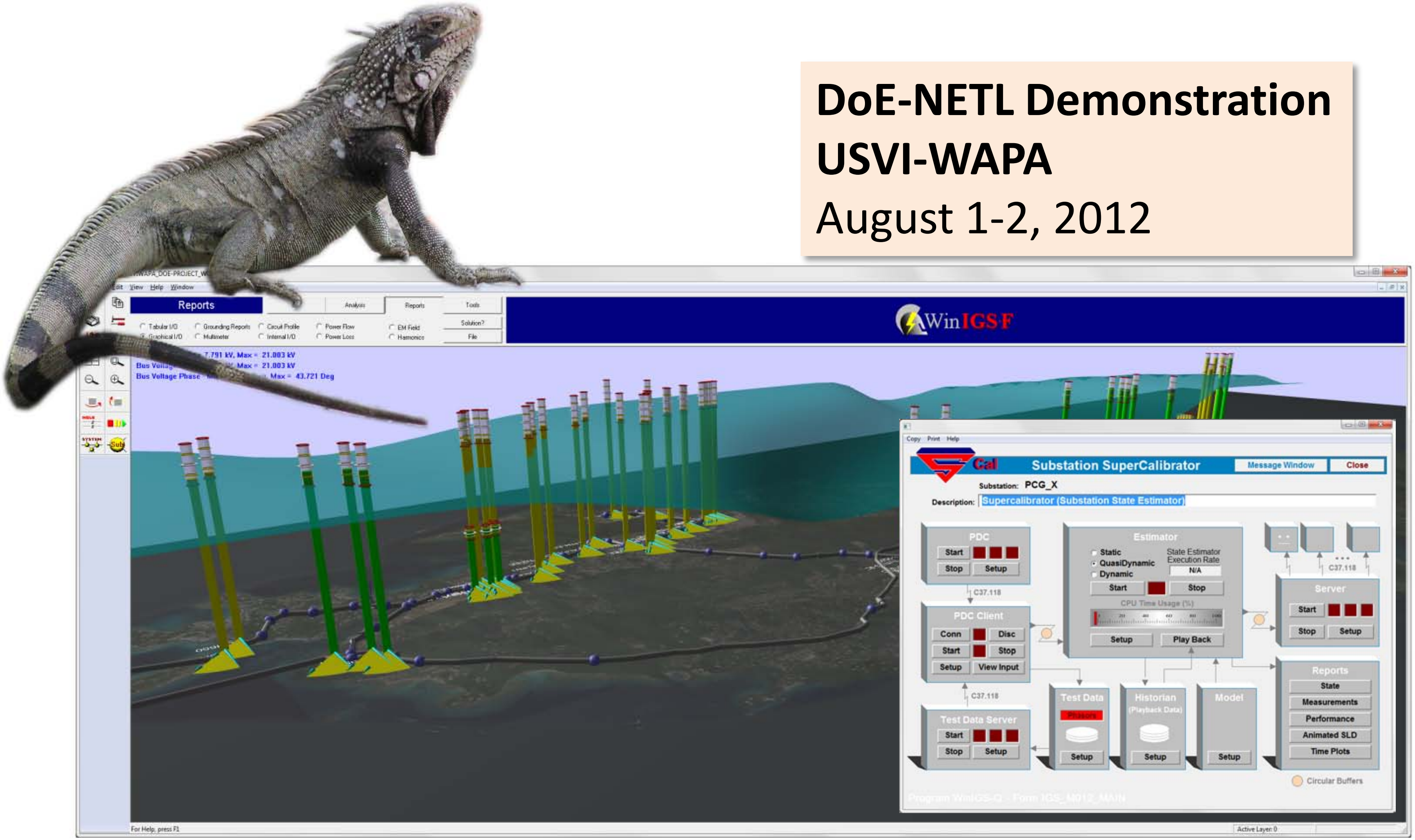
Distributed Dynamic State Estimator, Generator Parameter Estimation and Stability Monitoring

DoE-NETL Demonstration
USVI-WAPA
August 1-2, 2012



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Demonstration: USVI-WAPA
Project Team

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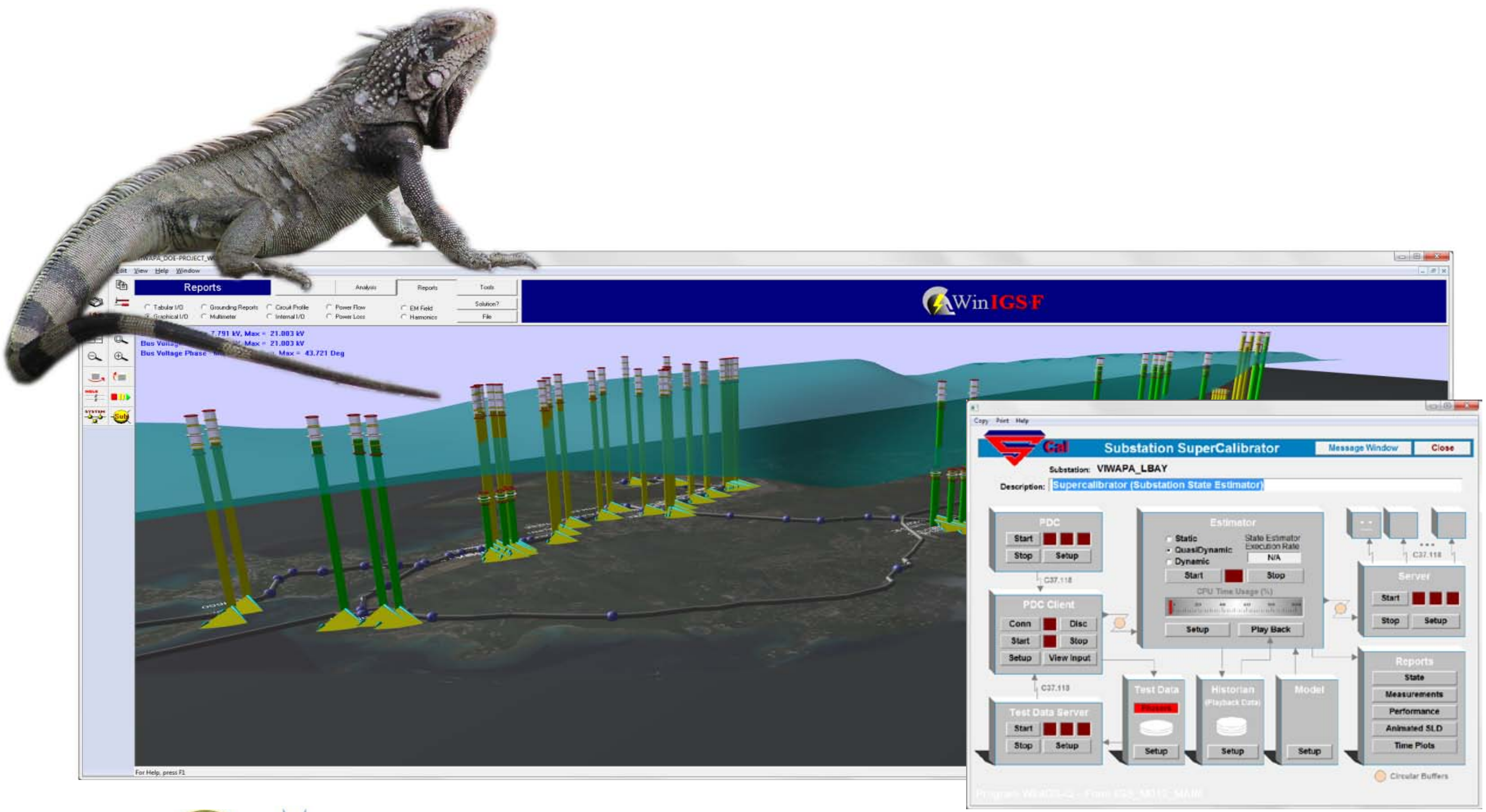
Demonstration: USVI-WAPA

Project Overview



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Project Objectives and Scope

This project addresses four fundamental problems in the operation of any electric power network, let it be the national grid, a distribution circuit with distributed resources or a μGrid:

(a) Real time modeling of the system via the proposed distributed dynamic state estimation using synchrophasor technology

(b) Parameter identification of important components of the system such as generating units

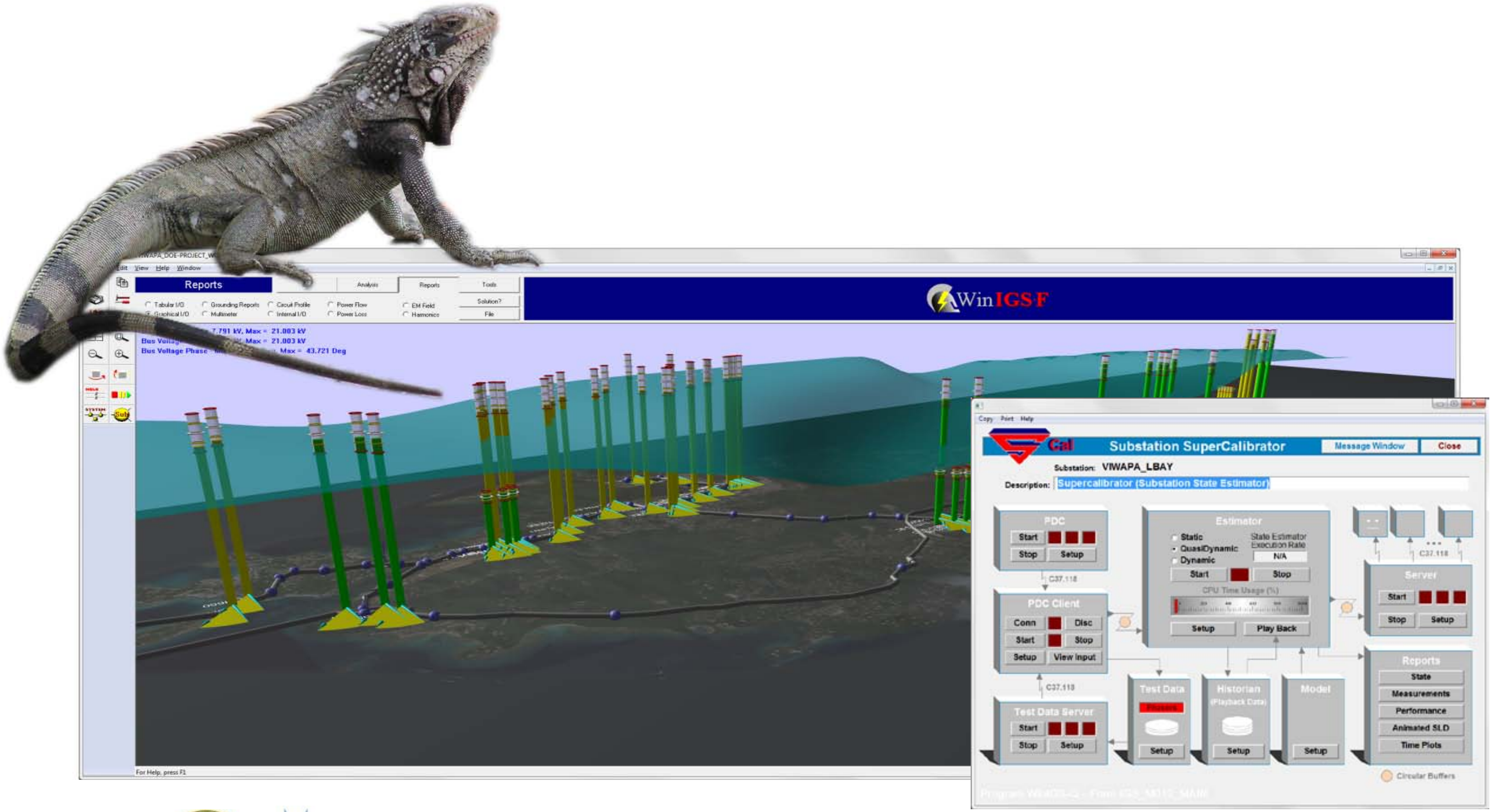
(c) Stability monitoring and prediction of eminent instabilities

(d) Disturbance “Play Back”

This work is fundamental for power system operations and optimization – we believe that the successful completion of the proposed work will provide a better infrastructure for power system operations and control.

Demonstration: USVI-WAPA

Distributed State Estimator



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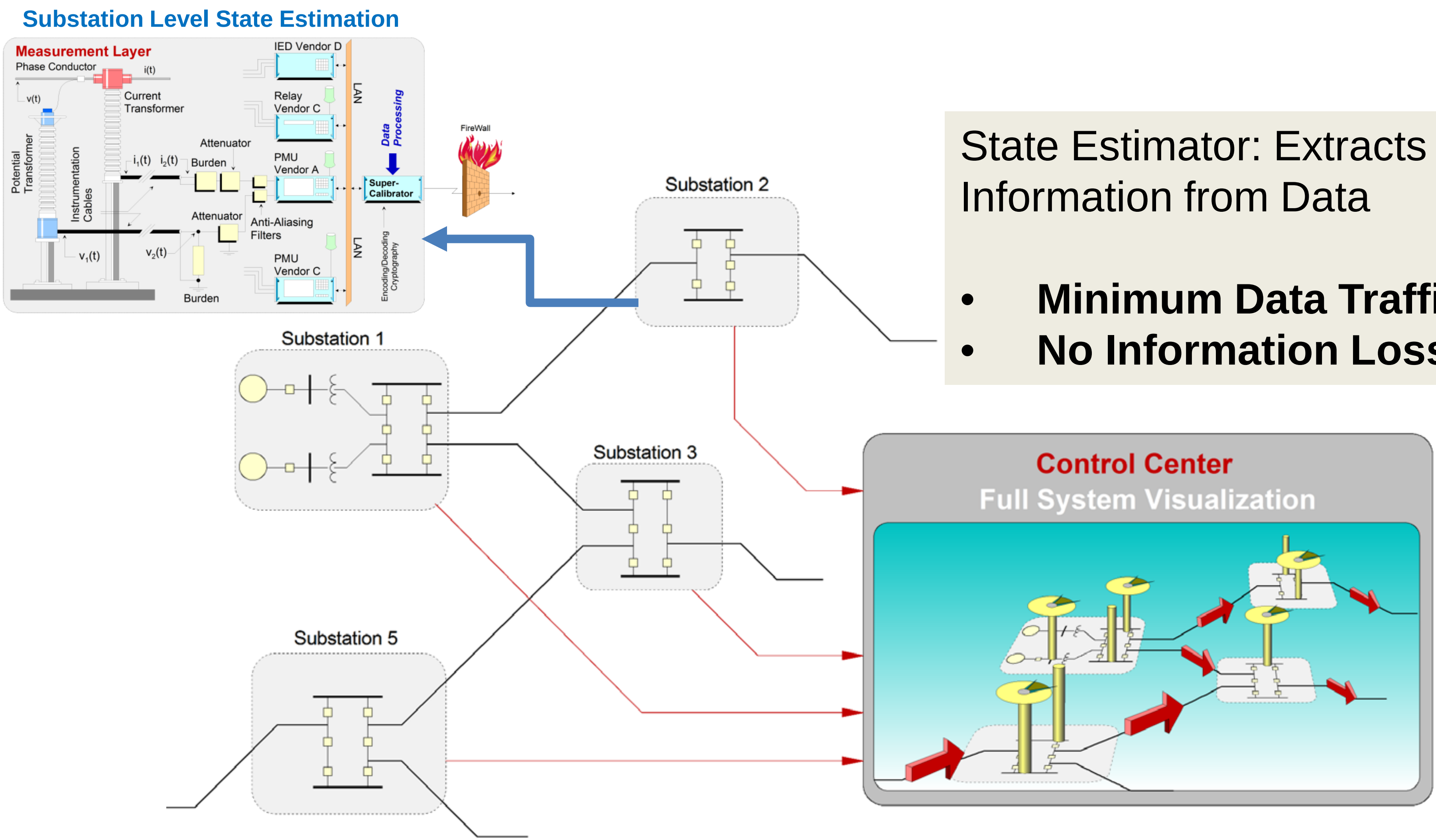
Distributed State Estimation

Substation Level SE → Synthesis of System Wide State at the Control Center
Enabling Technology: GPS-Synchronized Measurements



State Estimator: Extracts Information from Data

- **Minimum Data Traffic**
- **No Information Loss**

The SuperC Concept (Distributed SE)

The SuperC 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. Use “Derived” and “Virtual” Measurements by Application of Physical Laws

4. At least one GPS synchronized device (PMU, Relay with PMU, etc.) → Results on UTC time enabling a truly decentralized State Estimator

Distributed Dynamic State Estimation

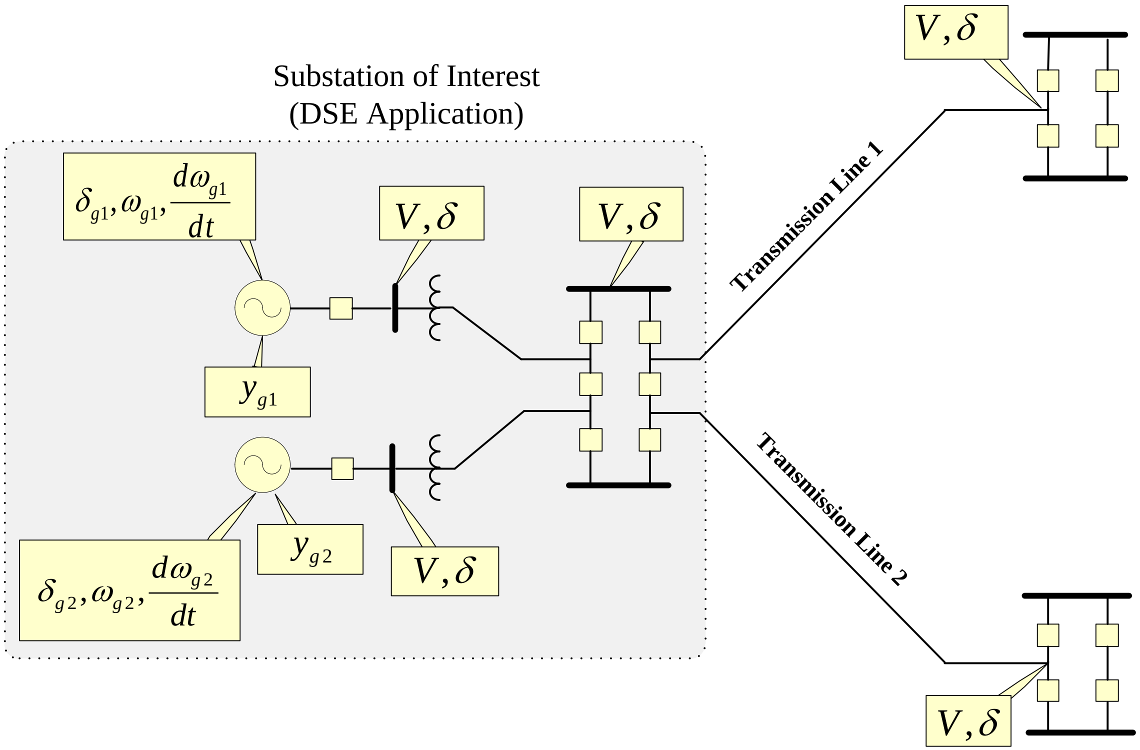
Implementation

The Estimator is Defined in Terms of:

- Model
- State
- Measurement Set
- Estimation Method

Observability

Redundancy



System is Represented with a Set of Differential Equations (DE)
The Dynamic State Estimator Fits the Streaming Data to the Dynamic Model (DE) of the System

Distributed SE Measurement Set

- Any Measurement at the Substation from Any IED
  - (Relays, Meters, FDR, PMUs, etc.)
- Data From at Least one GPS-Synchronized Device
- Derived Measurements
  - Based on Topology
- Virtual Measurements
  - Kirchoff's Current Law
  - Model Equations
- Pseudo-Measurements
  - Missing Phase Measurements
  - Neutral/Shield Current Measurement
  - Neutral Voltage

Object Oriented Measurement Model

Measurement Types:

•Actual Across Measurement: eg. voltage measurement
•Pseudo Across Measurement: eg. neutral voltage measurement
•Actual Through Measurement (related to a device): eg. current measurement
•Pseudo Through Measurement (related to a device)

Power System Component Model (Dynamic Model → Integration → Algebraic Model):

$$\begin{bmatrix} i(t) \\ 0 \\ i(t_m) \\ 0 \end{bmatrix} = Y_{eq} \begin{bmatrix} v(t) \\ y(t) \\ v(t_m) \\ y(t_m) \end{bmatrix} + \begin{bmatrix} \left[v^T(t) \quad y^T(t) \quad v^T(t_m) \quad y^T(t_m) \right] \cdot F_{eq} \cdot \begin{bmatrix} v(t) \\ y(t) \\ v(t_m) \\ y(t_m) \end{bmatrix} \end{bmatrix} - b_{eq}$$

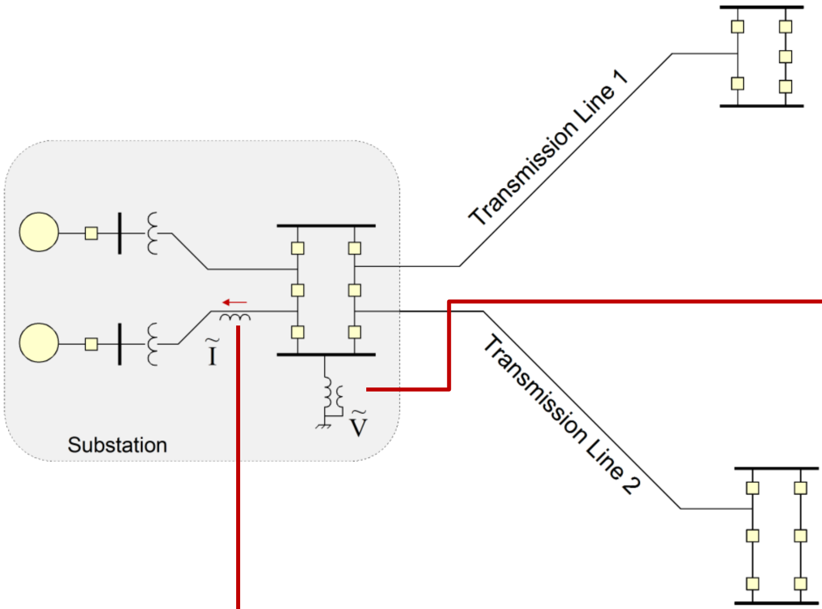
where

$$b_{eq} = \sum_i A_i \cdot \begin{bmatrix} v(t - i \cdot h) \\ y(t - i \cdot h) \end{bmatrix} + \sum_i B_i \cdot \begin{bmatrix} i(t - i \cdot h) \\ 0 \end{bmatrix} + C$$

Each Measurement is expressed as a function of the states (at most quadratic):

$$z_k(t) = \sum_i a_{i,t}^k \cdot x_i(t) + \sum_i a_{i,tm}^k \cdot x_i(t_m) + \sum_{i,j} b_{i,j,t}^k \cdot x_i(t) \cdot x_j(t) + \sum_{i,j} b_{i,j,tm}^k \cdot x_i(t_m) \cdot x_j(t_m) + c_k(t) + \eta_k$$

Object Oriented QSE



Across (Voltage) Measurement:

$$\tilde{z}_j(t) = \tilde{x}_j(t) + \eta_j$$

Through (Current, Torque, etc.) Measurement:

Measurement $z_j(t)$ represents a quality associated with one row of the Object oriented model

$$\tilde{z}_j(t) = \boxed{\text{row k of Object Oriented Model}} + \eta_j$$

Row k

Object Oriented Model

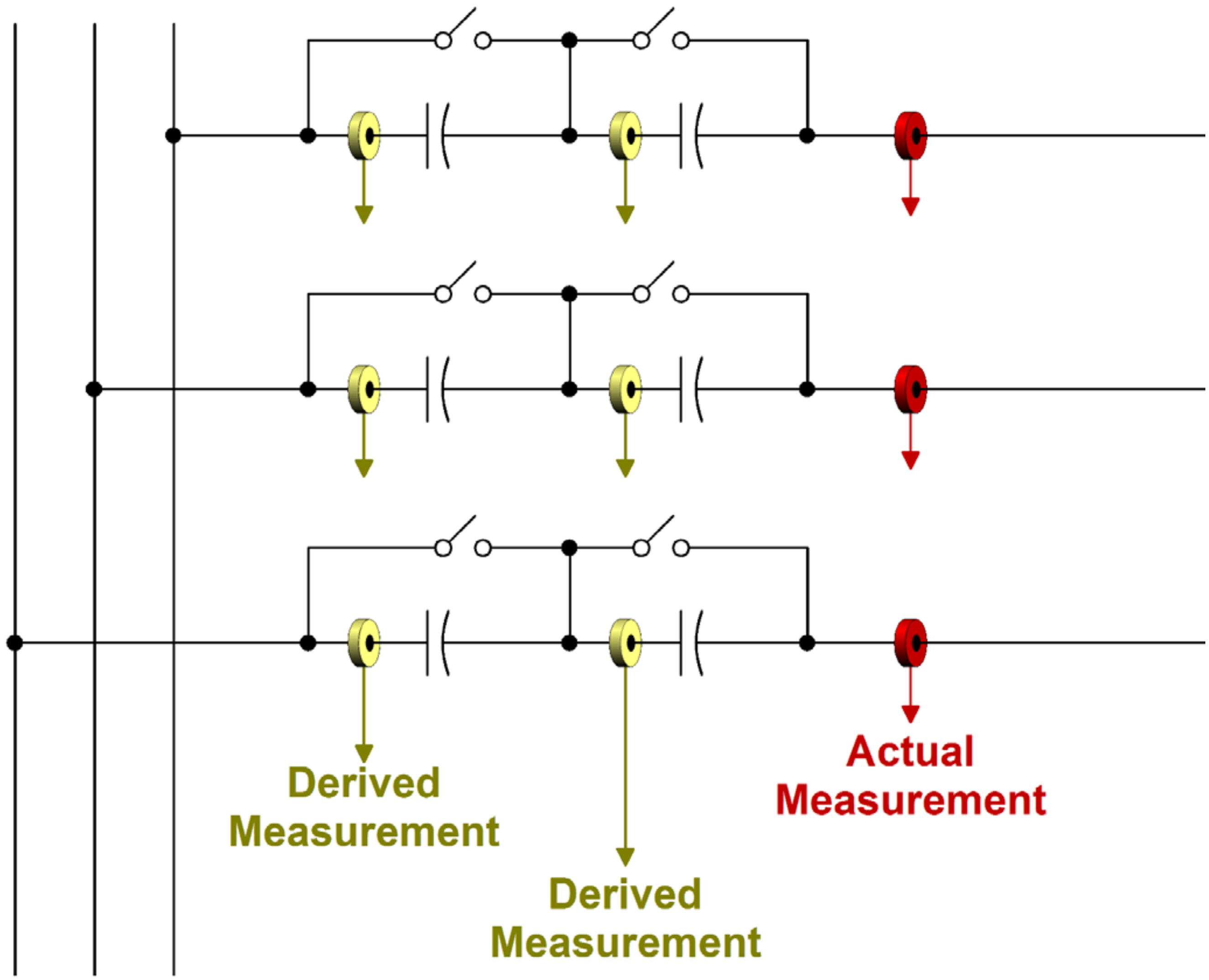
$$\begin{bmatrix} \tilde{I}(t) \\ 0 \\ \tilde{I}(t_m) \\ 0 \end{bmatrix} = Y_{eq} \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} + \left[\begin{bmatrix} \tilde{V}^T(t) & \tilde{Y}^T(t) & \tilde{V}^T(t_m) & \tilde{Y}^T(t_m) \end{bmatrix} \cdot F_{eq} \cdot \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} \right] - B_{eq}$$

$$where \quad B_{eq} = \sum_i A_i \cdot \begin{bmatrix} \tilde{V}(t - i \cdot h) \\ \tilde{Y}(t - i \cdot h) \end{bmatrix} + \sum_i B_i \cdot \begin{bmatrix} \tilde{I}(t - i \cdot h) \\ 0 \end{bmatrix} + C$$

QSE states are
Phasors, Speed, etc

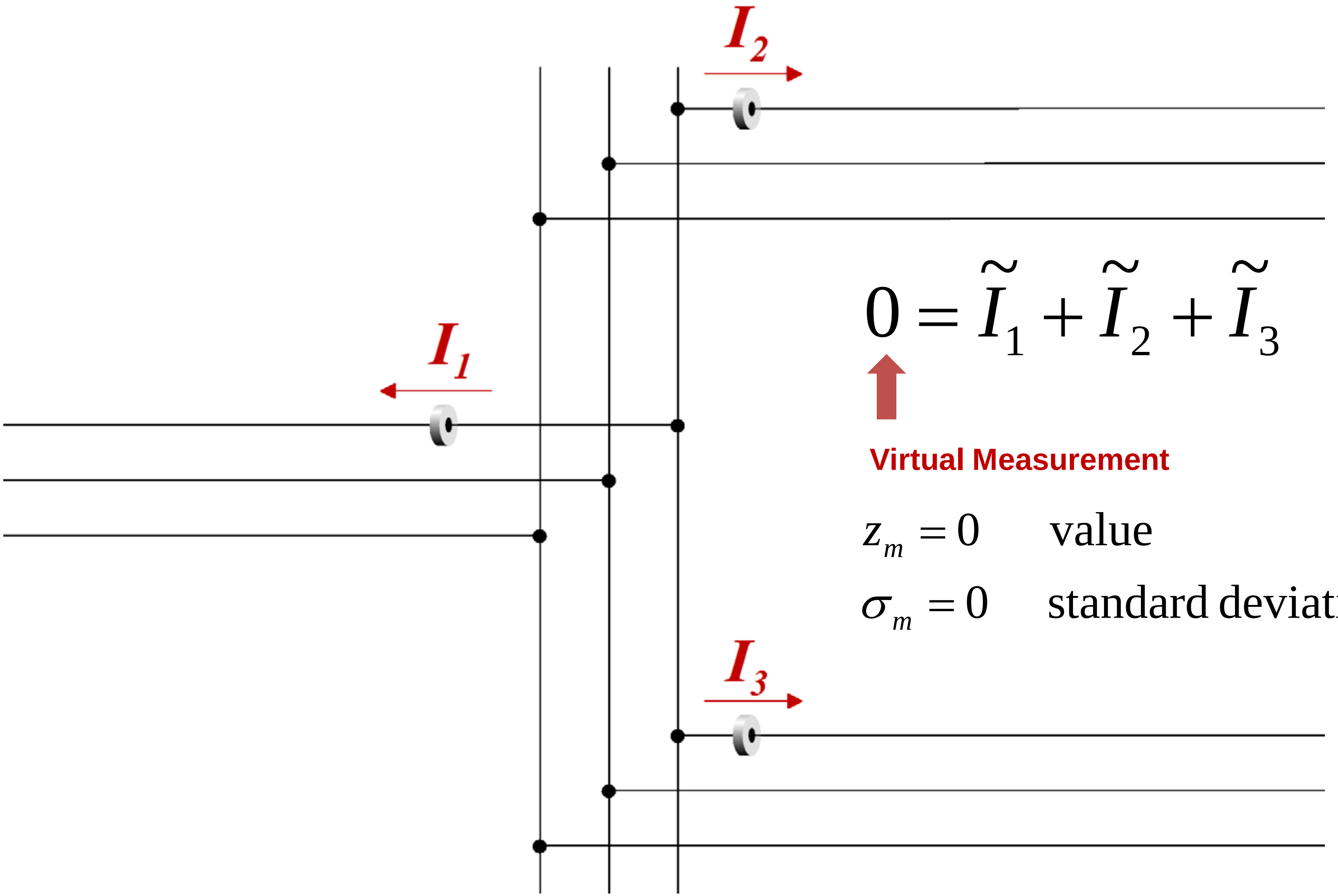
Distributed State Estimation

Derived Measurements - Examples



Distributed State Estimation

Virtual Measurements - Examples



$$0 = \tilde{I}_1 + \tilde{I}_2 + \tilde{I}_3$$

Virtual Measurement

$z_m = 0$ value

$\sigma_m = 0$ standard deviation

Distributed SE Measurement Set

Non-Synchronized Measurements

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

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

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

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

α is a synchronizing unknown variable.

$cos(\alpha)$ and $sin(\alpha)$ are unknown variables in the state estimation algorithm.

There is one α variable for each non-synchronized relay.

Distributed SE: Algorithm

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

Solution: $$x^{v+1} = x^v + A\left[z - h(x)\right]$$

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

Efficiency

Demonstrated the ability to execute the state estimator 60 times per second for substantial size substations.

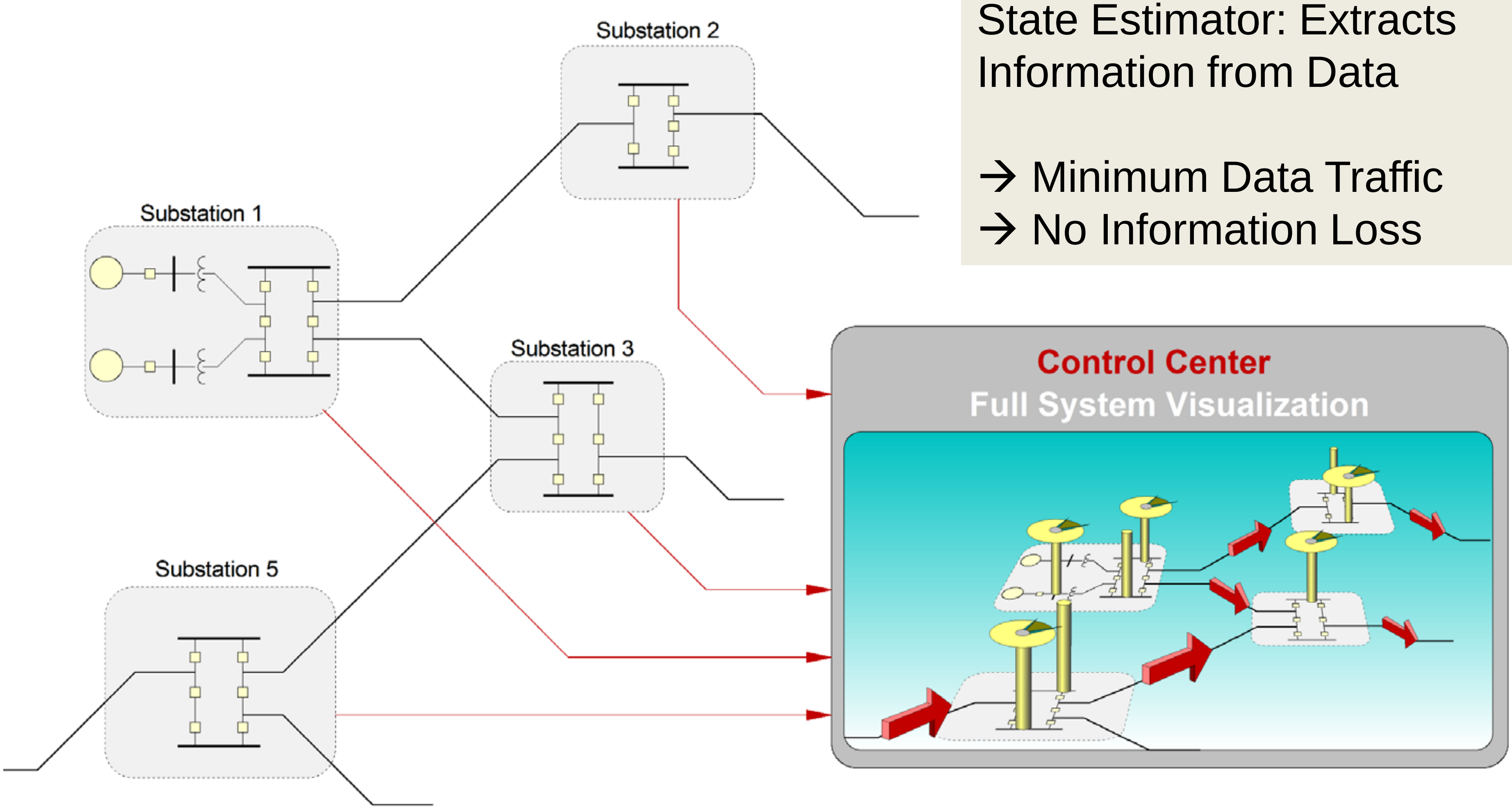
There is still space for improved computational efficiency.

Distributed State Estimation

Synthesis of System Wide State at the Control Center

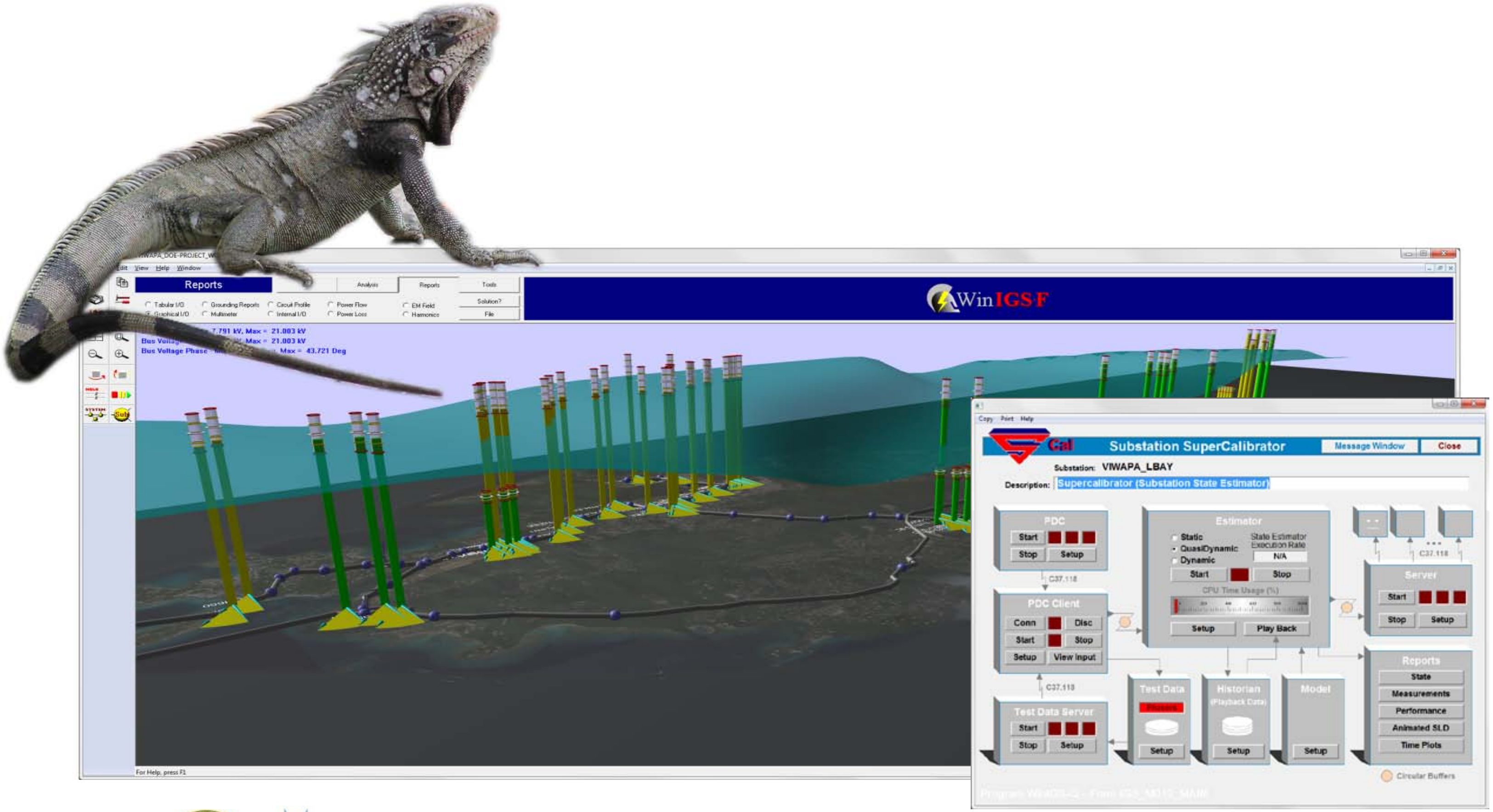
State Estimator: Extracts Information from Data

→ Minimum Data Traffic
→ No Information Loss



Demonstration: USVI-WAPA

Master DSE



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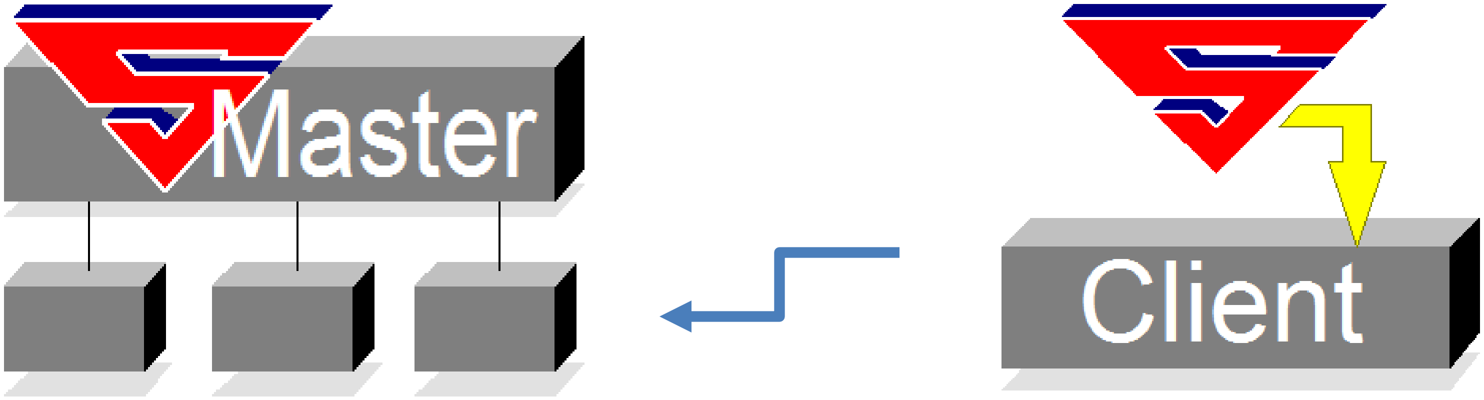
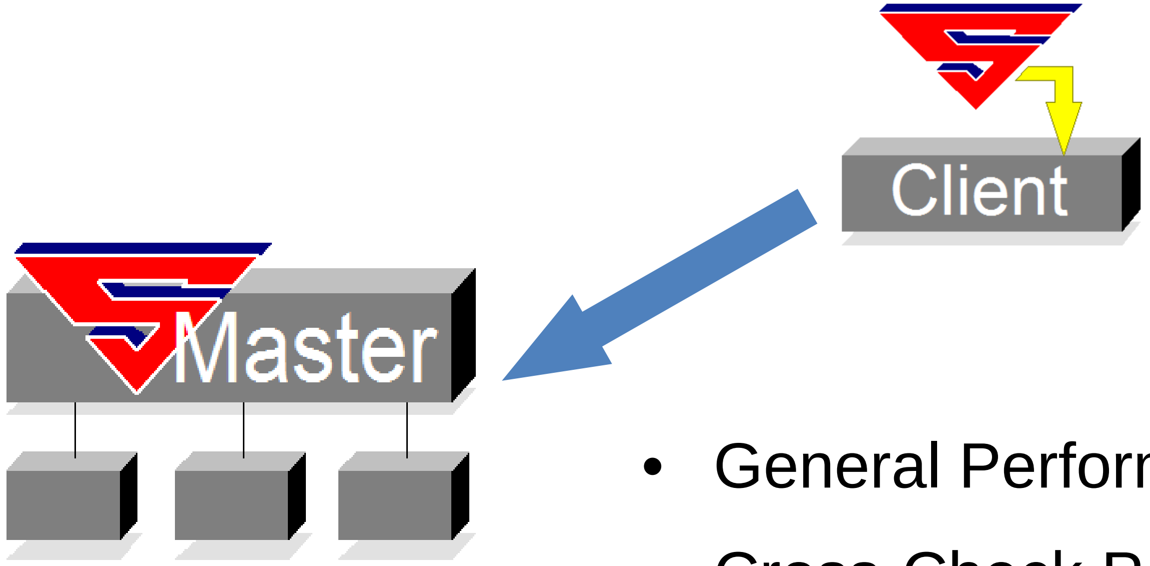
SuperCalibrator Master - Client

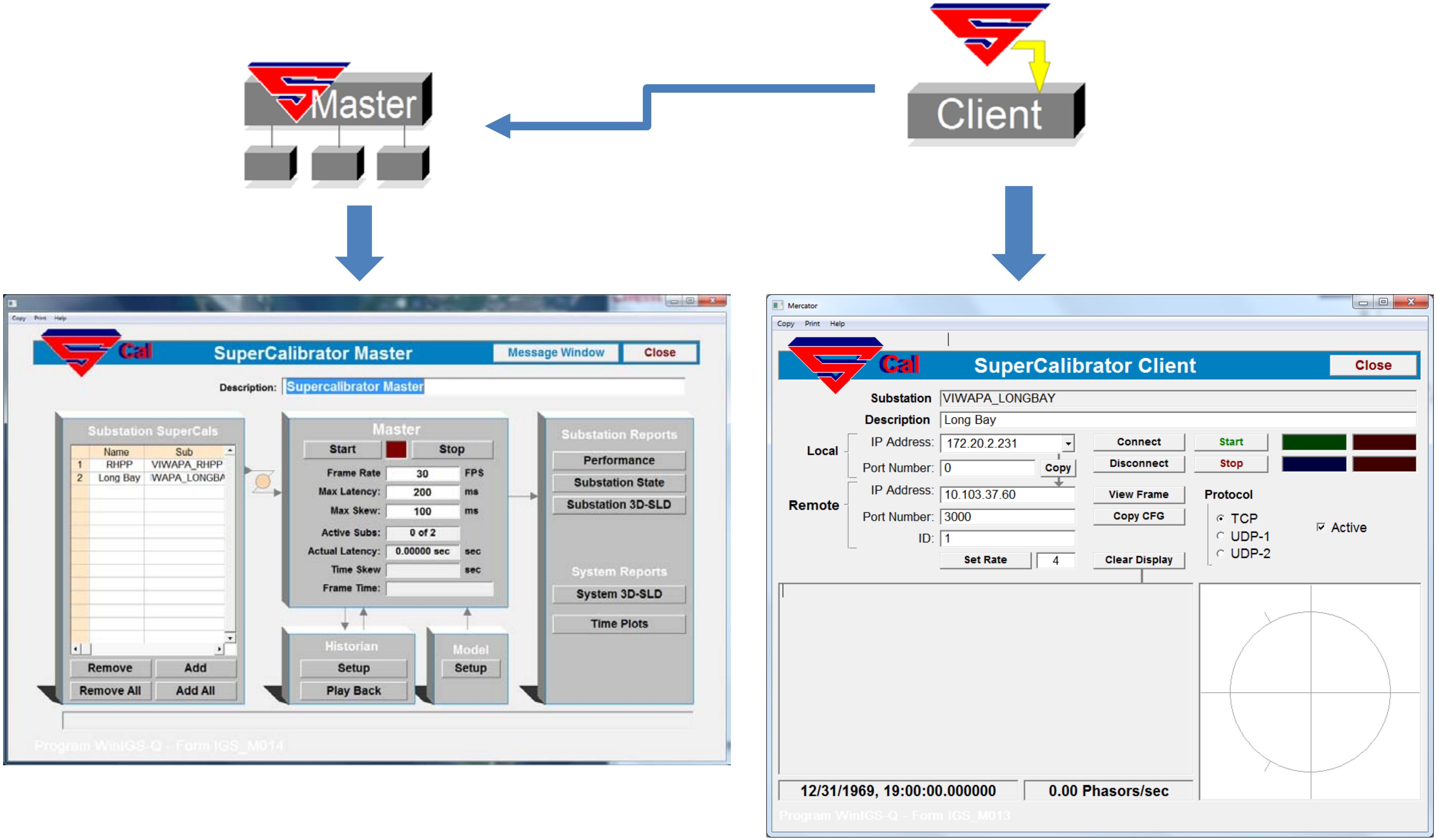


SuperCalibrator Master Reports



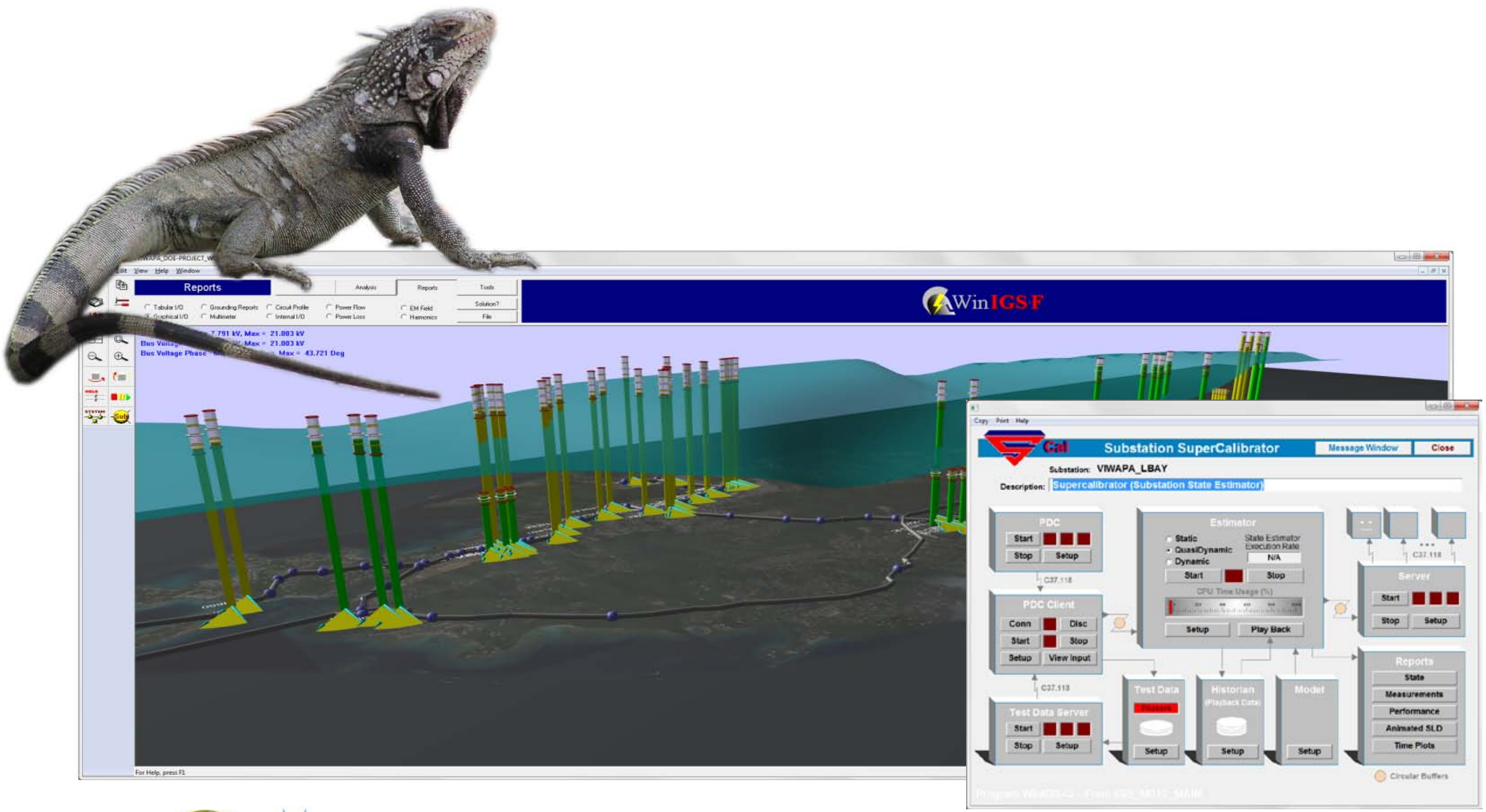
- General Performance
- Cross-Check Performance
- Animated SLD’s
- Etc…

SuperCalibrator Master & Client

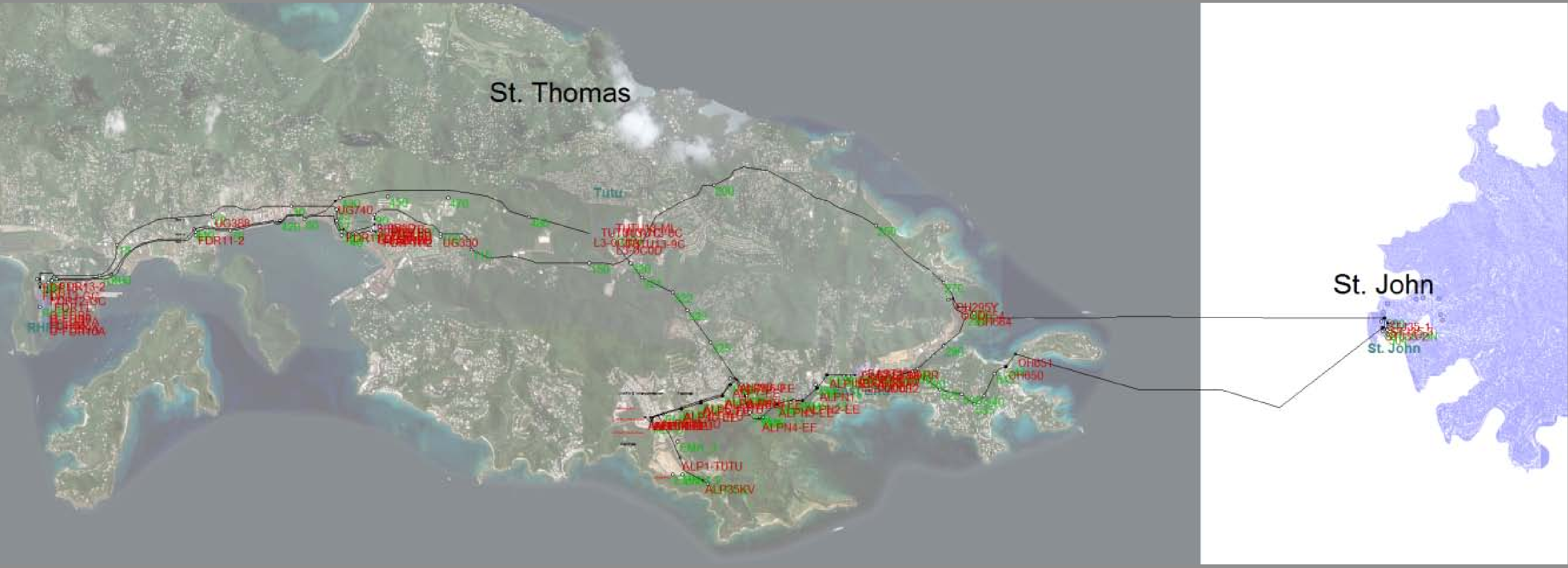


Demonstration: USVI-WAPA

The USVI-WAPA System



The USVI-WAPA System



VIWAPA – LONGBAY 35 kV Substation Instrumentation

Installation of PMUs at Longbay:

SEL 421 (3)

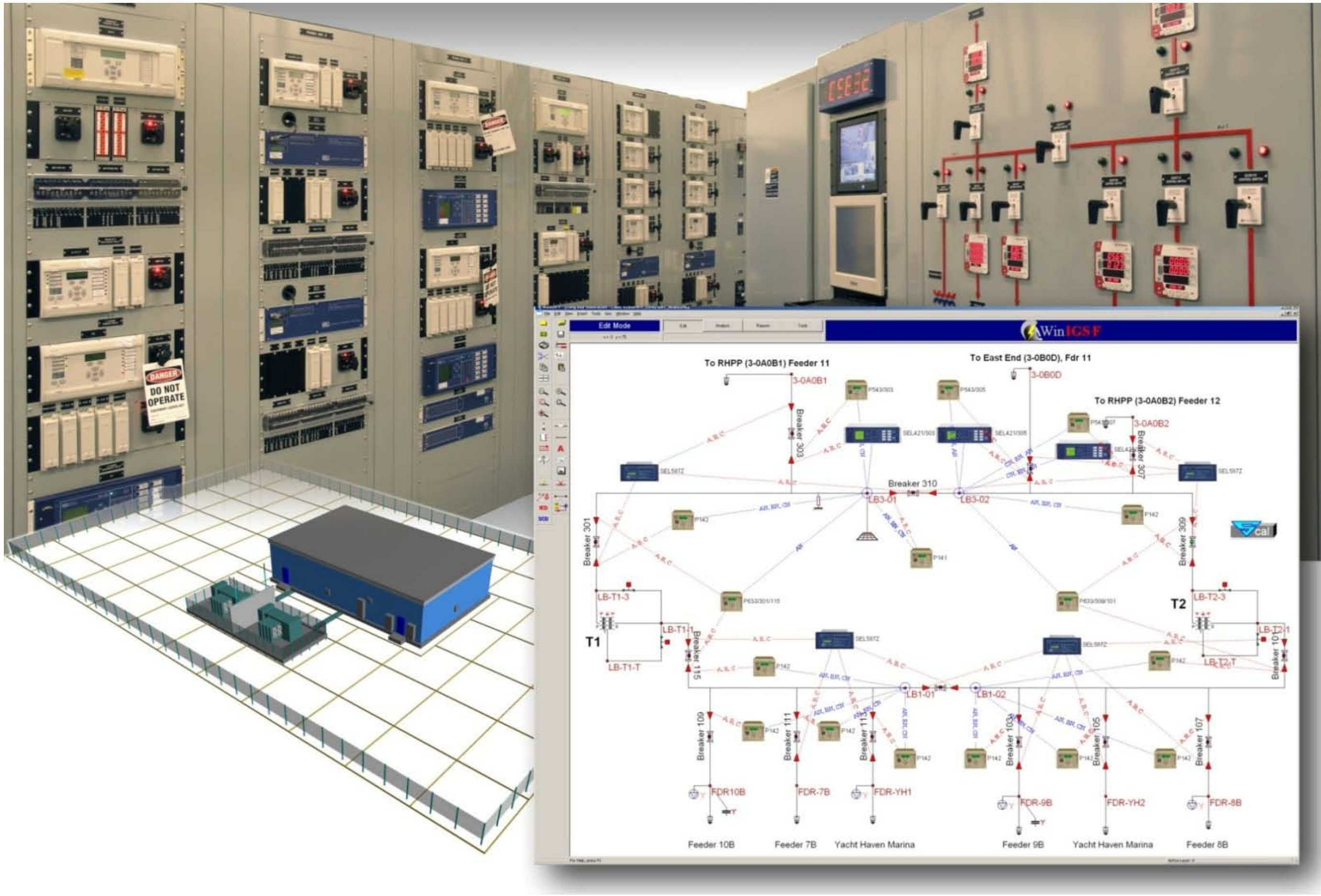
Numerical Relays at Longbay:

SEL 587 (4)
AREVA MiCOM P543 (3)
AREVA MiCOM 633 (2)
AREMA MiCOM P142 (10)

PMU Measurements: 18

Numerical Relay Measurements: 132

View of WAPA's Longbay substation



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VIWAPA – RHPP 35 kV Substation Instrumentation

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VIWAPA – RHPP 35 kV Substation Instrumentation

Installation of PMUs and Relays at RPHH

SEL 421 (3)

SEL 451 (4)

GE 60 (1)

Numerical Relays at RPHH

SEL 487 (6)

AREVA MiCOM P142 (6)

AREVA MiCOM P543 (5)

AREVA MiCOM P632 (1)

AREVA MiCOM P642 (3)

AREVA MiCOM P645 (3)

PMU Measurements: 40 (max possible 71)

Numerical Relay Measurements: 150

VIWAPA – TUTU 35 kV Substation Instrumentation

Installation of PMUs at TUTU

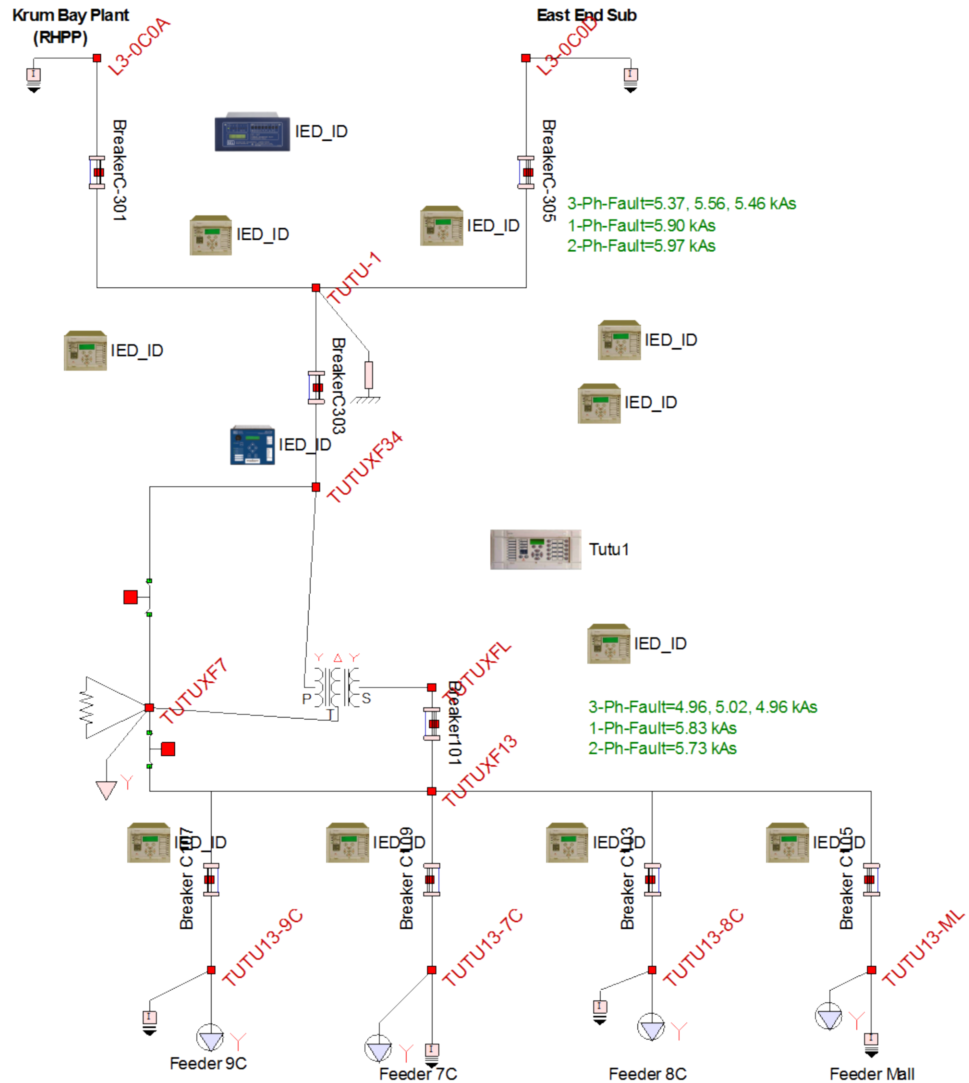
SEL 734 (1)

Numerical Relays at TUTU

SEL 587 (1)
AREVA MiCOM P543 (2)
AREVA MiCOM P544 (2)
AREVA MiCOM 634 (1)
AREMA MiCOM P142 (6)

PMU Measurements: 3
Numerical Relay Measurements: 39

VIWAPA's TUTU substation



VIWAPA – EAST END 35 kV Substation Instrumentation

Installation of PMUs at EAST END

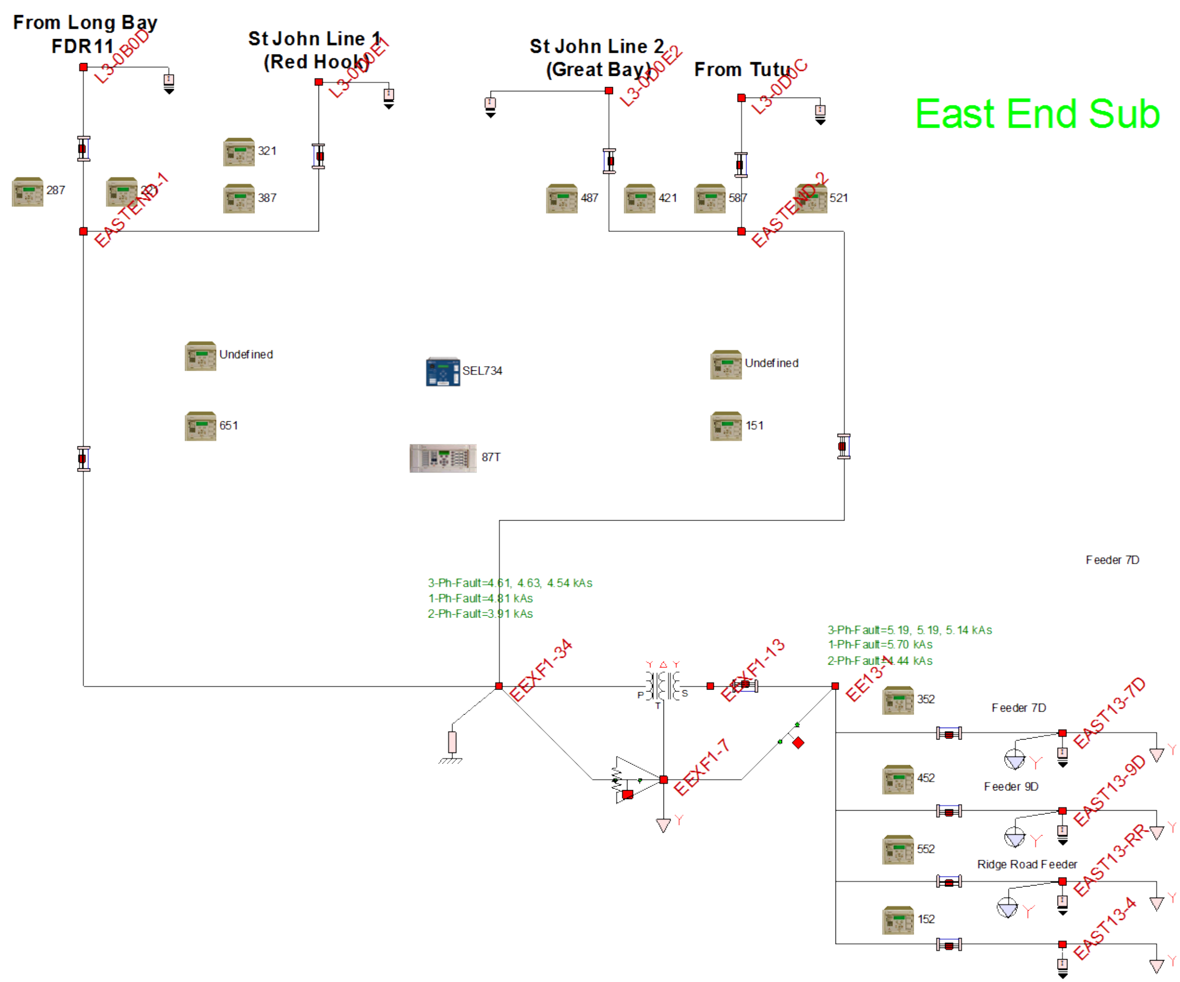
SEL 734 (1)

Numerical Relays at EAST END

AREVA MiCOM P542 (4)
AREVA MiCOM P543 (4)
AREVA MiCOM P633 (1)
AREMA MiCOM P141 (2)
AREMA MiCOM P142 (4)
AREMA MiCOM P143 (2)

PMU Measurements: 3
Numerical Relay Measurements: 51

VIWAPA's EAST END Substation



VIWAPA – St JOHN 35 kV Substation Instrumentation

VIWAPA's St JOHN substation

Installation of PMUs at St JOHN

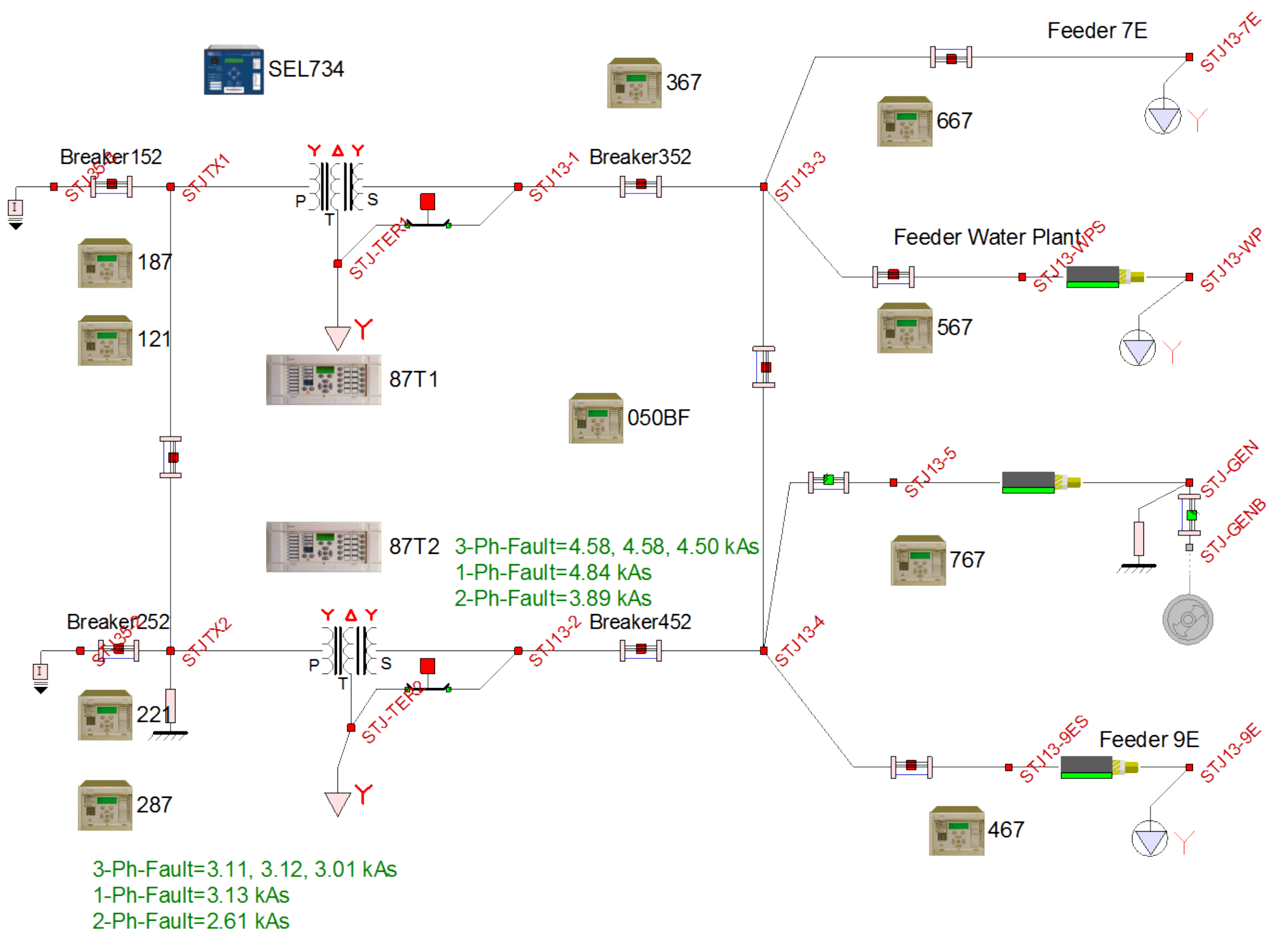
SEL 734 (1)

Numerical Relays at St JOHN

AREVA MiCOM P633 (2)
AREVA MiCOM P542 (2)
AREVA MiCOM P543 (2)
AREMA MiCOM P141 (1)
AREMA MiCOM P142 (2)
AREMA MiCOM P143 (3)

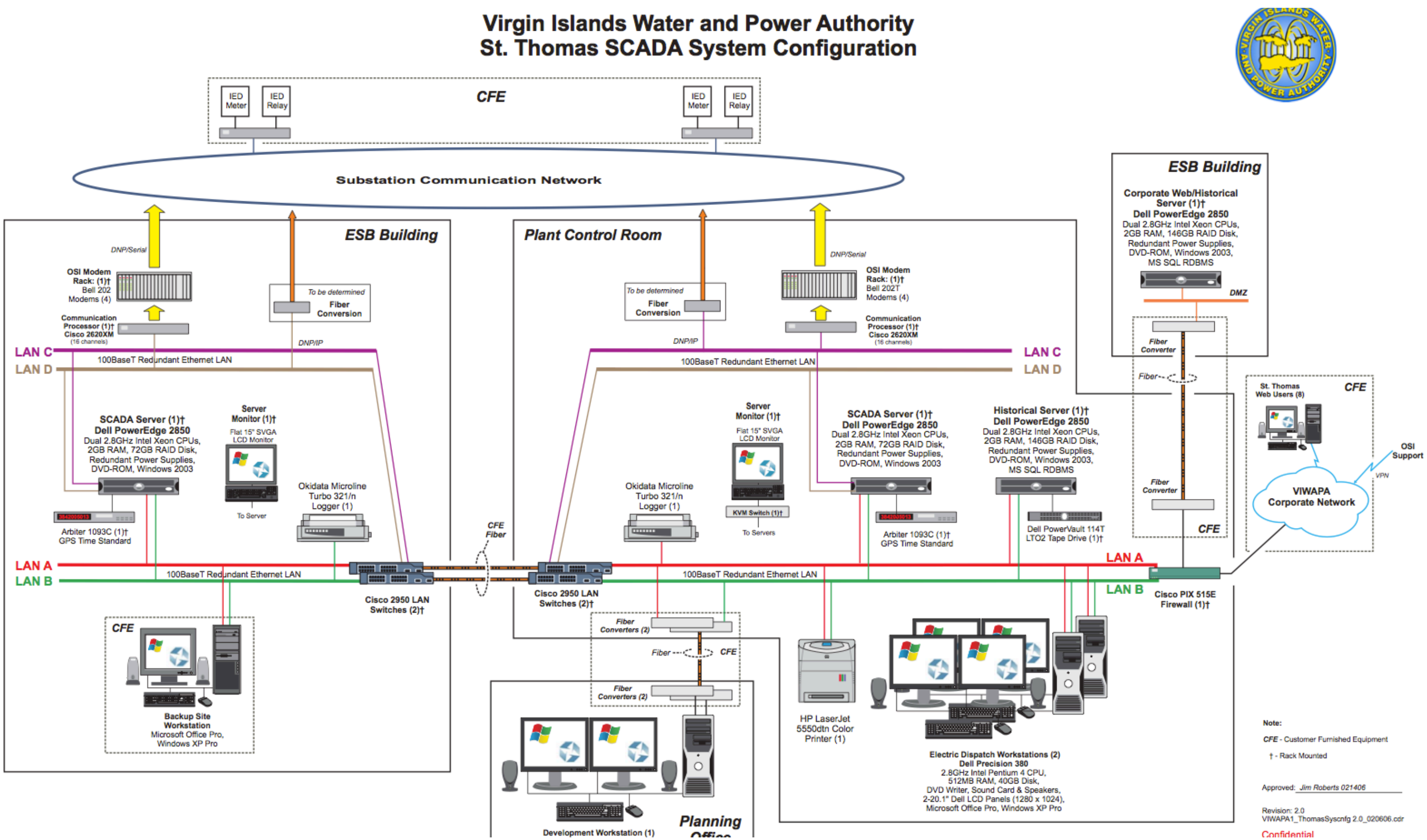
PMU Measurements: 3

Numerical Relay Measurements: 36



The USVI-WAPA System

The Communications Infrastructure



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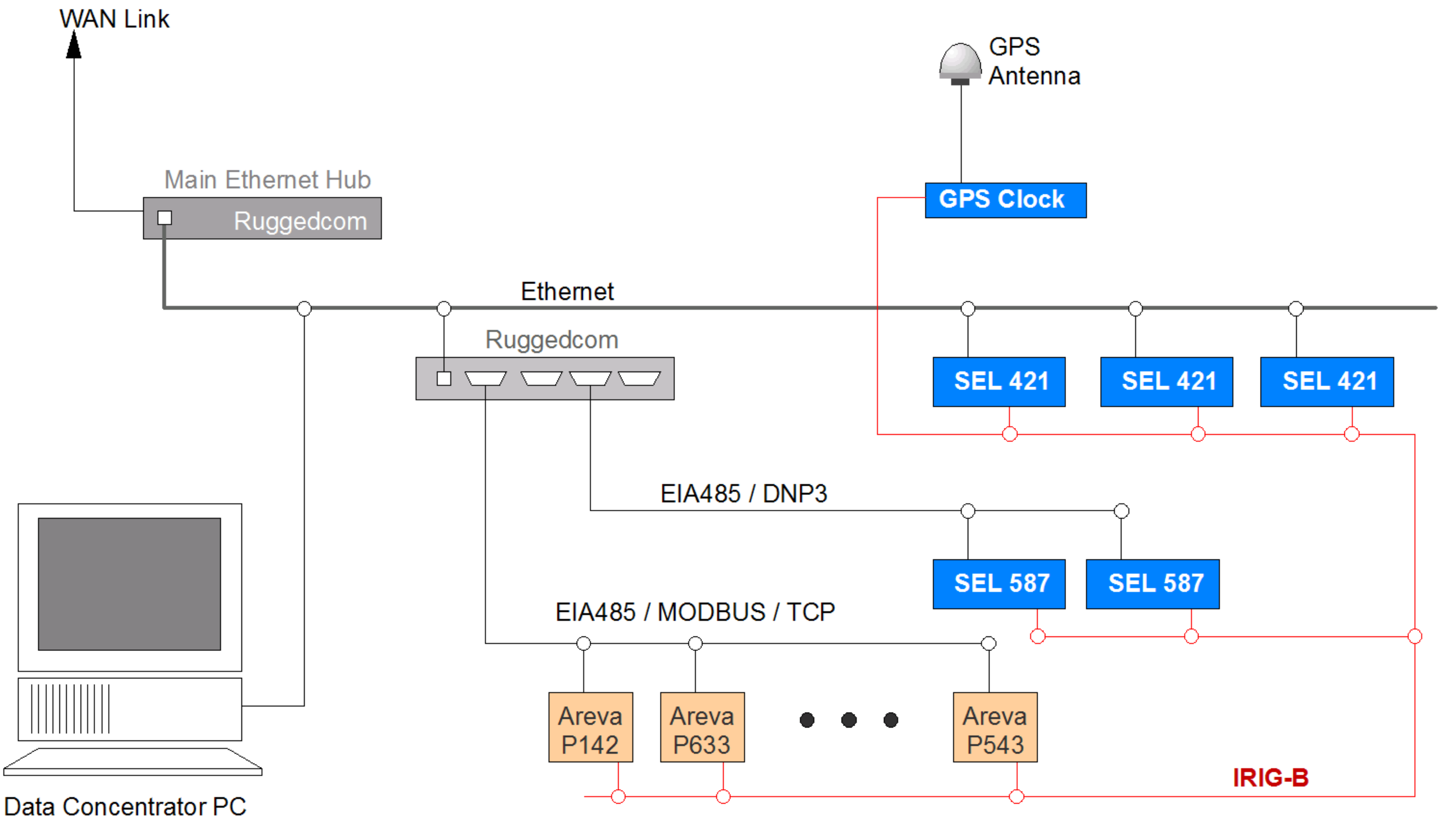
The USVI-WAPA System

The Communications Infrastructure



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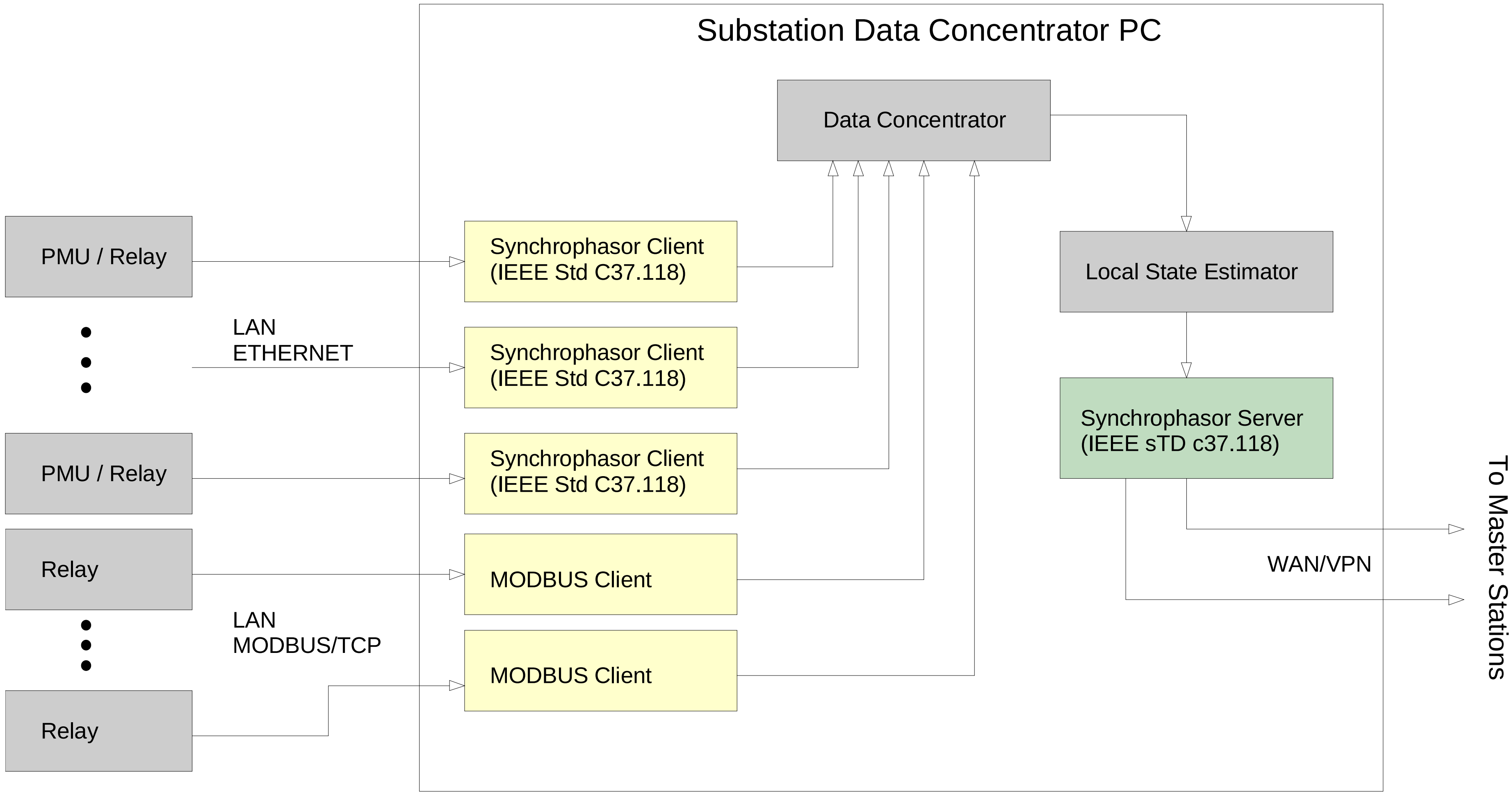
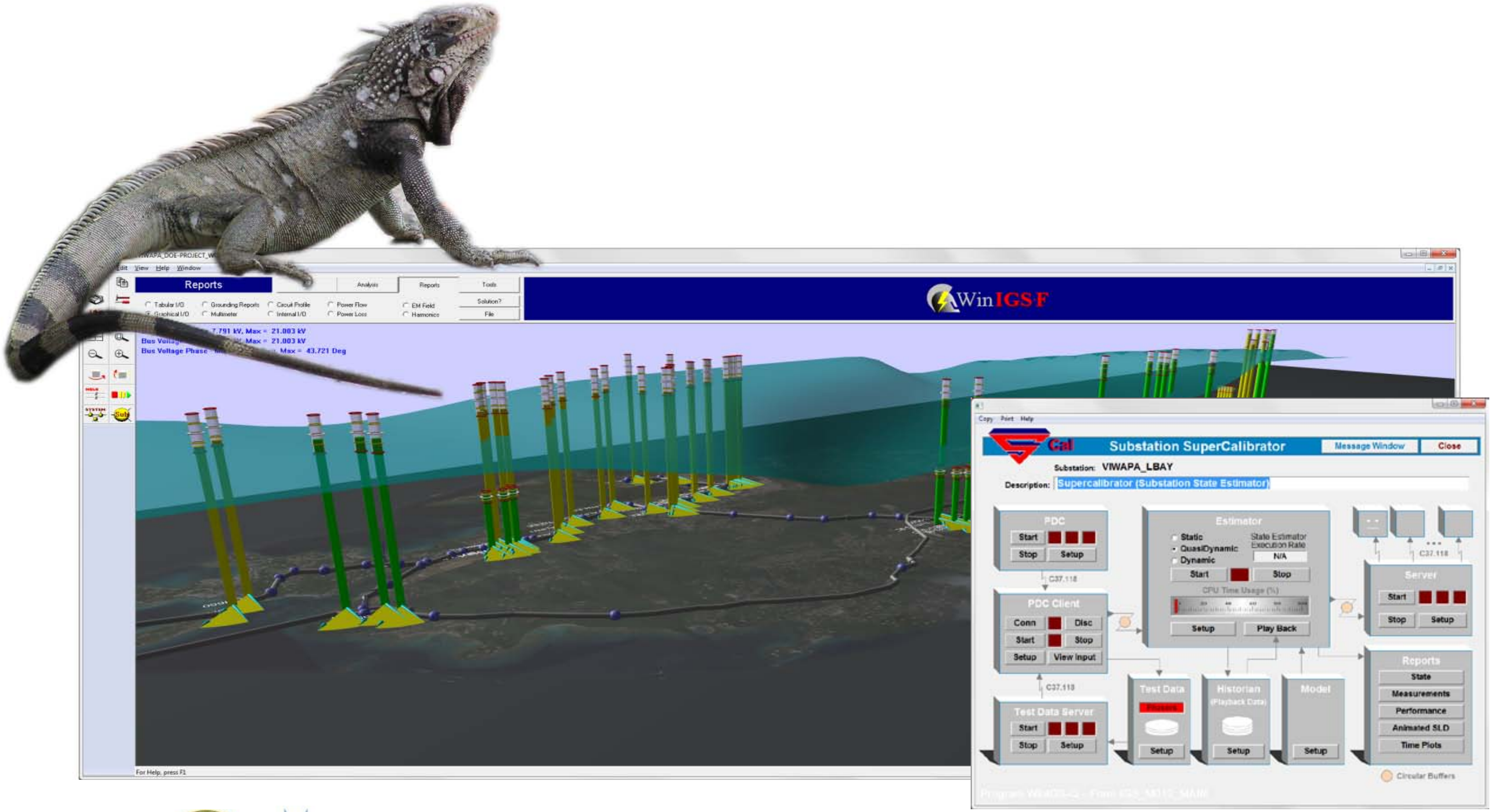
The USVI-WAPA System

The Communications Infrastructure



Demonstration: USVI-WAPA

Substation DSE and Master



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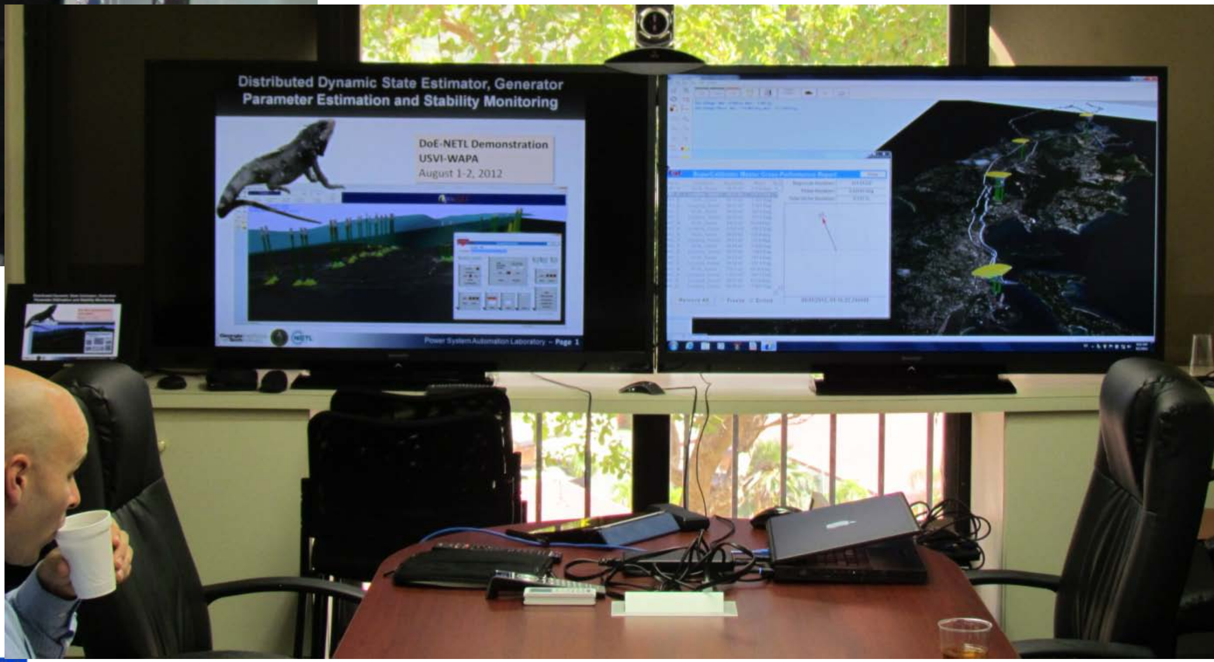
Demonstration: USVI-WAPA

Substation DSE and Master

Master
UI and Visualization



Substation DSE
UI and Visualization

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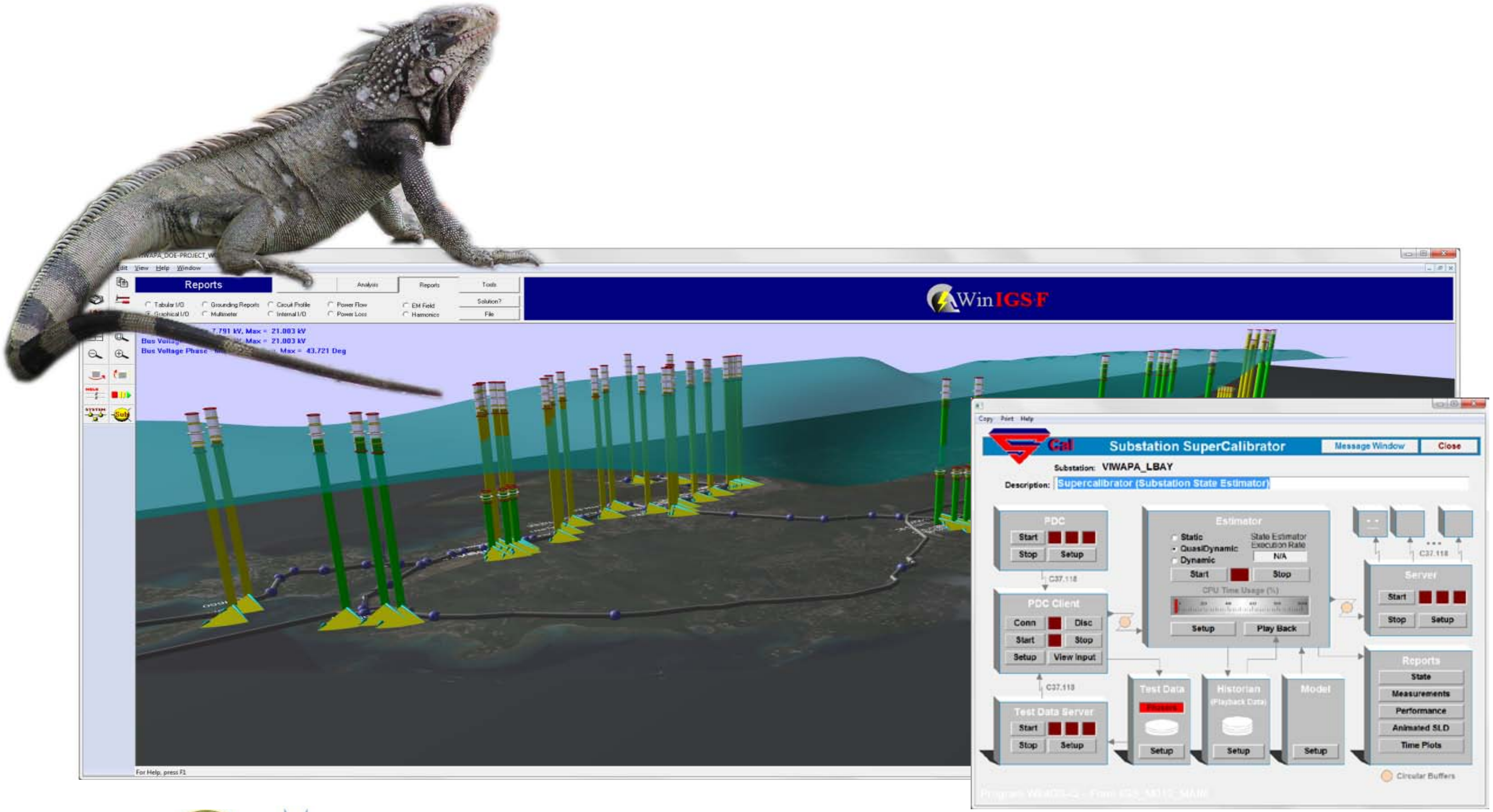
Demonstration: USVI-WAPA
Performance Evolution



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Performance Evolution: QSE: Timing Results* - Year 1

NYPA Gilboa-Blenheim plant

System States	**96**
Actual Measurements	**168**
Total Measurements (Actual + Virtual)	**744**
Average QSE Execution Time per Time Step	**9.5 msec**
Variability	**0.5 msec**

USVI LongBay Substation

System States	**164**
Actual Measurements	**171**
Total Measurements (Actual + Virtual)	**708**
Average QSE Execution Time per Time Step	**13 msec**
Variability	**1 msec**

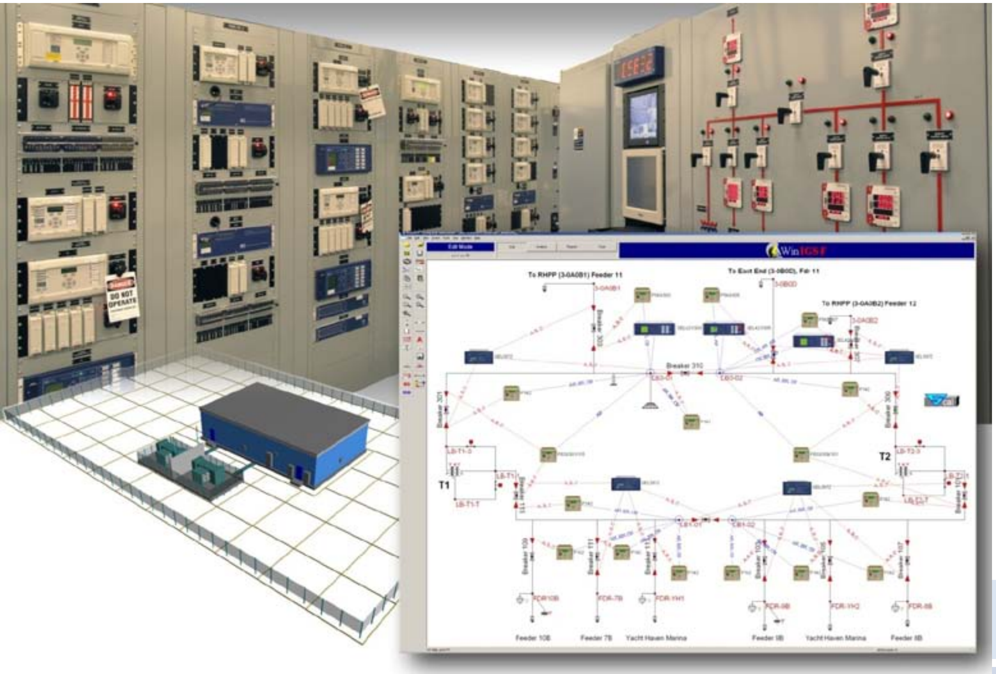
*PC, i7-930 Processor, 2.8 Gz

Additional Improvements Are Possible

- Additional Code Optimization
- Use of Multi-core Computers

Performance Evolution: Distributed State Estimation

Timing Results – Year 3



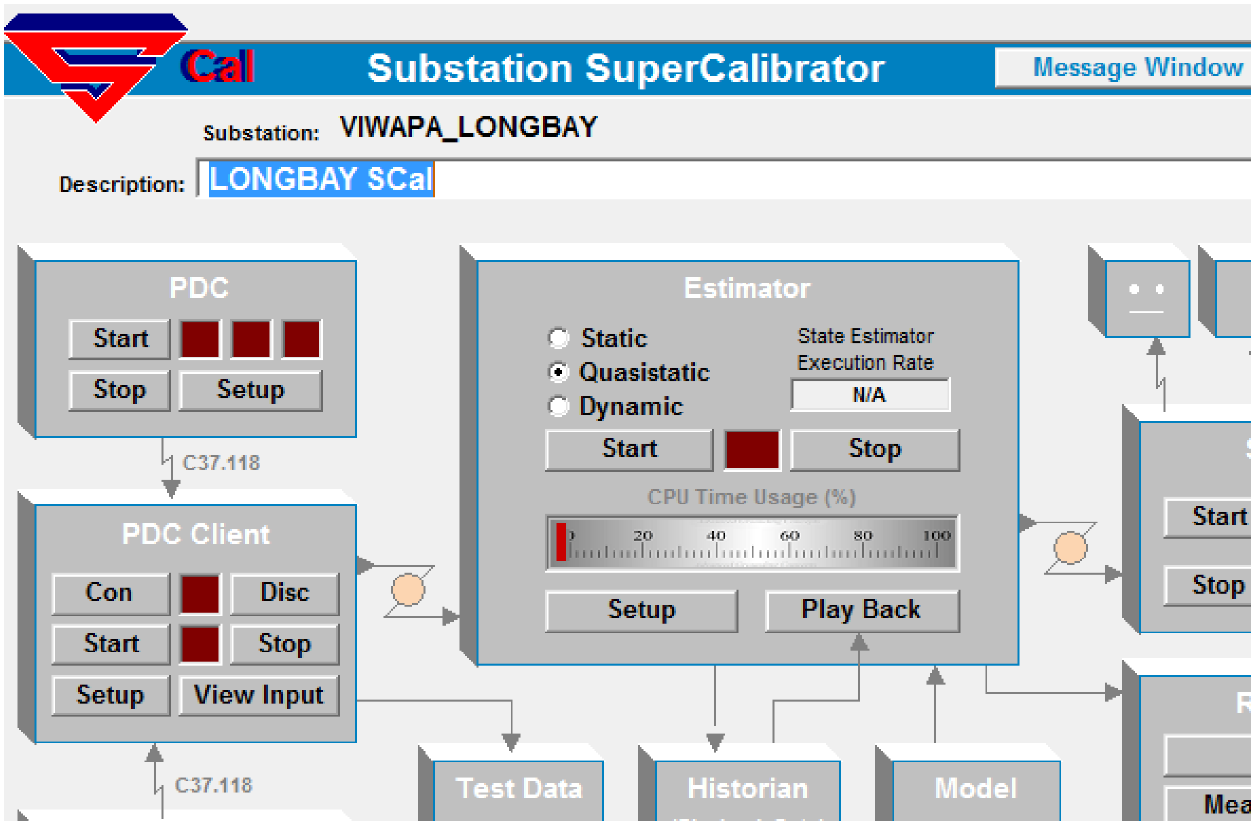
Timing Experiment Summary of the QSE for Long Bay Substation

System States	**82**
Actual Measurements	**171**
Total Measurements (Actual + Virtual)	**784**
Average QSE Execution Time per Time Step	**0.42 msec**
Variability	**0.05 msec**

- Two kV Level Substations
- Two Transformers
- Three Transmission Lines
- Six Distribution Circuits

Performance Evolution: Distributed State Estimation

Execution Time Monitor

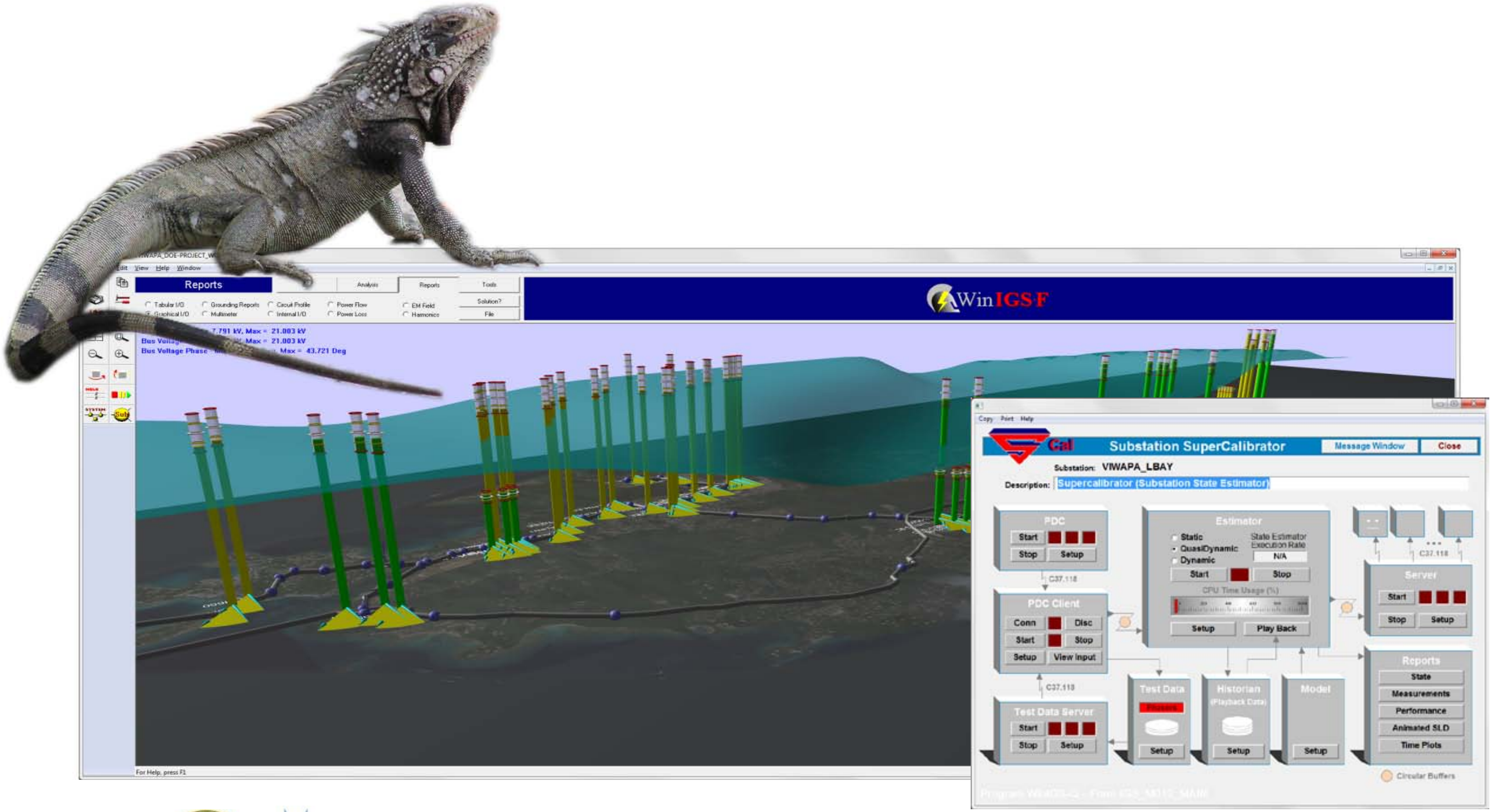


CPU Time Usage Indicates in Real Time the Portion of the Time Used by the SE Calculations.

100%=Time Between Two Successive SE Computations. example: if SE is set to execute 60 times per second, then 100%=16.6 ms

Demonstration: USVI-WAPA

Disturbance Playback



Disturbance Playback
Via Distributed Dynamic State Estimation

Objective: to provide an automated playback capability of past operating conditions and disturbances.

Project objective has been accomplished.

How: the results of the distributed dynamic state estimation are stored in a circular buffer (months long) together with the model. Playback requires only start and end times.

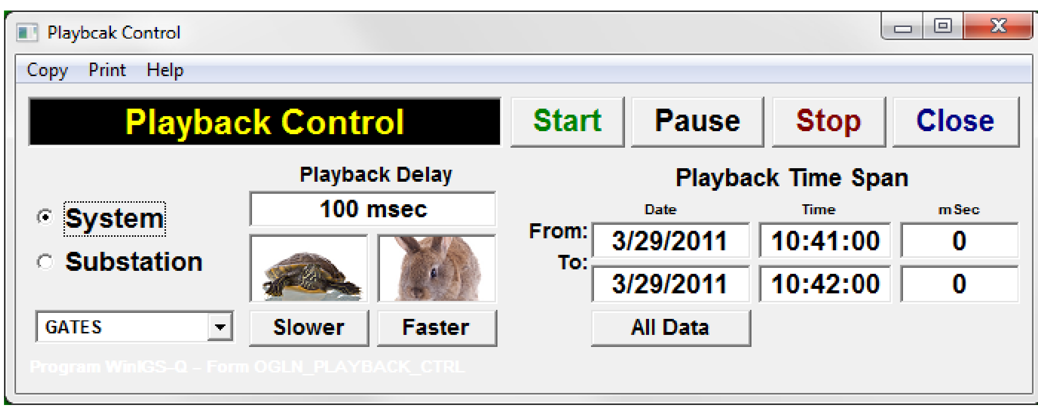
Disturbance Play-Back: User Interface

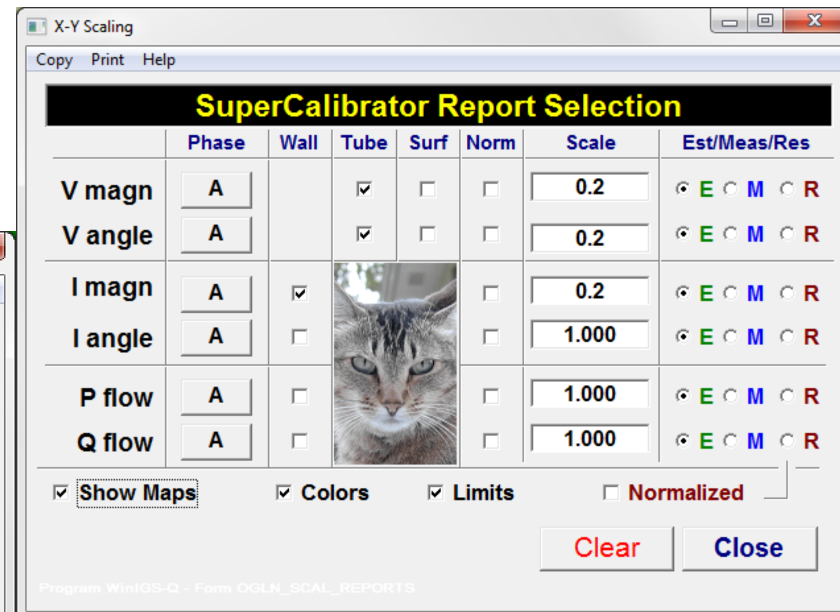
New Approach to Historian: Substation Storage Scheme

Full Model + Model Changes + Data

System Operations Can Be “Played Back” Over a User Specified Time Interval (From time t1 to time t2)

Then as simple as pressing a button…





Important Application: Disturbance Play-Back

Objective:

- System Operation “Play Back” over a user specified time interval (from time t1 to time t2)
- Reconstructed state is presented via graphical visualization Techniques, (3-D rendering, animation etc) with multiple user options.

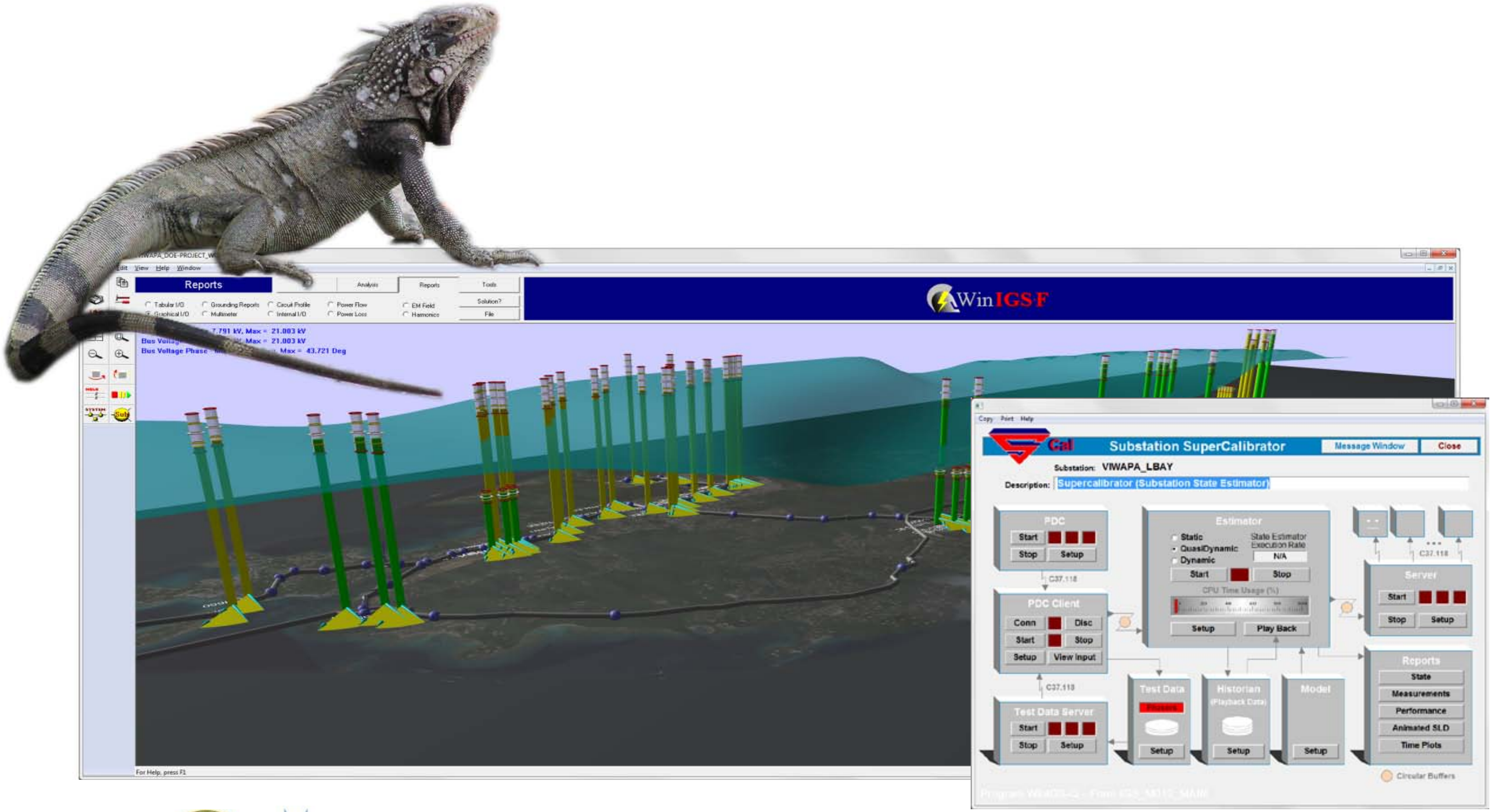
Substation Storage Scheme

Full Model + Model Changes + Data

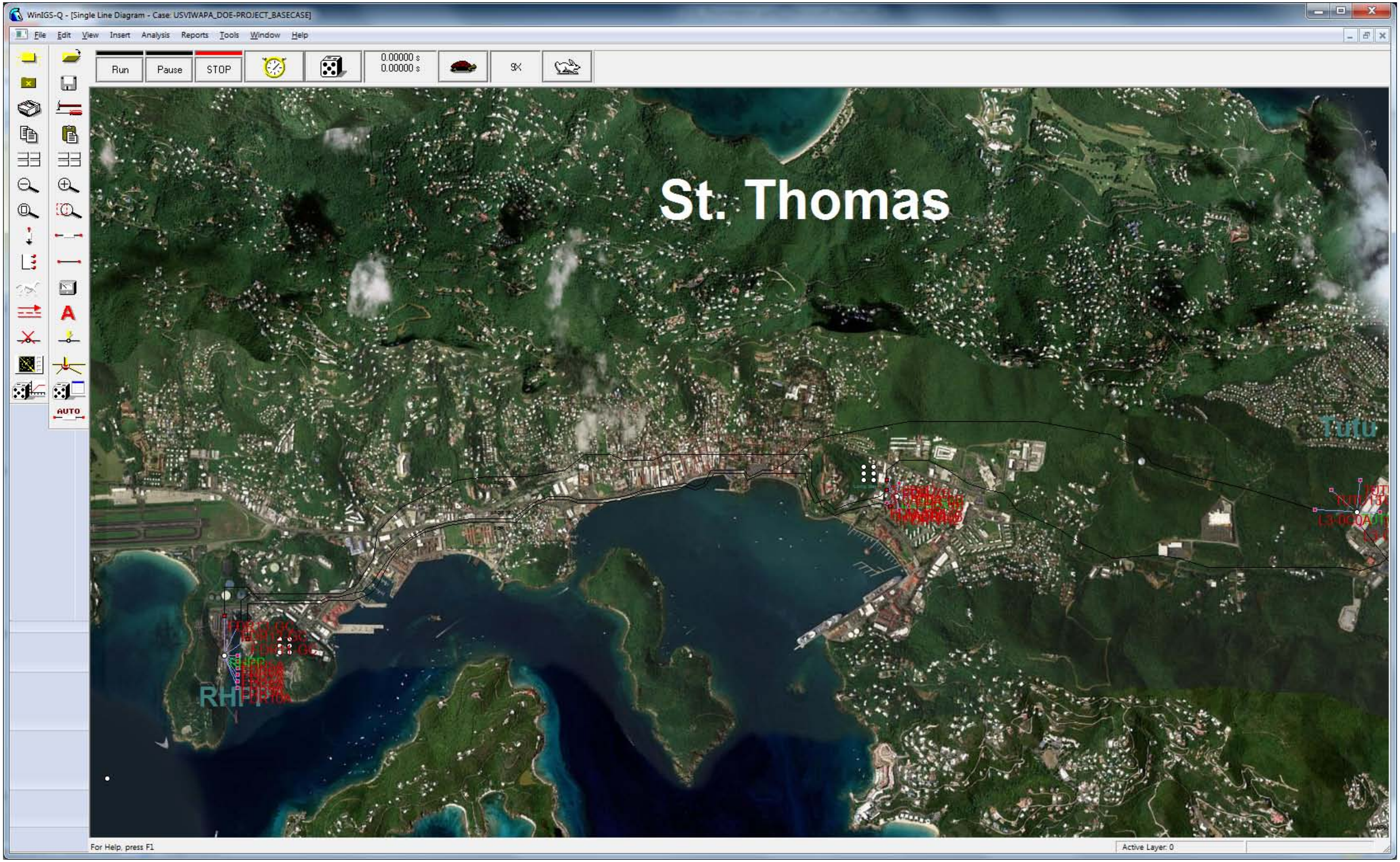
- System FULL MODEL stored once a day in WinIGS format – time of day can be arbitrarily selected, for example at 2 am. (example storage follows)
- Report system changes by exception – UTC time (example storage follows)
- Storage of state data: at each occurrence of the state estimator, the estimated states are stored in COMTRADE-like format. (example storage follows)

Demonstration: USVI-WAPA

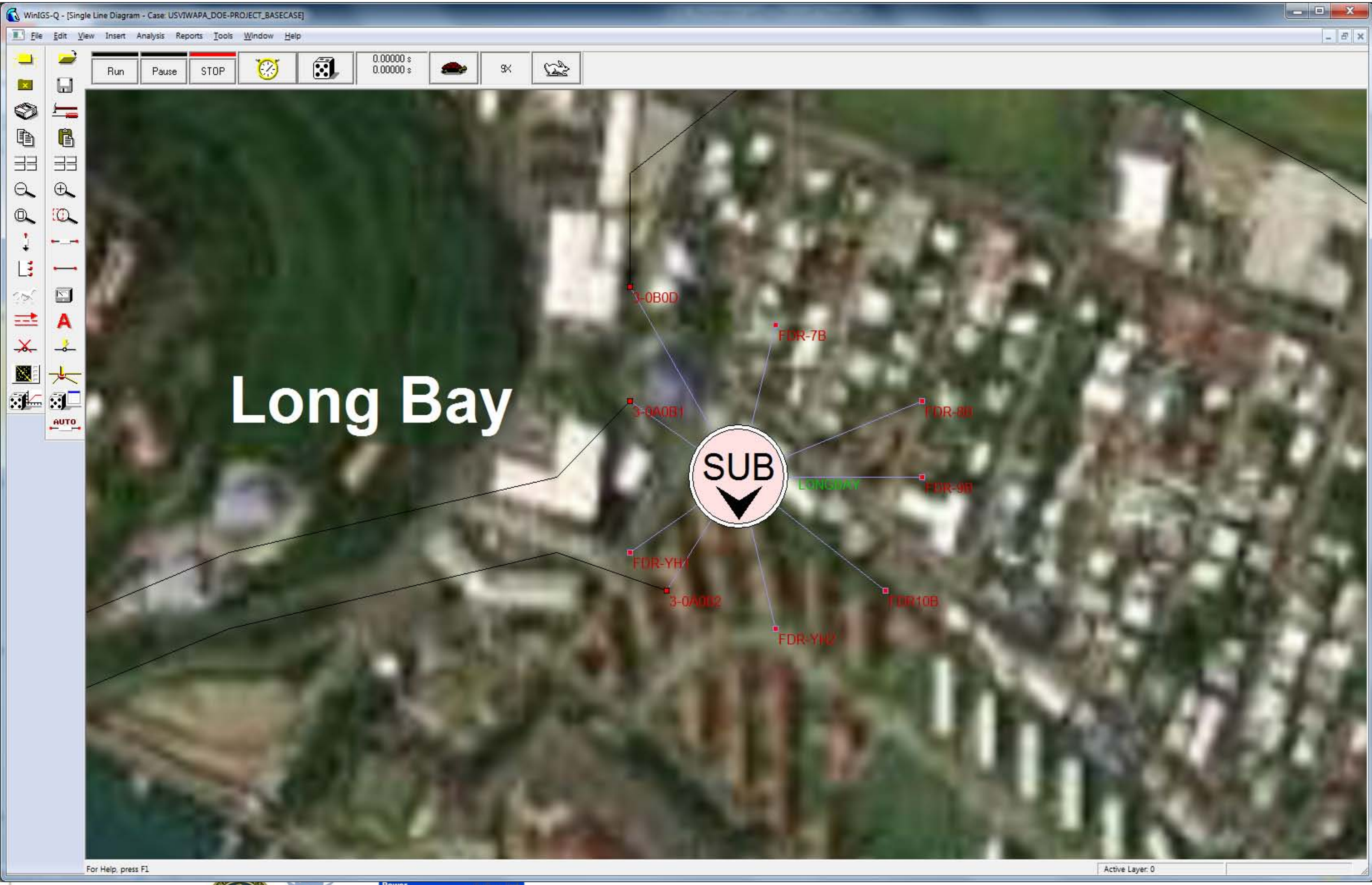
Substation DSE



DSE Substation Module User Interface



DSE Substation Module User Interface – Long Bay



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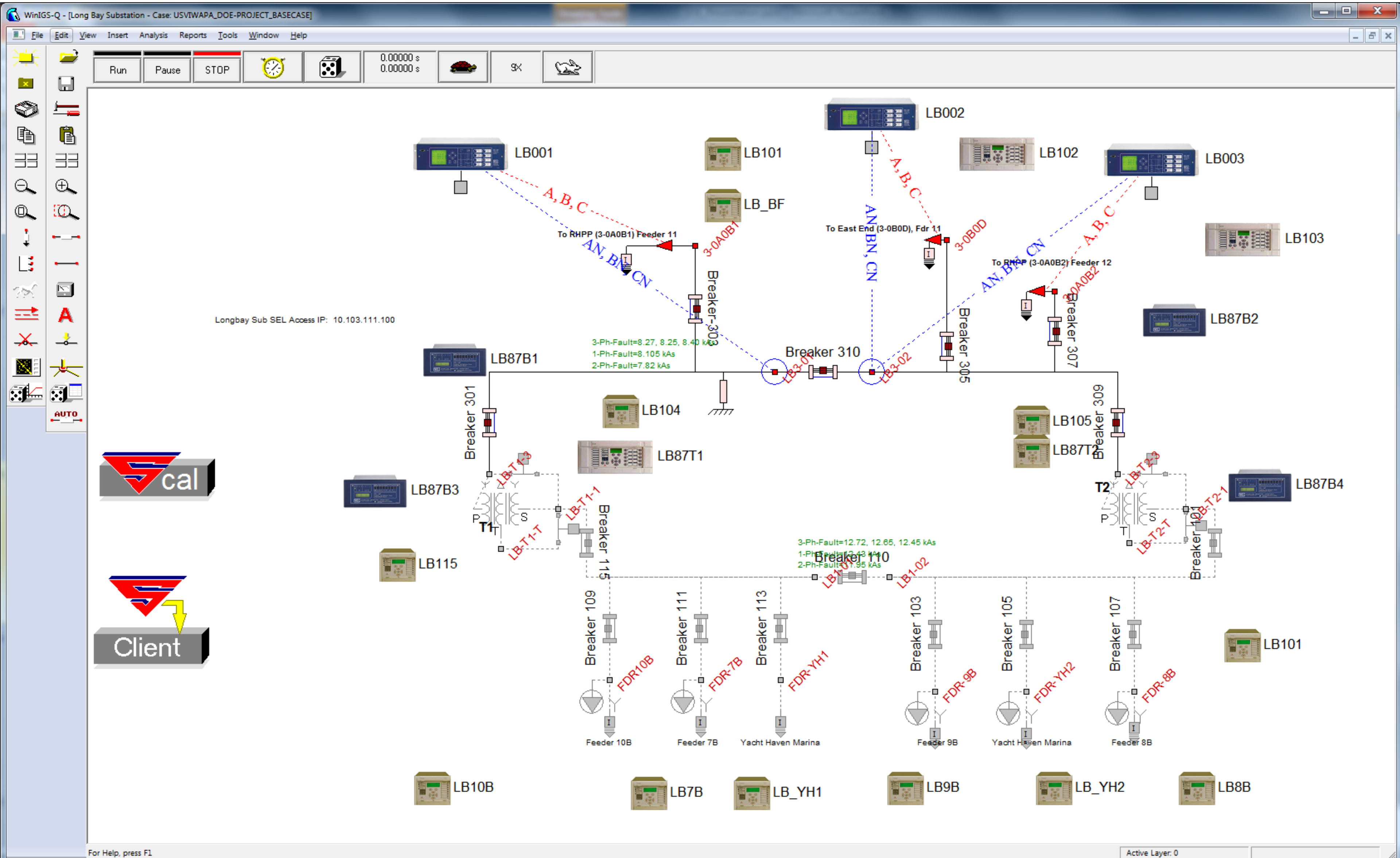
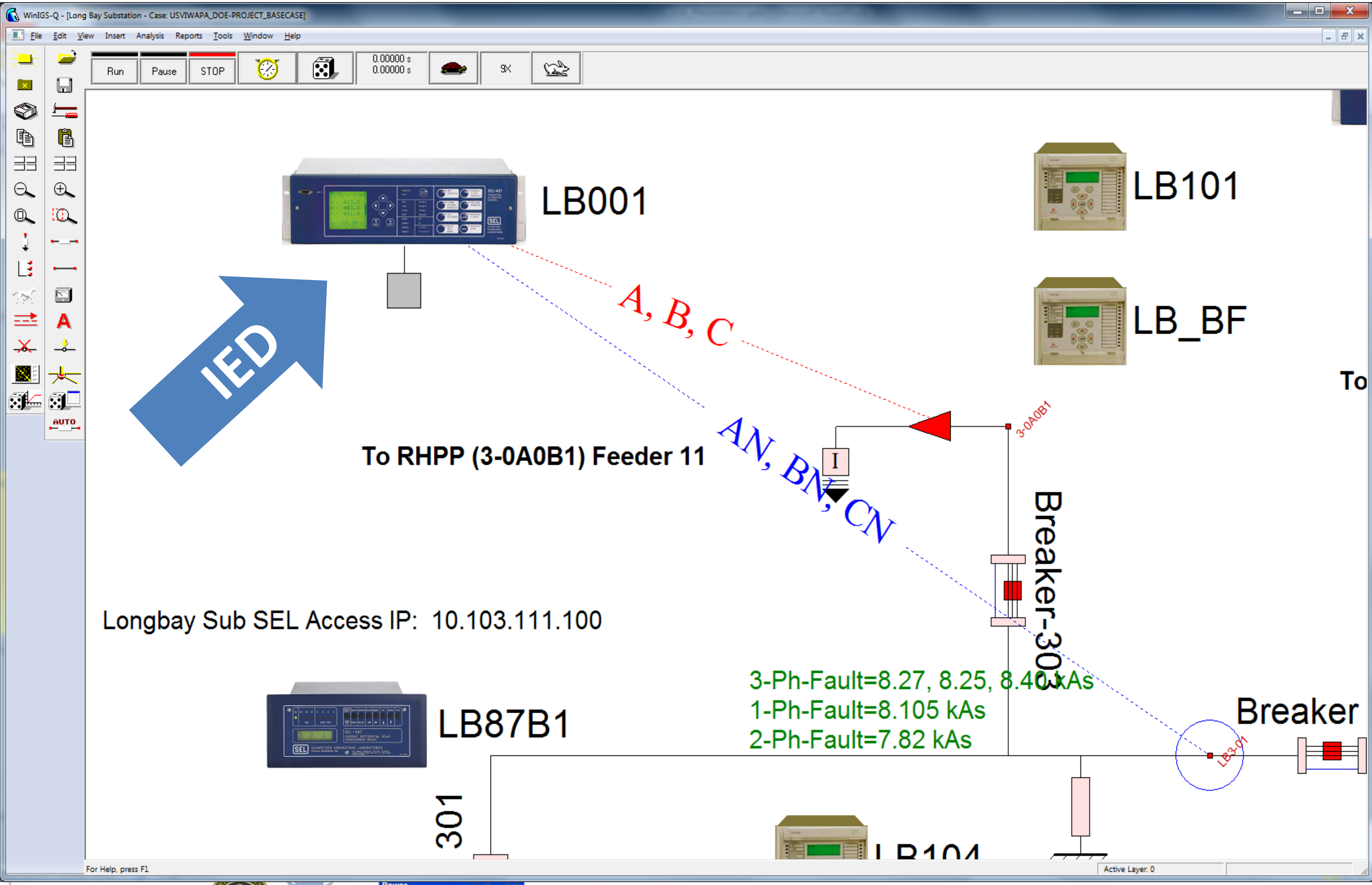
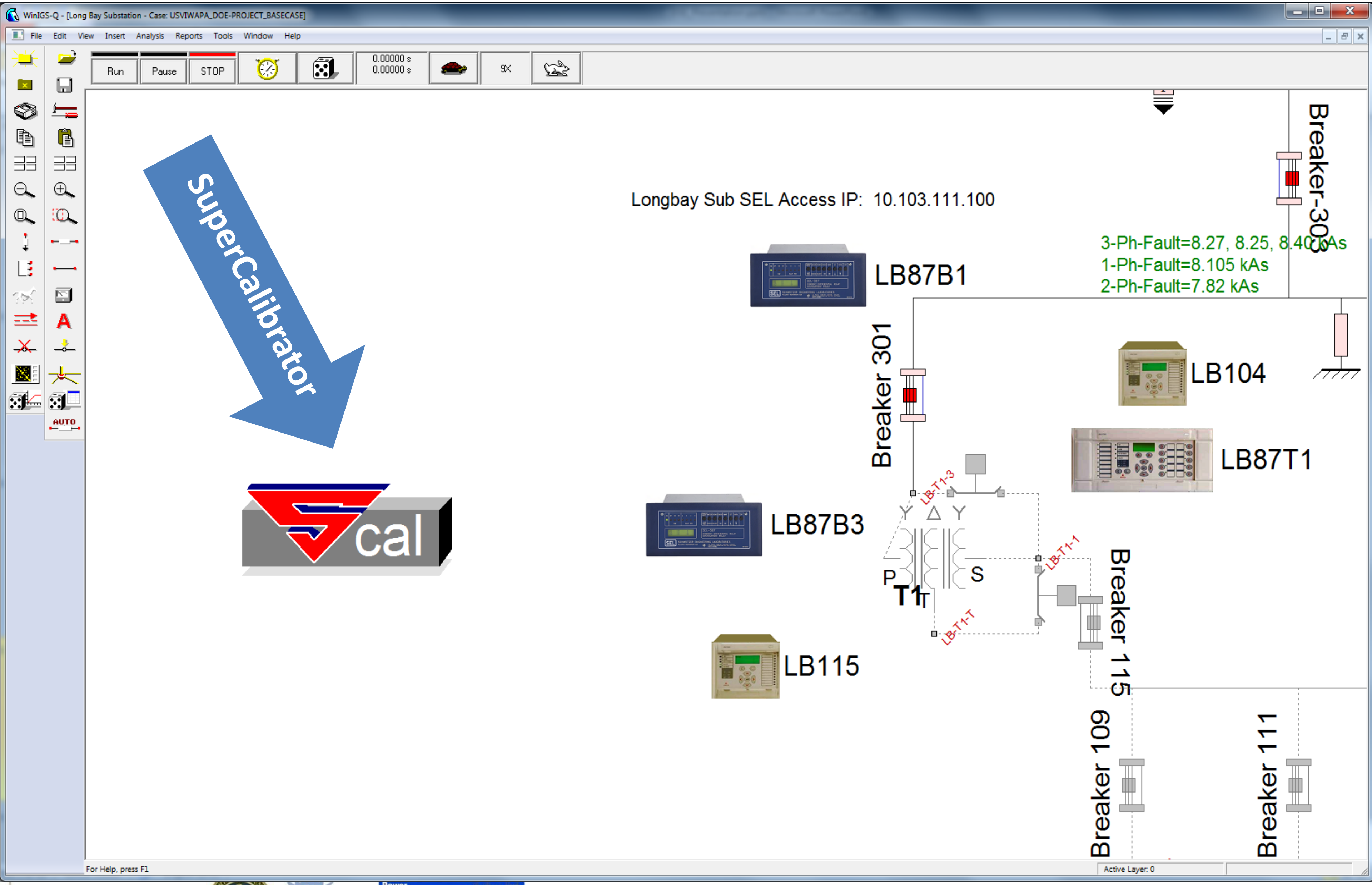
DSE Substation Module User Interface – Long Bay



DSE Substation Module – IED Model



DSE Substation Module – The SuperCalibrator Element



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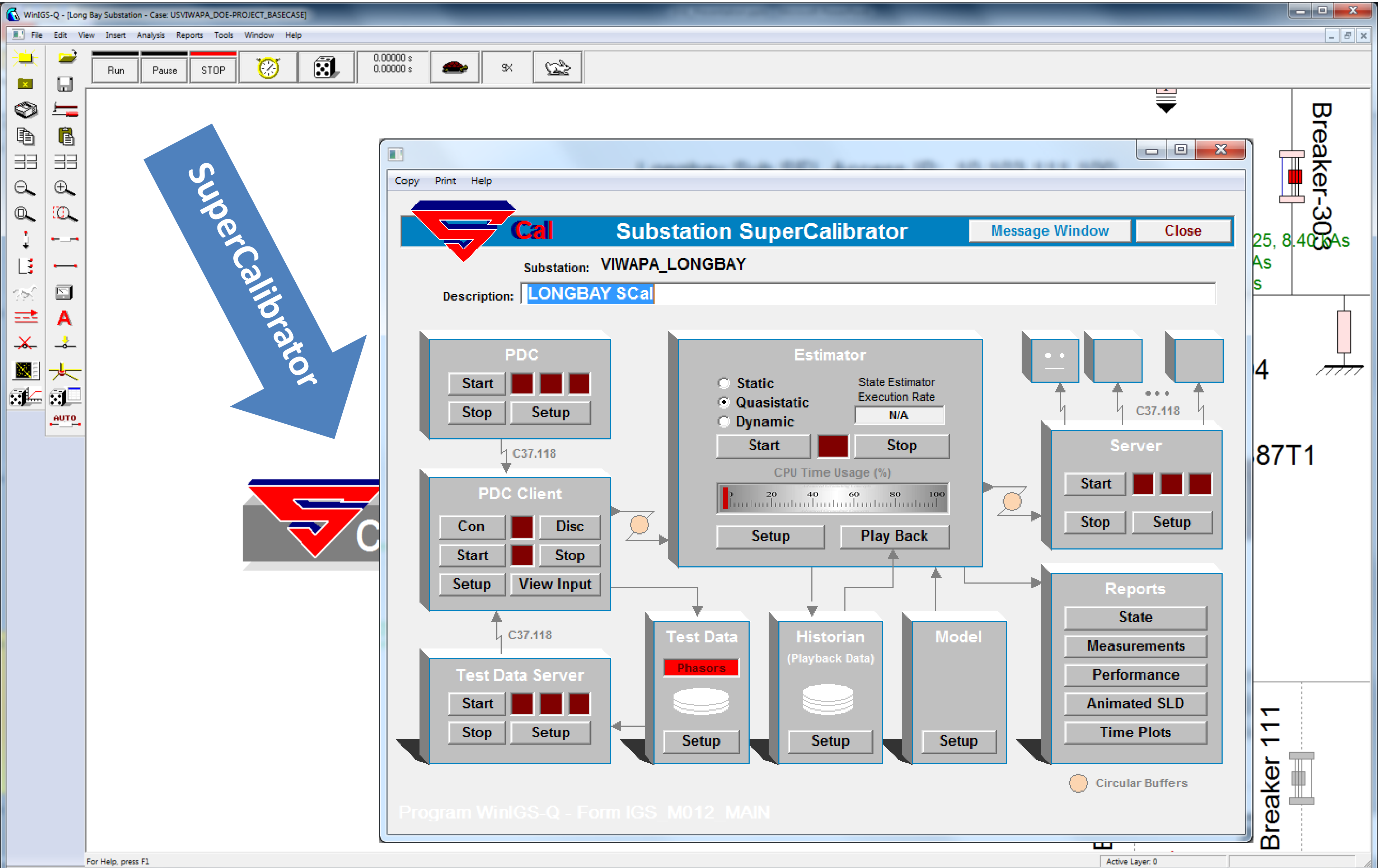
DSE Substation Module – The SuperCalibrator Element



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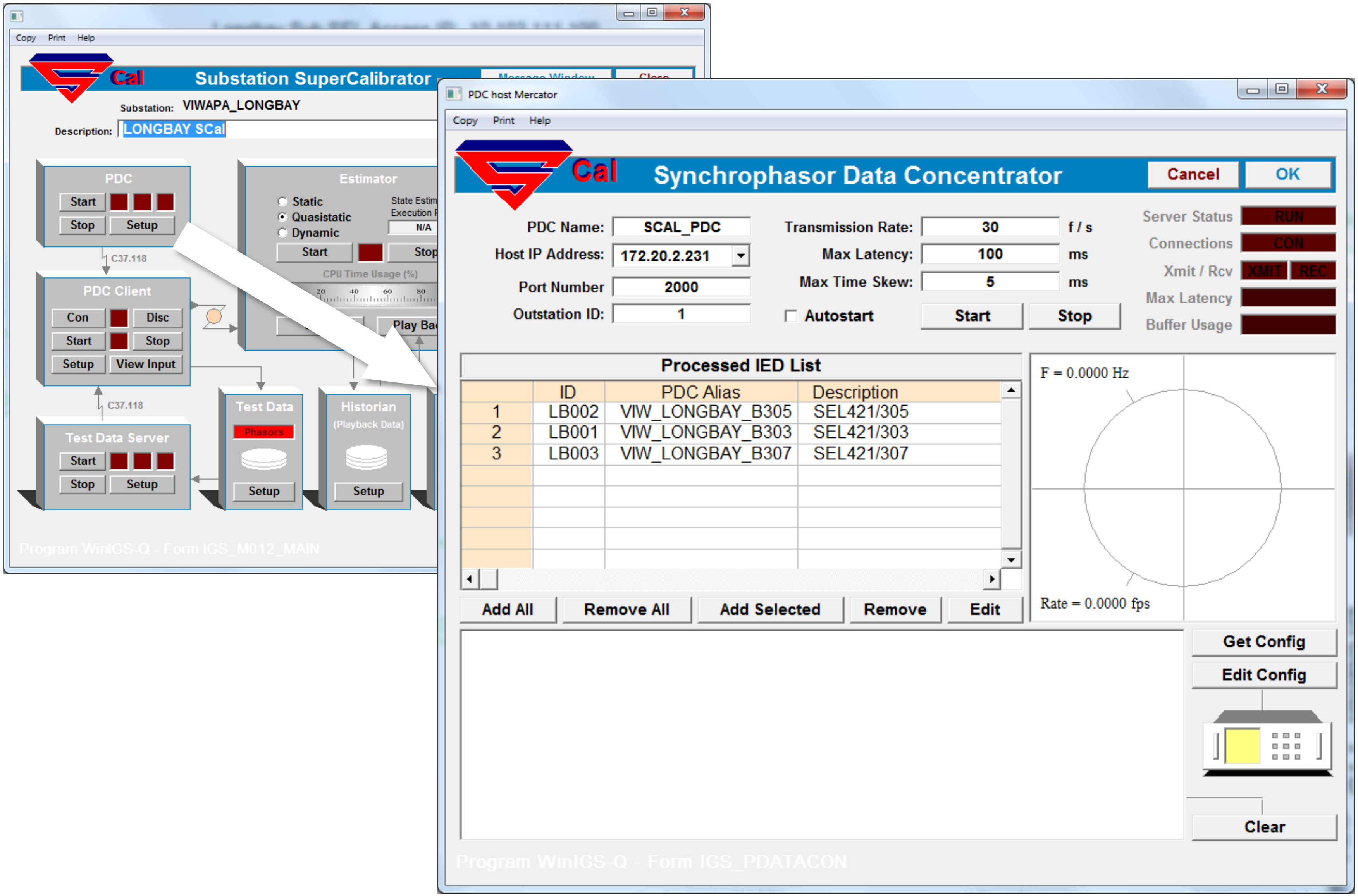
The SuperCalibrator SubModuldes

- Phasor Data Concentrator (PDC)
- PDC Client
- Test Data Server
- Historian
- Synchrophasor Server
- Reports

The SuperCalibrator Element – PDC Component



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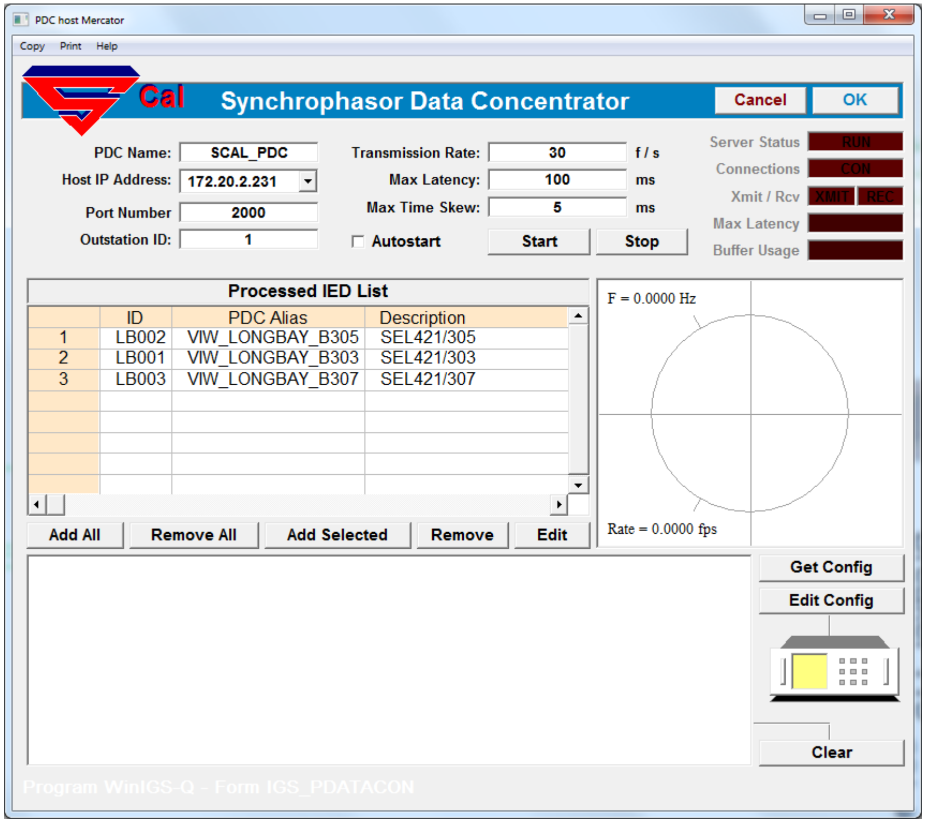
PDC Component Attributes



- IP Parameters
- Serviced IED List
- Desired Transmission Rate
- Max Latency
- Max Time Skew
- Test Data Server
- Historian
- Synchrophasor Server
- Reports

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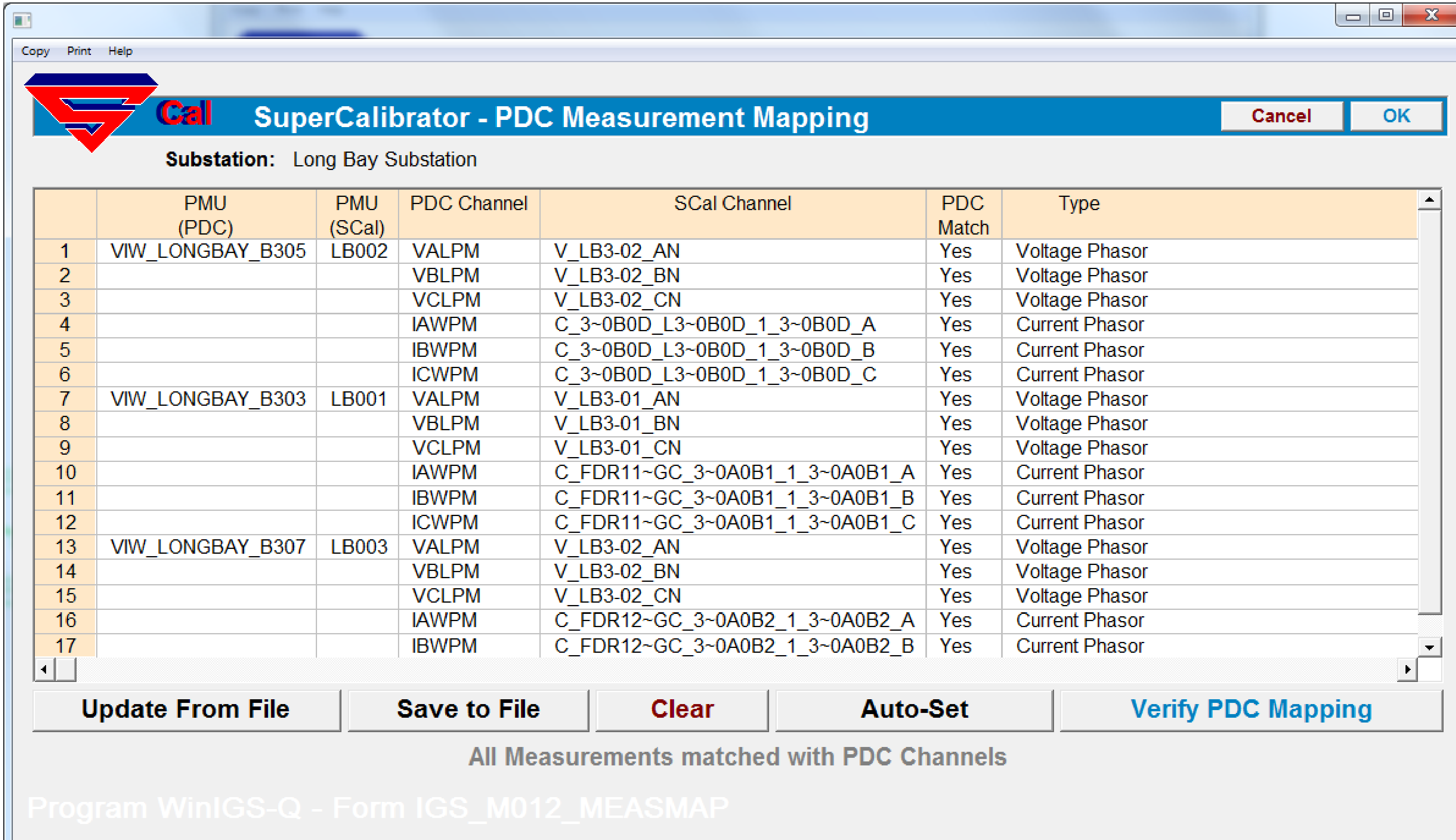
PDC Automatic Configuration & Channel Mapping Validation



	PMU (PDC)	PMU (SCal)	PDC Channel	SCal Channel	PDC Match	Type
1	VIW_LONGBAY_B305	LB002	VALPM	V_LB3-02_AN	Yes	Voltage Phasor
2			VBLPM	V_LB3-02_BN	Yes	Voltage Phasor
3			VCLPM	V_LB3-02_CN	Yes	Voltage Phasor
4			IAWPM	C_3~0B0D_L3~0B0D_1_3~0B0D_A	Yes	Current Phasor
5			IBWPM	C_3~0B0D_L3~0B0D_1_3~0B0D_B	Yes	Current Phasor
6			ICWPM	C_3~0B0D_L3~0B0D_1_3~0B0D_C	Yes	Current Phasor
7	VIW_LONGBAY_B303	LB001	VALPM	V_LB3-01_AN	Yes	Voltage Phasor
8			VBLPM	V_LB3-01_BN	Yes	Voltage Phasor
9			VCLPM	V_LB3-01_CN	Yes	Voltage Phasor
10			IAWPM	C_FDR11~GC_3~0A0B1_1_3~0A0B1_A	Yes	Current Phasor
11			IBWPM	C_FDR11~GC_3~0A0B1_1_3~0A0B1_B	Yes	Current Phasor
12			ICWPM	C_FDR11~GC_3~0A0B1_1_3~0A0B1_C	Yes	Current Phasor
13	VIW_LONGBAY_B307	LB003	VALPM	V_LB3-02_AN	Yes	Voltage Phasor
14			VBLPM	V_LB3-02_BN	Yes	Voltage Phasor
15			VCLPM	V_LB3-02_CN	Yes	Voltage Phasor
16			IAWPM	C_FDR12~GC_3~0A0B2_1_3~0A0B2_A	Yes	Current Phasor
17			IBWPM	C_FDR12~GC_3~0A0B2_1_3~0A0B2_B	Yes	Current Phasor

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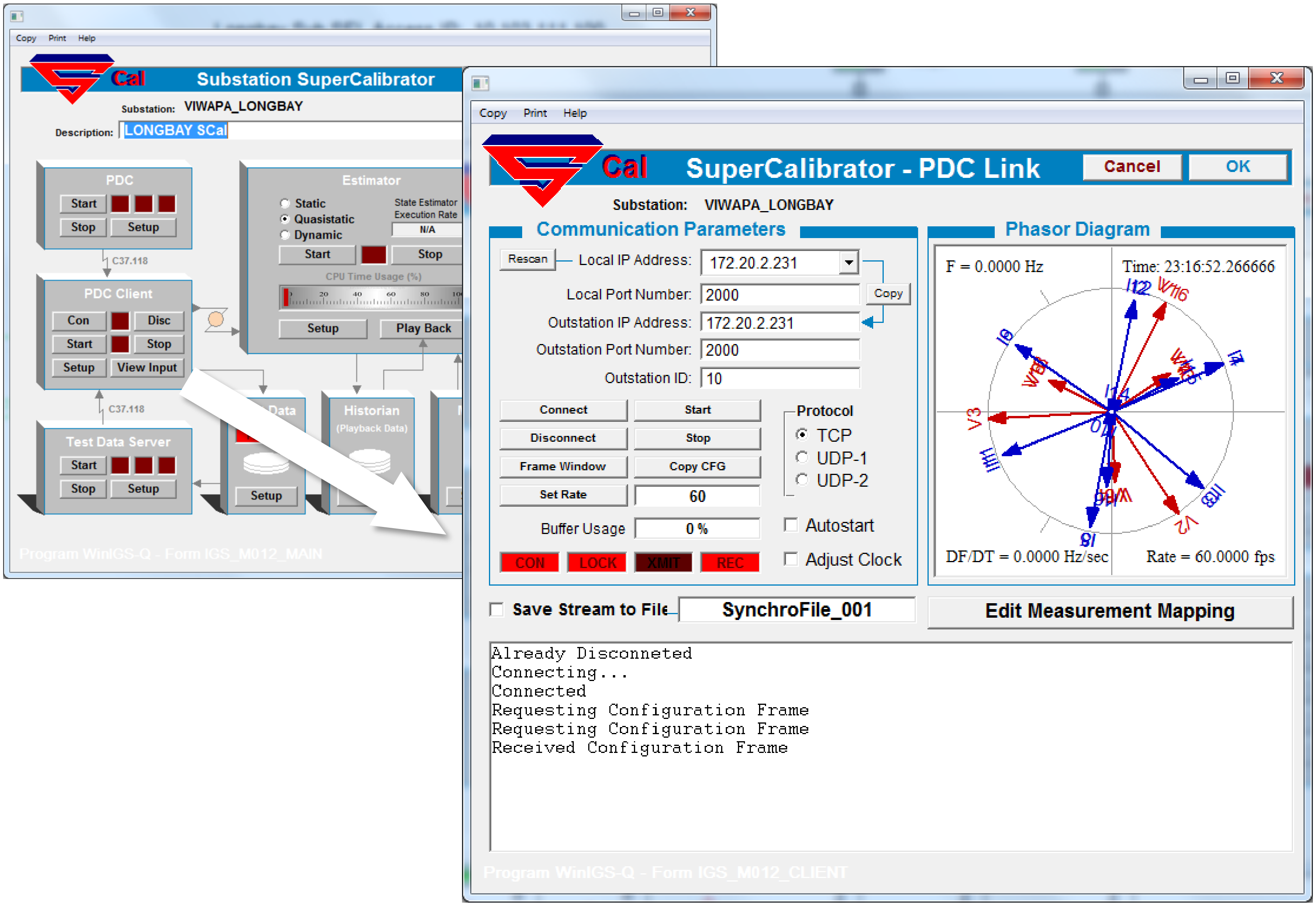
SuperCalibrator PDC Client – Setup Window



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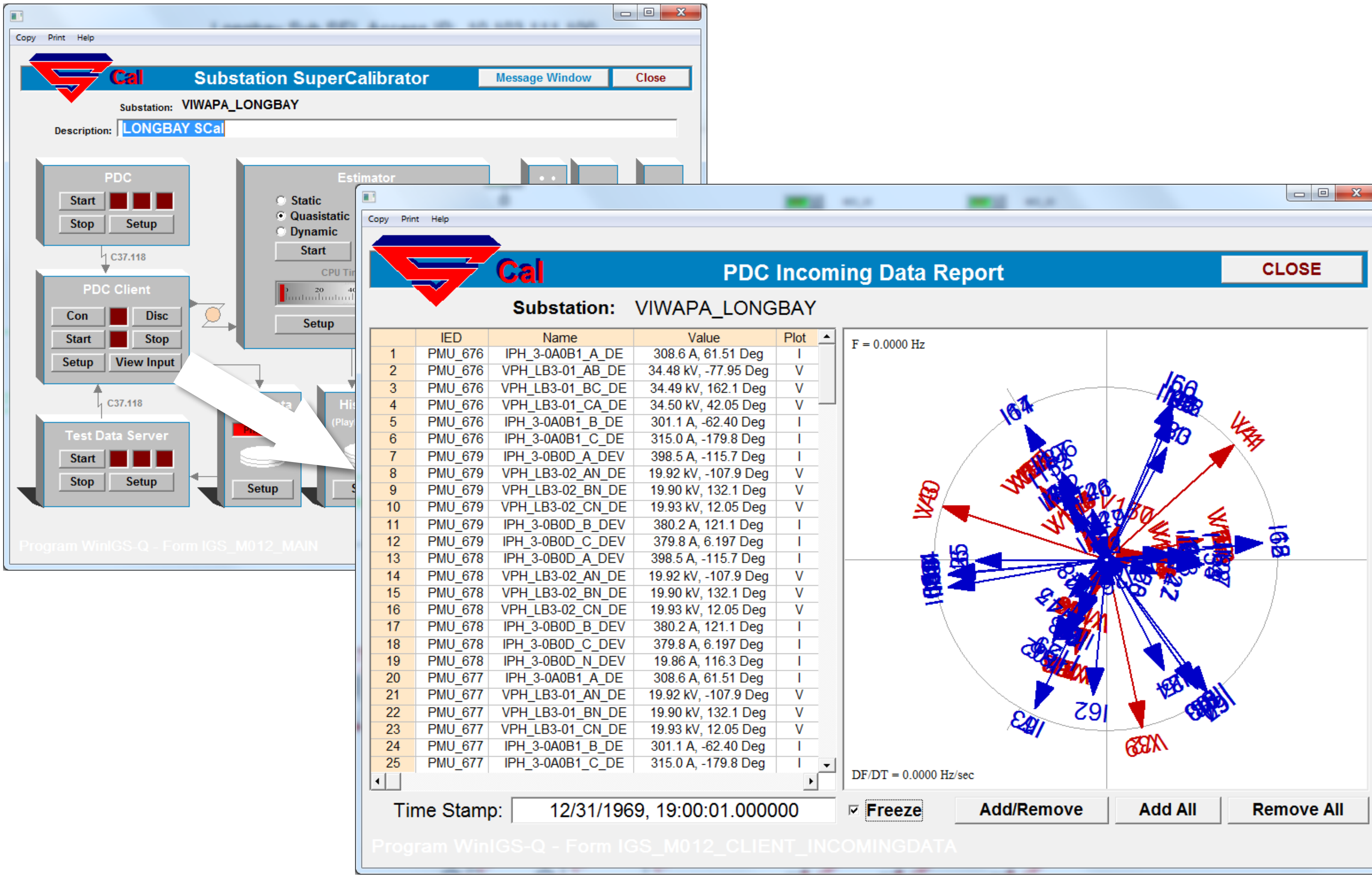
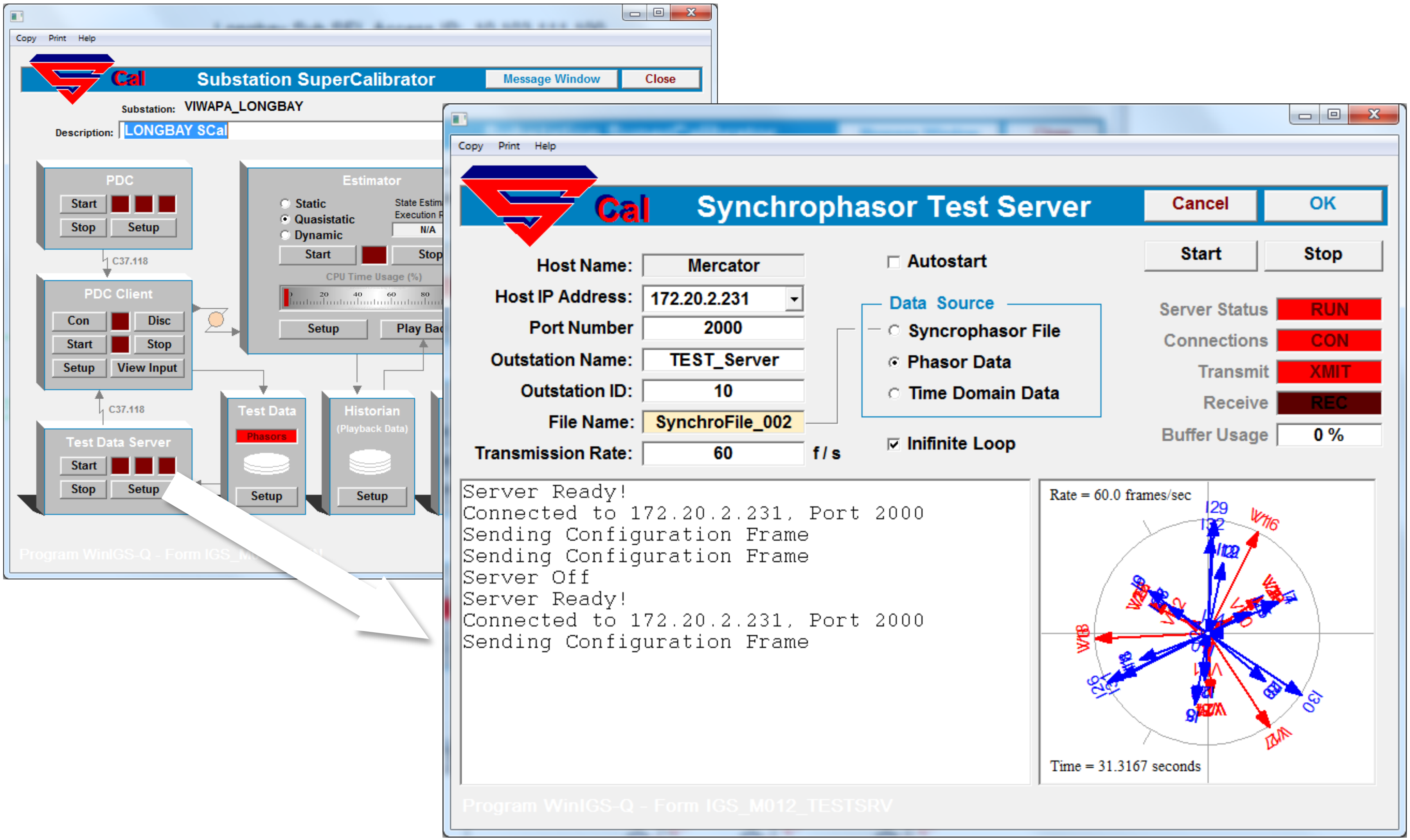
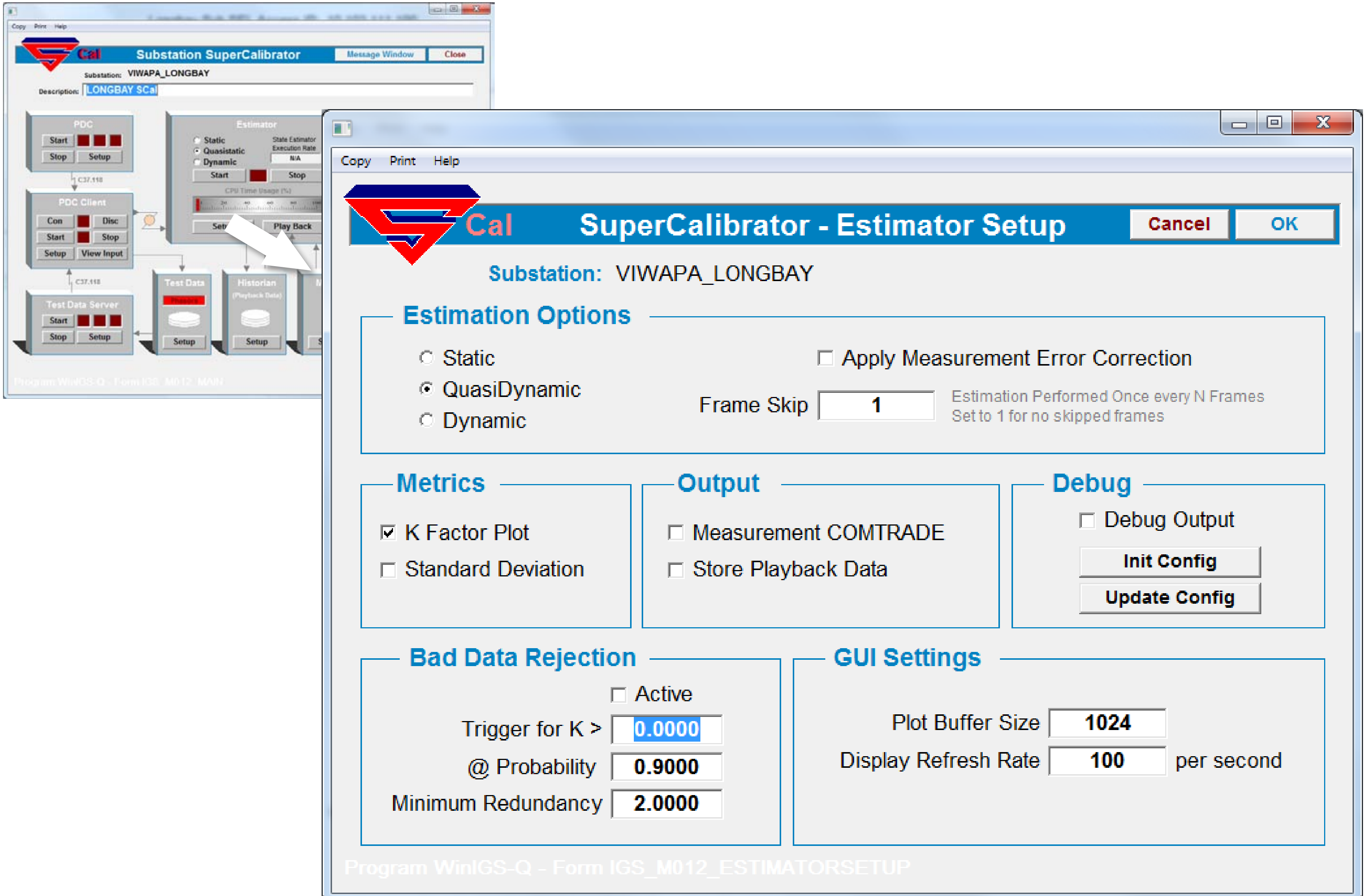
SuperCalibrator PDC Client – Input View Window



Test Data Server – Setup Window



DSE - Estimator Setup Window



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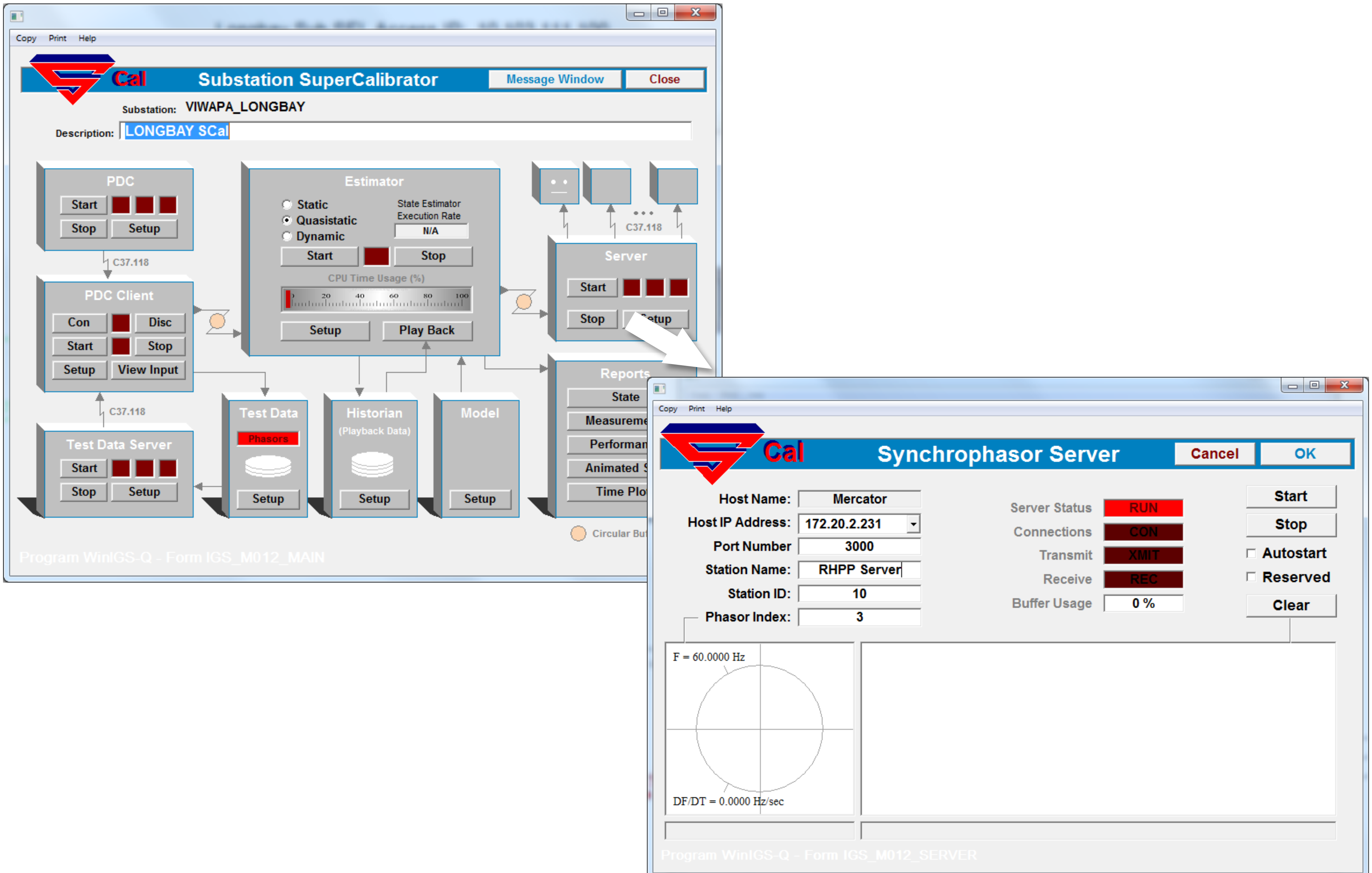
DSE - Synchrophasor Server – Setup Window



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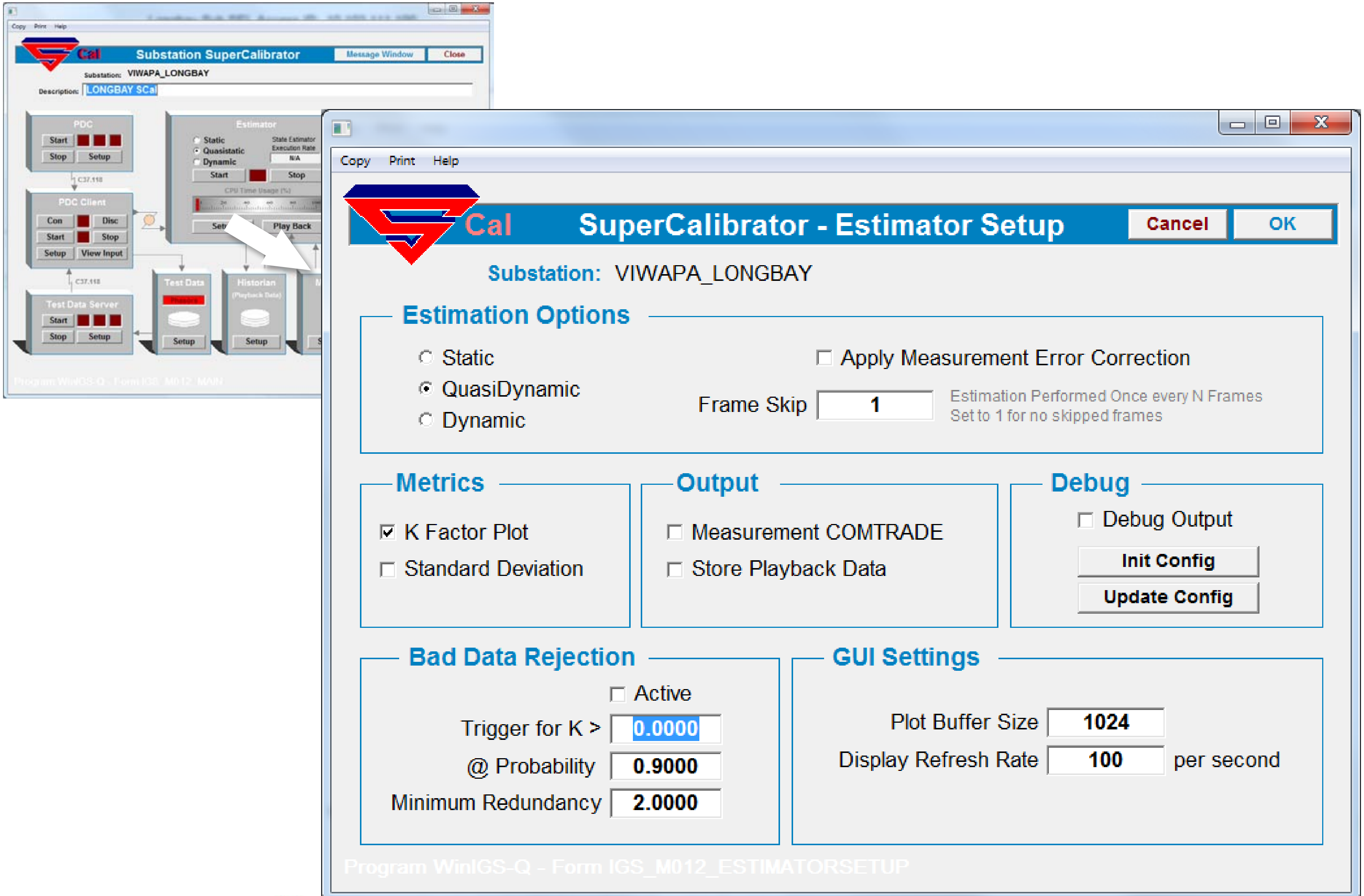
DSE - Estimator Setup Window



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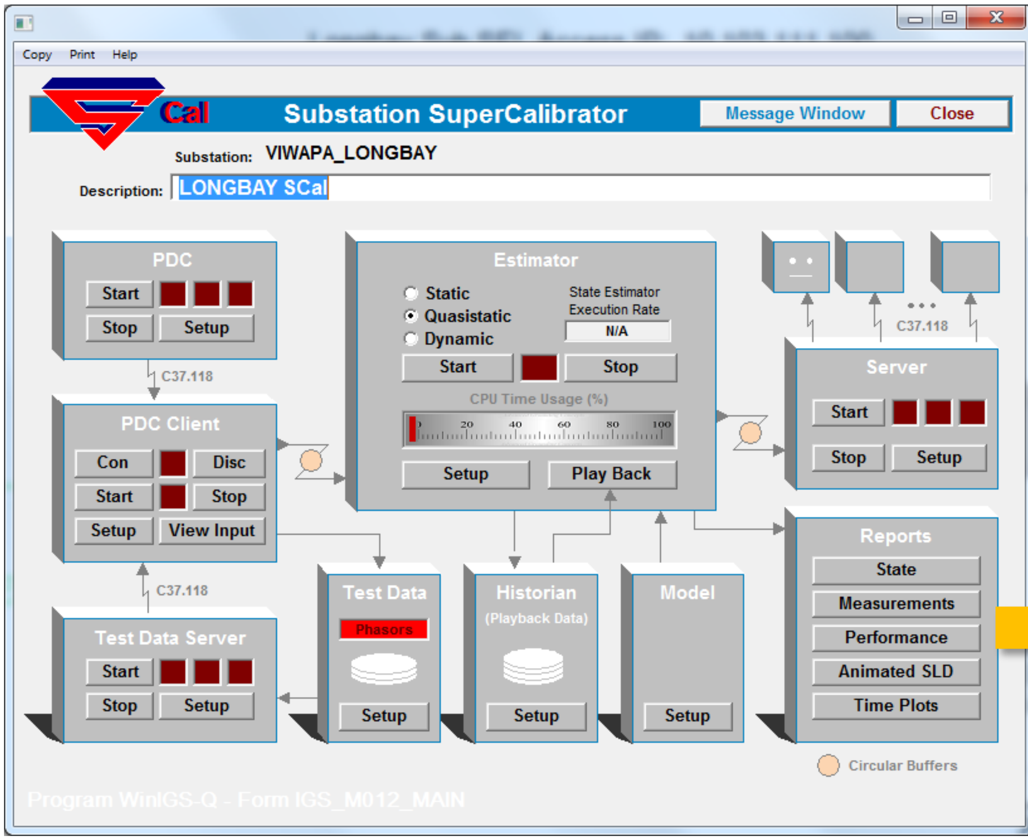
DSE - Reports



- State
- Measurements
- Performance Metrics
- Animated 3D - SLD
- Time Plots

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Summary

- Distributed State Estimation Enables State Estimation at Each Cycle (Sixty Times per Second).
- The Approach Requires a Detailed Three Phase Substation Model and at Least One PMU Device.
- Four Demonstration Projects Have Provided and Will Provide Tremendous Experience.
- The Approach Has Enabled a New Disturbance Play Back Which Has Proven to be Very Useful.