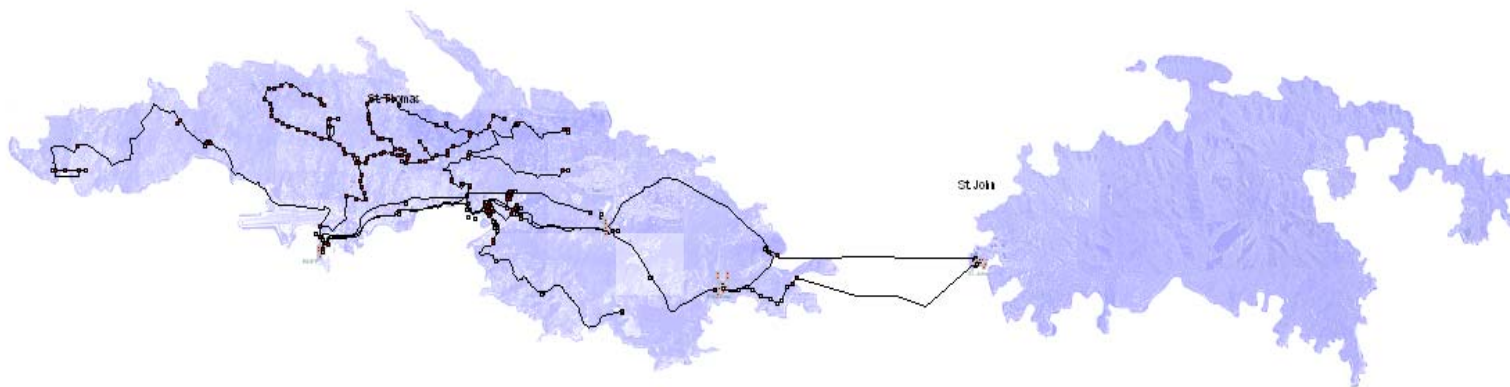




Distributed State Estimator at U.S. Virgin Islands Water and Power Authority St. Thomas and St. John



Terry L. Conrad
Concurrent Technologies Corporation

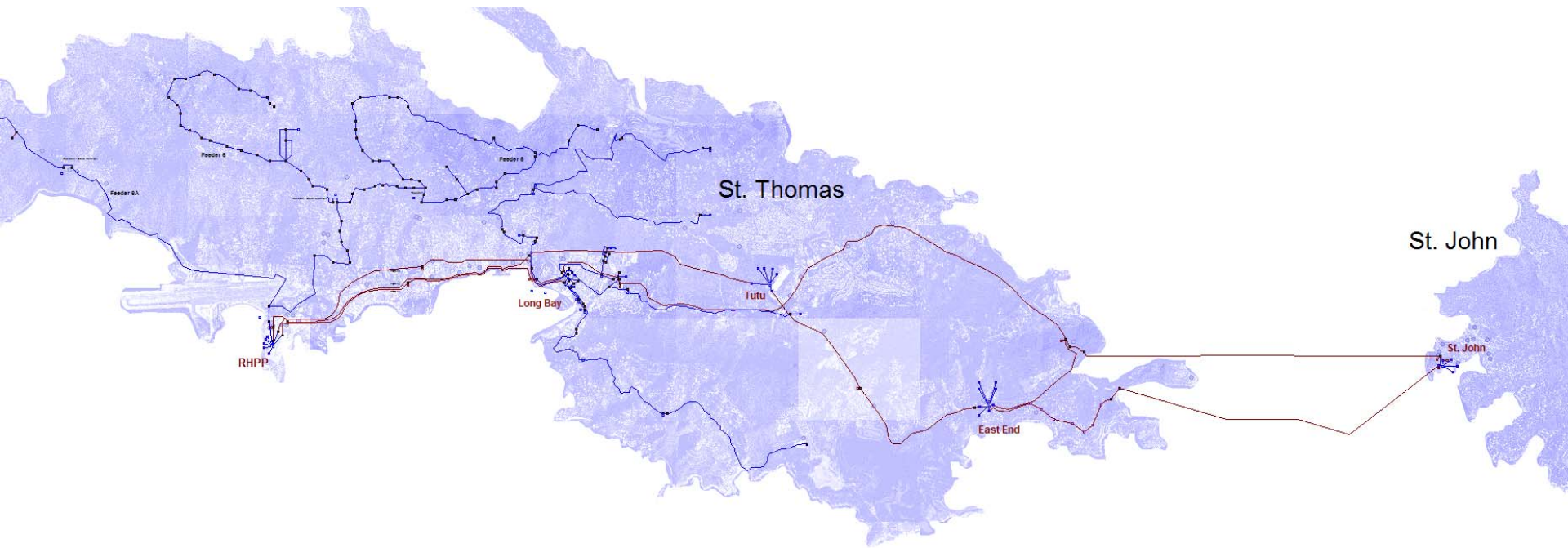
A. P. Sakis Meliopoulos
Georgia Tech

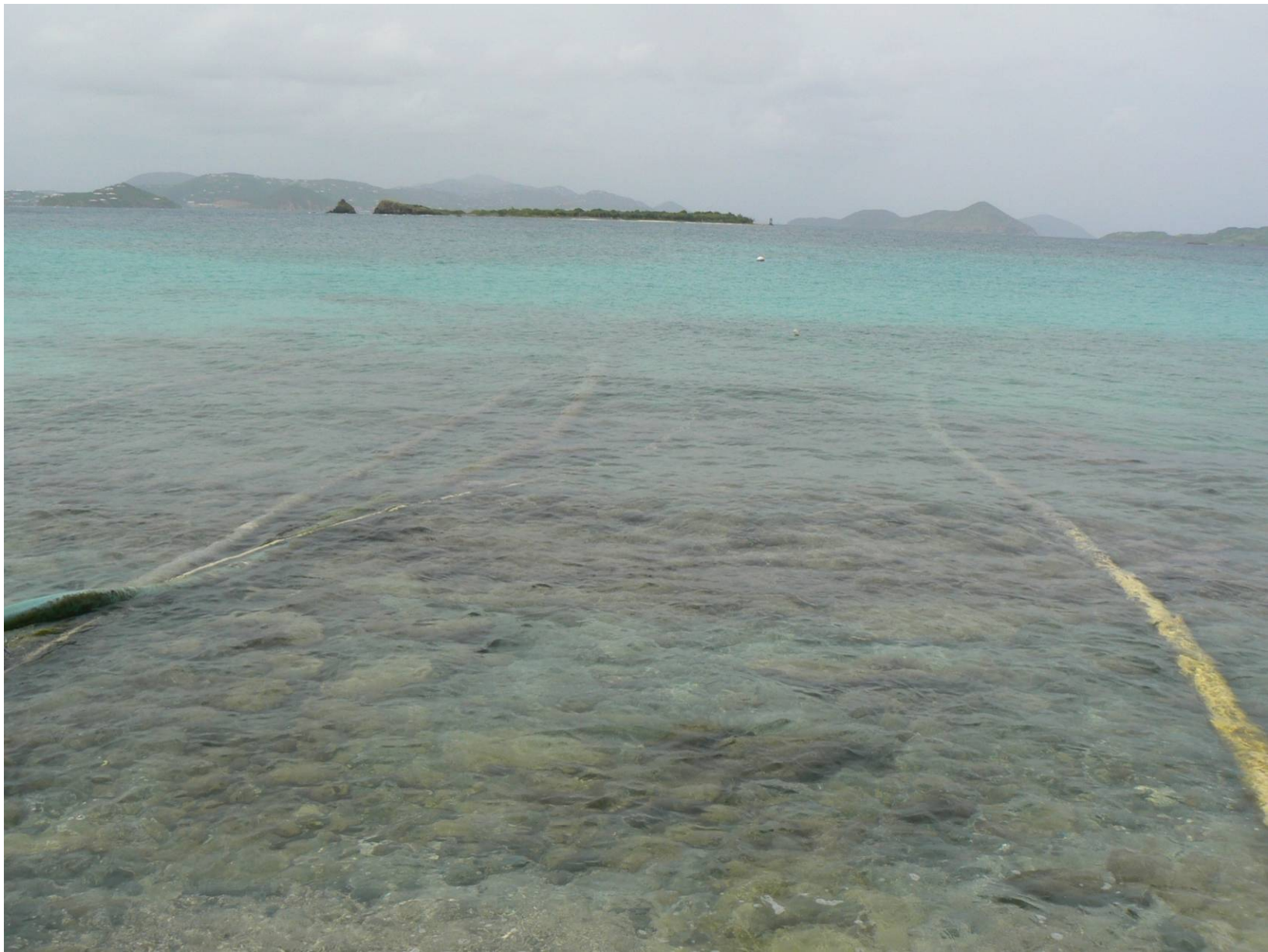
Outline

- Description of the VIWAPA System
- The SuperCalibrator Concept / Distributed State Estimation
- SuperCalibrator Implementation
- Future Plans / Demonstration
- Conclusions

The VIWAPA System

- Single Generating Plant (Randolph Harley Power Plant)
- Five Substations (RHPP, Long Bay, Tutu, East End, St. John)
- 34.5 kV Transmission
- 13.8 kV Distribution

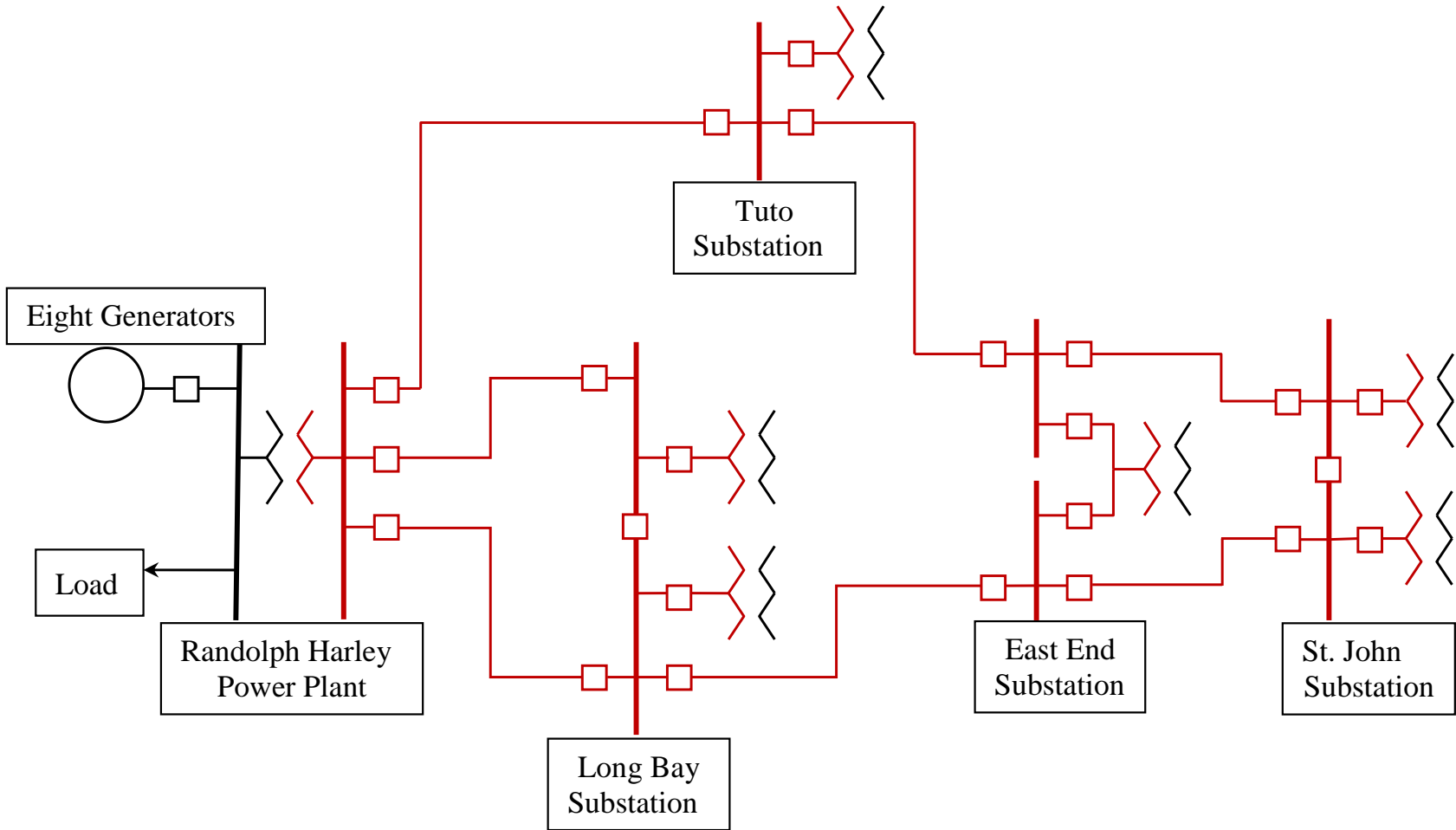




St. Thomas to St. John Water Line

NASPI Working Group Meeting

March 7, 2008



Simplified VIWAPA 34.5 kV Single Line



Randolph Harley Power Plant

NASPI Working Group Meeting
March 7, 2008



Randolph Harley Power Plant Outdoor Substation



Long Bay Substation



Long Bay Substation Transformers

NASPI Working Group Meeting

March 7, 2008



Long Bay Substation Switchgear Room

NASPI Working Group Meeting
March 7, 2008



Long Bay Substation
Control Room



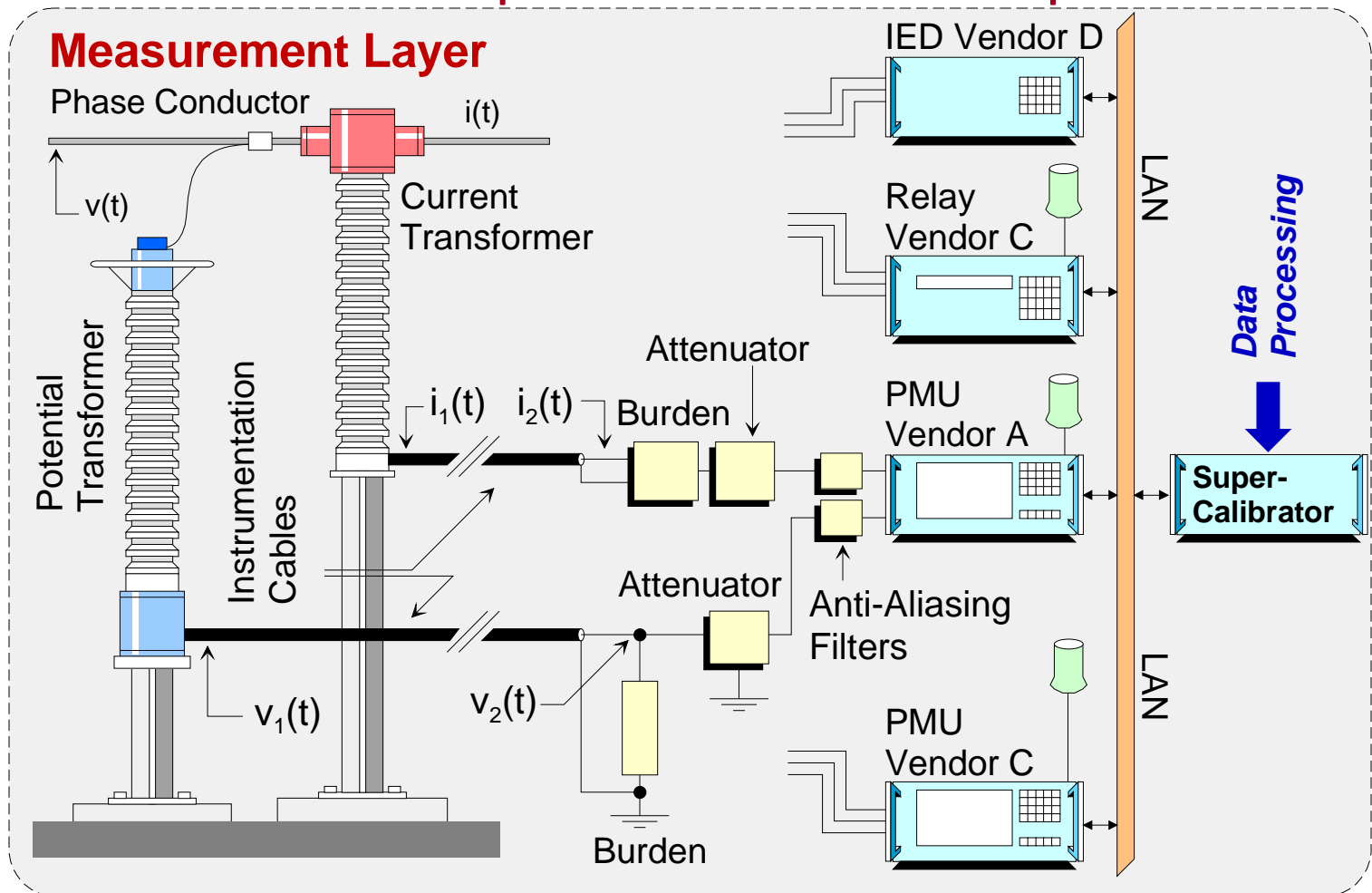
Long Bay Substation
Typical Relay Panel

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 SuperCalibrator is facilitated by the substation automation technology that makes all substation data readily accessible at a common point. The basic idea is to utilize a detailed 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 detailed substation model. An estimation algorithm determines the best estimate of the substation model state.

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

The SuperCalibrator Concept



- Three-Phase, Breaker-Oriented, Instrumentation Channel Inclusive Model
- Utilization of All Data Available in the Substation (Relays, Meters, Tap Controller, etc.)
- Static State Estimator at the Substation Level (See Additional Slides)

SuperCalibrator Implementation

Substation Equipment

All five substation equipped with:

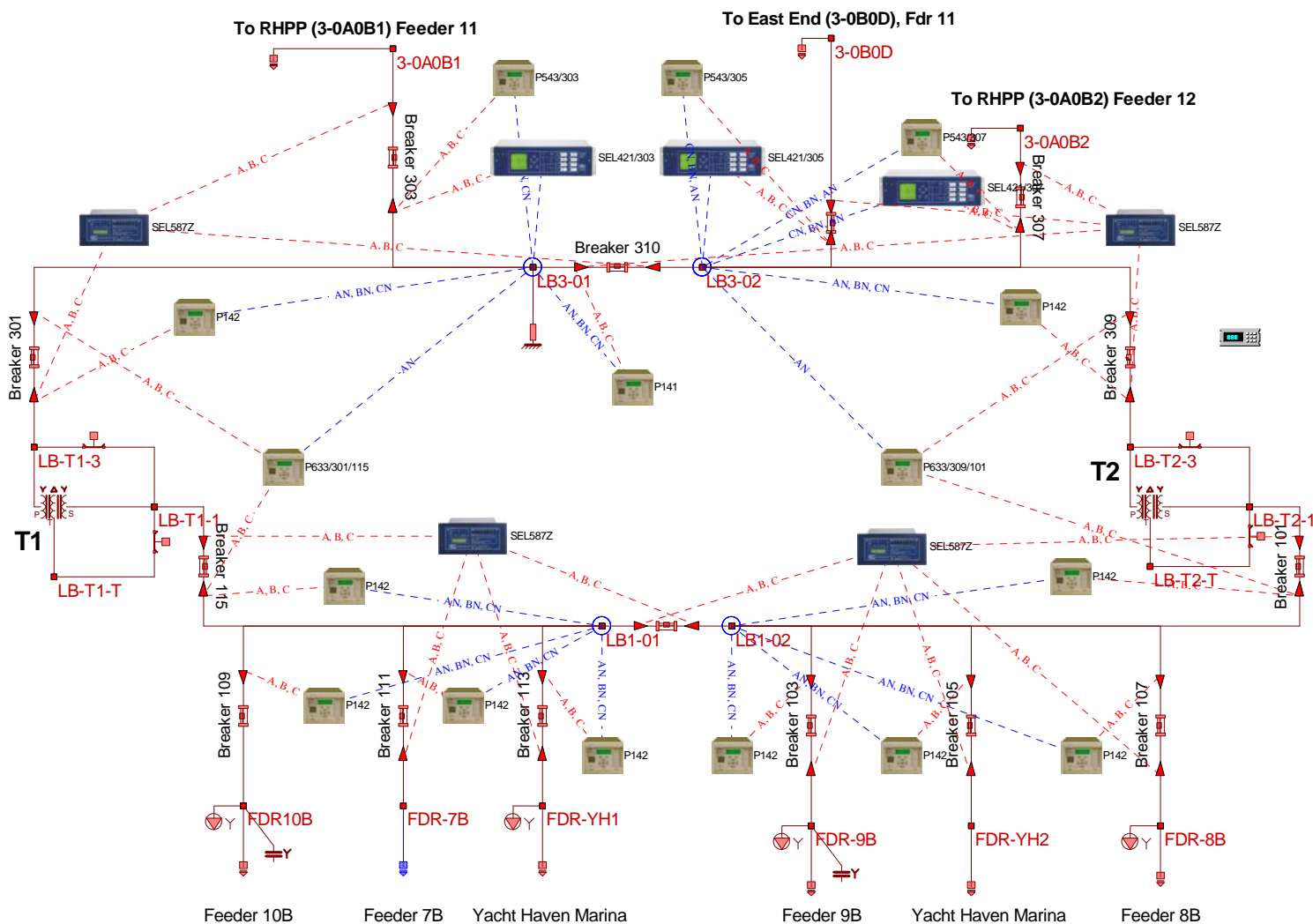
- Digital relays (SEL, Areva)
- GPS Clock
- Data Concentrator PC
- Local Area Network (Ruggedcom)

Communication Protocols Used (Relays to Data Concentrator):

- DNP3
- MODBUS/TCP
- IEEE C37.118

SuperCalibrator Implementation

Substation Configuration – Long Bay



SuperCalibrator Implementation

Substation Configuration – Long Bay

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

Breaker 309 Breaker 107 Breaker 101

T2

LB-T2-3 LB-T2-J

SuperCalibrator Implementation

Substation Configuration – Long Bay

The screenshot displays the 'Intelligent Electro' software interface. The main window is titled 'Instrumentation Channels' and 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	CT800-5	X1-X2	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
2	C_3031_B	Cur	LB3-01	B	Breaker 303	CT800-5	X1-X2	COP-PAIR-10	200.00	LB001	1.00	0.00	1.0
3	C_3031_C	Cur	LB3-01	C	Breaker 303	CT800-5	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

Below the table, there are buttons for 'New', 'Edit', 'Delete', 'Cancel', and 'Accept'. The status bar at the bottom of the window reads 'Program WinIGS-F - Form IGS_M007_ICHAN_LIST'.

On the left side of the interface, there is a configuration panel for the substation 'VIWAPA'. It includes fields for 'IED', 'Manufacturer' (SEL), 'Model' (SEL42), 'Name' (SEL42), and 'Identifier' (LB001). There are also radio buttons for 'Data Type' (Phasors, Waveforms) and 'Data' (Mea, Sim, Esti). A 'File Name' field and a 'File Location' field (Undefined) are also present.

At the bottom of the image, there is a schematic diagram showing connections to various feeders and equipment:

- Feeder 10B: Connected to FDR10B.
- Feeder 7B: Connected to FDR-7B.
- Yacht Haven Marina: Connected to FDR-YH1.
- Feeder 9B: Connected to FDR-9B.
- Yacht Haven Marina: Connected to FDR-YH2.
- Feeder 8B: Connected to FDR-8B.

SuperCalibrator Implementation

Substation Configuration – Long Bay

Intelligent Electro

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: Into Device Outof Device

Power Device: Breaker 303

Overall Nominal Ratio and Offset: 120.00 0.00

Instrument Transformer
Instr. Transformer Code: 3031
Type: CT600-5
Tap: X1-X2
Ratio: 600.0/5.0 A
Nominal Primary Voltage (kV): 34.50

Instrumentation Cable
Length (ft): 200.00
Cable Type: COP-PAIR-10

Attenuator
1.00

Burden
R (Ohms): 0.10
X (Ohms): 0.00

DAU
IDEAL16BIT
Peak Voltage(V): 2.00
Calibr Factor: 1.00
Calibr Offset: 0.00
Time Skew (us): 0.00
Data Concentrator

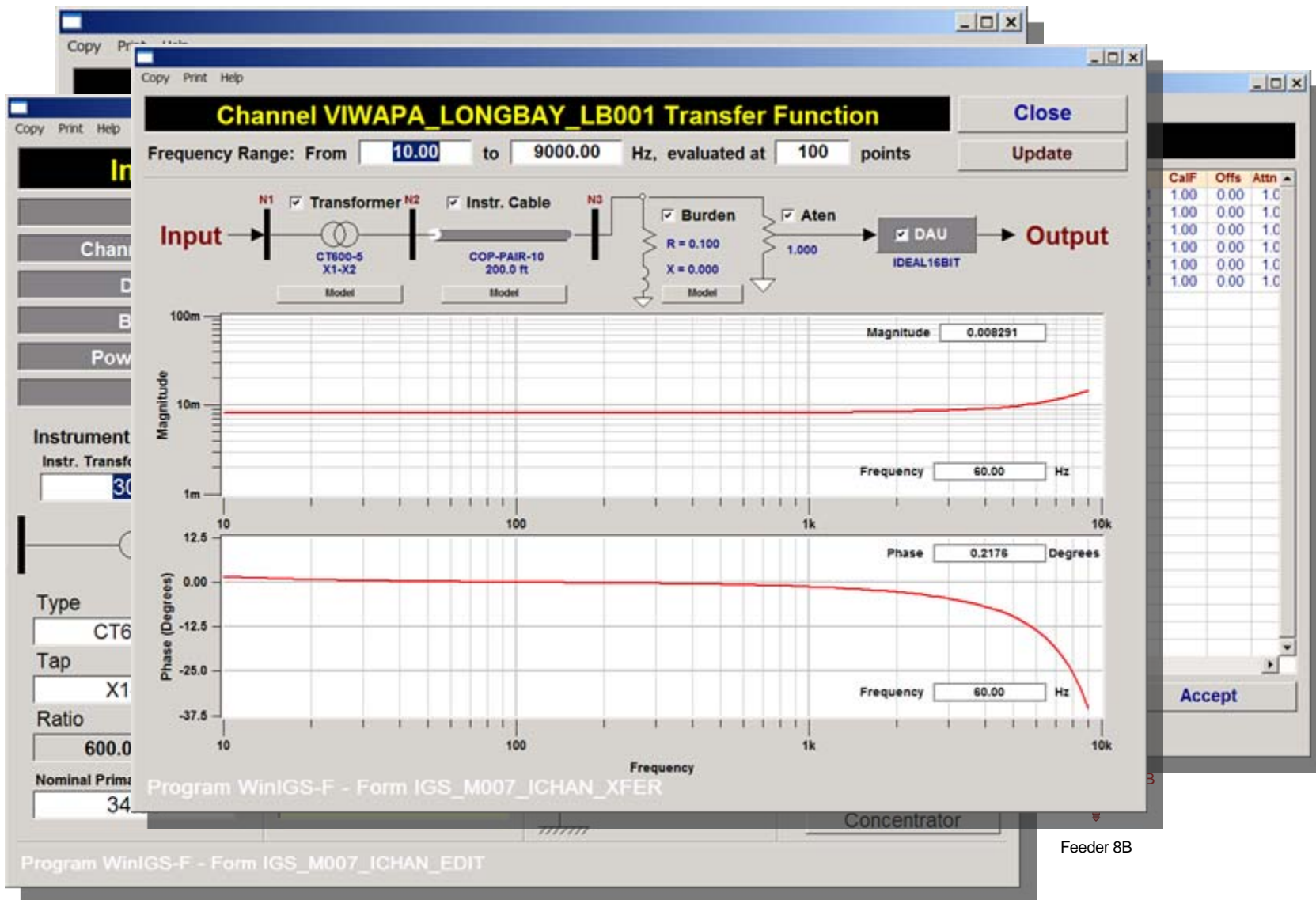
Length	IED	CalF	Offs	Attn
200.00	LB001	1.00	0.00	1.0
200.00	LB001	1.00	0.00	1.0
200.00	LB001	1.00	0.00	1.0
200.00	LB001	1.00	0.00	1.0
200.00	LB001	1.00	0.00	1.0
200.00	LB001	1.00	0.00	1.0

Program WinIGS-F - Form IGS_M007_ICHAN_EDIT

Feeder 8B

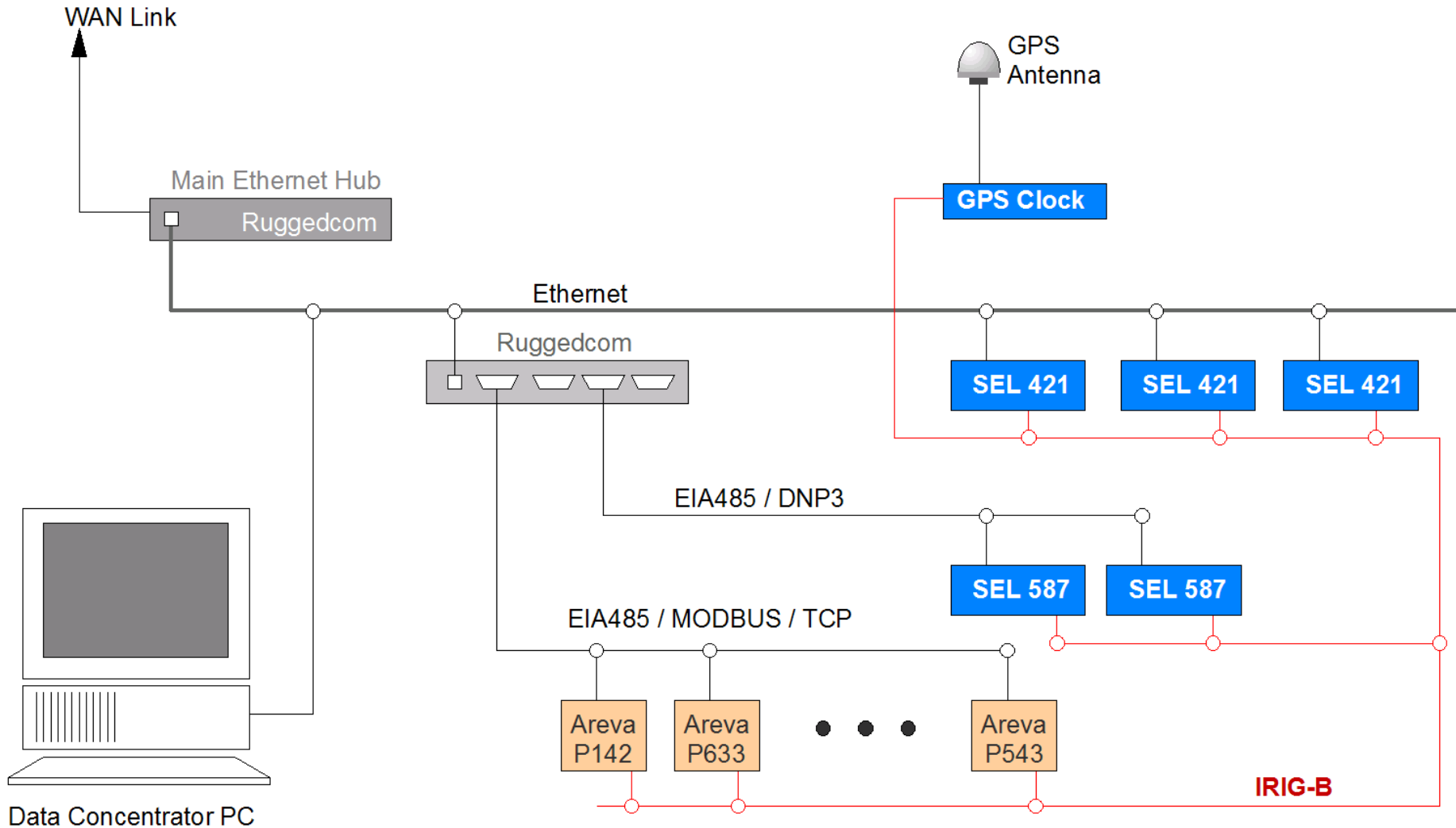
SuperCalibrator Implementation

Substation Configuration – Long Bay



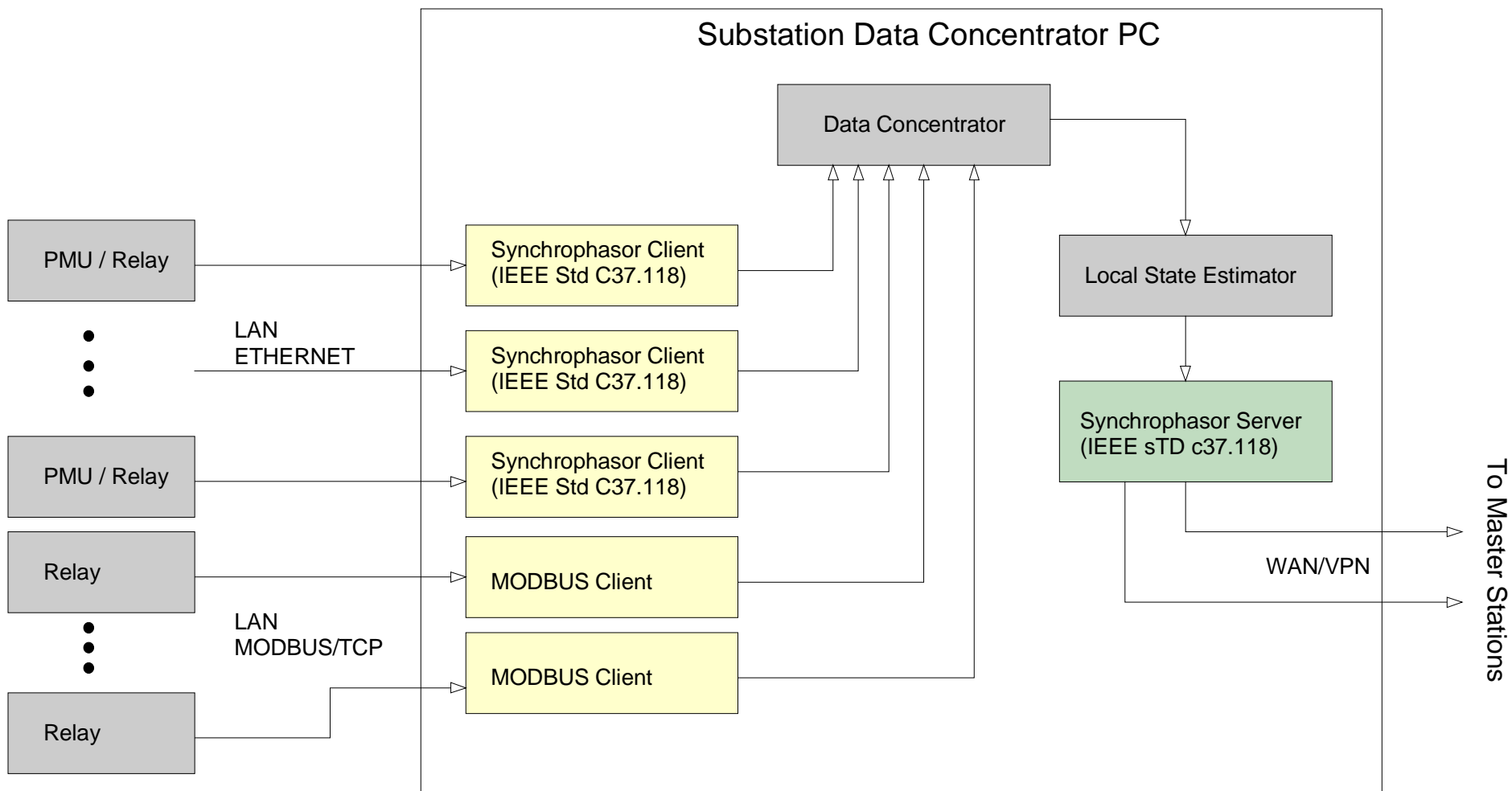
SuperCalibrator Implementation

Communications Hardware Setup – Long Bay



SuperCalibrator Implementation

Substation Data Concentrator - Organization



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 Power System State

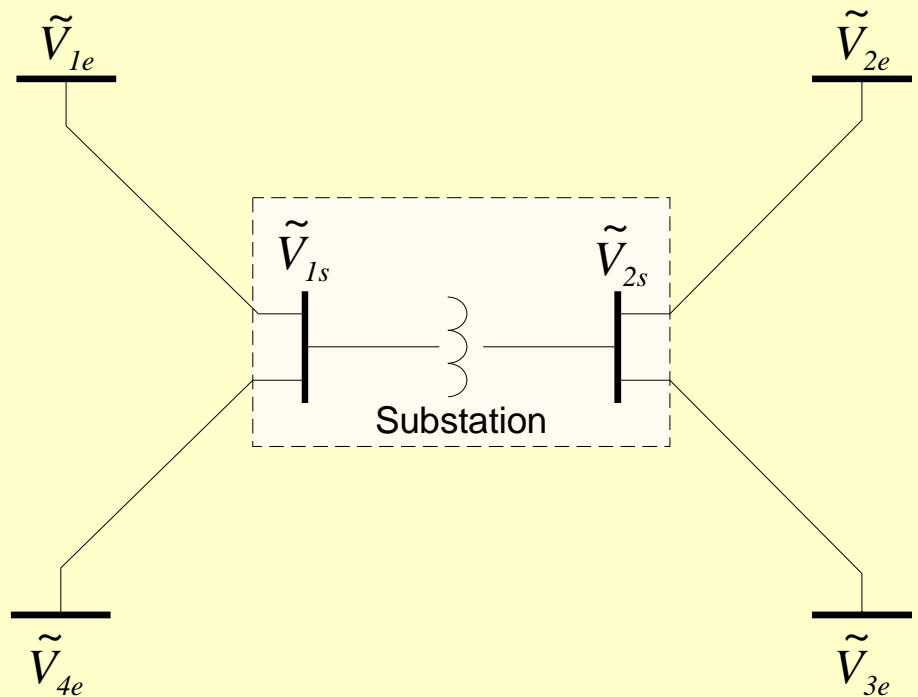
Definition of Substation Based System State

Substation State

$$\tilde{V}_{1s} = \begin{bmatrix} \tilde{V}_{1s,a} \\ \tilde{V}_{1s,b} \\ \tilde{V}_{1s,c} \\ \tilde{V}_{1s,n} \end{bmatrix} \quad \tilde{V}_{2s} = \begin{bmatrix} \tilde{V}_{2s,a} \\ \tilde{V}_{2s,b} \\ \tilde{V}_{2s,c} \\ \tilde{V}_{2s,n} \end{bmatrix}$$

Extended Substation State

$$\tilde{V}_{1e} = \begin{bmatrix} \tilde{V}_{1e,a} \\ \tilde{V}_{1e,b} \\ \tilde{V}_{1e,c} \\ \tilde{V}_{1e,n} \end{bmatrix} \quad \tilde{V}_{2e} = \begin{bmatrix} \tilde{V}_{2e,a} \\ \tilde{V}_{2e,b} \\ \tilde{V}_{2e,c} \\ \tilde{V}_{2e,n} \end{bmatrix} \quad \tilde{V}_{3e} = \begin{bmatrix} \tilde{V}_{3e,a} \\ V_{3e,b} \\ \tilde{V}_{3e,c} \\ \tilde{V}_{3e,n} \end{bmatrix} \quad \tilde{V}_{4e} = \begin{bmatrix} \tilde{V}_{4e,a} \\ \tilde{V}_{4e,b} \\ \tilde{V}_{4e,c} \\ \tilde{V}_{4e,n} \end{bmatrix}$$



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: Missing Phase Measurements

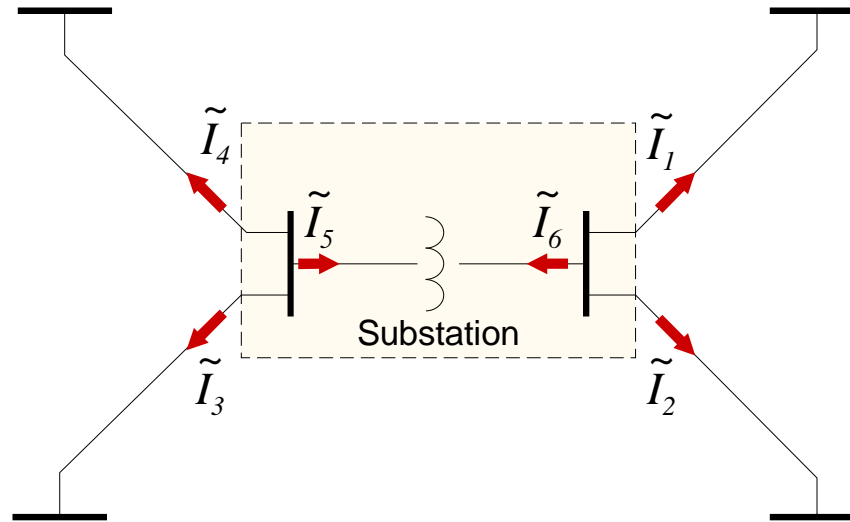
Assume There is a Phase A Voltage Phasor Measurement.
Assume there is no Phase C Measurement.

THEN:

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

Expected Error: Less than 3%

SuperCalibrator Measurement Set: Kirchoff's Current Law



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

Expected Error: 0.001%

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

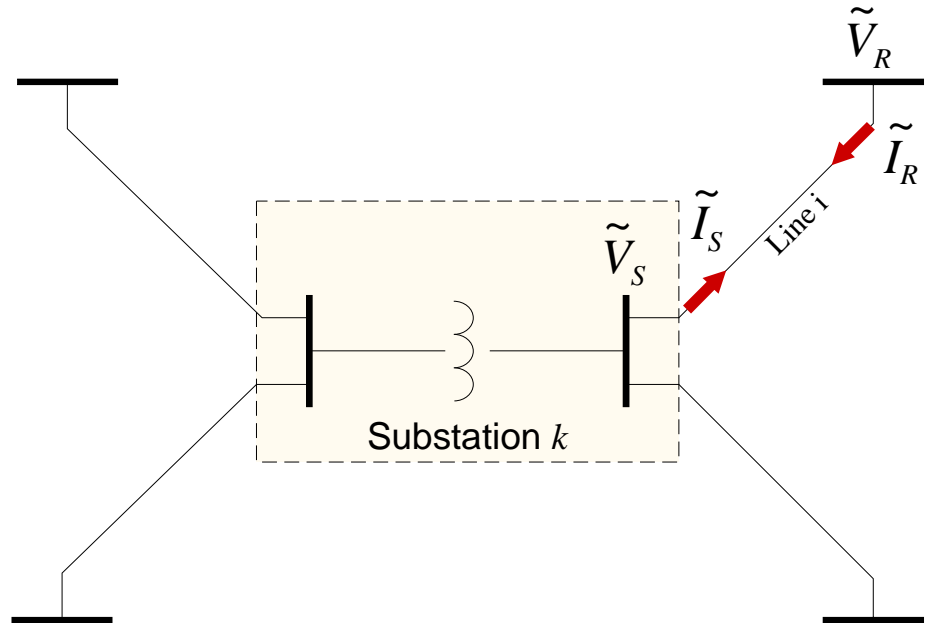
Expected Error: 0.001%

SuperCalibrator Measurement Set:

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

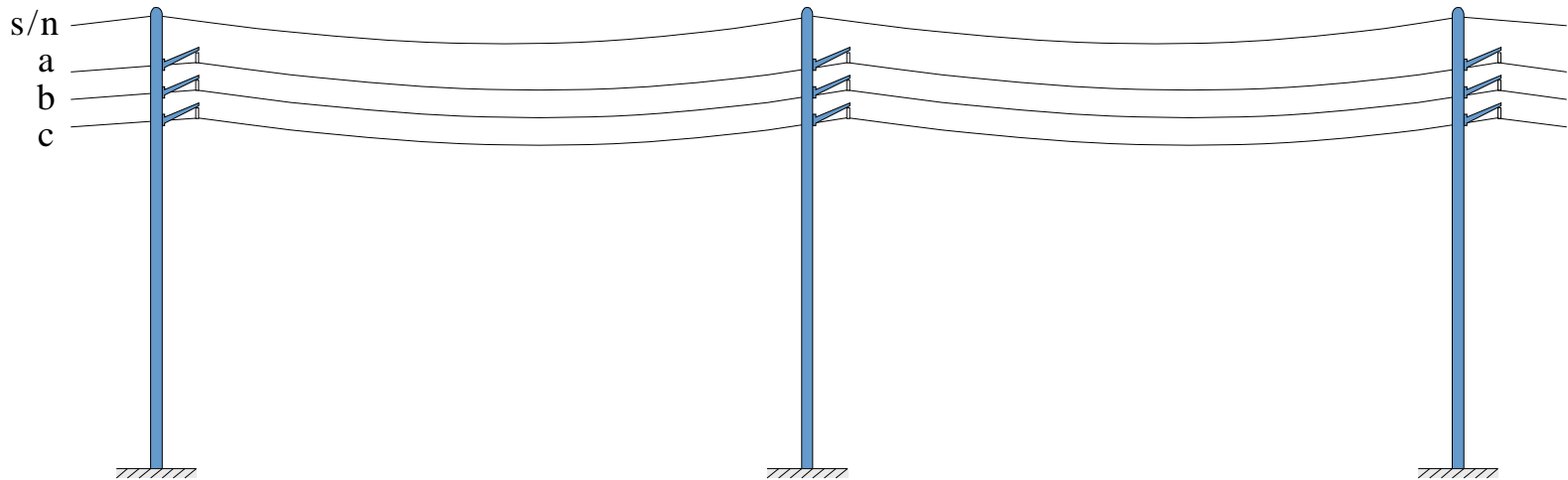
$$\tilde{V}_R^{pseudo,m} = (\mathbf{I} - Z_{22}Y_{22})^{-1}Z_{21}\tilde{I}_S + (\mathbf{I} - Z_{22}Y_{22})^{-1}Z_{22}Y_{21}\tilde{V}_S$$

Expected Error: 0.01%

Where:

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}^{-1}$$

SuperCalibrator Measurement Set: Neutral/Shield Current



$$\alpha = \frac{\tilde{I}_{s/n}}{-\left(\tilde{I}_a + \tilde{I}_b + \tilde{I}_c\right)}$$

$$\tilde{I}_{s/n}^{pseudo,m} + \alpha\left(\tilde{I}_a + \tilde{I}_b + \tilde{I}_c\right) = 0$$

Expected Error: 0.01%

Summary and Future Work

- The SuperCalibrator Provides a Fully Distributed and Scalable State Estimator. Accurately Accounts for:
 1. System Asymmetries,
 2. Voltage Imbalance,
 3. Instrumentation Channel Error.
- The SuperCalibrator Approach Requires at Least One GPS-Synchronized Device in Each Substation.
- The SuperCalibrator Is Being Implemented VIWAPA.
- Demonstration Has Been Scheduled for May 5-6, 2008.

PMU Enabled - Distributed State Estimation Demonstration

May 5-6, 2008

Virgin Islands Water and Power Authority

St. Thomas, USVI

One of the Research Projects that is Moving Towards Commercialization...



Concurrent Technologies Corporation (CTC) through the U.S. Department of Energy's Center for Grid Modernization has sponsored a project to implement, demonstrate and validate "SuperCalibrator." This technology enables distributed state estimation by using existing relay/PMU devices in substations. "SuperCalibrator" is based on the efforts of the Power Systems Engineering Research Center (PSERC) researchers at Georgia Tech that have been searching for improved state estimation and power grid visibility approaches that use advanced data acquisition hardware. This project expanded on work that was completed in 2006-07 to prove the concept on two two-substations systems of the NYPA and ENTERGY systems. This effort was focused on implementation of this technology in a full system (the U.S. Virgin Island WAPA system). This project is being performed by Professors A. P. Meliopoulos and George Cokkinides (School of Electrical and Computer Engineering – Georgia Tech) and Terry Conrad (CTC). The fully distributed three-phase state estimator will be demonstrated in this workshop.





Distributed State Estimator
at
U.S. Virgin Islands
Water and Power Authority
St. Thomas and St. John

Questions?

Terry L. Conrad
Concurrent Technologies Corporation

A. P. Sakis Meliopoulos
Georgia Tech