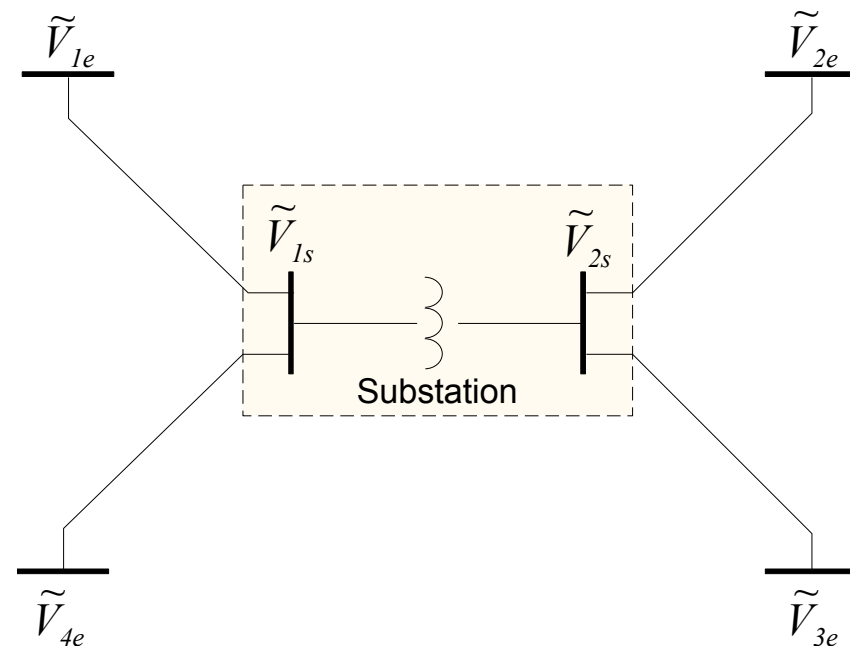


# Substation State

## SuperCalibrator Static State Estimation

## State Definition

### Definition of State for a Substation



$\tilde{V}_{1s}$  Vector of dimension 4:  $\tilde{V}_{1s,a}, \tilde{V}_{1s,b}, \tilde{V}_{1s,c}, \tilde{V}_{1s,n}$

$\tilde{V}_{2s}$  Vector of dimension 4:  $\tilde{V}_{2s,a}, \tilde{V}_{2s,b}, \tilde{V}_{2s,c}, \tilde{V}_{2s,n}$

$\tilde{V}_{1e}$  Vector of dimension 4:  $\tilde{V}_{2e,a}, \tilde{V}_{2e,b}, \tilde{V}_{2e,c}, \tilde{V}_{2e,n}$

... ..

$\tilde{V}_{4e}$  Vector of dimension 4:  $\tilde{V}_{4e,a}, \tilde{V}_{4e,b}, \tilde{V}_{4e,c}, \tilde{V}_{4e,n}$



# SuperCalibrator Measurement Set

- Any Measurement at the Substation from Any IED  
(Relays, Meters, FDR, PMUs, etc.)
- Data From at Least one GPS-Synchronized Device
- Pseudo-Measurements
  - Kirchoff's Current Law
  - Remote End State Measurement
  - Missing Phase Measurements
  - Neutral/Shield Current Measurement
  - Neutral Voltage



# SuperCalibrator Measurement Set

## GPS-Synchronized Measurements

### GPS-Synchronized Measurements

Voltage Phasor

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

Current Phasor

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



# SuperCalibrator Measurement Set

## Non-Synchronized Measurements

$$\tilde{A}_{sync} = \tilde{A}_{meas} e^{j\alpha}$$

alpha is a synchronizing unknown variable

Cos and sin of alpha are unknown variable in the state estimation algorithm

There is one alpha variable for each non-synchronized relay



# SuperCalibrator Measurement Set

## Non-Synchronized Measurements

### Example 1

#### Non-Synchronized Measurements

##### Voltage Magnitude

$$z_v = |\tilde{V}_{k,A} - \tilde{V}_{k,N}|^2 + 2\eta =$$

$$= (\tilde{V}_{k,A,r} - \tilde{V}_{k,N,r})^2 + (\tilde{V}_{k,A,i} - \tilde{V}_{k,N,i})^2 + 2\eta$$

##### Real Power

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

### Example 2

$$\tilde{A}_{sync} = \tilde{A}_{meas} e^{j\alpha} =$$

$$A_{real} \cos \alpha - A_{imag} \sin \alpha +$$

$$j(A_{real} \sin \alpha + A_{imag} \cos \alpha)$$

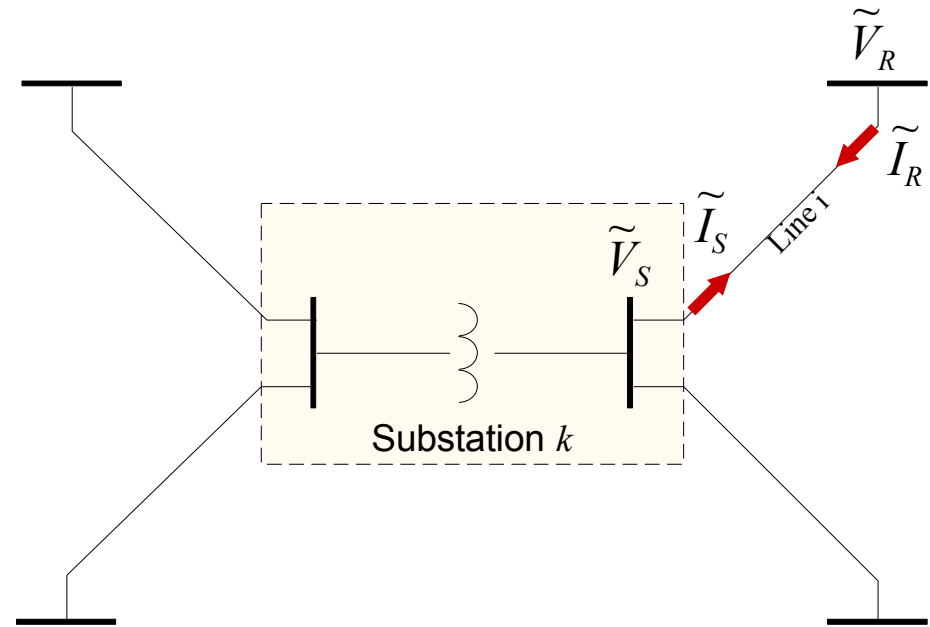


# SuperCalibrator Measurement Set:

## Remote End State Measurement

Line i Equations

$$\begin{bmatrix} \tilde{I}_S \\ \tilde{I}_R \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_S \\ \tilde{V}_R \end{bmatrix}$$



Solve for V at remote end

$$\tilde{V}_R^{pseudo,m} = \begin{bmatrix} -Z_{22}Y_{22} & -Z_{21} \end{bmatrix} \tilde{I}_S + \begin{bmatrix} -Z_{22}Y_{22} & -Z_{22}Y_{21} \end{bmatrix} \tilde{V}_S \quad \text{Expected Error: 0.01\%}$$

Where:

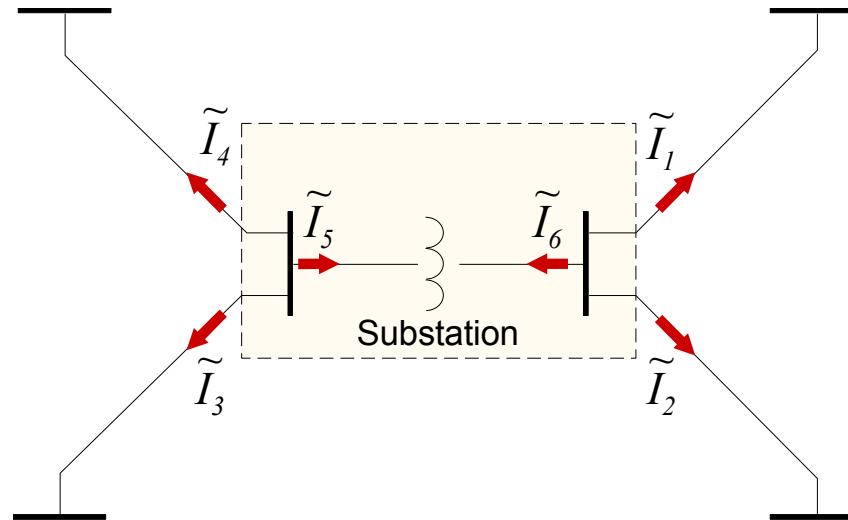
$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$$

Demonstration Example



# SuperCalibrator Measurement Set:

## Kirchoff's Current Law



$$\tilde{I}_1 + \tilde{I}_2 + \tilde{I}_6 = 0$$

Expected Error: 0.001%

$$k_1 \tilde{I}_3 + \tilde{I}_4 + k_2 \tilde{I}_1 + \tilde{I}_2 + \tilde{I}_m = 0$$

Expected Error: 0.001%



# SuperCalibrator Measurement Set: Missing Phase Measurements

Assume There is a Phase A Voltage Phasor Measurement.  
Assume there is no Phase C Measurement.

THEN:

$$\tilde{V}_{s/n}^{pseudo,m} - \tilde{V}_a e^{-j240^\circ} = 0$$

Expected Error: Less than 3%



# SuperCalibrator: Estimation Method

$$\text{Min } J = \sum_{v \in \text{phasor}} \frac{\tilde{\eta}^* \tilde{\eta}}{k^2 \sigma^2} + \sum_{v \in \text{non-syn}} \frac{\eta \gamma}{k^2 \sigma^2}$$

## GPS-Synchronized Measurements

### Voltage Phasor

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

### Current Phasor

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

## Non-Synchronized Measurements

### Voltage Magnitude

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

### Real Power

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



# SuperCalibrator: Estimation Method

$$\text{Min } J = \sum_{v \in \text{phasor}} \frac{\tilde{\eta}^* \tilde{\eta}}{k^2 \sigma^2} + \sum_{v \in \text{non-syn}} \frac{\eta \gamma}{k^2 \sigma^2}$$

## Solution

$$x^{v-1} = c^v + A^{-1} [ - \eta \gamma ]$$

$$\text{where: } A = [ H^T W H ] [ H^T W ]$$

## Efficiency

Example, Long Bay Substation, High End PC

One Iteration: 18,000 multiply-adds (0.002 seconds)

Compute Matrix A: Variable (sparsity) – Almost Invariant (0.010 secs)



# State Estimation Performance Evaluation

## Chi-Square Test

Step 1: Compute the state estimate  $\mathbf{x}^*$

Step 2: Evaluate the function  $J^* = \tilde{\mathbf{z}}^H \mathbf{W} \tilde{\mathbf{r}} = \frac{a}{k^2}$

Step 3: Compute  $p(k) = 1 - P(a/k^2, m-n)$

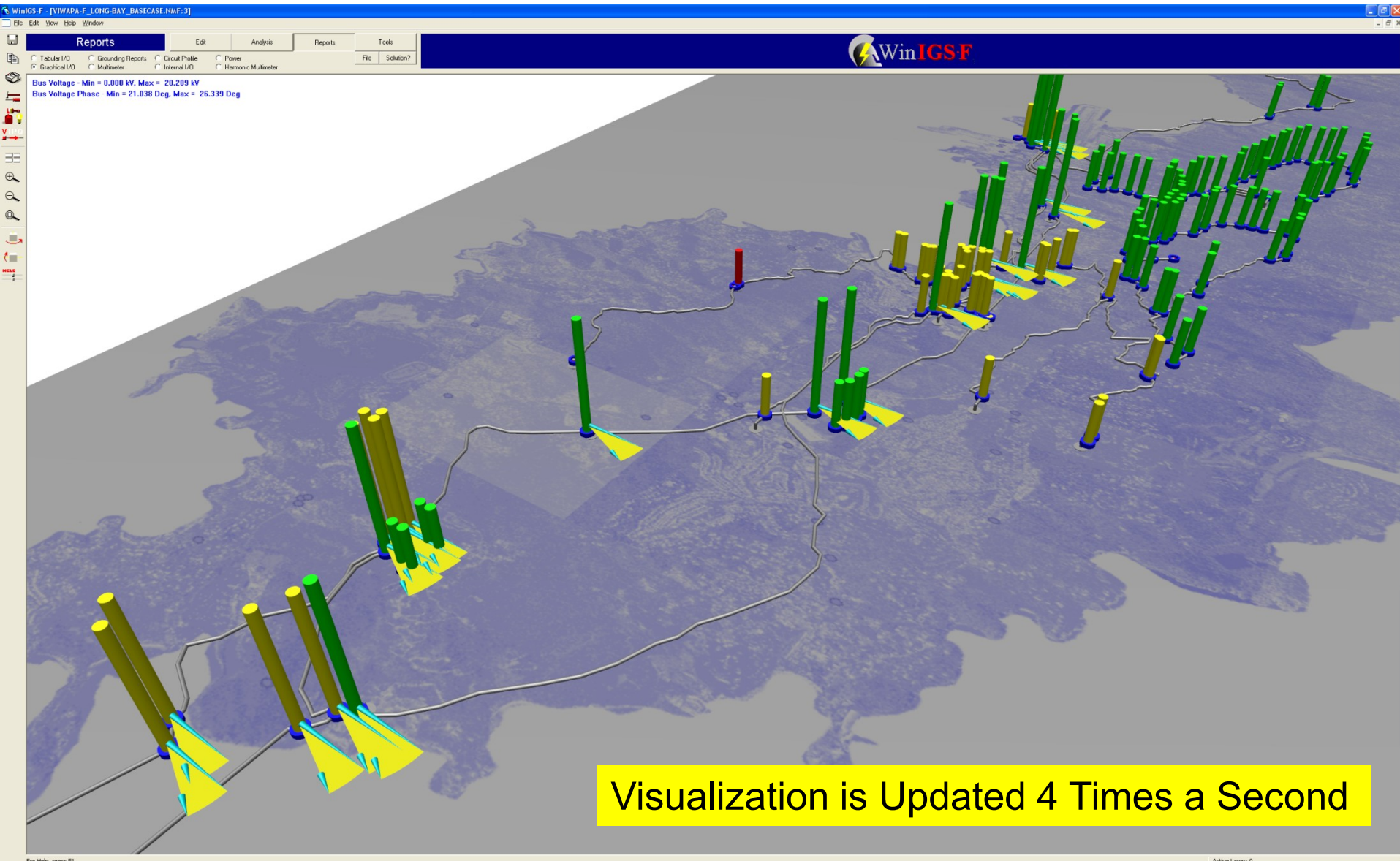
where:

$P(a/k^2, u)$  is the probability that  $J \leq a$

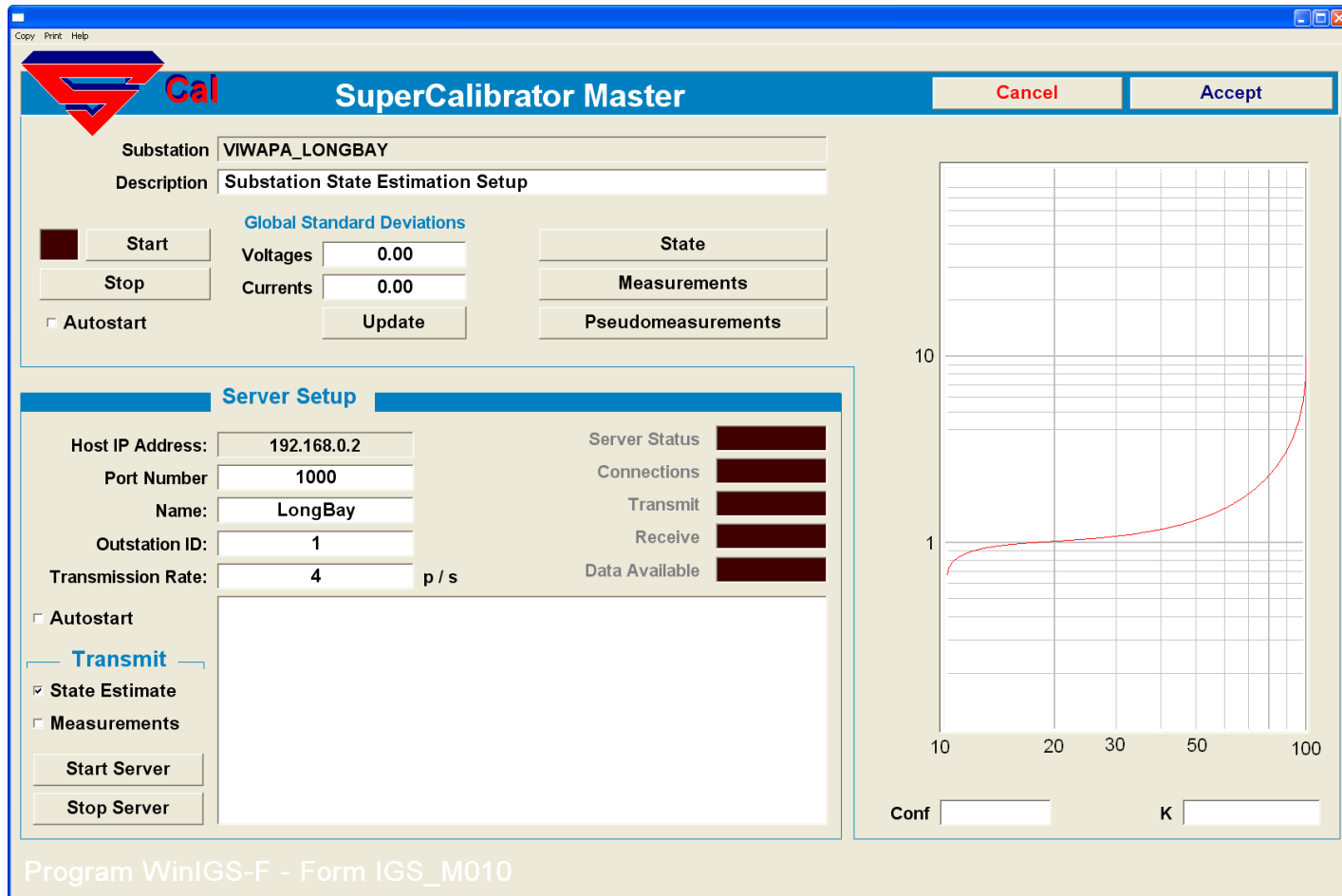
and  $u$  is the degrees of freedom



# Performance Achievement



# Overall Performance Metric Chi-Square Test



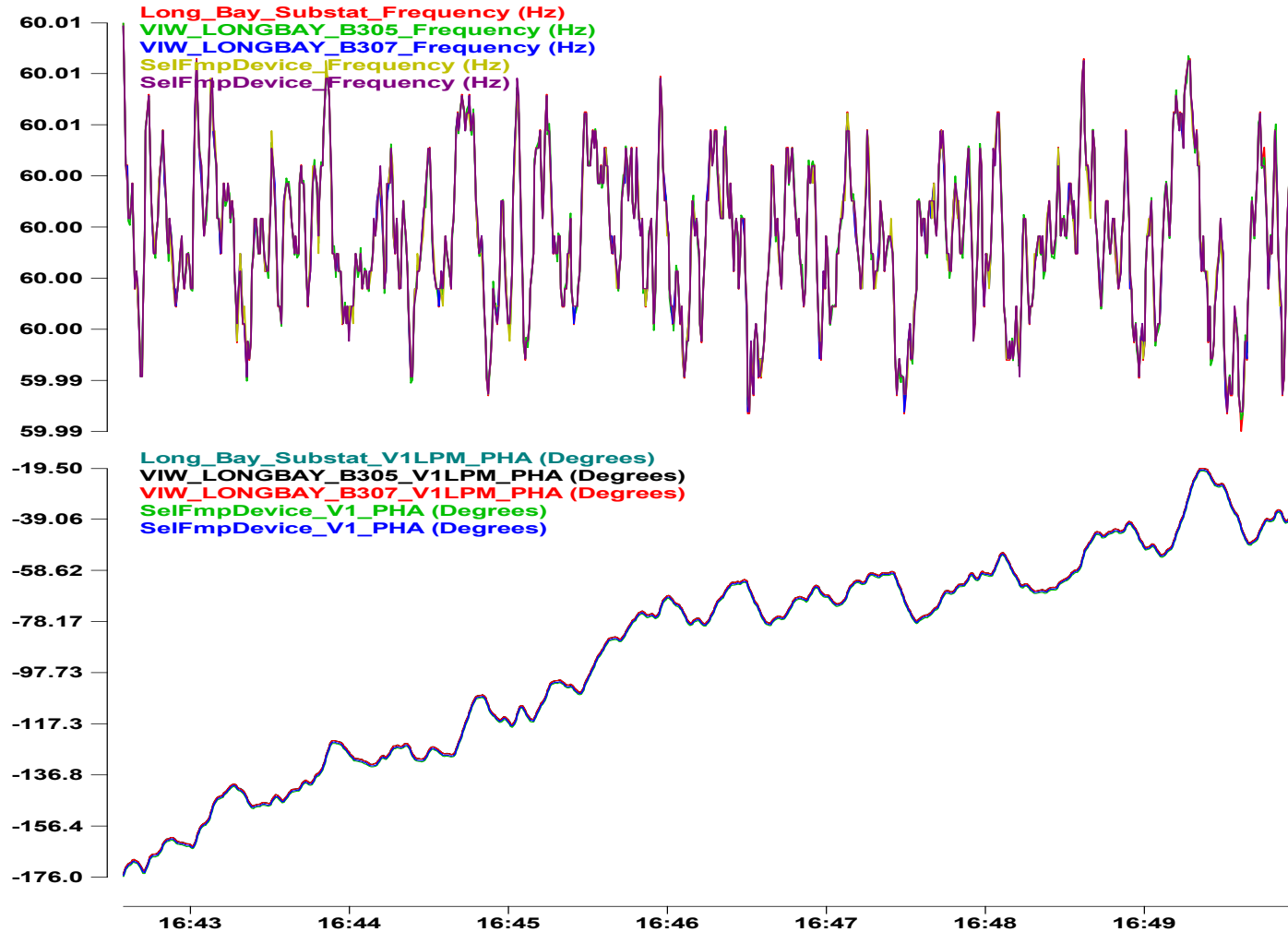
Master Report Provides Overall SE Performance in Terms of k factor



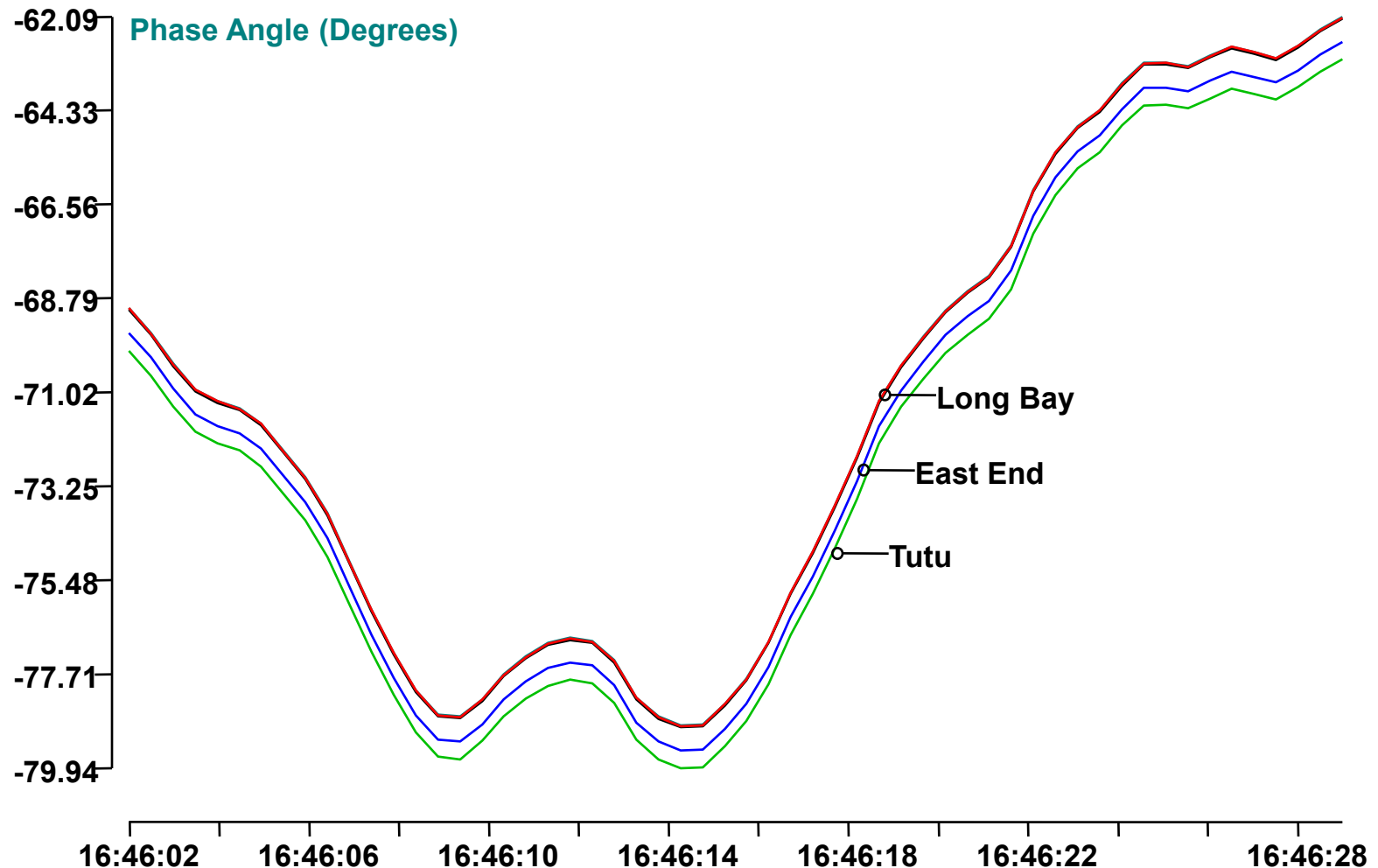
# SuperCalibrator – Storing and Retrieving Data

Program XfmHms - Page 1 of 1

c:\wmaster\xfm\data\viwapa\_001 - Apr 08, 2008, 16:42:01.500000 - 2.0 samples/sec - 1024 Samples



# SuperCalibrator – Storing and Retrieving Data



# SuperCalibrator Implementation

## Example of Measurement/Pseudo-M Count – Long Bay

### Long Bay Substation

Number of Analog Measurements: 318 real

Number of Pseudo-measurements: 72 real

Number of Status Measurements: 15

Future:

Beckwith Relay Measurements: 2

Number of States: 24+20

Long Bay 35 kV Bus: 3 (complex)

Long Bay 13 kV Bus: 3 (complex)

RHPP 35 kV Bus: 3 (complex)

East End 35 kV Bus: 3 (complex)

Redundancy  
886%



# SuperCalibrator: Estimation Method

## Scalability

### Large Substation Implementation

Assumptions: 3 kV levels, 70 relays, 5 PMUs, 35 breakers

Number of Analog Measurements: 1500 real

Number of Pseudo-measurements: 340 real

Number of Status Measurements: 35

Number of States:  $54+65=119$

### Efficiency

High End PC

One Iteration: 220,000 multiply-adds (0.022 seconds)

Compute Matrix A: Almost Invariant - Compute Once Upon SetUp



# Summary

- The SuperCalibrator Concept was Introduced to Solve the Limitations of Traditional State Estimators:
  1. System Asymmetries,
  2. Voltage Imbalance,
  3. Instrumentation Channel Error.
- The SuperCalibrator Concept has Been Successfully Demonstrated on Several Systems Including a Small Five-Substation Power System
- State Estimation rates of FOUR PER SECOND has been achieved
- The SuperCalibrator Approach is Scalable to Any Size System

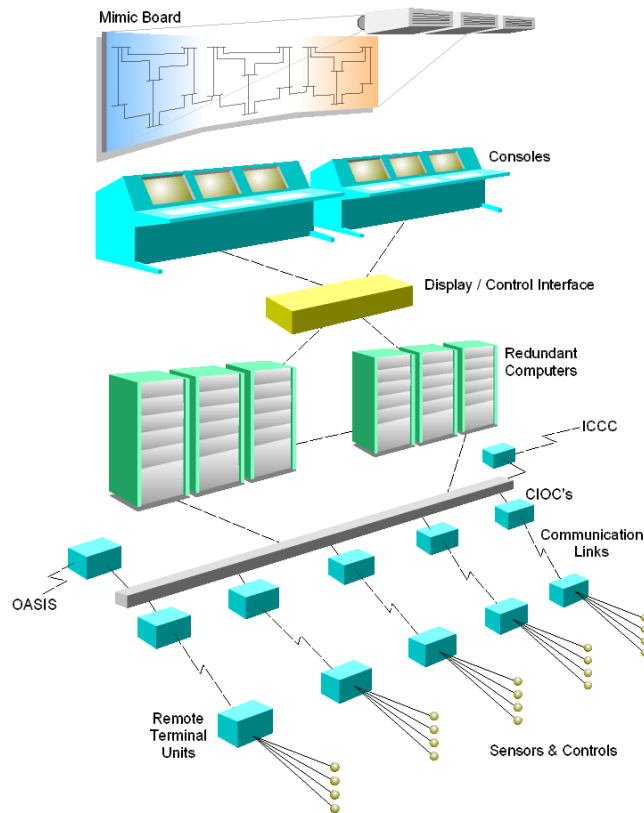


# Future Directions



# Present State of the Art: Separation of C&O and P&C

## Control & Operation



### Real Time Model

State Estimation

### Applications

Load Forecasting  
Optimization (ED, OPF)  
VAR Control  
Available Transfer capability  
Security Assessment  
Congestion management  
Dynamic Line Rating  
Transient Stability  
EM Transients, etc.  
Visualizations

### Markets:

Day Ahead, Power Balance,  
Spot Pricing, Transmission  
Pricing (FTR, FGR), Ancillary  
Services

## Protection & Control

### Component Protection

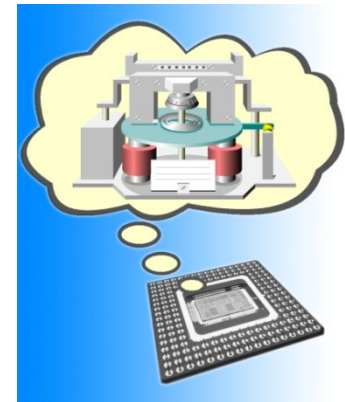
generators, transformers,  
lines, motors, capacitors,  
reactors

### System Protection

Special Protection  
Schemes, Load Shedding,  
Out of Step Protection, etc.

### Communications

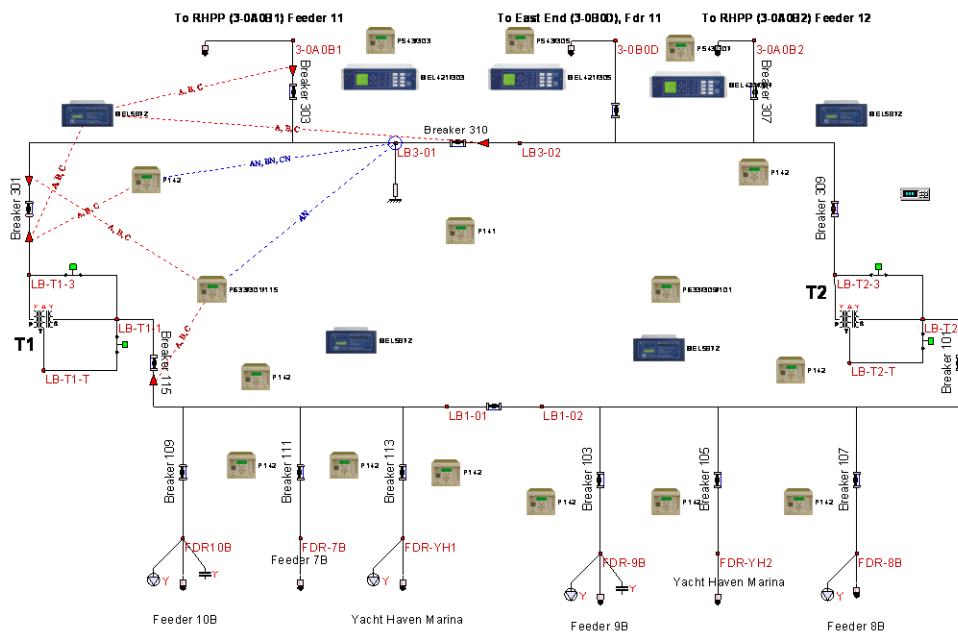
Substation Automation,  
Enterprise, InterControl  
Center



The Infrastructure for Both Functions is Based on Similar Technologies: Thus the Opportunity to Merge, Cut Costs, Improve Reliability



# PSERC Project T38 – Substation of the Future



From This

To This

