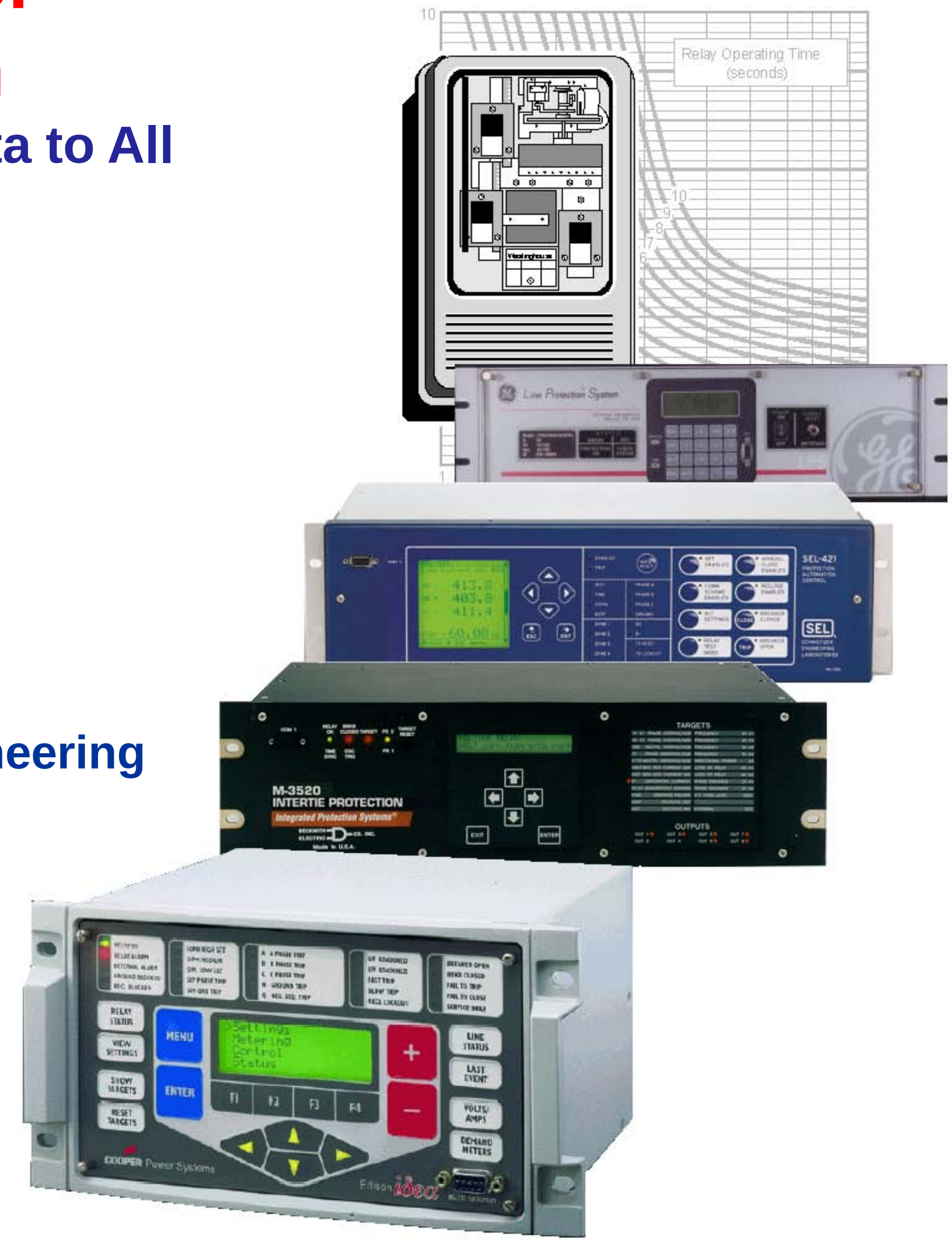
Distributed State Estimator - SuperCalibrator Approach

Delivering Accurate and Reliable Data to All

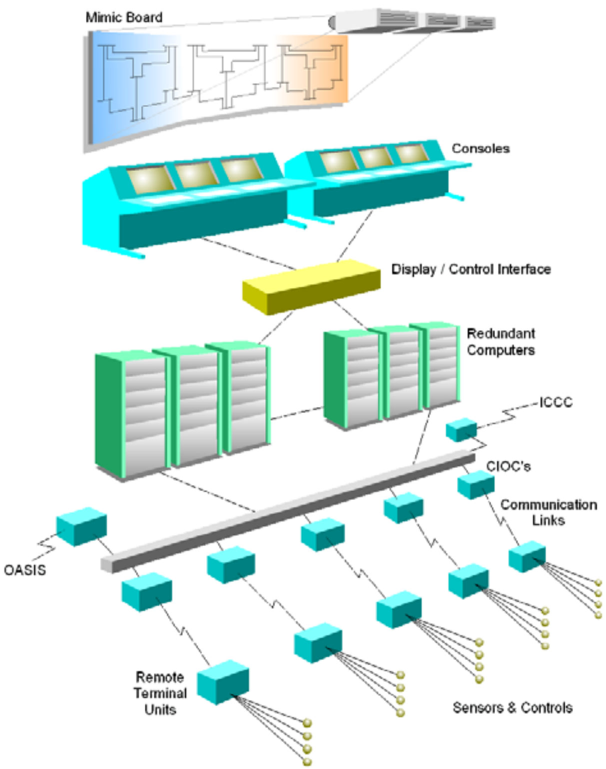


Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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

Model Based Control and Operation

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

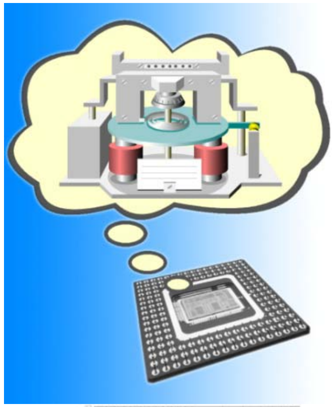
generators, transformers, lines, motors, capacitors, reactors

System Protection

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

Communications

Substation Automation, Enterprize, InterControl Center



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

Traditional State Estimation

Introduced After the 1965 Blackout

Centralized State Estimator – Long Response (min)
Model Biased State Estimator

Power System SE: Basic Assumptions

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

Implications:

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

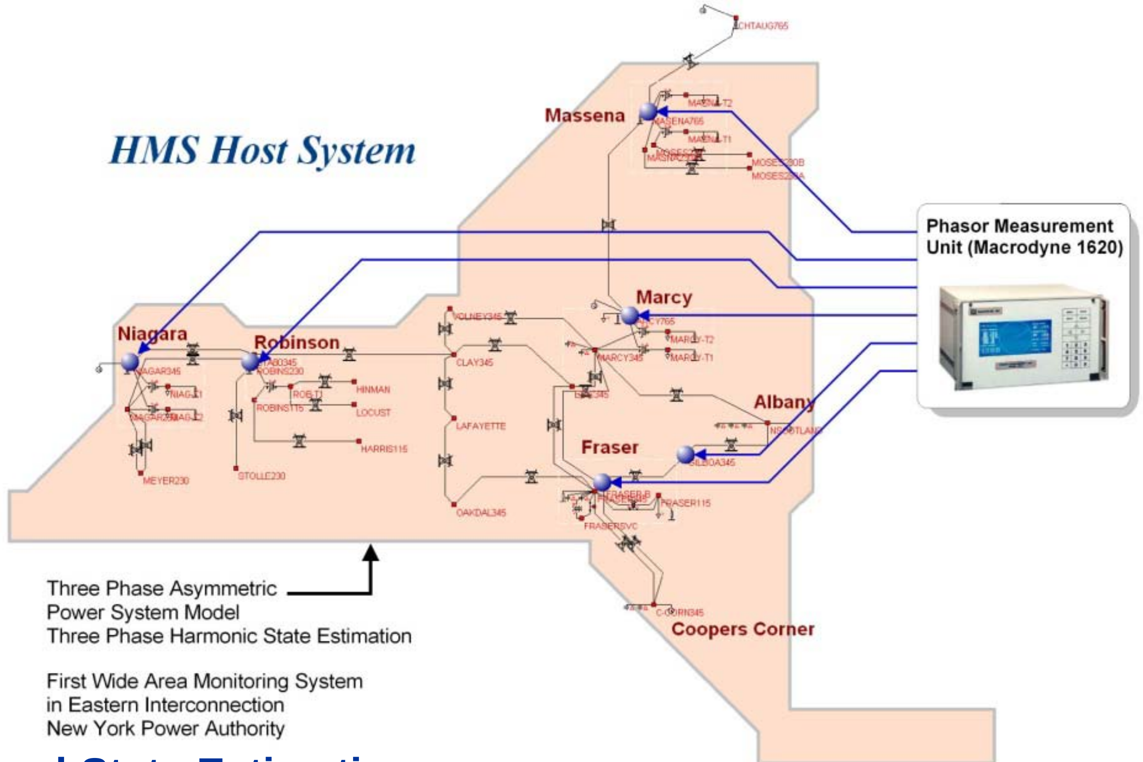
The SuperCalibrator Concept

The SuperCalibrator is conceptually very simple:

1. Utilize all available data (Relays, DFRs, PMUs, Meters, etc.)
2. Utilize a detailed substation model (three-phase, breaker-oriented model, instrumentation channel inclusive and data acquisition model inclusive).
3. At least one GPS synchronized device (PMU, Relay with PMU, etc.) → Results on UTC time enabling a truly decentralized State Estimator

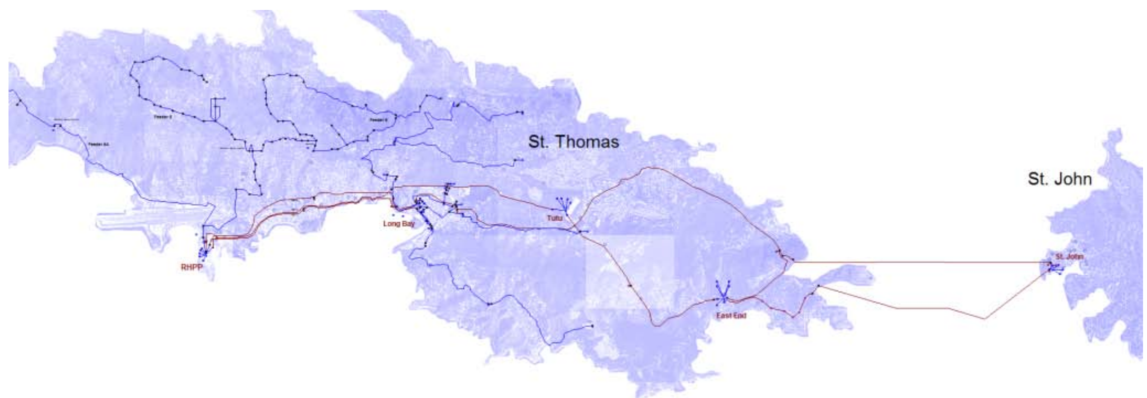
Key Projects That Led to the SuperCalibrator Concept

1989: HMS Project, NYPA



2004-6: PSERC S-22 Project: Advanced State Estimation

Jerry Heydt, Ali Abur, Sakis Meliopoulos



2006-2008: DoE/CTC Project

Distributed 3-Phase SE

SuperCalibrator

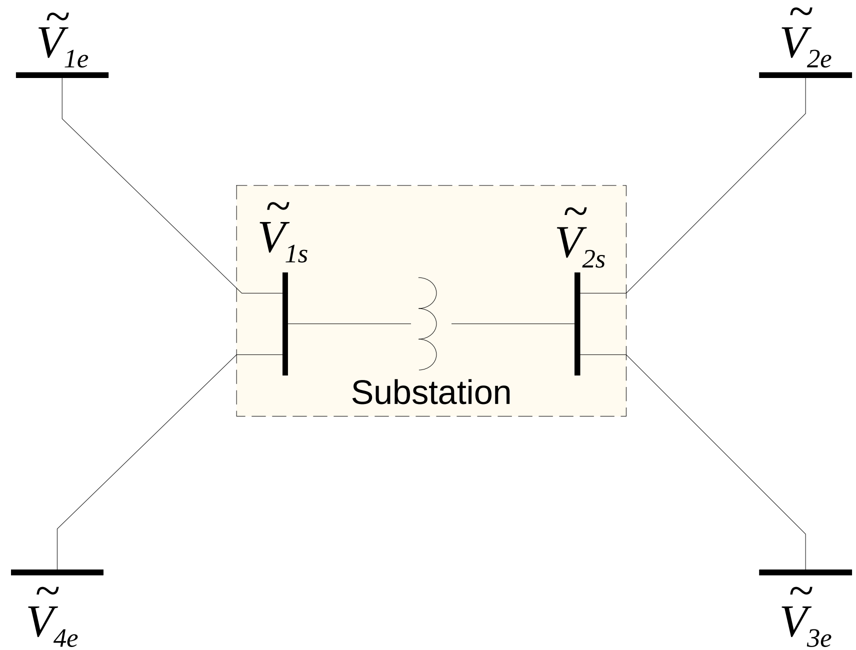
Theory

SuperCalibrator Approach
Static State Estimator Model

The Estimator is Defined in Terms of:

- **Model** (Model Fidelity Impacts SE Performance)
- **State**
- **Measurement Set**
- **Estimation Method**

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

Non-Synchronized Measurements

Non-GPS Synchronized Relays provide phasors referenced on “phase A Voltage”. The phase A Voltage phase is ZERO.

The SuperCalibrator provides a reliable and accurate estimate of the phase A voltage phase.

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

$$\tilde{A}_{sync} = \tilde{A}_{meas} e^{j\alpha} = A_{real}\cos\alpha - A_{imag}\sin\alpha + j(A_{real}\sin\alpha + A_{imag}\cos\alpha$$

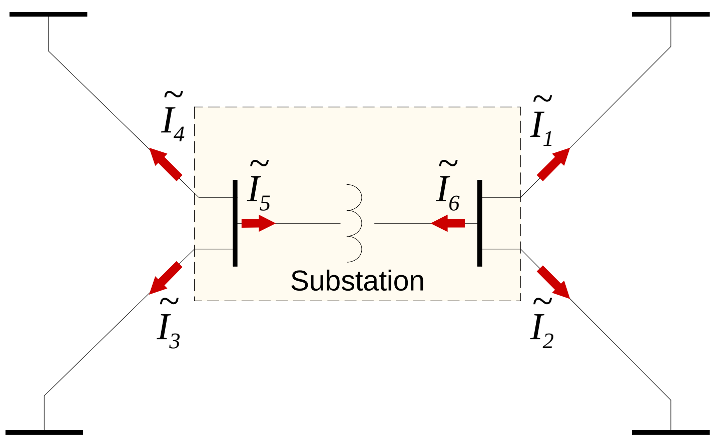
alpha is a synchronizing unknown variable

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

There is one alpha variable for each non-synchronized relay

SuperCalibrator Pseudo-Measurement Set

Kirchoff’s Current Law



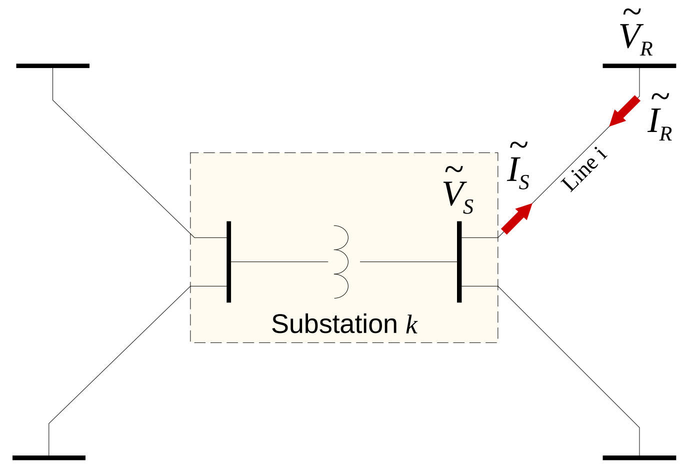
$$\tilde{I}_1 + \tilde{I}_2 + \tilde{I}_6 = 0$$

Expected Error: 0.001%

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

Expected Error: 0.001%

Remote End State Measurement



$$\tilde{V}_R^{pseudo,m} = \left(\mathbf{I} - Z_{22}Y_{22}\right)^{-1} Z_{21}\tilde{I}_S + \left(\mathbf{I} - Z_{22}Y_{22}\right)^{-1} Z_{22}Y_{21}\tilde{V}_S$$

Expected Error: 0.01%

SuperCalibrator: Estimation Method

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

GPS-Synchronized Measurements

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

Voltage Magnitude

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

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

Real Power

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

SuperCalibrator: Estimation Method

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

Solution

$$x^{\nu+1} = x^\nu + A[z - h(x)]$$

where: $A = \left[H^T W H\right]^{-1} \left[H^T W\right]$

Efficiency

Example, Long Bay Substation, High End PC

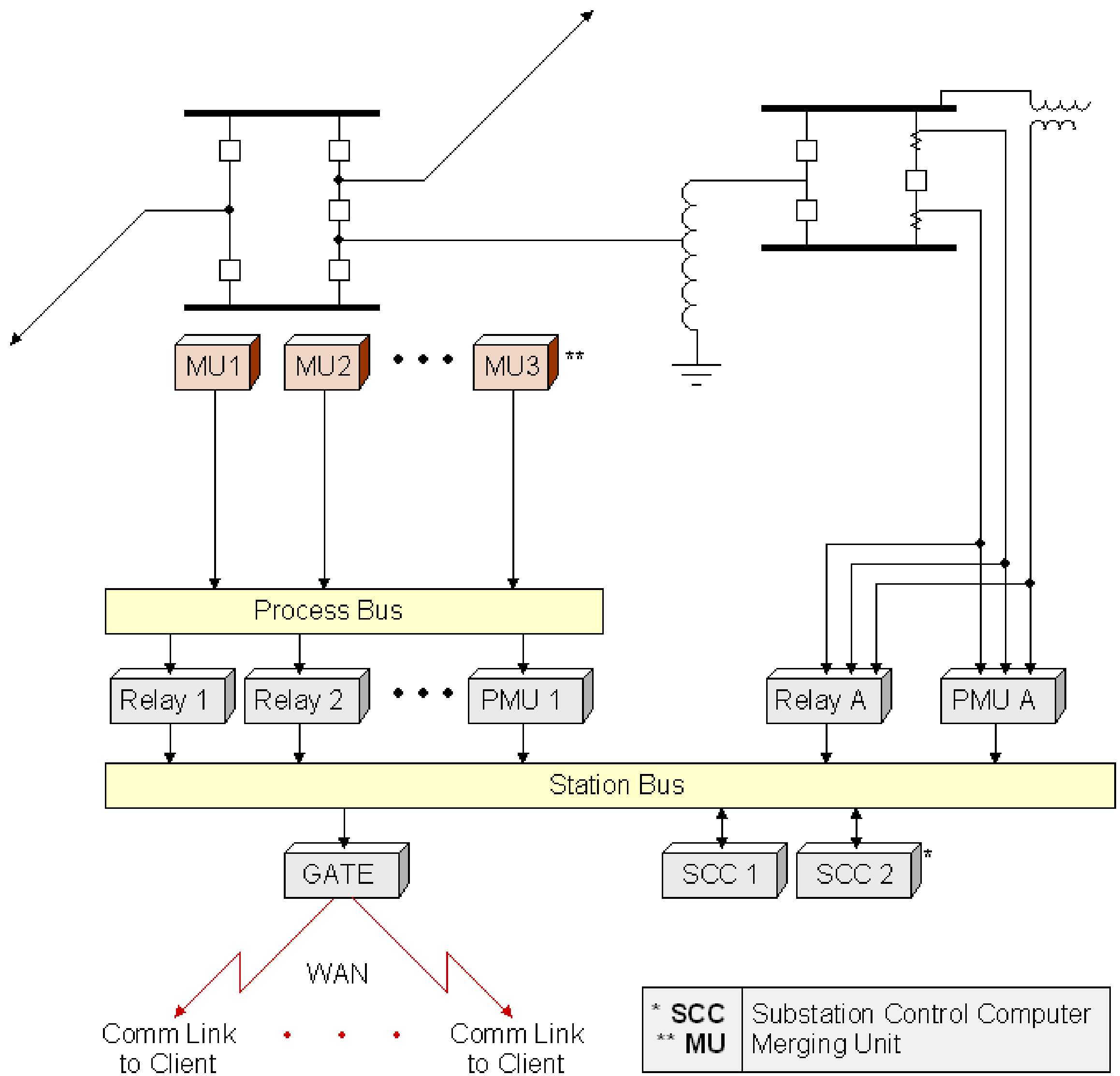
One Iteration: 18,000 multiply-adds (0.002 seconds)

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

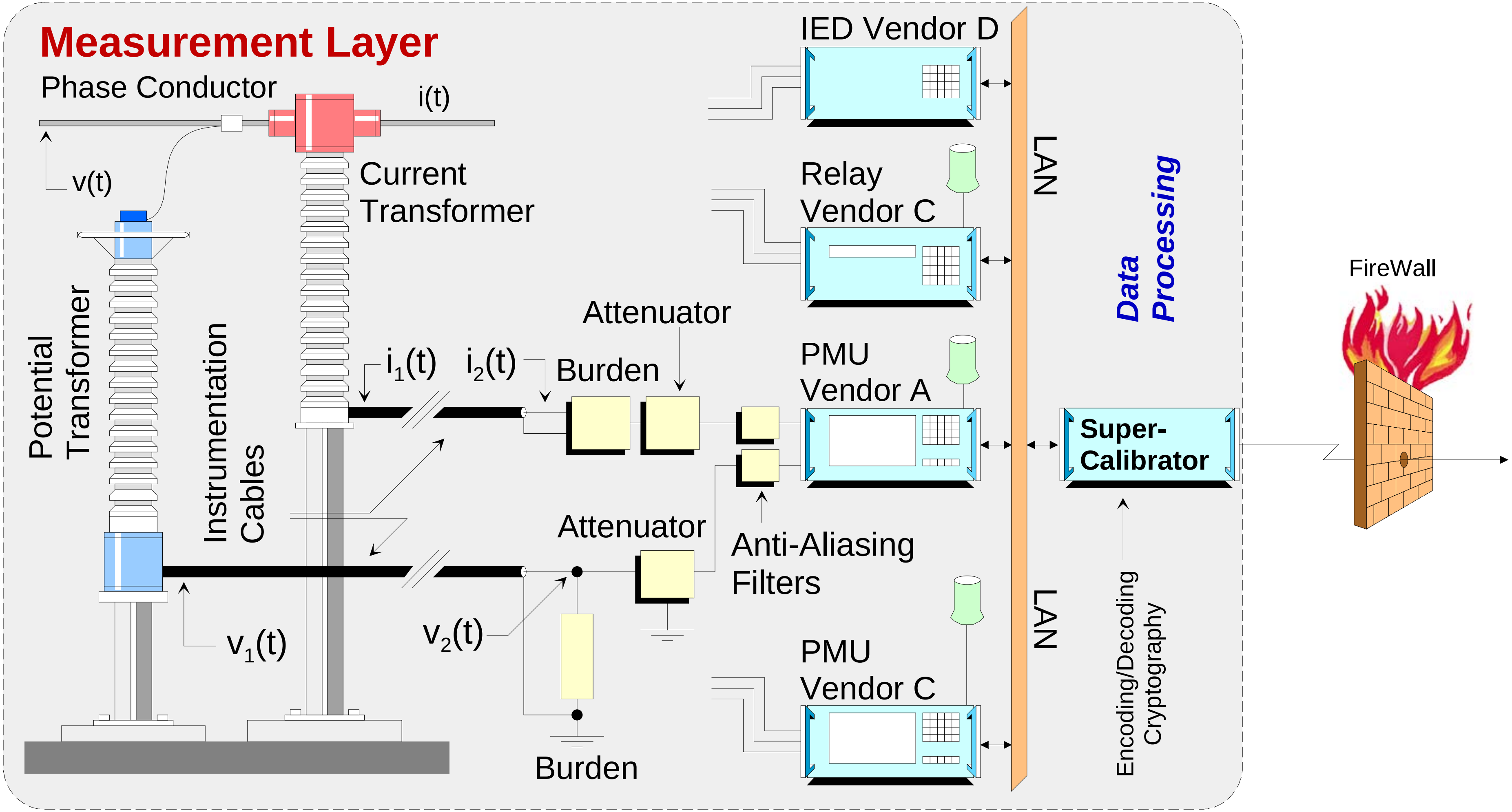
SuperCalibrator

Implementation

Present State of the Art: Smart Grid Infrastructure



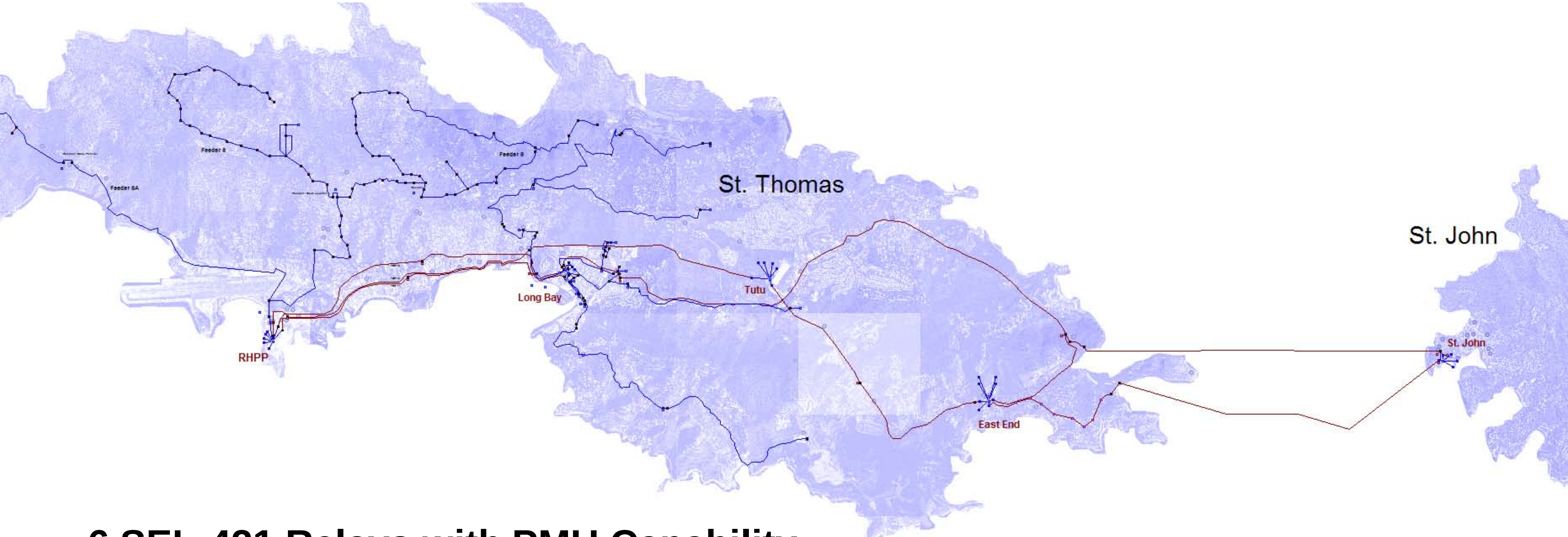
Providing Validated and High Accuracy Information



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

SuperCalibrator Implementation
Description: The VIWAPA System

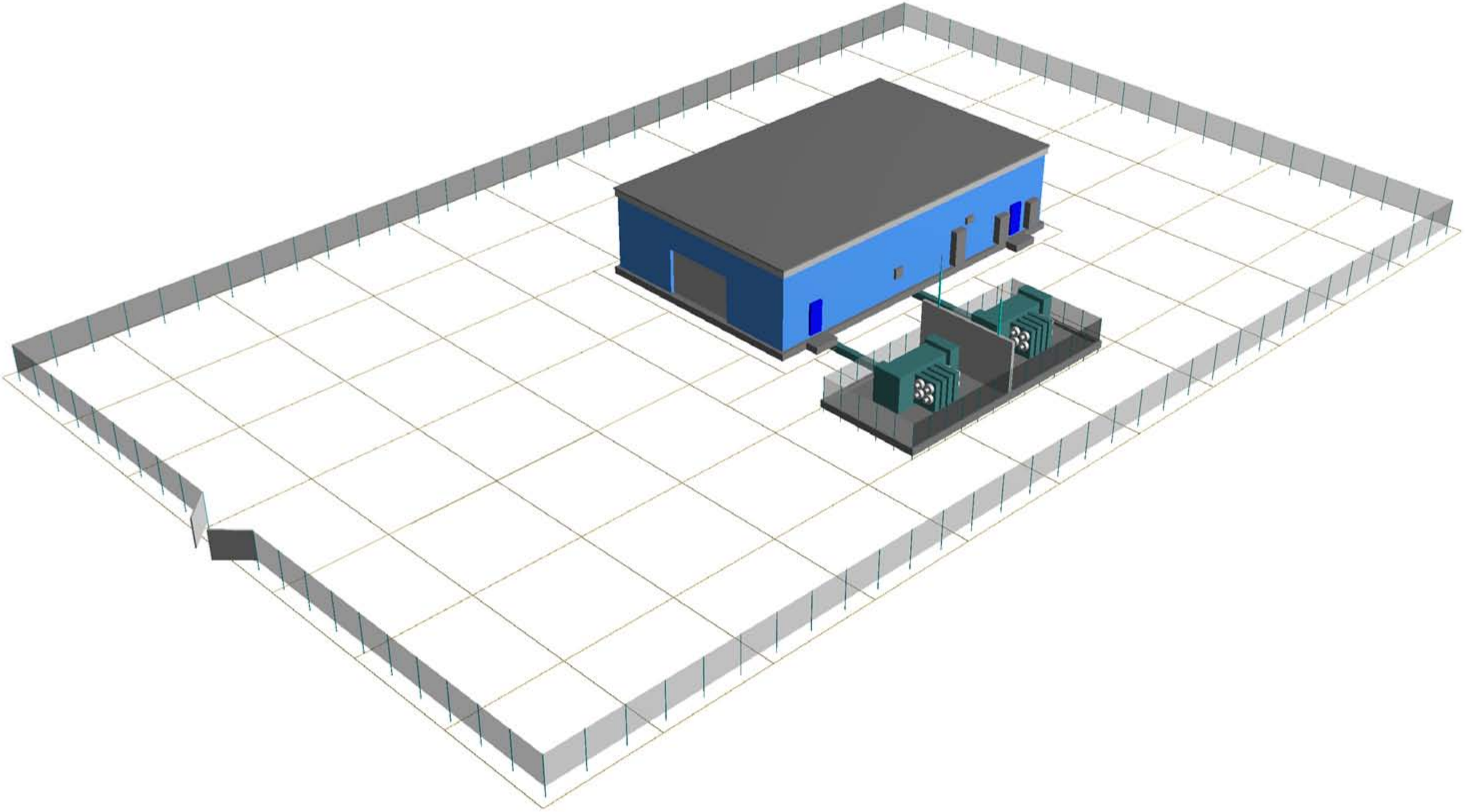
- 35 kV Transmission
- 13 kV Distribution
- Single Generating Plant (RHPP)
- Five Substations (RHPPlant, Long Bay, Tutu, East End, St. John)



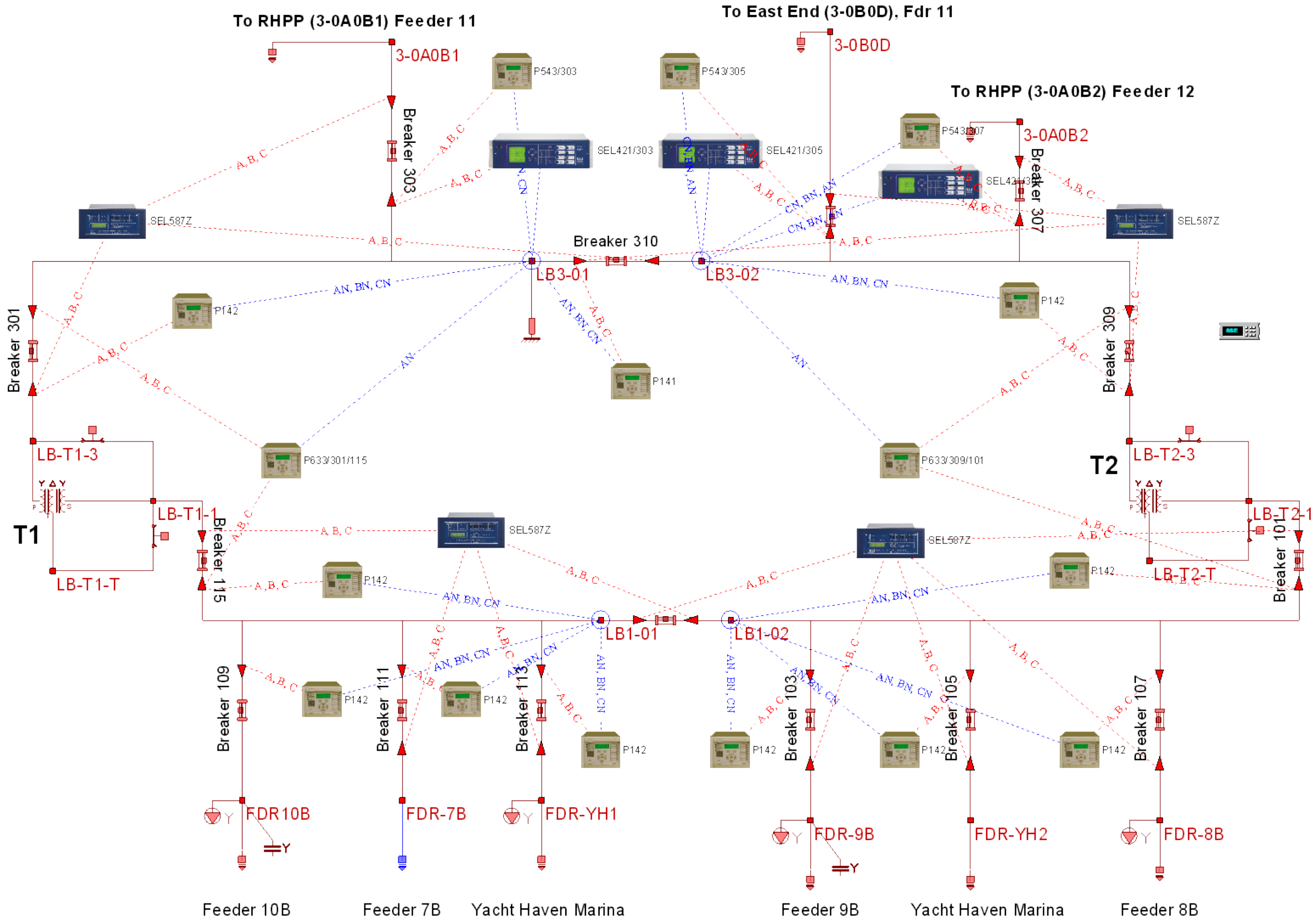
- 6 SEL-421 Relays with PMU Capability
- 3 SEL 734 Meters with PMU Capability
- Numerous Areva Relays (P141, P442, P142, etc.)
- There is at Least one PMU at Each Substation

SuperCalibrator Implementation

Substation Configuration – Long Bay – 3D Model

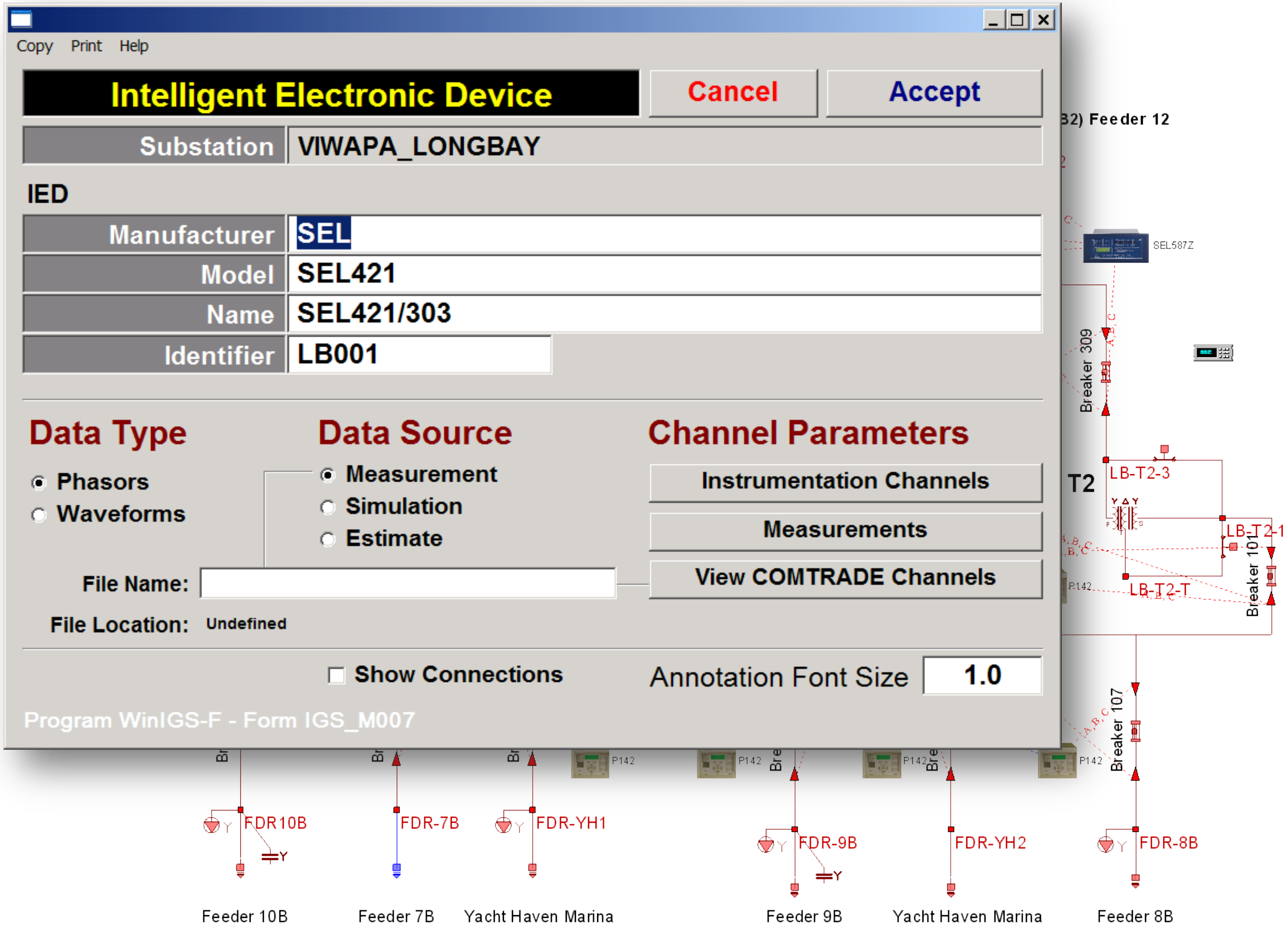


SuperCalibrator Implementation
Substation Configuration – Long Bay



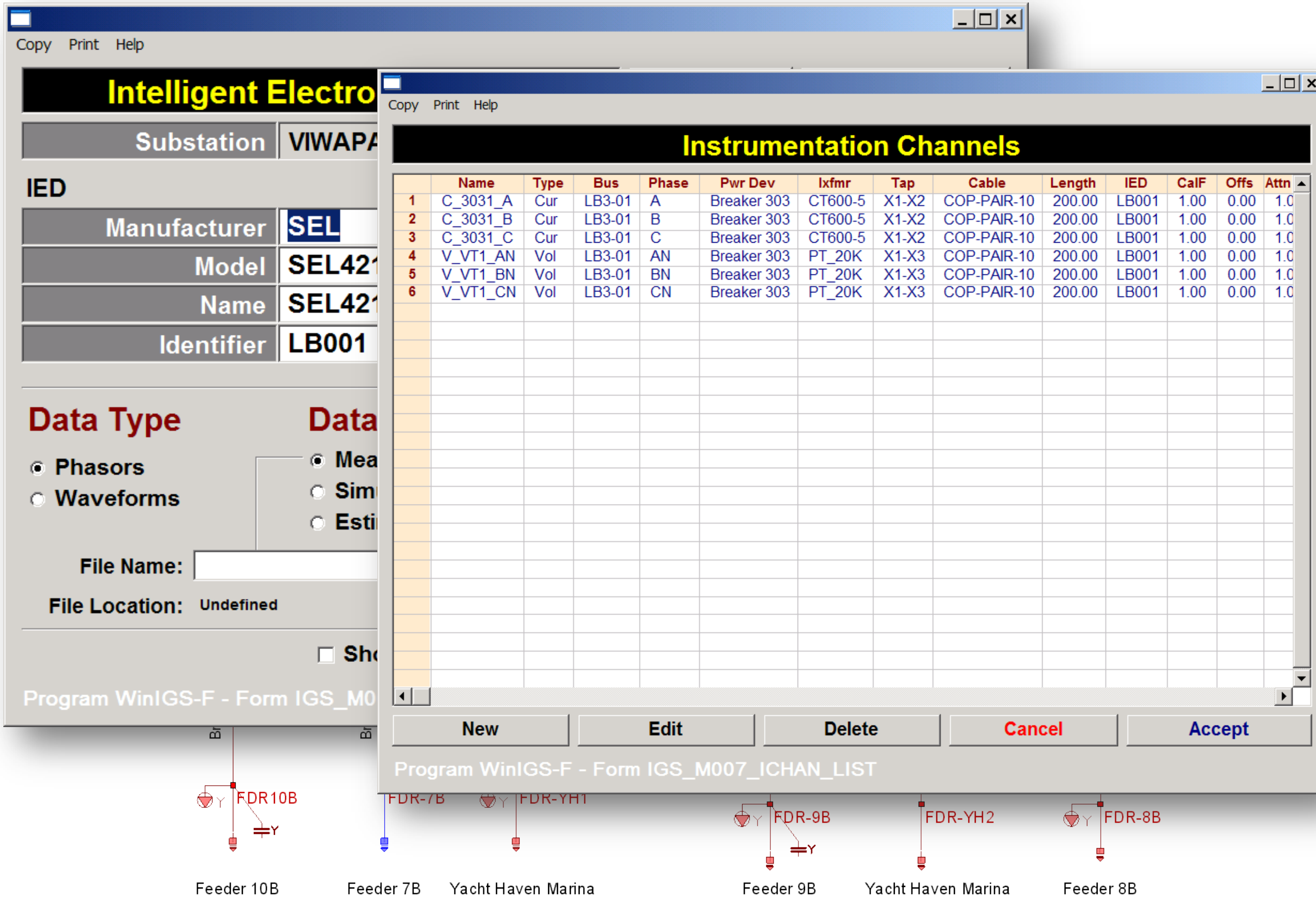
SuperCalibrator Implementation

Substation Configuration – Long Bay



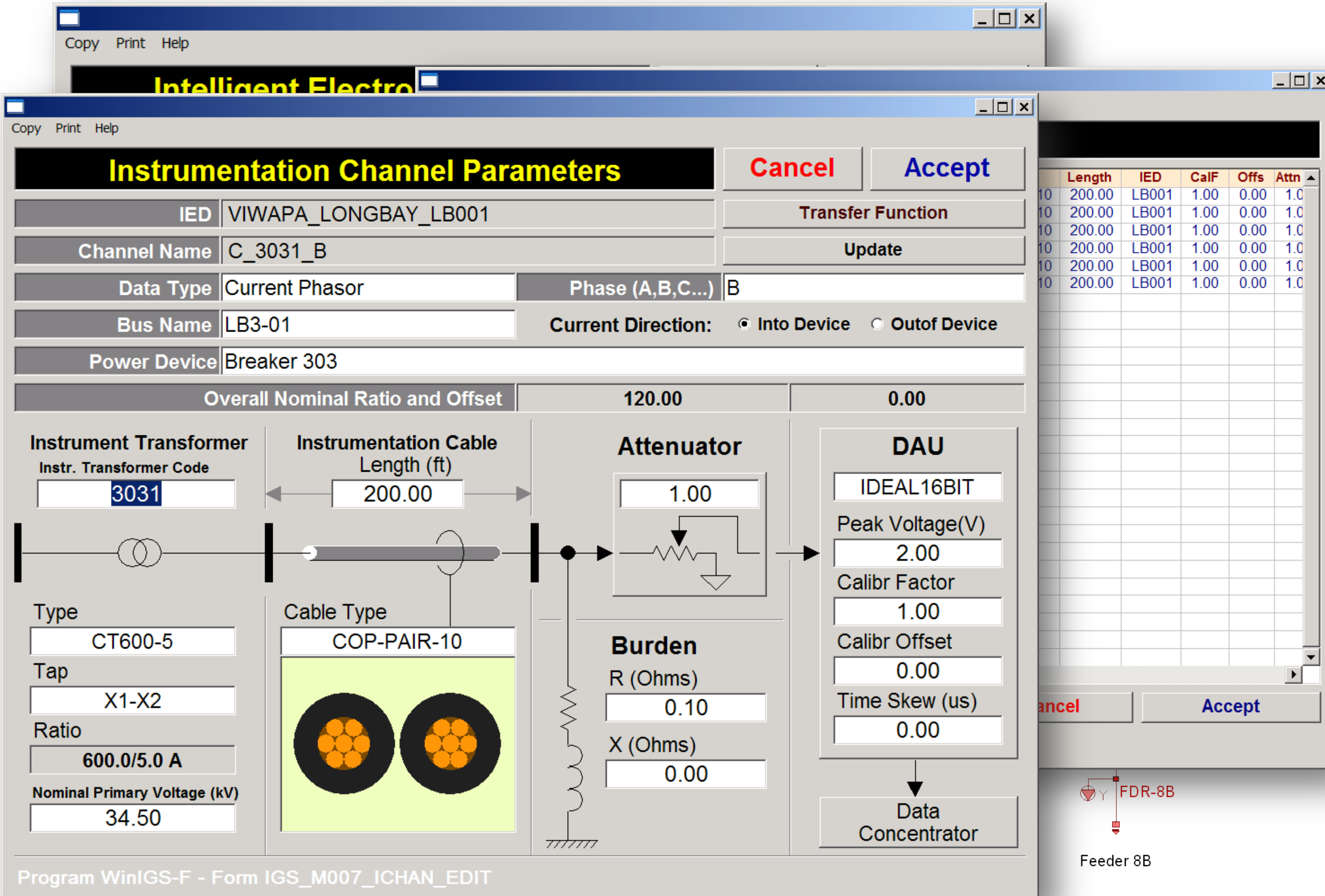
SuperCalibrator Implementation

Substation Configuration – Long Bay



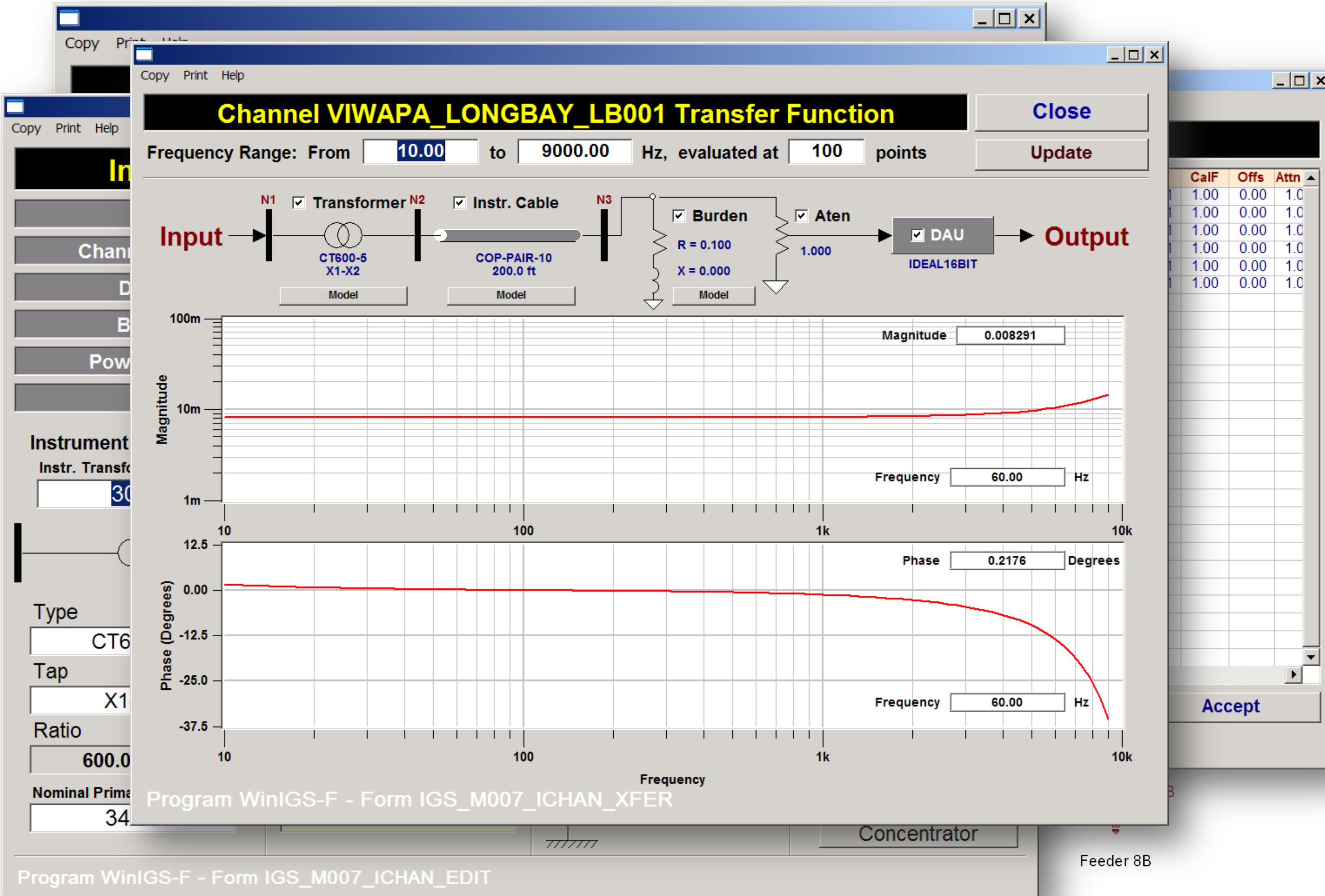
	Name	Type	Bus	Phase	Pwr Dev	Ixfmr	Tap	Cable	Length	IED	CalF	Offs	Attn
1	C_3031_A	Cur	LB3-01	A	Breaker 303	CT600-5	X1-X2	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
2	C_3031_B	Cur	LB3-01	B	Breaker 303	CT600-5	X1-X2	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
3	C_3031_C	Cur	LB3-01	C	Breaker 303	CT600-5	X1-X2	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
4	V_VT1_AN	Vol	LB3-01	AN	Breaker 303	PT_20K	X1-X3	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
5	V_VT1_BN	Vol	LB3-01	BN	Breaker 303	PT_20K	X1-X3	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
6	V_VT1_CN	Vol	LB3-01	CN	Breaker 303	PT_20K	X1-X3	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0

SuperCalibrator Implementation
Substation Configuration – Long Bay



SuperCalibrator Implementation

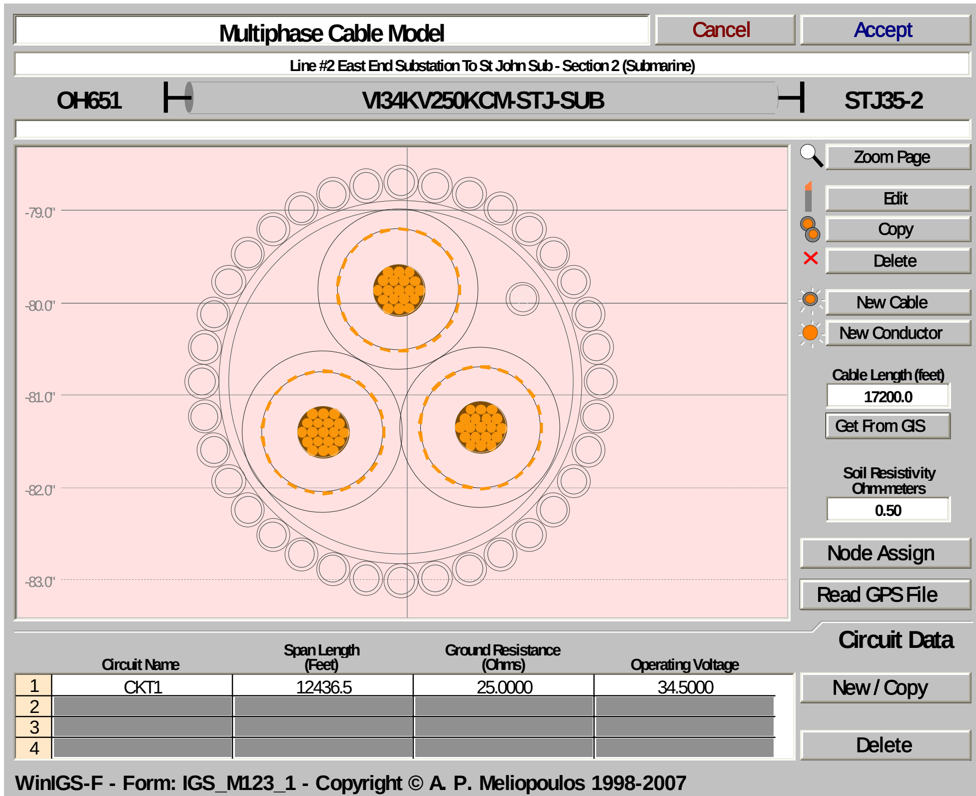
Substation Configuration – Long Bay



SuperCalibrator Power System Model:

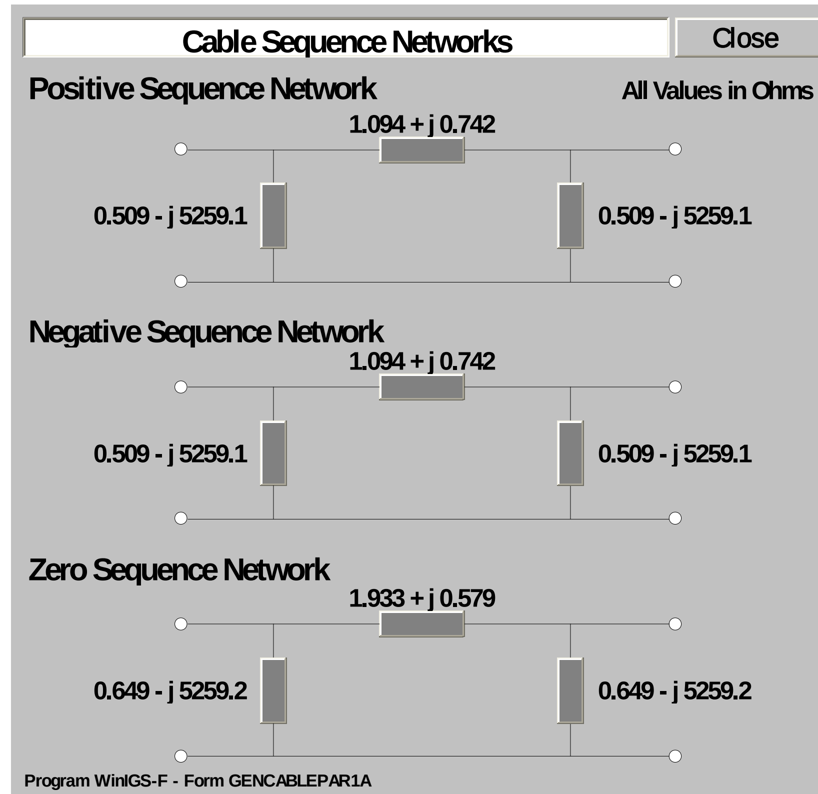
Physically Based Three-Phase Model: Example

Physically Based Model



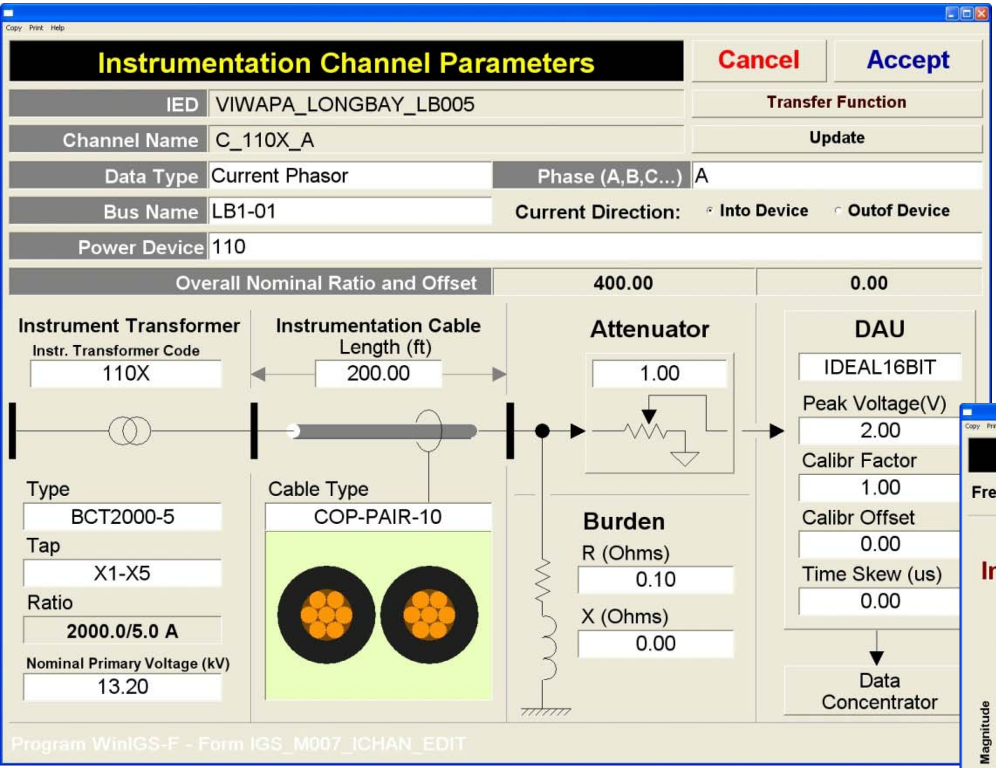
Sequence Parameter Model

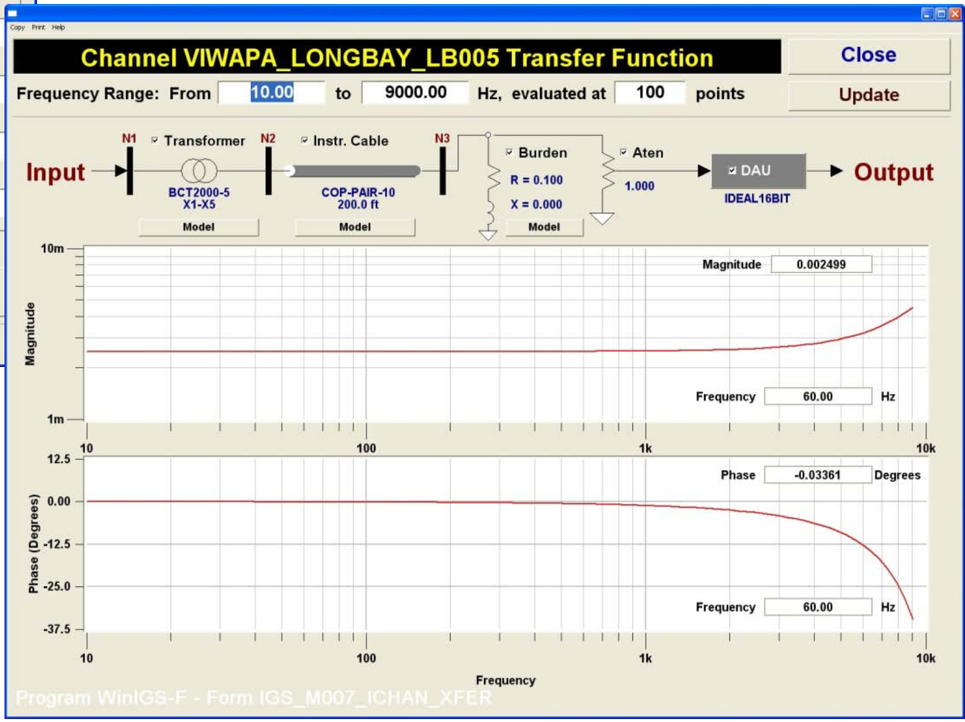
Not Used – for Info Only



SuperCalibrator Instrumentation Model:

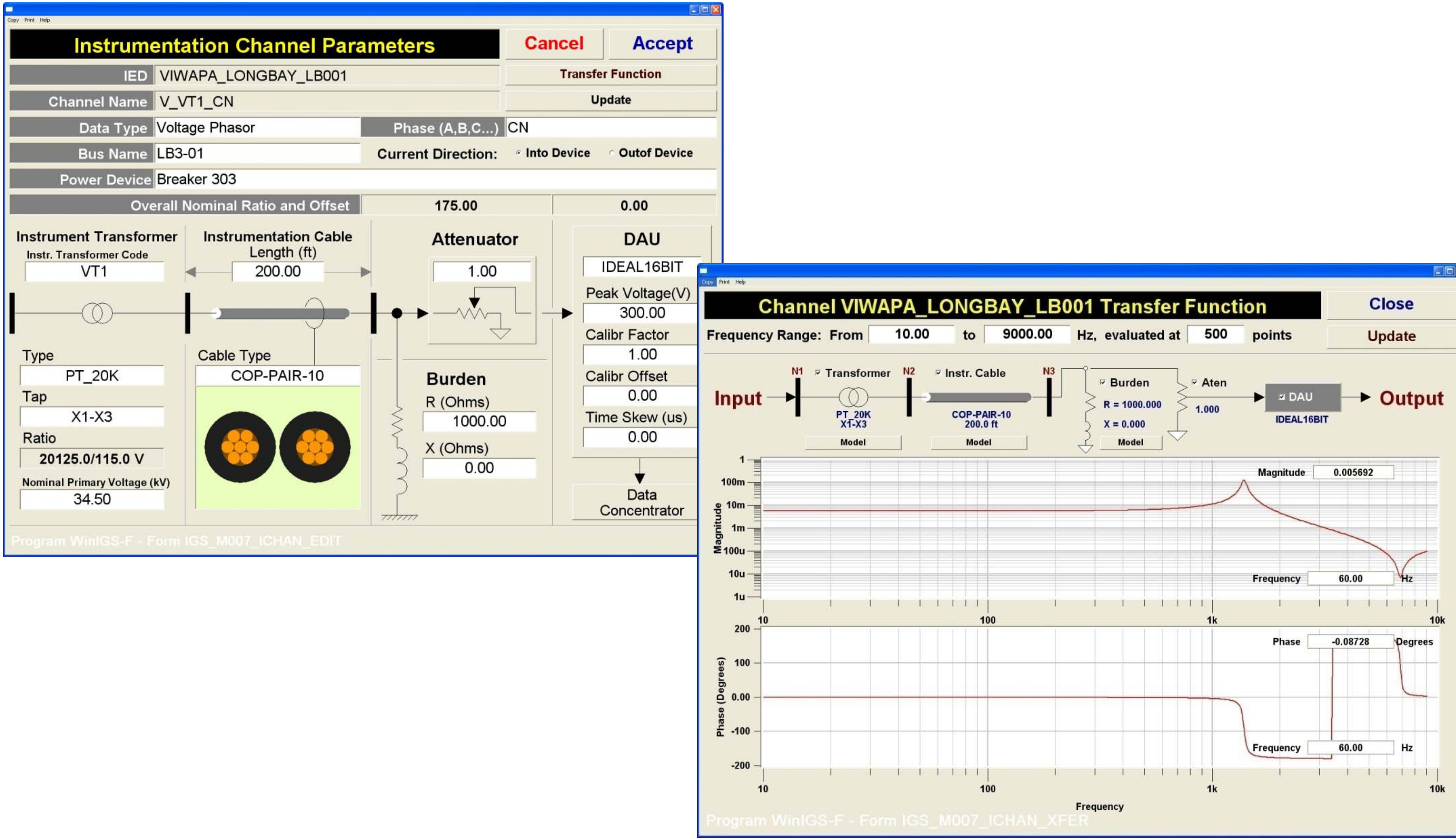
Physically Based Instrumentation Model: Example





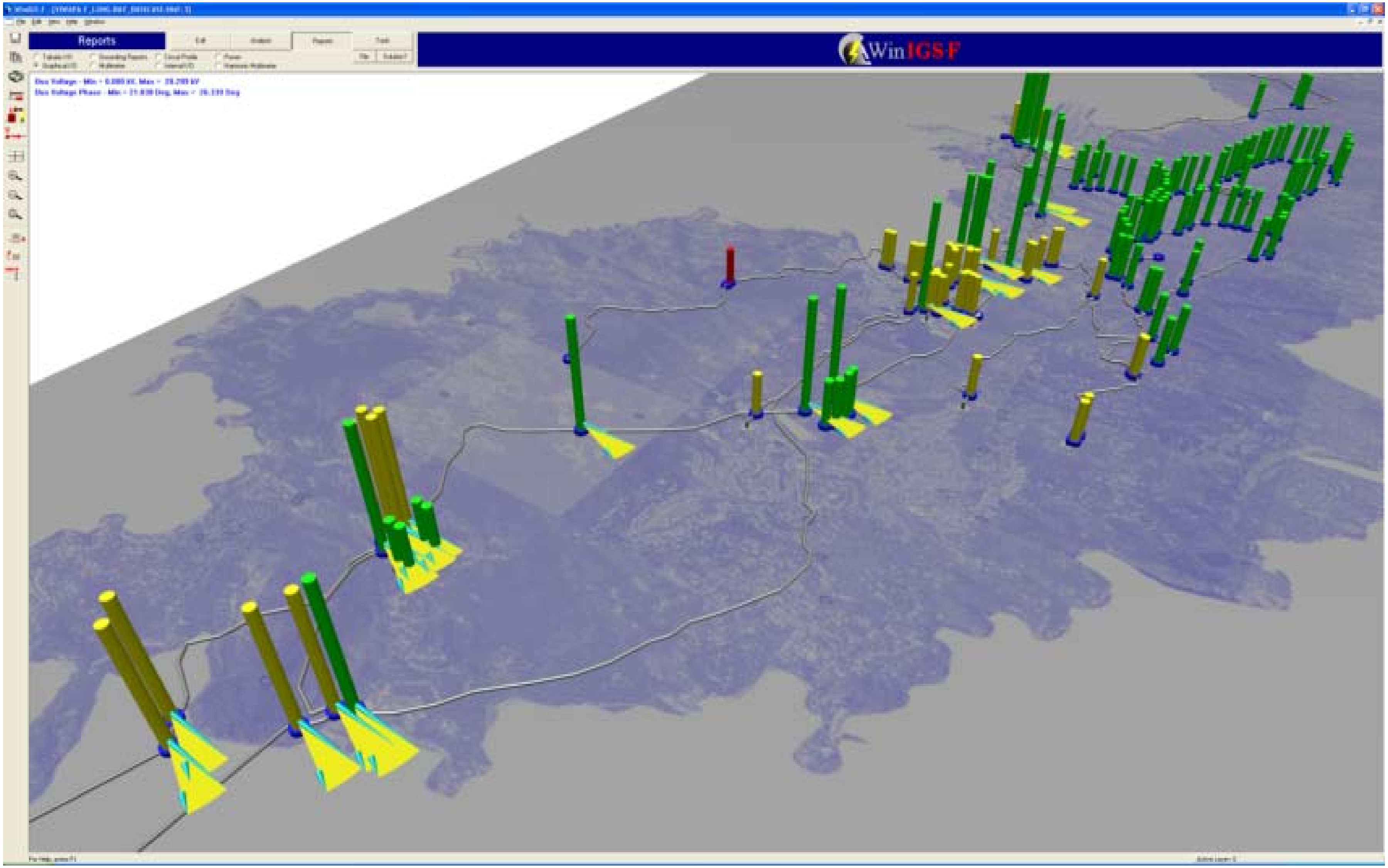
SuperCalibrator Instrumentation Model:

Physically Based Instrumentation Model: Example



SuperCalibrator Installation: USVI – 5 Substations

The SuperCalibrator Runs 4 Times per Second



SuperCalibrator

Accuracy Assessment

Quantification of SuperCalibrator Output Accuracy

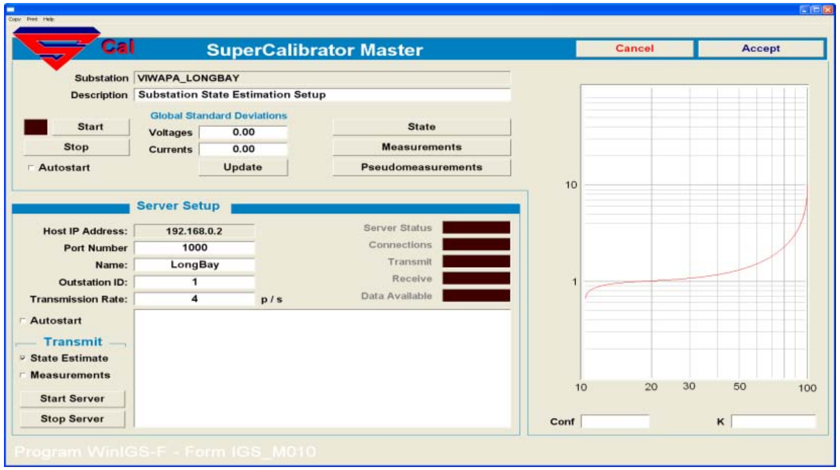
- Chi-Square Test provides a measure of how well the measurements "fit" the model on a probabilistic basis. Equations omitted

- The SuperCalibrator provides a measure of the uncertainty of the estimated states. Equations omitted.

- The SuperCalibrator provides a measure of Measurement error – to be used for remote calibration. Equations omitted.

Overall Performance Metric

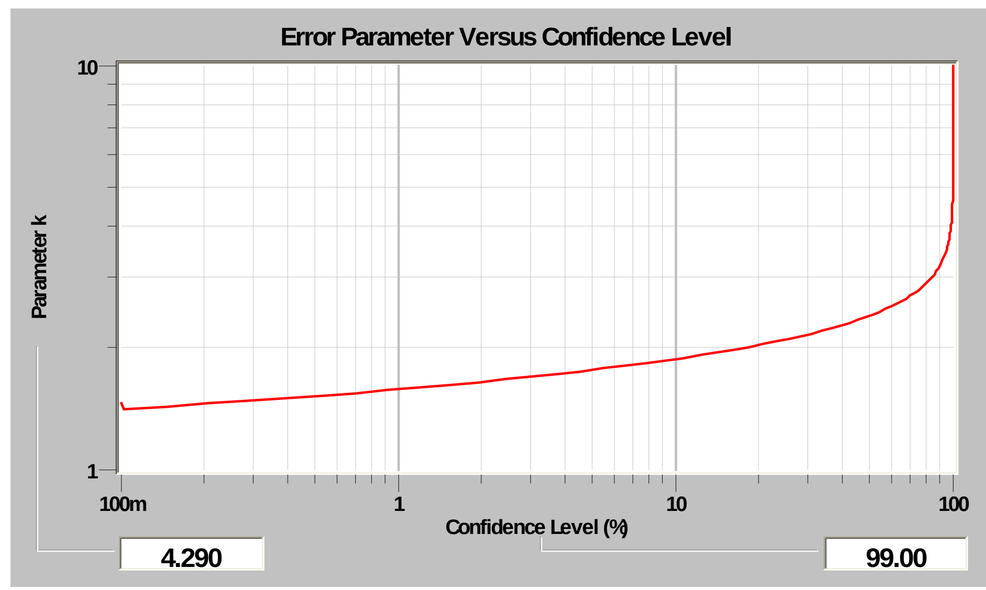
Chi-Square Test



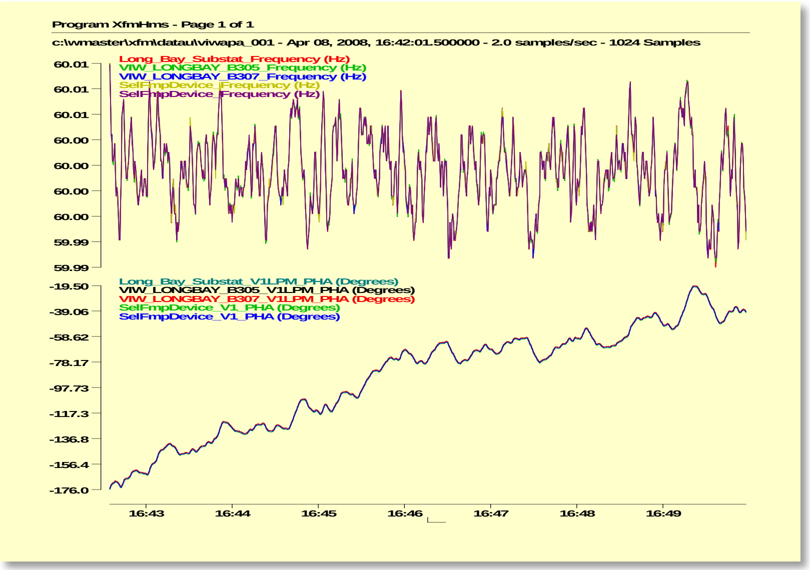
We have introduced the variable k

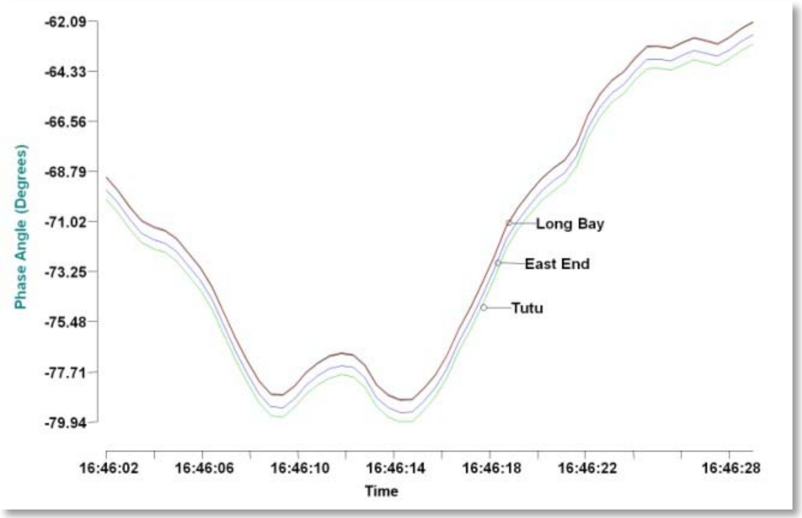
Error = k.MeterSigma

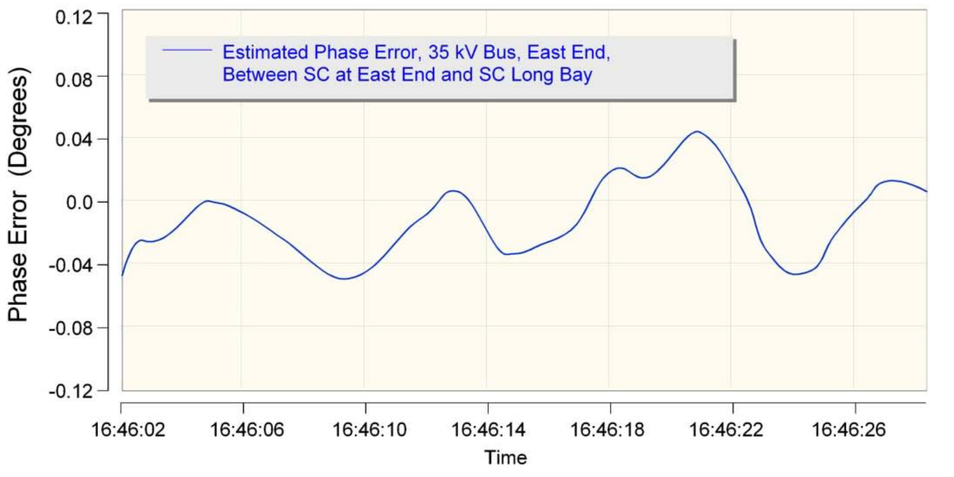
Overall Error is Provided in Terms of the Variable k



Performance Monitoring of the SC-Base SE

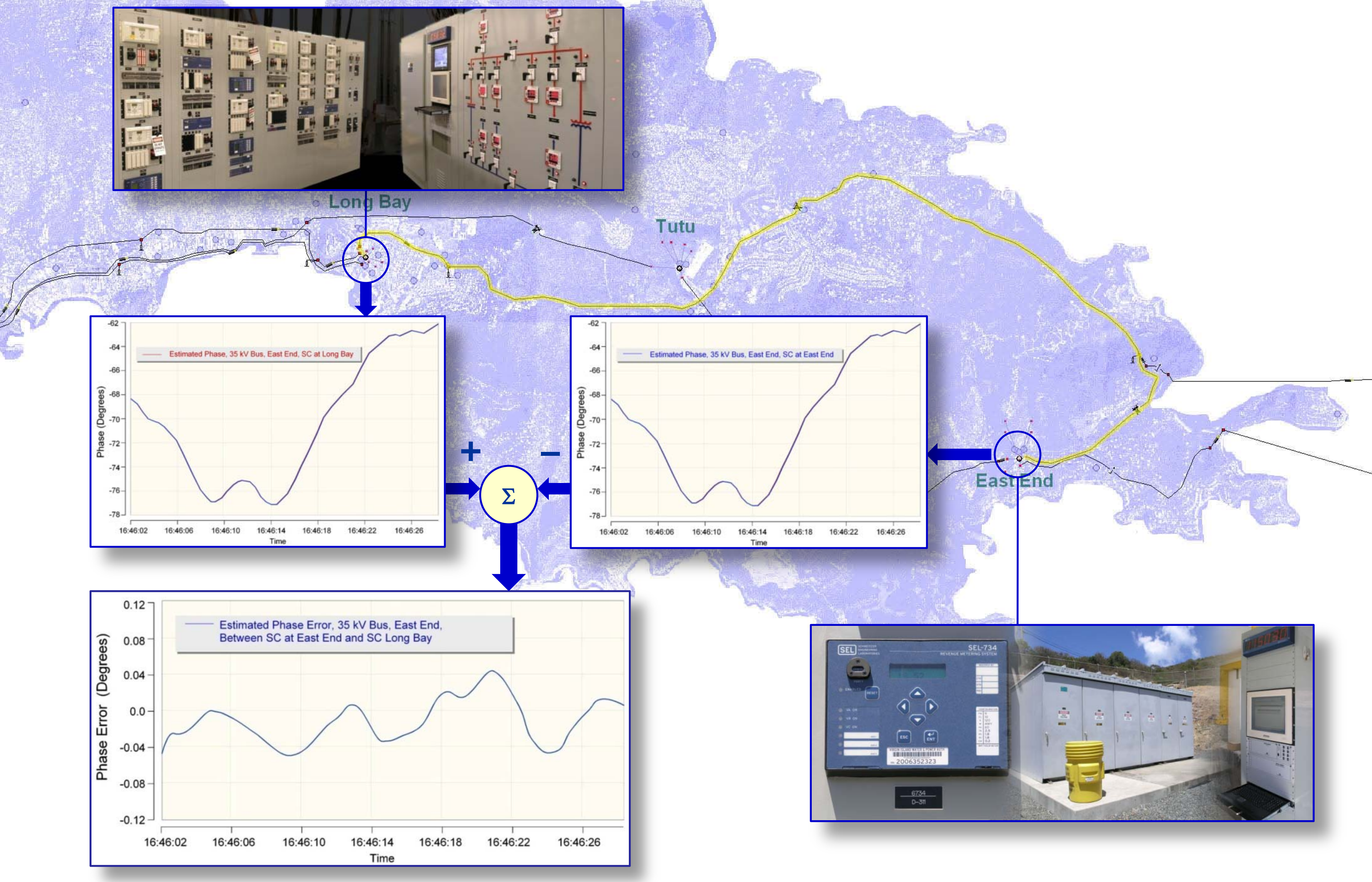






St. Thomas

Computation of Phase Error



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%

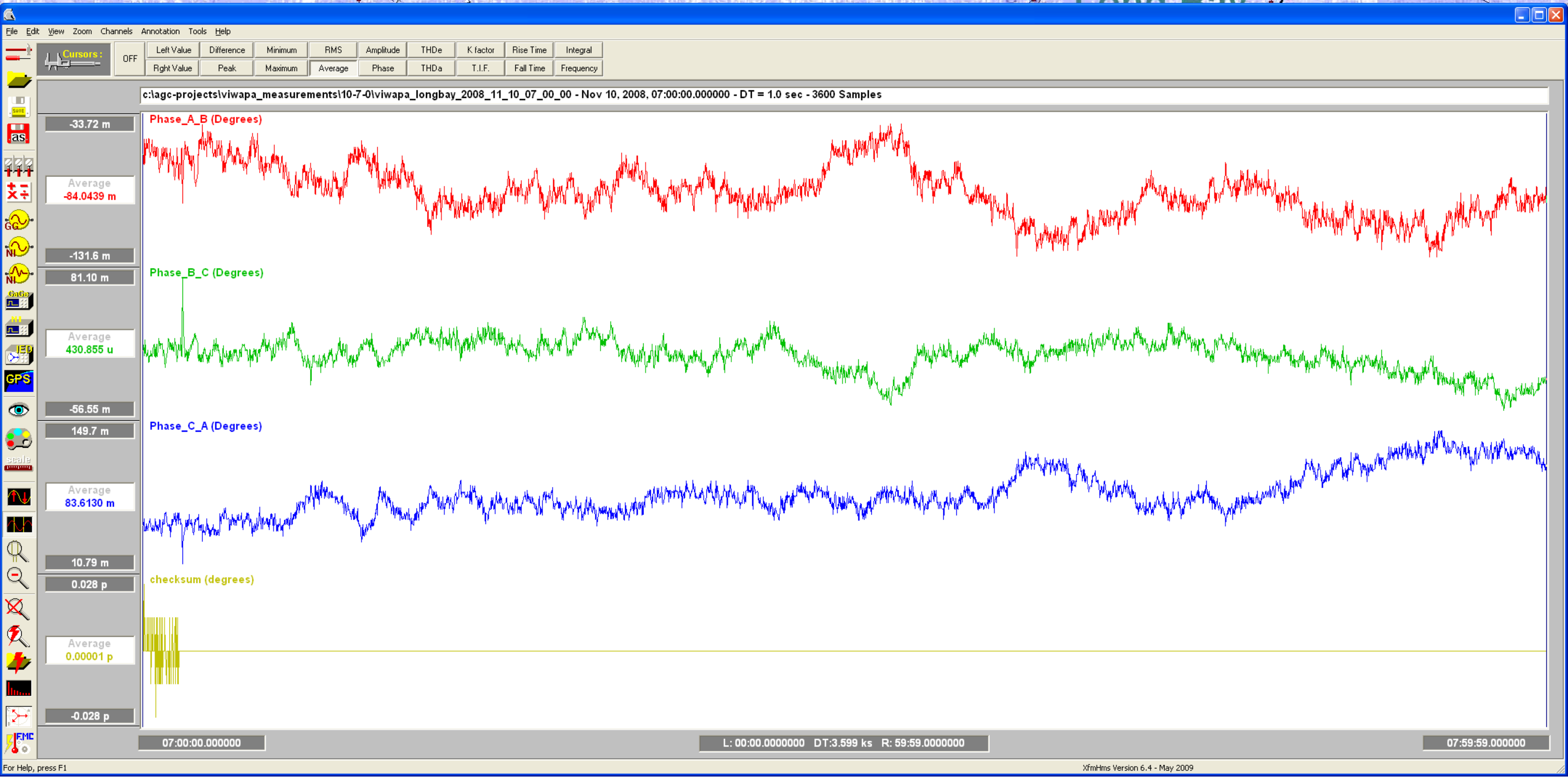
Syncrophasor Data Processing Example

Voltage Phase Imbalance

Max Phase Imbalance: 0.150 Degrees

Waveform Calculator Formula Example (Phases B and C):

LB001_V_VT1_CN_R LB001_V_VT1_CN_I R2PHAS UNWIND LB001_V_VT1_BN_R LB001_V_VT1_BN_I R2PHAS UNWIND – 120 +



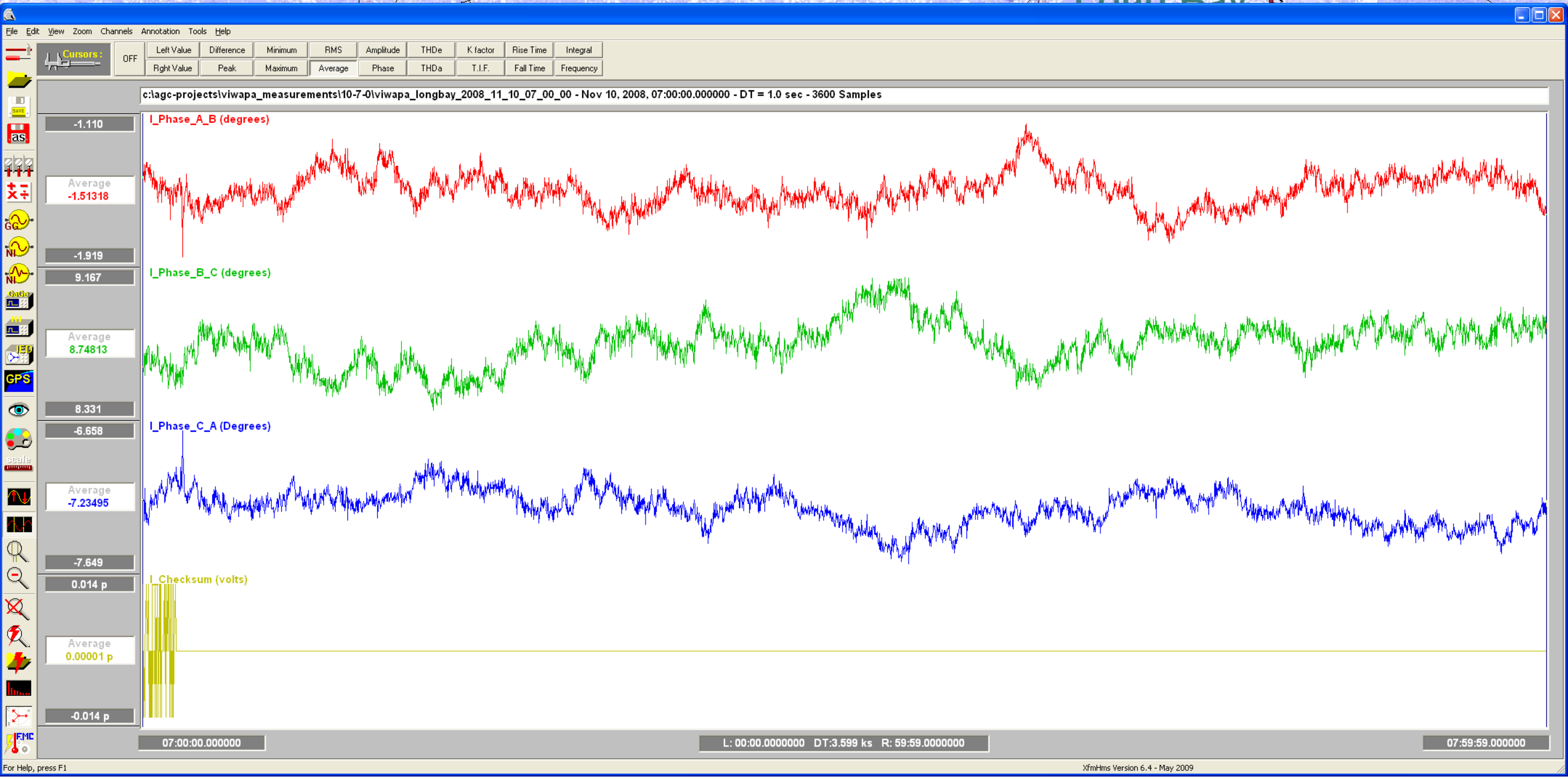
Syncrophasor Data Processing Example

Current Phase Imbalance

Max Phase Imbalance: 8.748 Degrees

Waveform Calculator Formula Example (Phases A and B):

LB001_C_3031_B_R LB001_C_3031_B_I R2PHAS UNWIND LB001_C_3031_A_R LB001_C_3031_A_I R2PHAS UNWIND – 120 +



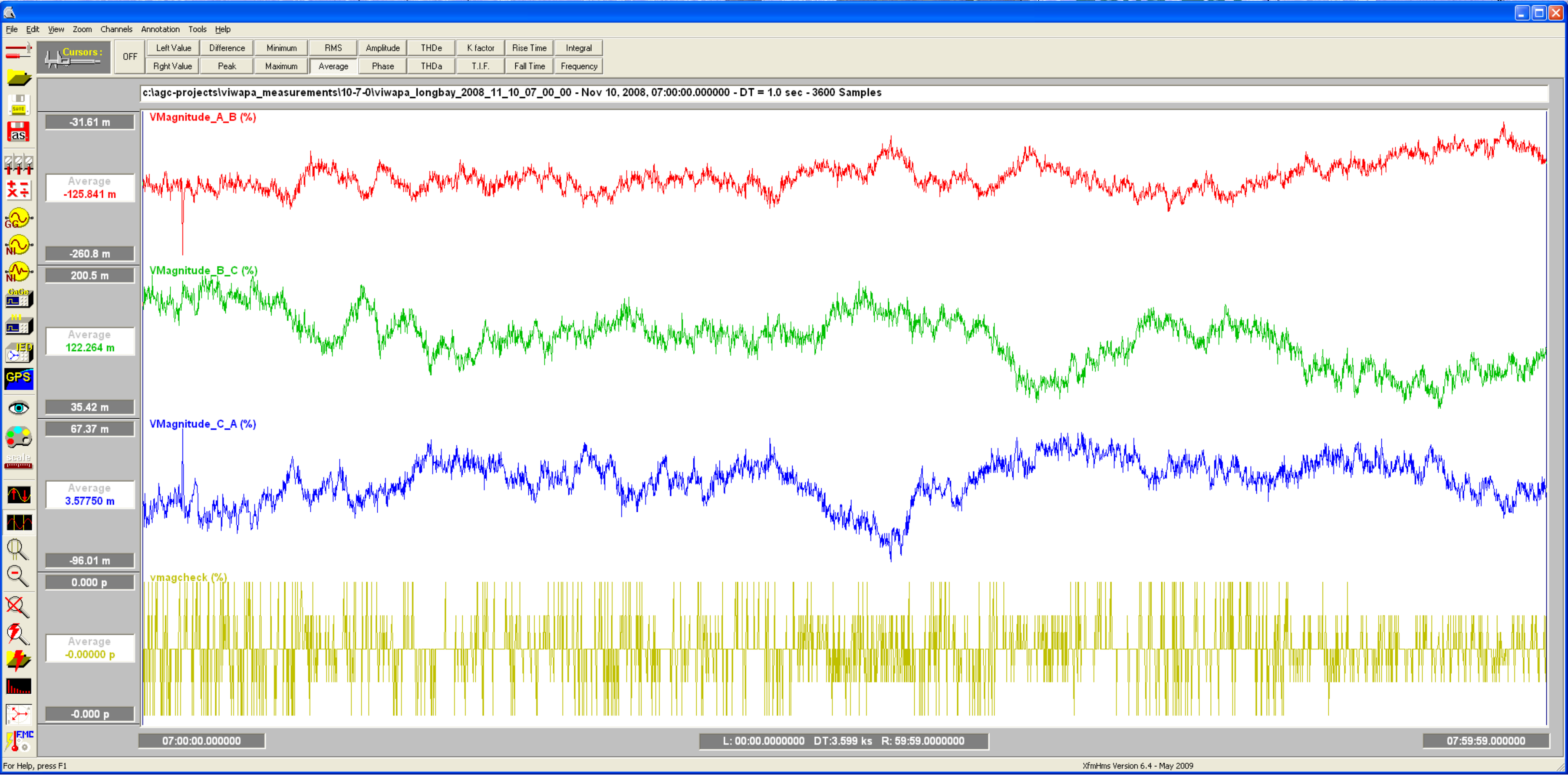
Syncrophasor Data Processing Example

Voltage Magnitude Imbalance

Max Magnitude Imbalance: 0.122 pu

Waveform Calculator Formula Example (Phases A and B):

LB001_V_VT1_BN_R LB001_V_VT1_BN_I R2MAGN LB001_V_VT1_AN_R LB001_V_VT1_AN_I R2MAGN – 199.185 /



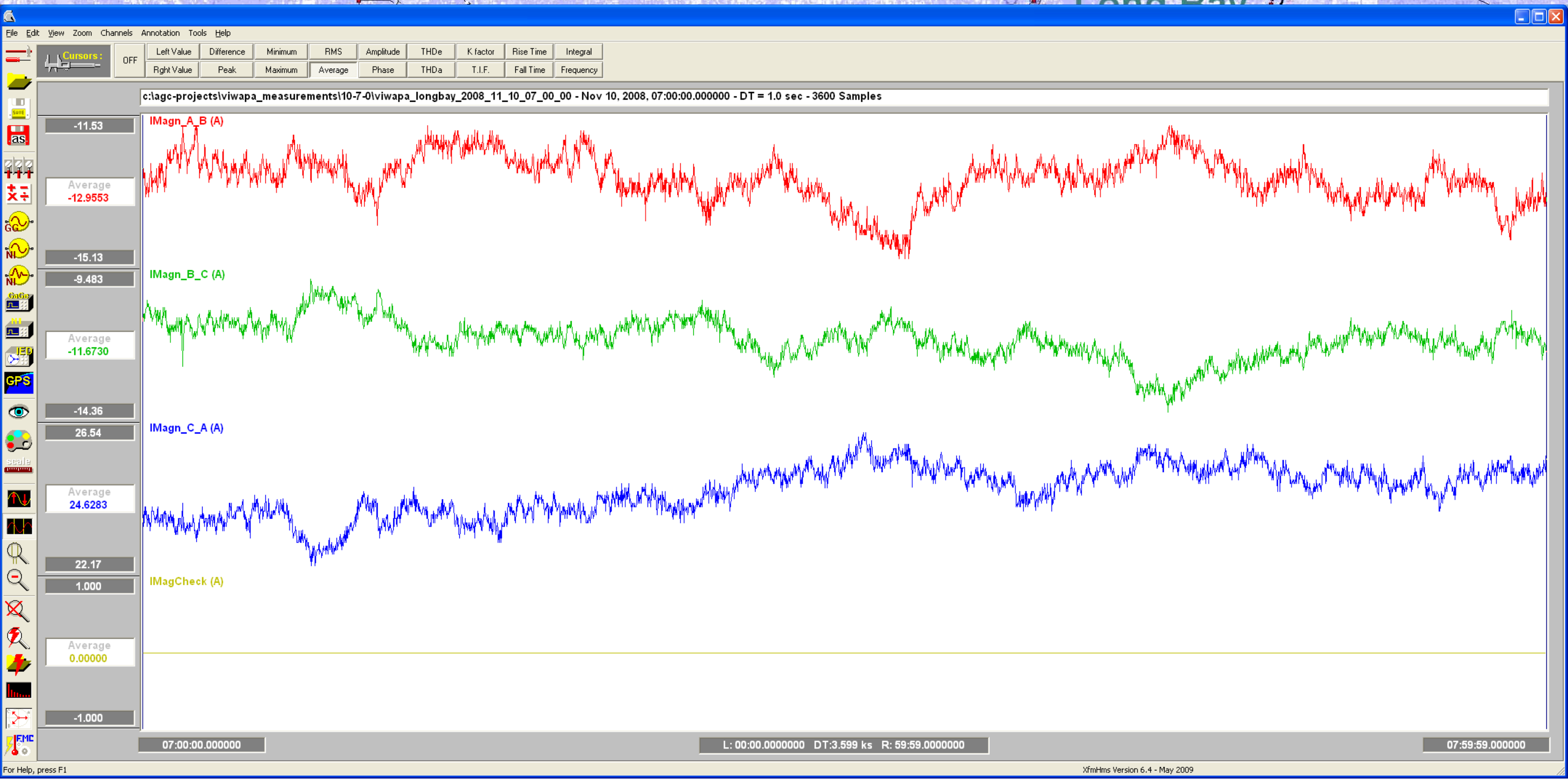
Syncrophasor Data Processing Example

Current Magnitude Imbalance

Max Current Imbalance: 24 A (About 13%)

Waveform Calculator Formula (Phases A and B):

LB001_C_3031_B_R LB001_C_3031_B_I R2MAGN LB001_C_3031_A_R LB001_C_3031_A_I R2MAGN –

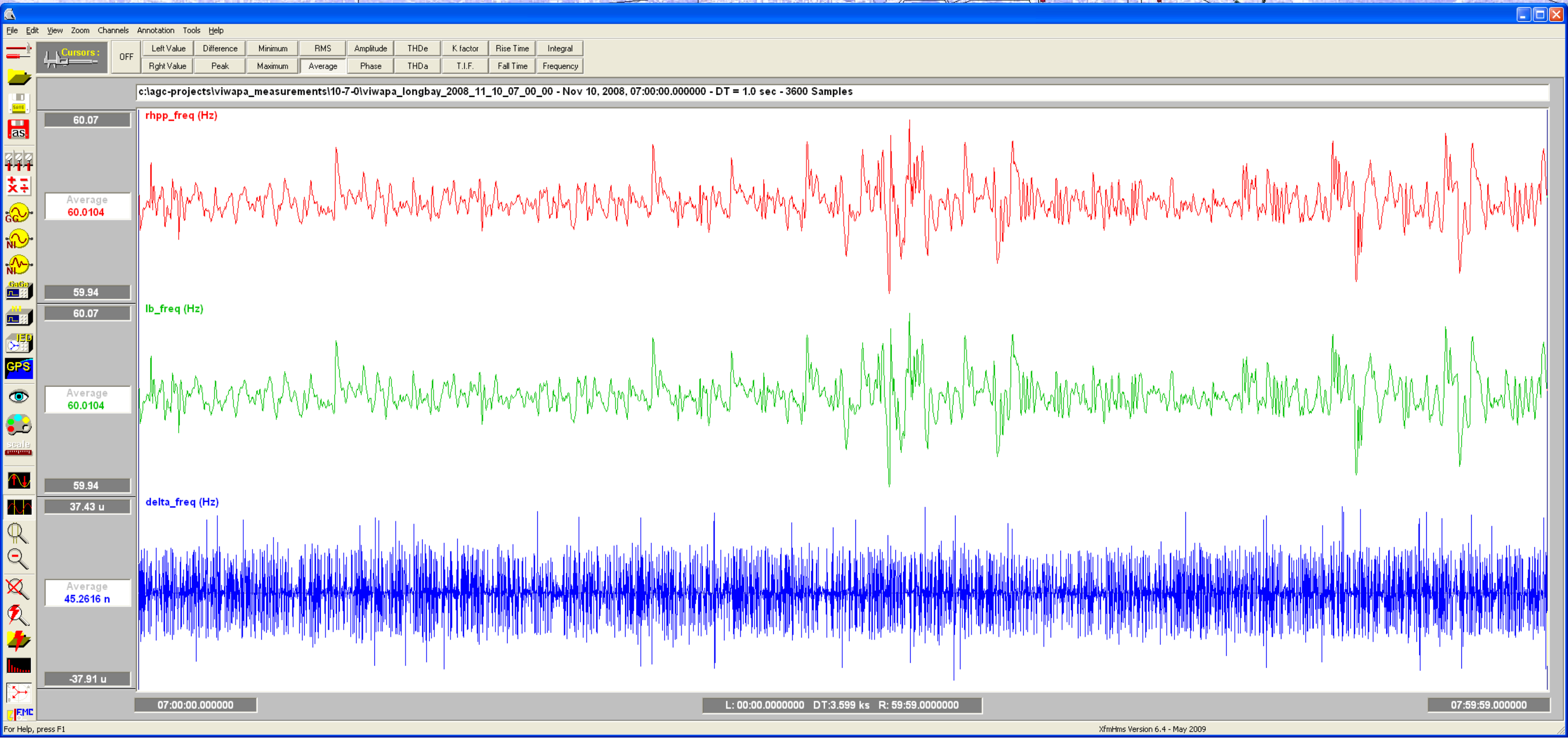


Syncrophasor Data Processing Example

Computation of Frequency

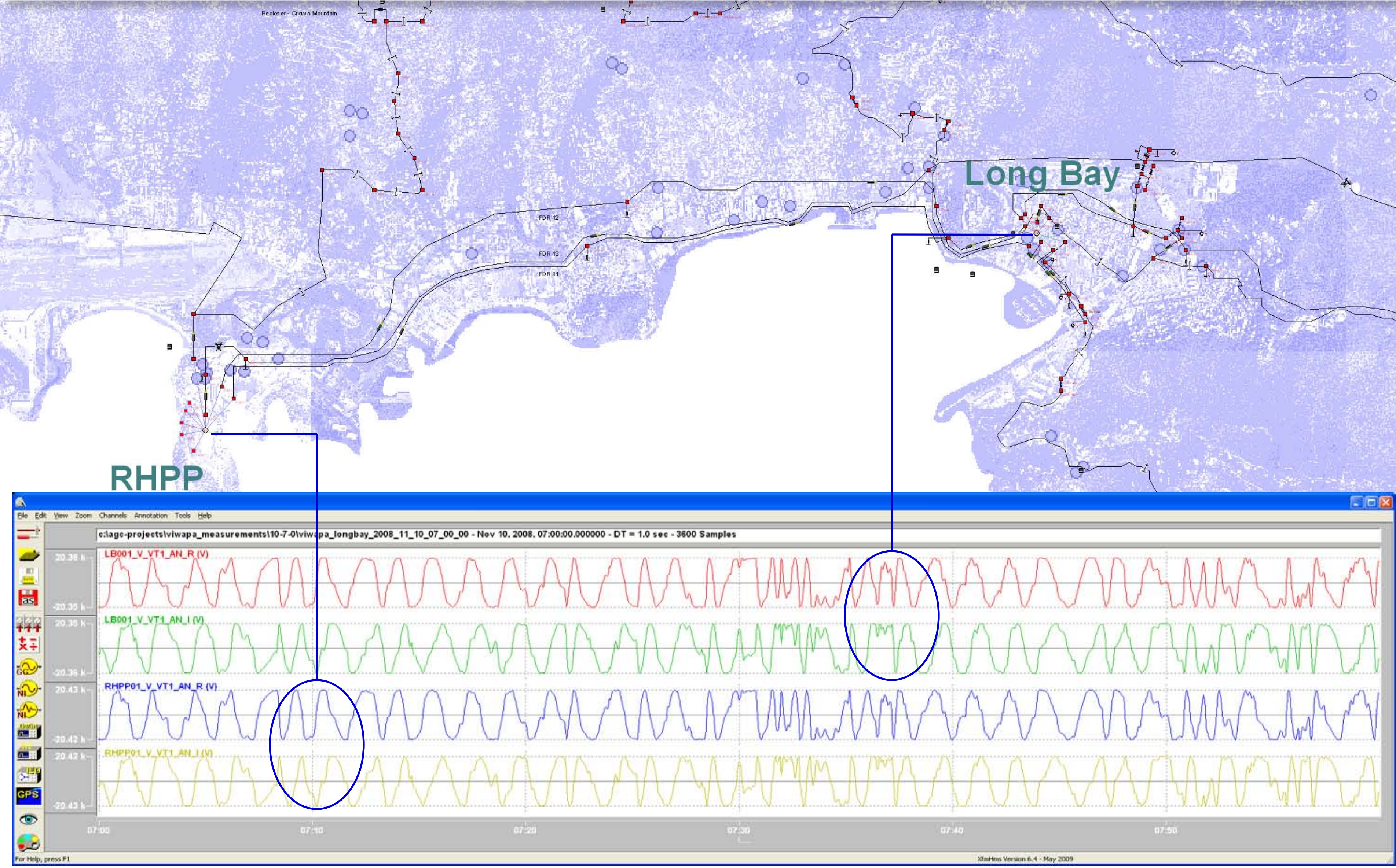
Note:
Average Frequency 60.0104 Hertz
Average Frequency Difference 45 NanoHertz

$$f = \frac{\Delta\theta}{\Delta t} \times 360 + 60$$



Synchrophasor Data Processing Example – Raw Data

1 hour at 1 sample per second

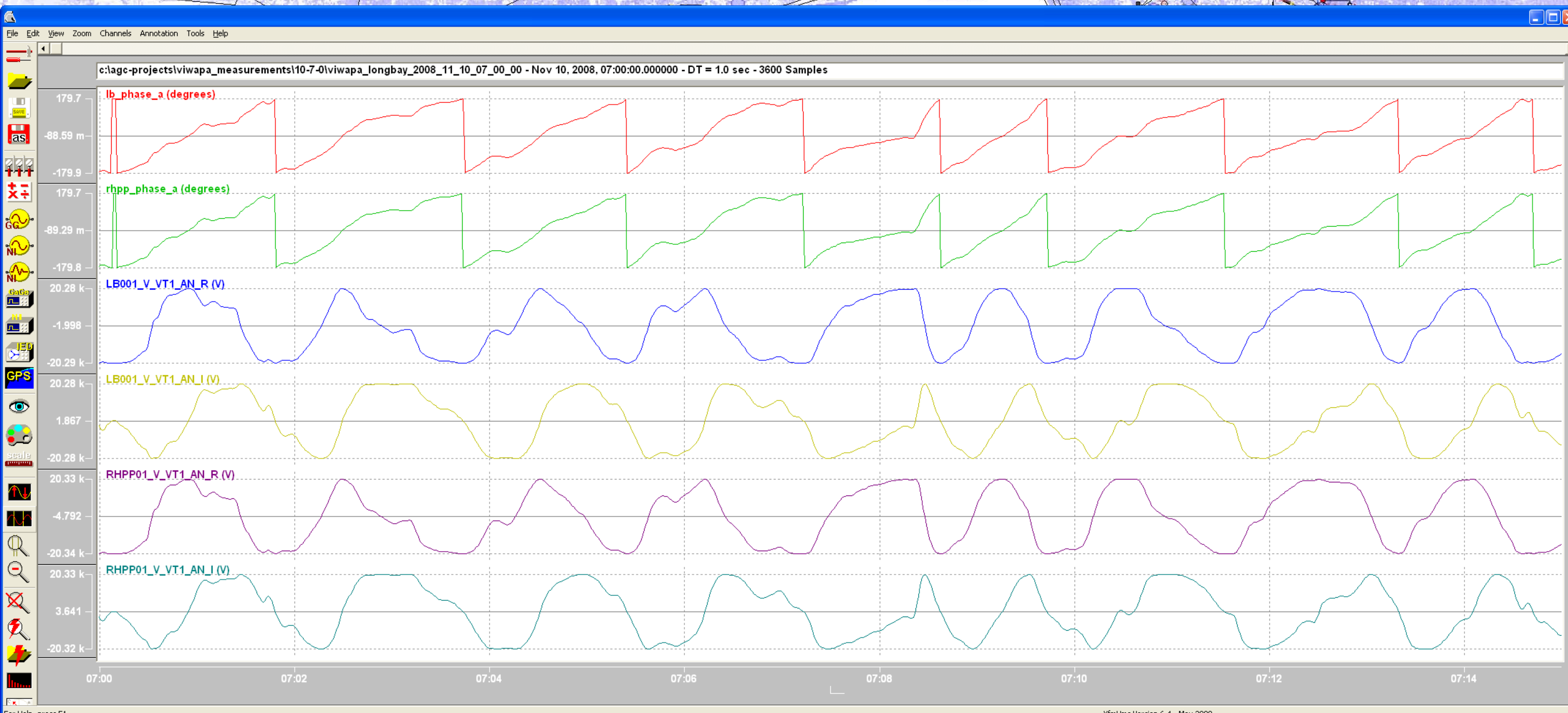


Syncrophasor Data Processing Example

Computation of Phase Angle

$$\theta = \operatorname{atan2}(\operatorname{Im}(V), \operatorname{Re}(V))$$

Note that the phase discontinuity is an artifact of the arctangent function range limits



Advantages of the Super-Calibrator Approach

- Utilization of All Data – Relay, SCADA, PMU
- Operates on Streaming Data from ALL DEVICES at the Substation Level – Distributed SE – Generates Streaming State to Other Concentrators (Information)
- DATA VALIDATION: Quantifies Data Accuracy – Remote Calibration
- Capable of Storing Data+Model Simultaneously
- Minimizes Data to be Transferred (very important)
  - - Communication of Information not Raw Data
  - - Improved Latencies