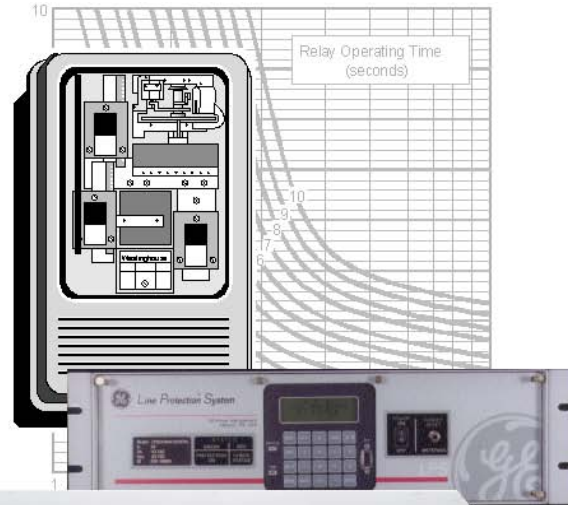


Distributed State Estimator - SuperCalibrator Approach

Delivering Accurate and Reliable Data to All



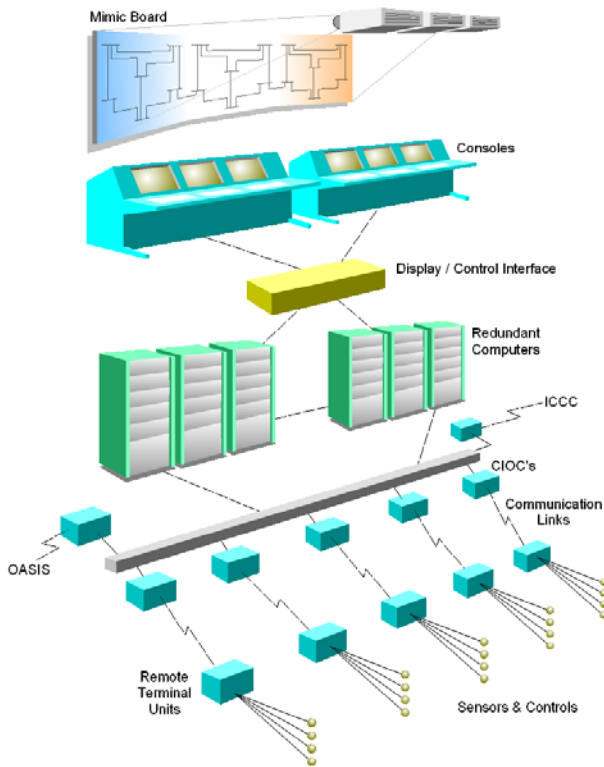
Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332



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

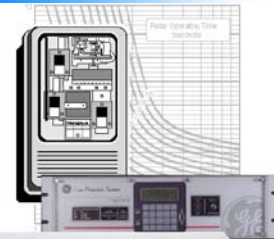
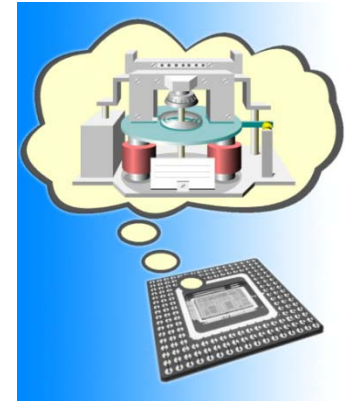
generators, transformers,
lines, motors, capacitors,
reactors

System Protection

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

Communications

Substation Automation,
Enterprise, 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**

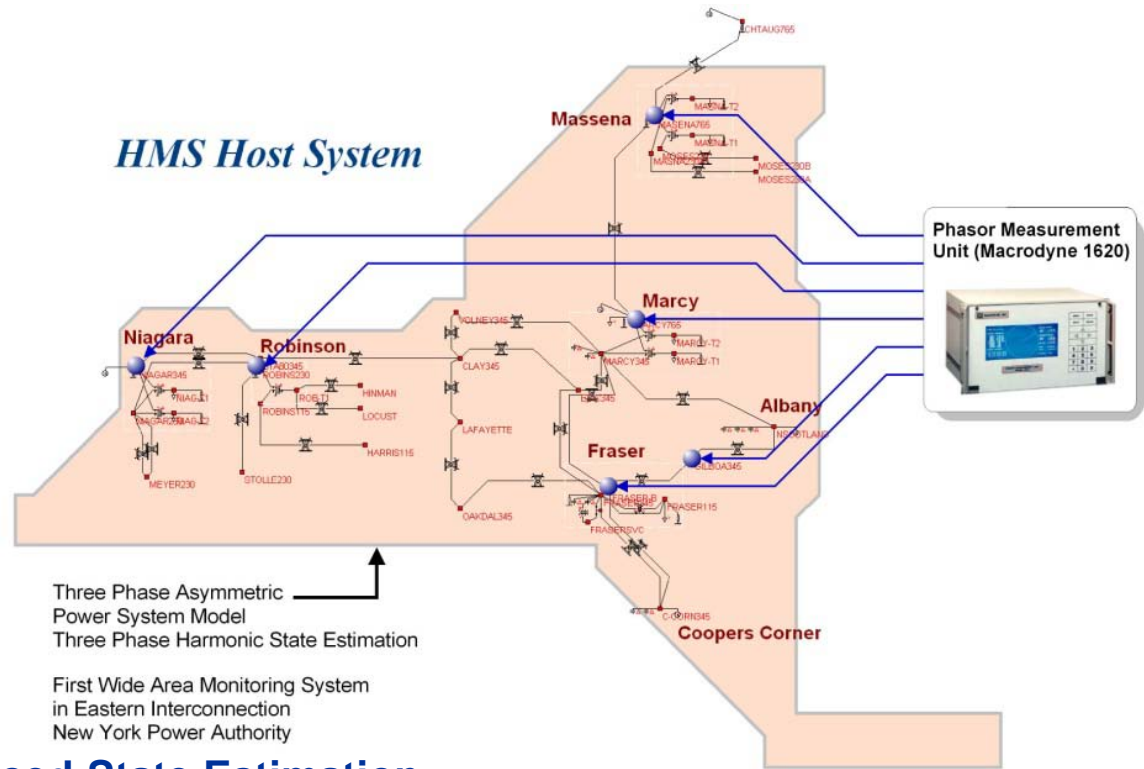
The SuperCalibrator Concept

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

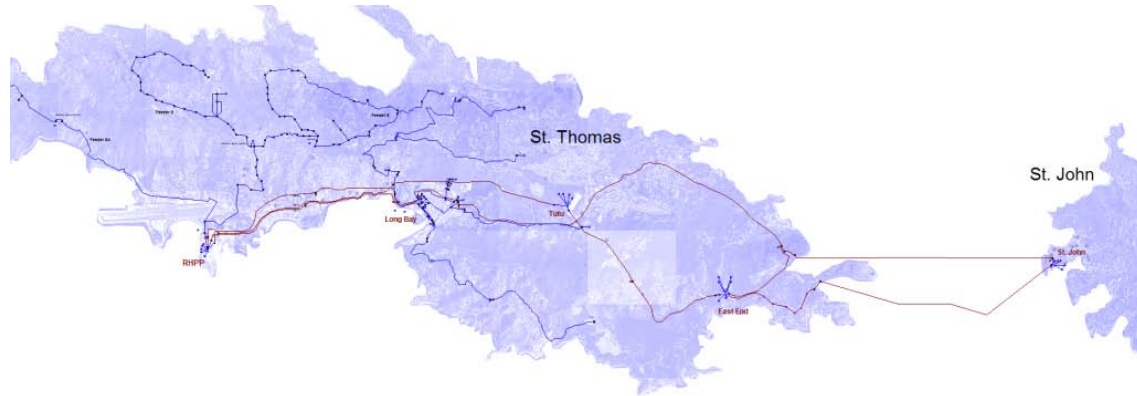
Key Projects That Led to the SuperCalibrator Concept

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**

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.

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

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

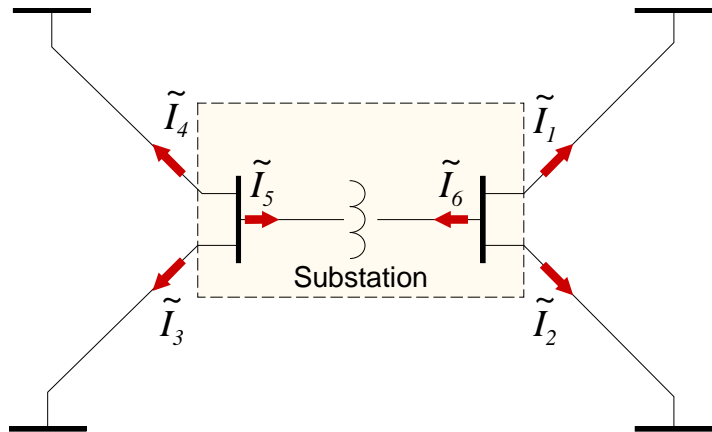
alpha is a synchronizing unknown variable

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



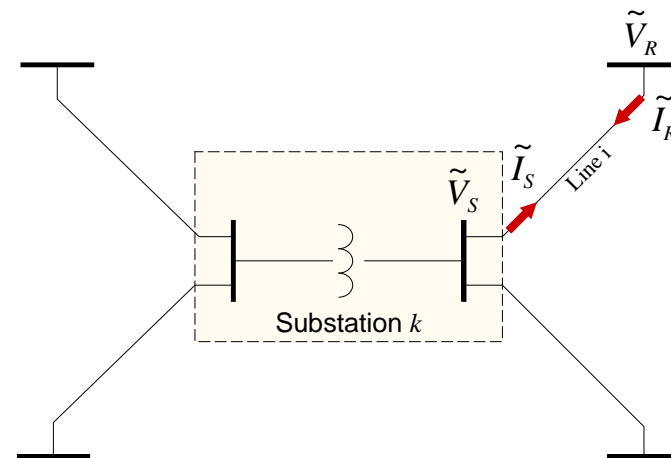
$$\tilde{I}_1 + \tilde{I}_2 + \tilde{I}_6 = 0$$

Expected Error: 0.001%

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

Expected Error: 0.001%

Remote End State Measurement



$$\tilde{V}_R^{pseudo,m} = (\mathbf{I} - \mathbf{Z}_{22}\mathbf{Y}_{22})^{-1}\mathbf{Z}_{21}\tilde{I}_S + (\mathbf{I} - \mathbf{Z}_{22}\mathbf{Y}_{22})^{-1}\mathbf{Z}_{22}\mathbf{Y}_{21}\tilde{V}_S$$

Expected Error: 0.01%

SuperCalibrator: Estimation Method

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

GPS-Synchronized Measurements

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

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

Real Power

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

SuperCalibrator: Estimation Method

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

Solution

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

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

Efficiency

Example, Long Bay Substation, High End PC

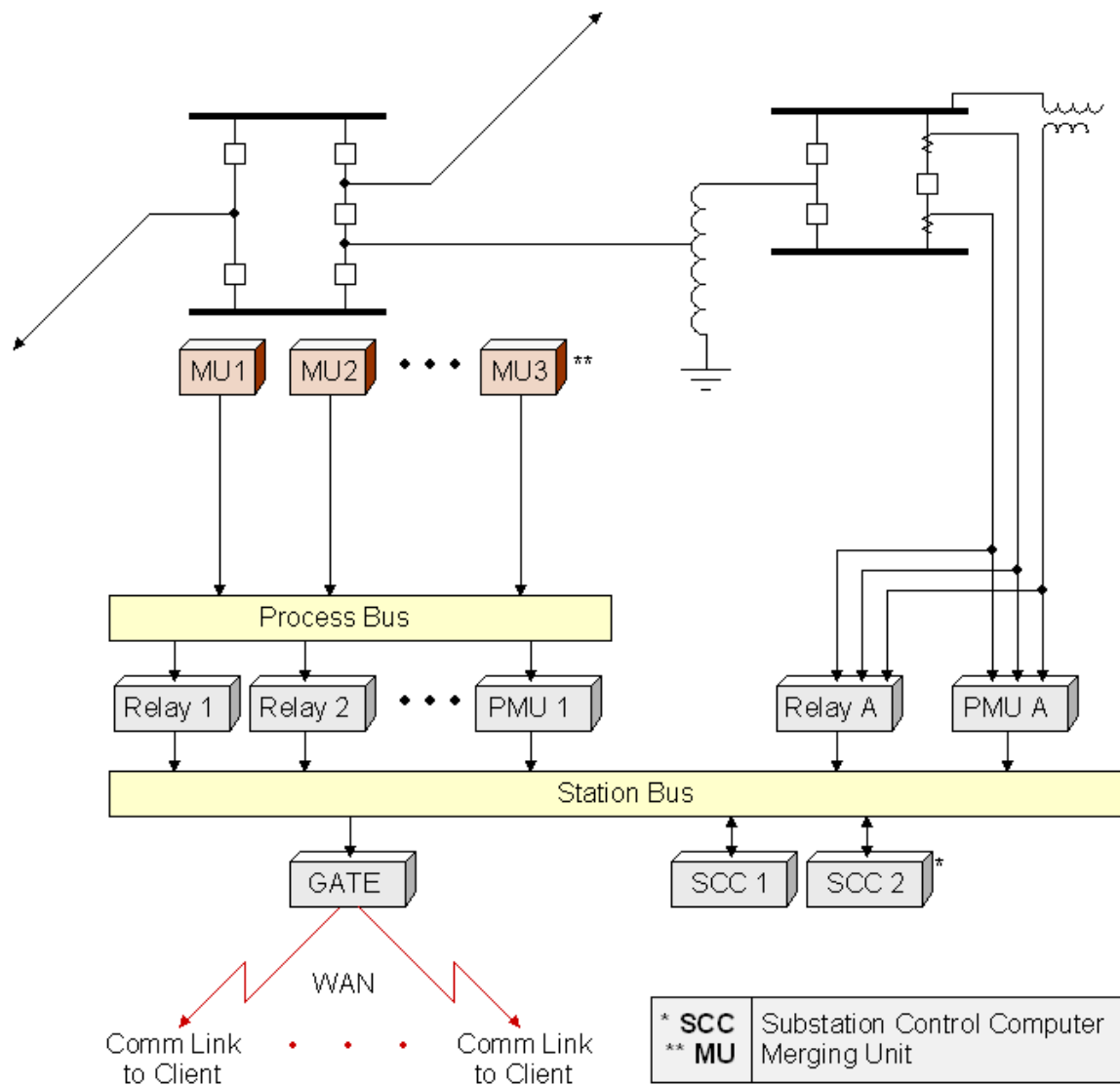
One Iteration: 18,000 multiply-adds (0.002 seconds)

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

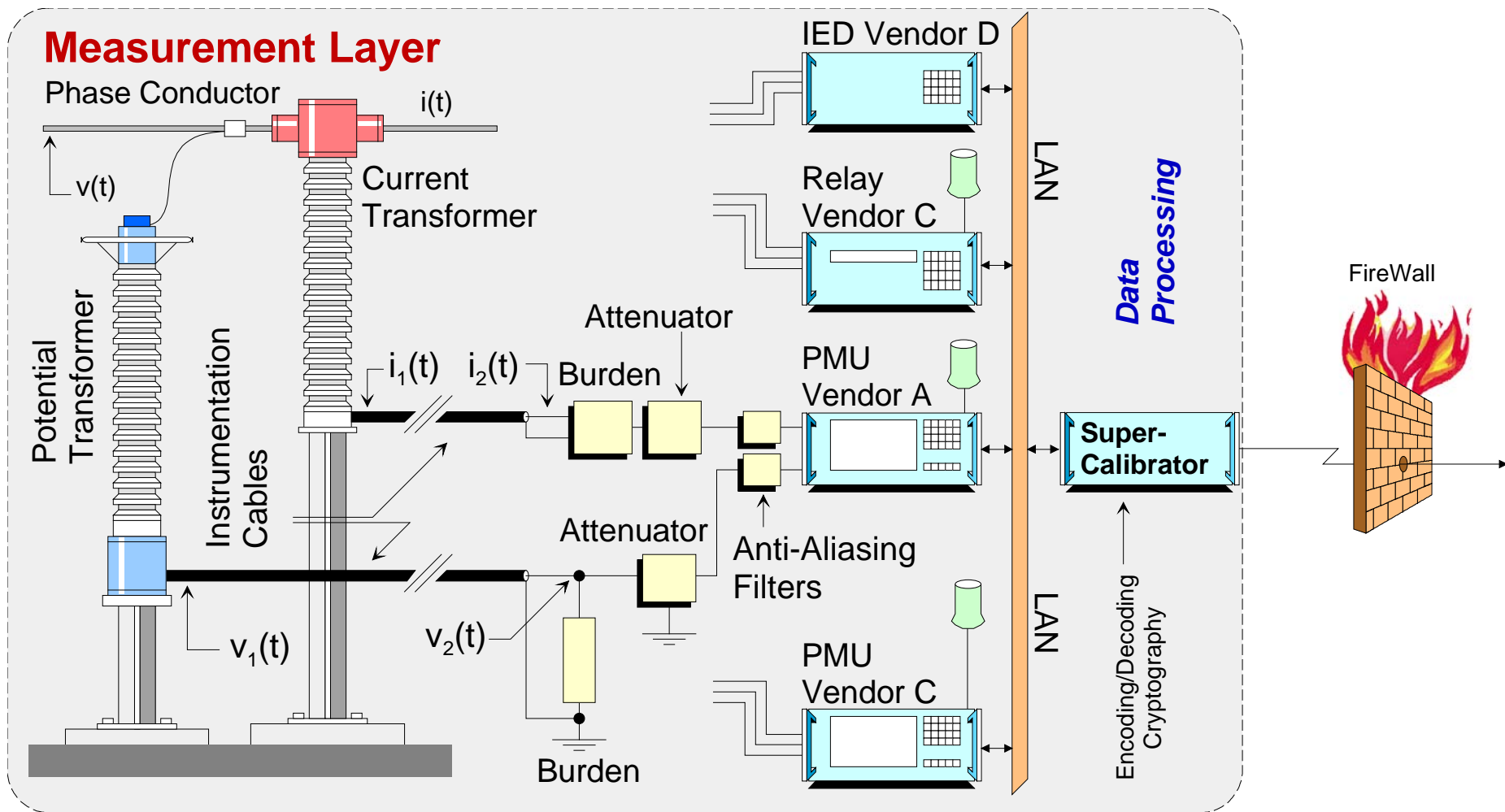
SuperCalibrator

Implementation

Present State of the Art: Smart Grid Infrastructure



Providing Validated and High Accuracy Information

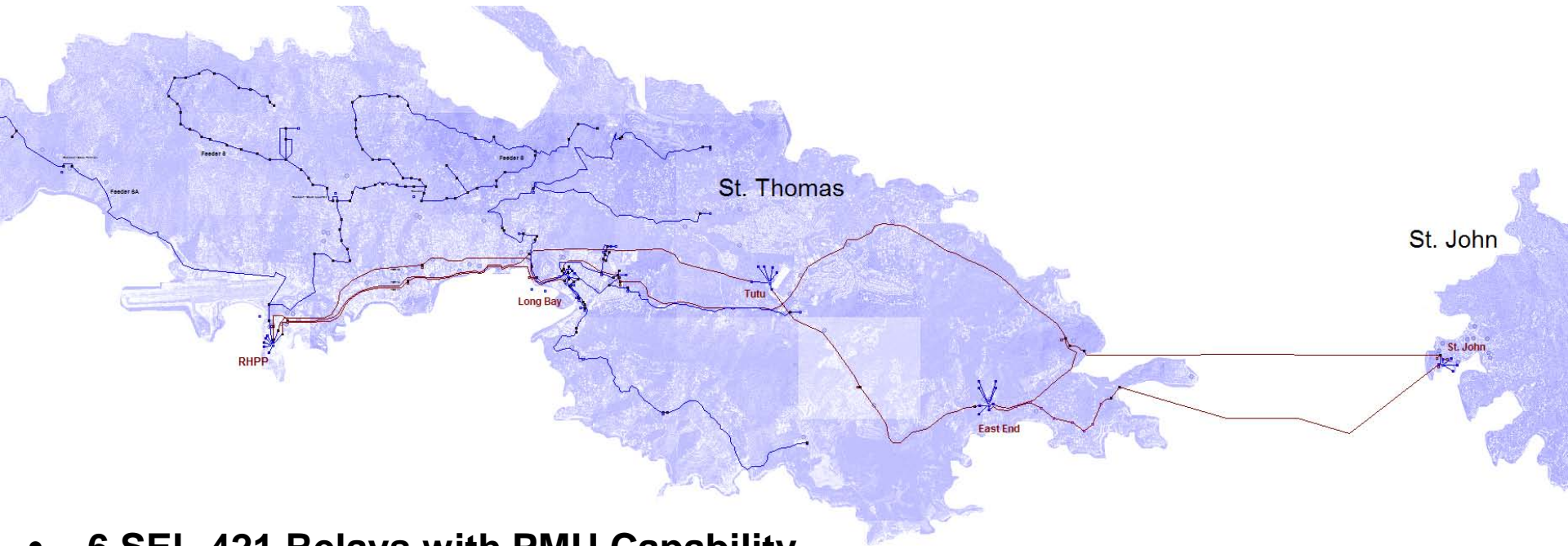


**Model Based Data Validation and Information Extraction
(Redundancy, Bad Data Rejection, Statistical Estimation, etc.)**

SuperCalibrator Implementation

Description: The VIWAPA System

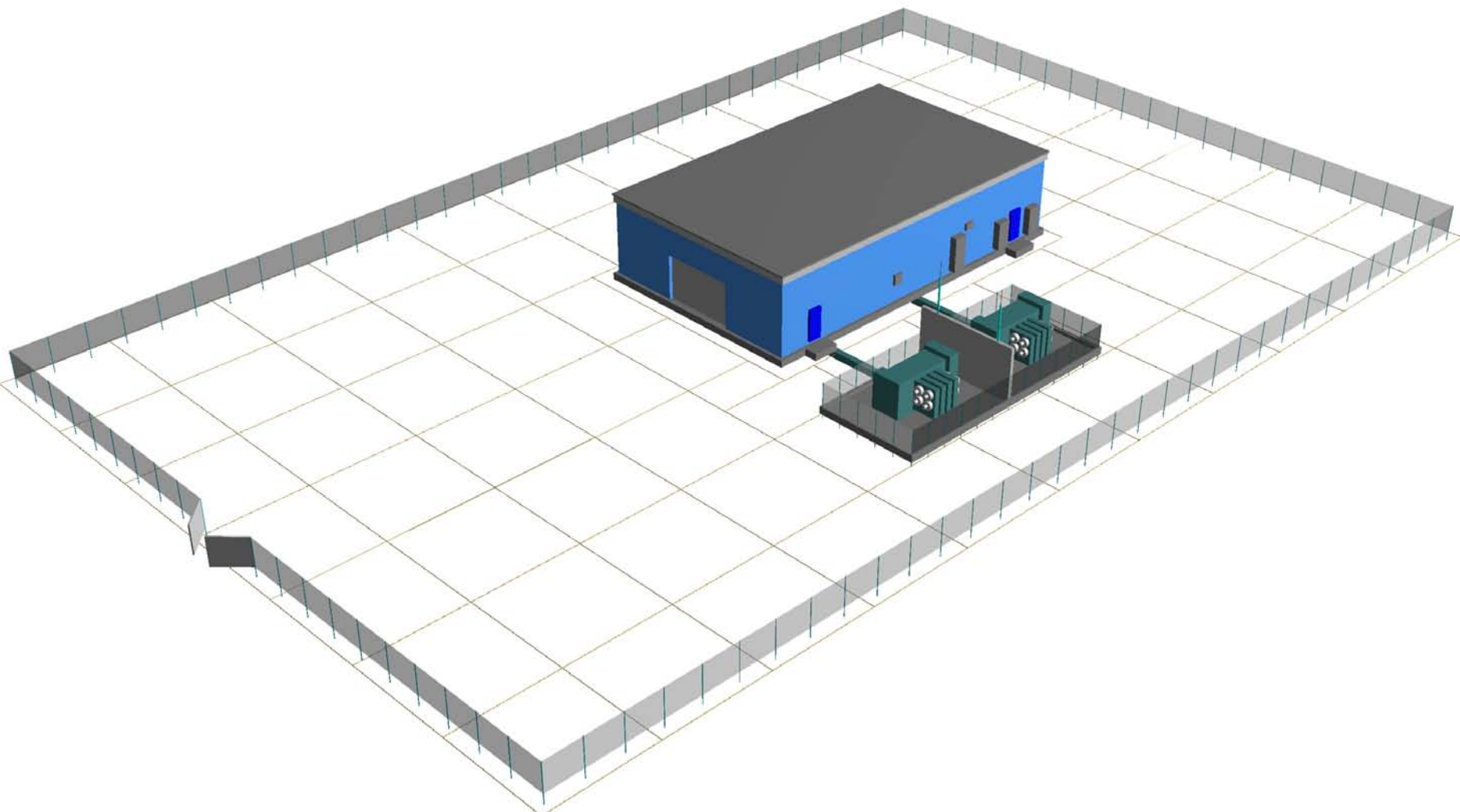
- 35 kV Transmission
- 13 kV Distribution
- Single Generating Plant (RHPP)
- Five Substations (RHPP Plant, Long Bay, Tutu, East End, St. John)



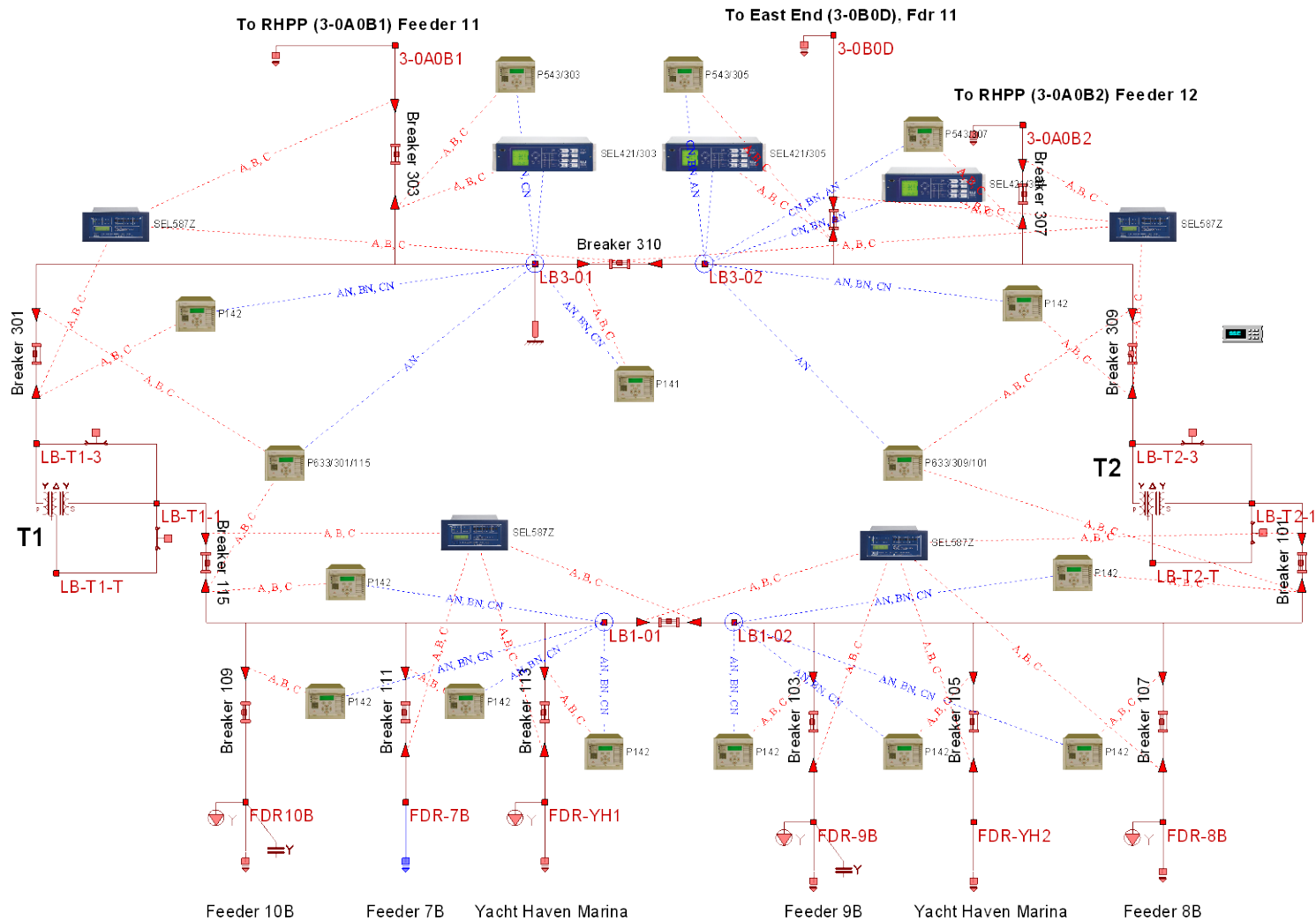
- 6 SEL-421 Relays with PMU Capability
- 3 SEL 734 Meters with PMU Capability
- Numerous Areva Relays (P141, P442, P142, etc.)
- There is at Least one PMU at Each Substation

SuperCalibrator Implementation

Substation Configuration – Long Bay – 3D Model



SuperCalibrator Implementation Substation Configuration – Long Bay



SuperCalibrator Implementation

Substation Configuration – Long Bay

The screenshot displays the 'Intelligent Electronic Device' configuration window. The window title is 'Intelligent Electronic Device' and it includes 'Cancel' and 'Accept' buttons. The 'Substation' field is set to 'VIWAPA_LONGBAY'. Under the 'IED' section, the 'Manufacturer' is 'SEL', 'Model' is 'SEL421', 'Name' is 'SEL421/303', and 'Identifier' is 'LB001'. The 'Data Type' section has 'Phasors' selected. The 'Data Source' section has 'Measurement' selected. The 'Channel Parameters' section includes buttons for 'Instrumentation Channels', 'Measurements', and 'View COMTRADE Channels'. The 'File Name' and 'File Location' fields are empty and 'Undefined' respectively. A 'Show Connections' checkbox is unchecked, and the 'Annotation Font Size' is set to '1.0'. The background shows a substation diagram with components like Breaker 309, Breaker 107, Breaker 101, and various feeders (Feeder 10B, Feeder 7B, Yacht Haven Marina, Feeder 9B, Yacht Haven Marina, Feeder 8B) connected to a transformer T2.

Intelligent Electronic Device [Cancel] [Accept]

Substation: VIWAPA_LONGBAY

IED

Manufacturer: SEL
 Model: SEL421
 Name: SEL421/303
 Identifier: LB001

Data Type
 Phasors
 Waveforms

Data Source
 Measurement
 Simulation
 Estimate

Channel Parameters
 [Instrumentation Channels]
 [Measurements]
 [View COMTRADE Channels]

File Name:
 File Location: Undefined

Show Connections Annotation Font Size: 1.0

Program WinIGS-F - Form IGS_M007

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

SuperCalibrator Implementation

Substation Configuration – Long Bay

The screenshot displays the 'Intelligent Electro' software interface. On the left, a configuration panel shows details for a substation named 'VIWAPA'. The 'IED' section is set to 'SEL', with manufacturer 'SEL', model 'SEL421', name 'SEL421', and identifier 'LB001'. The 'Data Type' section has radio buttons for 'Phasors' (selected), 'Waveforms', 'Measurements', 'Simulation', and 'Estimation'. Below this are fields for 'File Name' and 'File Location: Undefined', and a 'Show' checkbox.

The main window, titled 'Instrumentation Channels', contains a table with the following data:

	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

At the bottom of the software interface, a diagram shows several feeders: Feeder 10B, Feeder 7B, Yacht Haven Marina, Feeder 9B, Yacht Haven Marina, and Feeder 8B. Each feeder is connected to a corresponding FDR (Feeder Disconnector) device.

SuperCalibrator Implementation

Substation Configuration – Long Bay

Instrumentation Channel Parameters

Cancel
Accept

IED	VIWAPA_LONGBAY_LB001		
Channel Name	C_3031_B		
Data Type	Current Phasor	Phase (A,B,C...)	B
Bus Name	LB3-01	Current Direction:	<input checked="" type="radio"/> Into Device <input type="radio"/> Outof Device
Power Device	Breaker 303		
Overall Nominal Ratio and Offset		120.00	0.00

Instrument Transformer

Instr. Transformer Code

Type

Tap

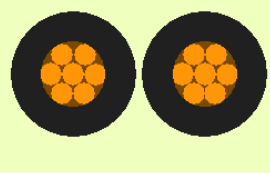
Ratio

Nominal Primary Voltage (kV)

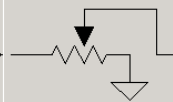
Instrumentation Cable

Length (ft)

Cable Type



Attenuator



Burden

R (Ohms)

X (Ohms)

DAU

Peak Voltage(V)

Calibr Factor

Calibr Offset


Time Skew (us)

Data Concentrator

Program WinIGS-F - Form IGS_M007_ICHAN_EDIT

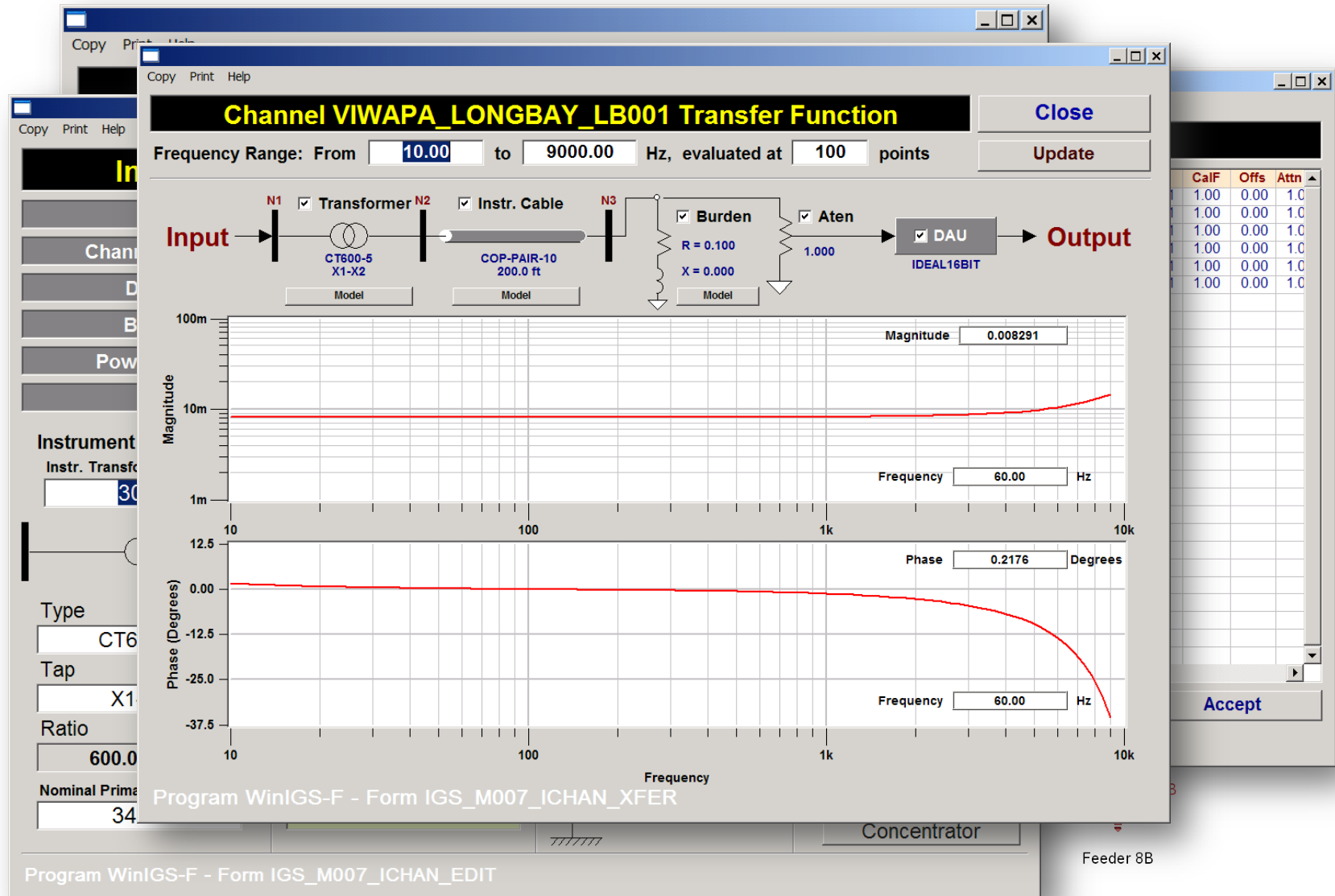
Length	IED	CalF	Offs	Attn	
10	200.00	LB001	1.00	0.00	1.0
10	200.00	LB001	1.00	0.00	1.0
10	200.00	LB001	1.00	0.00	1.0
10	200.00	LB001	1.00	0.00	1.0
10	200.00	LB001	1.00	0.00	1.0
10	200.00	LB001	1.00	0.00	1.0

Cancel
Accept



Feeder 8B

SuperCalibrator Implementation Substation Configuration – Long Bay



SuperCalibrator Power System Model:

Physically Based Three-Phase Model: Example

Physically Based Model

Multiphase Cable Model Cancel Accept

Line #2 East End Substation To St John Sub - Section 2 (Submarine)

OH651 VI34KV250KCM-STJ-SUB STJ35-2

Zoom Page
Edit
Copy
Delete
New Cable
New Conductor

Cable Length (feet)
17200.0
Get From GS

Soil Resistivity Ohm-meters
0.50

Node Assign
Read GPS File

Circuit Data

	Circuit Name	Span Length (Feet)	Ground Resistance (Ohms)	Operating Voltage
1	CKT1	12436.5	25.0000	34.5000
2				
3				
4				

New / Copy
Delete

WinIGS-F - Form: IGS_M123_1 - Copyright © A. P. Meliopoulos 1998-2007

Sequence Parameter Model

Not Used – for Info Only

Cable Sequence Networks Close

Positive Sequence Network All Values in Ohms

$1.094 + j0.742$

$0.509 - j 5259.1$ $0.509 - j 5259.1$

Negative Sequence Network

$1.094 + j0.742$

$0.509 - j 5259.1$ $0.509 - j 5259.1$

Zero Sequence Network

$1.933 + j0.579$

$0.649 - j 5259.2$ $0.649 - j 5259.2$

Program WinIGS-F - Form GENCABLEPAR1A

SuperCalibrator Instrumentation Model:

Physically Based Instrumentation Model: Example

Copy Print Help

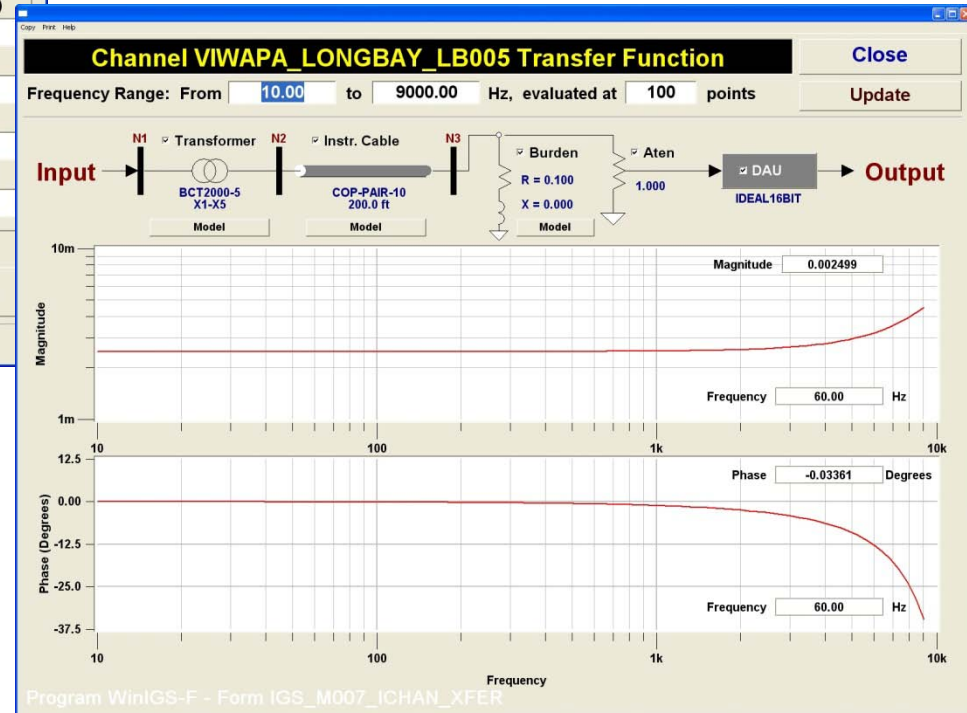
Instrumentation Channel Parameters

Cancel Accept

IED	VIWAPA_LONGBAY_LB005		Transfer Function
Channel Name	C_110X_A		Update
Data Type	Current Phasor	Phase (A,B,C,...)	A
Bus Name	LB1-01	Current Direction:	<input checked="" type="radio"/> Into Device <input type="radio"/> Outof Device
Power Device	110		
Overall Nominal Ratio and Offset		400.00	0.00

Instrument Transformer	Instrumentation Cable	Attenuator	DAU
Instr. Transformer Code 110X	Length (ft) 200.00	1.00	IDEAL16BIT
Type BCT2000-5	Cable Type COP-PAIR-10		Peak Voltage(V) 2.00
Tap X1-X5		Burden	Calibr Factor 1.00
Ratio 2000.0/5.0 A		R (Ohms) 0.10	Calibr Offset 0.00
Nominal Primary Voltage (kV) 13.20		X (Ohms) 0.00	Time Skew (us) 0.00
			Data Concentrator

Program WinIGS-F - Form IGS_M007_ICHAN_EDIT



SuperCalibrator Instrumentation Model: Physically Based Instrumentation Model: Example

Instrumentation Channel Parameters Cancel Accept

IED: VIWAPA_LONGBAY_LB001

Channel Name: V_VT1_CN

Data Type: Voltage Phasor Phase (A,B,C...): CN

Bus Name: LB3-01 Current Direction: Into Device Outof Device

Power Device: Breaker 303

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): 200.00

Cable Type: COP-PAIR-10

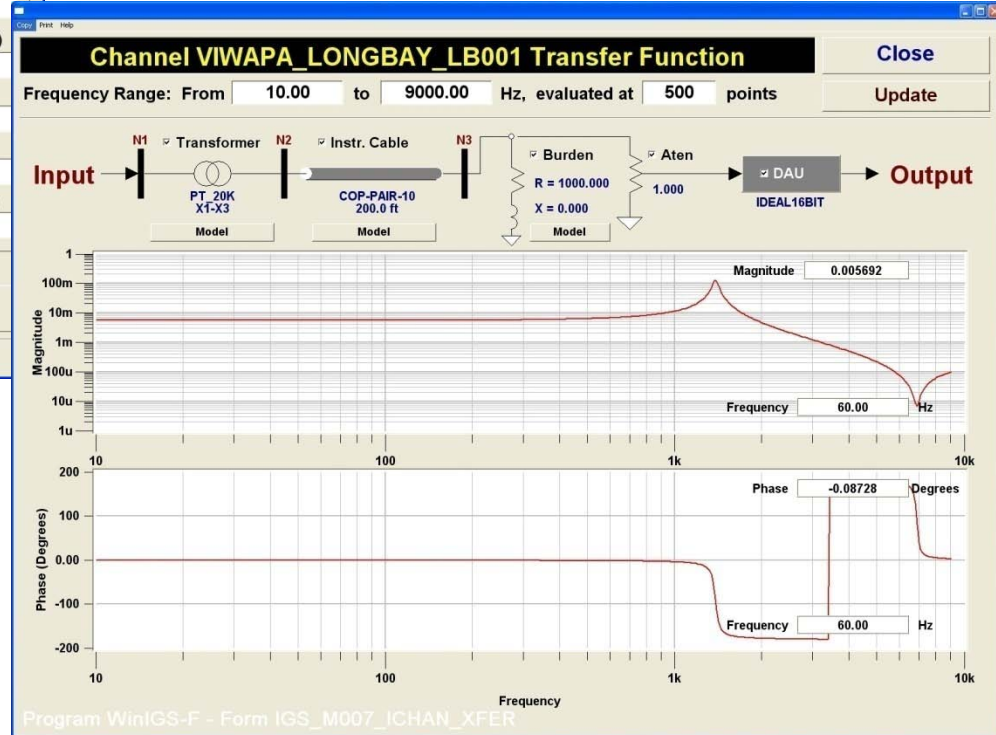
Attenuator
1.00

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

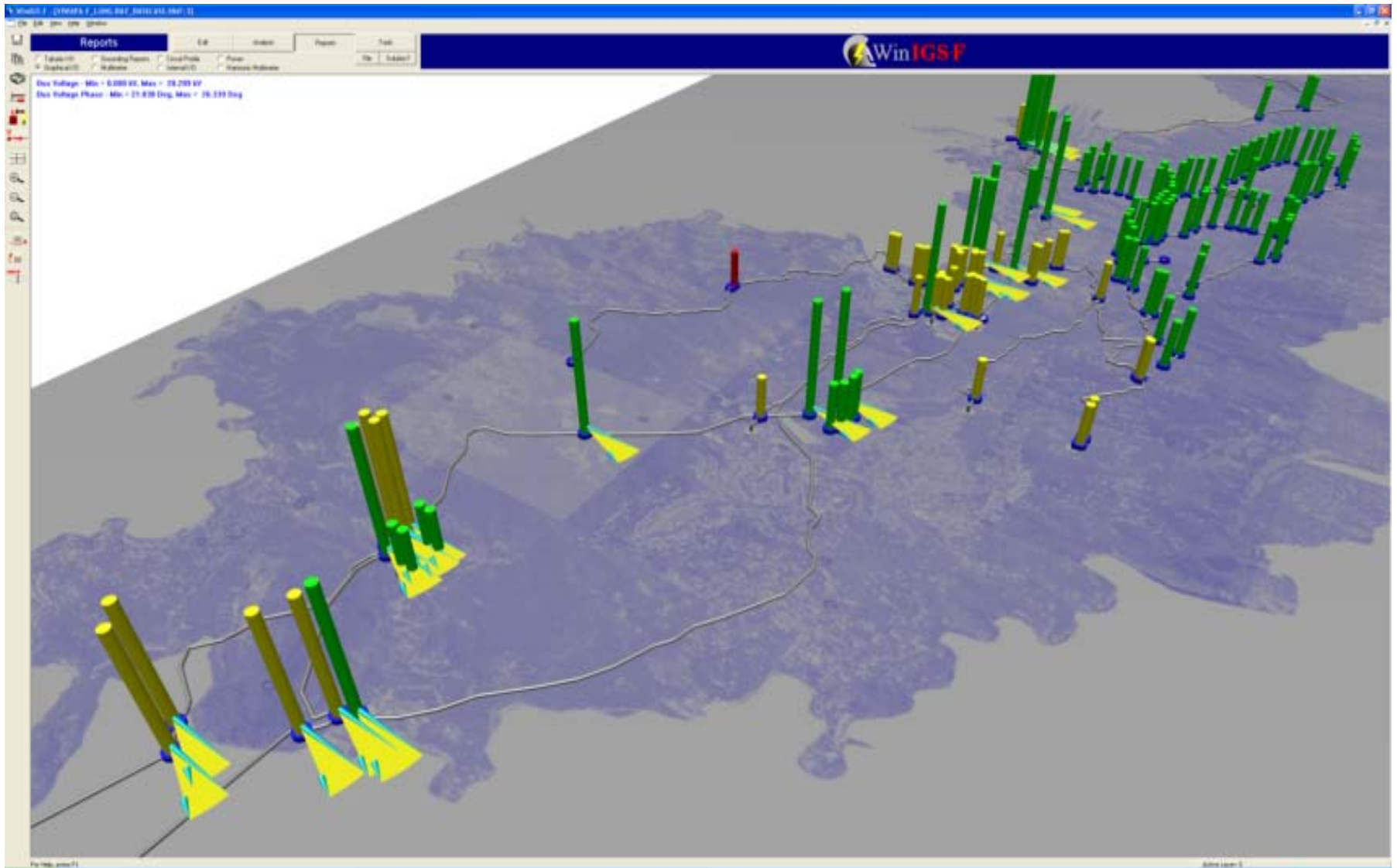
Data Concentrator

Program WinIGS-F - Form IGS_M007_ICHAN_EDIT



SuperCalibrator Installation: USVI – 5 Substations

The SuperCalibrator Runs 4 Times per Second



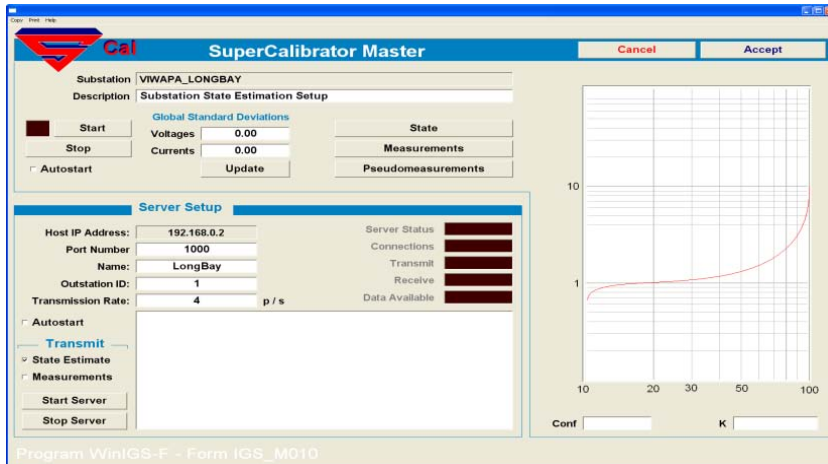
SuperCalibrator

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.**

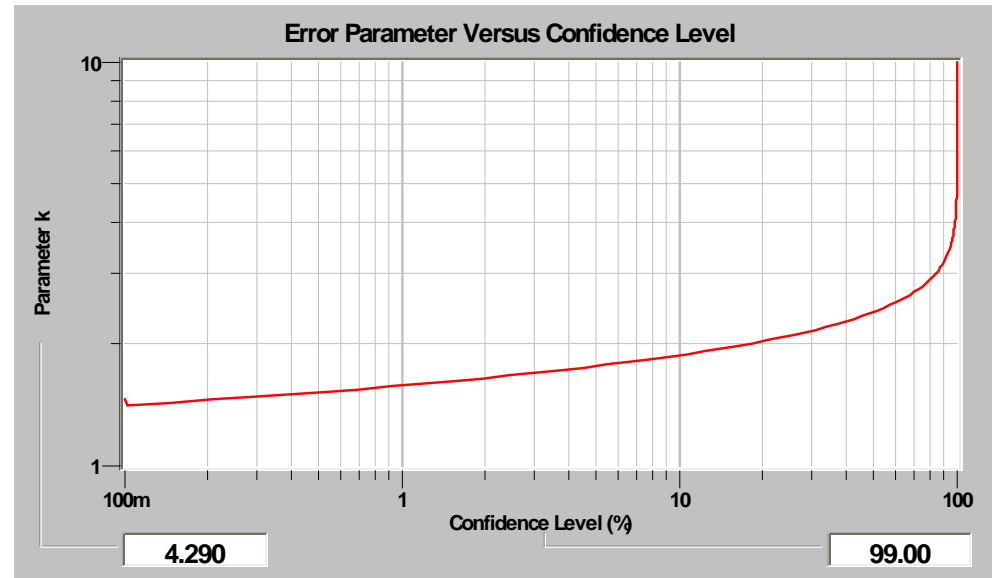
Overall Performance Metric Chi-Square Test



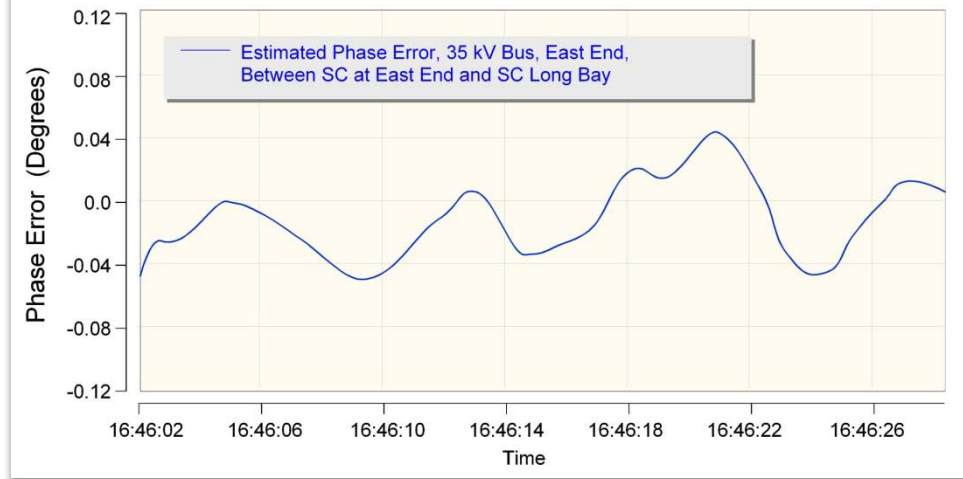
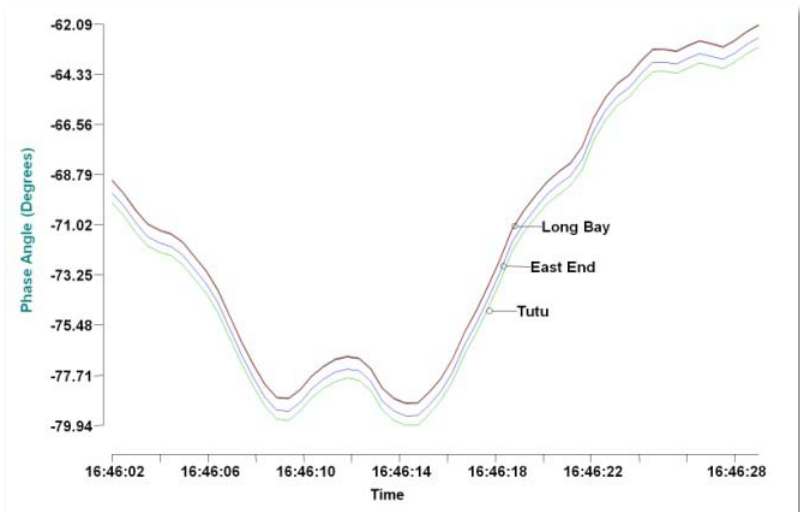
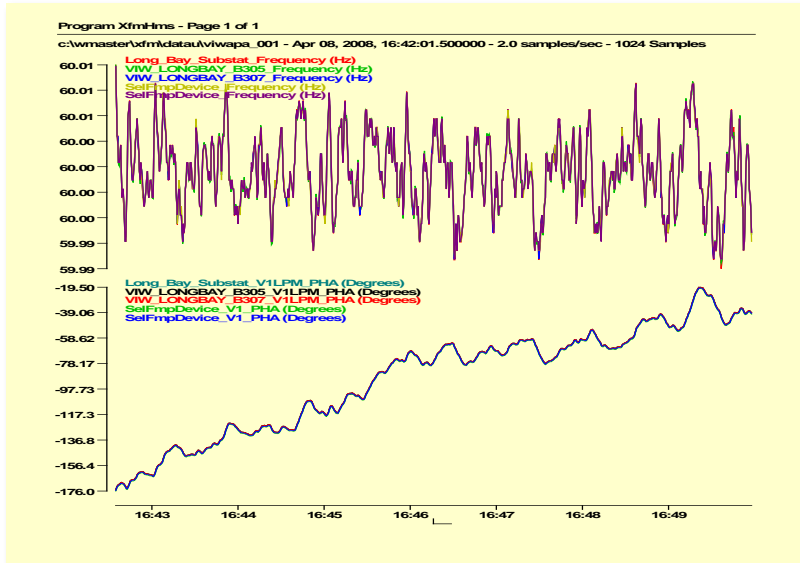
We have introduced the variable k

$$\text{Error} = k \cdot \text{MeterSigma}$$

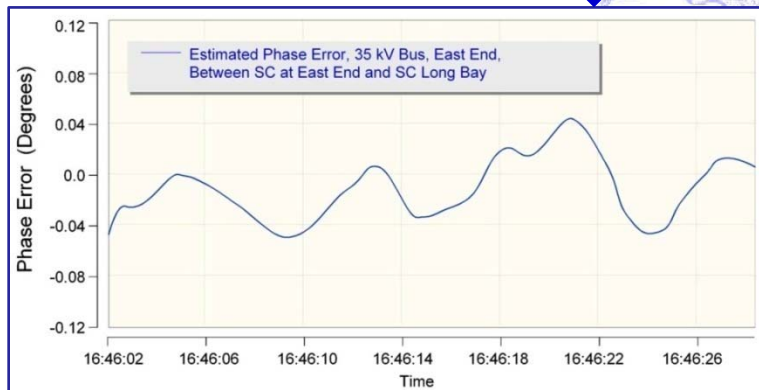
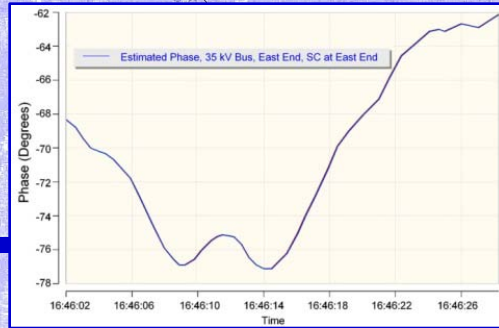
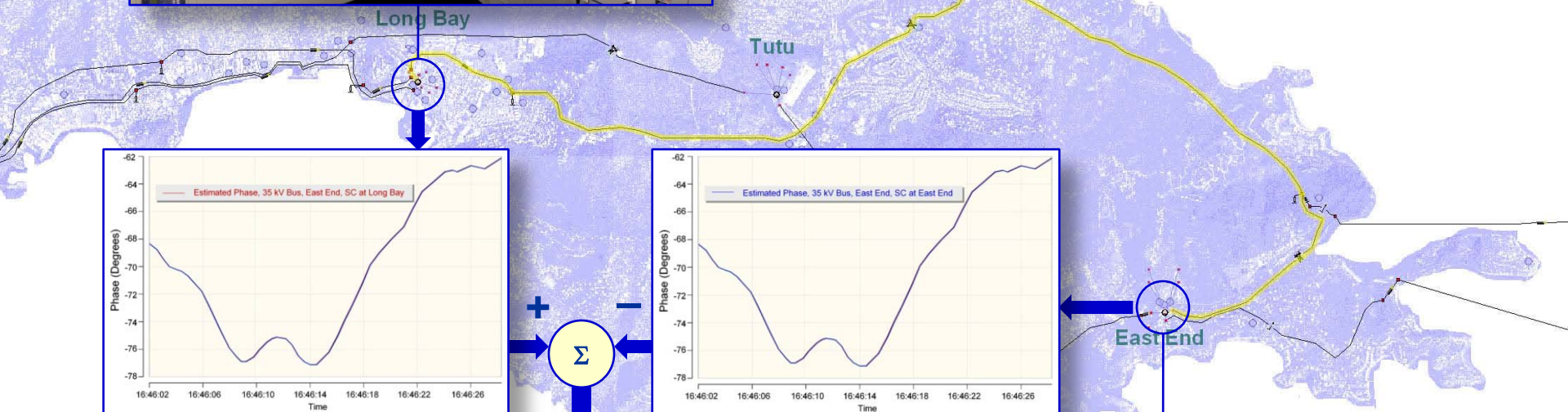
Overall Error is Provided in
Terms of the Variable k



Performance Monitoring of the SC-Base SE



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%

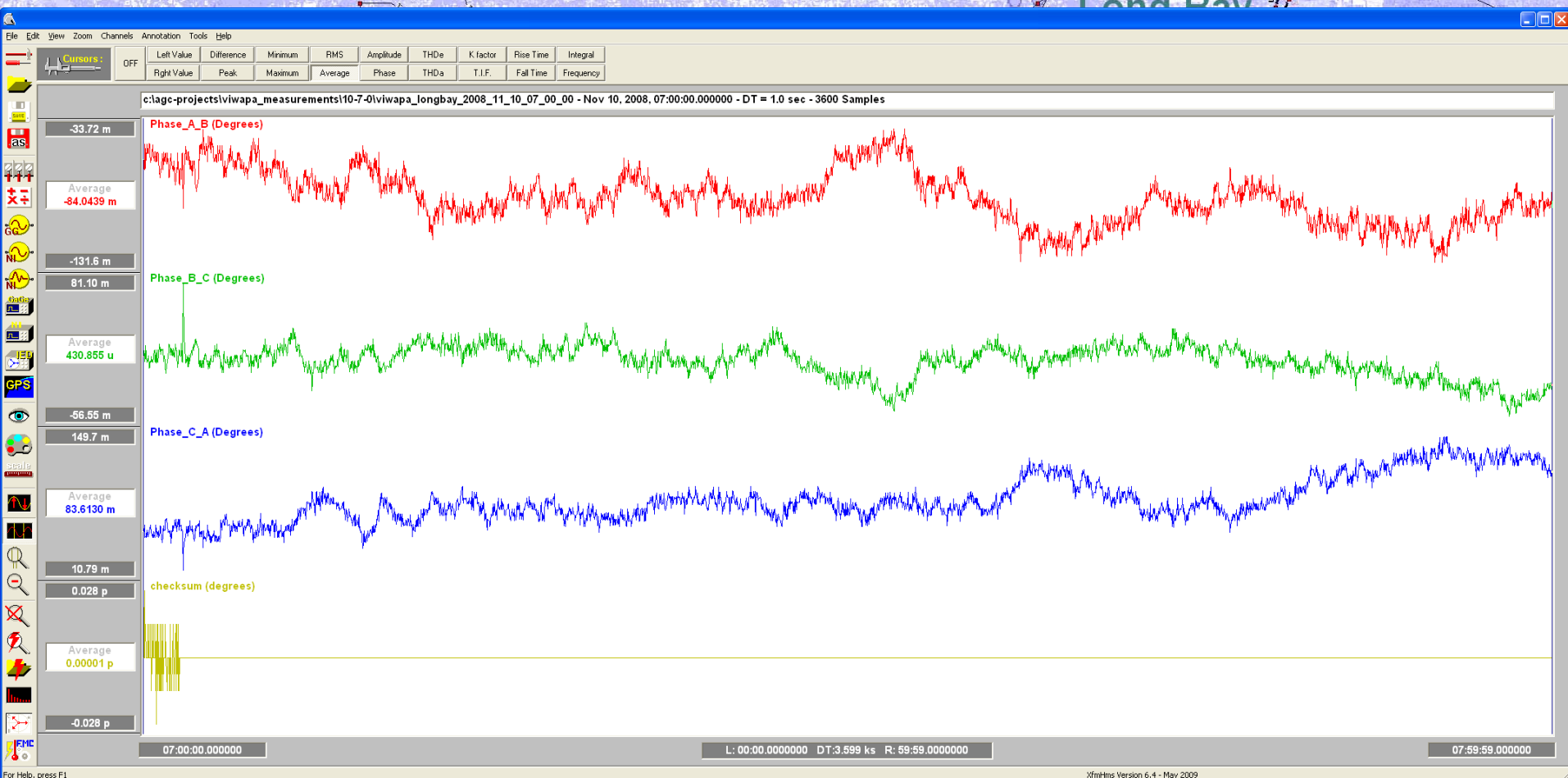
Syncrophasor Data Processing Example

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 +



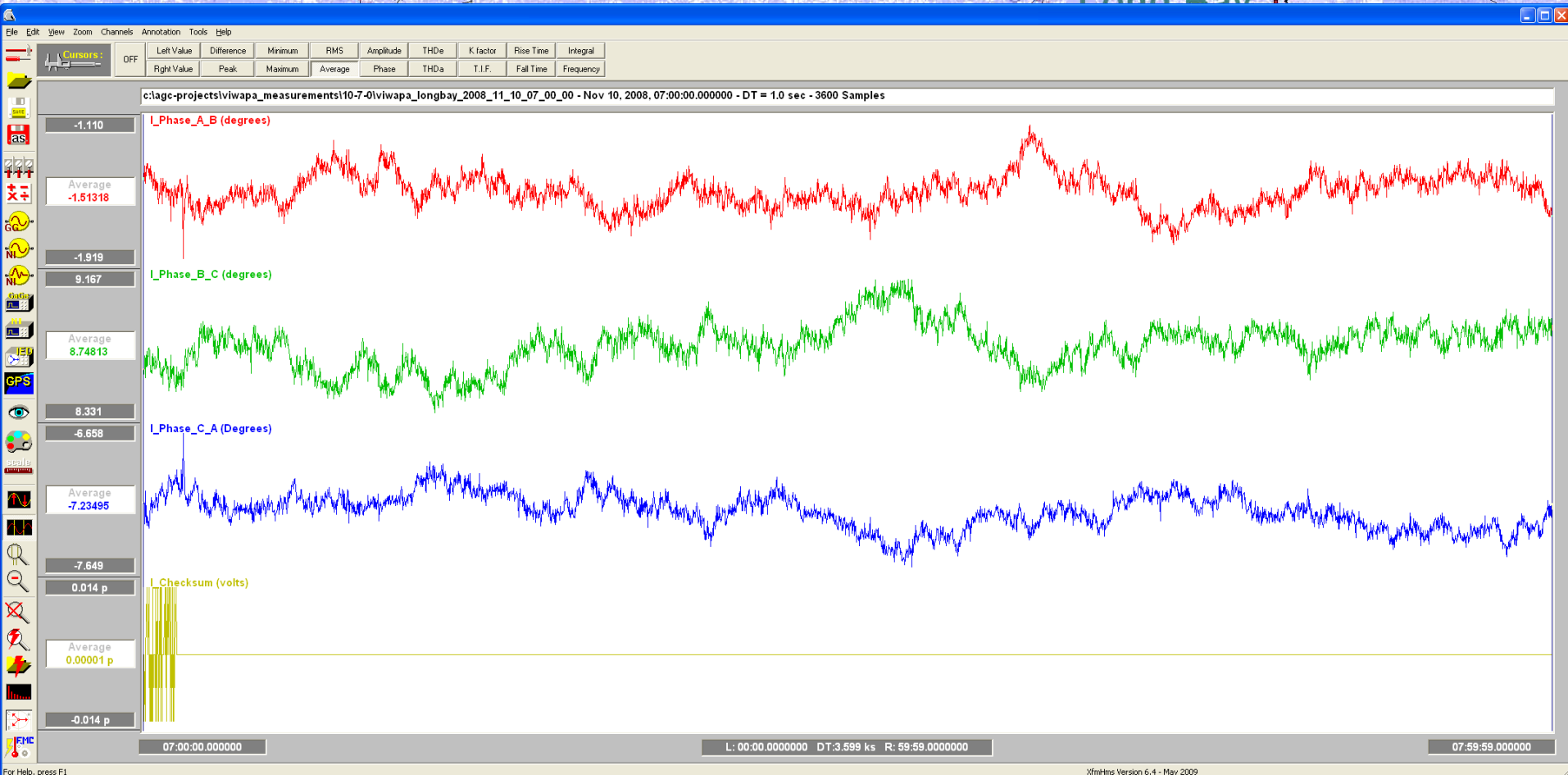
Syncrophasor Data Processing Example

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 +



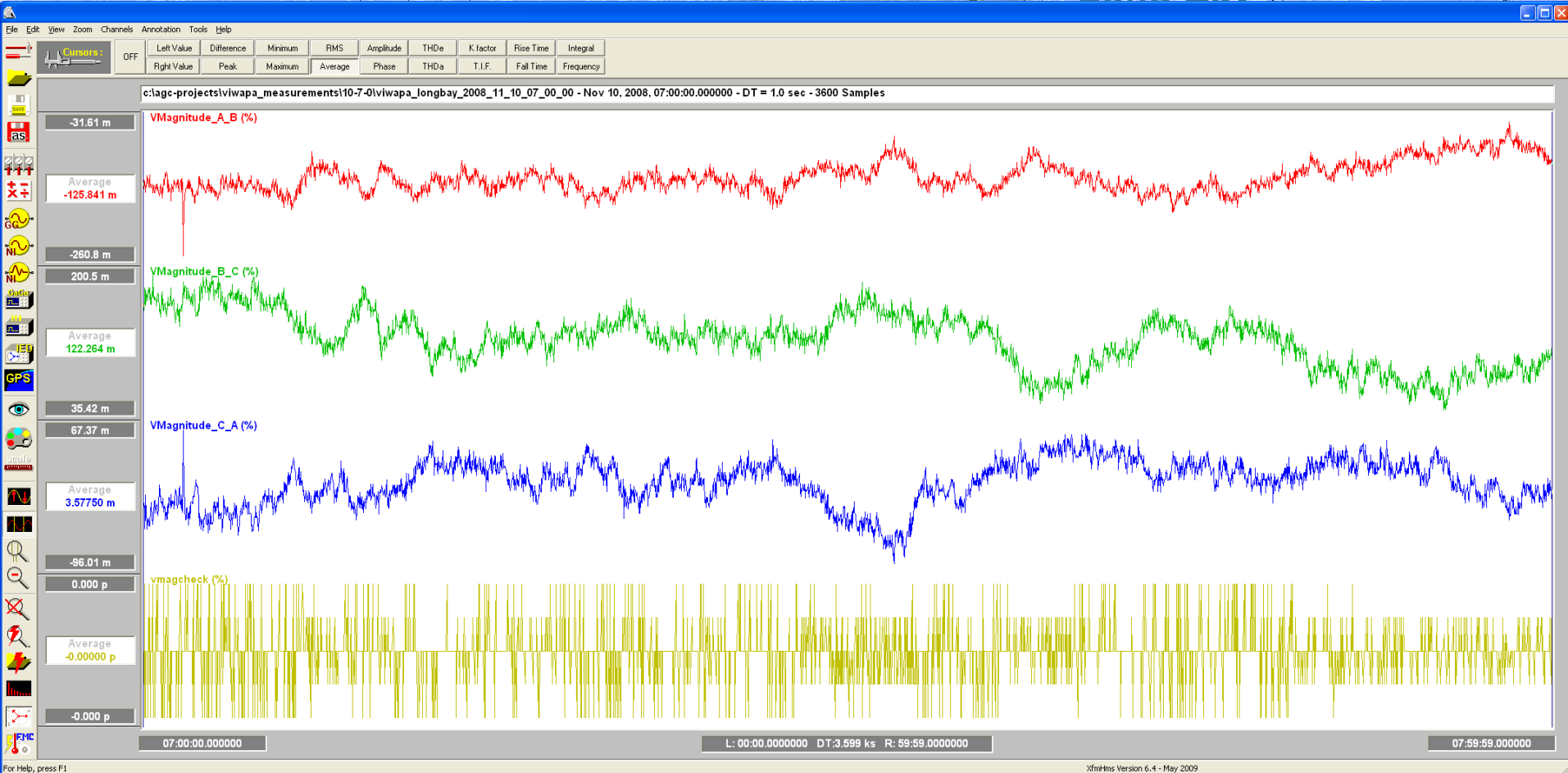
Syncrophasor Data Processing Example

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 /



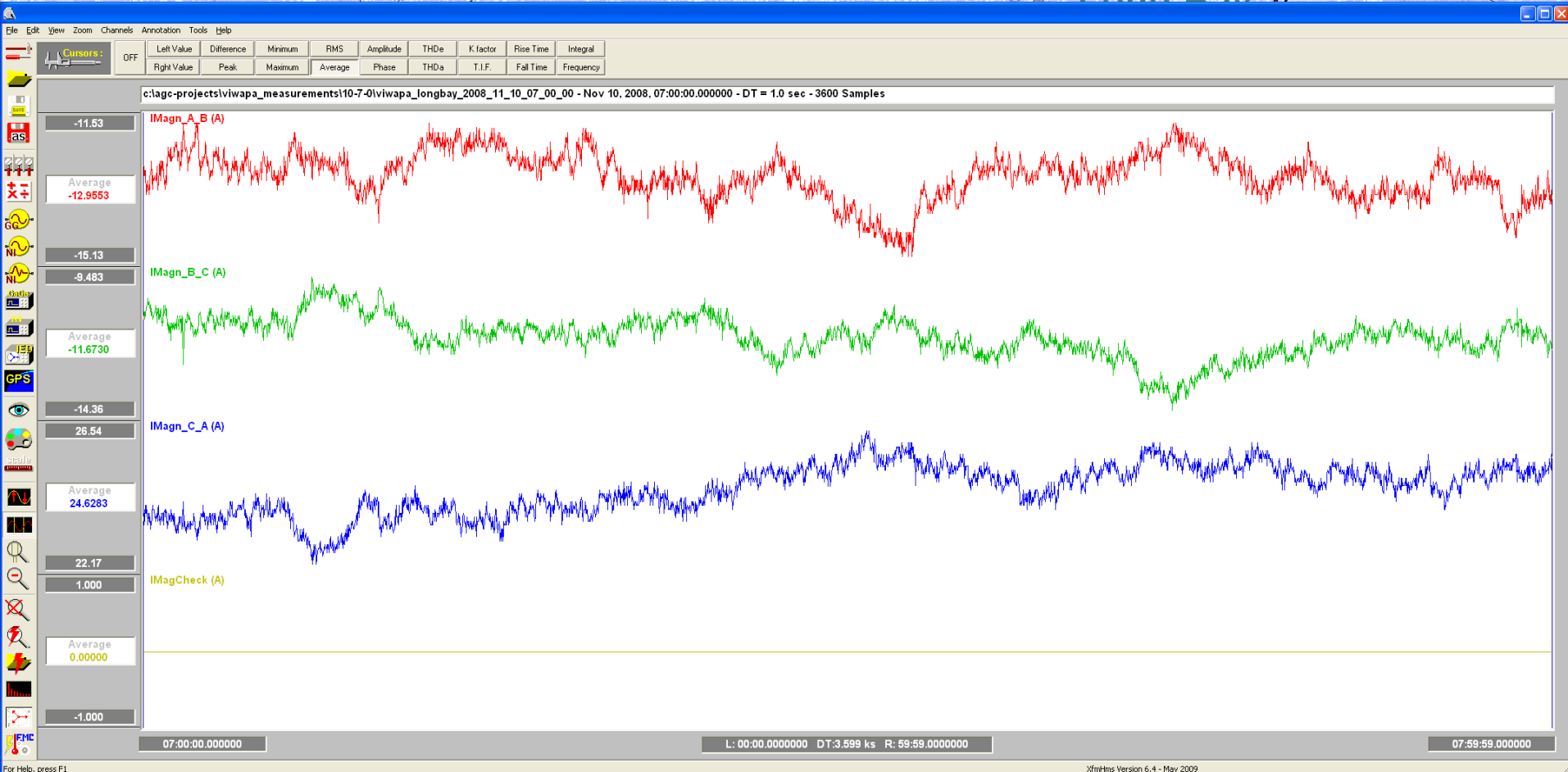
Syncrophasor Data Processing Example

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

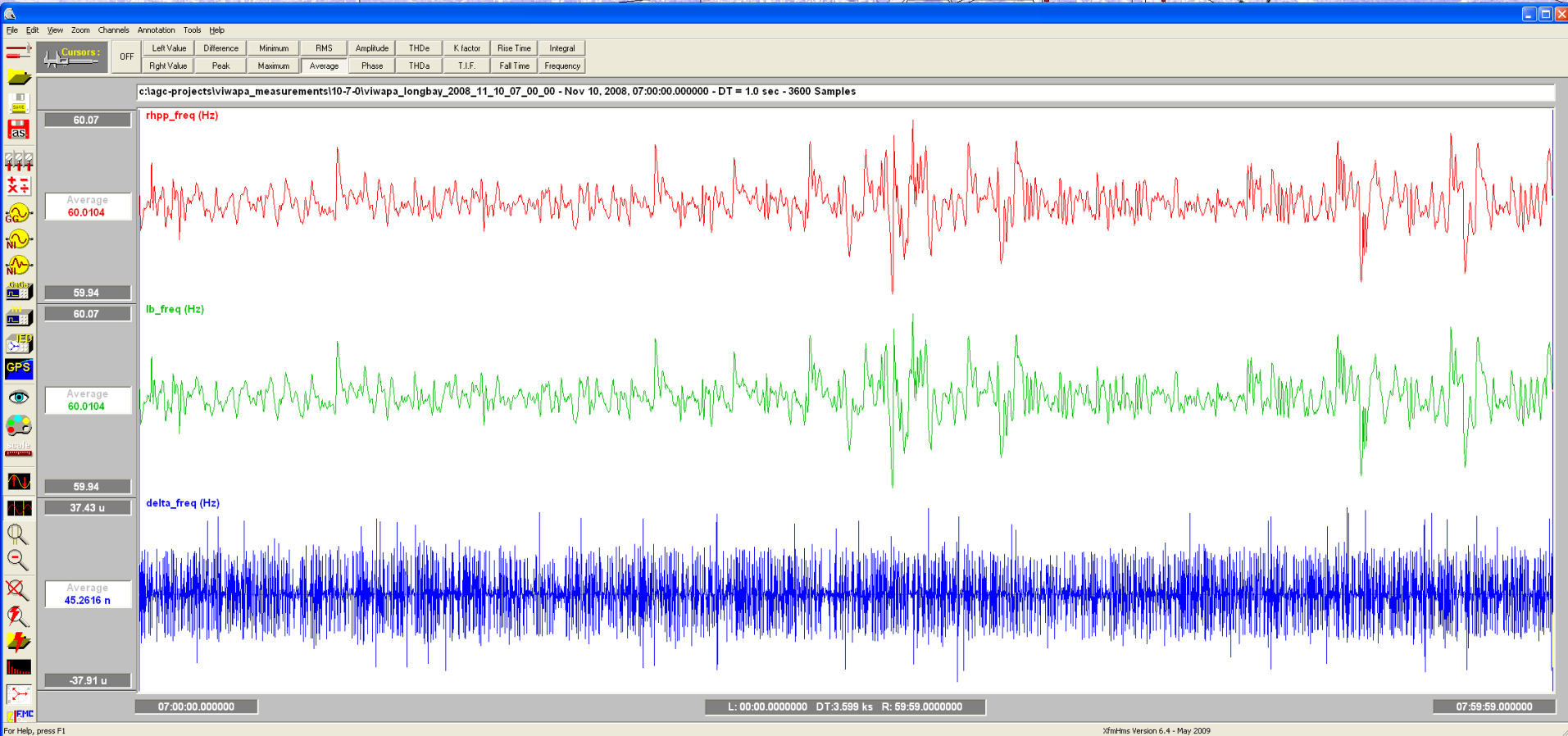
Computation of Frequency

Note:

Average Frequency 60.0104 Hertz

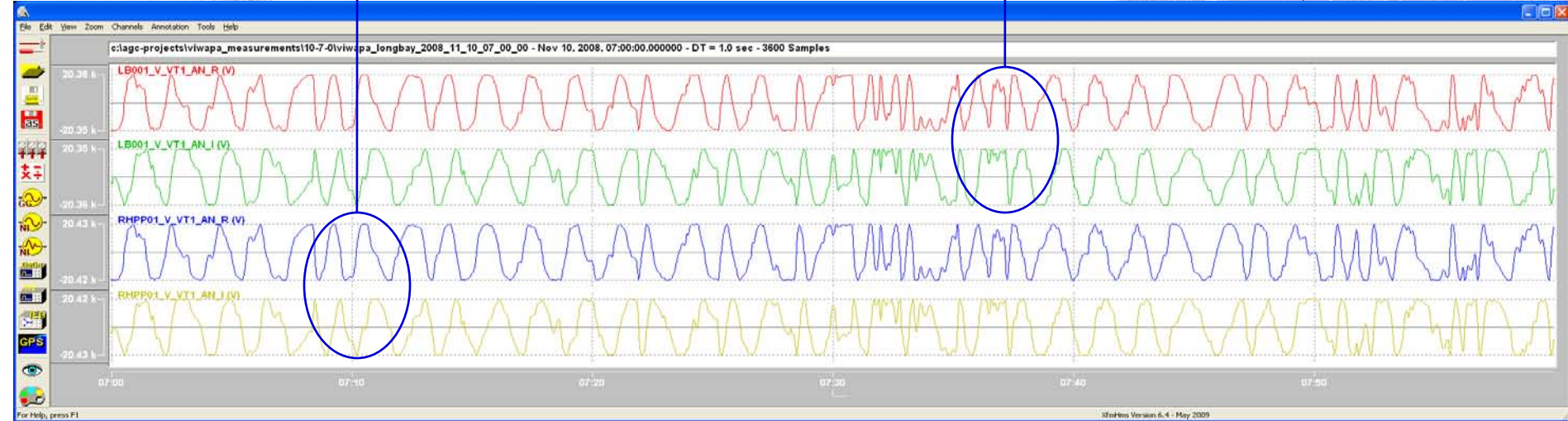
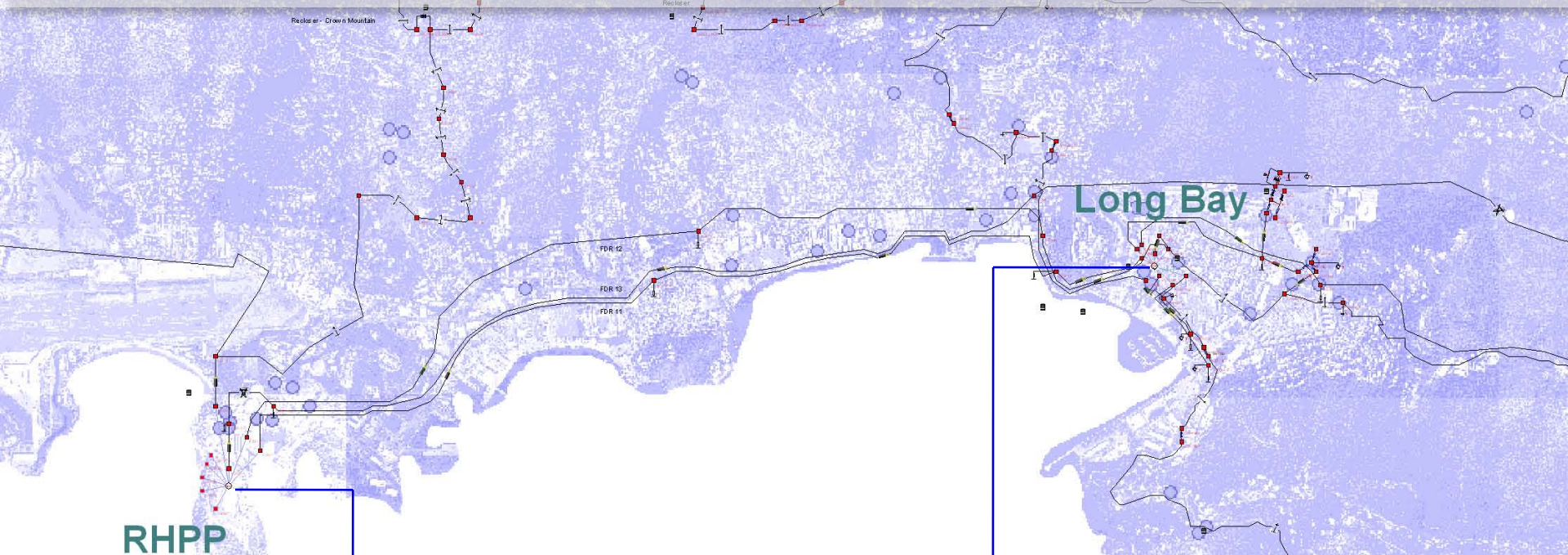
Average Frequency Difference 45 NanoHertz

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



Synchrophasor Data Processing Example – Raw Data

1 hour at 1 sample per second

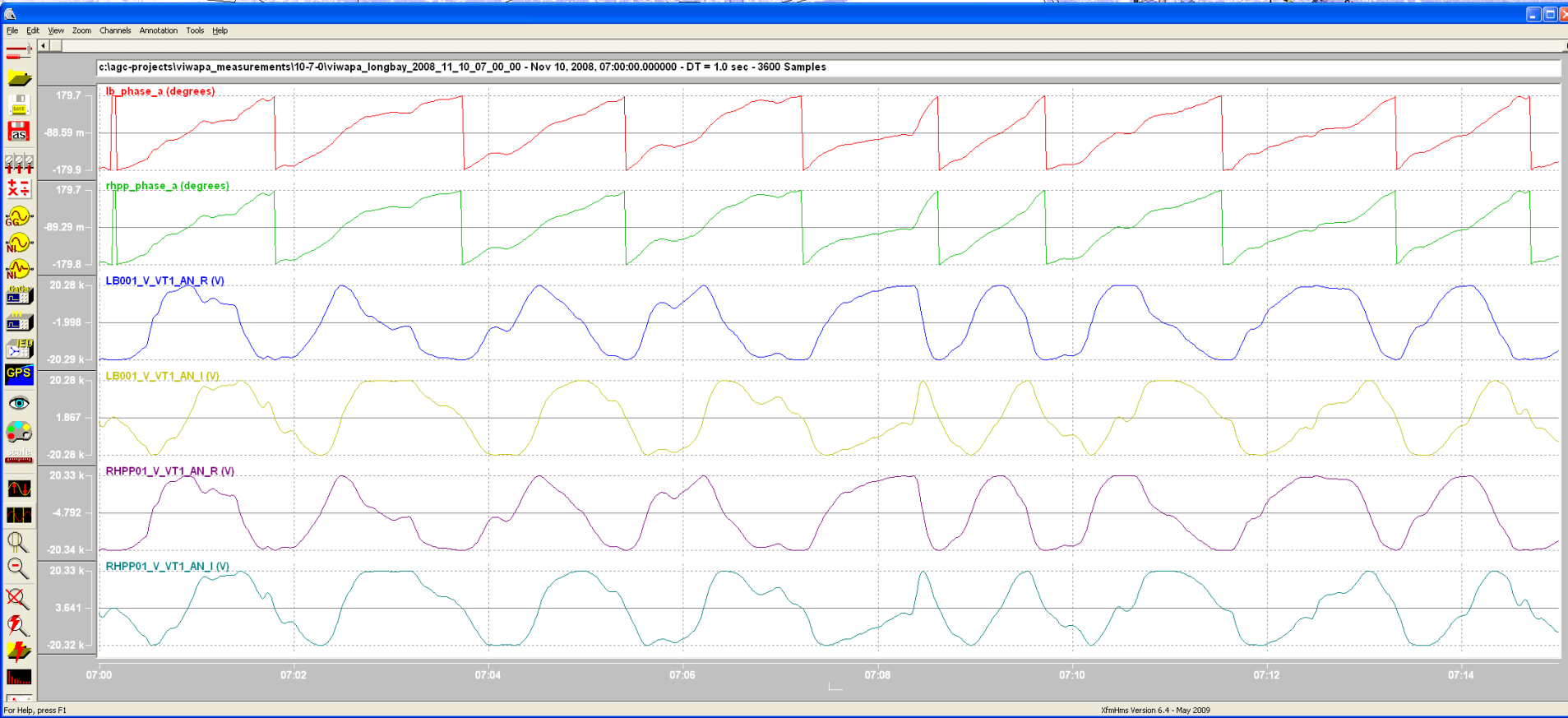


Syncrophasor Data Processing Example

Computation of Phase Angle

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

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



For Help, press F1

Xfme4ms Version 6.4 - May 2009

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