# Cyber-Security of Wide Area Protection Systems

Annarita Giani
Electrical Engineering & Computer Sciences
University of California at Berkeley
agiani@eecs.berkeley.edu

LANL

October 23, 2010

# 50 Years ago
# Now

# Outline

- Previous work
- Power Systems Background
- Phase Measurement Units
- State Estimation & PMU Data
- Our Approach to Integrity Attack Detection

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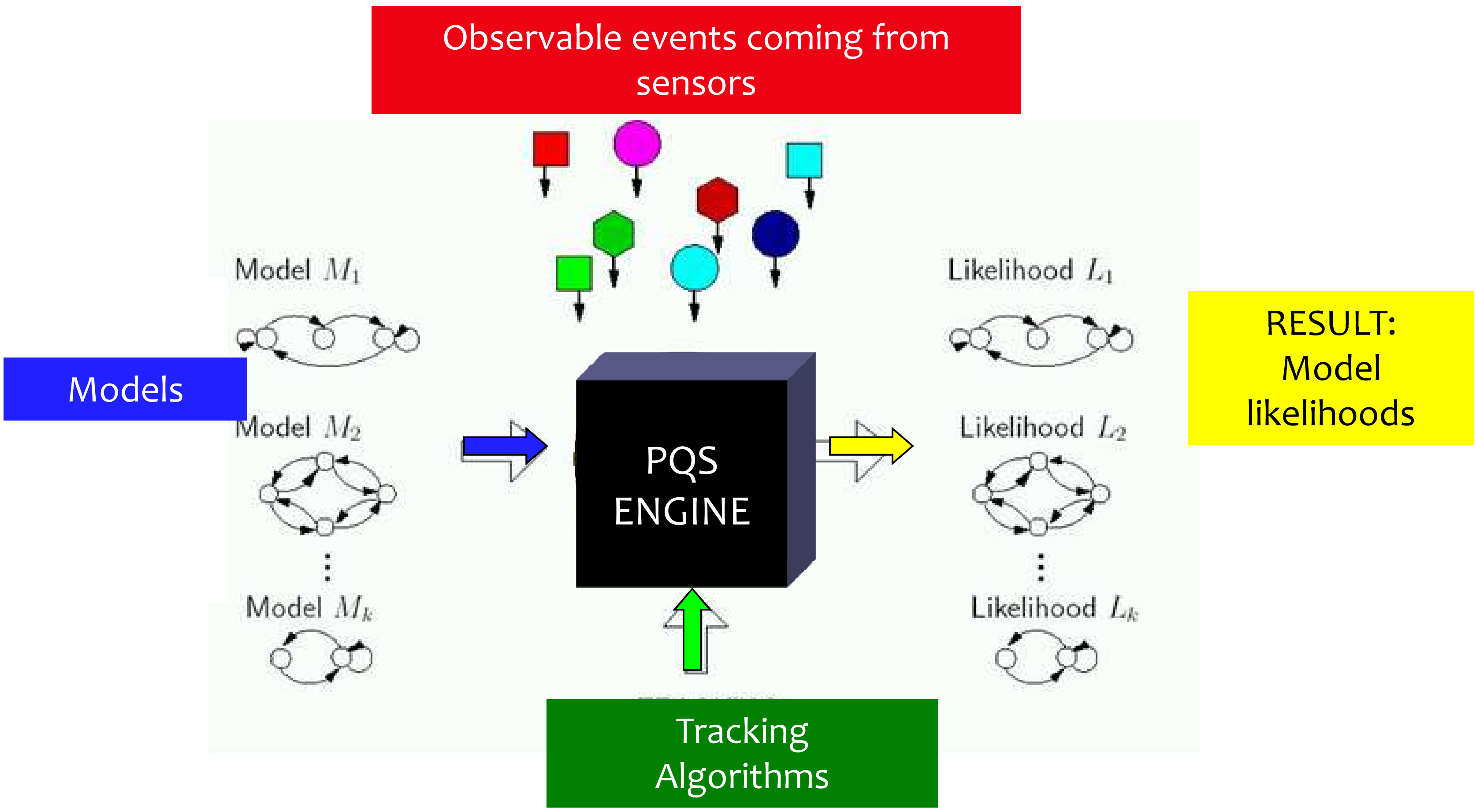
# My Background

- PhD Dartmouth 2007
  - Detection of attacks on cognitive channels
  - [G. Cybenko]
- Post-doc TRUST Center [2007-2009]
  - Trustworthy information systems
  - [S. Sastry]
- Post-doc Berkeley [2009- ]
  - Renewable integration, Cyber-security in power systems
  - [K. Poolla]

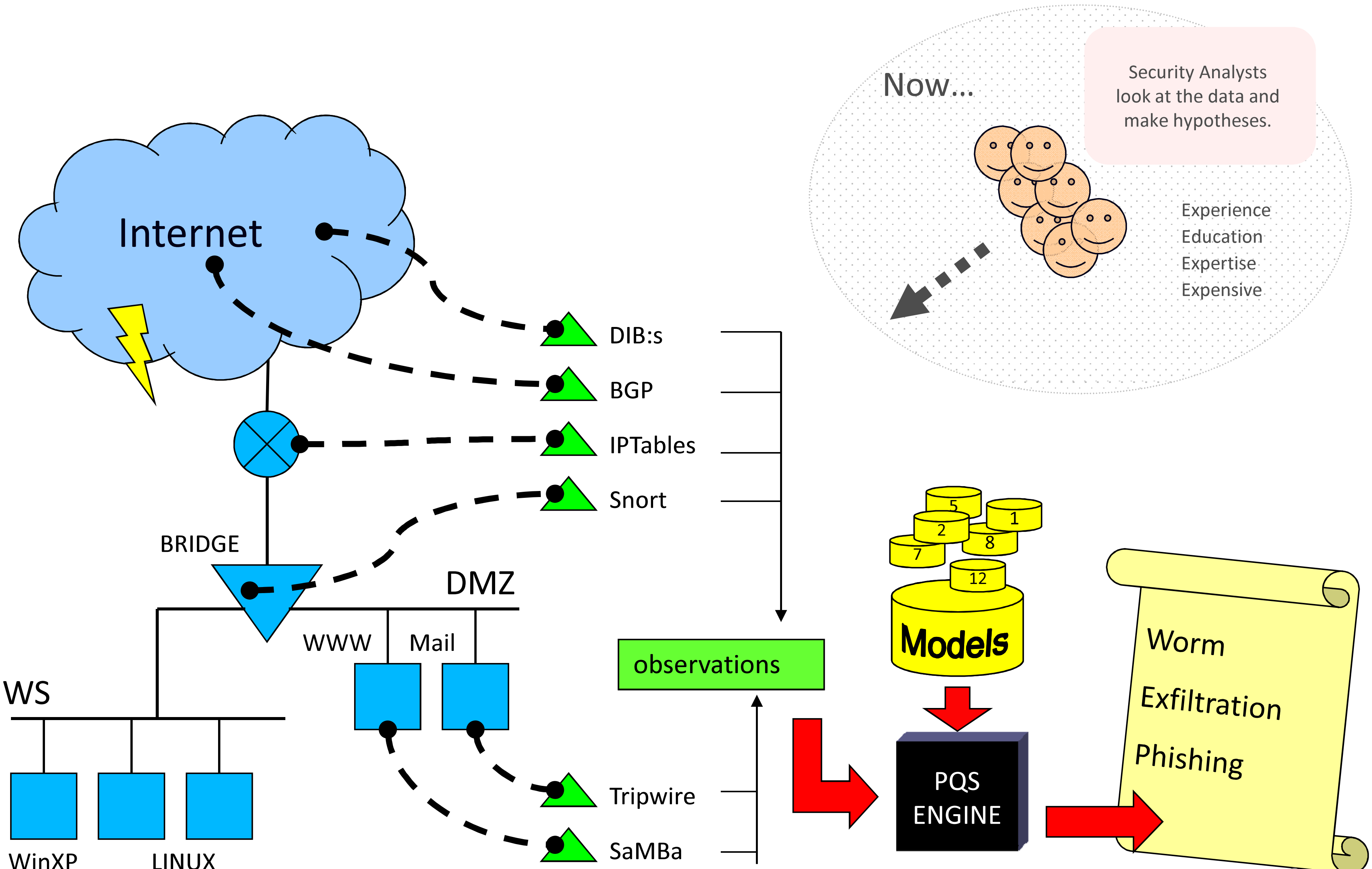
# Security Objectives

- **C**onfidentiality: information disclosure only to authorized users
  - Eavesdropping, Phishing
  - Access Control, Authentication, Authorization, Encryption
- **I**ntegrity: trustworthiness of information resources
  - Replay, Man in the Middle, Data Injection, Data Jam, Data Corruption
  - Encryption, Redundancy
- **A**vailability: Availability of data whenever need it
  - Denial-of-Service
  - Traffic Anomaly Detection
- Authorization
- Authentication
- Non Repudiation

# Process Query System



# PQS in computer security

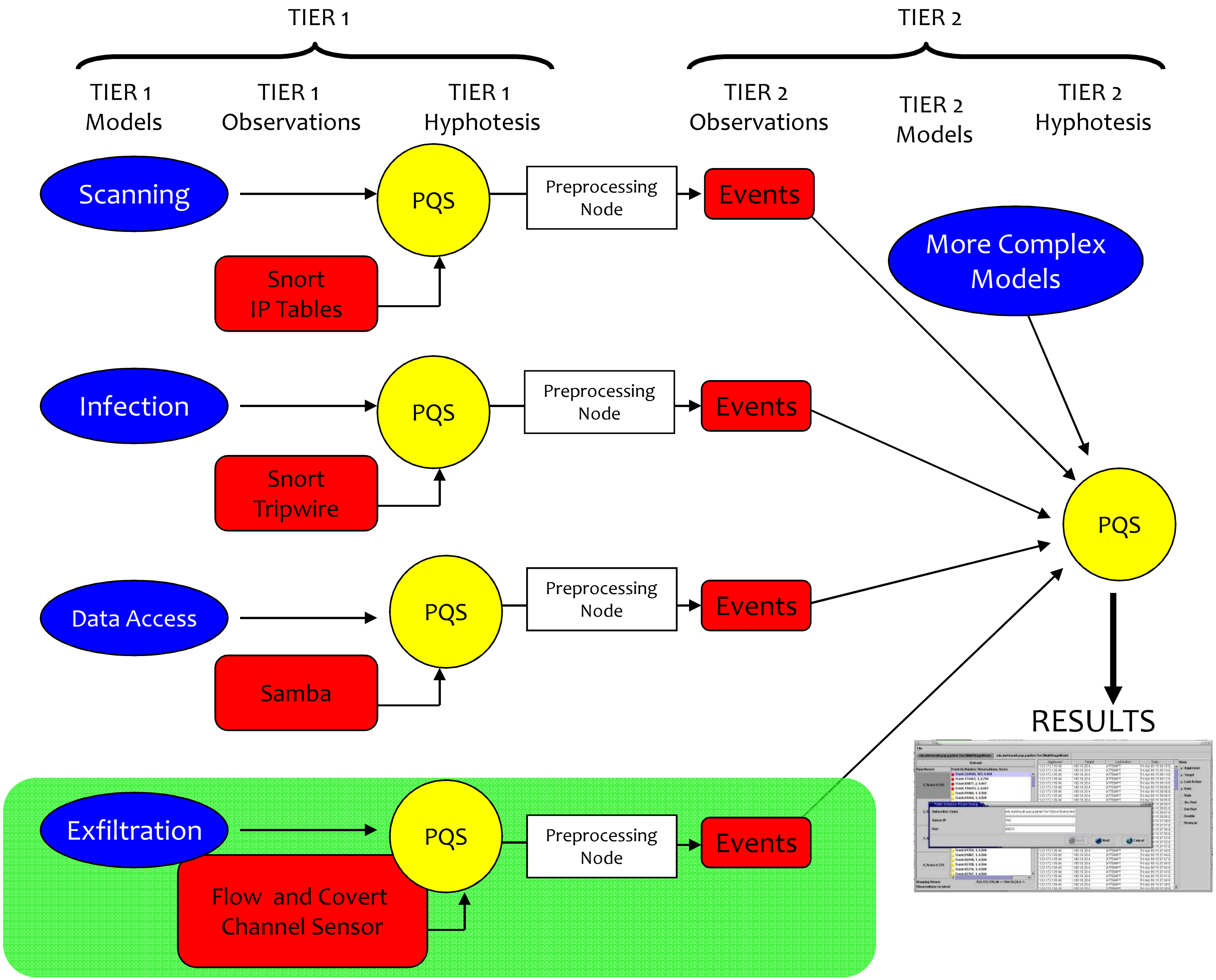


# Sensors and Models

| | | |
|---|---|---|
| 1 | DIB:s | Dartmouth ICMP-T3 Bcc: System |
| 2 | Snort, Dragon | Signature Matching IDS |
| 3 | IPtables | Linux Netfilter firewall, log based |
| 4 | Samba | SMB server - file access reporting |
| 5 | Flow sensor | Network analysis |
| 6 | ClamAV | Virus scanner |
| 7 | Tripwire | Host filesystem integrity checker |

| | |
|---|---|
| 1 | Noisy Internet Worm Propagation – fast scanning |
| 2 | Email Virus Propagation – hosts aggressively send emails |
| 3 | Low&Slow Stealthy Scans – of our entire network |
| 4 | Unauthorized Insider Document Access – insider information theft |
| 5 | Multistage Attack – several penetrations, inside our network |
| 6 | DATA movement |
| 7 | TIER 2 models |

# Hierarchical PQS Architecture



# PQS Applications

- Vehicle tracking
- Worm propagation detection
- Plume detection
- Dynamic Social Network Analysis
- Cyber Situational Awareness
- Fish Tracking
- Autonomic Computing
- Border and Perimeter Monitoring
- First Responder Sensor Network
- Protein Folding

# Current Work Summary

- Testbed for Secure and Robust SCADA Systems
  (with Vanderbilt and CMU)
  [IEEE Real-Time and Embedded Technology and Applications Symposium2008 ]
- Optimal Contracts for Wind Power Producers in Electricity Markets
  [CDC 2010]
- Renewable integration and smart grid
- Integrity Attack Detection of PMU data [This talk]

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# Context and Notation

- Considering AC synchronous power systems
- Assume quasi steady-state analysis

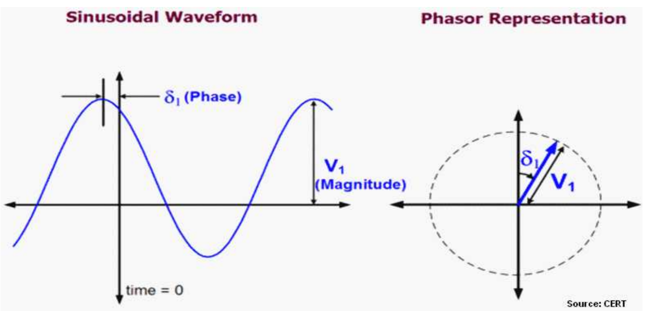
  Voltages and currents are well approximated as

  fixed frequency sinusoids with slowly changing phases

| | | |
|---|---|---|
| time-domain: | signal | $v(t) = V\sin(\omega_o t + \phi)$ |
| frequency-domain: | phasor | $\mathbb{V} = V \exp\,(j\phi)$ |

- Notation

| | |
|---|---|
| $M^*$ | complex-conjugate transpose |
| $\|\| \cdot \|\|$ | standard euclidean norm |
| $\sigma^2$ | noise variance |
| $\mathbb{V}, \mathbb{I}$ | phasors |
| $Y = G + jB$ | bus admittance matrix |
| $G$ | bus conductance matrix |
| $B$ | bus susceptance matrix |
| $E$ | expectaton operator |



# Static State of a Power System

- What is it?

  The set of voltage magnitudes and angles at all network buses

- Why is it important?

  Bus voltages and angles are the key variables

  These determine

  - static flows on transmission lines
  - locational marginal prices
  - current stress state of system
  - future generation that should be scheduled

# Measurements

- Bus powers [real, reactive] are commonly measured
  - Used for settlement of contract, compensation, etc
- Bus voltages magnitudes are easy to measure
  - Used for voltage regulation, system protection, etc
- Bus voltage phases are much harder to sense
  - Power flows depend on the phase difference between buses
  - Need global clock to determine times of voltage maxima
  - So, voltage phases are estimated
- Dynamic state estimation
  - Not commonly used
  - Computationally prohibitive
- Static state estimation

# Static State Estimation

- What is it?

  Find the phase angles given:

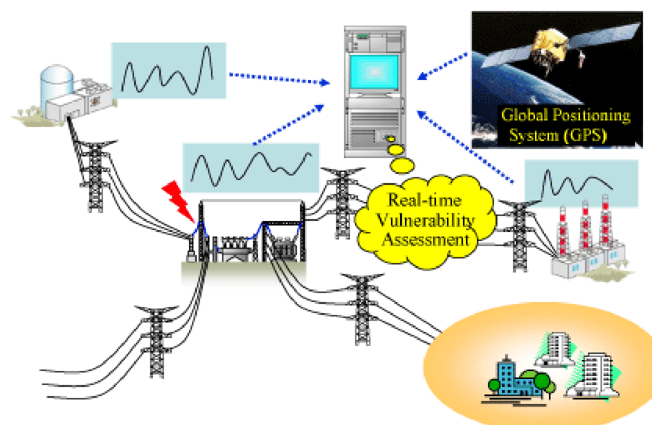
    measured real power P and reactive power Q at load buses

    measured real power P and voltage V at generator buses

- Current practice
  - Data available every 1-15 minutes thru SCADA system
- Load flow equations
  - Over-determined set of algebraic nonlinear equations
  - Nonlinear programming to estimate states V, $\delta$
  - Takes 5-15 minutes depending on problem size
  - Can have > 5000 buses

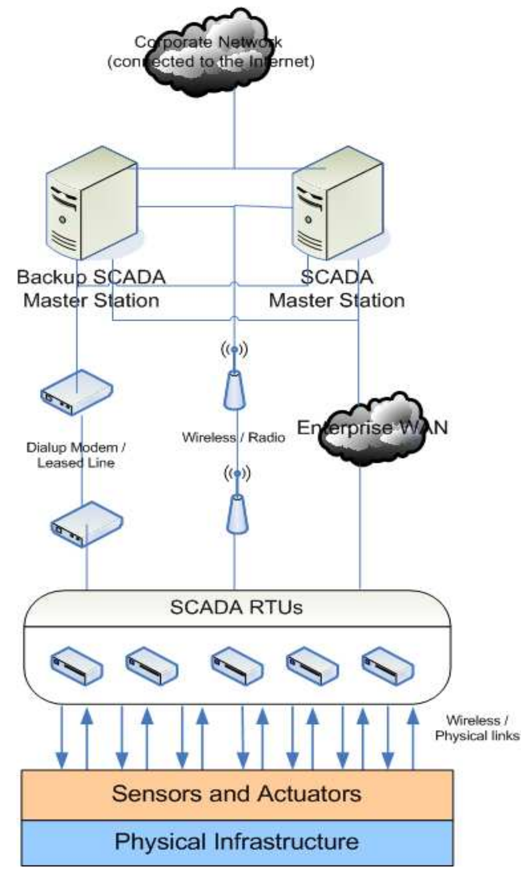
# WAMS

- WAMS = wide area monitoring systems
- Integral component of power system operation today
  - Telemetry
  - Data storage
  - Alarming and status
- Application
  - Situational awareness
  - Alarming and status (early warning)
  - Root cause analysis of events
  - State estimation



# Today: SCADA Data

- Supervisory control and data acquisition (SCADA) data since the 1960's
  - Voltage & Current Magnitudes
  - Frequency
  - Every 2-4 seconds
- Believed to be secure (not part of the commodity internet)
- Limitation
  - Low speed data acquisition
  - Steady state observability of the system



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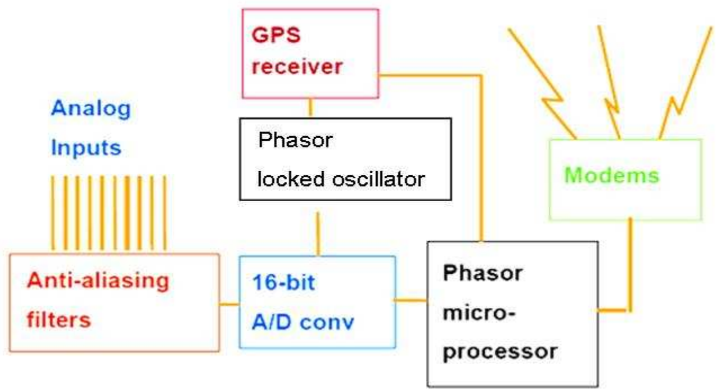
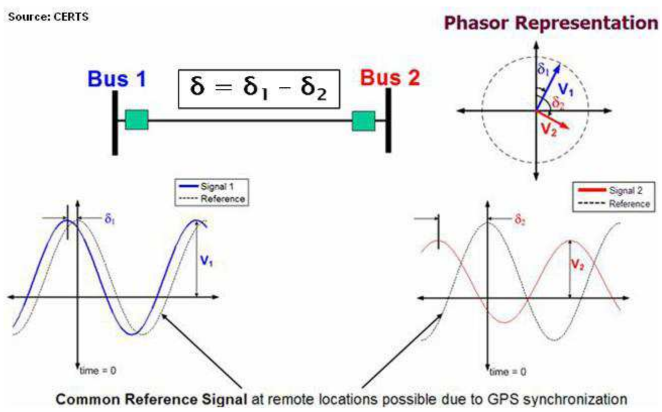
# Synchro Phasors

- Synchronized sampling with 1 microsecond accuracy using GPS
- *Protocol:* IEEE C37.118-2005 standard
- Cost: 2-3000$ each




*http://www.phasor-rtdms.com/phaserconcepts/phasor_adv_faq.html*

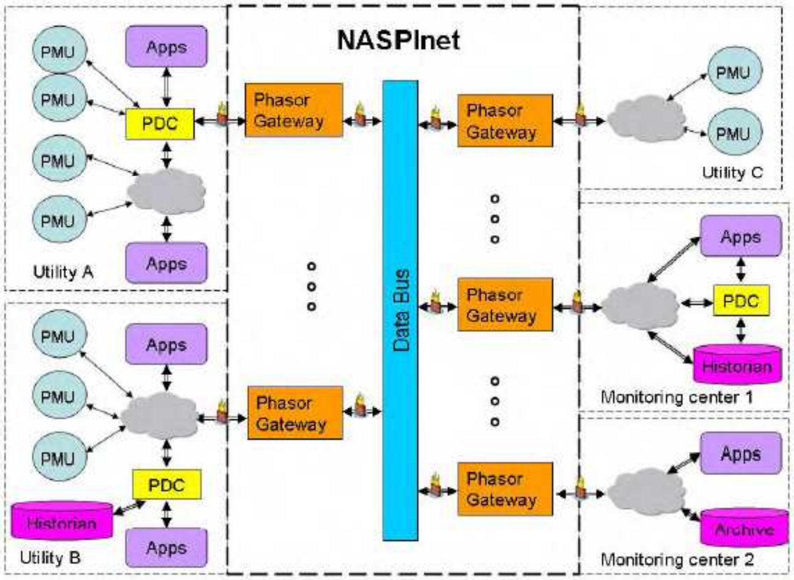


# Advantages of PMU Data

- PMUs collect location, time, frequency, current, voltage and phase angle (>40 Hz sampling)
- Why are they important?
  - Grid-scale renewable energy systems [ex: photovoltaic and wind]
  - Large unexpected variability
  - Can produce phase instability
  - Results in poor decision making [ex: scheduling]
  - Which can lead to big problems [ex: voltage instability, islanding, cascading failures]
- Directly provides the phase angles [from State Estimation to State Measurement]

# PMU Architecture

- Measurement Layer
  - PMUs
- Data Collection Layer
  - Phasor Data Concentrator (PDC)
  - A hardware/software device
  - Performs precise time alignment of data from multiple PMUs
  - Usually centrally located
  - Archives, processes and display PMU data (optional)
- Communication Network
  - NASPInet




*http://www.naspi.org/*

North American SynchroPhasor Initiative (*NASPI*)

# NASPInet

- High speed for fast data streaming
- Secure exchange of data
- The owner of a phasor gateway that publishes the data to naspinet has full control of its data distribution
- Pilot phase by 2014
- Fully operational by 2019

NASPI North American SynchroPhasor Initiative

U.S. Department of Energy, the North American Electric Reliability Corporation, and North American electric utilities, vendors, consultants, federal and private researchers and academics.

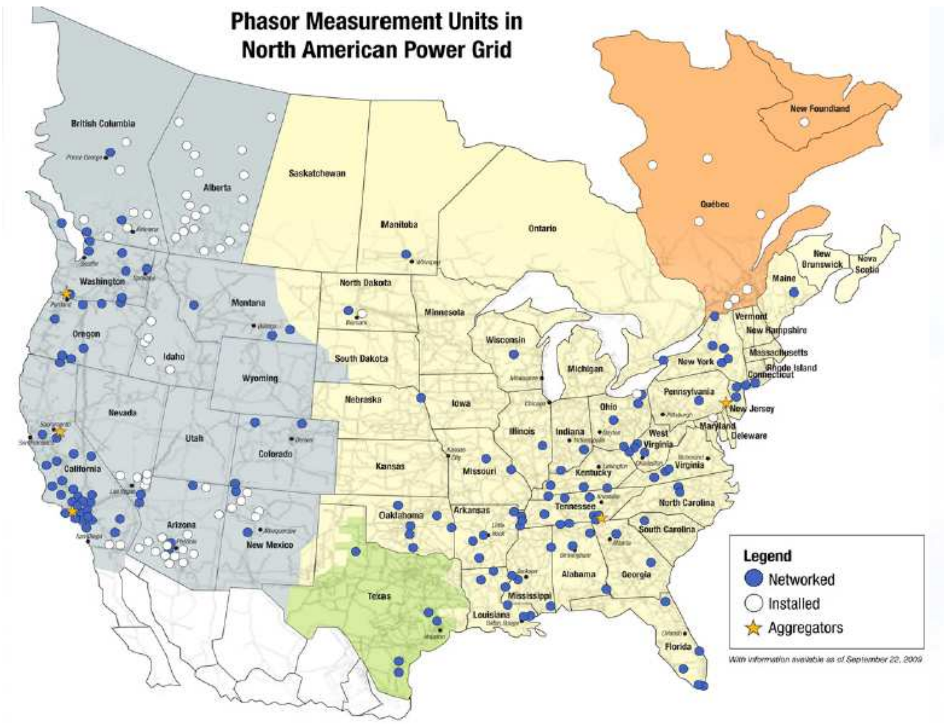
# NaspiNET Software Components


**NASPINET SECURITY**

Authentication
Authorization
Access Control
Confidentiality
Non Reputation
Auditing
Key Management
Identity Management
Trust Authorization Management
Network Based Components
Physical Component

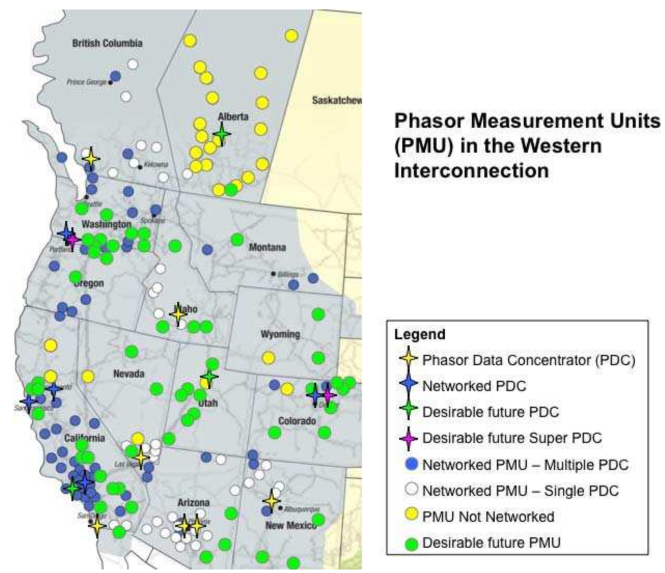
*http://www.naspi.org/*

# PMU Deployment Today




Currently 200+ PMUs Installed.
Expected to exceed 800+ PMUs by 2013
*(under SGIG Investments)*

Currently 137 PMUs Installed




34 Gigabytes of data collected Daily from 100 PMUs
(~ 1 Terabyte per Month).

# PMU System Security

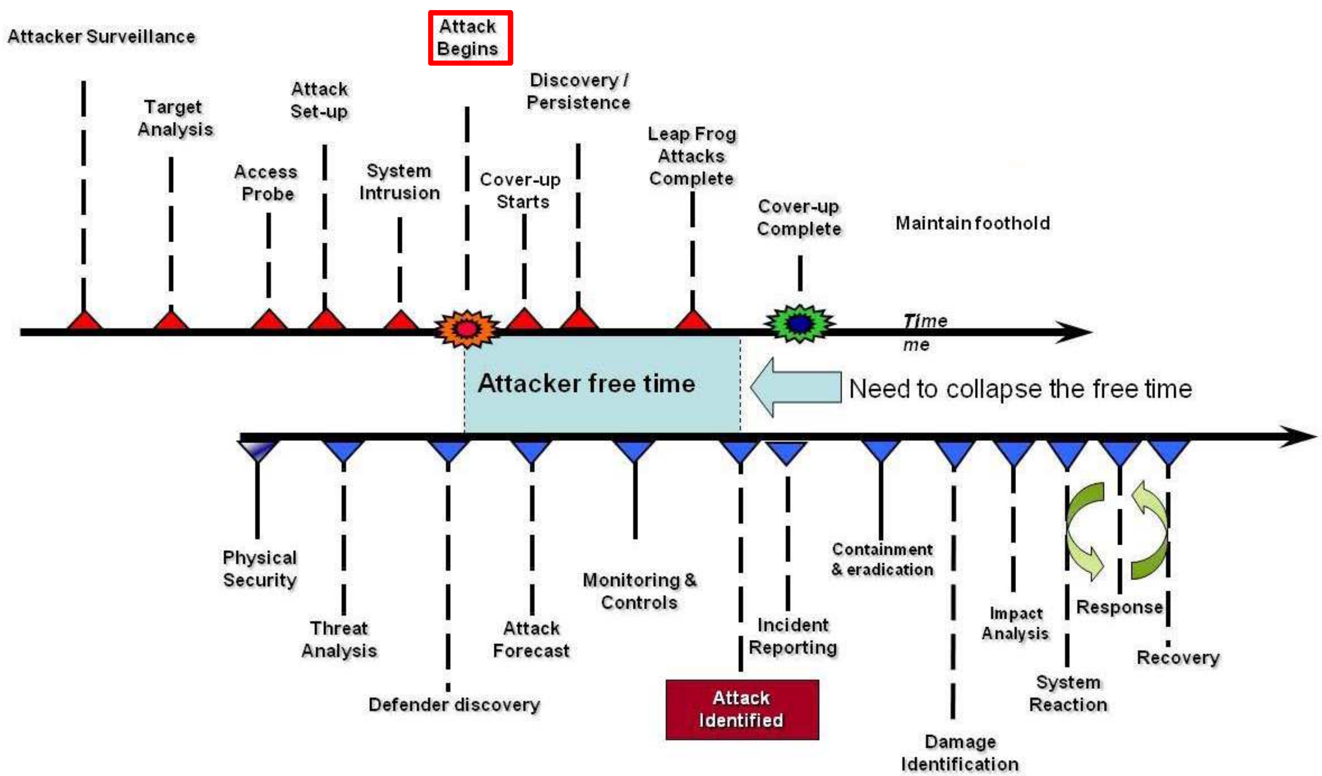
- Cyber-security is one of the main obstacles to widespread deployment of PMUs
- Availability & Confidentiality attacks are secondary
- Integrity attacks are most critical
  - Can initiate inappropriate generator scheduling
  - Can result in voltage collapse, and subsequent cascading failures
- Our initial approach

  Consistency checking between cyber network [PMU data received] and physical network [load flow equations]  using static state estimation tools

# Taxonomy of cyber attacks

Potential Attack points:

Sensors, Phasor Data Concentrator (PDC), comm infrastructure (NASPInet)




http://www.nerc.com/files/HILF.pdf

# Related Projects

- The Trustworthy Cyber Infrastructure for the Power Grid
  http://www.iti.illinois.edu
- Roadmap to Secure Control Systems,
  http://www.controlsystemsroadmap.net
- Control Systems Security Program
  http://www.uscert.gov/control_systems/
- National SCADA Testbed Program, http://www.inl.gov/scada/
- Smart Grid Recovery Act, https://www.arrasmartgridcyber.net

These use:
*traditional* cyber-security detection and protection methods

Our approach and broader objective:
to bring the physics of load flow to cyber-security methods

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# Static State Estimation with PMU Data

- Recall: What is static state estimation?

  Find the phase angles given:

    measured real power P and reactive power Q at load buses

    measured real power P and voltage V at generator buses

- Ubiquitous placement of PMUs
  - Will eliminate need to do state estimation
  - But this is too expensive
  - Must live with PMU data at limited number of buses
- Recent results
  - incorporate PMU data
  - retain standard-form static estimation
  - Phadke et al [2006]

# State Estimation Equations

- Coupled algebraic nonlinear equations

| | |
|---|---|
| Power Flow Constraint: | $\mathbb{I} = \mathbb{Y}\mathbb{V}$ |
| Bus admittance matrix | $\mathbb{Y}$ |
| Injected bus current phasor | $\mathbb{I}$ |
| Bus voltage phasor | $\mathbb{V}$ |

Measurement equations:

| | |
|---|---|
| At load bus: | $P_k + jQ_k = \mathbb{V}_k \mathbb{I}_k^* + e_k + jf_k$ |
| At generator bus: | $P_k = \text{Re}\{\mathbb{V}_k \mathbb{I}_k^*\} + e_k$ |
| | $V_k = \lvert\mathbb{V}_k\rvert + f_k$ |
| At PMU bus: | $y_k = \angle\mathbb{V}_k + g_k$ |
| SCADA data: | $P_k, Q_k, V_k$ |
| PMU data: | $y_k$ |
| IID noises: | $e_k, f_k, g_k$ |

# State Estimation Problem

- Minimum variance of bus voltage and phase
- Estimate is $\hat{\mathbb{V}}$

$$
\begin{array}{ll}
\text{minimize} & E \sum_k \|\hat{\mathbb{V}}_k - \mathbb{V}_k\|^2 \\
\text{subject to} & \text{load flow equations} \\
 & \text{measurement equations}
\end{array}
$$

exploit: $\sigma_g^2 \ll \sigma_e^2, \sigma_f^2$

# "DC load flow"

- For better intuition
- Assume:

  Lossless lines: $Y \approx jB$

  Voltage support: $\mathbb{V} \approx 1$ per-unit

  Small angles: $\sin(\delta_k - \delta_l) \approx (\delta_k - \delta_l)$

- Problem:

  Estimate power angles $\delta$ using

  - Real power data [at all buses, noisy, possibly stale]
  - PMU data [at select buses, clean]

# “DC load flow” eqns

- Problem becomes weighted least-squares

DC load flow: $P = B\delta$

measurement eqn: $\begin{bmatrix} R \\ y \end{bmatrix} = \begin{bmatrix} P + e \\ C\delta + f \end{bmatrix} = \begin{bmatrix} B \\ C \end{bmatrix} \delta + \begin{bmatrix} e \\ f \end{bmatrix}$

$C$ is a permutation matrix:
selects buses at which we have PMU data

solution: $\hat{\delta} = \left[B^* B + \gamma C^* C\right]^{-1} \left[B^* R + \gamma C^* y\right]$

$$\hat{n} = \begin{bmatrix} \hat{e} \\ \hat{f} \end{bmatrix} = \Pi \begin{bmatrix} R \\ y \end{bmatrix}$$

where $\gamma^2 = \dfrac{\sigma_e^2}{\sigma_f^2}, \Pi =$ standard projection matrix

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# Integrity Attack Detection

- Basic Idea: Consistency checking between cyber network [PMU data] and physical network [load flow equations]
- Assumptions:

  PV data at generator buses are known secure

  PQ data at load buses are known secure

  at most one compromise in PMU data
- Comments:
  - Realistic because of rarity of coordinated attacks
  - Methods can be extended to two or more simultaneous uncoordinated attacks
  - Doesn't distinguish between faults and attacks

# Problem Formulation

- Given traditional static state estimation data set
  - PV data at generator buses
  - PQ data at load buses
  - Assumed secure
  - Updated asynchronously at slow time scales [5-15 minutes]
- Given data from $p$ PMUs
  - Assume at most one PMU is compromised
  - Updated at fast time scales [60 Hz]
- Find
  - Which (if any) PMU data is compromised
- Solution strategy – Hypothesis testing

# Digression: LS Hypothesis Testing

- Observation Model

parameters: $\delta \in \mathbb{R}^n$
noisy observations: $y \in \mathbb{R}^m$
linear observation model: $y = A\delta + n$
i.i.d. noise model $E[n] = 0, \quad E[nn^*] = \sigma^2 I$

- Fault/attack Hypothesis

$\mathcal{H}_0$ all observations are clean
$\mathcal{H}_k$ observation $y_k$ is compromised

- Problem: determine most likely hypothesis
- Easy under linear observation model

# ML Approach

- For each hypothesis, calculate log-likelihood:

assume: hypothesis $\mathcal{H}_k$

compute: $J_k = -\min \|n\|^2$

subject to: load flow, observation model

- Choose most-likely hypothesis:

$$k^{\text{ML}} = \arg\max_k J_k$$

# Solution

- Problem formulation:

model: $y = A\delta + n$

noise: $n$ is i.i.d. with variance $\sigma^2$

find: which one (if any) observation $y_k$ is compromised

- Theorem:

define $N = I - A\left(A^*A\right)^{-1}A^*$

compute for $k = 1 : m$

$\alpha = e_k^* N y, \quad \beta = e_k^* N e_k, \quad J_k = \alpha/\beta$

end

find $k^o = \arg\max_k J_k$

then, the ML hypothesis is $\begin{cases} \mathcal{H}_{k^o} & \text{if } J_{k^o} \geq \sigma^2 \\ \mathcal{H}_0 & \text{else} \end{cases}$

# Application to PMU data

- Observation model

DC load flow: $P = B\delta$

measurement eqn: $\begin{bmatrix} R \\ y \end{bmatrix} = \begin{bmatrix} P + e \\ C\delta + f \end{bmatrix} = \begin{bmatrix} B \\ C \end{bmatrix} \delta + \begin{bmatrix} e \\ f \end{bmatrix}$

where $C$ is a permutation matrix that selects PMU buses

- Normalization [to make noise i.i.d.]

$$\begin{bmatrix} R \\ \gamma y \end{bmatrix} = \begin{bmatrix} B \\ \gamma C \end{bmatrix} \delta + \begin{bmatrix} e \\ \gamma f \end{bmatrix} = A\delta + n$$

where $\gamma^2 = \frac{\sigma_e^2}{\sigma_f^2}$

# PMU Integrity Attack Detection Algorithm

| | | | |
|---|---|---|---|
| $n$ | # of buses | $R$ | measured real powers |
| $p$ | # of PMU | $y$ | PMU data |
| $\sigma_e^2$ | standard bus noise covariance | $e_k$ | $k^{\text{th}}$ unit vector |
| $\sigma_f^2$ | PMU noise covariance | $B$ | bus susceptance matrix |
| $\gamma$ | $\sigma_e/\sigma_f$ | $C$ | matrix that selects PMU buses |

1. define $N = \begin{bmatrix} I_n & 0 \\ 0 & I_p \end{bmatrix} - \begin{bmatrix} B \\ \gamma C \end{bmatrix} \left( B^* B + \gamma^2 C^* C \right)^{-1} \begin{bmatrix} B^* & \gamma C^* \end{bmatrix}$
2. compute for $k = n+1 : n+p$

   $$\alpha = e_k^* N z, \quad \beta = e_k^* N e_k, \quad J_k = \alpha/\beta, \quad z = \begin{bmatrix} R \\ \gamma y \end{bmatrix}$$

   end
3. find $k^o = \arg\max_k J_k$
4. assess if $J_{k^o} \geq \sigma_e^2$ PMU $k^o$ is compromised

   else all PMU data are likely secure

# Extensions

- Exploiting sparsity of bus susceptance matrix
  - Can be done using only matrix-vector products
- Extending from DC load flow to nonlinear load flow
  - This is difficult
- Explicitly accounting for stale bus data
  - Can use bus power variance for this

# Open research

- Metrics of attack detectability
- Vigilance

  How frequently must we conduct attack detection? At what fidelity?
- Distinguishing between faults and malicious attacks
- Security-aware PMU placement
  - Which buses? Maybe in pair ?
  - Competing objectives

    WAMS applications vs. Integrity attack detectability
- Large scale simulation study

# Conclusion

- Cyber security research for PMUs is critical and challenging
- Our approach:

  consistency checking between

  cyber network [PMU data] & physical network [load flow] using static state estimation tools
- Questions, comments?

agiani@eecs.berkeley.edu

poolla@berkeley.edu

**Thanks**