High Impact Project

Life-cycle management of mission-critical systems through certification, commissioning, in-service maintenance, remote testing, and risk assessment

Research Team

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T. Overbye, A. Srivastava

PSERC Webinar

Jan 24, 2017

PSERC HI Project Features

- High Impact Projects are for advancing PSERC research toward applications that have wide-spread adoption possibilities.
- They are broader in scope than typical projects, but will still have definite and well-defined deliverables.
- They require supplemental funding from PSERC members of at least a 1:1 match.
- They can be funded for a maximum period of three years.
- They have an upper limit of six funded investigators, with funding priority given to student support as with typical projects.

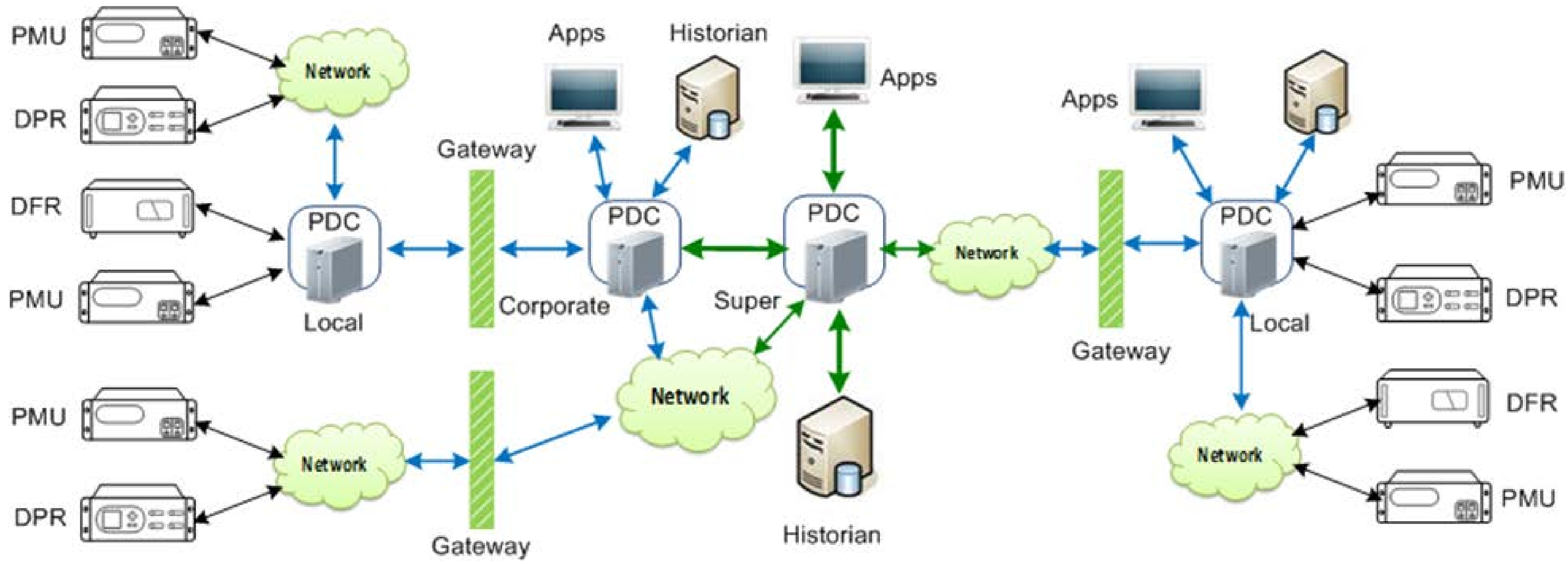
Prior Work

- Real Time PMU-Based Stability Monitoring, S-50
- Adaptive and Intelligent PMUs for Smarter Applications, S-57
- Systematic Integration of Large Data Sets for Improved Decision-Making, T-51
- Setting-less Protection: Laboratory Demonstrations, T-52G as well as in earlier PSerc projects:
- Setting-less Protection Methods, T-49G
- Testing and Validation of Phasor Measurement Based Devices and Algorithms, S-45
- Data Mining to Characterize Signatures of Impending System Events or Performance from PMU Measurements, S-44
- Toward a Systematic Framework for Deploying Synchrophasors and their Utilization for Improving Performance of Future Electric Energy Systems, S-37
- Using PMU Data to Increase Situational Awareness, S-36
- System Protection Schemes: Limitations, Risks, and Management, S-35
- Detection, Prevention and Mitigation of Cascading Events: Prototype Implementation, S-29
- Visualization of Power Systems, S-9
- The Next Generation Energy Management System Design, T-45
- Substation of the Future: A Feasibility Study, T-38
- The 21st Century Substation Design, T-37
- Transient Testing of Protective Relays: Study of Benefits and Methodology, T-30
- Performance Assessment of Advanced Digital Measurement and Protection Systems, T-22

Industry participation

- RTE, Patrick Panciatici
- Entergy, Floyd Galvan
- ISONE, Eugene Litvinov
- MISO, Mark Westendorf
- NYISO, Michael Swider
- NYPA, Bruce Fardanesh
- PowerWorld, Mark Laufenberg

Problem


PMU
DPR
DFR
PMU
Network
PDC
Local
Gateway
Corporate
Apps
Historian
PDC
PDC
Super
Apps
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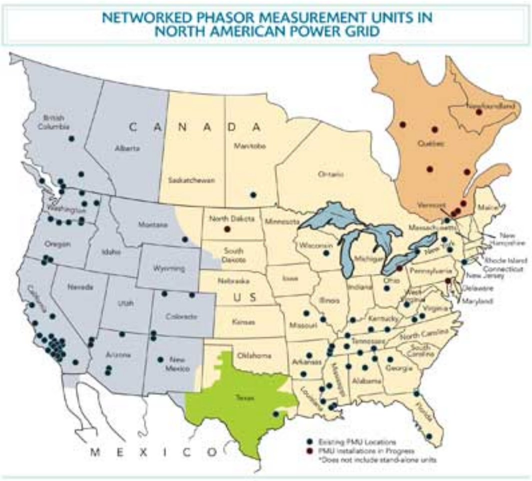
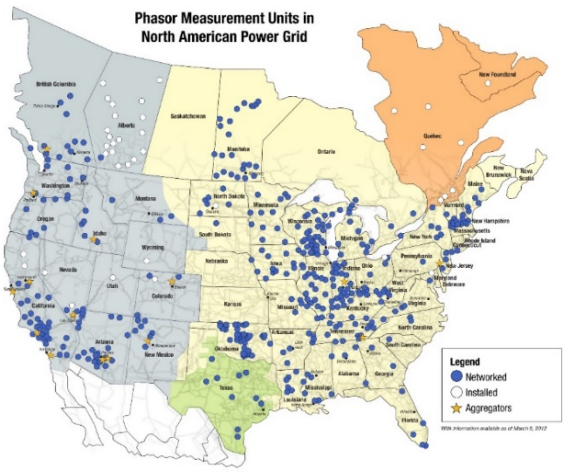
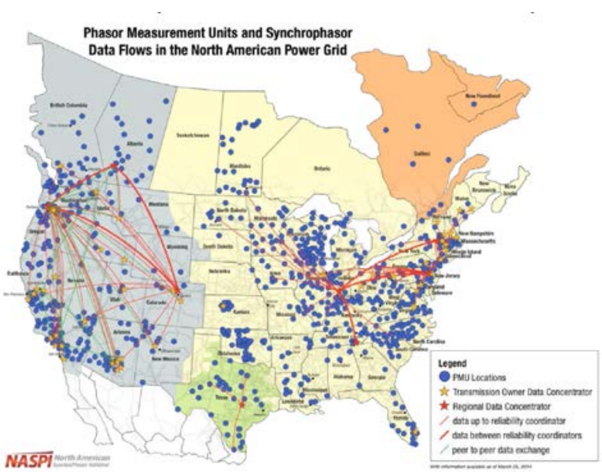
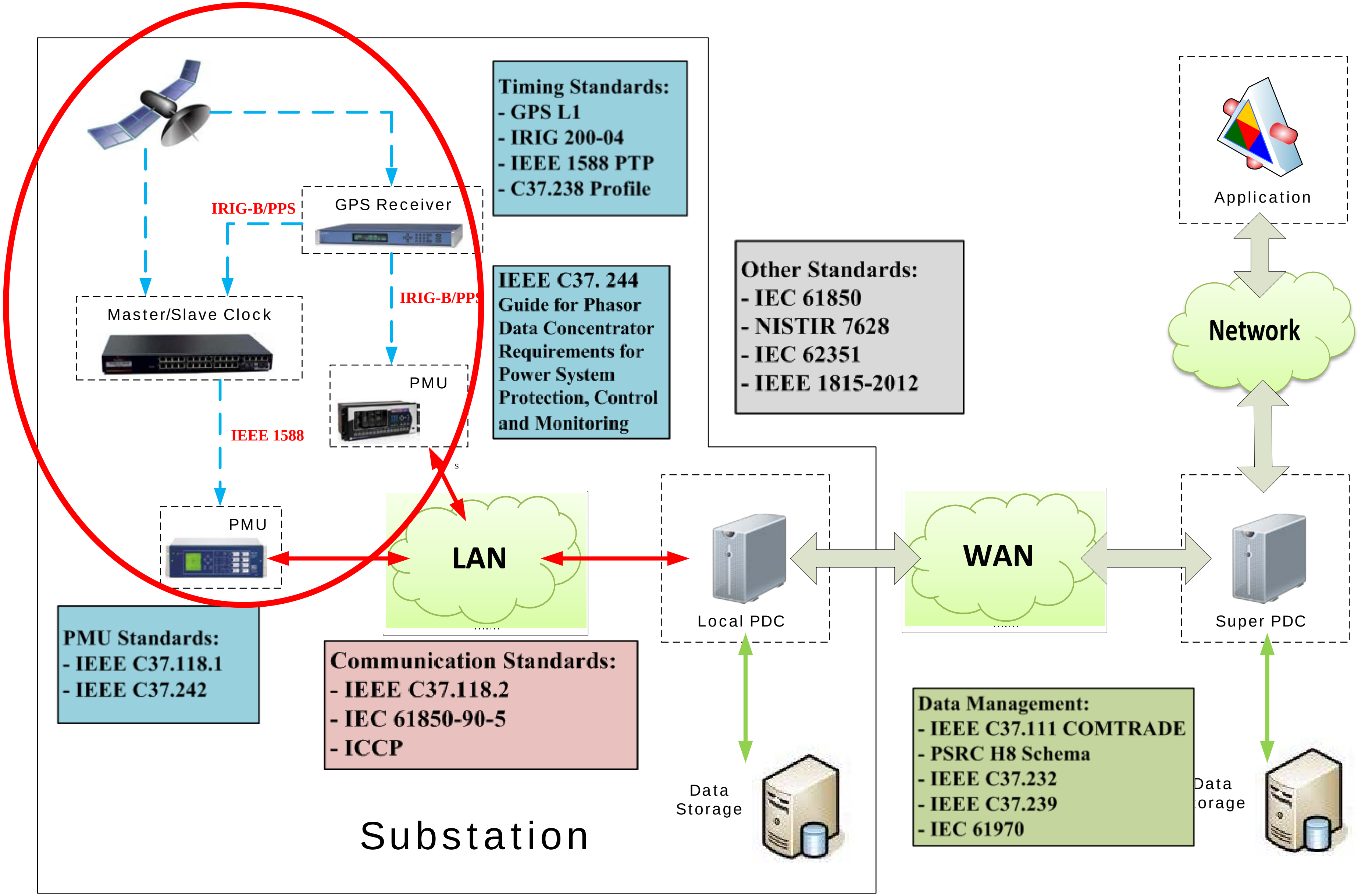
PMU


NETWORKED PHASOR MEASUREMENT UNITS IN NORTH AMERICAN POWER GRID


Phasor Measurement Units in North American Power Grid
Legend
Networked
Installed
Aggregators


Phasor Measurement Units and Synchrophasor Data Flows in the North American Power Grid
Legend
PMU Locations
NASPI

Standards

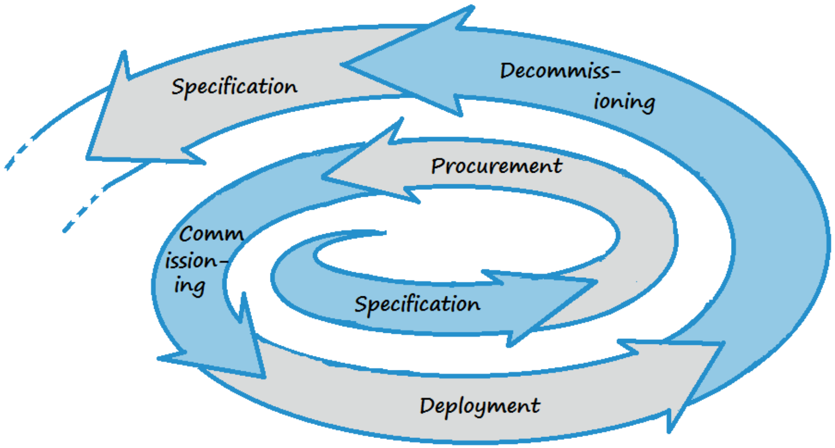


Timing Standards:
- GPS L1
- IRIG 200-04
- IEEE 1588 PTP
- C37.238 Profile
GPS Receiver
IRIG-B/PPS
IRIG-B/PPS
Master/Slave Clock
IEEE 1588
PMU
PMU
IEEE C37. 244 Guide for Phasor Data Concentrator Requirements for Power System Protection, Control and Monitoring
Other Standards:
- IEC 61850
- NISTIR 7628
- IEC 62351
- IEEE 1815-2012
Application
Network
LAN
WAN
Local PDC
Super PDC
PMU Standards:
- IEEE C37.118.1
- IEEE C37.242
Communication Standards:
- IEEE C37.118.2
- IEC 61850-90-5
- ICCP
Data Storage
Data Management:
- IEEE C37.111 COMTRADE
- PSRC H8 Schema
- IEEE C37.232
- IEEE C37.239
- IEC 61970
Substation

Synchrophasor lifecycle

New evaluation tools are needed

Synchrophasors
- **Certification**
- **Field commissioning**
- **Periodic maintenance testing**
- **Detecting abnormalities**
- **Troubleshooting**
- **Periodic application evaluation**



RAS
- **Initial Testing**
- **Periodic maintenance testing**
- **Detecting hidden failures**
- **Troubleshooting**
- **Periodic application evaluation**

Project Objective

- Develop and demonstrate tools for life-cycle management of mission-critical system
- Make calibration facilities for PMU certification readily available for industry use at the host universities
- Offer educational and training program how to use the tools in a production environment
- Share experiences and designs with the PSerc community for eventual use in production environment

Washington State University

Deliverables

A. Srivastava, D. Bakken

Task 1	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Testing and certification lab	Lab equipment with certified testing protocol	Testing protocol and lab equipment specification	Demonstration of automated testing using certified protocol	Anurag Srivastava
PMU Testing Analyzer	Software for analysis of PMU test results	Software specification following standard	Automated analysis demonstration using several PMUs	Anurag Srivastava
Task 2	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Erkios software for end-to-end testing	Software for remote field testing to detect hidden logic failures	Software specification	Hidden logic failure detection demonstration using simulator set-up	David Bakken

Task 4	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Integration of PMU testing Analyzer and Erkios Software	Integrated software for remote field testing of PMUs	Specification for PMU input/output and timing coordination	Demonstration using simulator set-up	David Bakken and Anurag Srivastava
Integration of RAS Logic and Erkios Software	Integrated software for field testing RAS	Specification for RAS logic, I/O and time coordination	Demonstration using simulator set-up	David Bakken and Anurag Srivastava

SOW for WSU

Prototype PMU Testing using PMU Performance Analyzer (PPA), Testing Lab and prototype testing following IEEE TSS

Remote PMU testing using PPA, test lab and middleware based Erkios

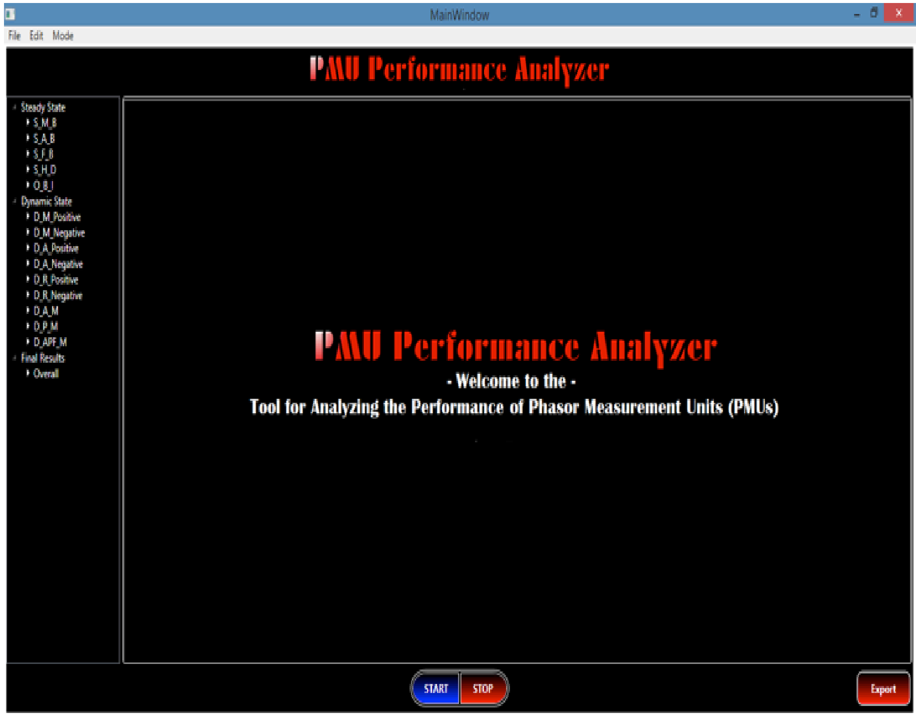
End-to-end testing of RAS using Erkios

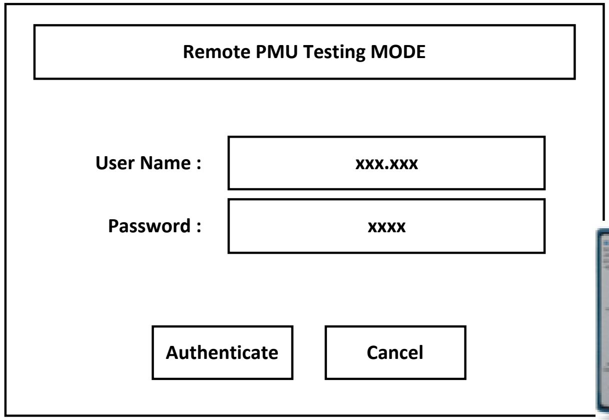
Validation of PMU testing, remote PMU testing and end-to-end RAS testing using WSU testbed

Modules and Tool Development

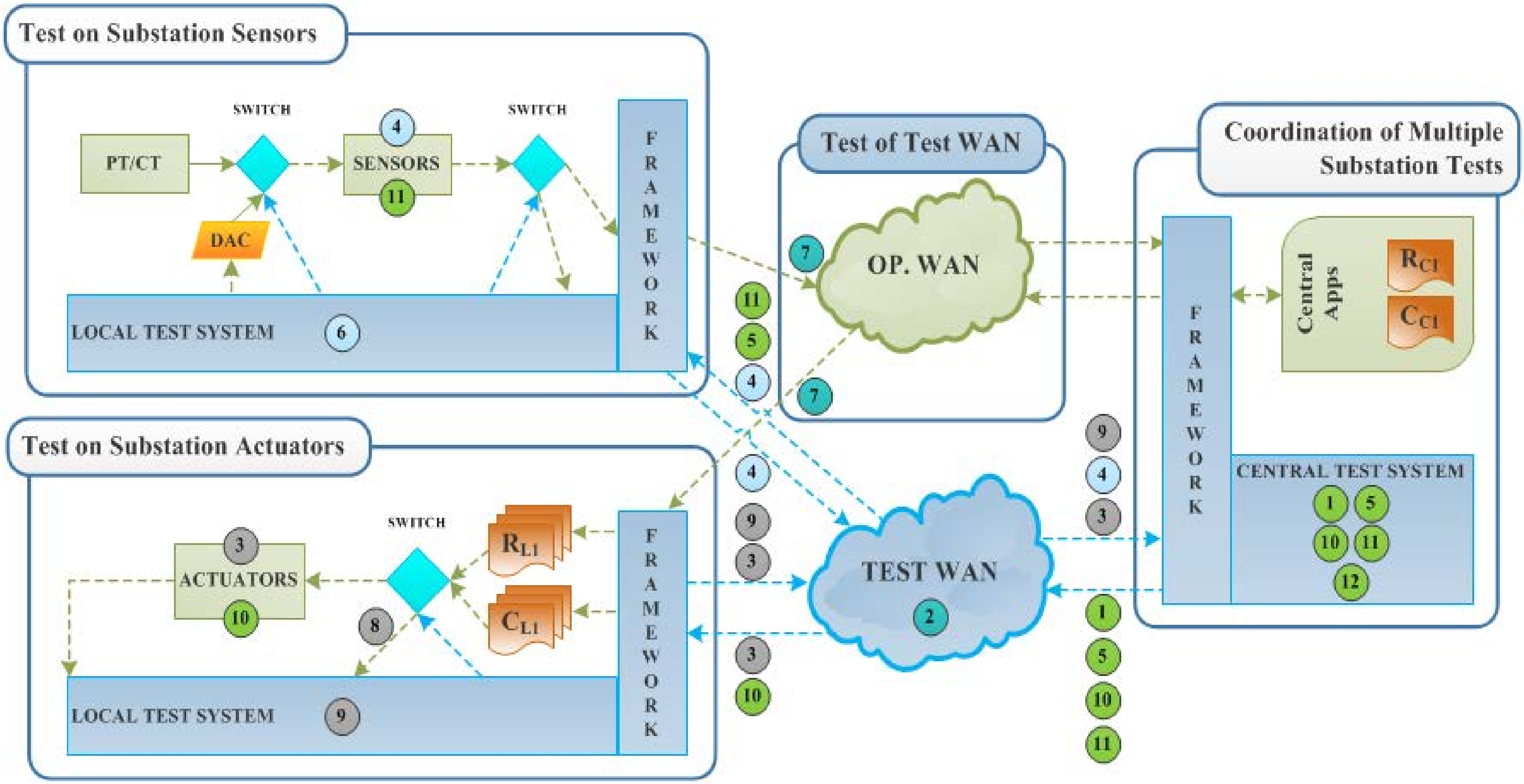
PMU Performance Analyzer (PPA) is a software tool to:

a) Test PMU in lab
b) Test PMU at substation remotely with authentication to connect
c) Test PMU following IEEE C37.118.1-2011 and IEE TSS
d) Test PMU for steady state and dynamic test cases
e) Requires real time hardware to generate test and reference signals (e.g. NI, RTDS)
f) Automatically time aligns data and generate test reports



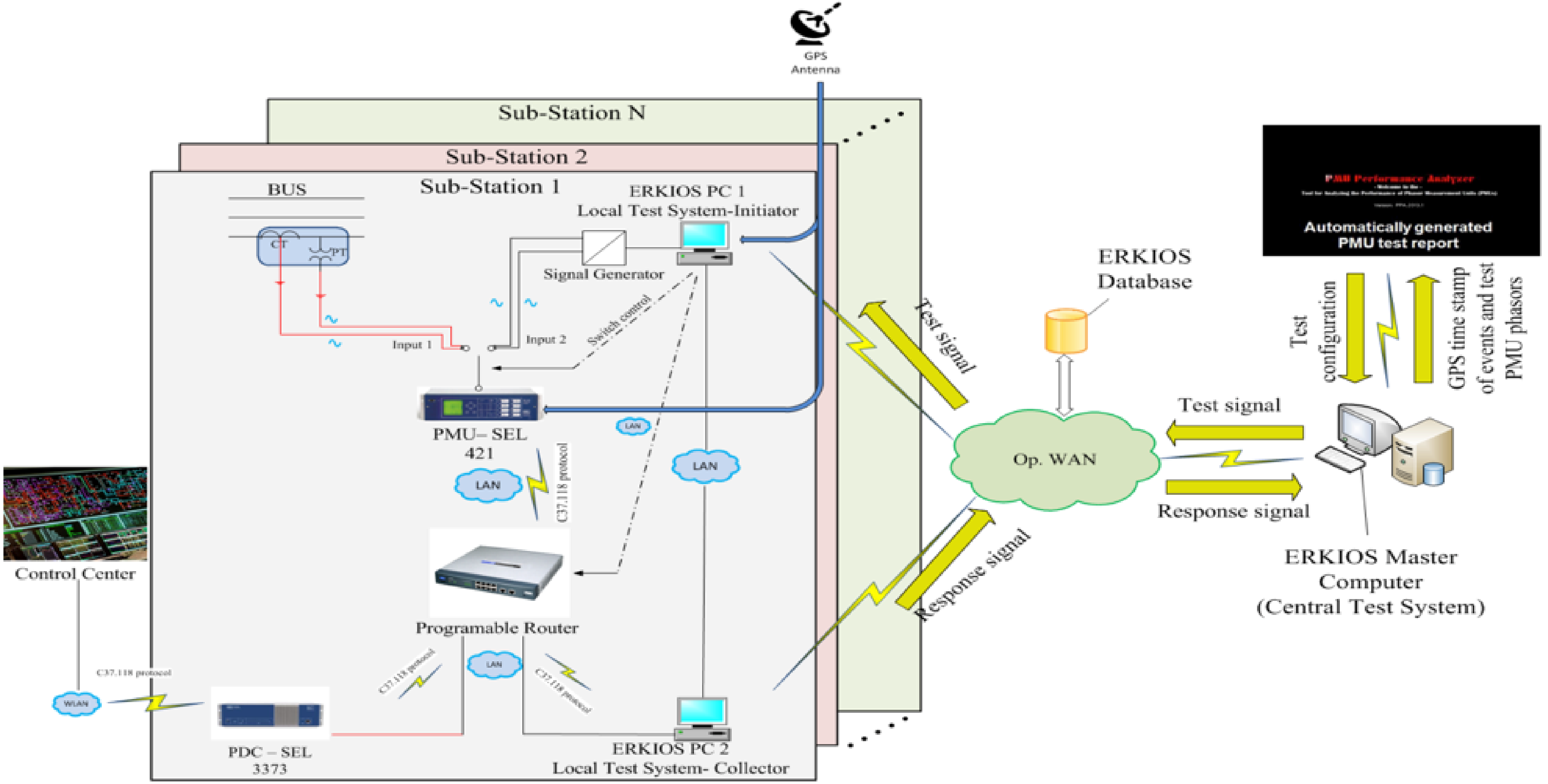


Modules and Tool Development



- Erkios is a middleware based software tool for end-to-end testing including software hidden failures using data delivery, data management and data interface mechanisms.
- End-to-end testing includes sensor, controllers, and actuators testing as well as interface with test signals and test results.

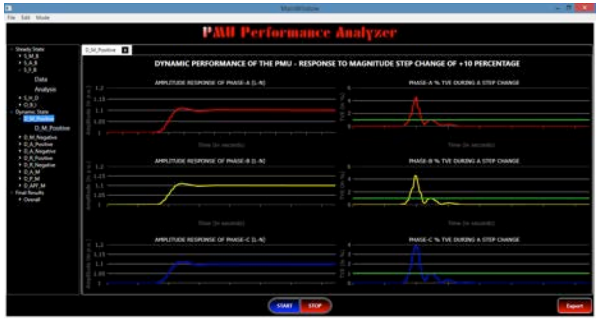
Use Case for Modules



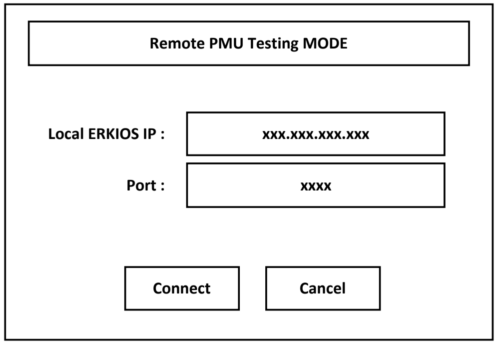
- Use case will be end-to-end testing of PMU based RAS using PPA and Erkios interfaced with WSU test bed
- This will include remote PMU testing, RAS controller testing utilizing local test system –initiator and local test system-collector and Erkios master central test system

Current Status of Development

- Specification and requirement documents
  - Test lab for PMU testing following IEEE C37.118.1-2011, IEEE TSS and ISO/ IEC 17025 standards
  - Middleware for PMU testing, user interface, data interface
  - Erkios Interfacing with PPA and RAS
  - RAS Test Suite

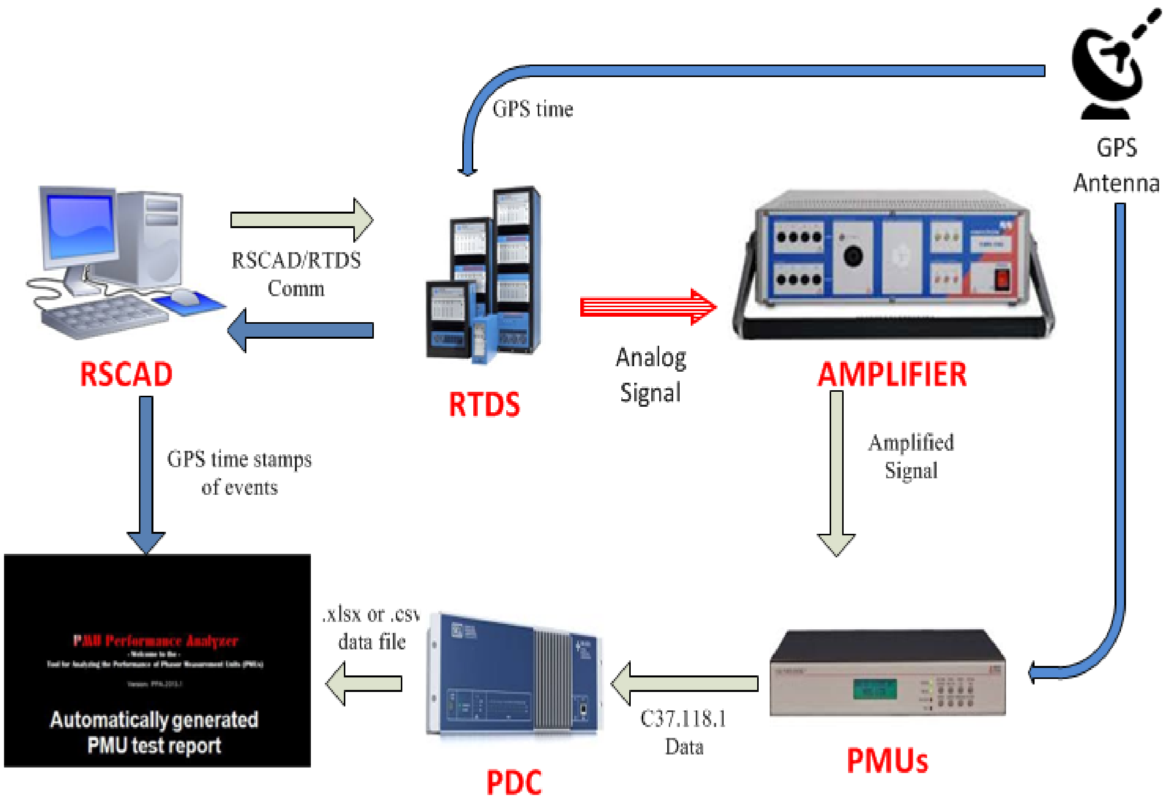


- PMU Performance Analyzer (PPA)
  - Industry-Grade PPA v2
  - Interface with NI Processor as an additional option to RTDS
  - Interfacing with Erkios for remote testing



- End-to-End testing of RAS
  - Erkios interface with substation
  - Erkios v2 with integration of RAS

Testing of Modules



- Participated in NIST inter-lab comparison (ILC) for PMU testing
- Compared with test results of PMU developed at WSU with known error
- Component level analysis to minimize the noise or measurable
- PPA being used at Southern California Edition and at University of Illinois for PMU testing and any feedback received have been integrated in next version

- Self test-mode has been designed in Erkios.
- Self test-mode is based on common failure mode possible at software and data interface level at substation or central system

Involvement with PSERC Companies

- Number of interactions with RTE related to Erkios and cyber-resilient RAS
- RTE provided test case for RAS
- Interaction with Entergy for PMU testing
- Interaction with Idaho Power for PMU data quality
- Provided PPA software to UIUC

Texas A&M University

Deliverables

Task 1	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Testing and certification lab	Lab equipment with certified testing protocol	Testing protocol and lab equipment specification	Demonstration of automated testing using certified protocol	Mladen Kezunovic

Task 2	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
“Gold” PMU	High accuracy PMU	Algorithm specification	Accuracy Demonstration using simulator set-up	Mladen Kezunovic
Field end-to-end calibrator	Hardware and software	Equipment specification	End-to-end calibration demonstration using simulator set-up	Mladen Kezunovic
Integration of “gold” PMU and in-service calibrator	Use Case for application testing and calibration	Use case specification	Demonstration of State Estimator testing using simulator set-up	Mladen Kezunovic

SOW for TAMU

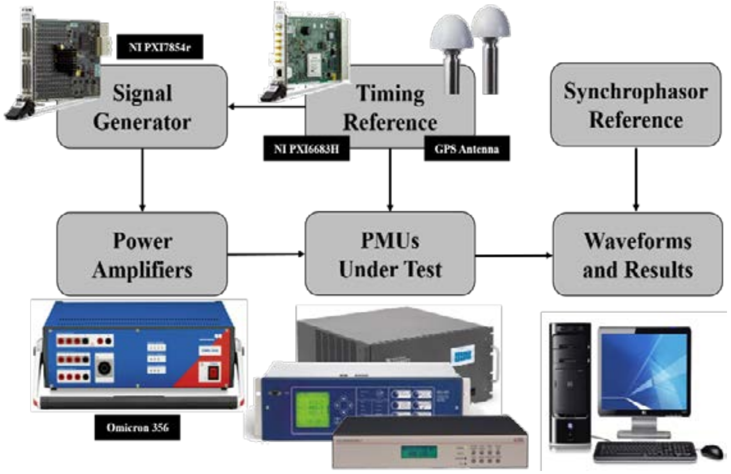
Development of PMU Calibration and Testing Laboratory in Full Compliance with the IEEE Standards and Pursuing the ICAP Certification Process

Gold PMU: A device empowered by accurate algorithm, and is leveraged to provide synchrophasor reference in PMU testing

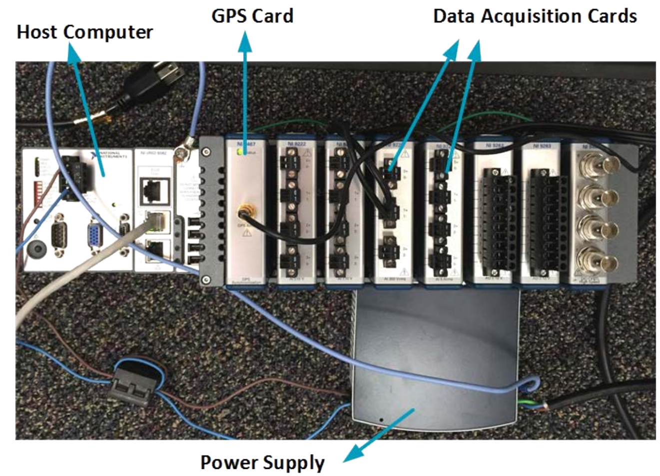
End-to-end testing of the synchrophasor system in the field using a portable field calibrator

End-to-end application testing of synchrophasor system using fault location and oscillation monitoring applications

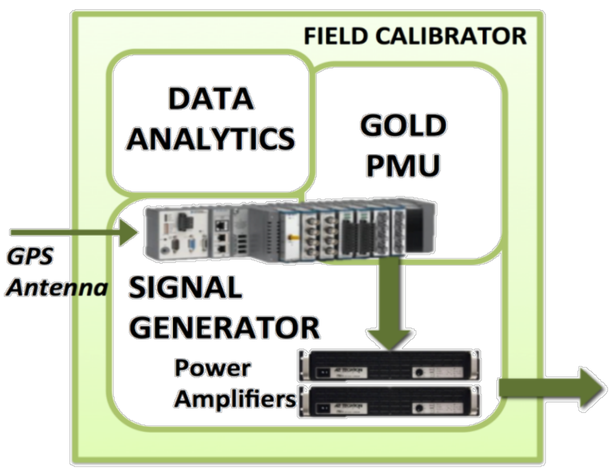
Modules and Tools Development



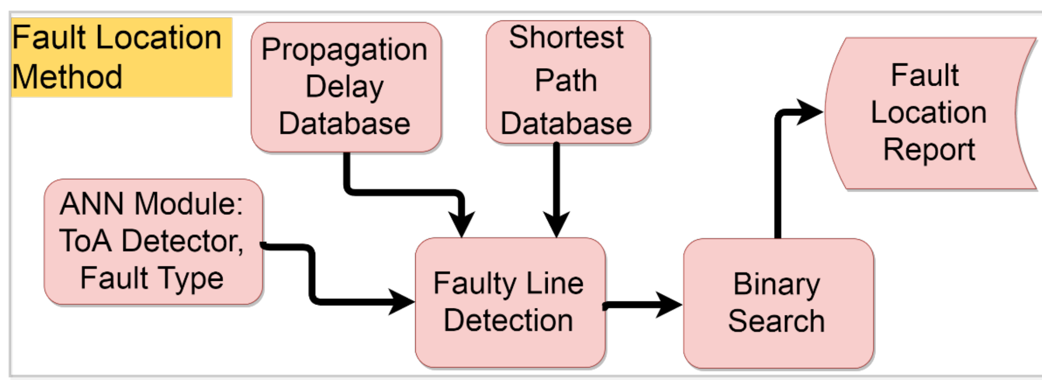
PMU Calibration/Testing Laboratory



Gold PMU Development Environment in NI CompactRIO



Portable field calibrator

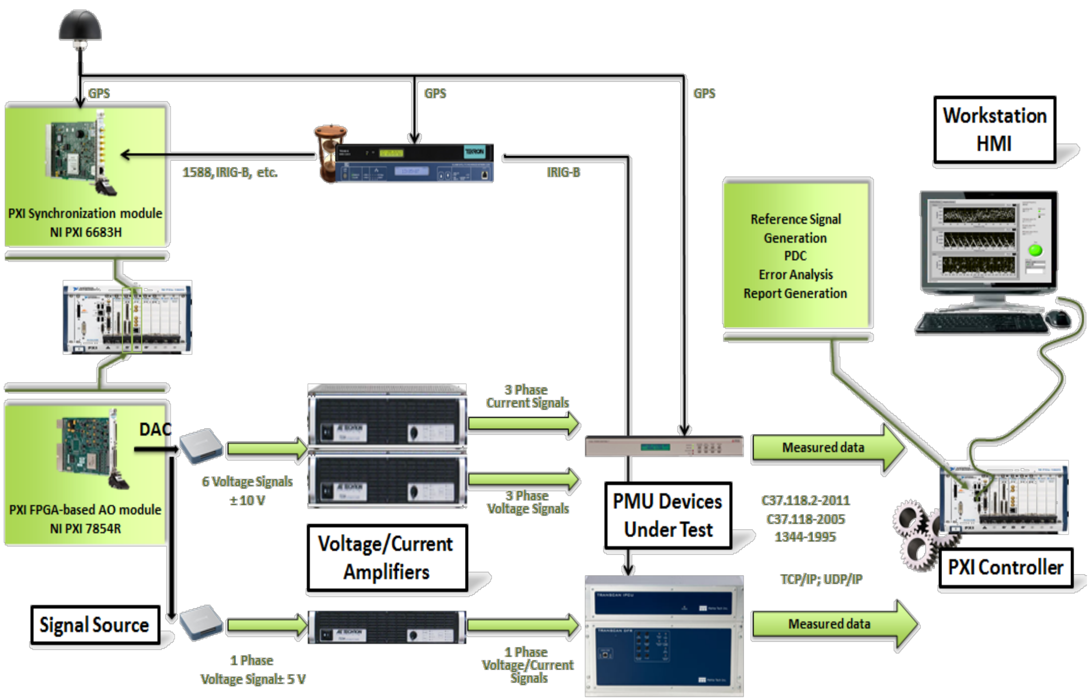


Fault Location Application Module

Modules and Tools Development

Use cases for PMU Calibration/Testing Lab

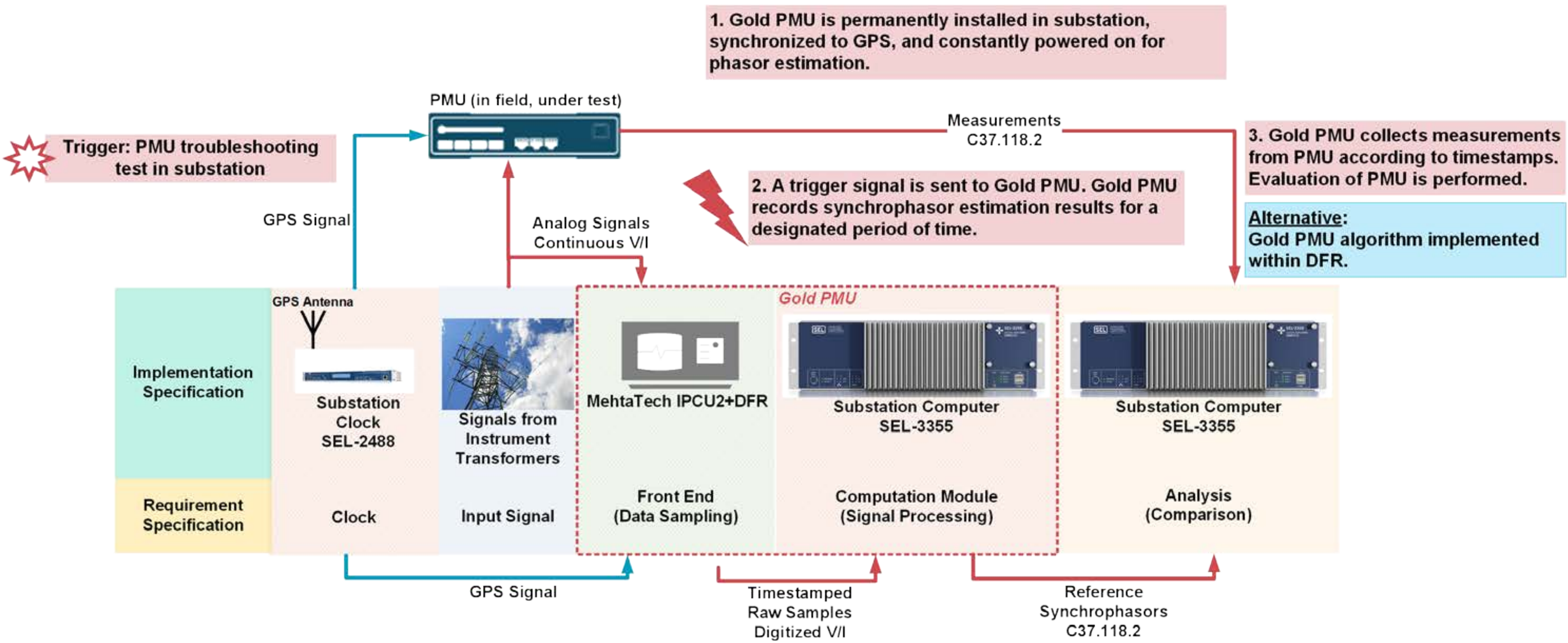
1. PMUs with TCP Communication Protocol
2. PMUs with UDP Communication Protocol
3. PMUs with Serial Communication Protocol
4. Digital Fault Recorders with PMU Functionality



Use Case for Modules

Two use case for Gold PMU installed permanently in substation

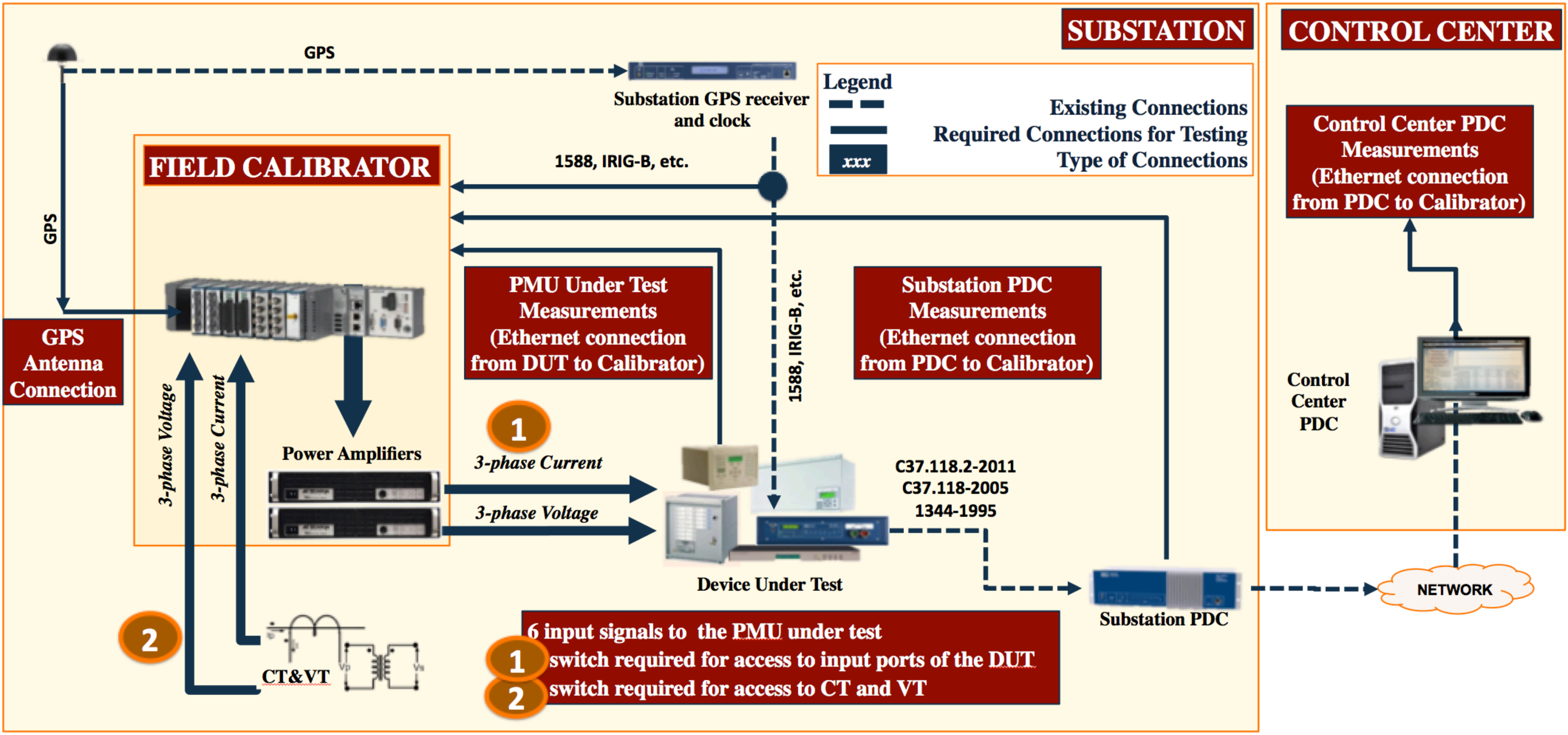
1. Gold algorithm implemented in substation computer
2. Gold algorithm embedded in DFR



Use Case for Modules

Two use cases for portable field calibrator

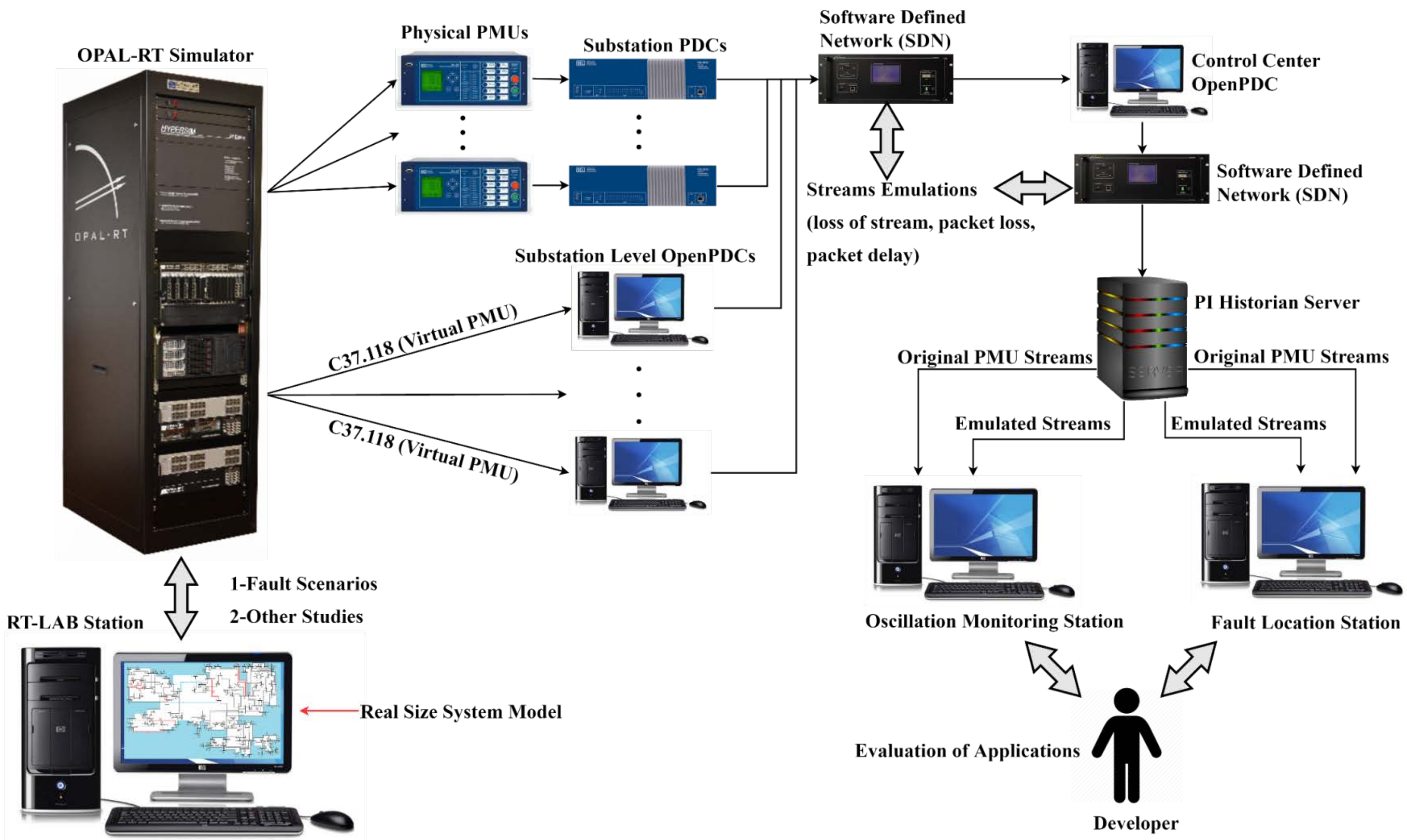
1. Periodic Maintenance in the field
2. Troubleshooting of the synchrophasor system applying nested testing approach



Use Case for Modules

Two use cases for Application Testing

1. Fault Location Application
2. Oscillation Monitoring Application

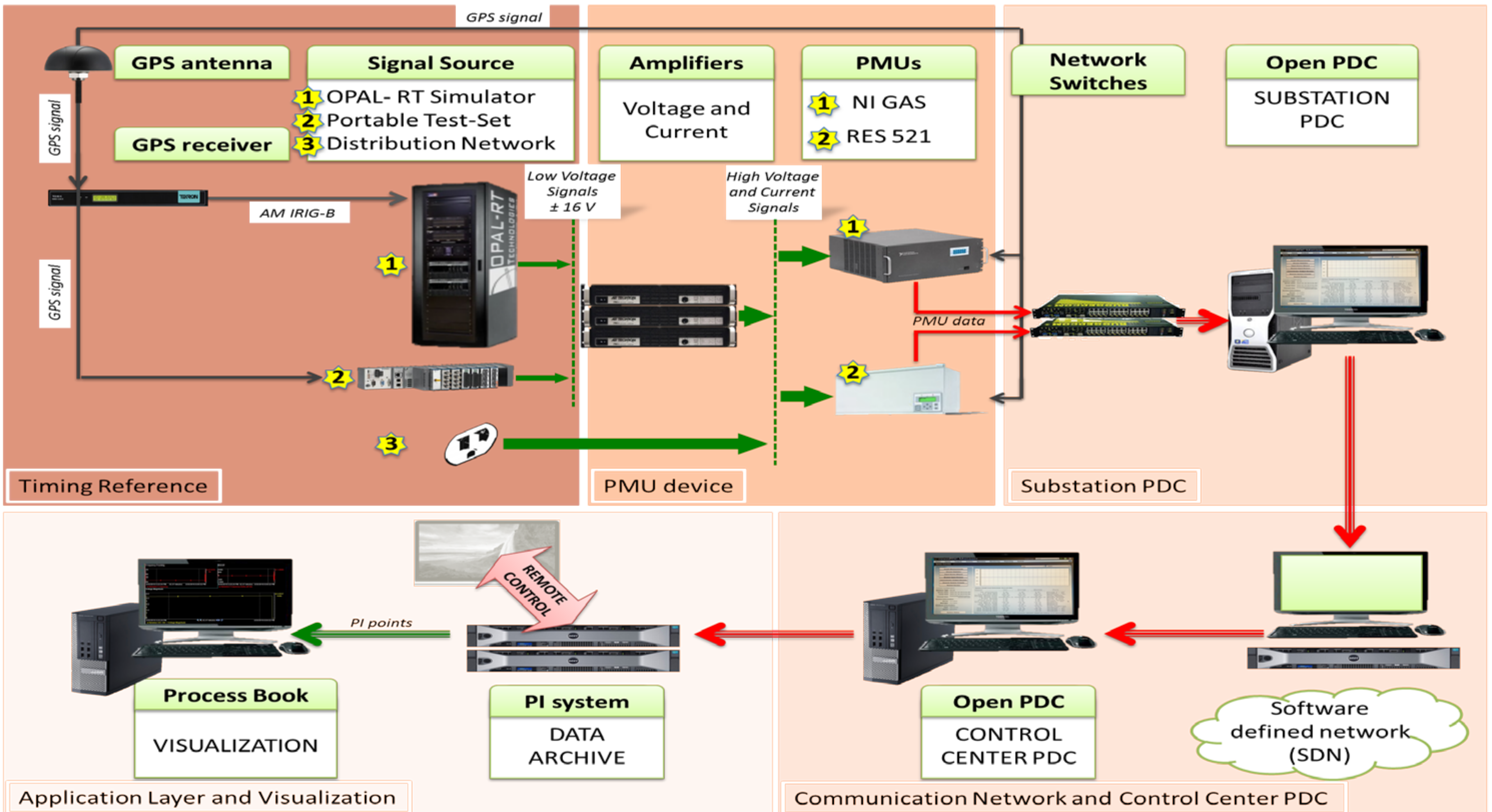


Current Status of Development

- **Calibration Lab**
  - Hardware and software specification
  - Standard static and dynamic type-test implementation
  - NIST inter-laboratory comparison (ILC) evaluation
  - Efforts on certification of the TAMU PMU calibration lab
- **Gold PMU**
  - Hardware and algorithm specification
  - Characterization of front end data acquisition modules
  - Gold algorithm implemented in TAMU development environment
- **Field Calibrator**
  - Hardware specification and design for testing in the field environment
  - Signal generator for set of type tests (known signals for the DTUs)
  - Characterization of the signal generator
- **Application Testing**
  - Hardware specification for end-to-end application testing
  - Software and system model development for fault location application testing

Testing of Modules

- Filed calibrator testing in the TAMU testbed environment



Involvement with PSERC Companies

- Interaction with Entergy for acquiring:
  - equipment for testing (DFR, substation computer, etc.)
  - field measurement data
  - System powerflow and dynamic models
  - Oscillation Monitoring tool
  - Recorded PMU, DFR and maintenance reports of fault events

Georgia Institute of Technology Deliverables

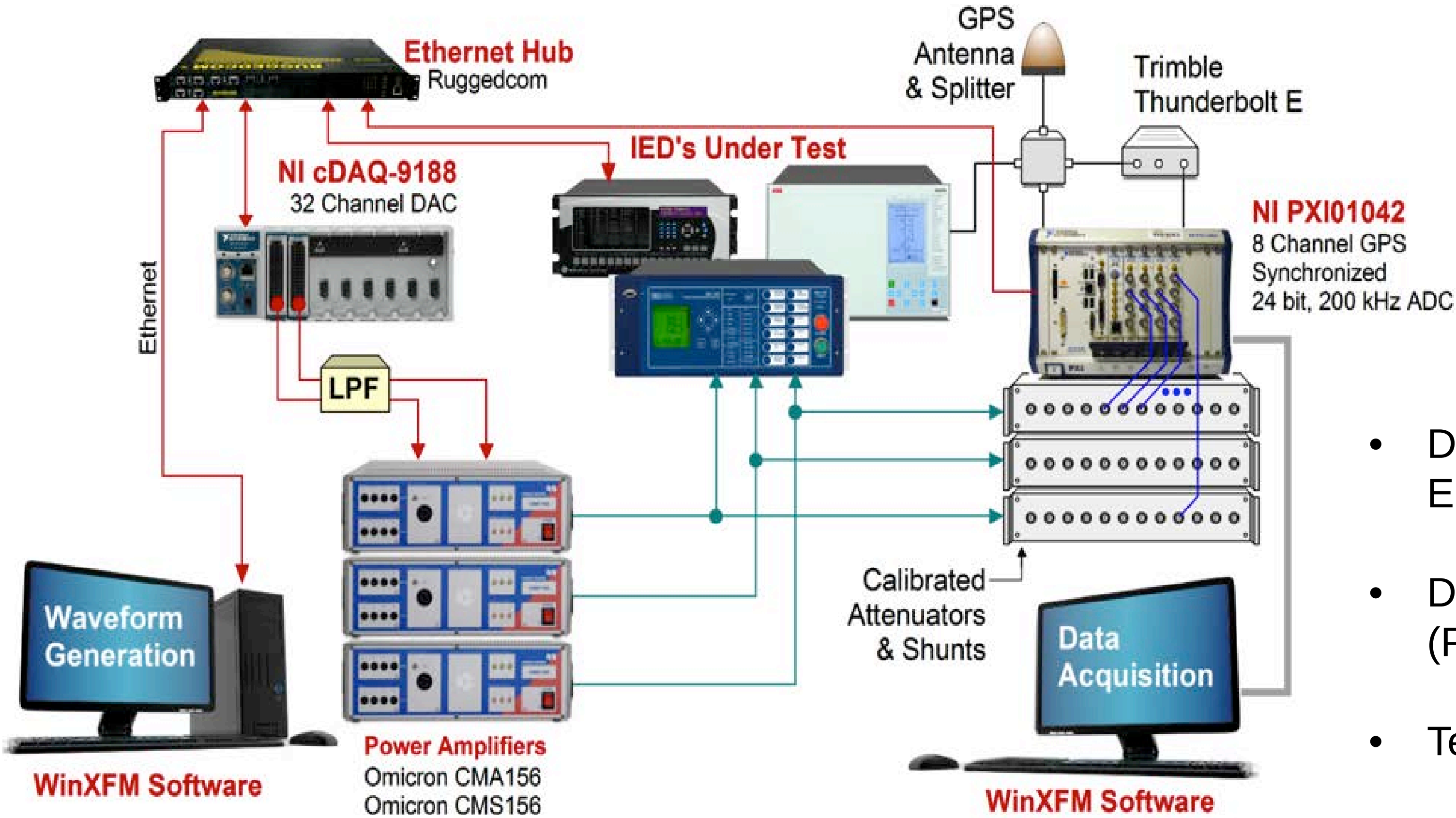
Sakis Meliopoulos

Task 1	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Testing and certification lab	Lab equipment with certified testing protocol	Testing protocol and lab equipment specification	Demonstration of automated testing using certified protocol	Sakis Meliopoulos

Task 3	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Substation based dynamic state estimator	Tools for in-service calibration, testing, hidden failure detection and data compression	Use case specification; development of co-model of an actual substation; software spec.	Laboratory demonstration of in-service calibration, testing, hidden failure detection and data compression	Sakis Meliopoulos

PMU & MU Testing Lab Development

Basic Approach: Capture input to PMUs or MUs with high precision (sub-microsecond, 0.01%), import output of PMUs or MUs and Compare. End Result: Low Cost, High Precision Testing method

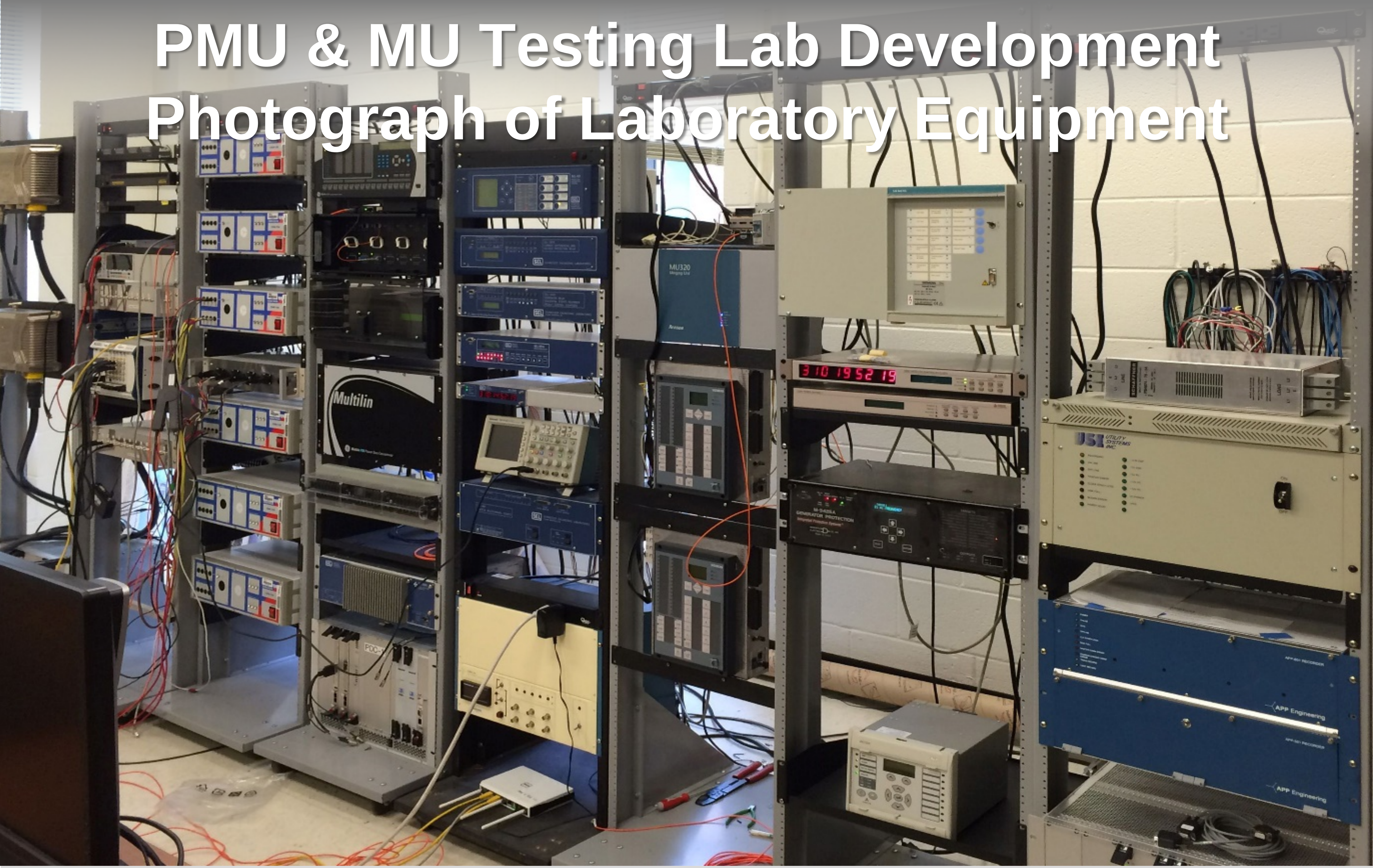


- Data Generation Equipment
- Devices under test (PMUs or MUs)
- Test Equipment
- WinXFM Software

Two tasks are under way:

1) Testing and characterization of the PMUs
2) Processing of the sample data using the standard PMU and creating a C37.118 stream

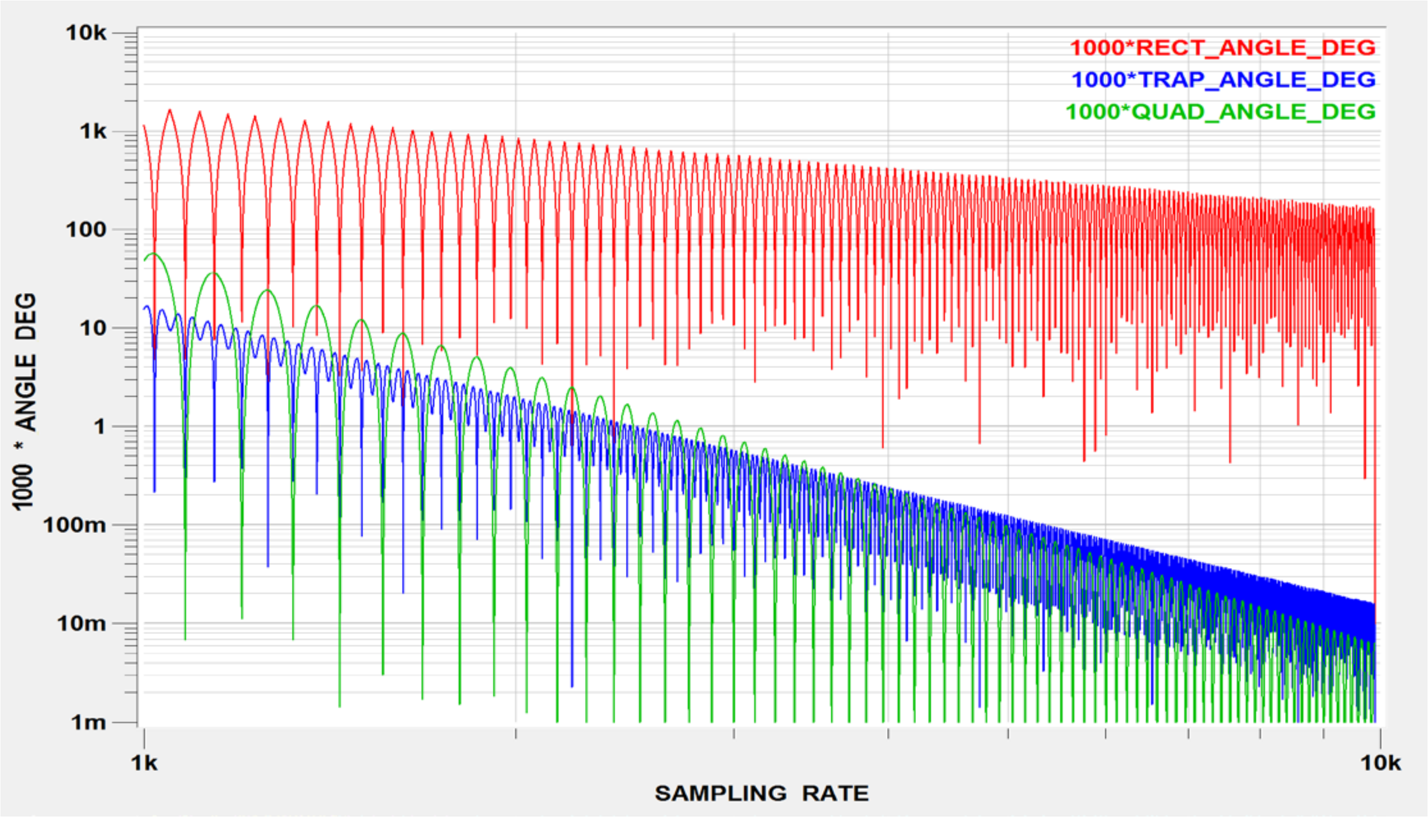
PMU & MU Testing Lab Development
Photograph of Laboratory Equipment



Presently, the laboratory includes several PMUs (SEL, GE, USI, etc.) and several Merging Units (2 GE Hardfiber, 1 Alstom (Reason), 2 Siemens).

MU Data Processing, Standard PMU

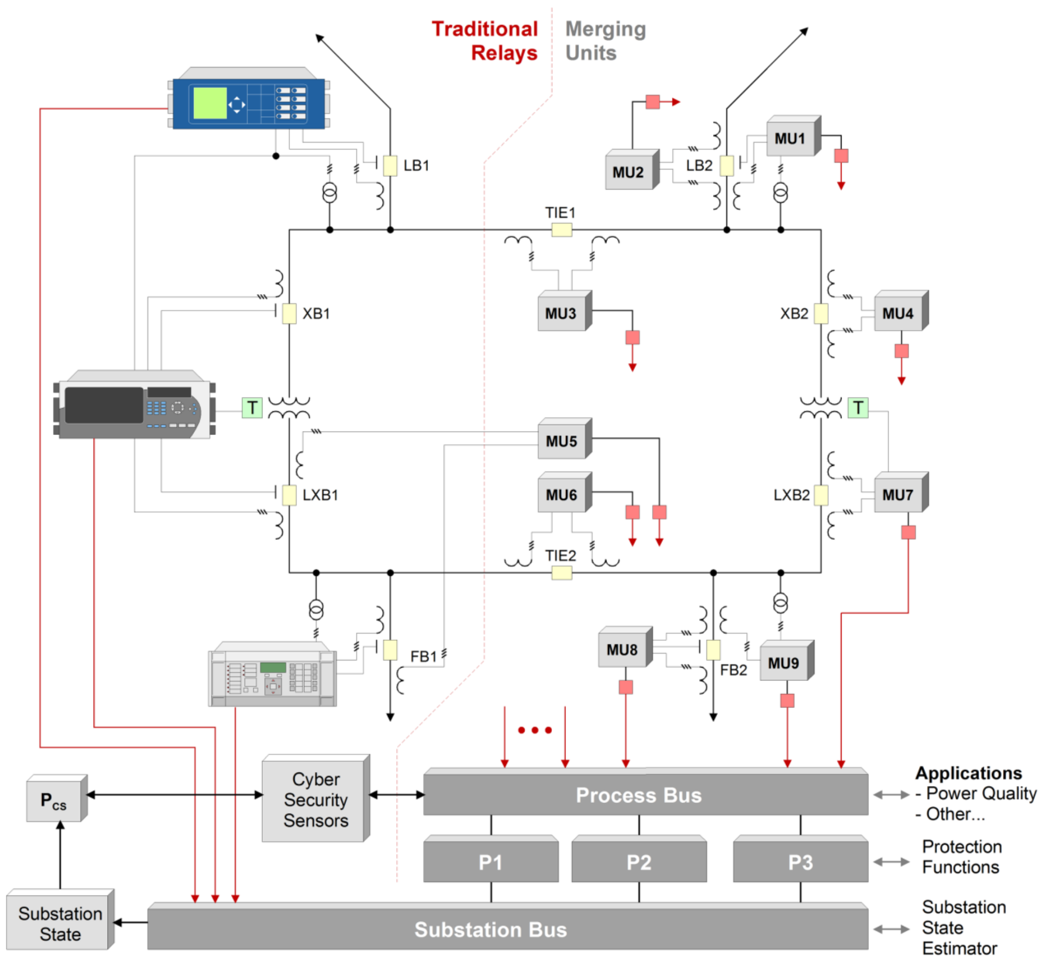
Discrete Fourier Transform Over an exact integer number of cycles, variable period as frequency varies. Excellent accuracy.



Performance evaluation of fractional sample correction method

- Range of sampling rates (1 to 10 ks/s)
- Different approximation methods

Distributed Dynamic State Estimator



Laboratory Infrastructure for Testing the Distributed Dynamic State Estimator (Numerical Relays and Merging Units)

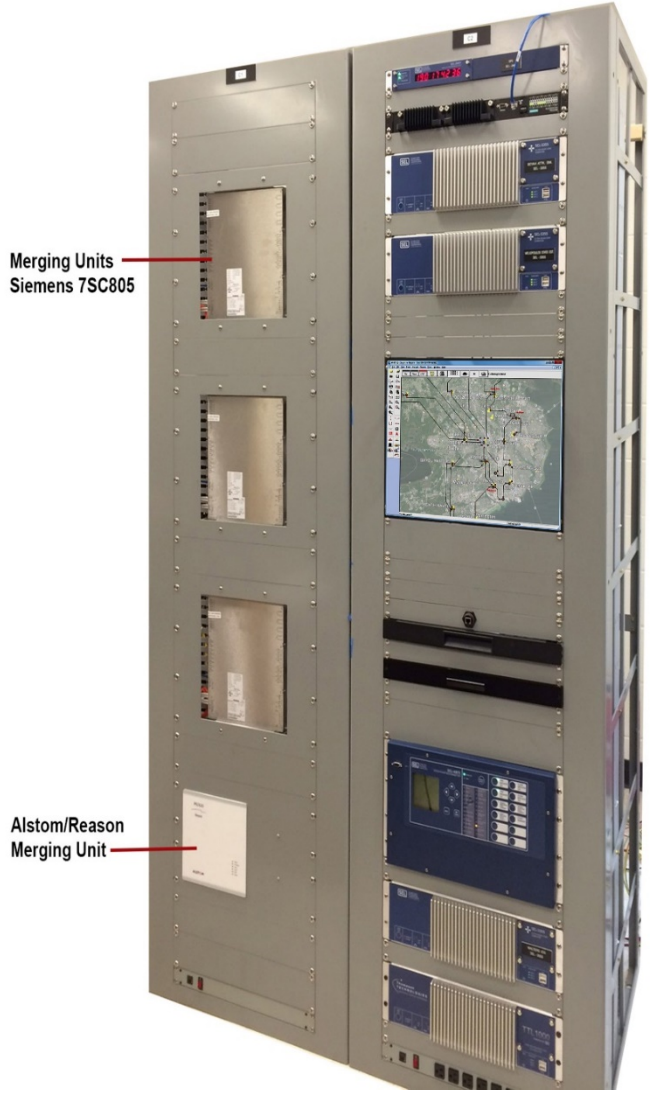
Capabilities of the Integrated Physical-Cyber Co-Model:

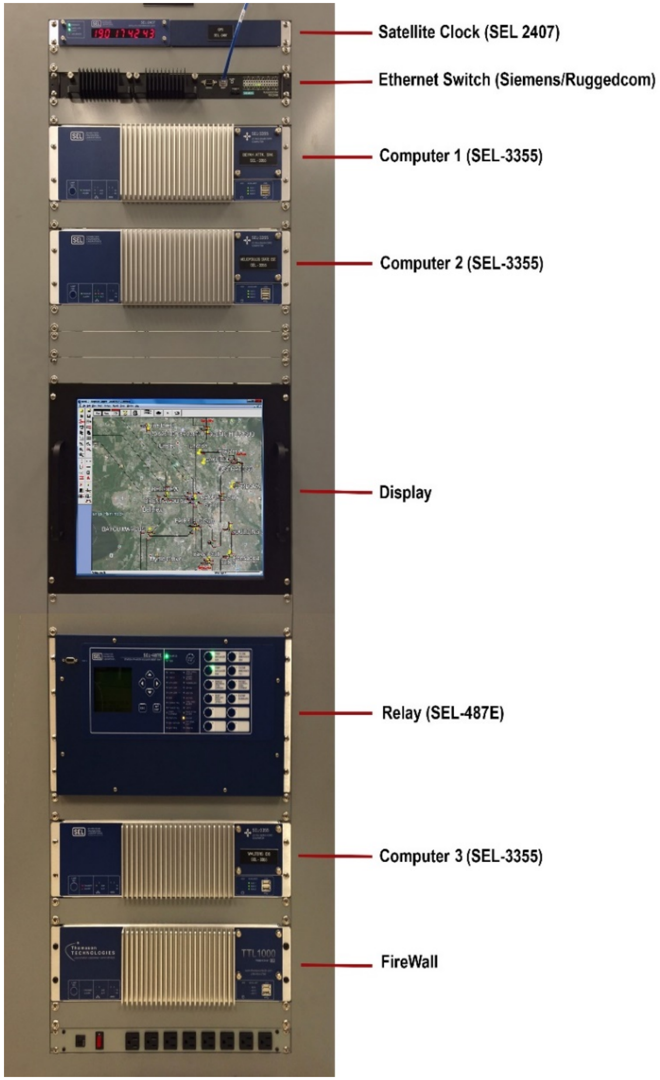
a) Data validation
b) Anomalies detection and root cause identification
c) Missing data creation
d) Data further utilization

Dynamic State Estimation method:

a) Unconstrained Least Square Method
b) Constrained Least Square Method
c) Extended Kalman Filtering Method

Synergistic Activities
Implementation of DSE on Three SoCo Substations





Distributed Dynamic State Estimator Functionality

Hybrid System: PMUs and MUs

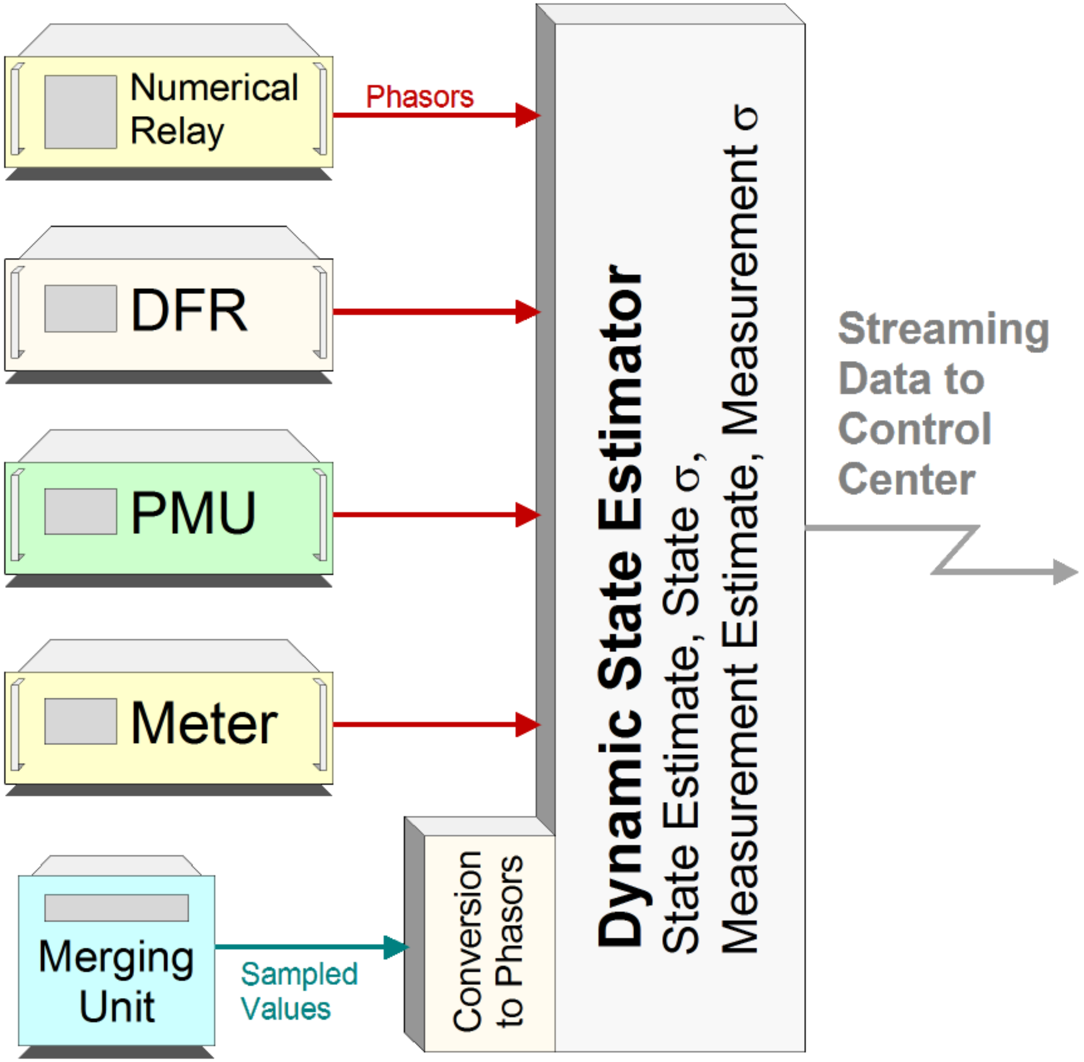
Converts All Available Data in the Substation into

Time-Tagged

VALIDATED PHASORS

With Expected

ERROR



Demonstration

- Implement System on a NYPA Substation (Marcy) – Implementation will be Hybrid (PMUs and Mus) but Partial (not all existing devices will be reporting to the Dynamic State Estimator).

- Stream Data to NYISO and visualize substation operation as well as data accuracy.

University of Illinois-Urbana Champaign

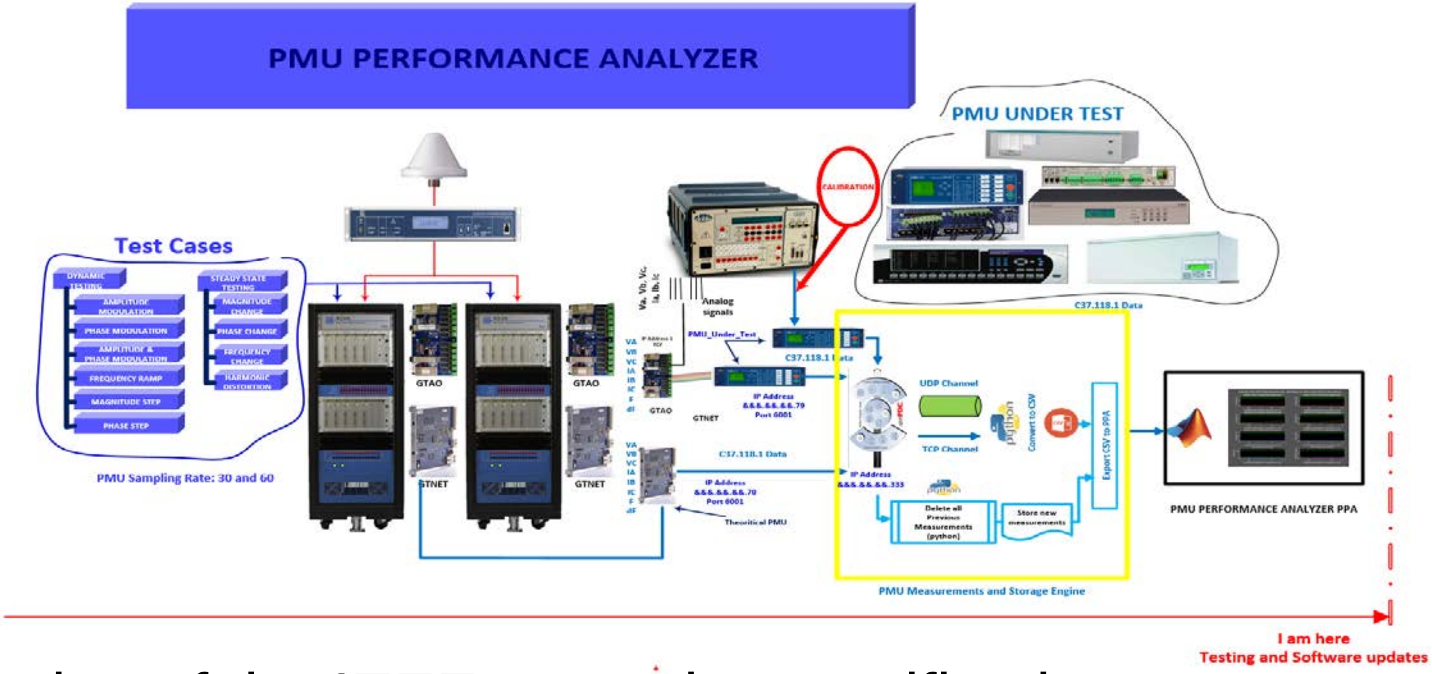
Deliverables

Tom Overbye

Task 1	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Testing and certification lab	Lab equipment with certified testing protocol	Testing protocol and lab equipment specification	Demonstration of automated testing using certified protocol	Tom Overbye

Task 5	Deliverable	1st year go/no go	2nd year go/no go	Responsibility
Visualization for risk assessment	Software for risk assessment using test results	Software specification	Demonstration using simulator set-up	Tom Overbye

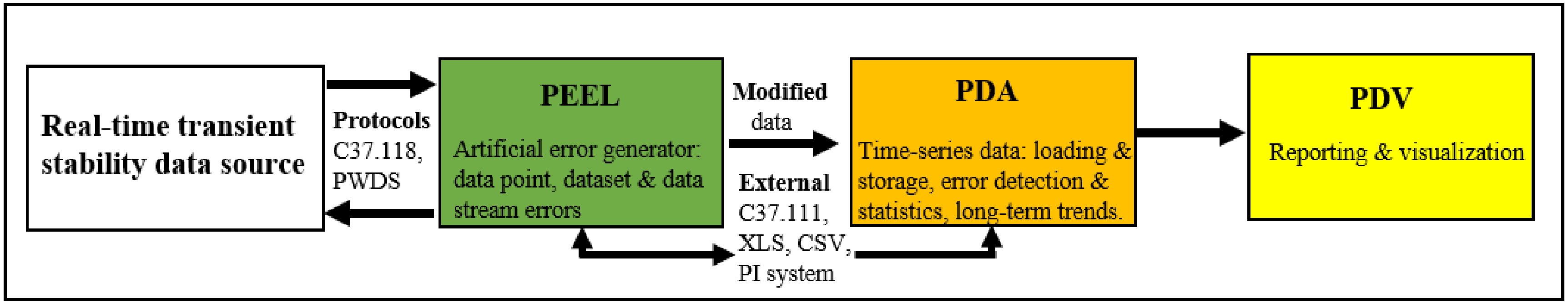
PMU Testing Lab Testbed



- Automation of the IEEE test suite specifications
- Procedures
  - PMU measurements are collected with the OpenPDC. Three python program have been developed to accommodate measurements
  - Measurements are exported to the PPA program
- Hardware: RTDS, Power Amplifier, PMU;
- Software: PPA, OpenPDC, Wrote three python programs

Modules

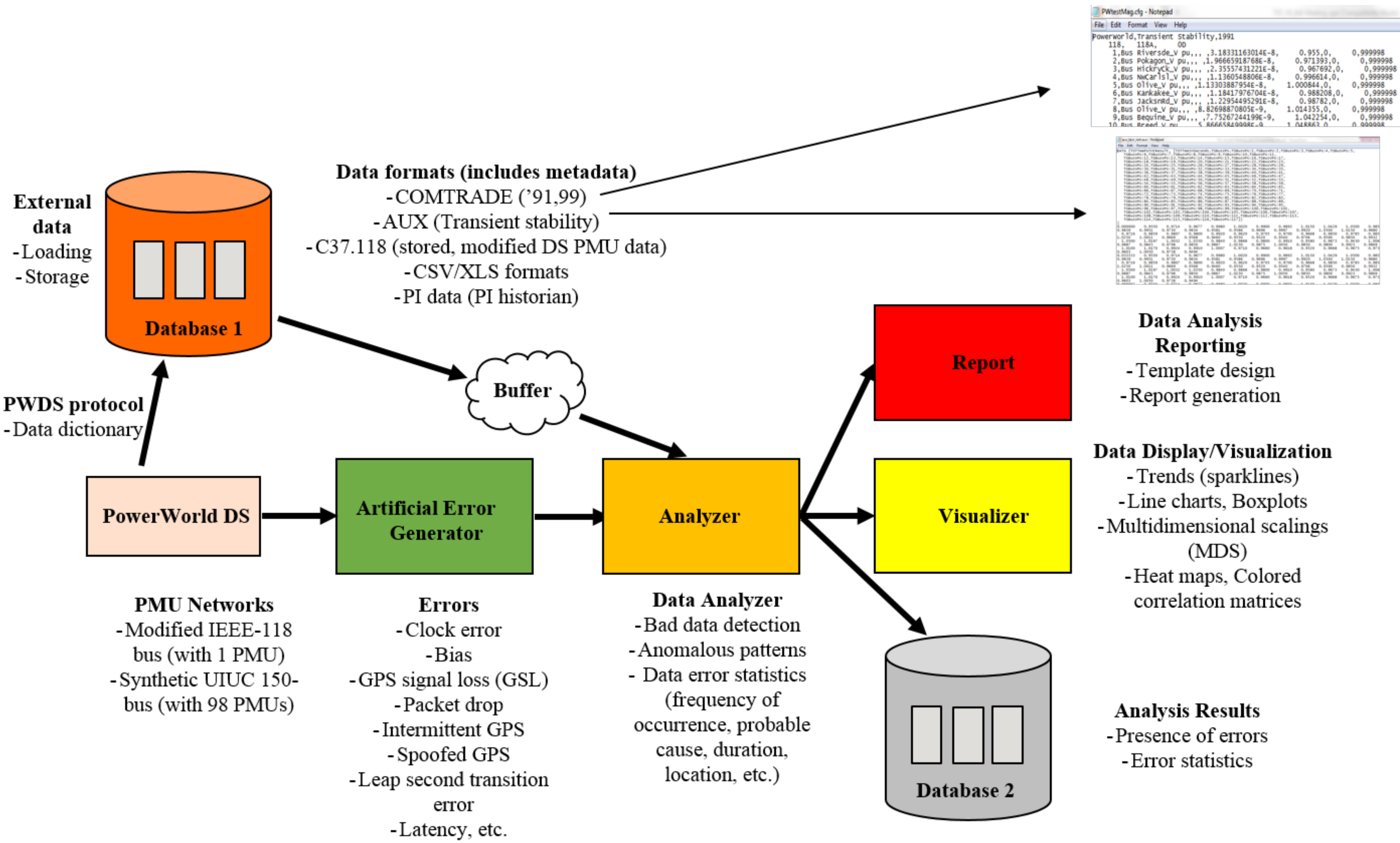
PEEL: PMU Error Emulation Environment; **PDA**: PMU Data Error Analysis; **PDV**: PMU Data Visualization



- Application: A PMU data error analysis package
- Core modules
  - Data source provider: Includes IEEE C37.118, C37.111 (Comtrade), transient stability auxiliary files, PI historian
  - Artificial data error generator: Prototype errors associated with GPS/PMU clock, cybersecurity, network limitations, etc.
  - Data analyzer: Executes algorithms for error detection; and generates statistics on error and anomalous data patterns
  - Visualizer: Reports and displays error statistics

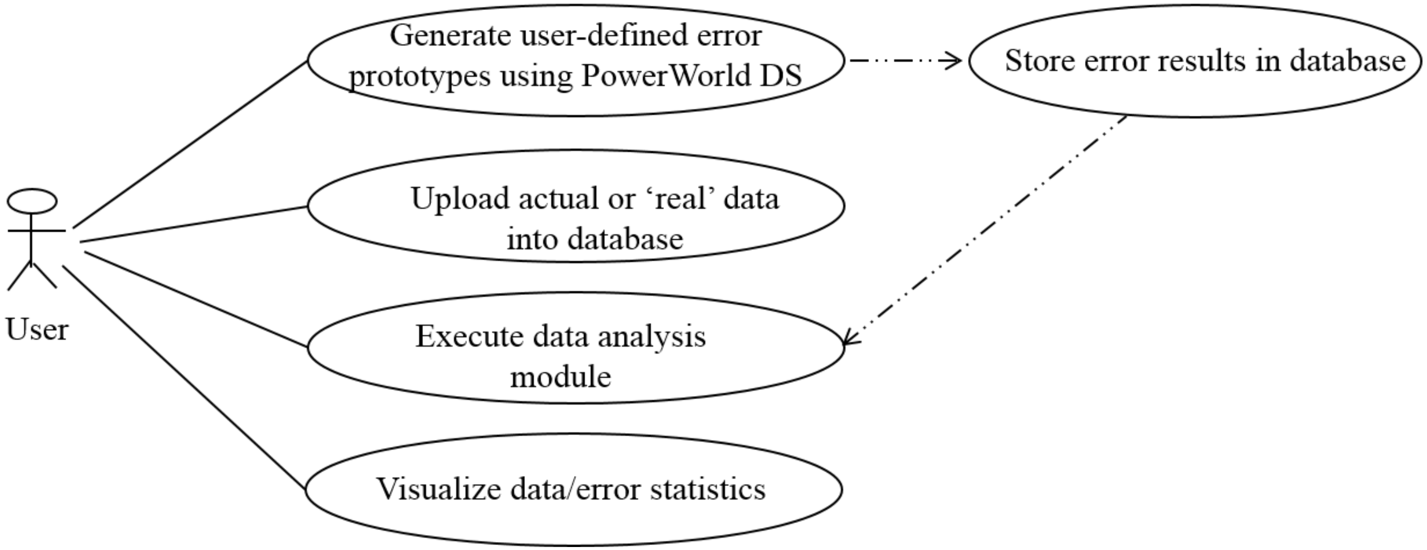
Modules

- Software being used
  - Application Development: Delphi on RAD Studio
  - Database Management System: MySQL Workbench



Module Demo - Use Cases

- Use case will involve data obtained from:
  - Synthetic networks (150-bus & IEEE 118-bus)
  - Actual Industry measurements (C37.118, C37.111, PI data)



  - Transient stability run will be done on the steady-state networks using PowerWorld DS.
    - e.g. slowly-changing loads

Testing

- Task1.1: Test scenarios will be developed and implemented in RTDS
  - RTDS will produce two streams of PMU measurements: data from theoretical (GTNET RTDS) and PMU under test.
  - Stream from test device will be amplified using a power amplifier

- Task5.0: Similar test cases will involve data obtained from use case
  - Usability testing: Ascertain user's level of ease in using the application interfaces (data loading, prototype errors, report, etc.)
  - Specification requirement testing: Verify all module functionalities
  - Validation & acceptance testing: Match application-generated statistics with actual errors; Obtain stakeholder's approval

- Possible sources of industry data: Entergy, MISO

PSerc Companies & Advisor

- Companies
  - Entergy
  - MISO

- Working Partner/Advisor
  - Param (WSU) – Task 1.1
  - Mr. Galvan Floyd (Entergy) – Task 5.0

Conclusions

- Project results should meet project objectives by offering the tools NOT readily available today
- The evaluation of the tools will be performed in realistic production-like environments
- The go/no go criteria will serve as a safeguard that project is progressing as planned
- The team is working with interested industry participants that wish to host tools demonstration
- The tools are quite diverse developed for different purposes, so they may be used selectively

Contacts for further Information

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