PNNL-SA-106051

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Synchrophasor Technology and Systems

Jeff Dagle, PE
Chief Electrical Engineer and Team Lead
Electricity Infrastructure Resilience
Pacific Northwest National Laboratory
Richland, Washington
+1 (509) 375-3629
jeff@pnnl.gov

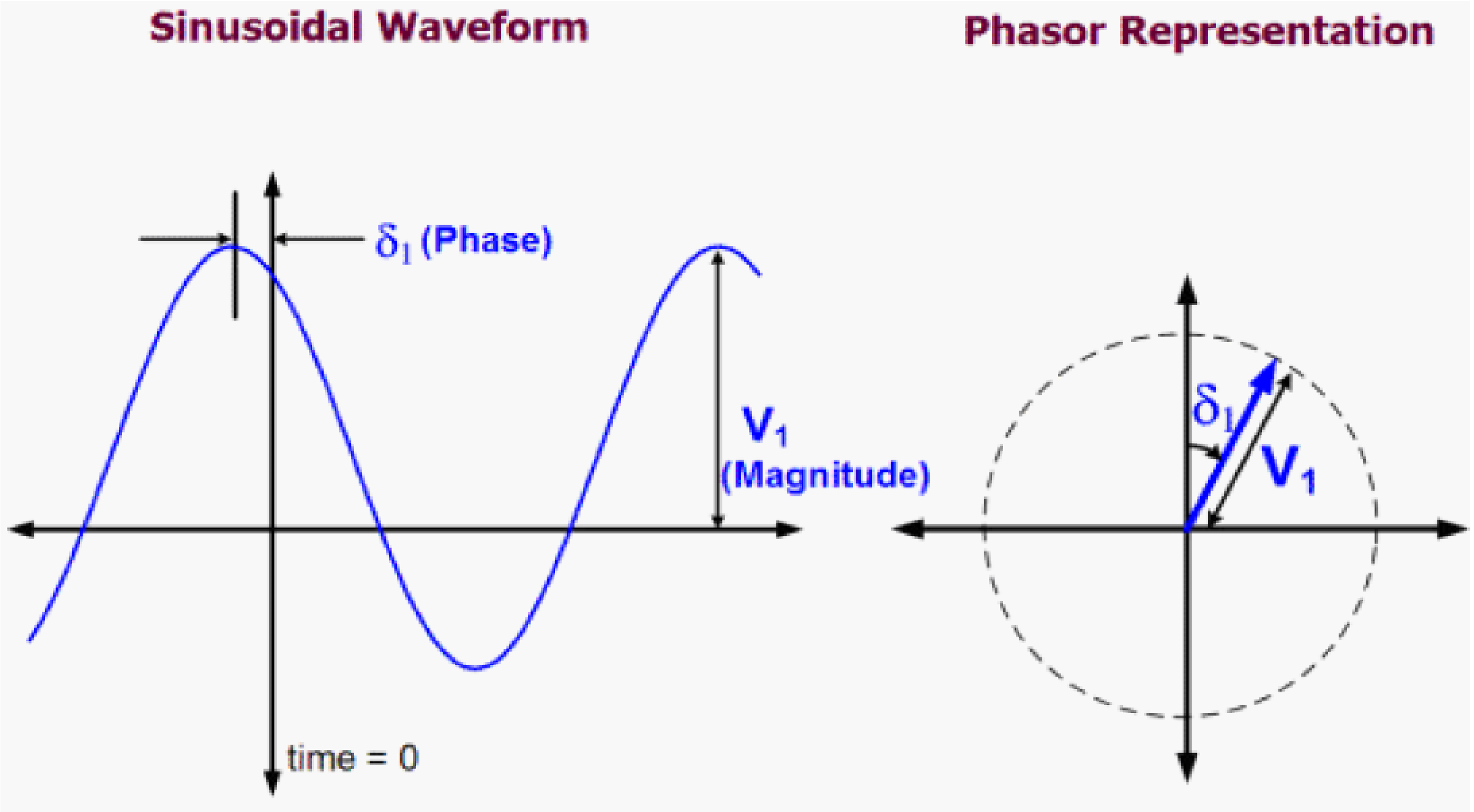
CIGRE-NASPI SYNCHROPHASOR TECHNOLOGY TUTORIAL
Houston, Texas
October 19, 2014

Outline

- Synchrophasor technology and systems (this presentation)
  - Time-synchronized measurements
  - What's a PMU?
  - Data collected by PMUs; PMU v. SCADA
  - PMU data networks -- network, PDC, analytics, gateway
  - PMU deployments across North America
  - Technical standards and protocols
  - Data quality and availability
  - Security and NERC CIP
- Synchrophasor uses and applications (Dmitry Kosterev)
- Synchrophasor technology benefits and business case (Matt Gardner)
- The future of synchrophasor technology (Alison Silverstein)
- Q&A

What is a "Phasor"?

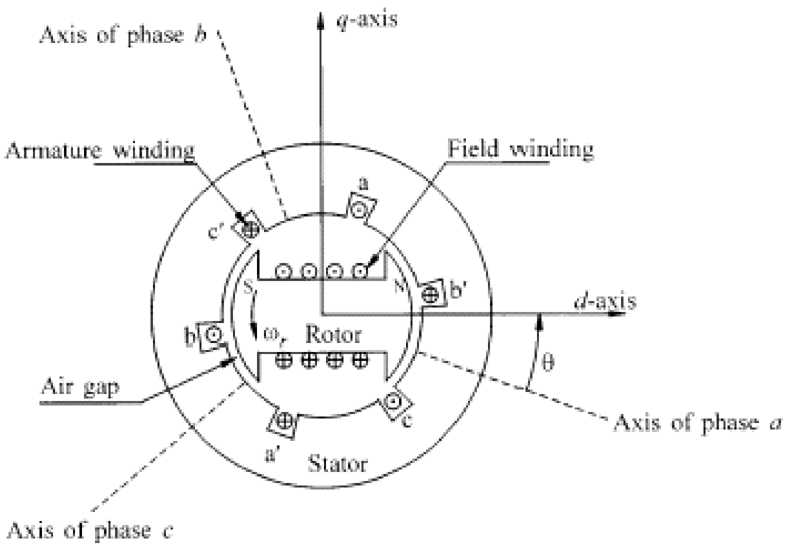
- Like a vector, a phasor represents both magnitude and relative phase angle

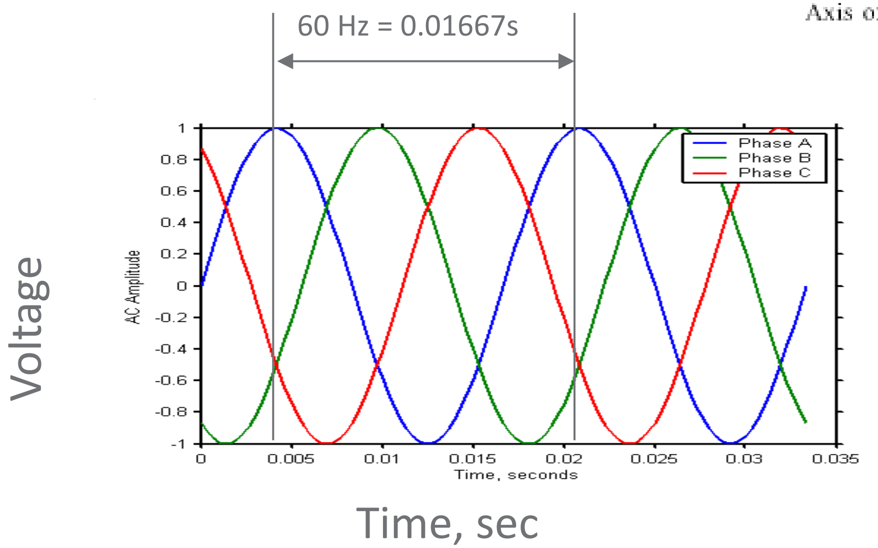


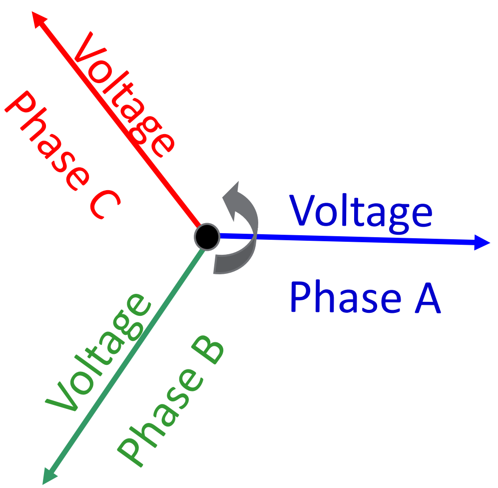
Source: CERTS, Phasor Technology Overview

Conceptual Overview

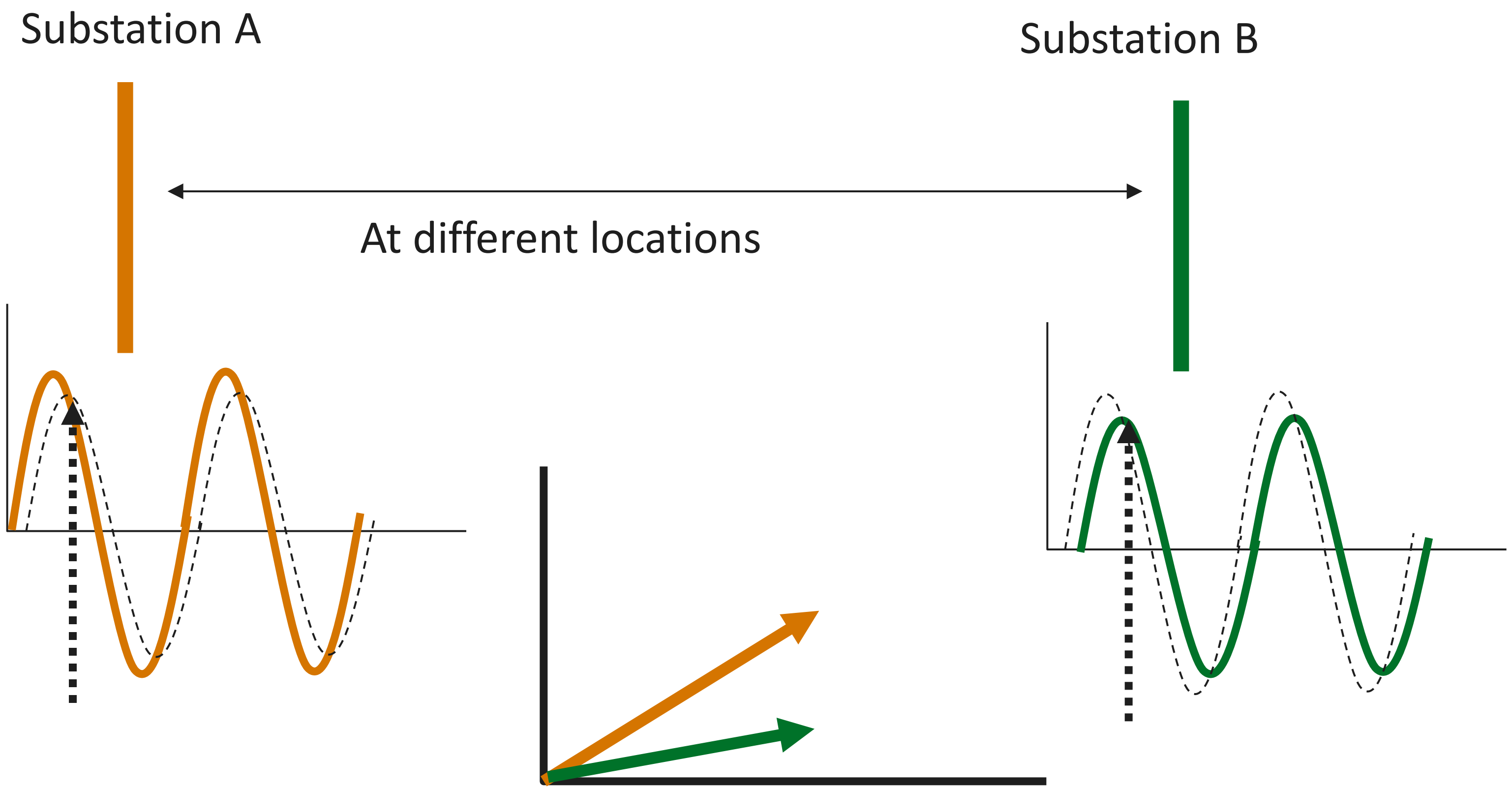
- Mathematical concept of physical quantities
- Phasors rotate counterclockwise, each corresponding to a sinusoidal parameter
- The rotating frame of reference can be modified (e.g., relative phase angle)







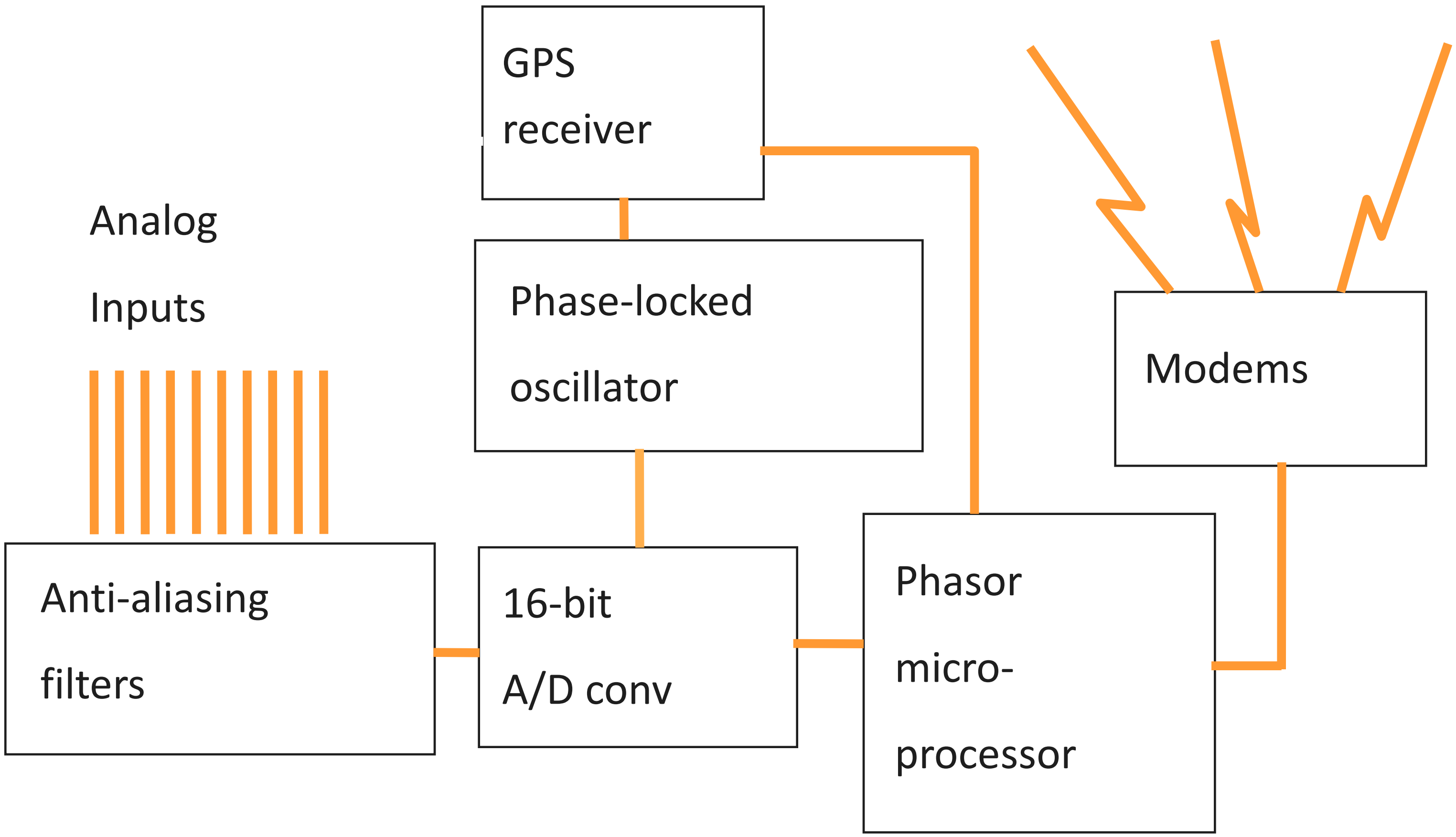
Time Synchronized Measurements



By synchronizing the sampling processes for different signals - which may be hundreds of miles apart, it is possible to put their phasors on the same phasor diagram.

Credit: A.G. Phadke

Phasor Measurement Unit



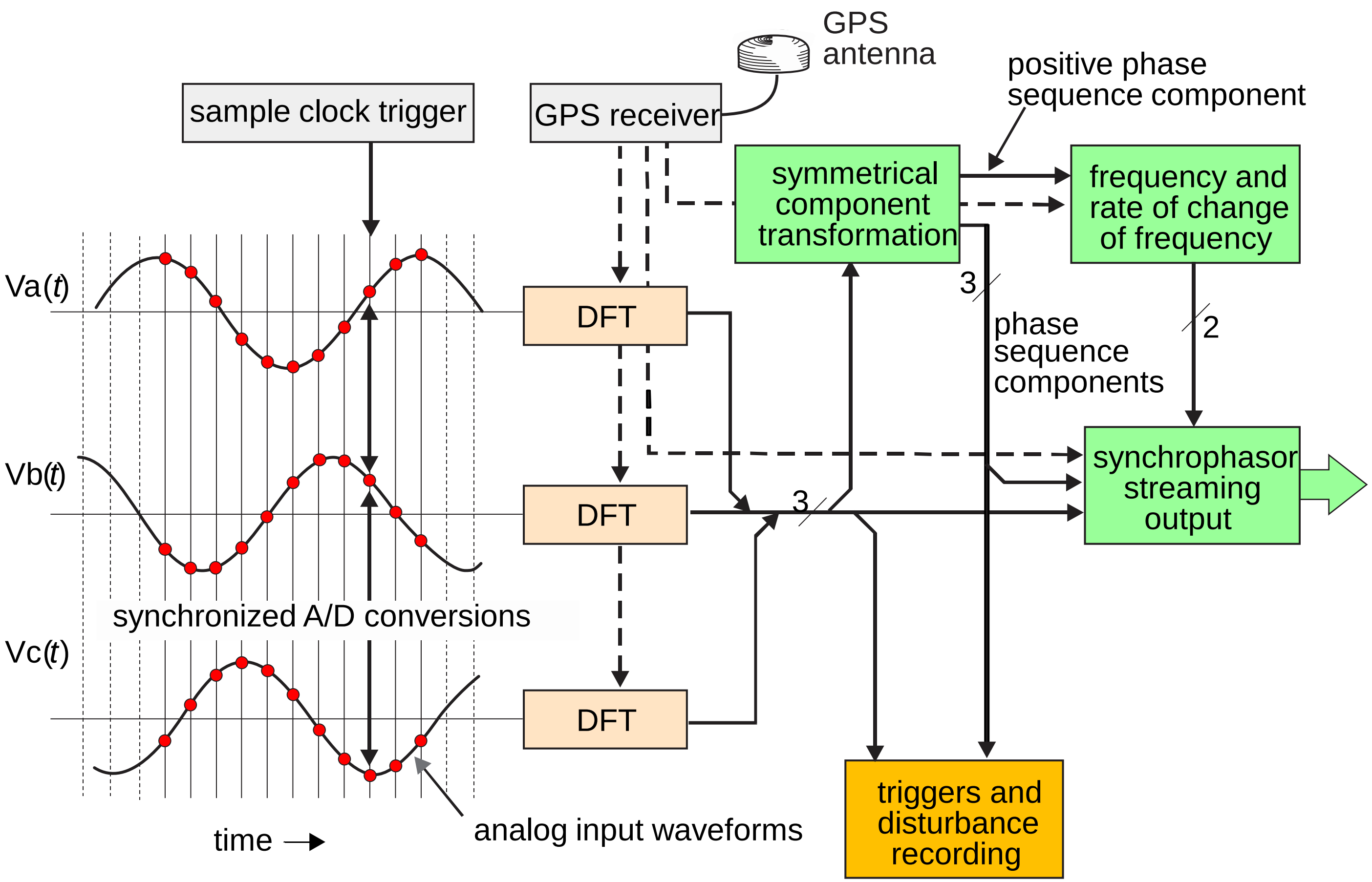
Except for synchronization, the hardware is the same as that of a digital fault recorder or a digital relay.

Credit: A.G. Phadke

Phasor Measurement Unit

Pacific Northwest NATIONAL LABORATORY

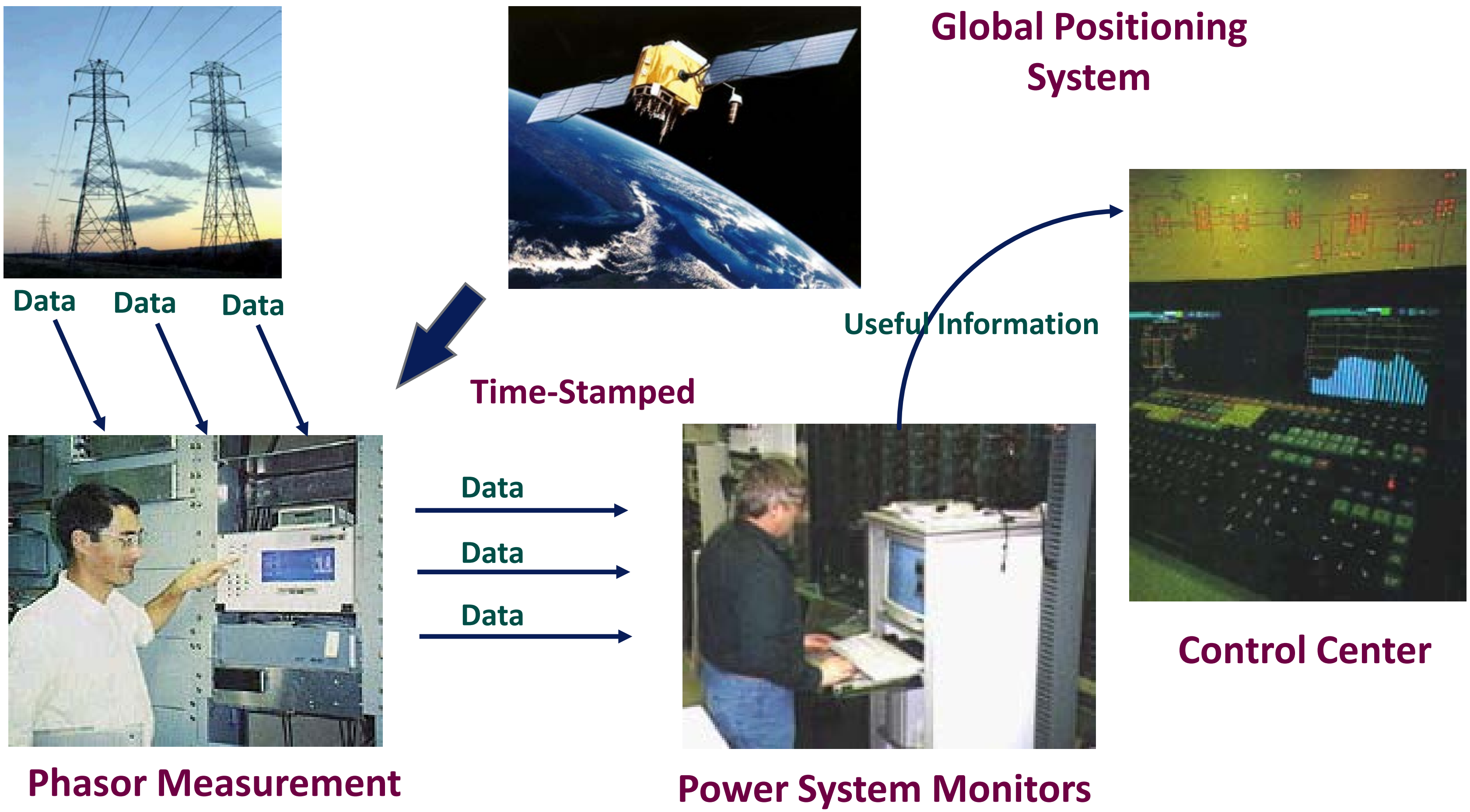
Proudly Operated by Battelle Since 1965



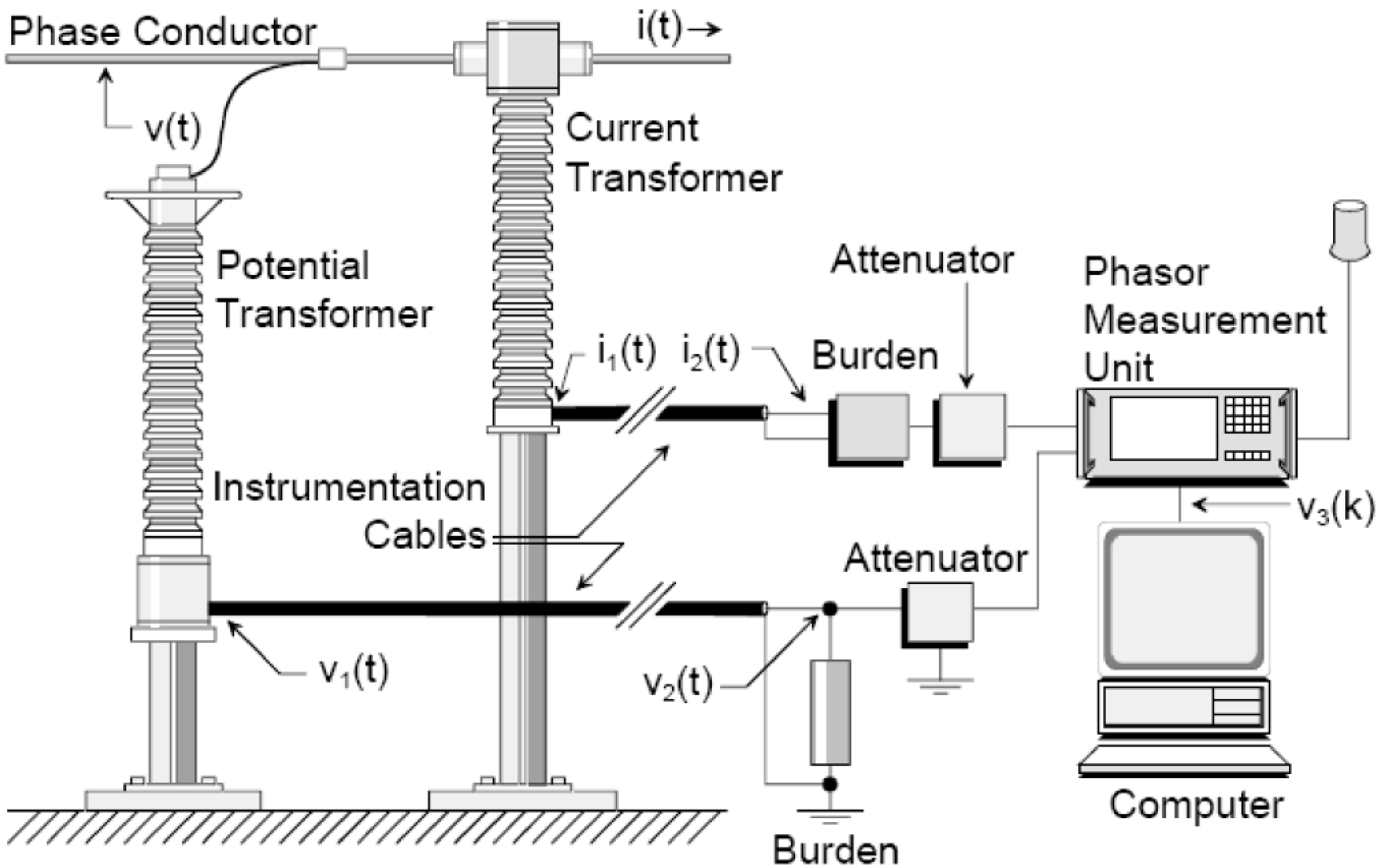
Credit: A.G. Phadke

Wide Area Measurement System Overview

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*



Substation PMU Installation



Wide Area Measurement System (WAMS)

Data acquisition devices (continuously recording and time synchronized)

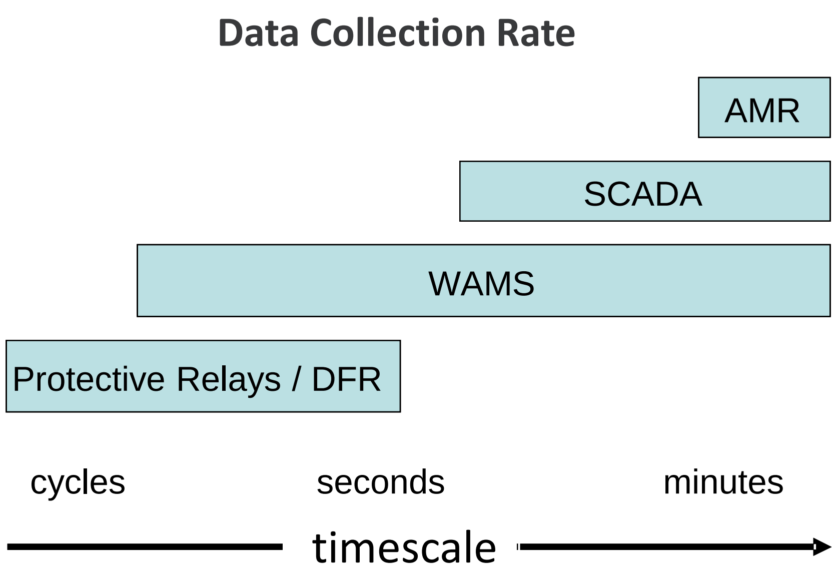
- Phasor Measurement Units (PMU)
  - Inputs from potential transformers (PT) and current transformers (CT)
- Analog signal recorders (with transducer inputs)
- Point-on-wave (POW) recorders (with PT, CT inputs)
- Controller monitors (generators, HVDC, FACTS)
  - Inputs from the controller interface or the controlled device
- Advanced relays and other Intelligent Electronic Devices (IED)
- Digital fault recorders and other sequence of events recorders

- What we are covering today is **NOT** supervisory control and data acquisition (SCADA) technology
  - SCADA traditionally relies on a polling style communication architecture
  - Older SCADA protocols do not include time with the data, the time is applied when the data is logged into the energy management system
    - This can sometimes result in significant delay between when the event occurs and when it is time stamped

Technology to Meet Emerging Industry Needs

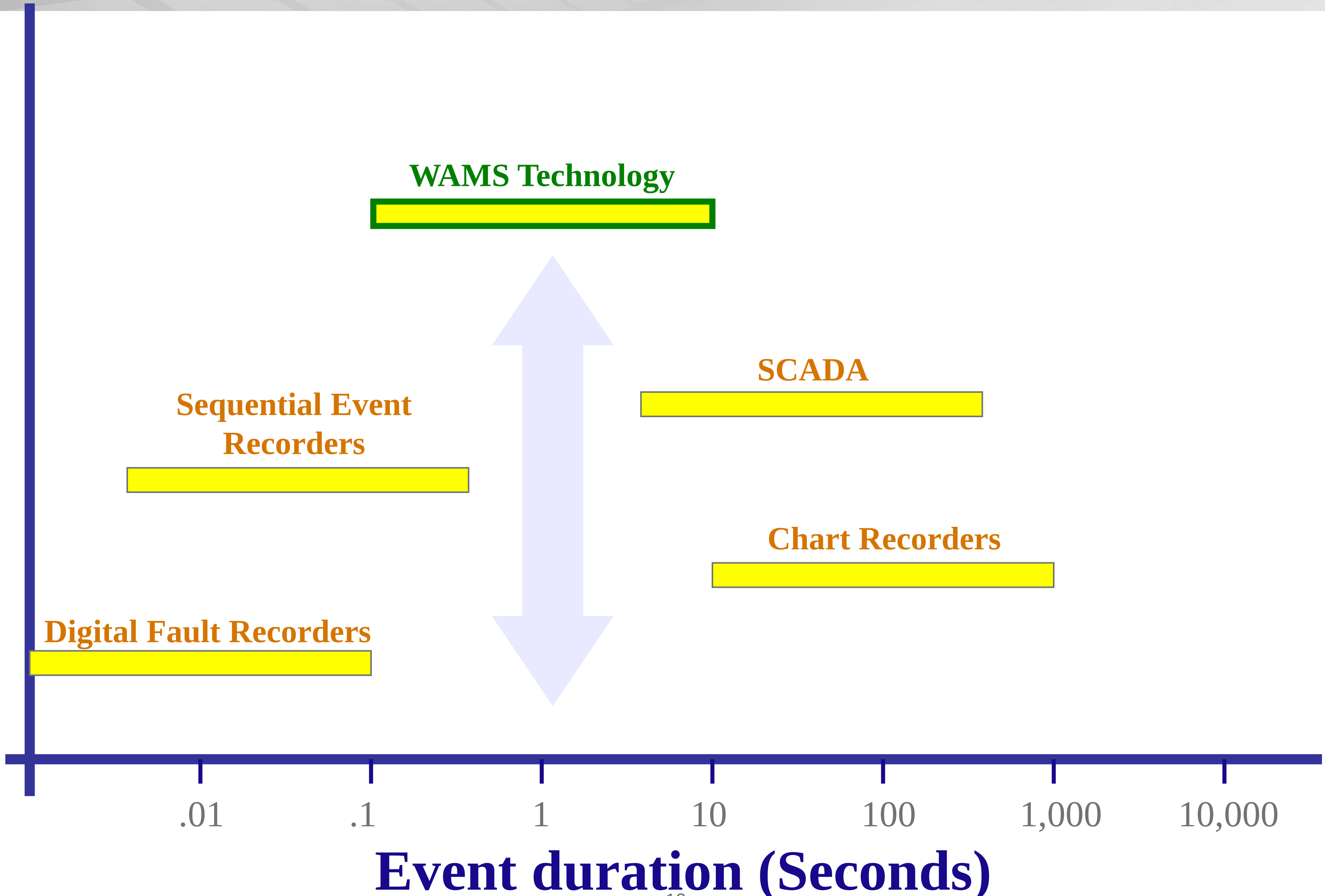
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- WAMS technology is being rapidly deployed by several utilities throughout the world and across North America
- Both on-line and off-line applications are emerging, particularly those that require faster time synchronized measurements than are available from existing technology
- The measurement infrastructure is tailored to the requirements of the installation
- Vendors are providing new solutions including measurement technology, networking, and applications



Time synchronized WAMS data is gathered at sample rates much faster than SCADA systems, and provide the missing link between localized digital fault recorders (DFR) and SCADA systems, which are much slower. However, unlike most SCADA systems, WAMS utilizes Internet protocols to exchange measurement information.

Filling a Measurement Gap

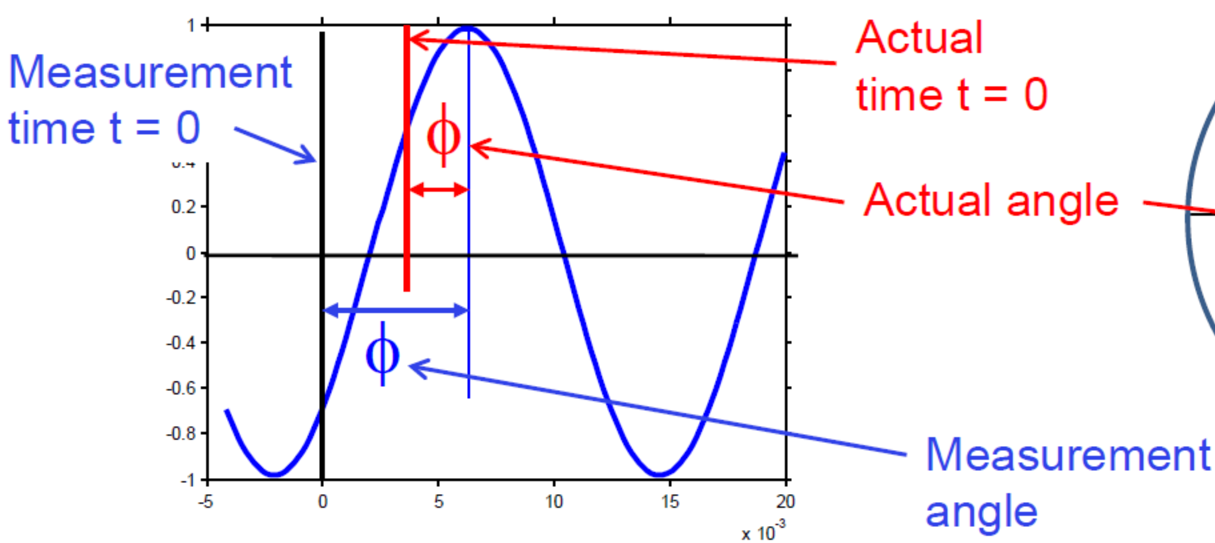


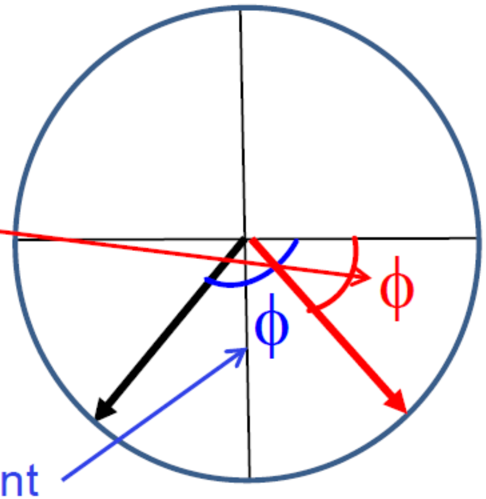
How accurate does your time need to be?

- The phase angle is determined by the time reference
- If t = 0 is displaced by *x* seconds, the phase angle will be rotated by $x/46\text{x}10^{-06}$ degrees (1° ~ 46 µs at f_0 = 60 Hz)
- Note the error ONLY effects phase angle – magnitude ok

$$v(t) = \sqrt{2}\, A \cos(2\pi\omega_0 t + \phi)$$

$$V = A e^{j\phi}$$

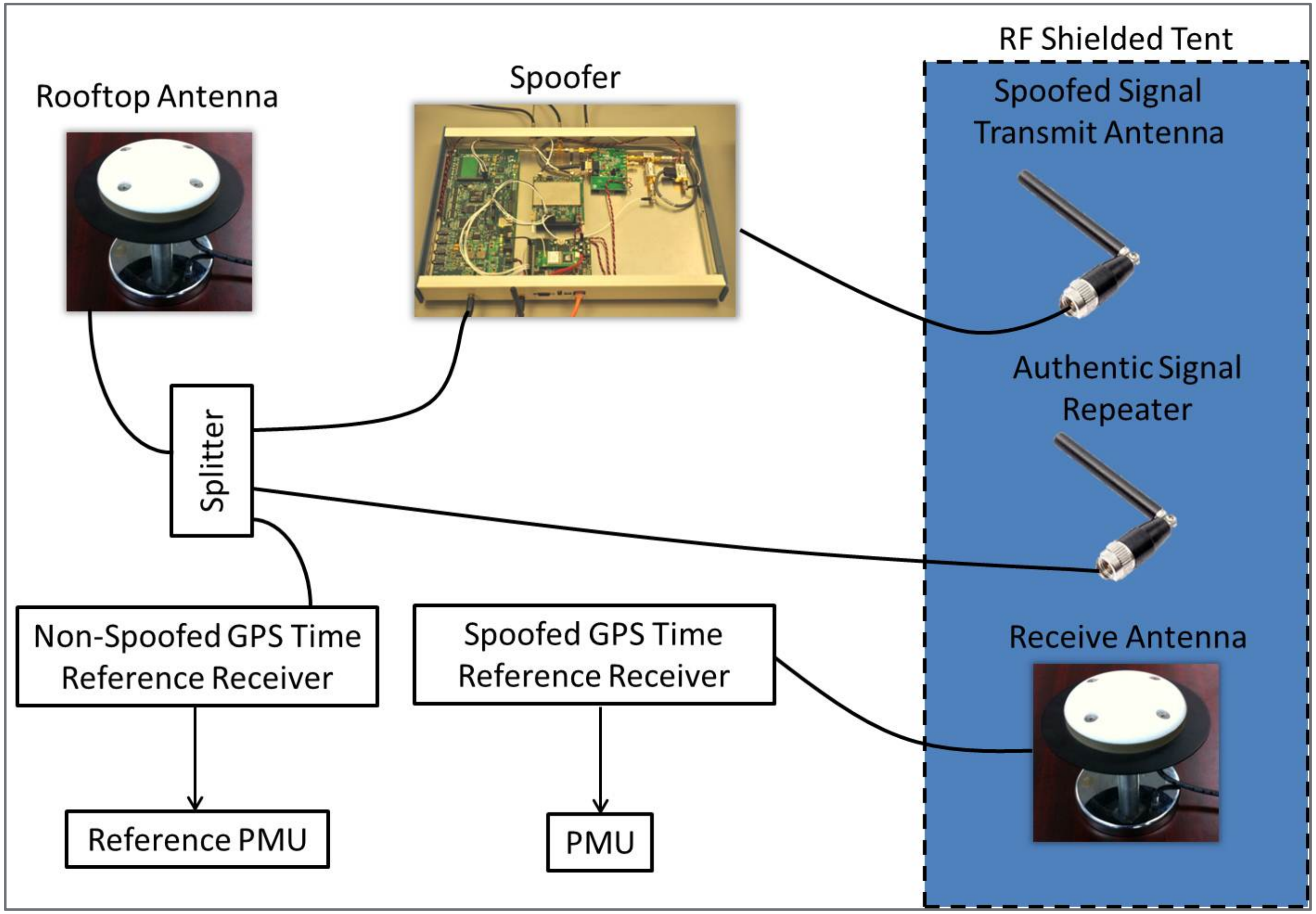




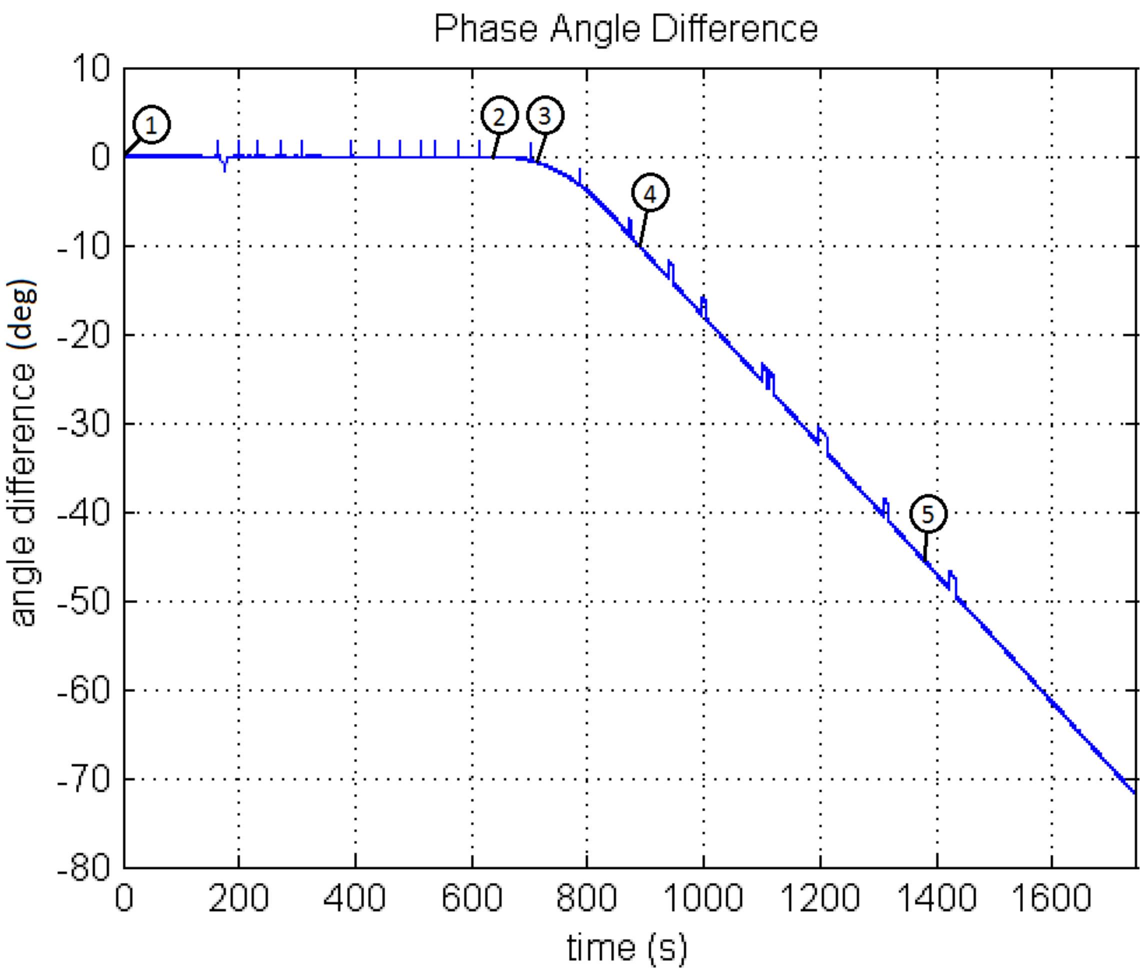
Credit: K. Martin

Testing the Susceptibility of Satellite Clocks to Spoofing (Deliberate Error)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



Satellite Clock Spoofing Test Results



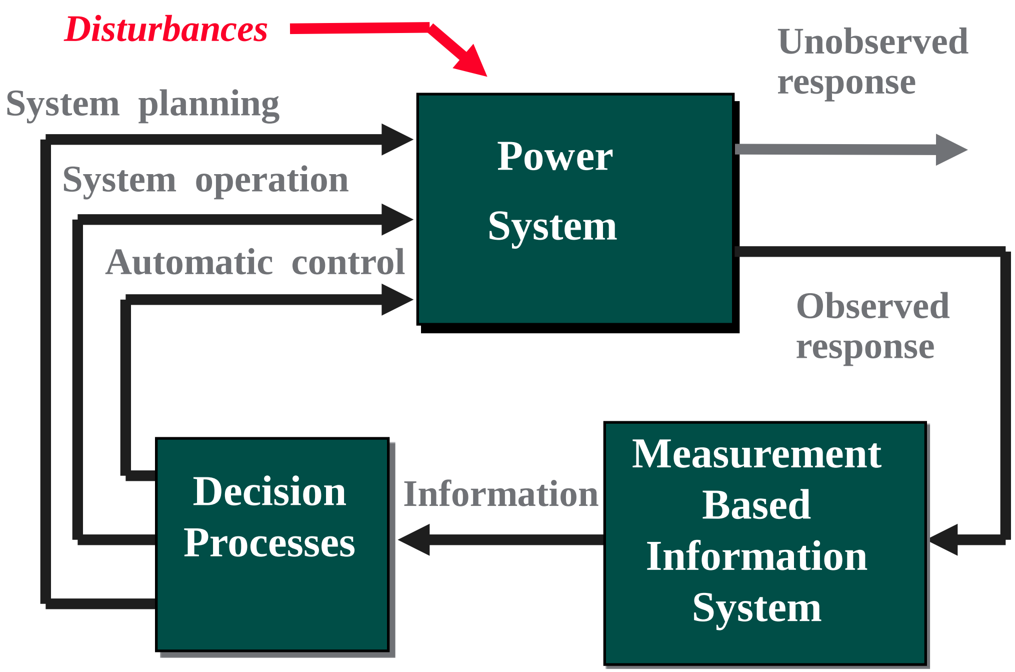
Satellite Clock Spoofing Conclusions

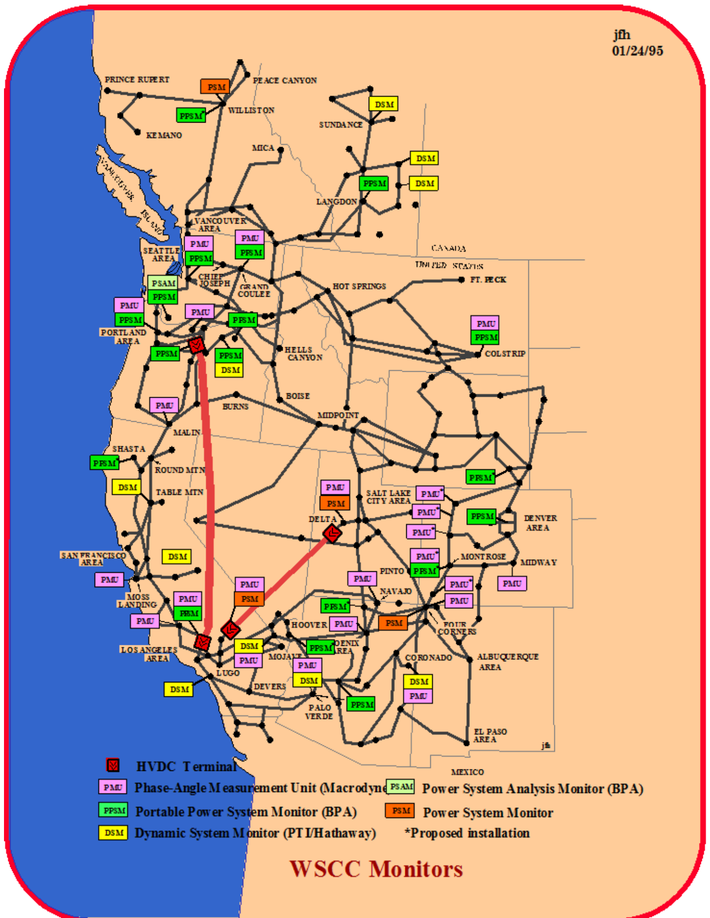
- All three satellite clocks that we tested were susceptible to time errors being introduced
  - Some differences in the rate of change that could be implemented (defeating the internal error checking algorithms)
  - Some differences in how the clocks responded when the spoofing signal was turned off
- Need to find alternative methods for ensuring critical applications cannot be undermined
  - Currently investigating various alternatives including the IEEE 1588 Precision Time Protocol Standard

WAMS Deployment in the Western Interconnection

Dynamic monitor network that supports advanced situational awareness and analysis

"Better information supports better - and faster - decisions."

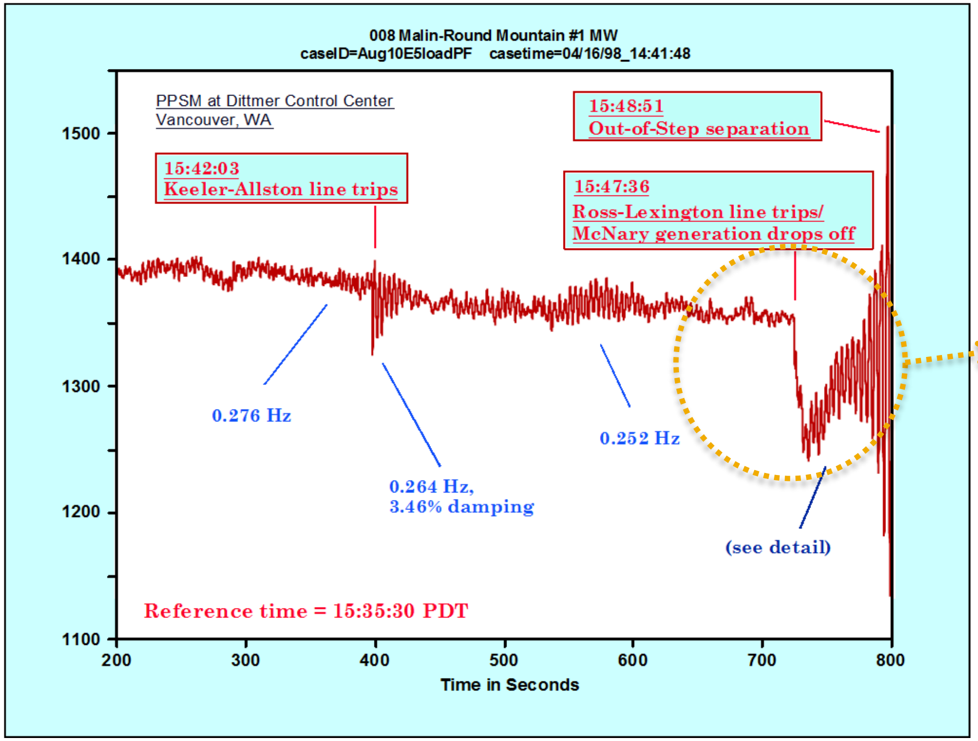




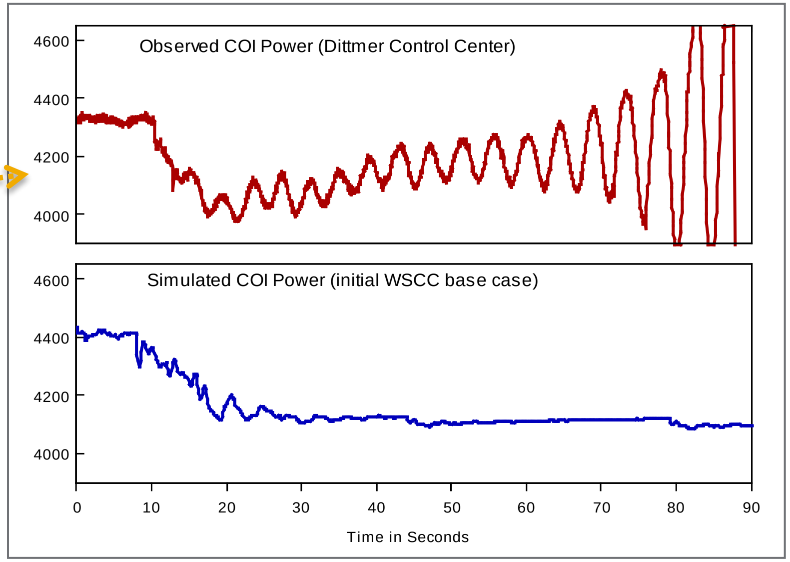
WAMS Background – Disturbance Analysis

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

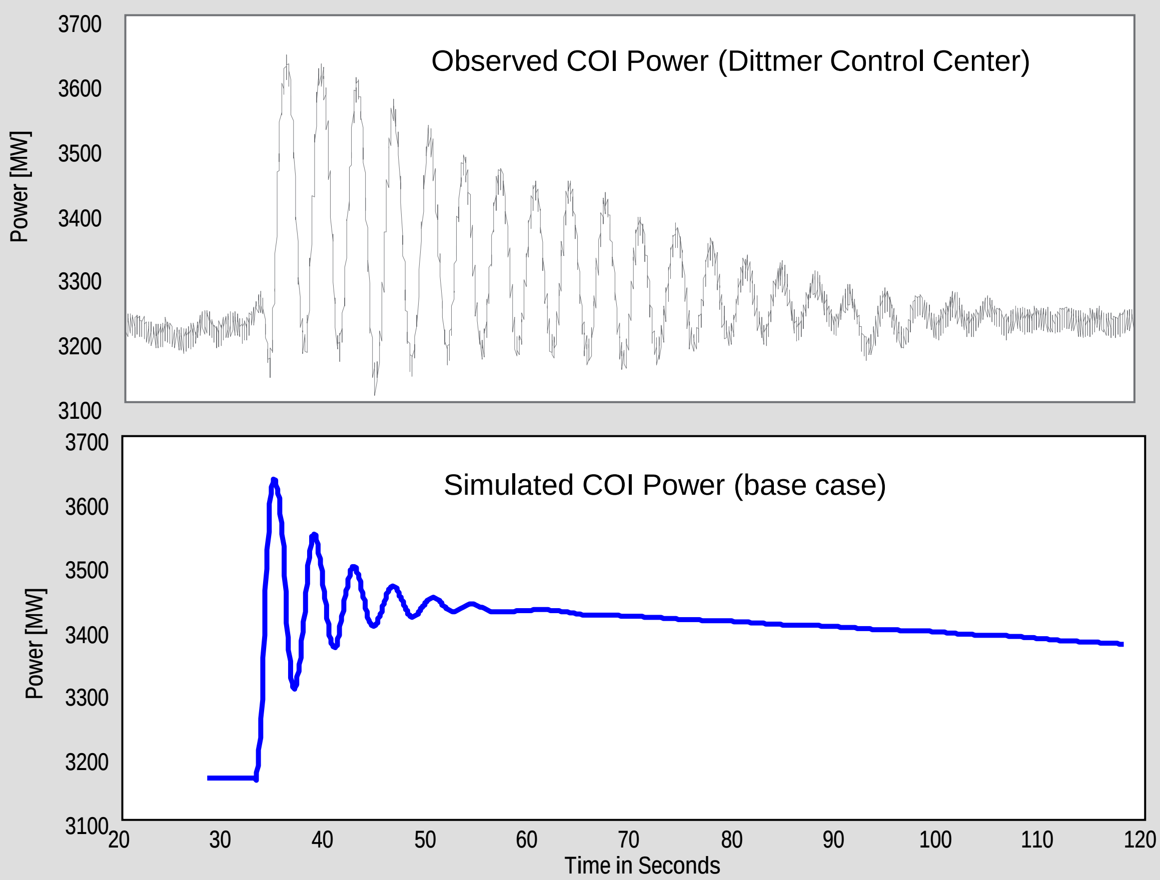
August 10, 1996 Post-Disturbance Analysis



Better Models Were Needed!



System Disturbance August 4, 2000

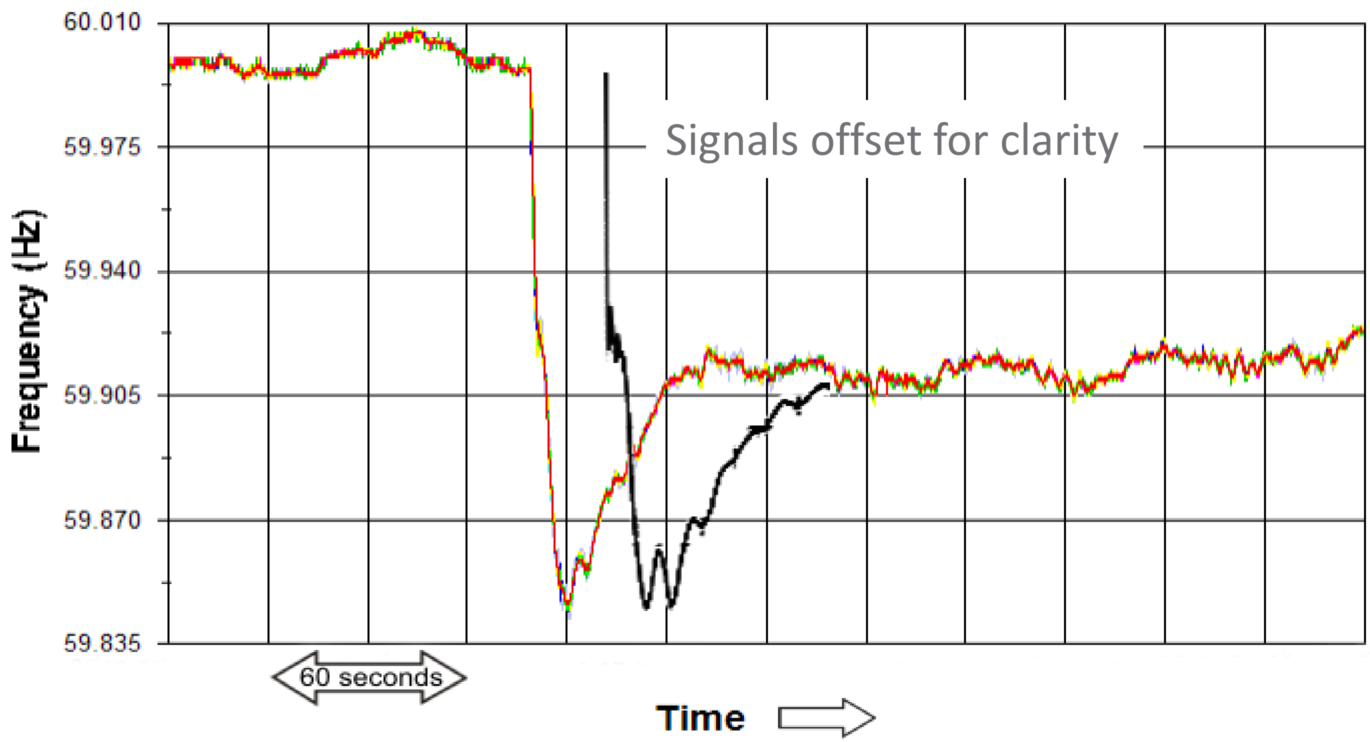


Graphics by D. N. Kosterev, Bonneville Power Administration

A More Recent Example --- The Models Have Been Improved Significantly!

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

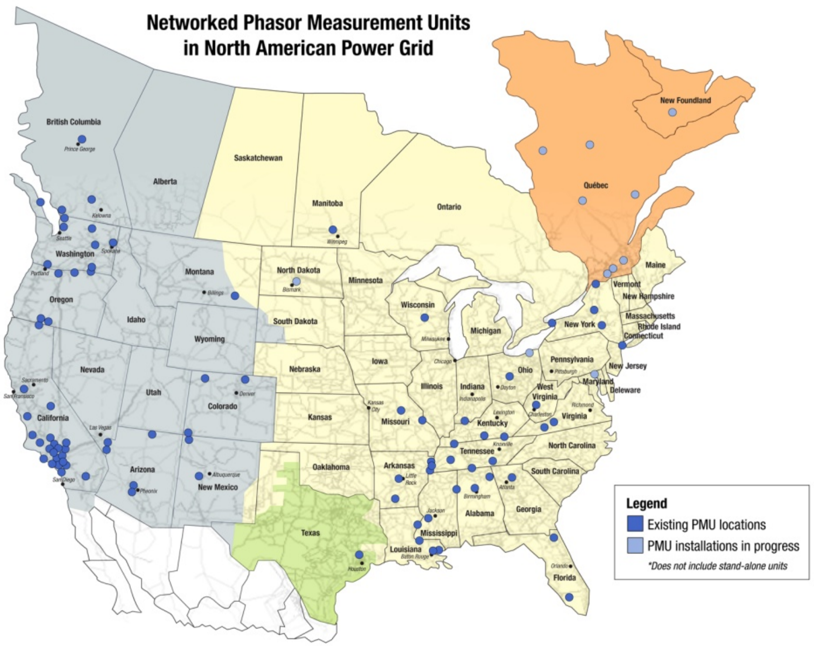
Loss of major generator in WECC, actual and modeled



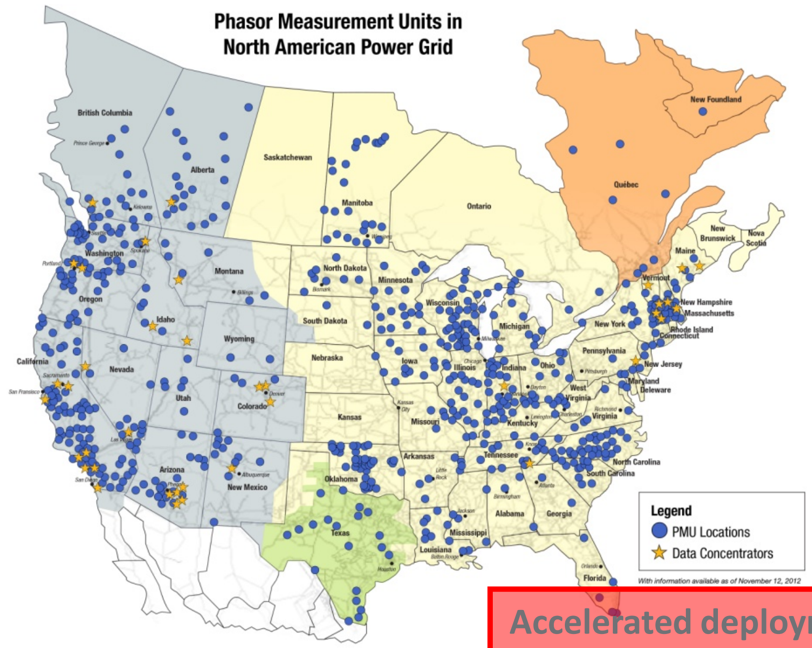
North American SynchroPhasor Initiative

The U.S. Department of Energy (DOE) and EPRI are working together closely with industry to enable wide area time-synchronized measurements that will enhance the reliability of the electric power grid through improved situational awareness and other applications

April 2007



November 2012



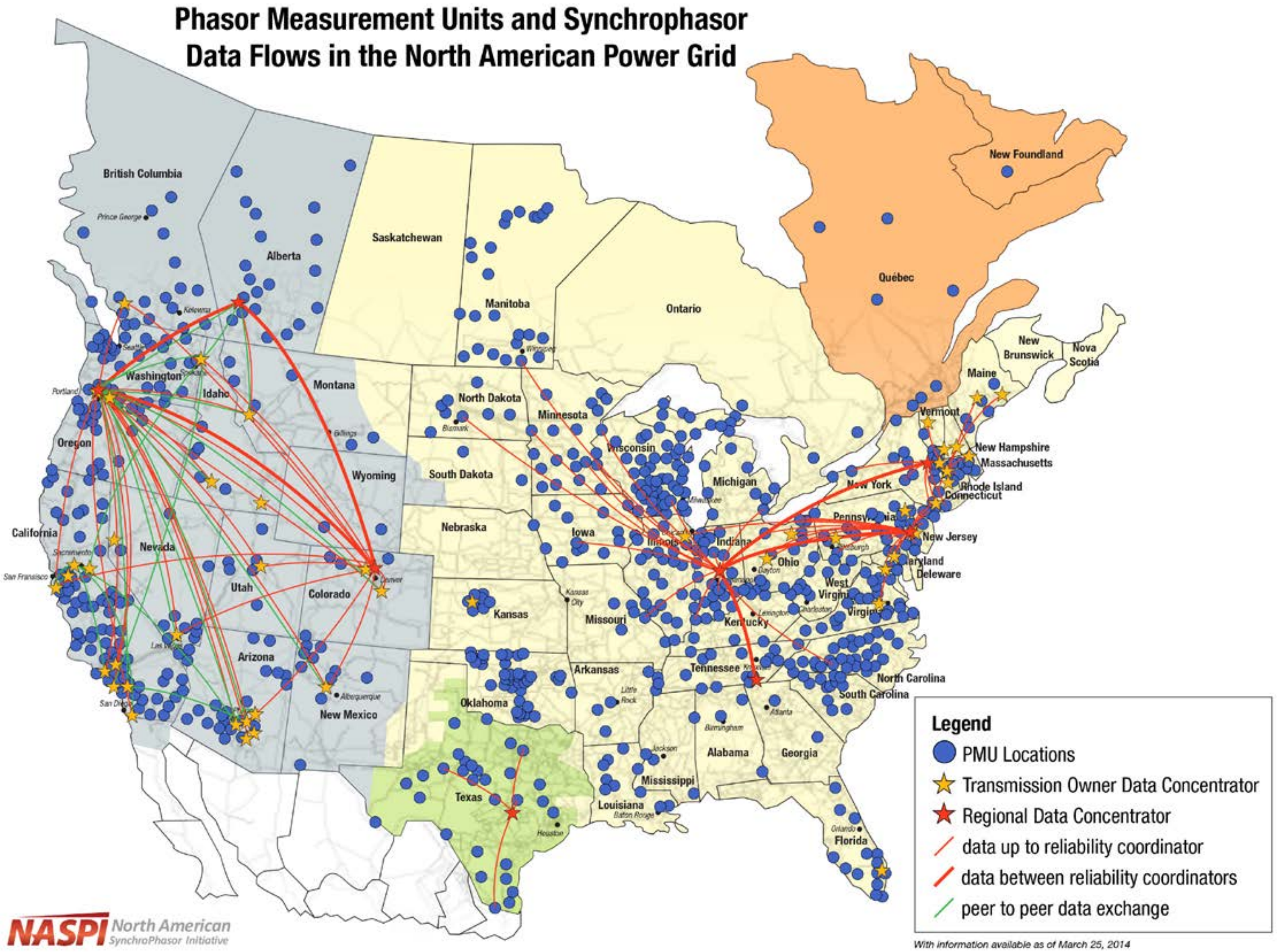
Accelerated deployment facilitated by ARRA funding

"Better information supports better - and faster - decisions."

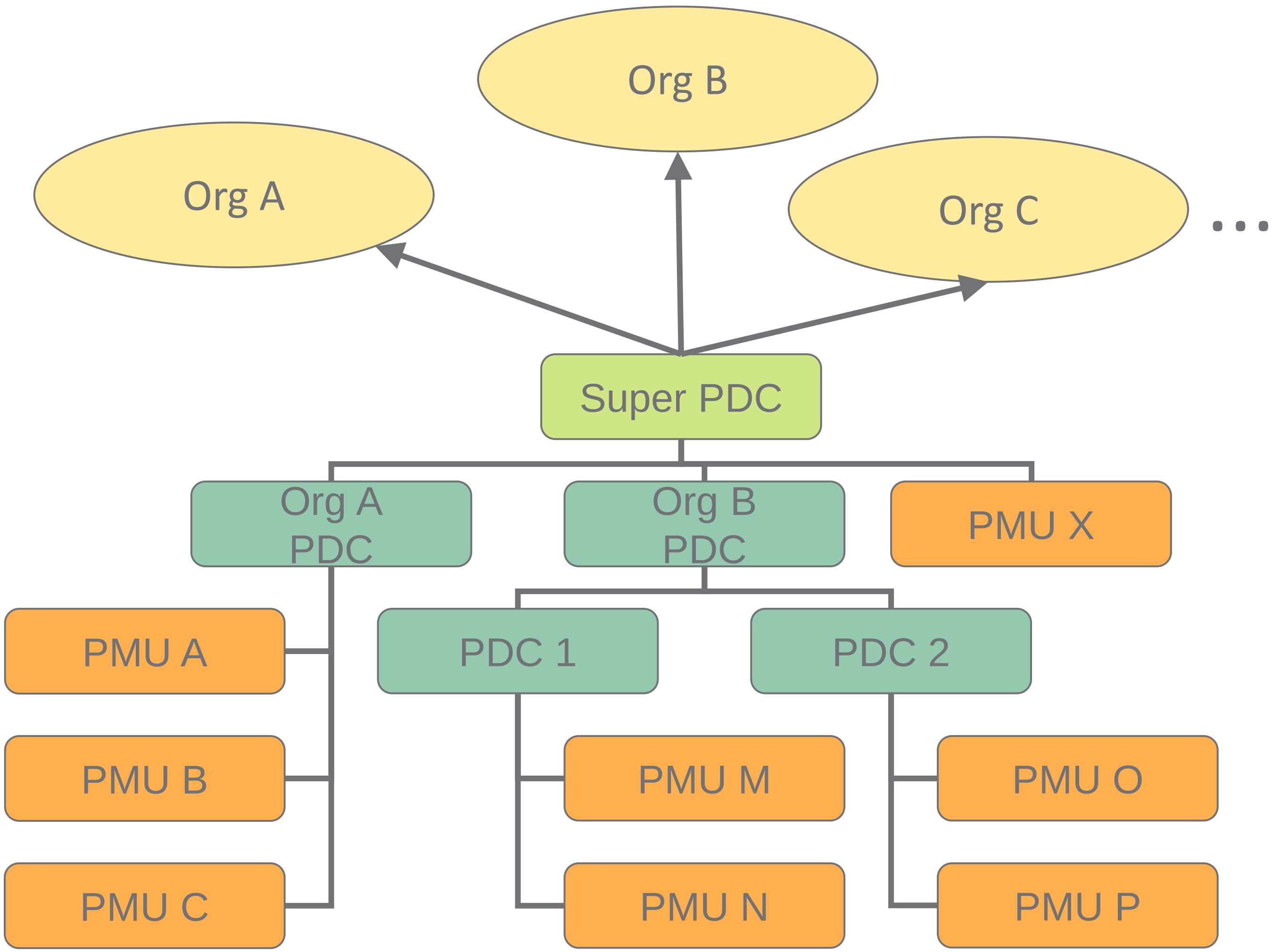
NASPI North American SynchroPhasor Initiative

ELECTRIC POWER RESEARCH INSTITUTE

Networking and Data Sharing are Key Elements of the Technology



Logical Measurement Data Network



Phasor Data Concentrator (PDC)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- A PDC gathers data from a number of devices and forwards it as a single stream
- PDC as defined in IEEE C37.244:
  - A ***function*** that collects phasor data, and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications
- PDC as defined in IEEE C37.118.1/2
  - A ***device*** used in phasor measurement systems that combined data from several sources

Security requirements are a function of the "box"

- Definitions basically equivalent, but the semantic difference is debated
- IEEE PDC Guide C37.244-2013
  - Covers definitions, functions, performance, and testing

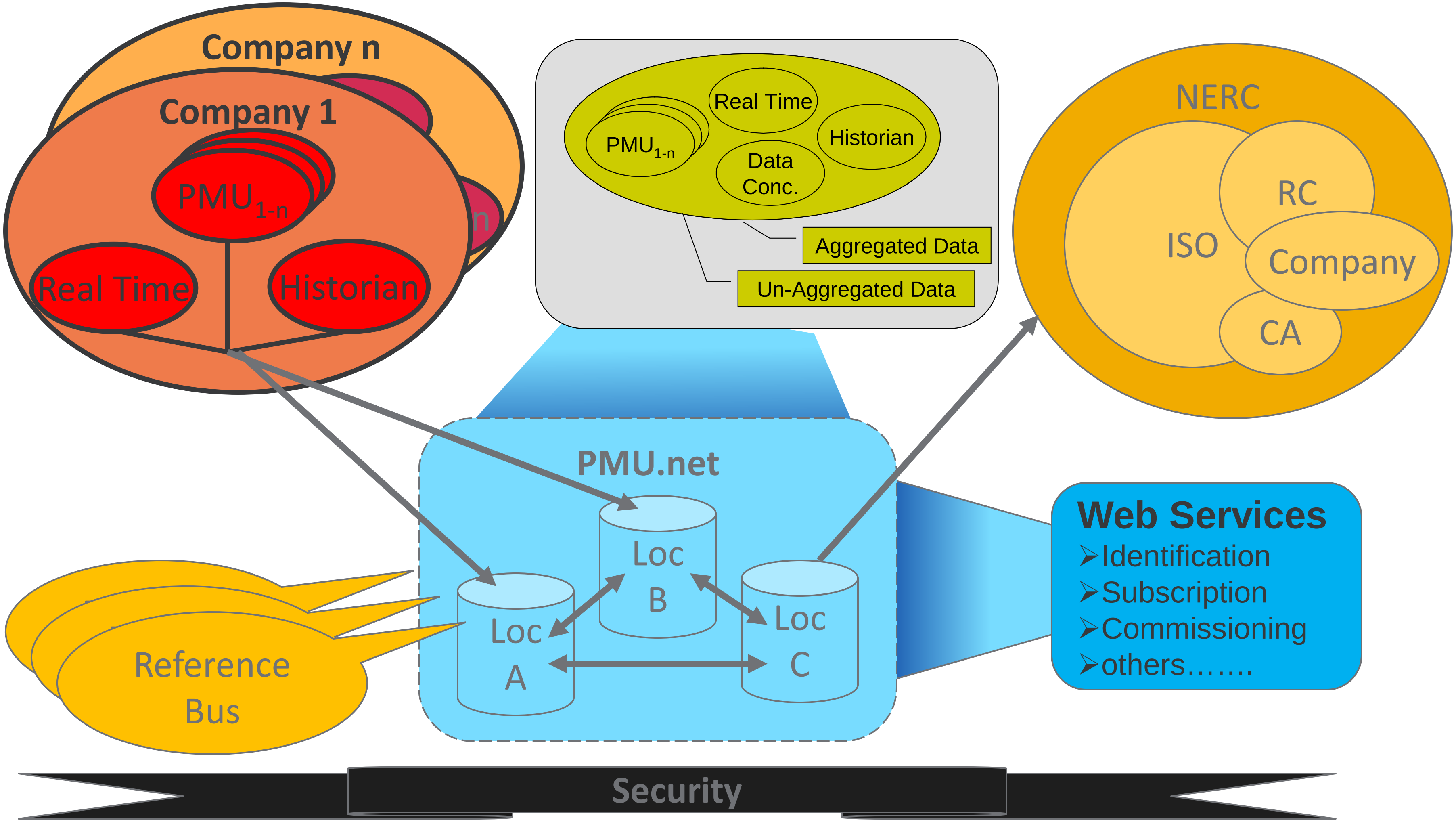
Basic PDC Functions

- Input data from PMUs
  - Decode, error check, and manage communications
- Combine input data, generally by timetag
- Output data to applications
  - Construct message and manage communications
- Manage measurement system
  - Create record of outages, errors
  - Provide real-time monitor of operation
- Phasors must be matched by timetag to compare phase angles across system

Credit: K. Martin

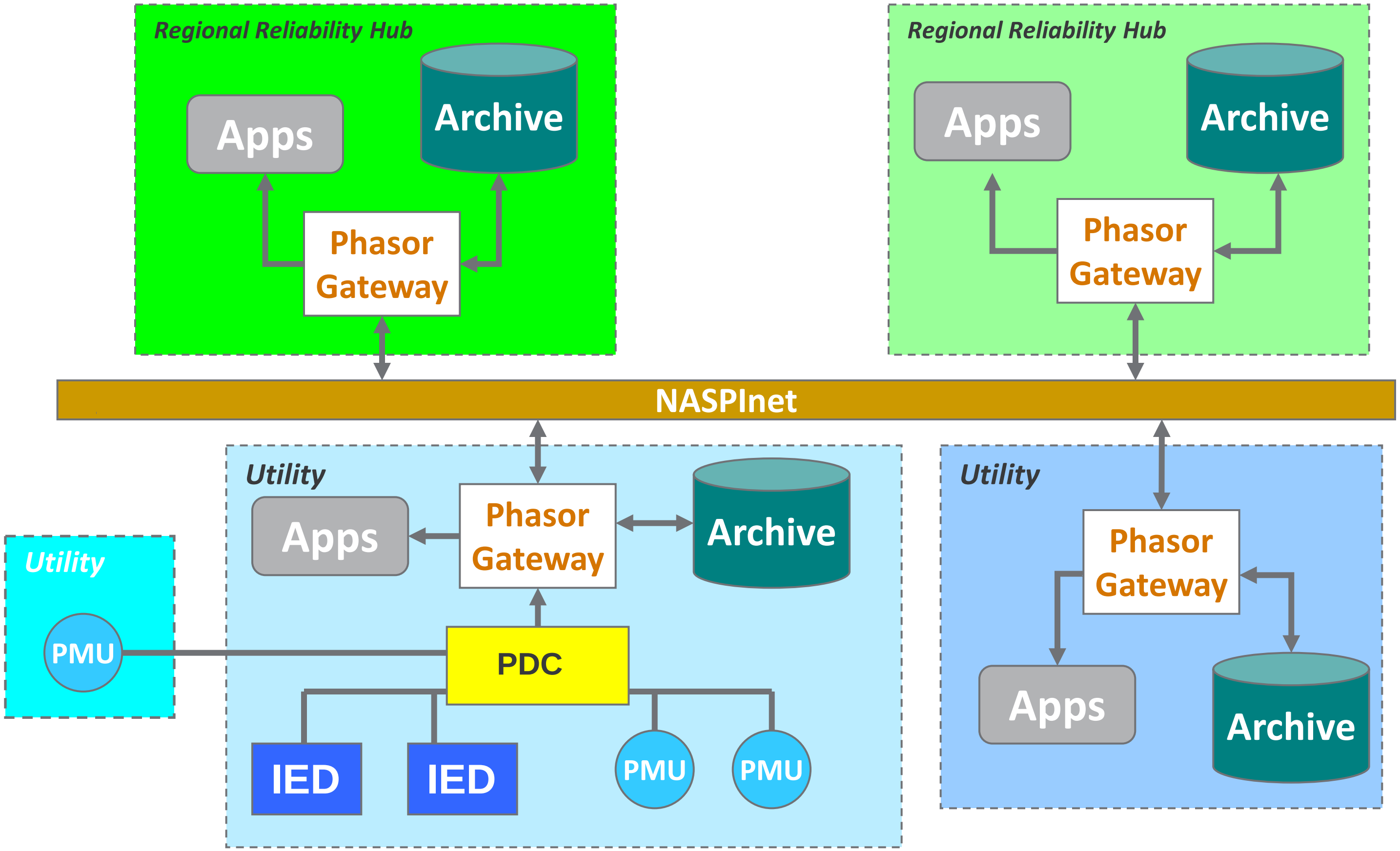
Future Network Architecture Concept

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



Credit to Paul Myrda, former Data Mgmt Task Team Lead

The NASPInet Vision –
A Distributed Network for Data Exchange and Sharing



NASPI Application Classification

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Class	*Basic Description*	*Sampling/ Data Rate*	*Required Latency*
A	Feedback Control	Fast	Fast
B	Open Loop Control	Medium	Medium
C	Visualization	Medium	Medium
D	Event Analysis	Fast	Slow
E	Research/Experimental	N/A	N/A

Data Quality Requirements

- Measurement accuracy
- Data availability
- Data delivery speed
  - Includes cumulative latency throughout the entire measurement, communications, and processing system infrastructure

Highly dependent on the* application *requirements!

- Some examples of data quality issues:
  - PMU device
    - Including configuration settings, hardware or software failure
  - PDC device
    - Same as above
  - Instrument transformers, including substation cabling
  - Communications infrastructure including routers, firewalls, etc.
  - Applications, including servers, data historians, software compatibility

Data Availability Example

Dates:	8/25/2014 -8/31/2014	
Entity	Percent Availability	PMU Count
	94.09%	17
	94.99%	17
	81.76%	11
	99.86%	55
	83.13%	20
	99.58%	15
	69.14%	6
	62.91%	3
	73.19%	4
	0.00%	2
	75.86%	6
	38.07%	7
	99.86%	4
	99.89%	1
	100.00%	2
	98.45%	2
	99.81%	5
Overall:	90.13%	177

Other Important Standards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- IEEE C37.118
  - Part 1 - This standard defines synchrophasors, frequency, and rate of change of frequency (ROCOF) measurement under all operating conditions.
  - Part 2 - This standard specifies messaging that can be used with any suitable communication protocol for real-time communication between phasor measurement units (PMU), phasor data concentrators (PDC), and other applications.
- IEC 61850.90-5.1 and 90-5.2
  - 90-5 is the synchrophasor profile for IEC 61850, substation automation
- IEEE 1588 – time synchronization

Security of Synchrophasors

- Synchrophasors are becoming part of the bulk electric system and will require physical and cyber security
  - ***But these systems shouldn't be treated any differently than other forms of measurement and control telemetry***
- Synchrophasor systems will coexist with other bulk electricity system (BES) cyber infrastructure and will have similar dependencies on common communications and network elements
- System designers and owners are aware of emerging cyber-security standards and technologies
- Currently available phasor applications require further data analysis, software refinement and operational validation to be fully effective; many are in advanced development and testing and are not in full operational use
  - Therefore, many of these systems are not currently considered critical cyber assets
- Due to nature of continuous, high-volume data flows, new technology will likely be required for measurement, communications, and applications
  - Technology anticipated to undergo rapid change and refinement over the next several years

Different Types of PMUs

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- P class (protection)
  - Minimal filtering
  - Possible aliasing of higher frequency components
  - Less delay in estimation
  - Important for real-time controls requiring minimum delay
- M class (measurement)
  - Some anti-alias protection
  - Wider frequency response, lower noise
  - Latency longer (depends on reporting rate)
  - Important for situations with higher frequencies present
- Both classes
  - Essentially the same measurement in all other respects

Credit: K. Martin

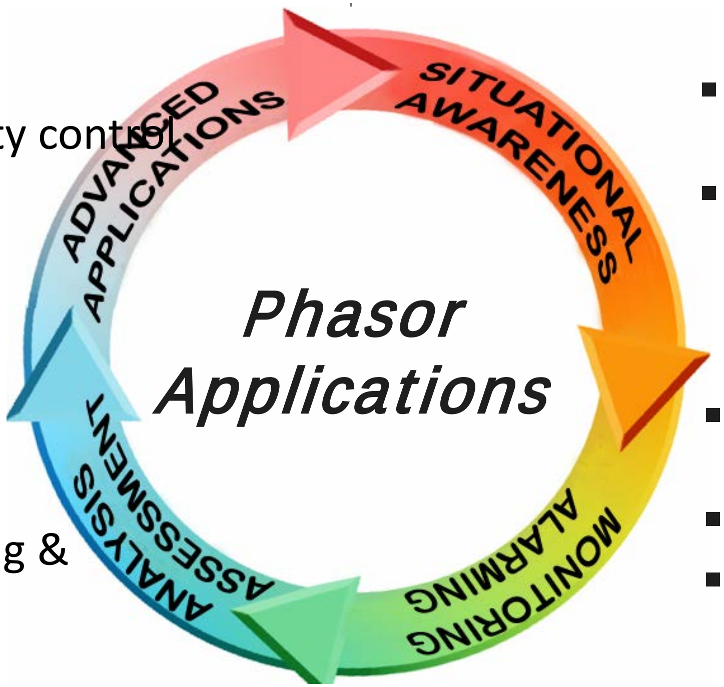
Phasor Applications Taxonomy

RESEARCHERS

- Automatic alarming of remedial action schemes
- Out of step protection
- Short/long-term stability control
- Feedback control

PLANNERS

- Post-mortem analysis
- Model validation
- Phasor network performance monitoring & data quality
- Email notifications
- Test new real-time applications



RELIABILITY COORDINATORS

- Situational awareness dashboard
- Real time compliance monitoring
- Frequency Instability Detection/Islanding

OPERATORS

- Real time performance monitoring
- Real time alerts and alarms
- Event detection, disturbance location
- Suggest preventive action
- Interconnection state estimation
- Dynamic ratings

Credit to Terry Bilke (MISO),
Former leader of the Operations Implementation Task Team

NASPI North American SynchroPhasor Initiative

http://www.naspi.org/