Management of Precursors to Catastrophe: Identifying & Measuring Precursors

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Lead, Mathematics & Information Sciences

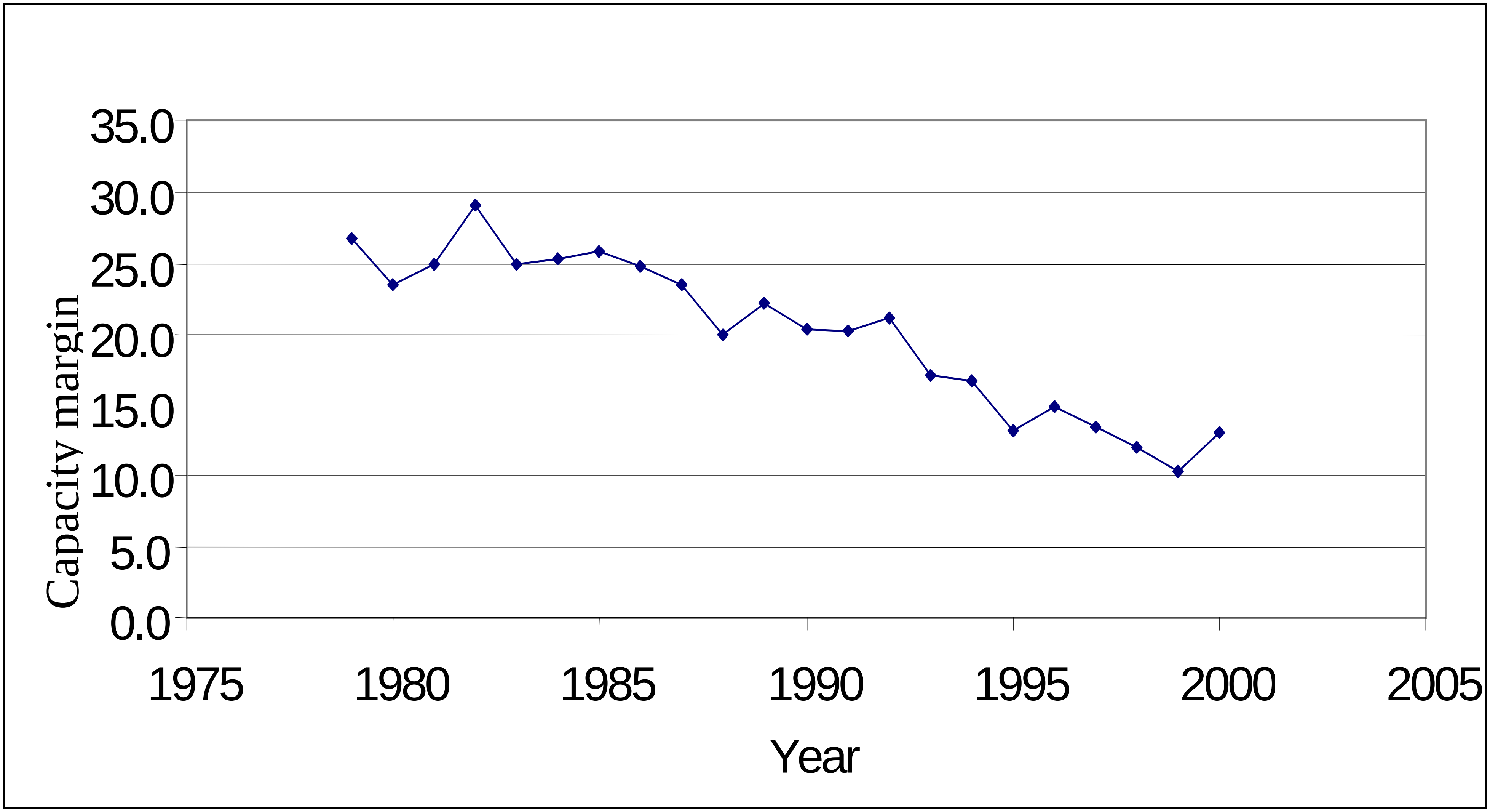
Roundtable on Management of Precursors to Catastrophe

National Academy of Engineering

February 21, 2002, Washington, D.C.

EPRI

Context: Generation Capacity Margin in North America



Source: Western States Power Crises White Paper, EPRI, Summer 2001

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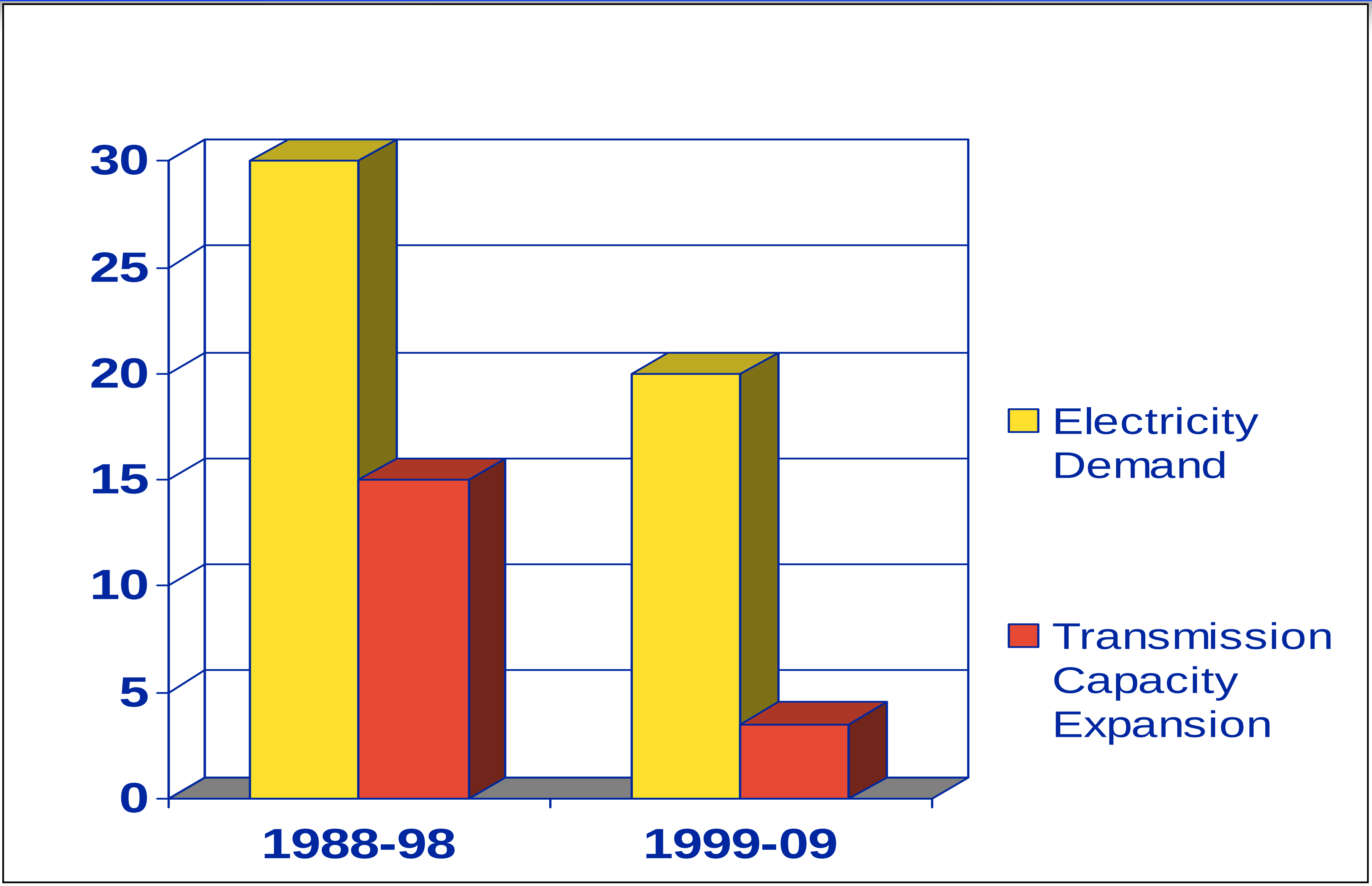
Context: Transmission Additions in The U.S.



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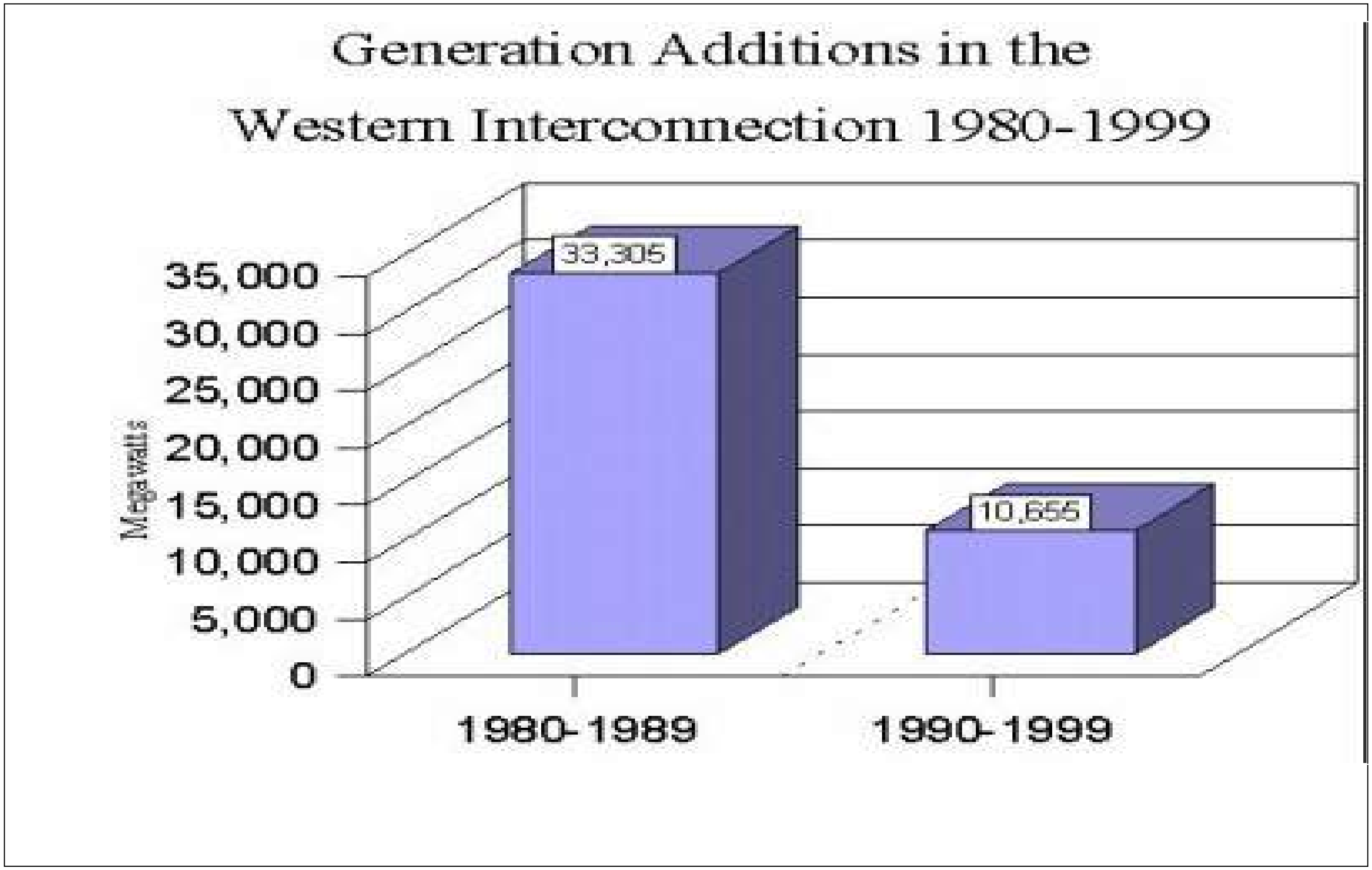
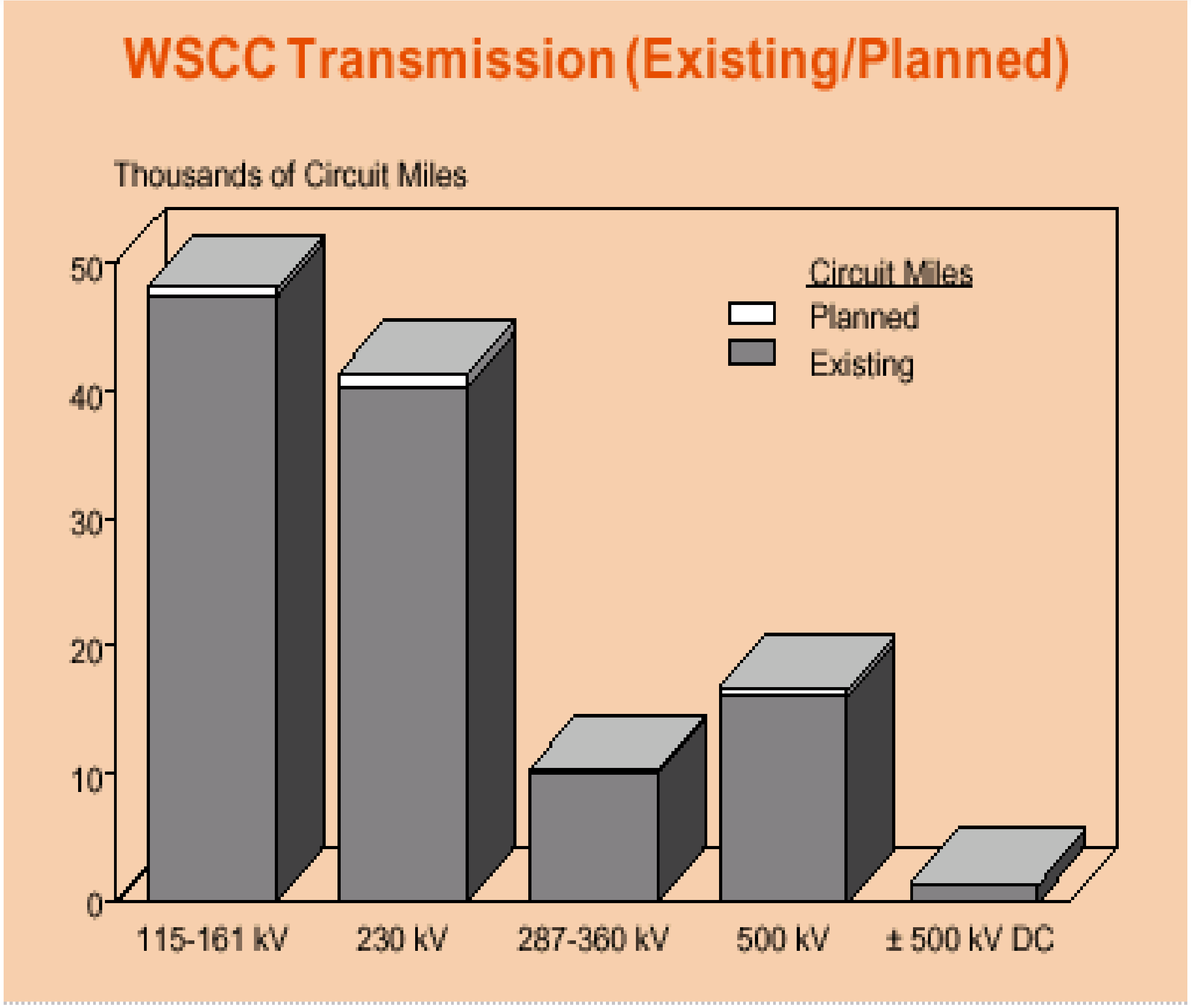
Context: Generation Additions in Western U.S.



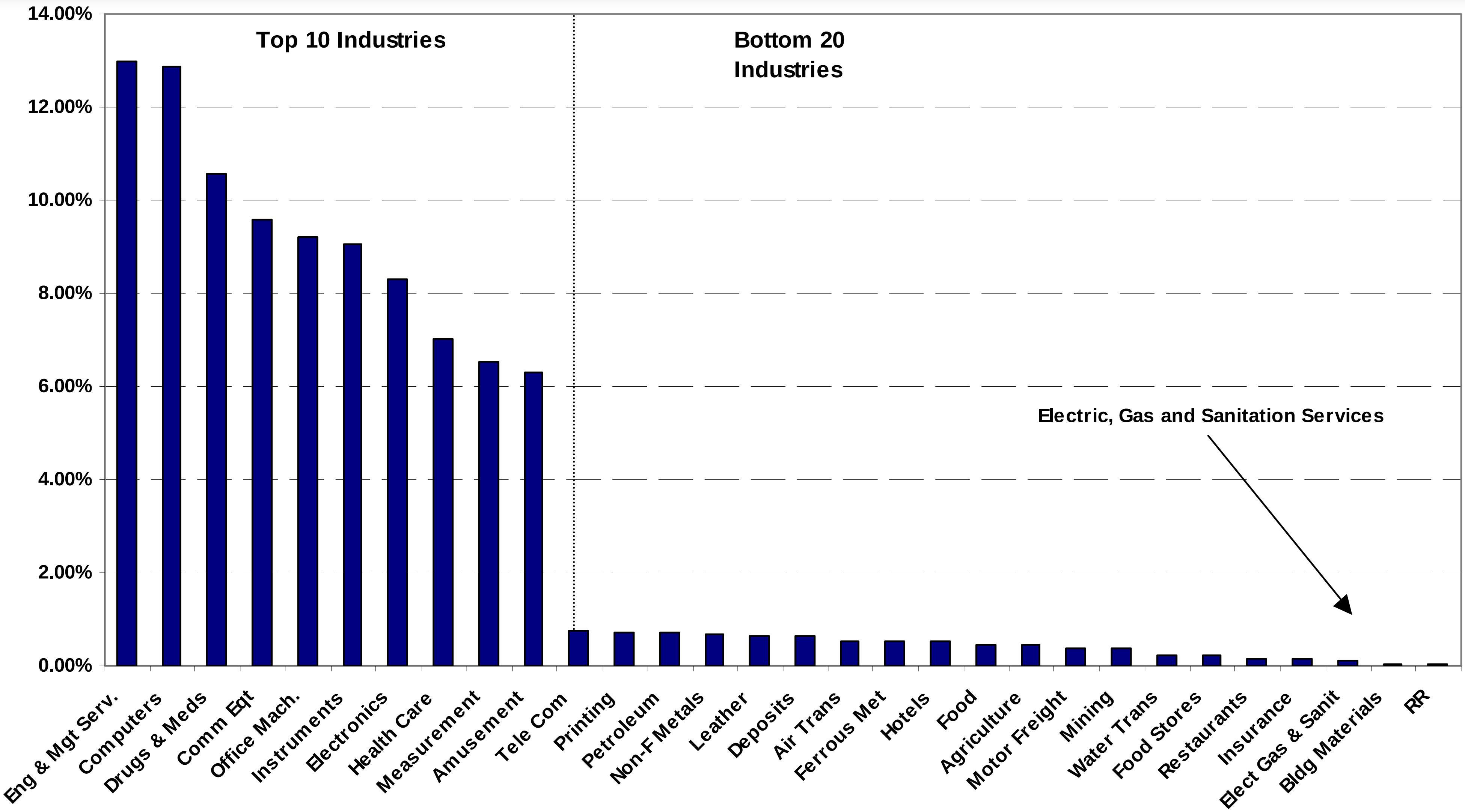
Source: Western Governors' Association

Western Region: Existing and Planned Transmission



- Existing as of 1/1/00
- Planned: 0.23% per year, even though load growth is projected to be over 1.8% per year

Context: R&D Expenditures*



*R&D expenditures as % of net sales

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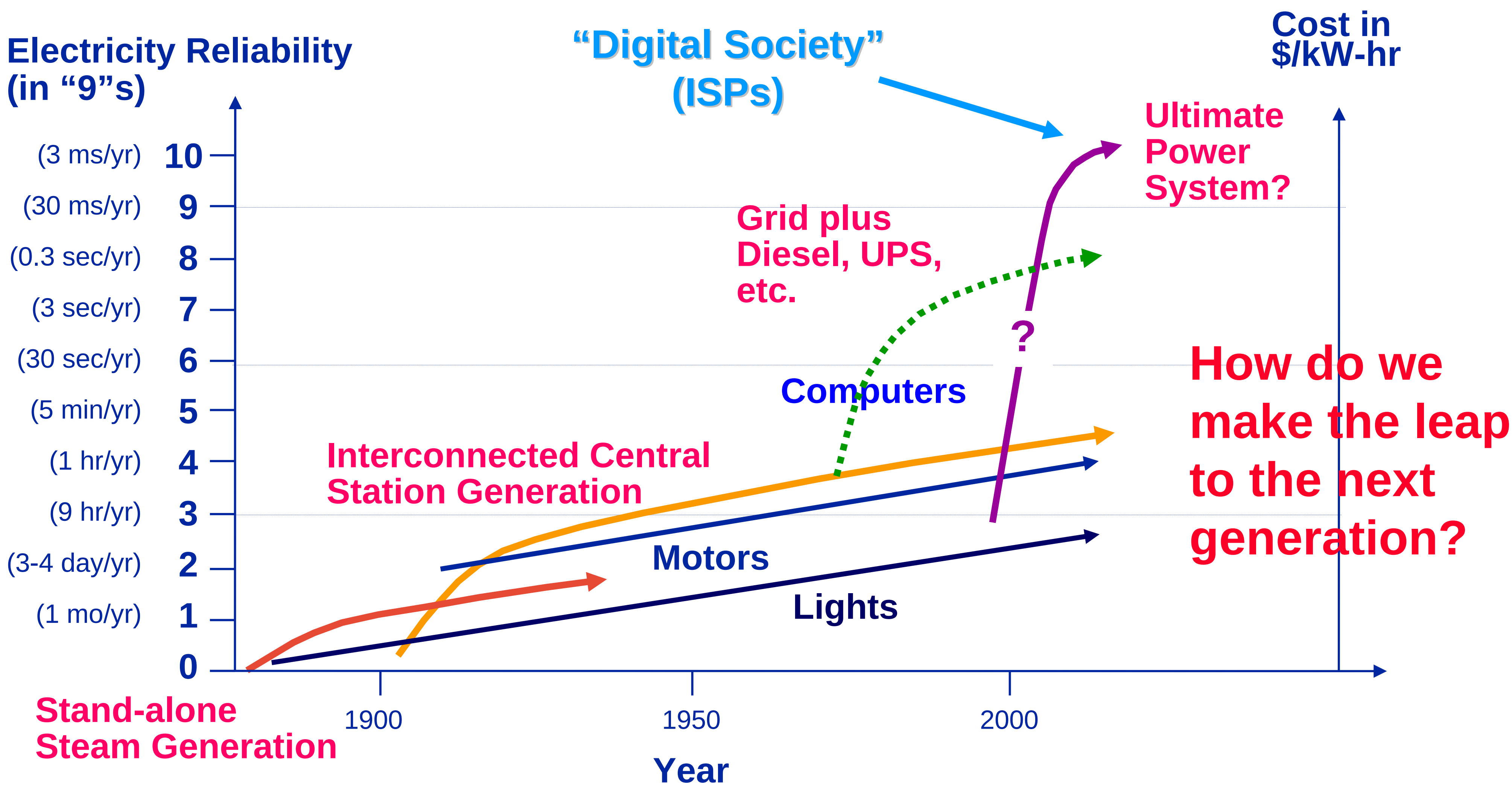
Technology Challenge for Powering the Digital Society



Power interruptions & inadequate power quality cause economic losses to our nation conservatively estimated to be over $119 Billion/year.

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Vulnerabilities: Power Grid Examples

- November 1965 blackout in the Northeast U.S., which cascaded system collapse in ten states.
- 1967 Pennsylvania-New Jersey-Maryland.
- July 13, 1977 blackout in New York City.
- December 19, 1978 blackout due to voltage collapse in France.
- July and August 1996 outages in the western U.S.
- December 1998, Bay Area black-out. NY July 7, 1999 blackout.
- December 1998 ice storms in Hydro Quebec
- December 1999 winter storms in France
- Industry-wide Y2K readiness program identified telecommunications failure as the biggest risk of the lights going out on rollover to 2000.
- Past summers' price spikes
- Aftermath of tragic events of 11th September.

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EPRI/DOD Complex Interactive Network/Systems Initiative

The Reason for this Initiative: "Those who do not remember the past are condemned to repeat it."
George Santayana

- Two faults in Oregon (500 kV & 230 kV) led to…
  - …tripping of generators at McNary dam
  - …500 MW oscillations
  - …separation of the Pacific Intertie at the California-Oregon border
  - …blackouts in 13 states/provinces
- Some studies show with proper "intelligent controls," all would have been prevented by shedding 0.4% of load for 30 minutes!
- … everyone wants to operate the power system closer to the edge. It's a good idea. But to do that we should know
  - *where is the edge*, and
  - *how close are we to it*.

August 10, 1996

Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative

"We are sick and tired of them and they had better change!"
Chicago Mayor Richard Daley on the August 1999 Blackout

Complex interactive networks:

- *Energy infrastructure*: Electric power grids, water, oil and gas pipelines
- *Telecommunication:* Information, communications and satellite networks; sensor and measurement systems and other continuous information flow systems
- *Transportation and distribution networks*
- *Energy markets, banking and finance*

1999-2001: $5.2M / year —
Equally Funded by DoD/EPRI

Develop tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intelligence and self-healing abilities

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EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

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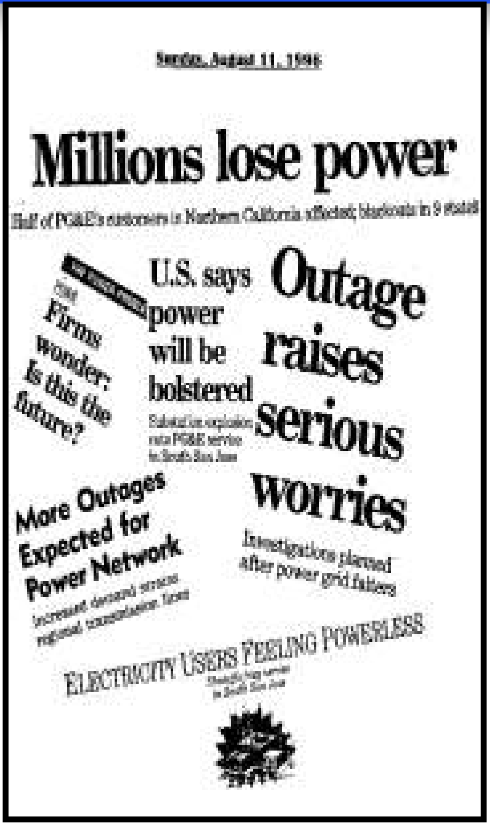

August 10, 1996

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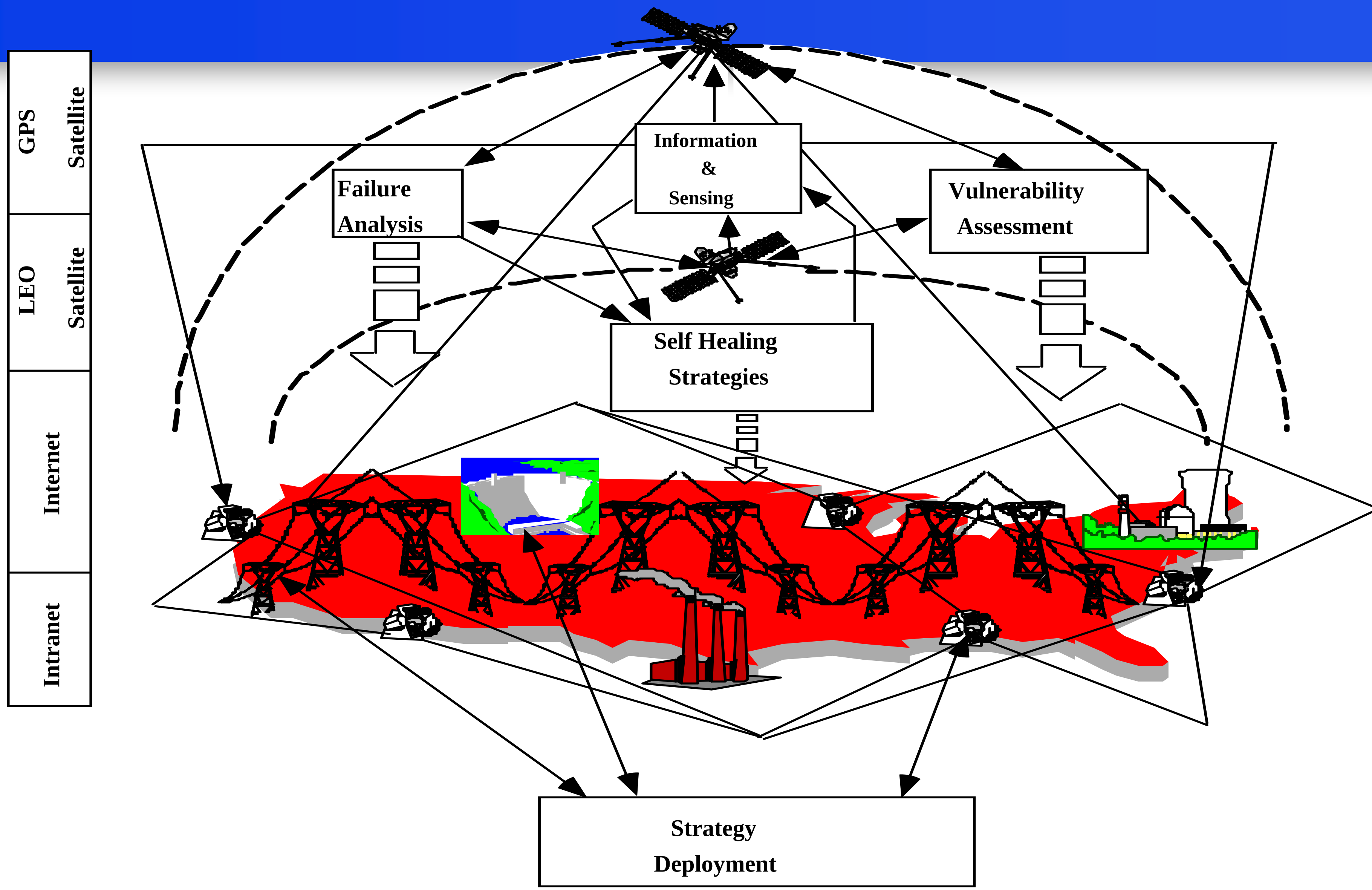
Everyone wants to operate the power system closer to the edge.
A good idea! but *where is the edge* and *how close are we to it*.

Complex Interactive Networks



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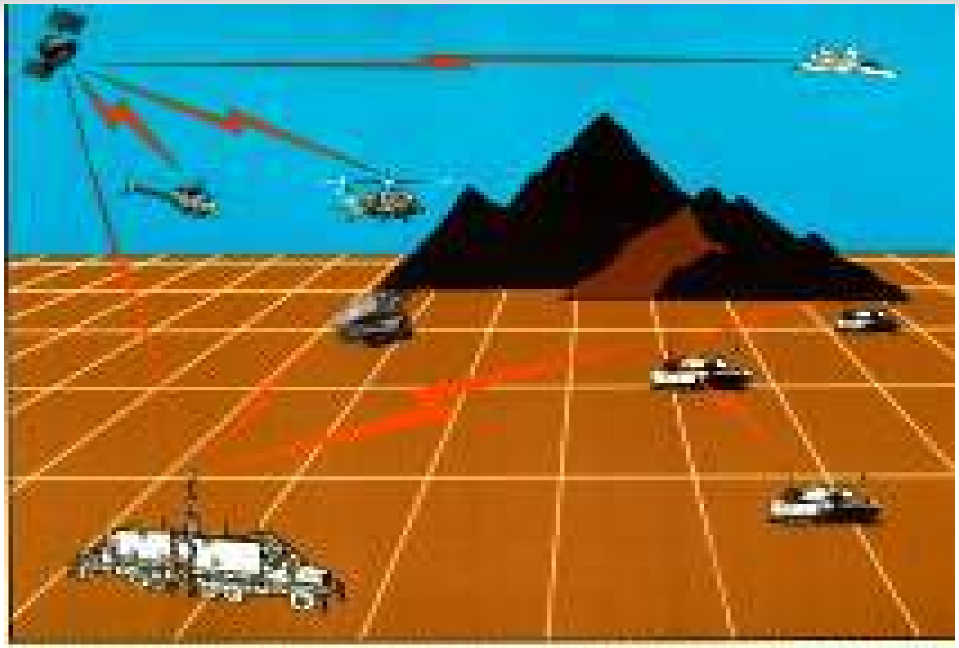
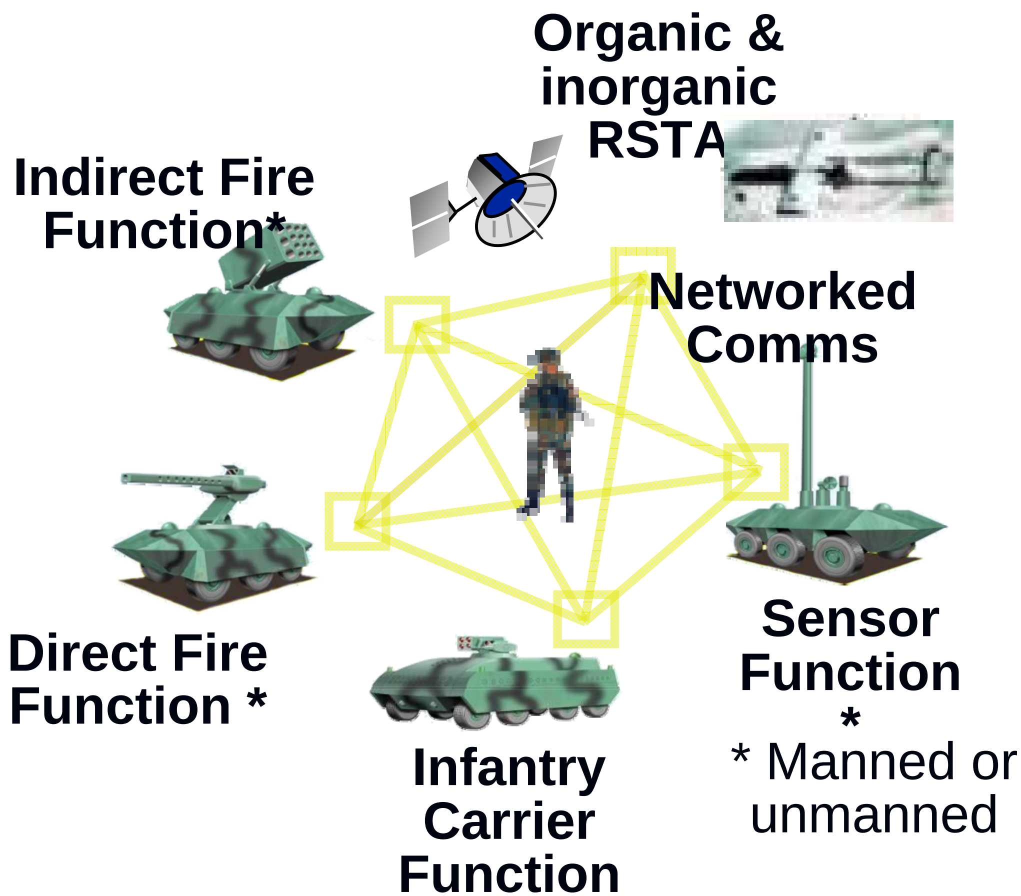
Network Centric Objective Force





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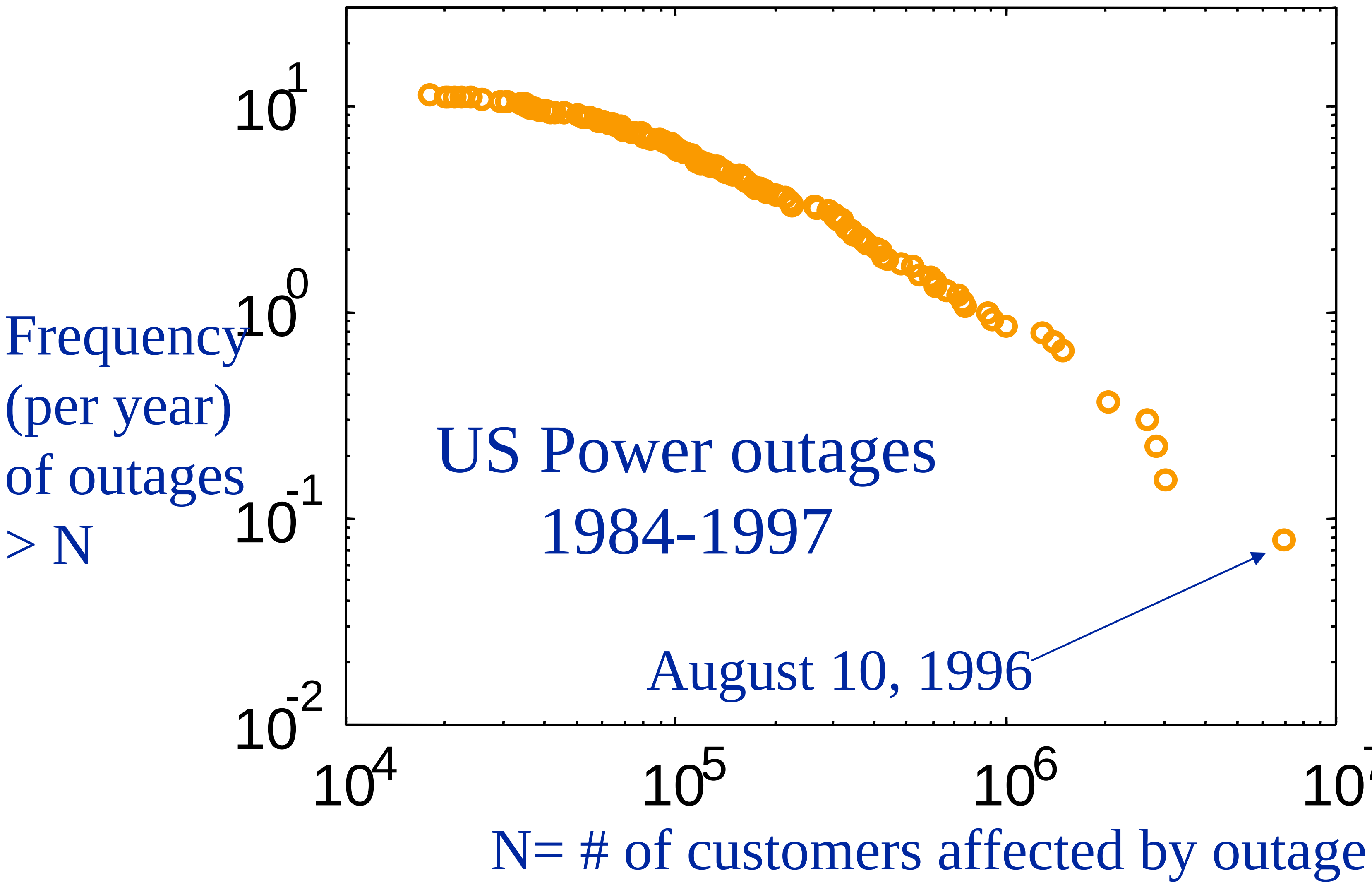
CIN/SI Funded Consortia

107 professors in 28 U.S. universities are funded: Over 360 publications, and 19 technologies extracted, in the 3-year initiative

- U Washington, Arizona St., Iowa St., VPI
- Purdue, U Tennessee, Fisk U, TVA, ComEd
- Harvard, UMass, Boston, MIT, Washington U.
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin
- CMU, RPI, UTAM, Minnesota, Illinois
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford

- Defense Against Catastrophic Failures, Vulnerability Assessment
- Intelligent Management of the Power Grid
- Modeling and Diagnosis Methods
- Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- Context Dependent Network Agents
- Mathematical Foundations: Efficiency & Robustness of Distributed Systems

Modeling and Simulation:
An Example- US Power Outages



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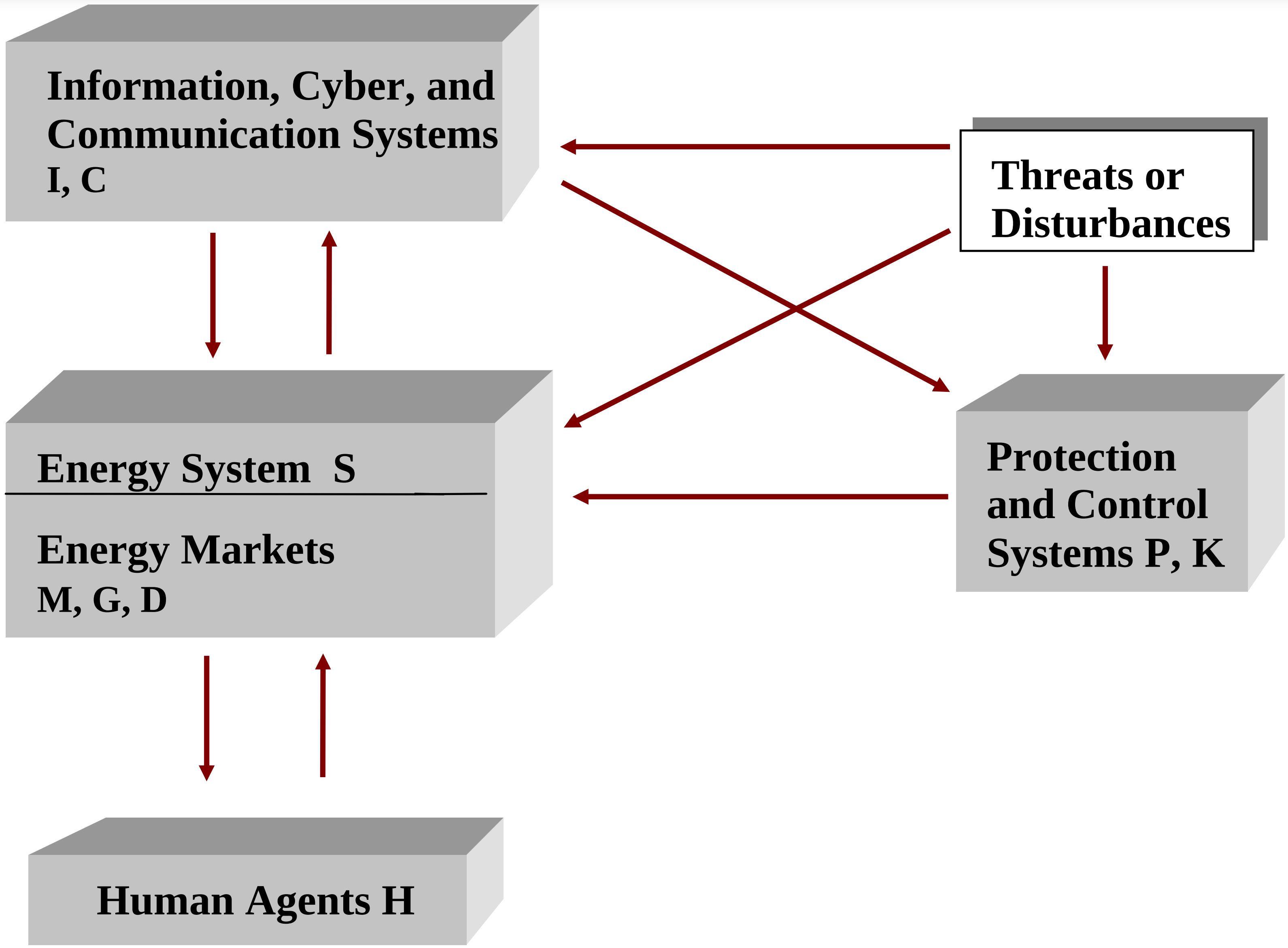
Integrated Protection and Control



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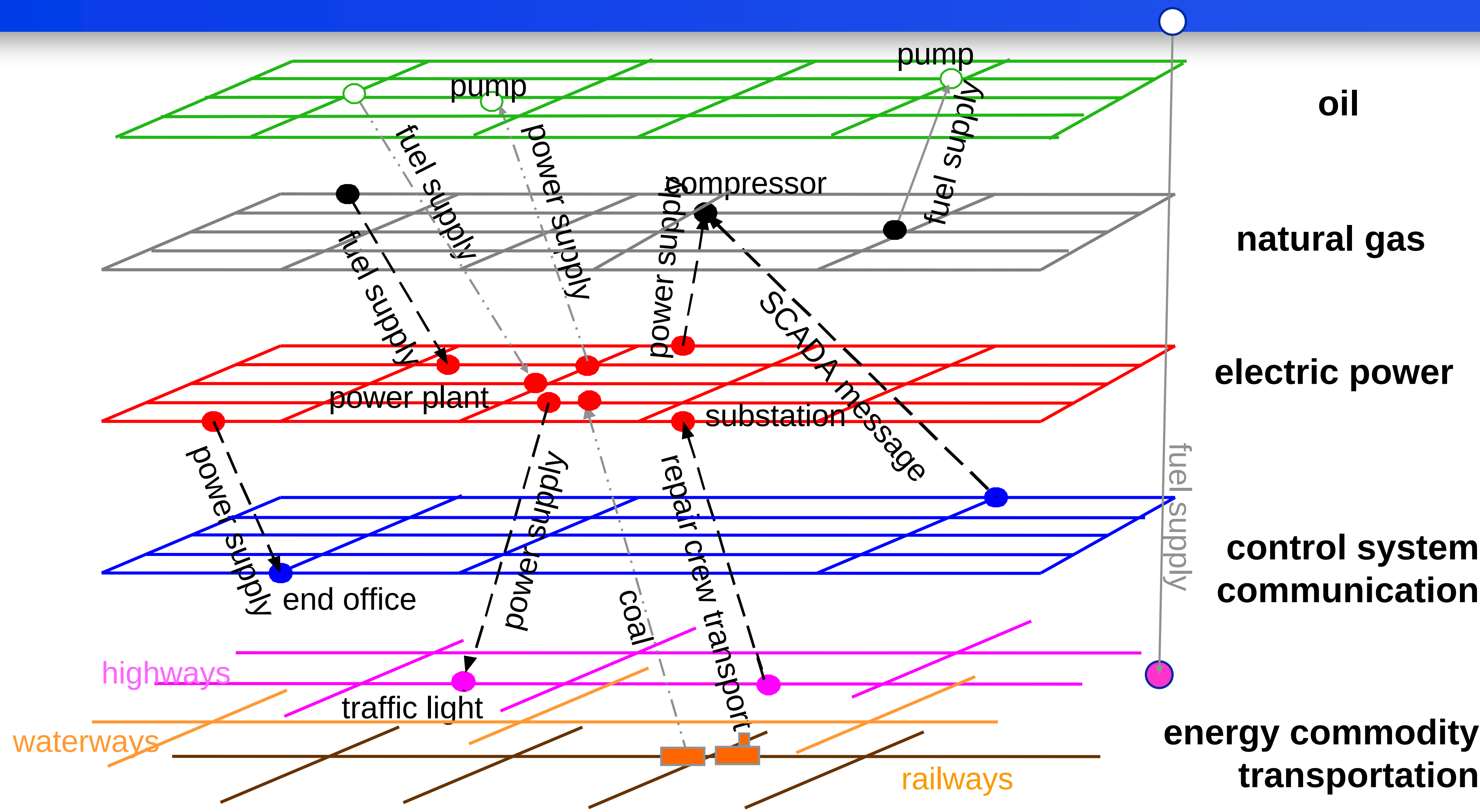
Infrastructure Interdependencies



- Critical system components
- Interdependent propagation pathways and degrees of coupling
- Benefits of mitigation plans

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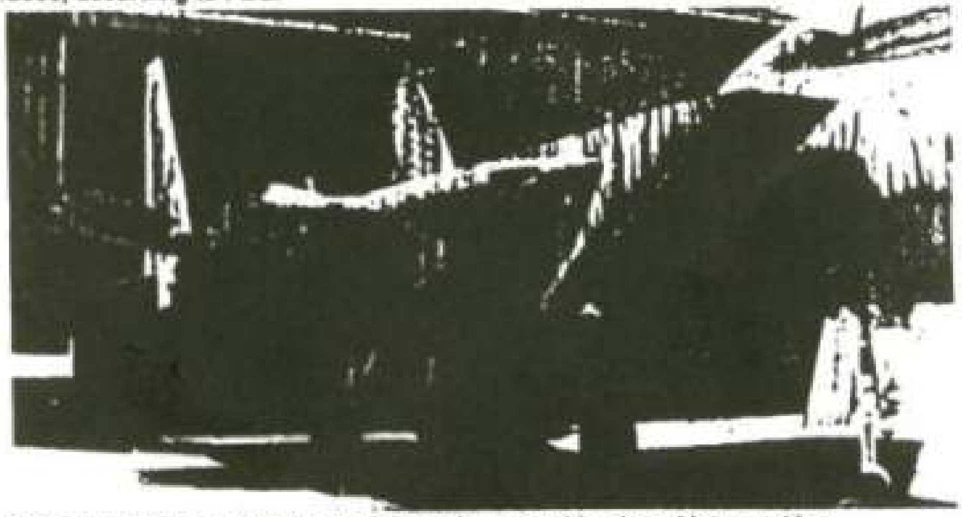
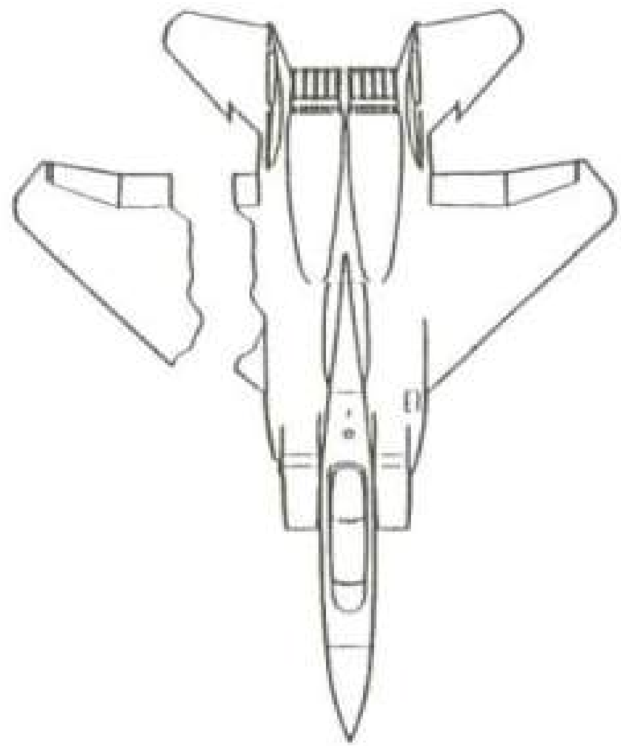
Background:
The Self Healing Grid

Background: The Case of the Missing Wing

Believe it or not, this one made it back! This F-15, with half its wing missing, is a good example of what is currently considered an "unflyable" aircraft. However, the pilot's success in bringing it home helped to inspire a new program at Aeronautical Systems Division's Flight Dynamics Laboratory aimed at enabling future fighter pilots to fly aircraft with severely damaged control surfaces. The pilot of this F-15 configured in unusual ways the control surfaces that were still working to compensate for the damaged wing. The FDL program will make this "survivors" reaction automatic to the aircraft. Therefore, flying a damaged aircraft will be much easier on the pilot. Through a self-repairing flight control system nearing development, a computerized "brain" will automatically reconfigure such surfaces as rudders, flaperons, and ailerons to compensate for grave damage to essential flying surfaces, according to FDL.

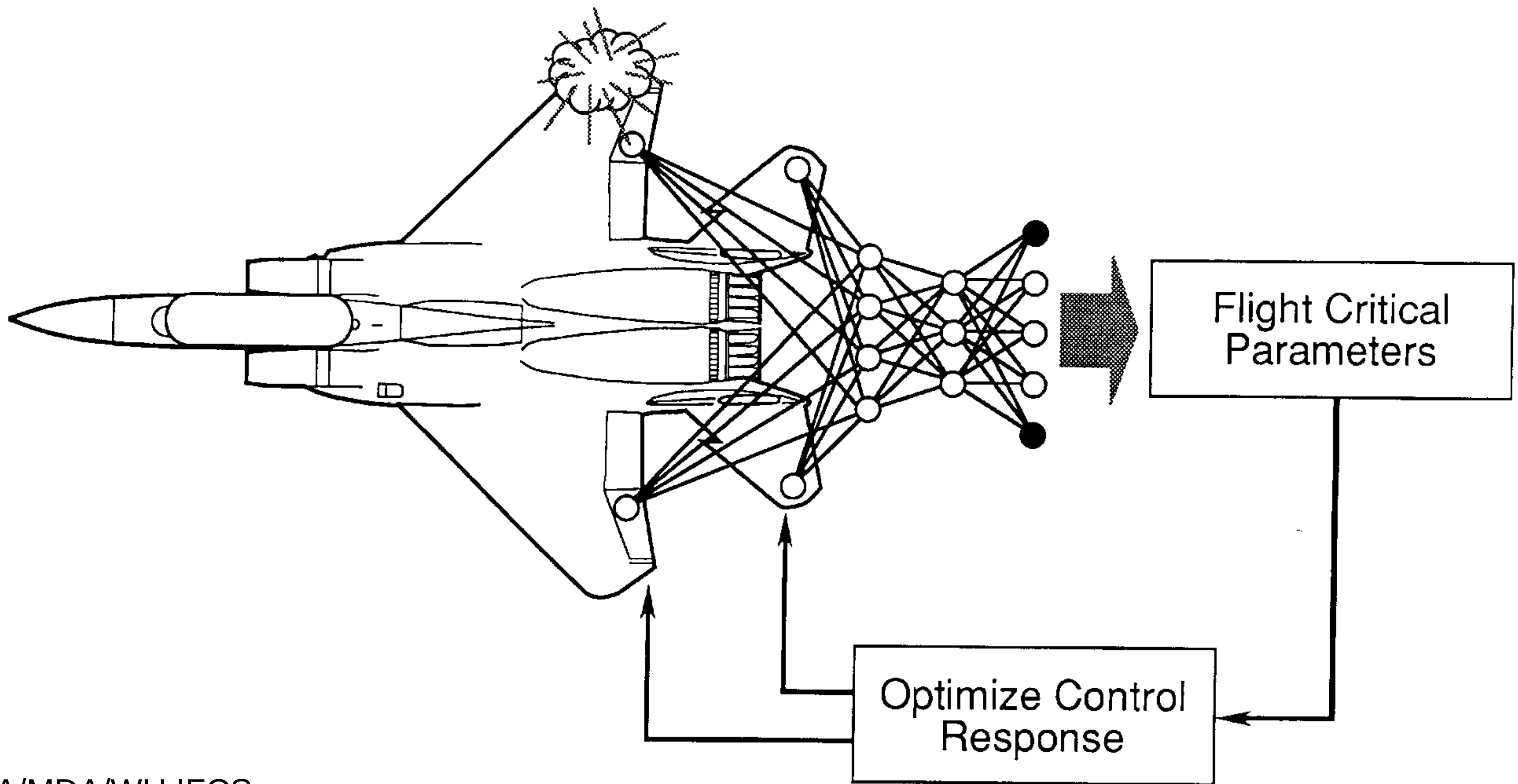


Only smart work by the pilot and the unique combination of interworking control surfaces on the F-15 brought this one back alive. With old-fashioned conventional ailerons and horizontal stabilizer, it couldn't have happened.



NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University in St. Louis (our team at WU with my graduate students 1994-1997).

Goal: Optimize controls to compensate for damage or failure conditions of the aircraft*



NASA/MDA/WU IFCS

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Dynamical System Estimation: Topology of RHONN

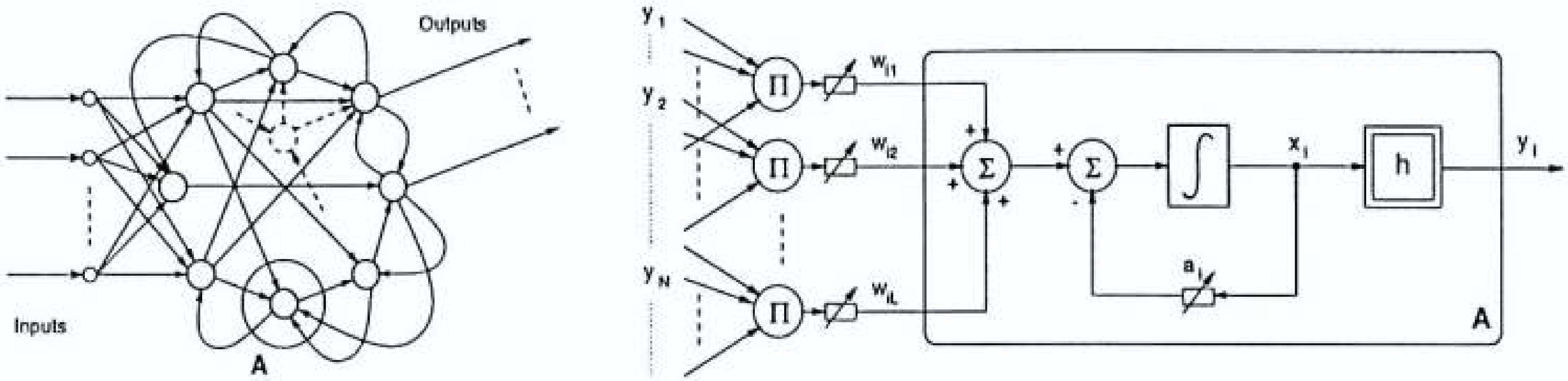


Figure 2: Network structure with higher-order unit ($d_{jk} = 1$)

- Dynamical elements in the form of feedback connections.
- Dynamical components are distributed in form of dynamical units throughout the network.
- Higher-order interactions between neurons: the input to a unit is a linear combination of the components of outputs and their products.

System Estimator: Unit Dynamics

$$
\begin{aligned}
\dot{x}_i &= -a_i x_i + \sum_{k=1}^{L} w_{ik} \prod_{j \in I_k} y_j^{d_{jk}}, \quad x_i(0) = x_{i0}, \quad i = 1, \ldots N \\
y &= [y_1, y_2, \cdots, y_M, y_{M+1}, \cdots, y_{M+N}]^T \\
&= [u_1,\ u_2,\ \ldots,\ u_M,\ h(x_1),\ h(x_2),\ \ldots,\ h(x_N)]^T
\end{aligned}
$$

where

$\{I_1, I_2, \ldots, I_L\}$	: collection of L not-ordered subsets of $\{1, 2, \ldots, M+N\}$
M	: number of inputs u_i
N	: number of dynamical units (states) x_i
$a_i > 0$	: dynamical parameter
w_{ik}	: weight parameter
$d_{jk} > 0$	: integer
$h(\cdot)$	: nonlinear continuous functions

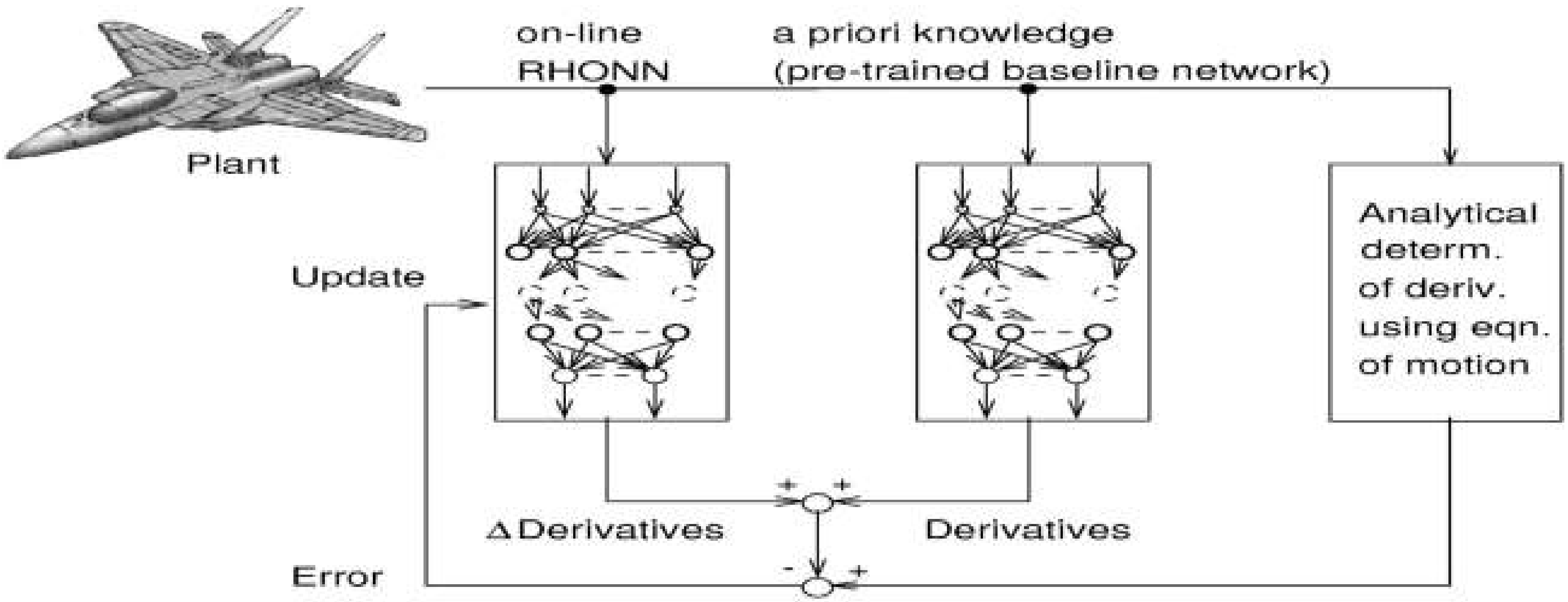
RHONN Overall System Dynamics

$$\begin{aligned} \dot{x} &= Ax + Bg(x,u), \quad x(0) = x_0 \\ y_{ext} &= Cx \end{aligned} \tag{1}$$

where

$$\begin{aligned} g &= [\prod_{j\in I_1} y_j^{d_{j1}},\ \prod_{j\in I_2} y_j^{d_{j2}},\ \ldots,\ \prod_{j\in I_L} y_j^{d_{jL}}]^T \in \mathcal{R}^L \\ x &= [x_1,\ x_2,\ \ldots,\ x_N]^T \in \mathcal{R}^N \\ A &= -diagonal\,\{a_1,\ a_2,\ \ldots,\ a_N\} \in \mathcal{R}^{N\times N} \\ b_i &= [w_{i1},\ w_{i2},\ \ldots,\ w_{iL}]^T \in \mathcal{R}^L \\ B &= [b_1,\ b_2,\ \ldots,\ b_N]^T \in \mathcal{R}^{N\times L} \end{aligned}$$

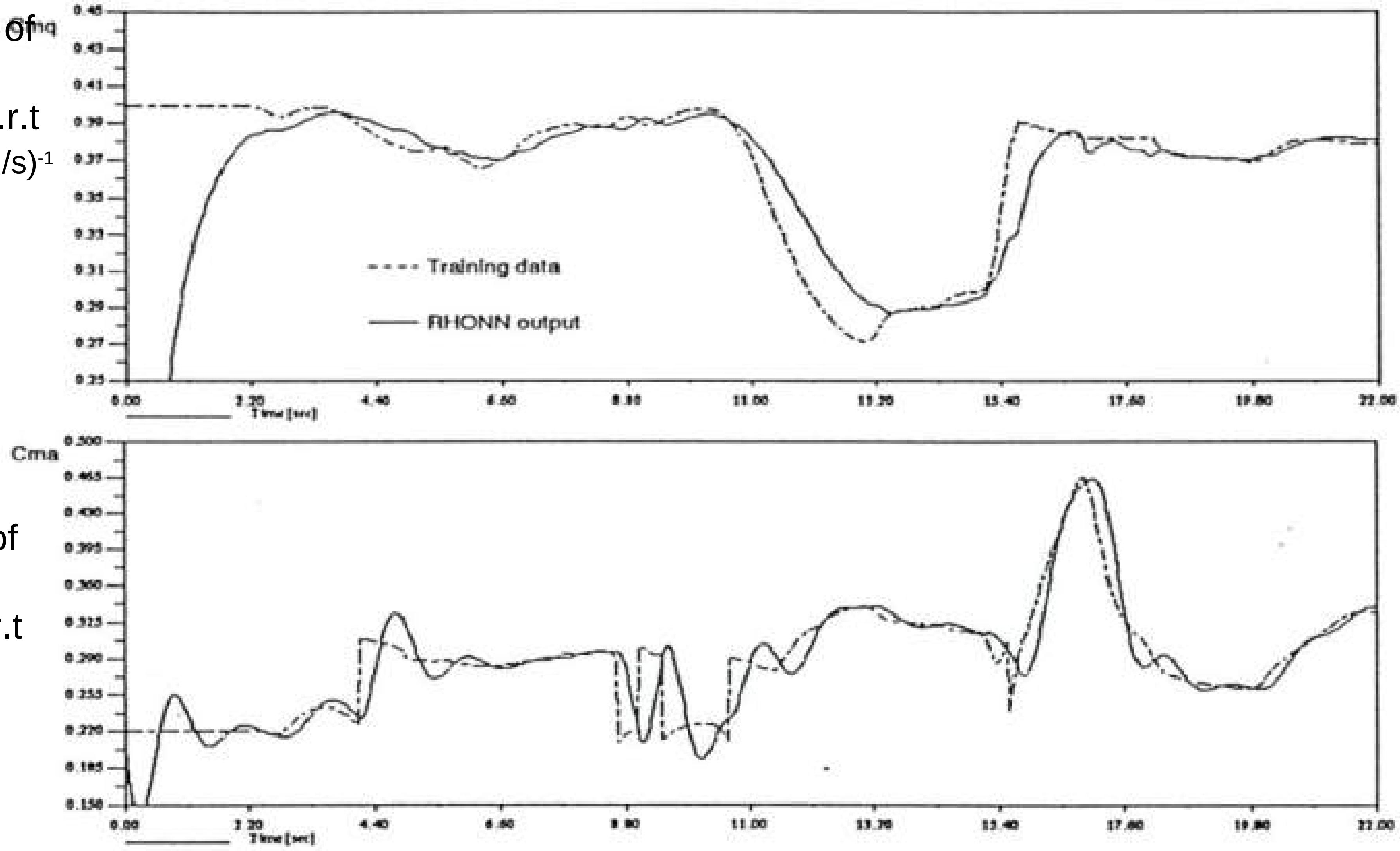
Architecture



On-Line Learning Without Baseline Network

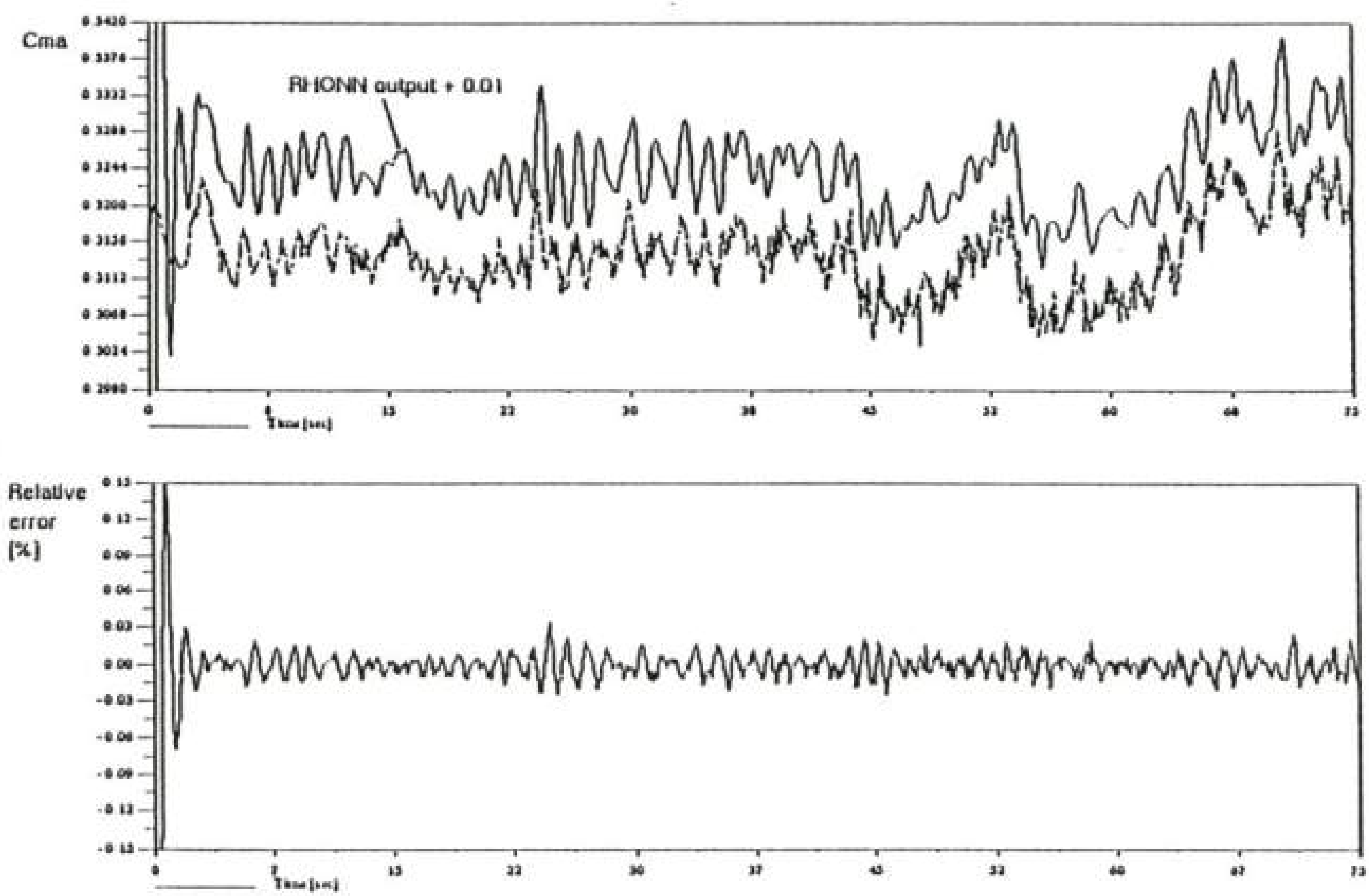
Partial Derivative of Pitching moment w.r.t pitch rate (d/s)$^{-1}$

Partial Derivative of Pitching moment w.r.t AoA (d)$^{-1}$

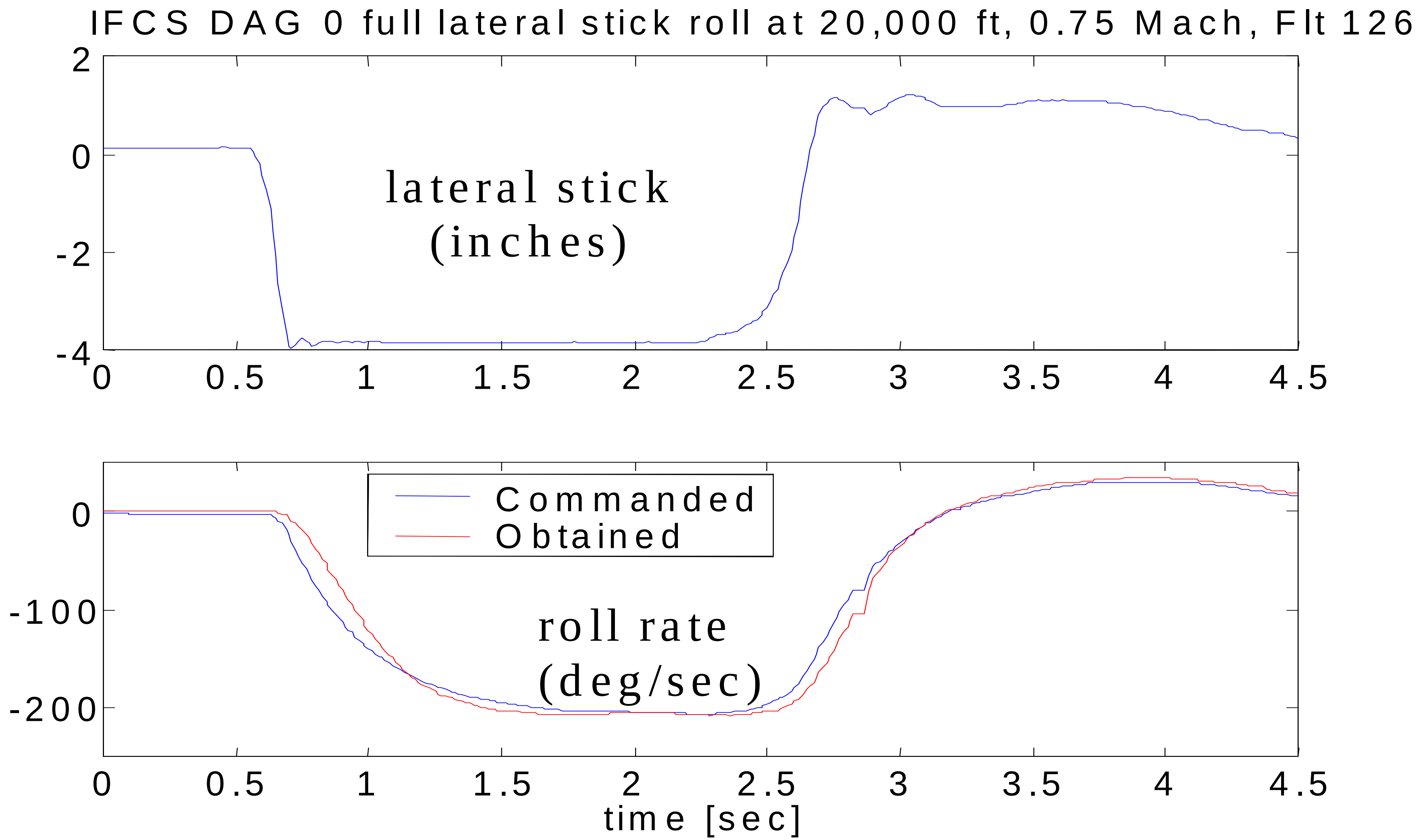


On-Line Learning Without Baseline Network

Partial Derivative of Pitching moment w.r.t AoA $(d)^{-1}$



Roll Axis Response of the Intelligent Flight Control System



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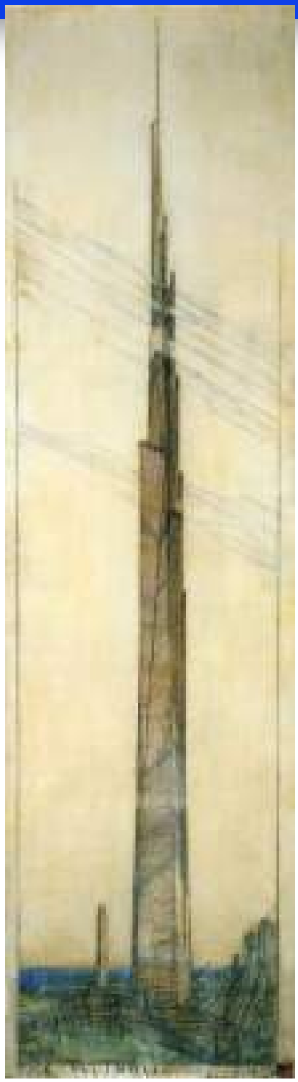
Accomplishments in the IFCS program

- The system was successfully test flown on a test F-15 at the NASA Dryden Flight Research Center:
  - Fifteen test flights were accomplished, including flight path control in a test flight envelope with supersonic flight conditions.
  - Maneuvers included 4g turns, split S, tracking, formation flight, and maximum afterburner acceleration to supersonic flight.
- Stochastic Optimal Feedforward and Feedback Technique (SOFFT) continuously optimizes controls to compensate for damage or failure conditions of the aircraft.
- Flight controller uses an on-line solution of the Riccati equation containing the neural network stability derivative data to continuously optimize feedback gains.
- Development team: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University.

Self-healing Grid



Building on the Foundation:

- Anticipation of disruptive events
- Look-ahead simulation capability
- Fast isolation and sectionalization
- Adaptive islanding

Tools: EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

Tools:

- Dynamical systems
- Statistical physics
- Information & communication science
- Computational complexity

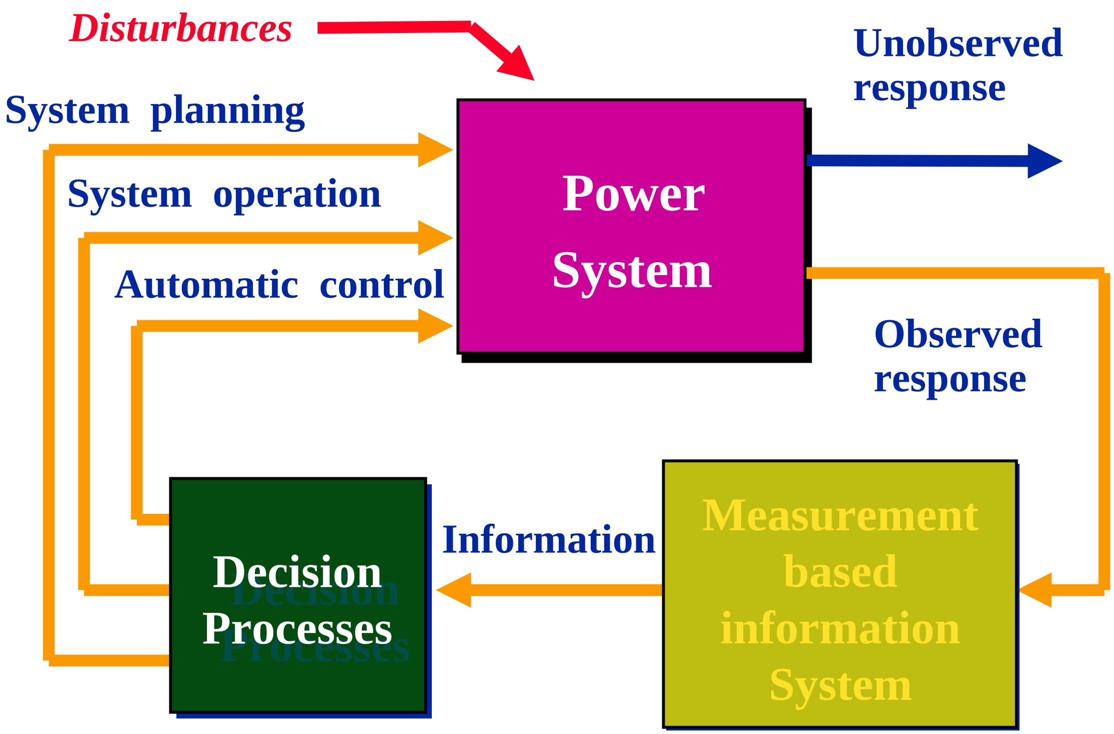
To measure and model coupled large-scale systems including:

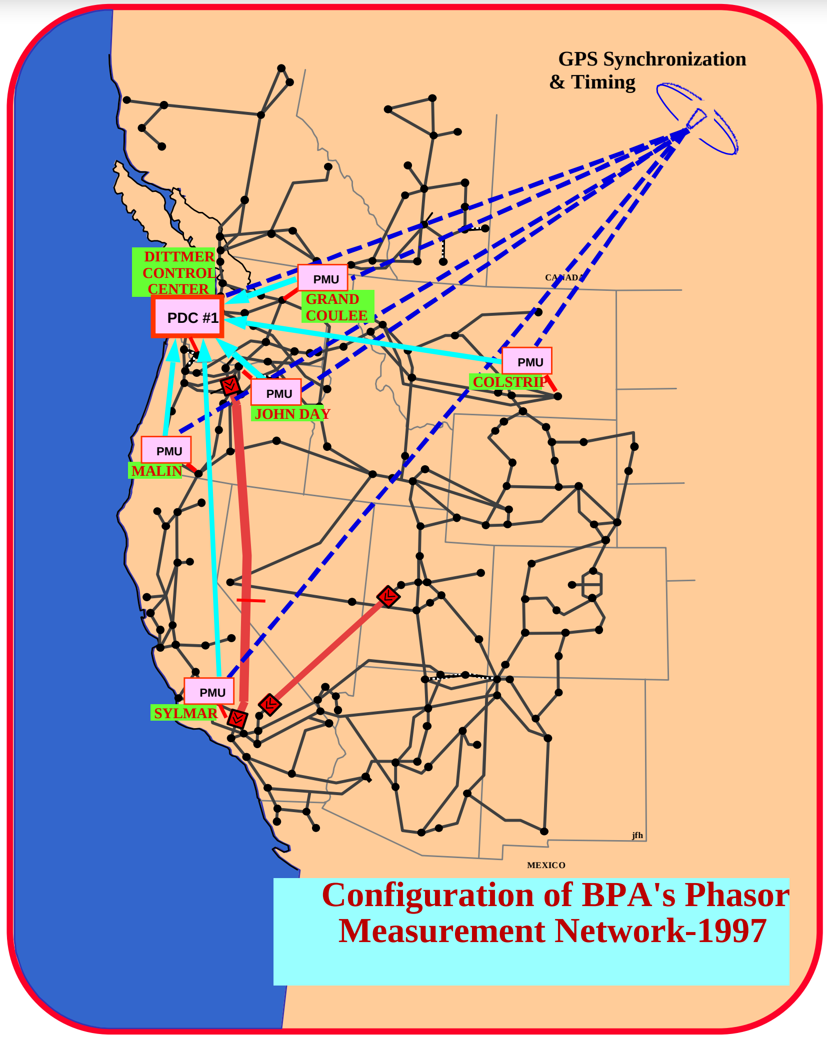
- Electricity Infrastructure
- Telecommunication networks
- Economic markets
- Cell phone networks and the Internet
- Other complex systems

Wide-Area Measurement System (WAMS)

Integrated measurements facilitate system management

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





Source: DOE/EPRI WAMS project-- BPA & PNNL

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Real-Time System Data

Collected from various monitors throughout the grid

Example: BPA's Phasor Data Concentrator

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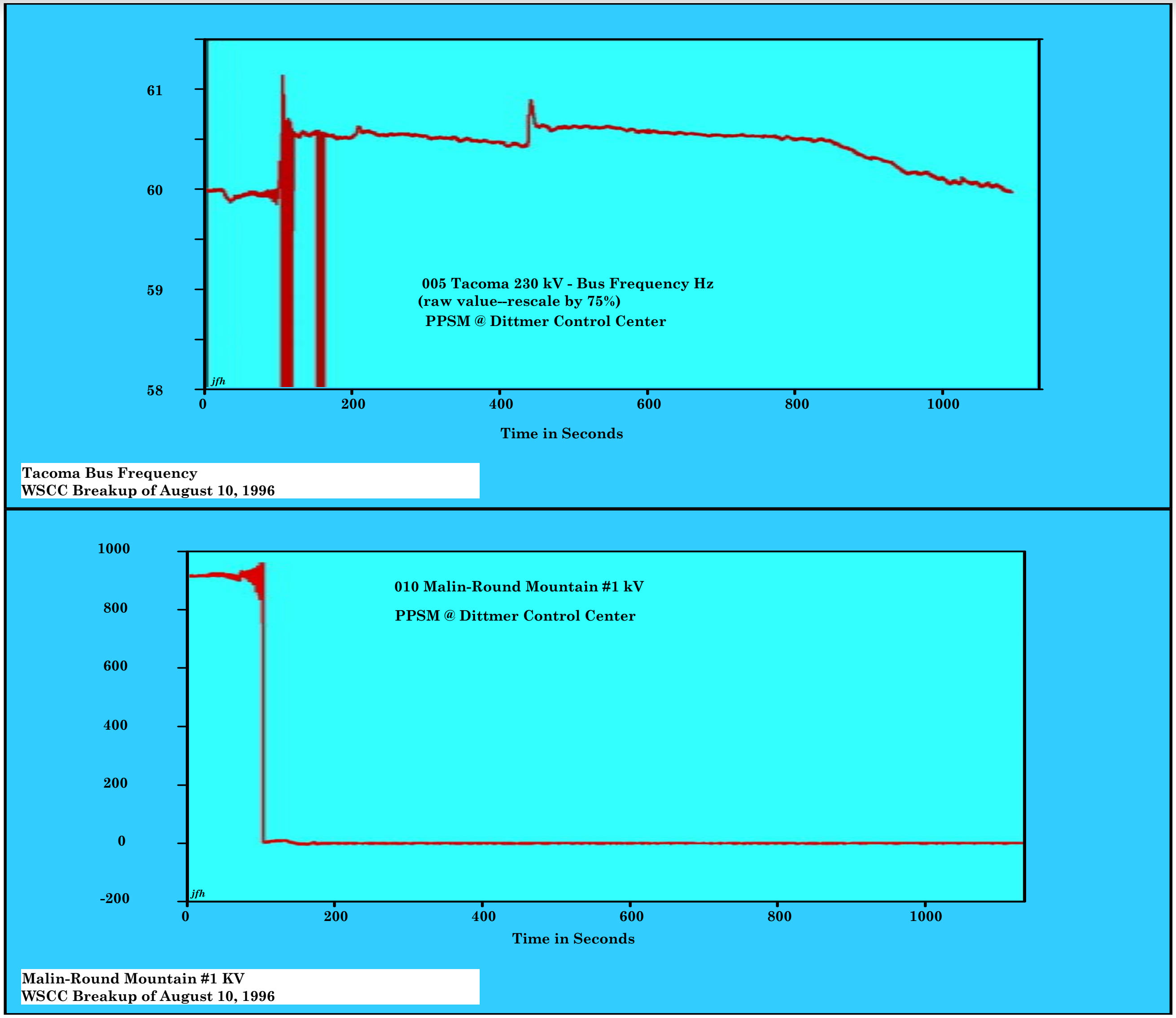
Disturbance records for WSCC breakup of August 10, 1996



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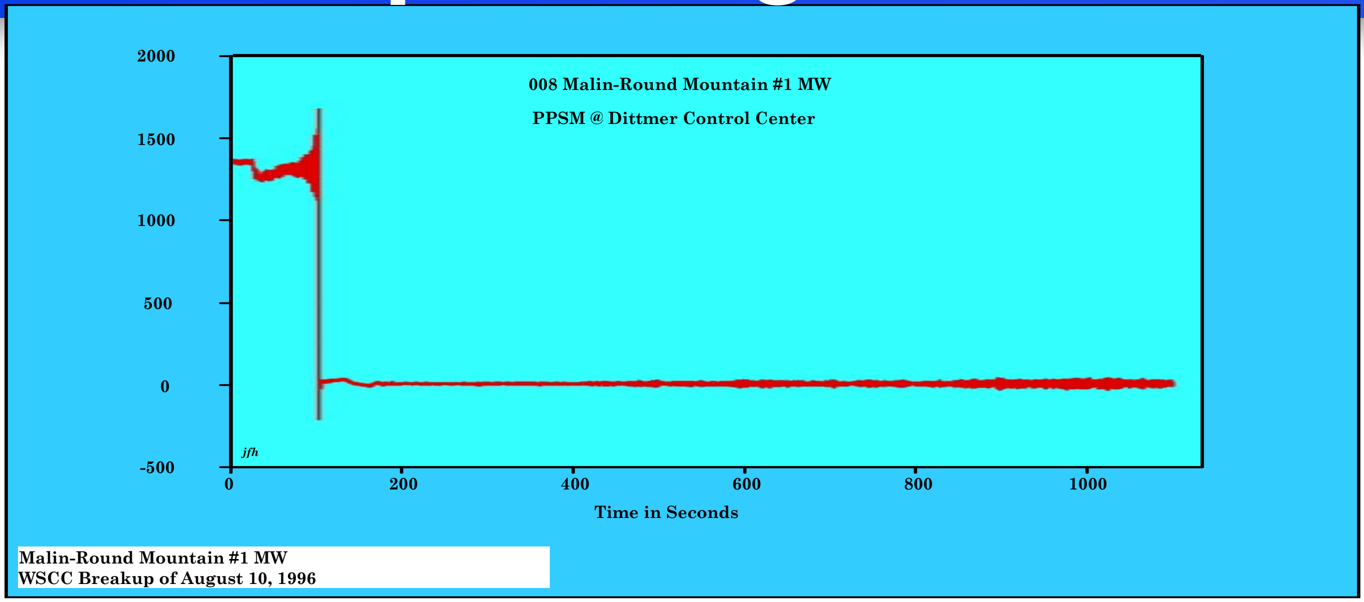

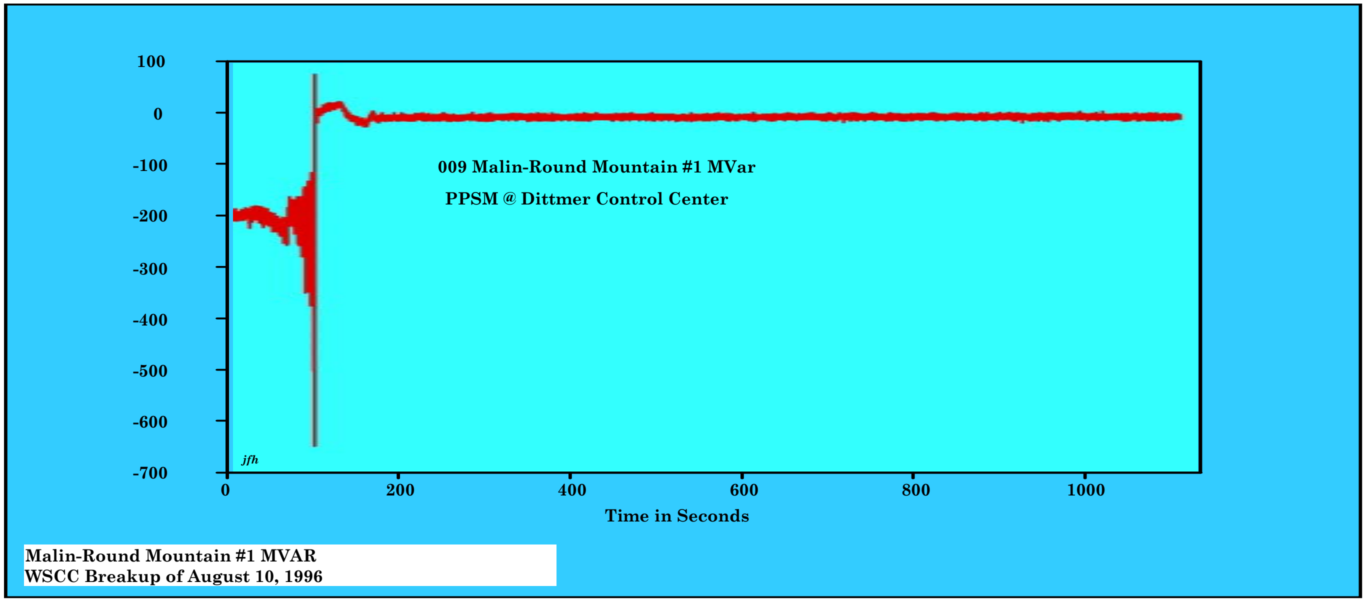

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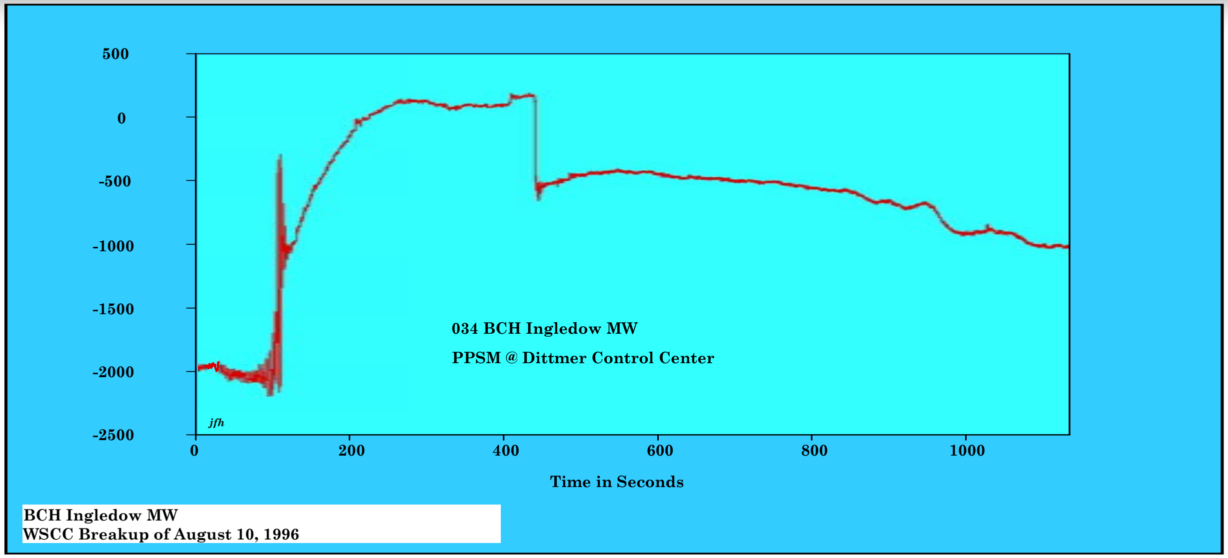

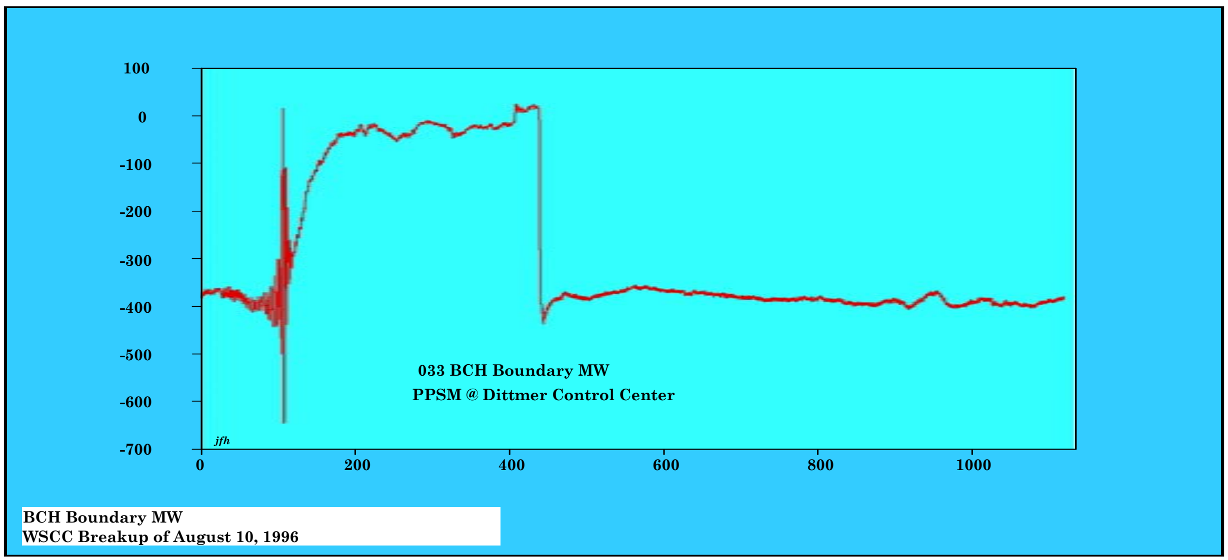

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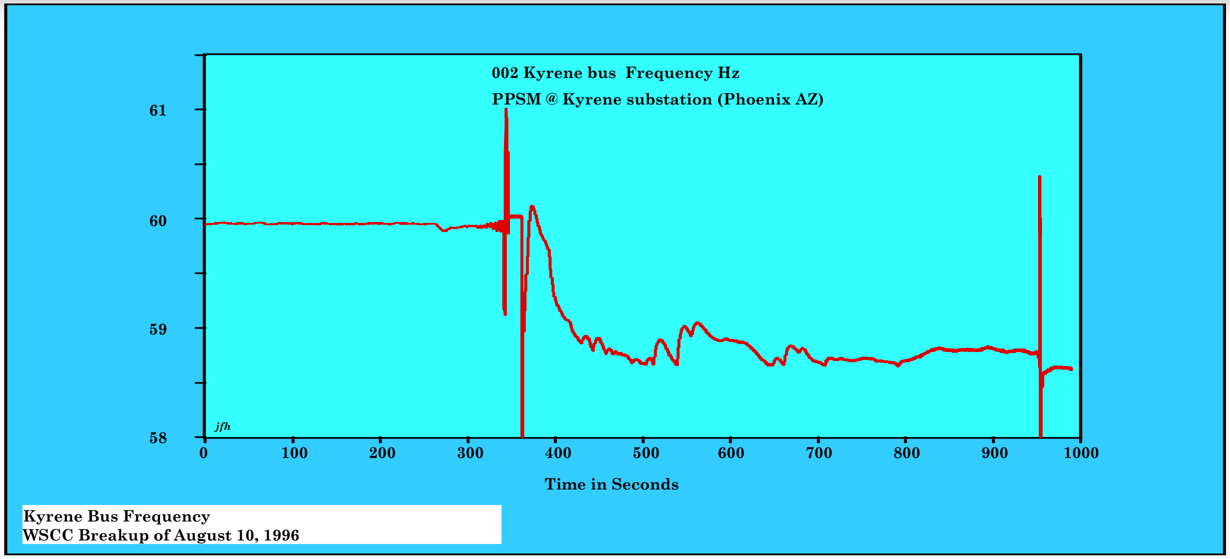

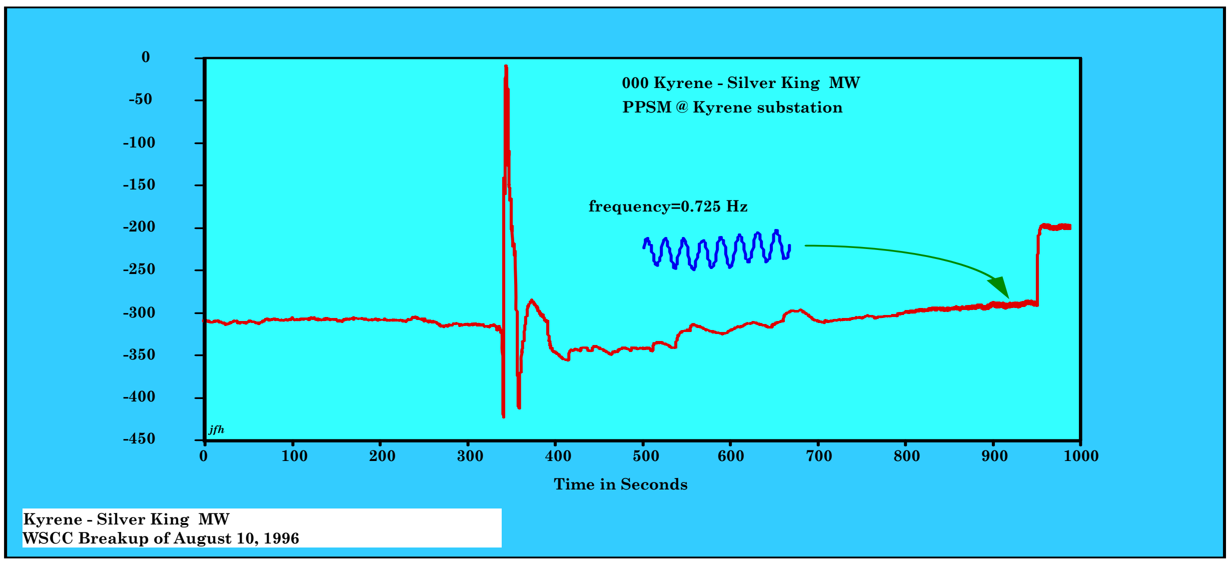

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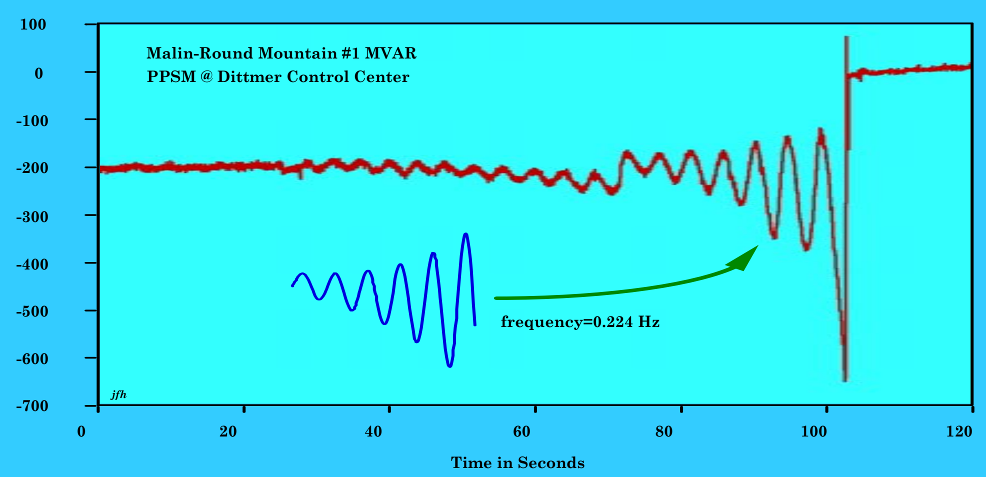
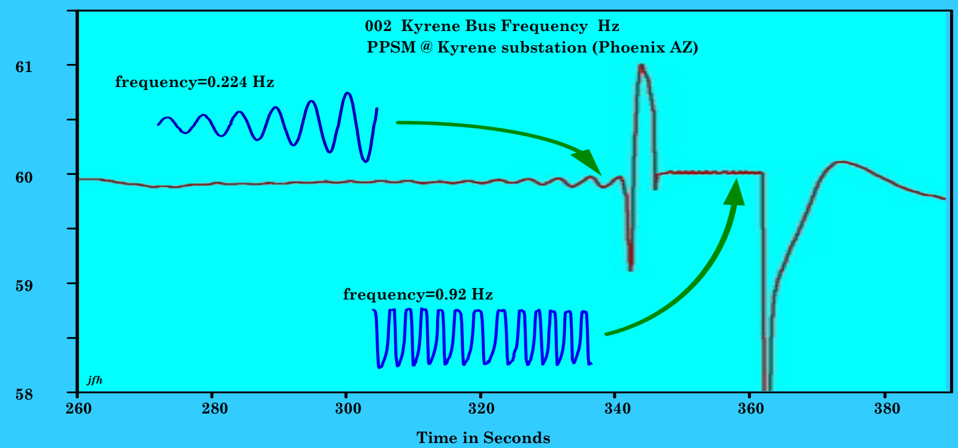


Malin-Round Mountain #1 MVAR (detail)
WSCC Breakup of August 10, 1996



Kyrene Bus Frequency (detail)
WSCC Breakup of August 10, 1996

EPRI/DoD Complex Interactive Networks
Use DRDs to Enhance Real Time System Operation

Use recorded data to

1. identify the type and location of disturbances
2. determine whether multiple events have occurred
3. assess the impact of disturbances on system
4. monitor whether the system is adequately damped
5. evaluate the needs for immediate control actions or retuning control algorithms

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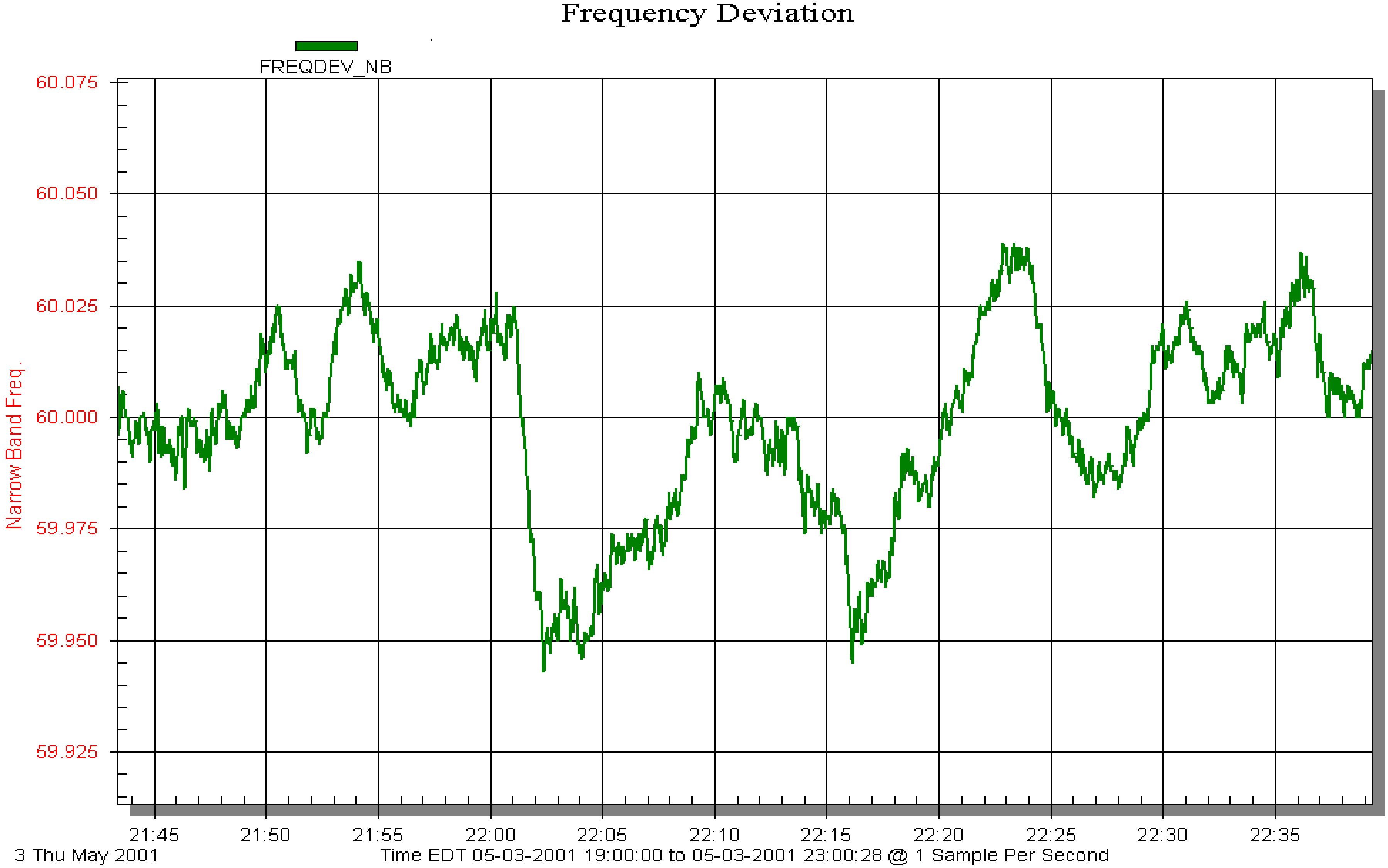
Last Episode of the TV series“Survivor”

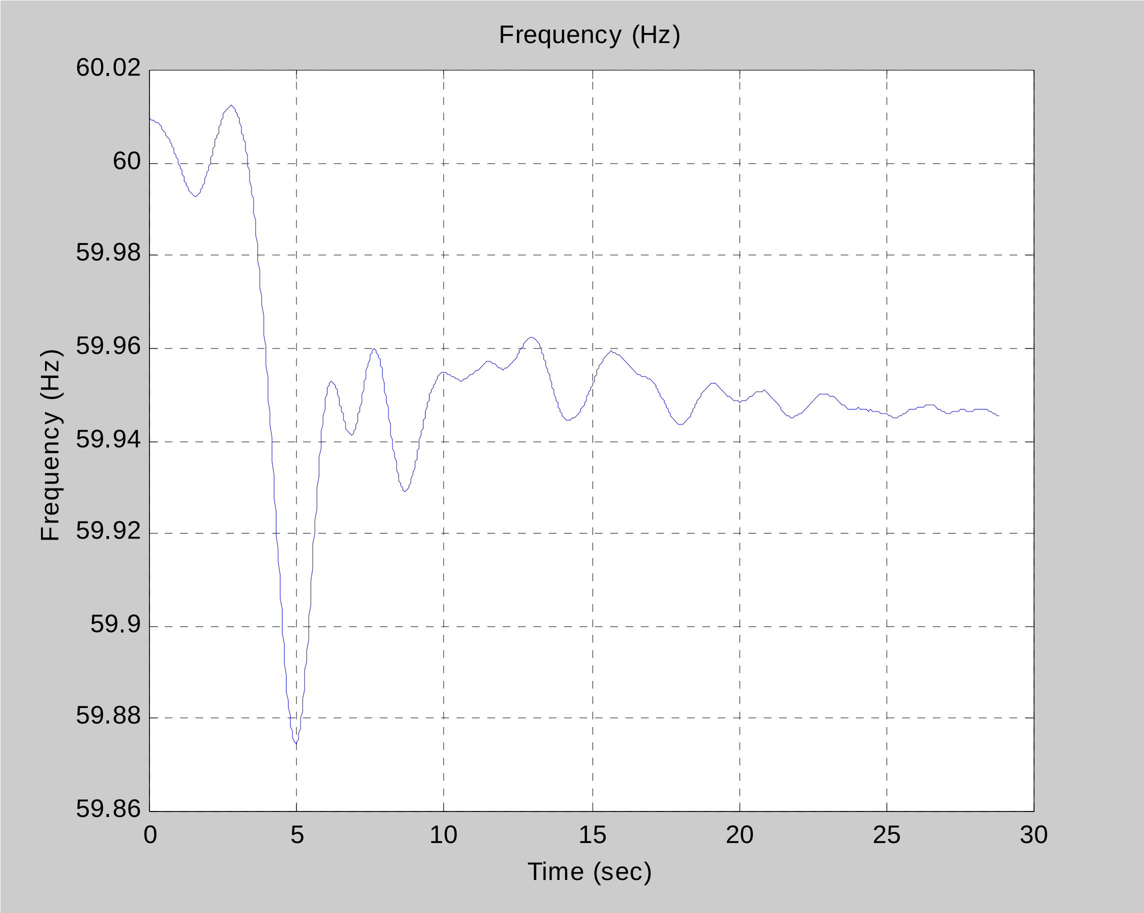


Source:Jim Ingleson of NYISO and Joe Chow (RPI)

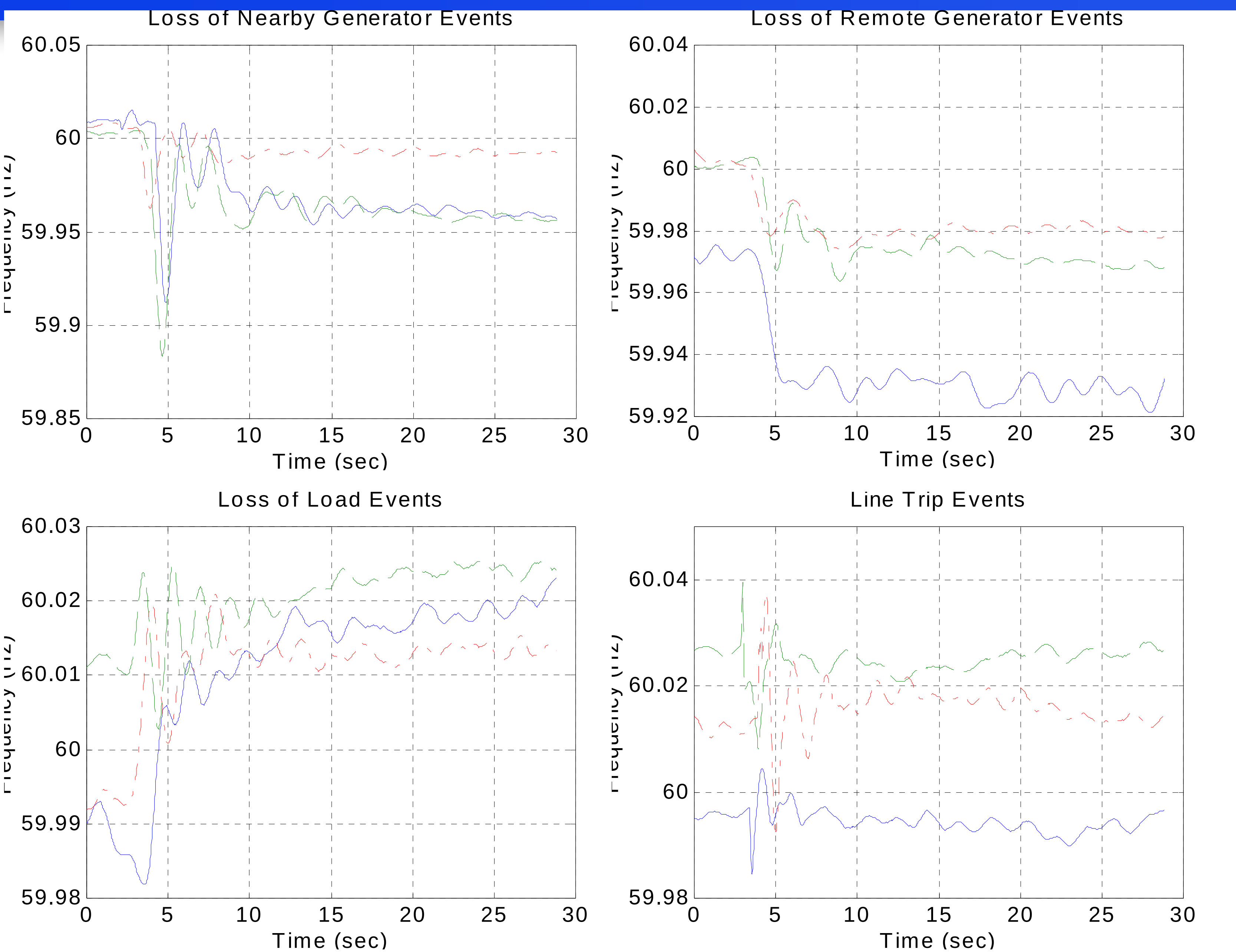
Disturbance Identification using Dynamic Recorded Data

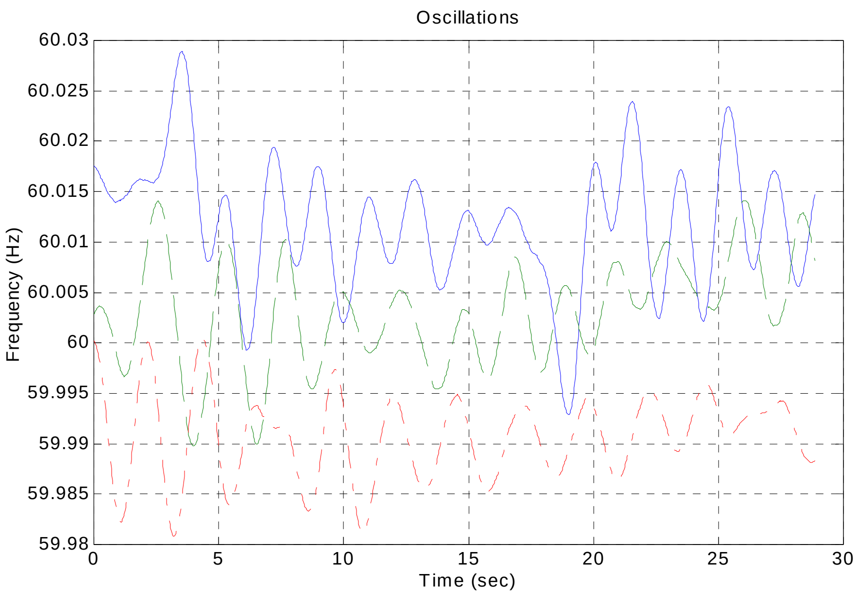
- 47 disturbance (out of several hundreds) events recorded at Northfield Substation in New England Power System were analyzed
- Feature extraction – frequency deviation, frequency derivative, and power flows
- Clustering algorithm based on frequency deviation and frequency derivative features

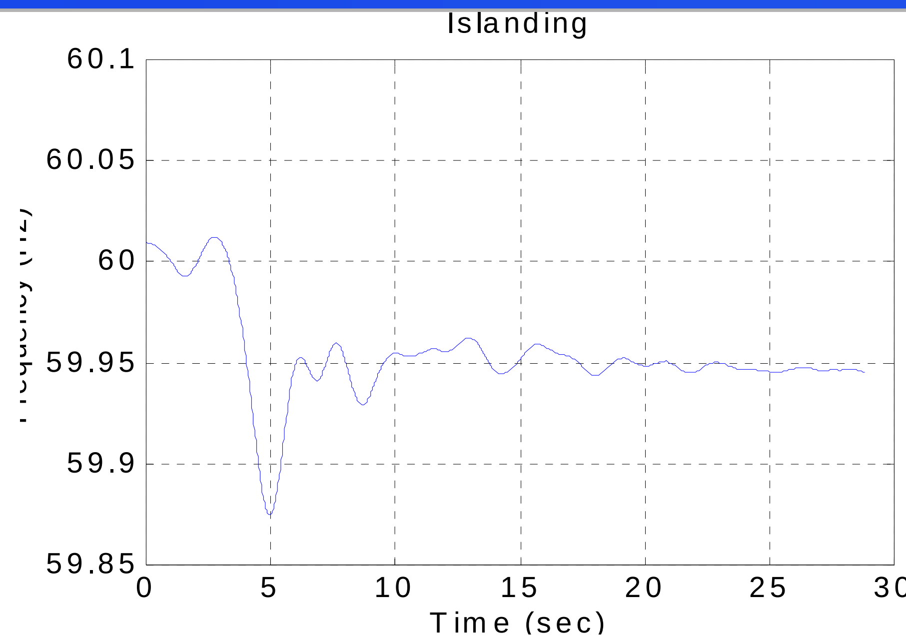
Disturbance

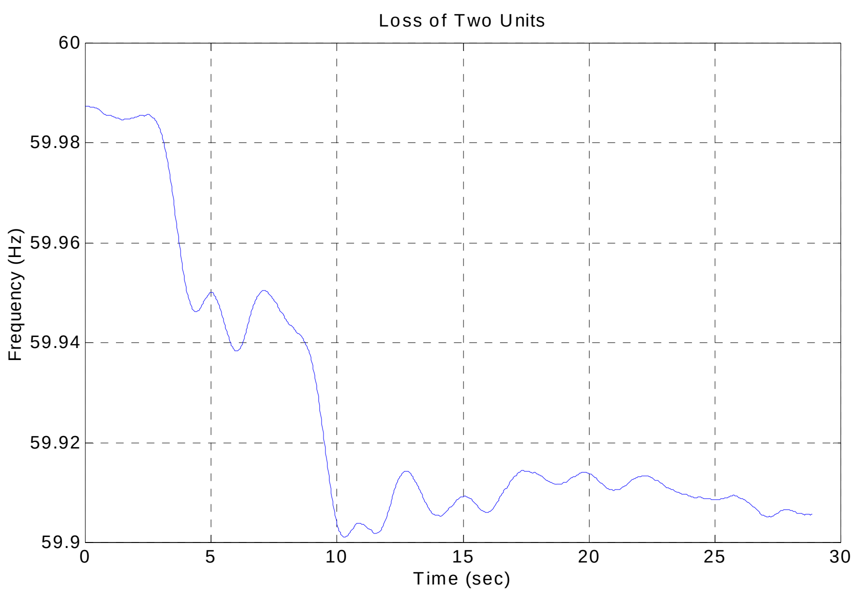


- Loss of close by generation
- Estimate how much generation is lost from tracking system frequency


Loss of Nearby Generator Events
60.05
60
59.95
59.9
59.85
0
5
10
15
20
25
30
Time (sec)
Loss of Remote Generator Events
60.04
60.02
60
59.98
59.96
59.94
59.92
0
5
10
15
20
25
30
Time (sec)
Loss of Load Events
60.03
60.02
60.01
60
59.99
59.98
0
5
10
15
20
25
30
Time (sec)
Line Trip Events
60.04
60.02
60
59.98
0
5
10
15
20
25
30
Time (sec)


Oscillations
Frequency (Hz)
60.03
60.025
60.02
60.015
60.01
60.005
60
59.995
59.99
59.985
59.98
0 5 10 15 20 25 30
Time (sec)


Islanding
60.1
60.05
60
59.95
59.9
59.85
0 5 10 15 20 25 30
Time (sec)


Loss of Two Units
Frequency (Hz)
60
59.98
59.96
59.94
59.92
59.9
0 5 10 15 20 25 30
Time (sec)

Disturbance Feature Extraction

Disturbance	Frequency change	Frequency derivative	Line flow change
Loss of nearby generation	Negative	Steep	Large
Loss of remote generation	Negative	Moderate	Negligible
Loss of load	Positive	Moderate	Detectable
Line trip close to DRD	Negligible	Steep	Large
Oscillations	Negligible	Small	oscillations

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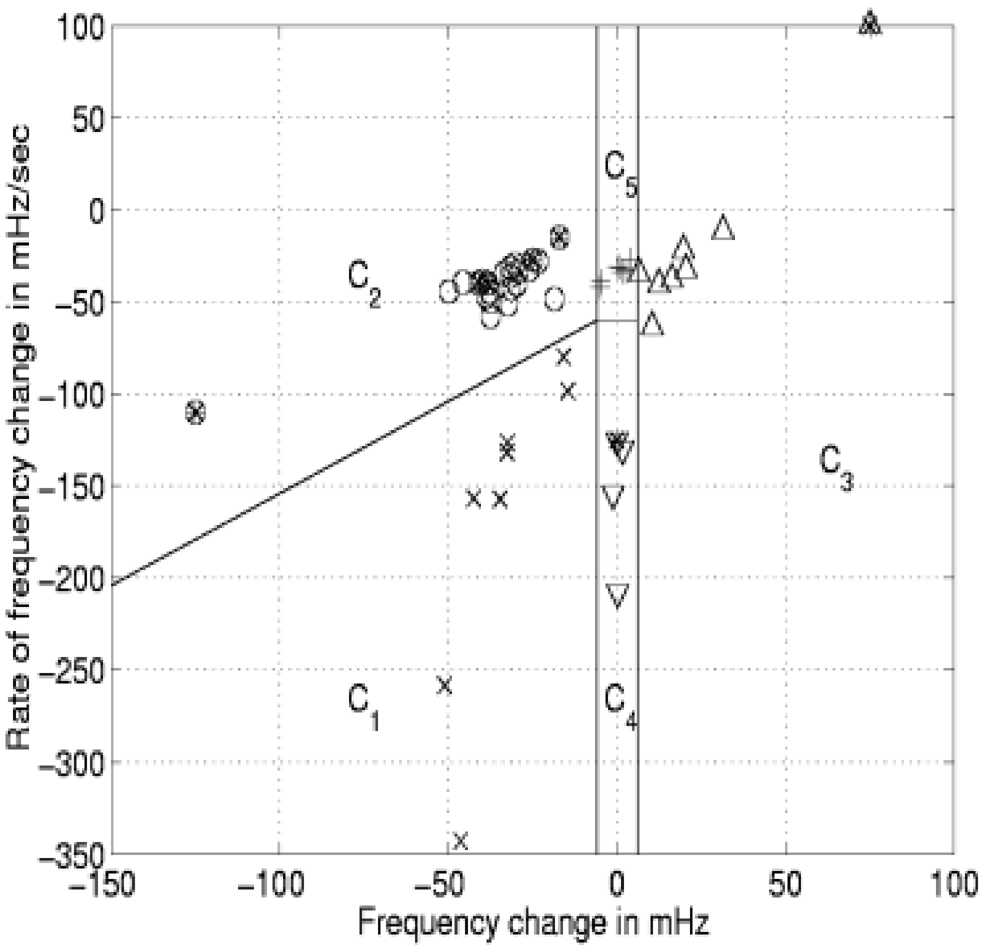
Clustering Algorithm – separate disturbance classes by hyperplanes

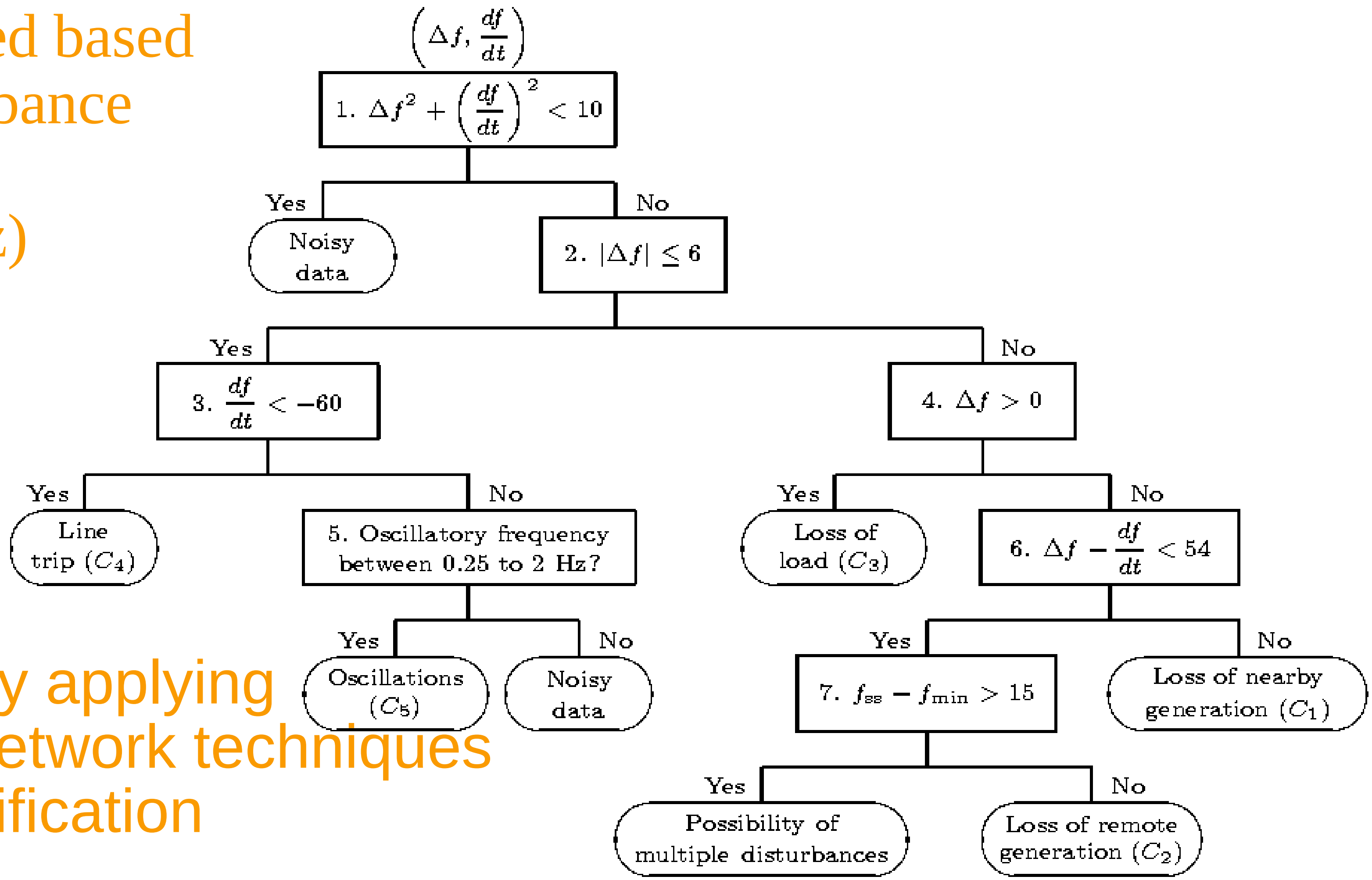


- C_1 – loss of nearby generation
- C_2 – loss of remote generation
- C_3 – loss of load
- C_4 – line trip
- C_5 – oscillations

* Markers show recorded data

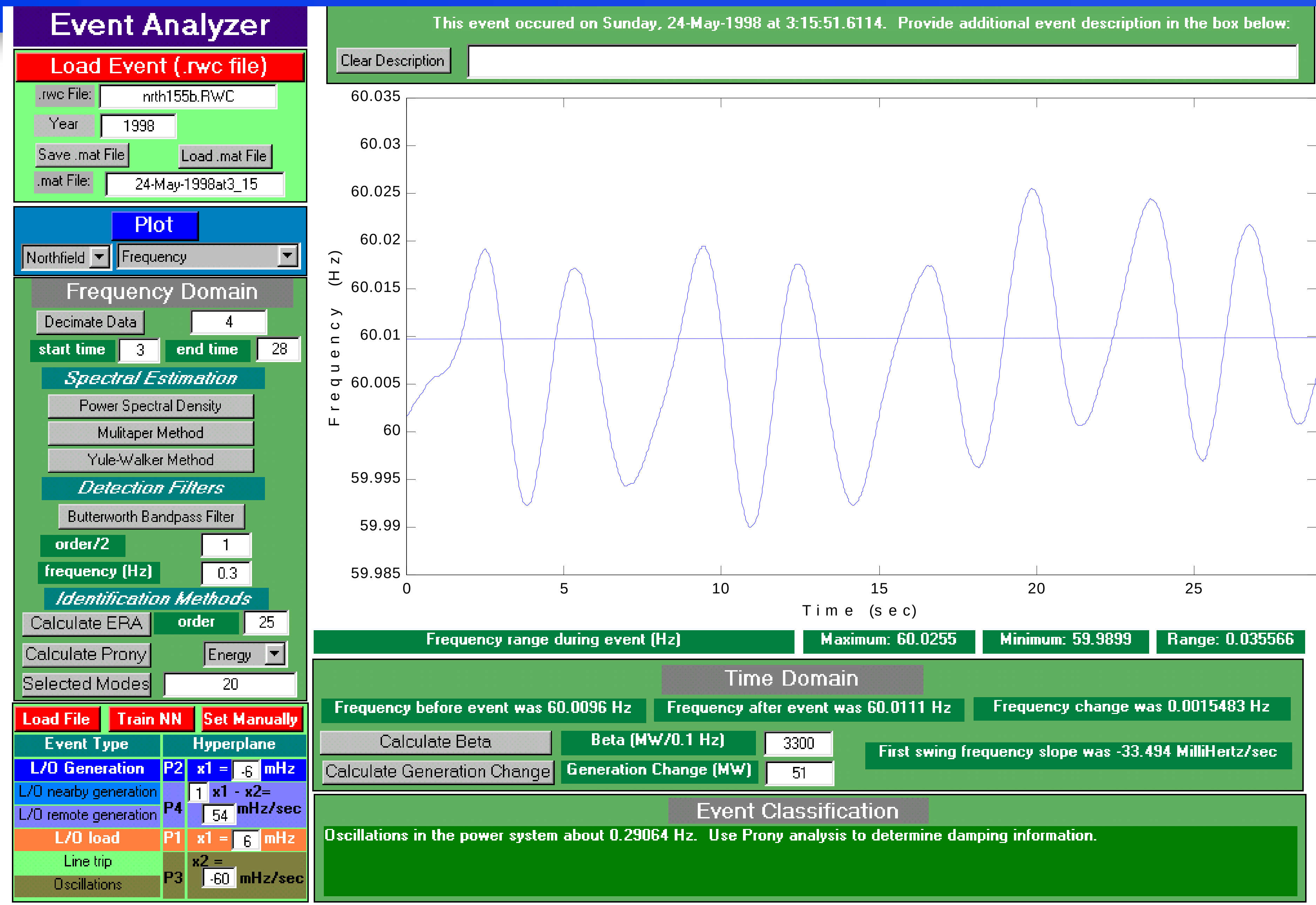
Decision Tree for Disturbance Identification

- Developed based on disturbance classes (f in mHz)



- Presently applying neural network techniques for identification

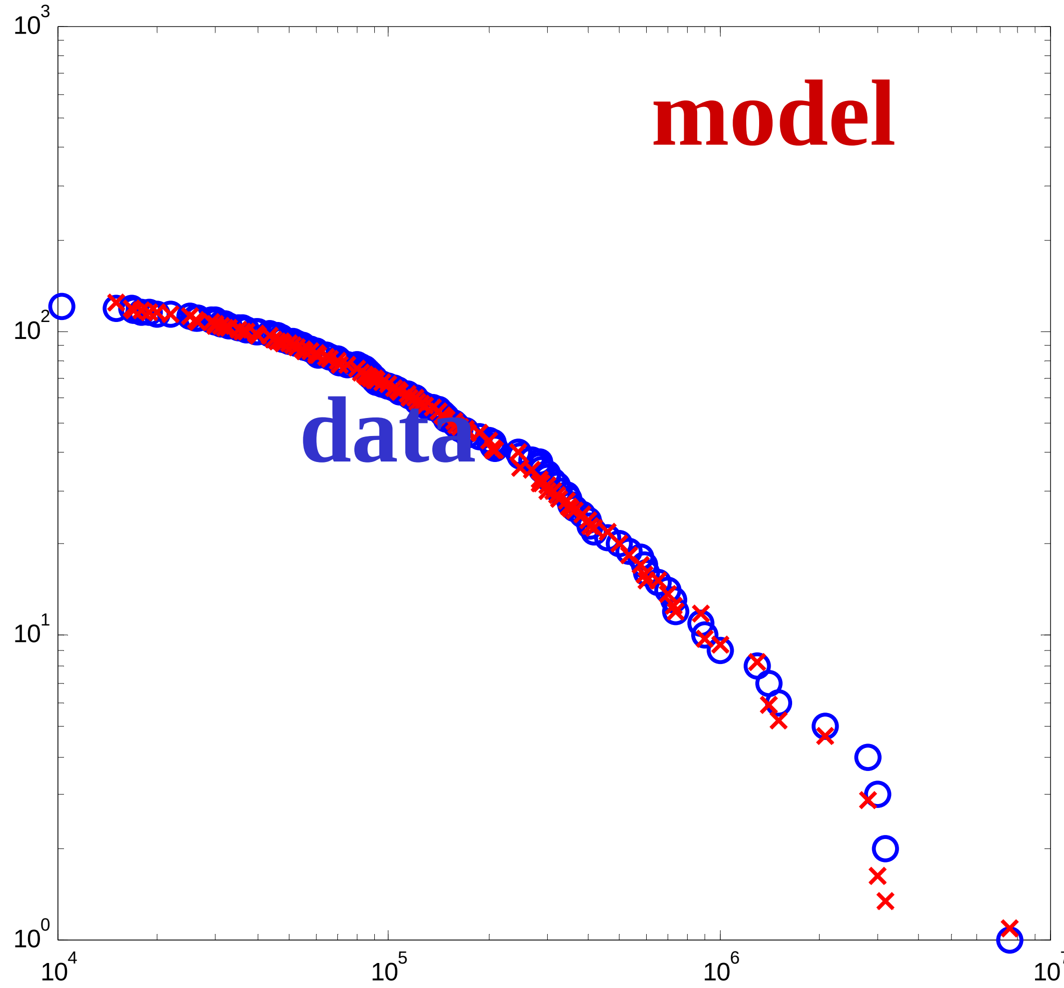
Disturbance Event Analyzer



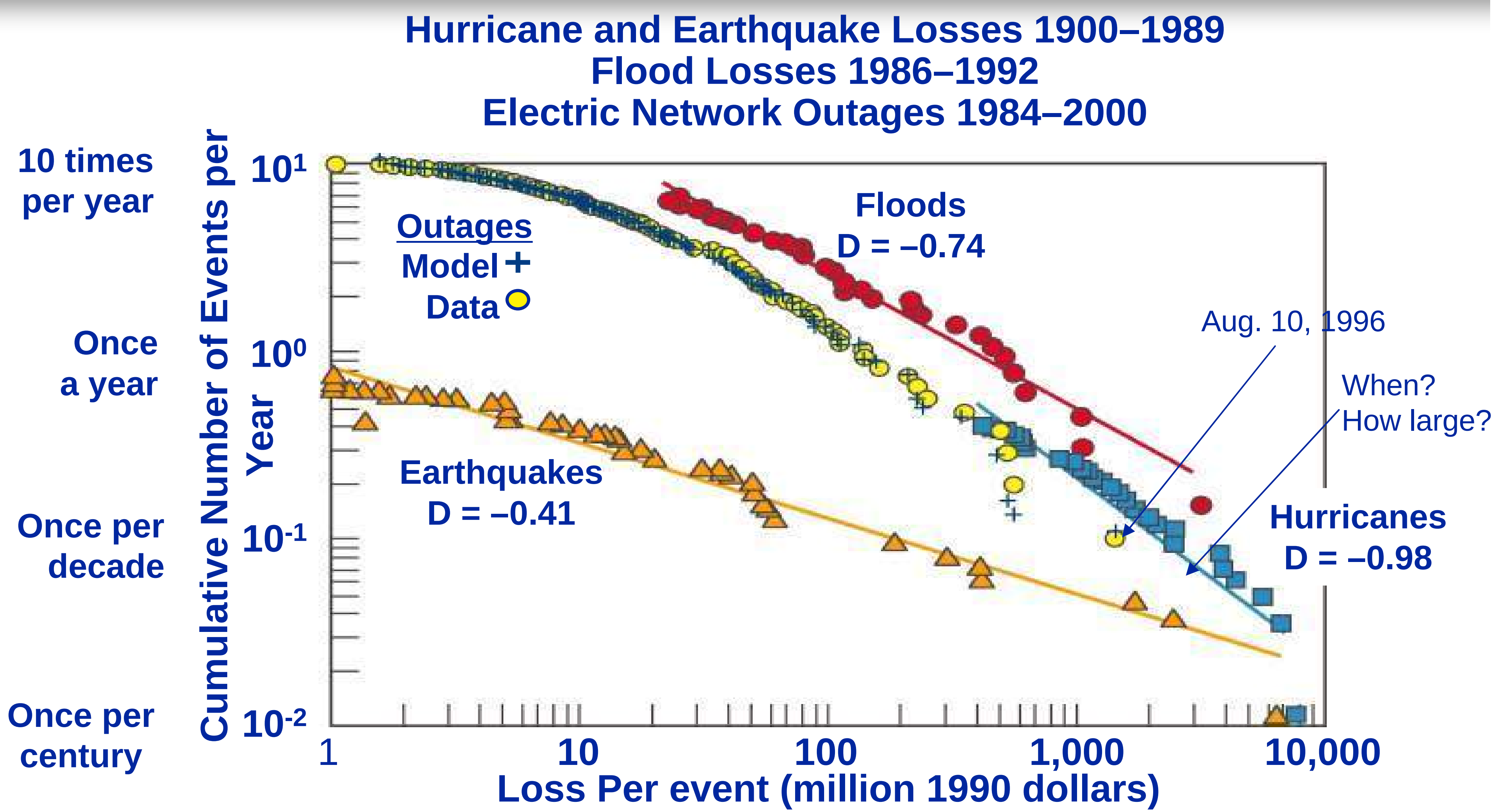
Modeling: Power law distributions

Power system

$\beta = 1$



Power Law Distributions: Frequency & impacts of major disasters



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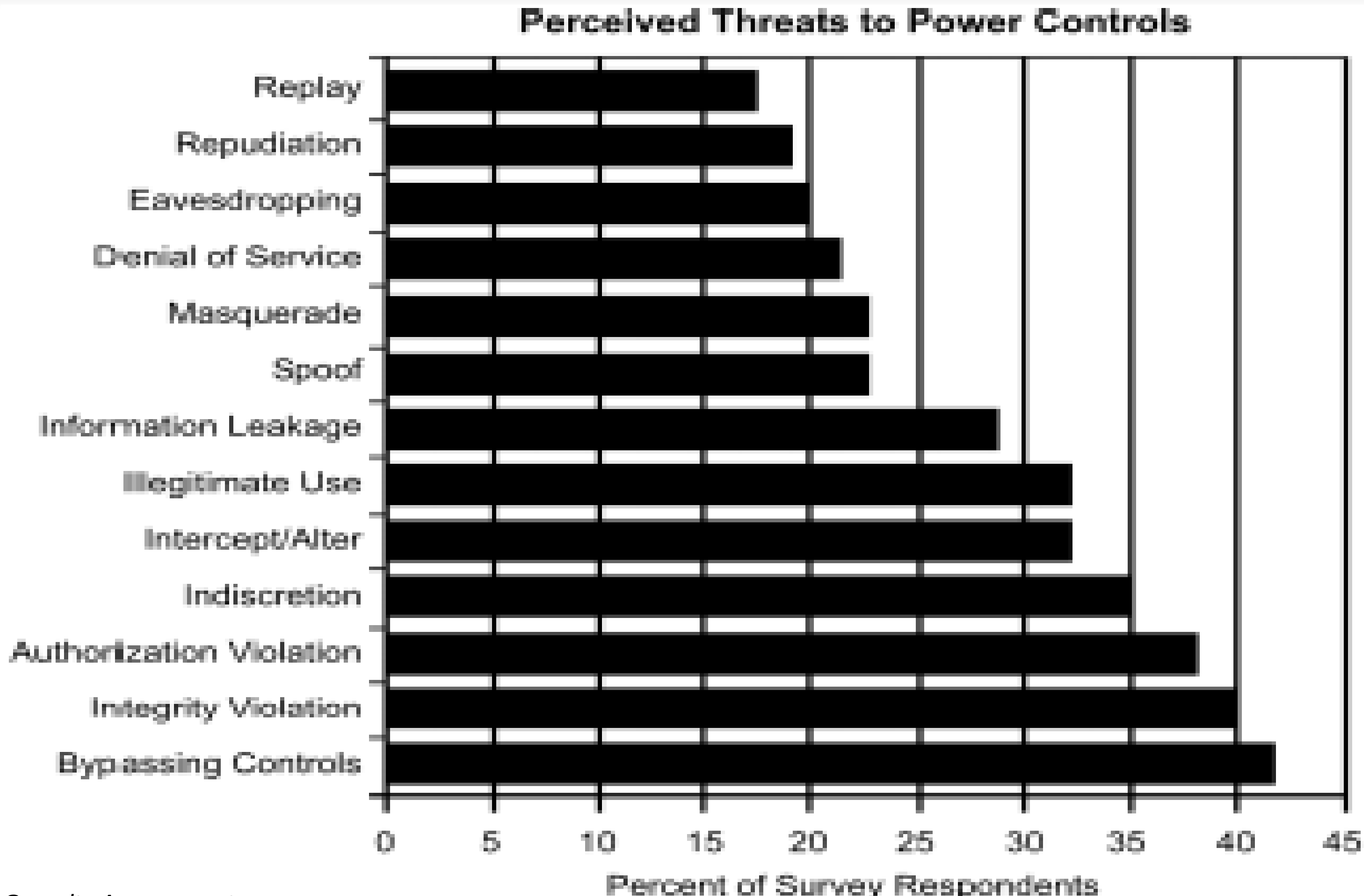
Cyber Threats to Controls



Source: *EPRI, Communication Security Assessment for the United States Electric Utility Infrastructure,* EPRI, Palo Alto, CA: 2000. 1001174.

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Prioritization: Security Index

General

1. Corporate culture (adherence to procedures, visible promotion of better security, management security knowledge)
2. Security program (up-to-date, complete, managed, and includes vulnerability and risk assessments)
3. Employees (compliance with policies and procedures, background checks, training)
4. Emergency and threat-response capability (organized, trained, manned, drilled)

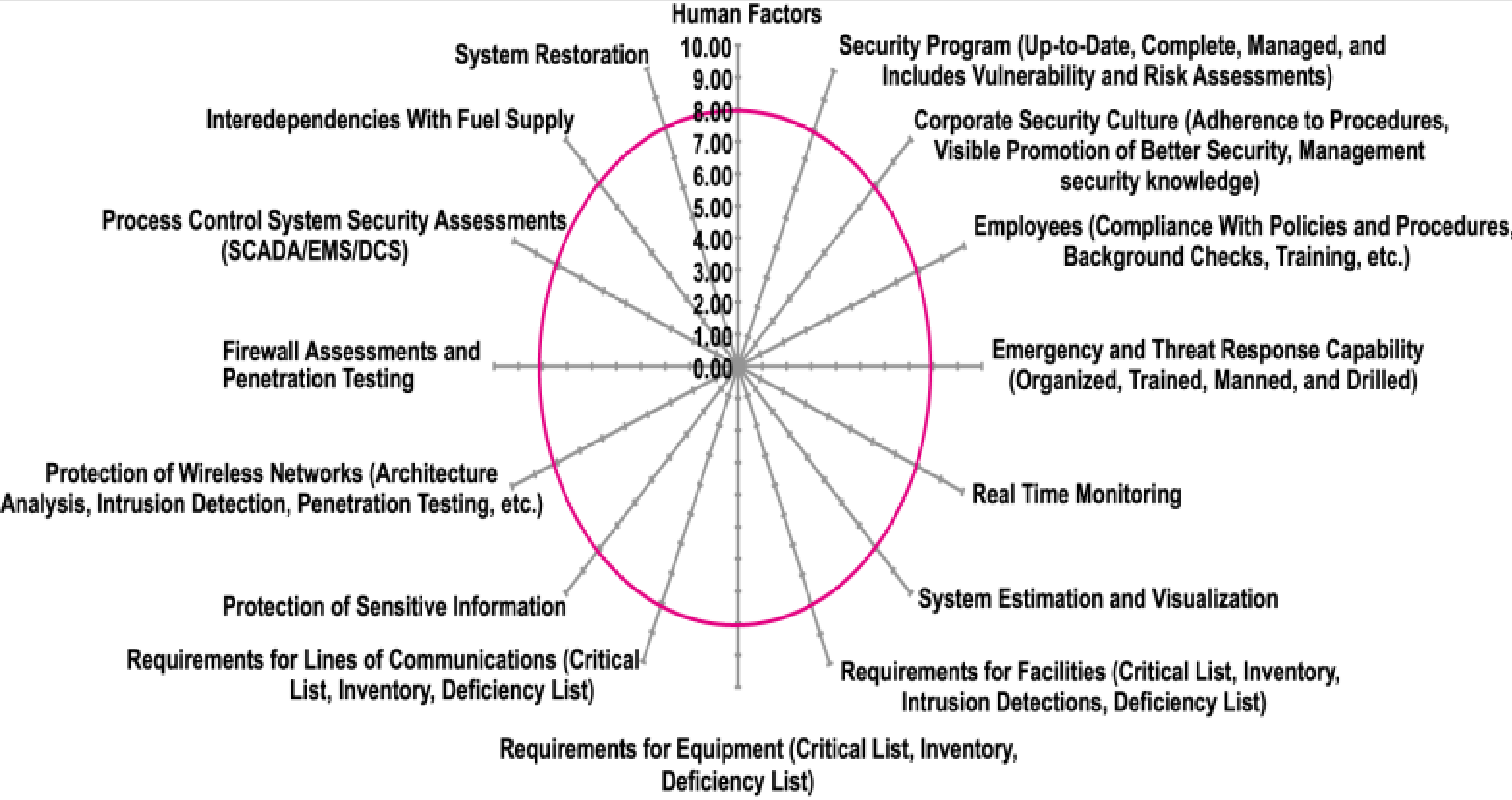
Physical

1. Requirements for facilities (critical list, inventory, intrusion detections, deficiency list)
2. Requirements for equipment (critical list, inventory, deficiency list)
3. Requirements for lines of communications (critical list, inventory, deficiency list)
4. Protection of sensitive information

Cyber and IT

1. Protection of wired networks (architecture analysis, intrusion detection)
2. Protection of wireless networks (architecture analysis, intrusion detection, penetration testing)
3. Firewall assessments
4. Process control system security assessments (SCADA, EMS, DCS)

Assessment & Prioritization: A Composite Spider Diagram to Display Security Indices



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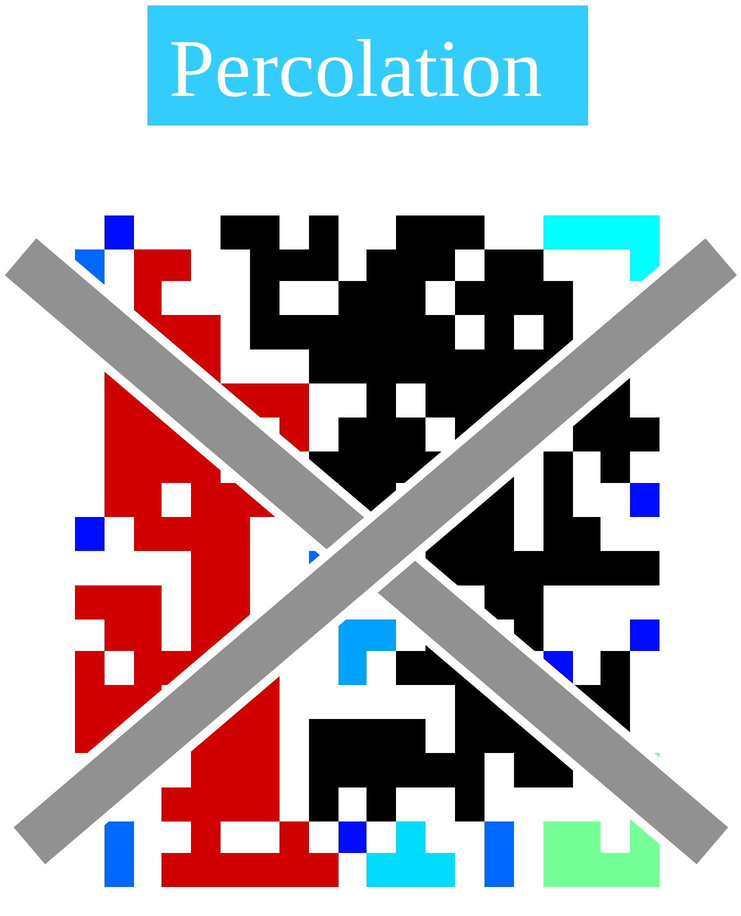
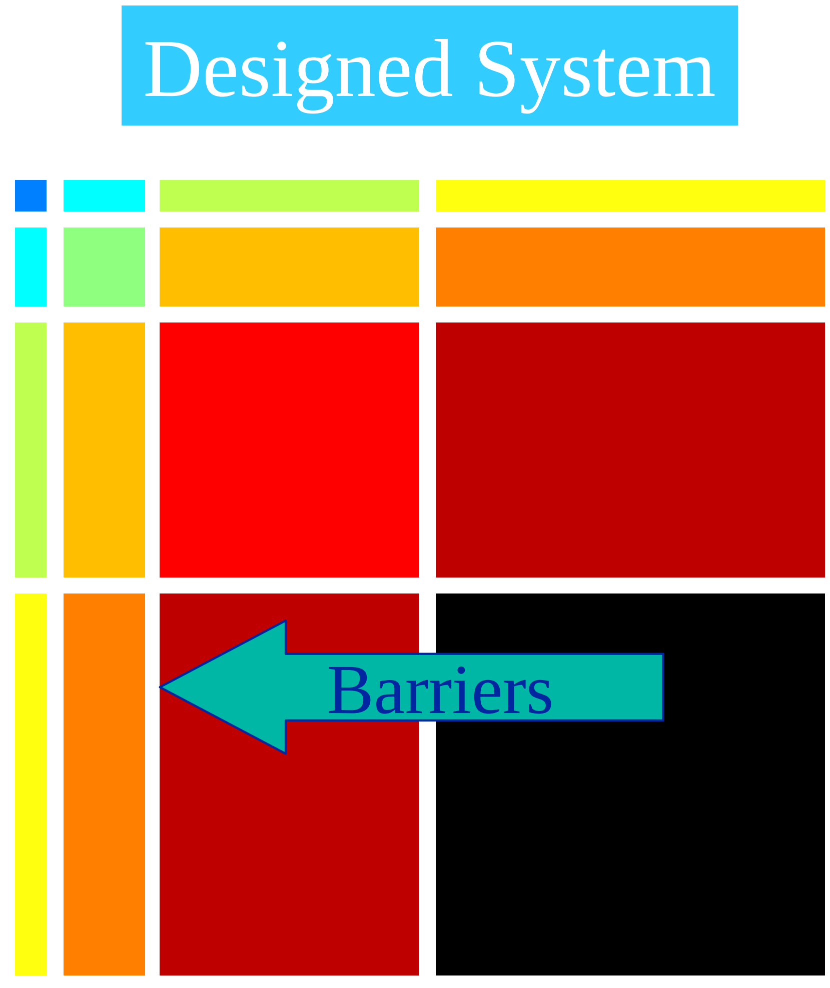
Complex Interactive Networks: Precursors detection, Protection, Resilience, and Graceful Degradation

Failure Propagation on Grid





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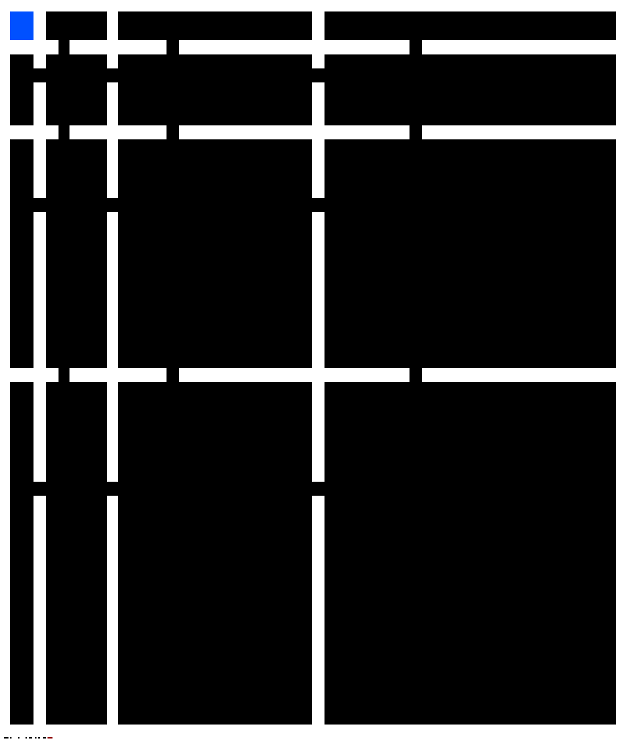
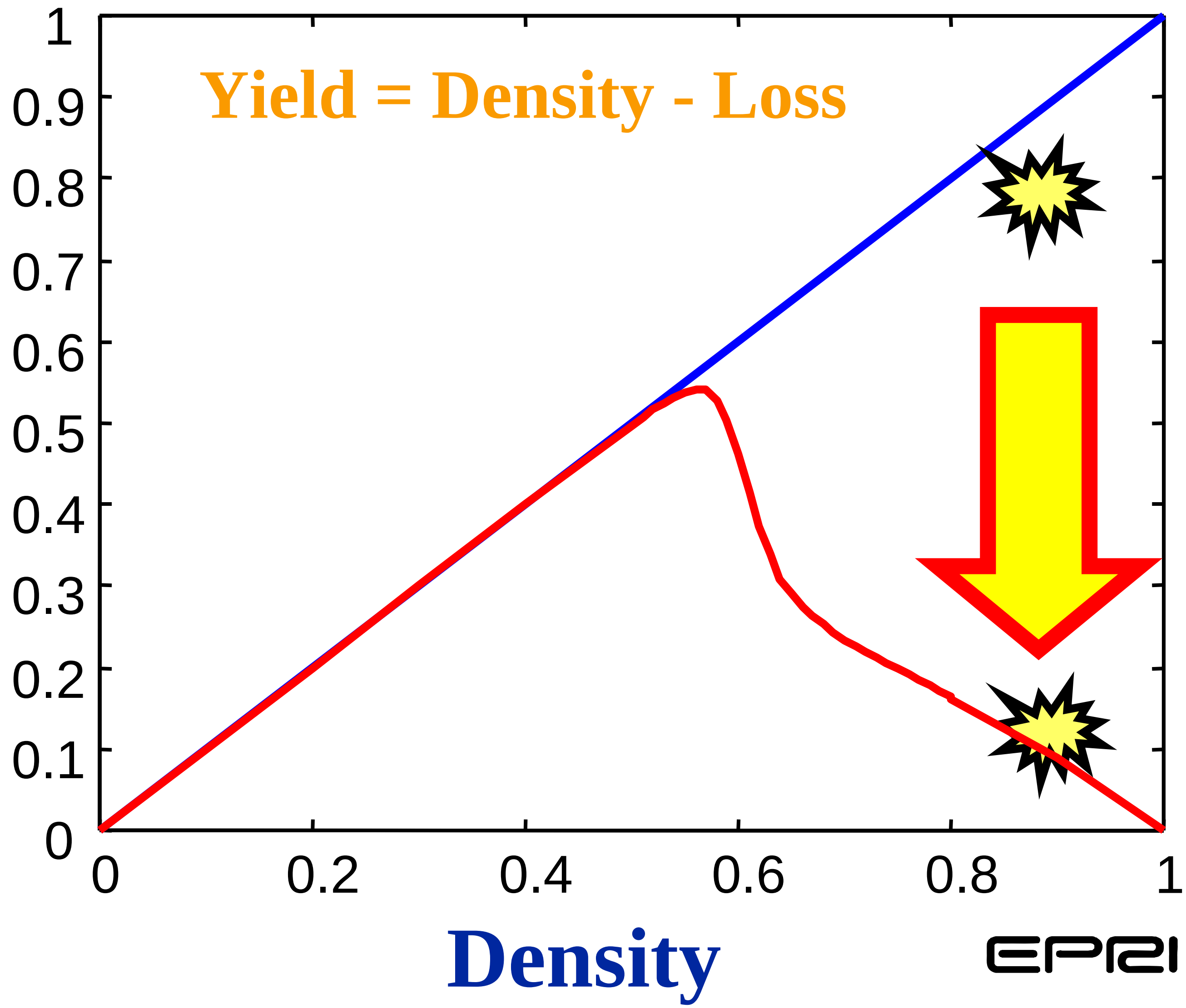
Complex Interactive Networks

Failure Propagation on Grid – Topology & Probability





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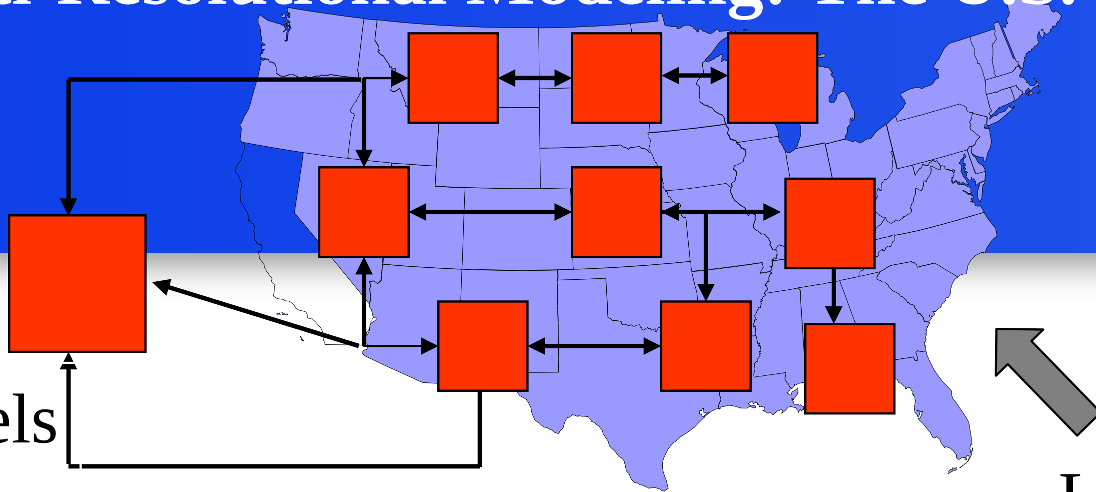
Multi-Resolutional Modeling: The U.S. Power Grid



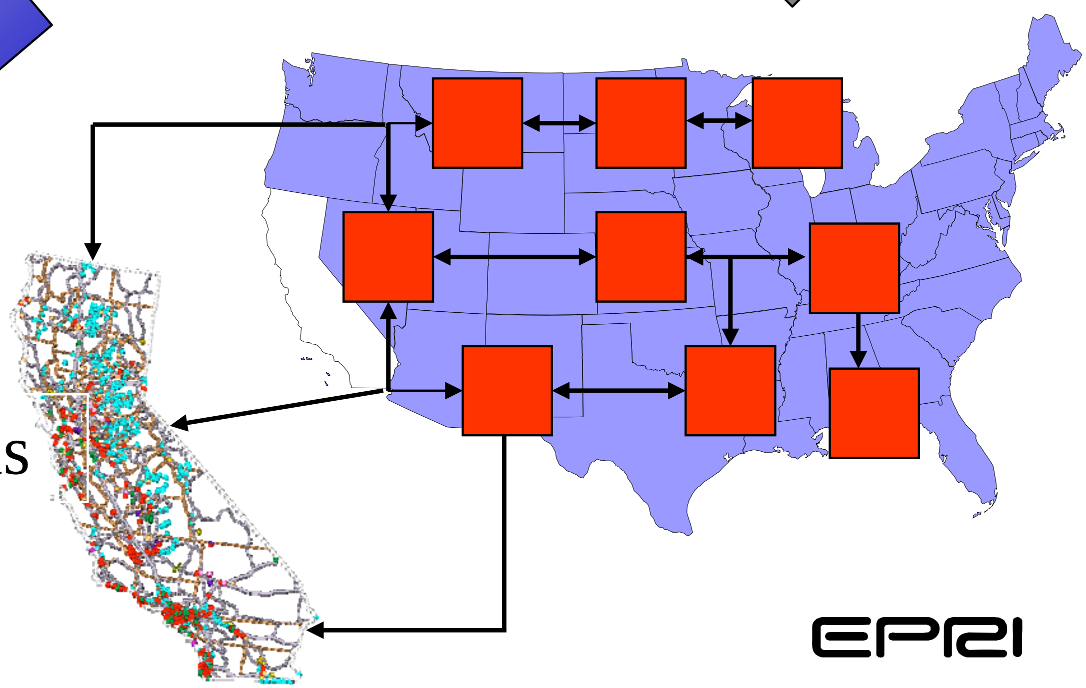
Simplified models

Low-resolution model

MODEL REDUCTION

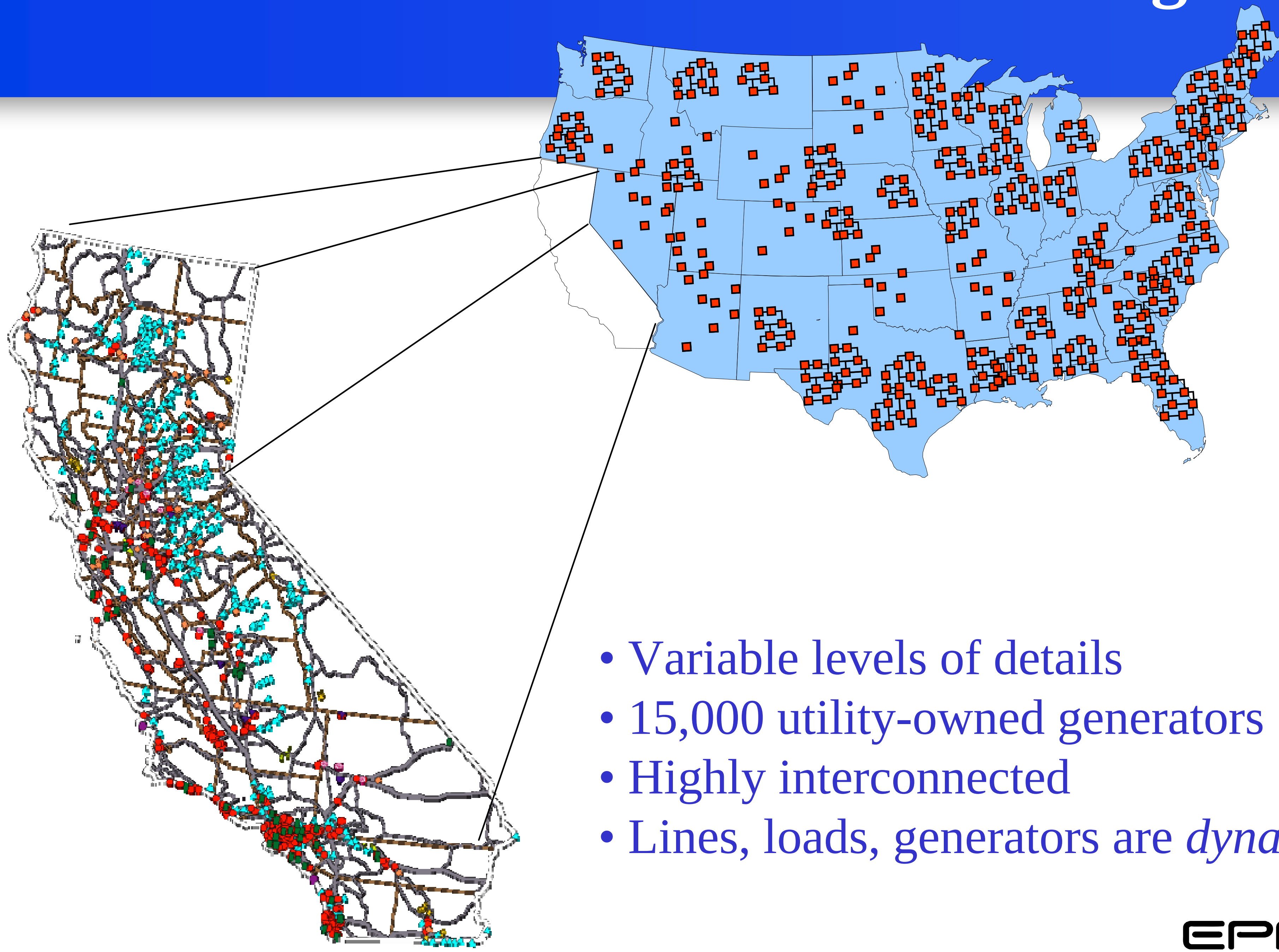
MODEL REFINEMENT

- Variable levels of details
- Lines, loads, generators are *dynamic*



Detailed models

Multi-Resolutional Modeling



- Variable levels of details
- 15,000 utility-owned generators
- Highly interconnected
- Lines, loads, generators are *dynamic*

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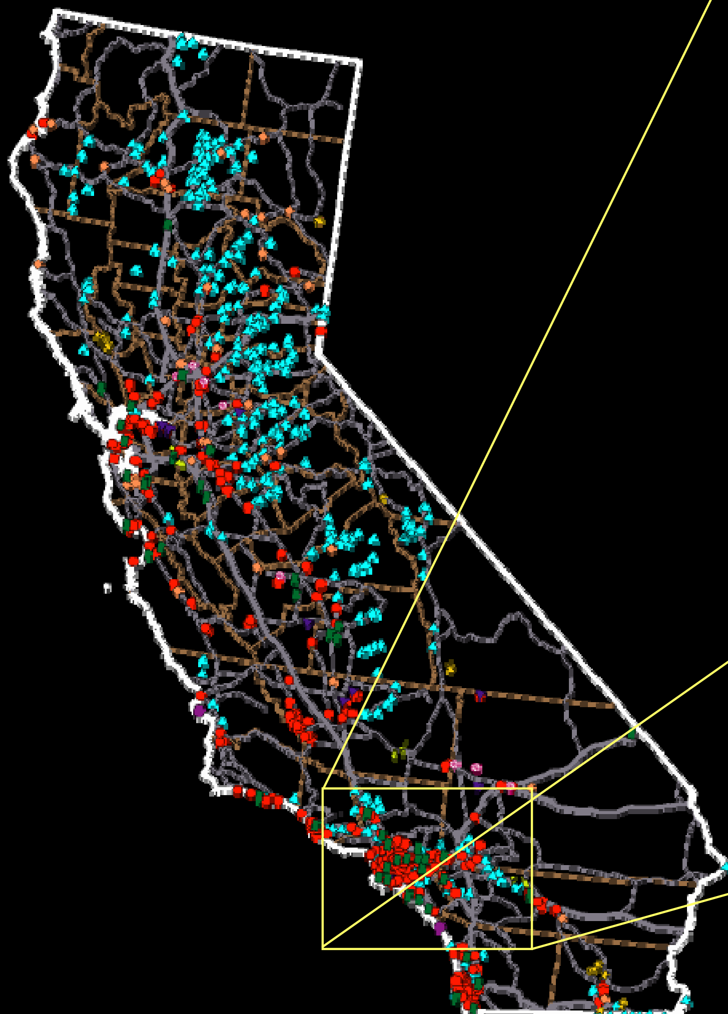
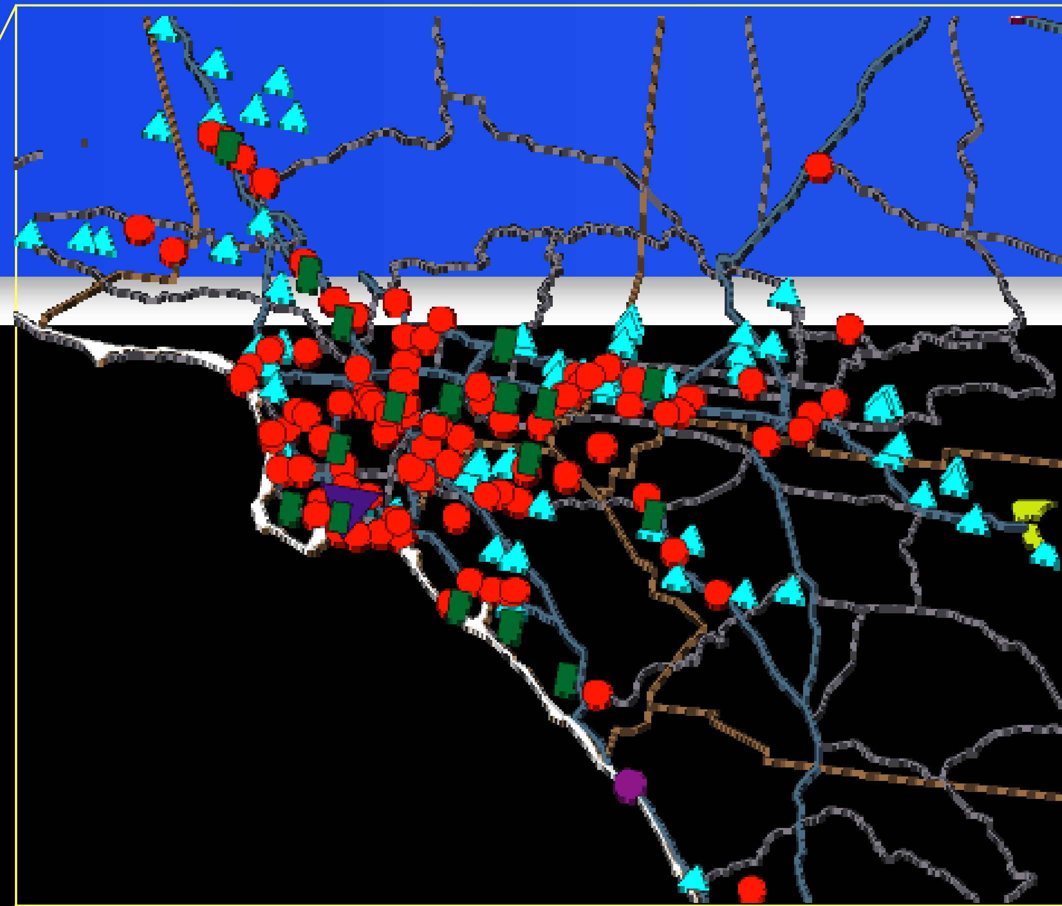
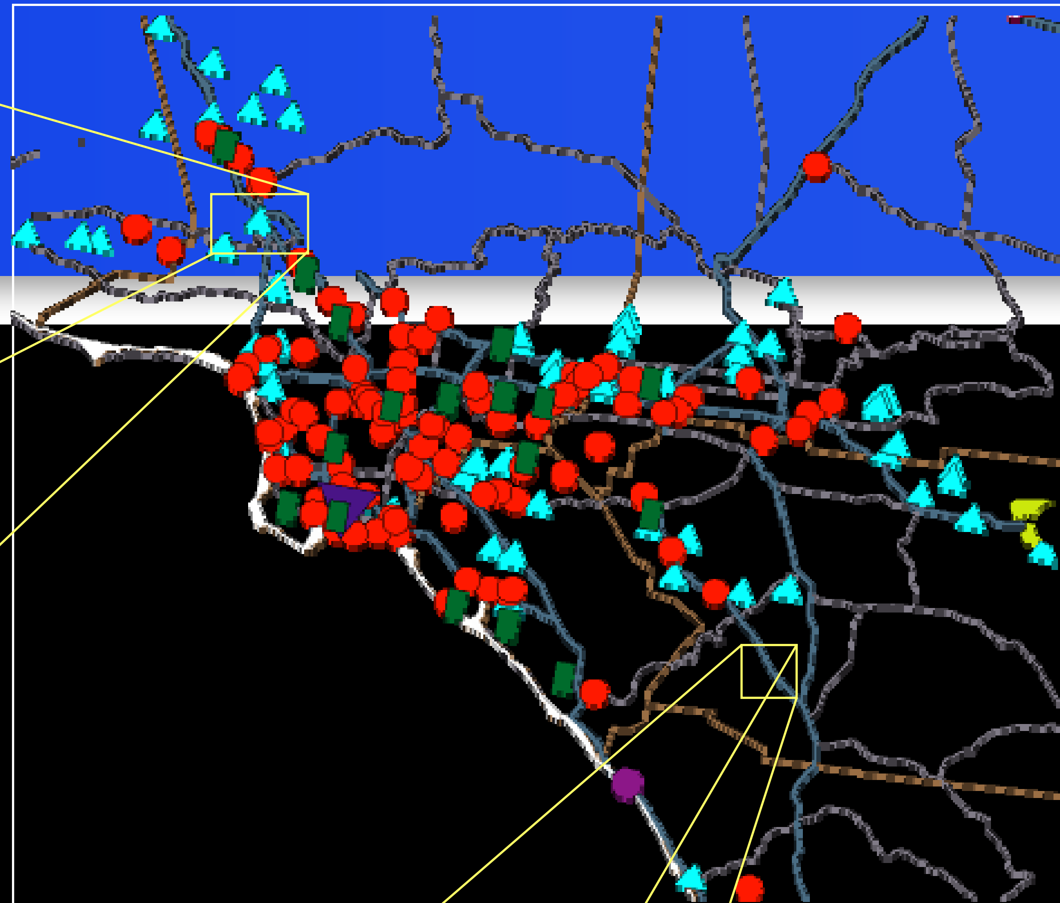
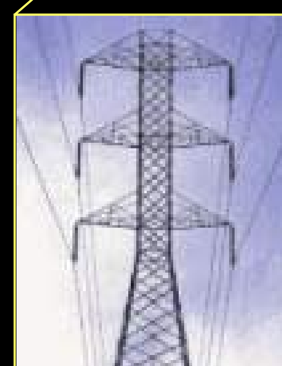




The system can be modeled at many levels of detail

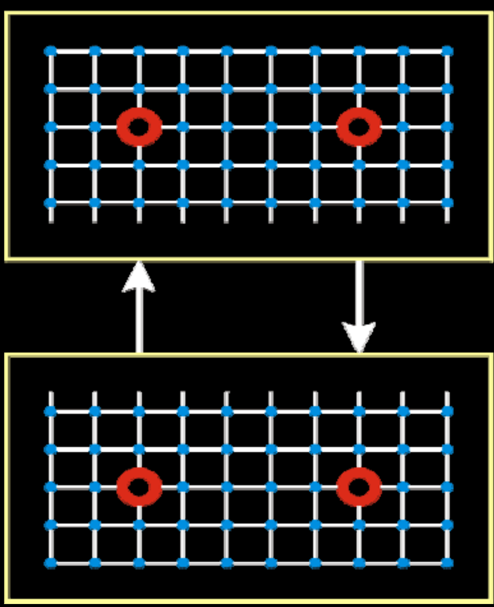




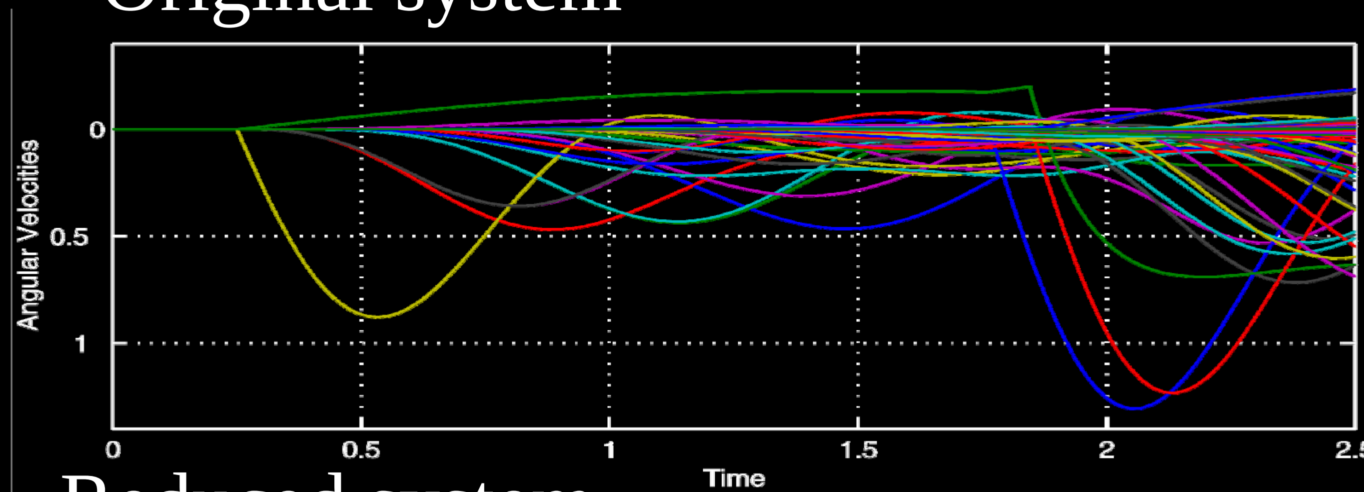
At this level, dynamic models include the *swing equations*

$$m_i \ddot{\delta}_i + D_i \dot{\delta}_i = P_i + \sum_j b_{ij} \sin(\delta_i - \delta_j)$$

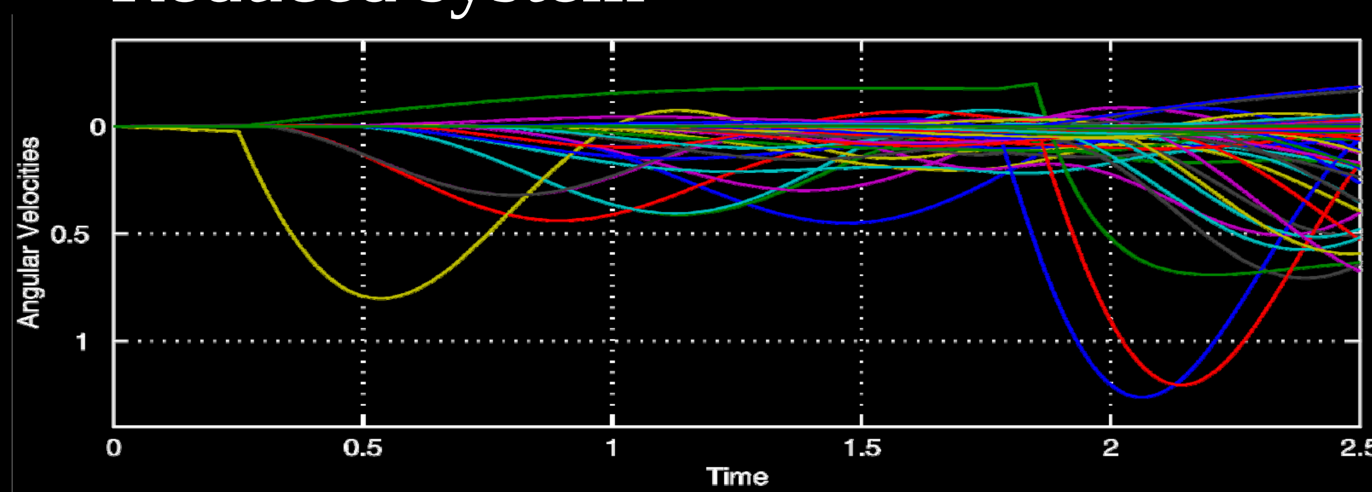
Fast Simulation



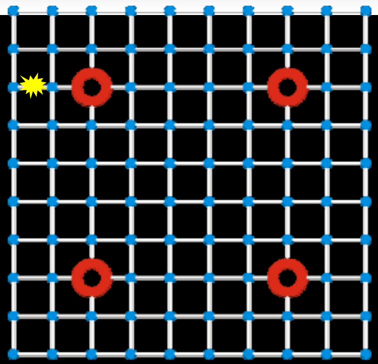
Original system



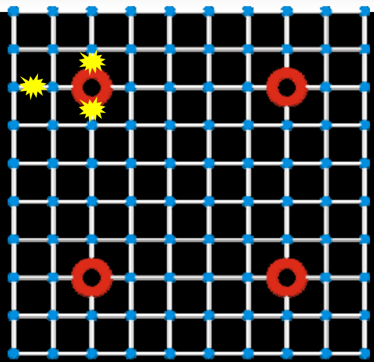
Reduced system



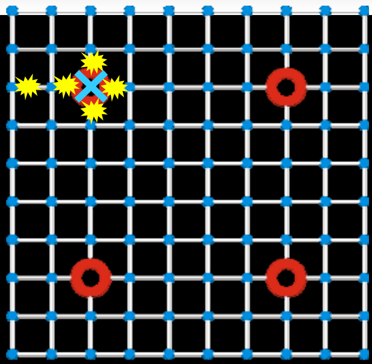
Cascading failures



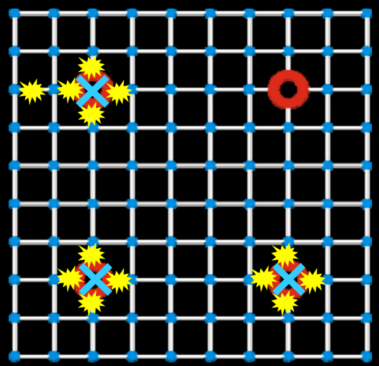
0.25
0.25



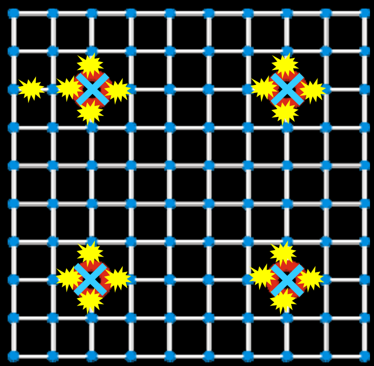
1.764
1.773



1.845
1.848



2.570
2.574



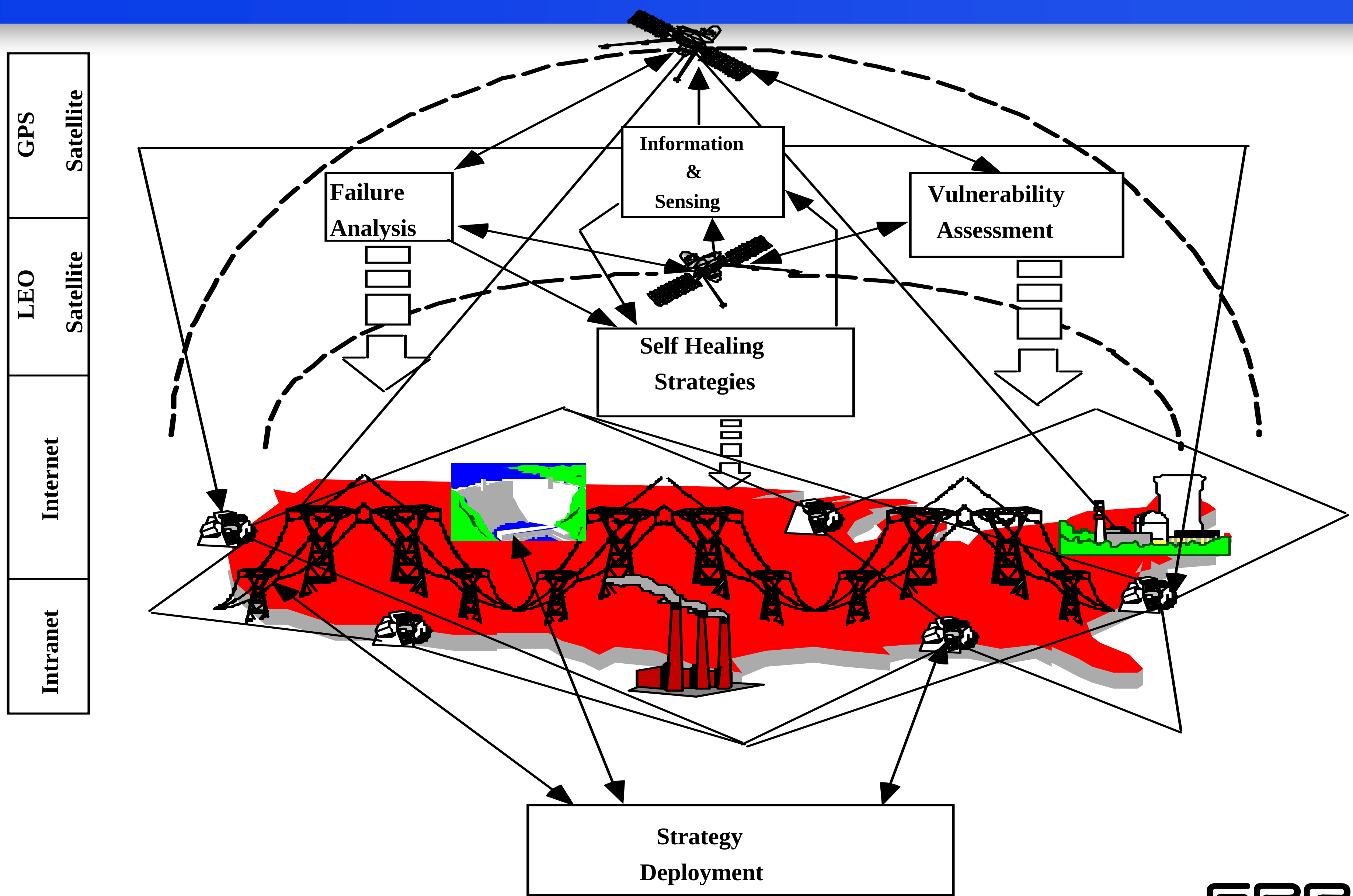
2.582
2.594

Failure time:

Original system
Reduced system

P. A. Parrilo, S. Lall, F. Paganini, G. C. Verghese, B. C. Lesieutre, J. E. Marsden, 1998

Complex Interactive Networks



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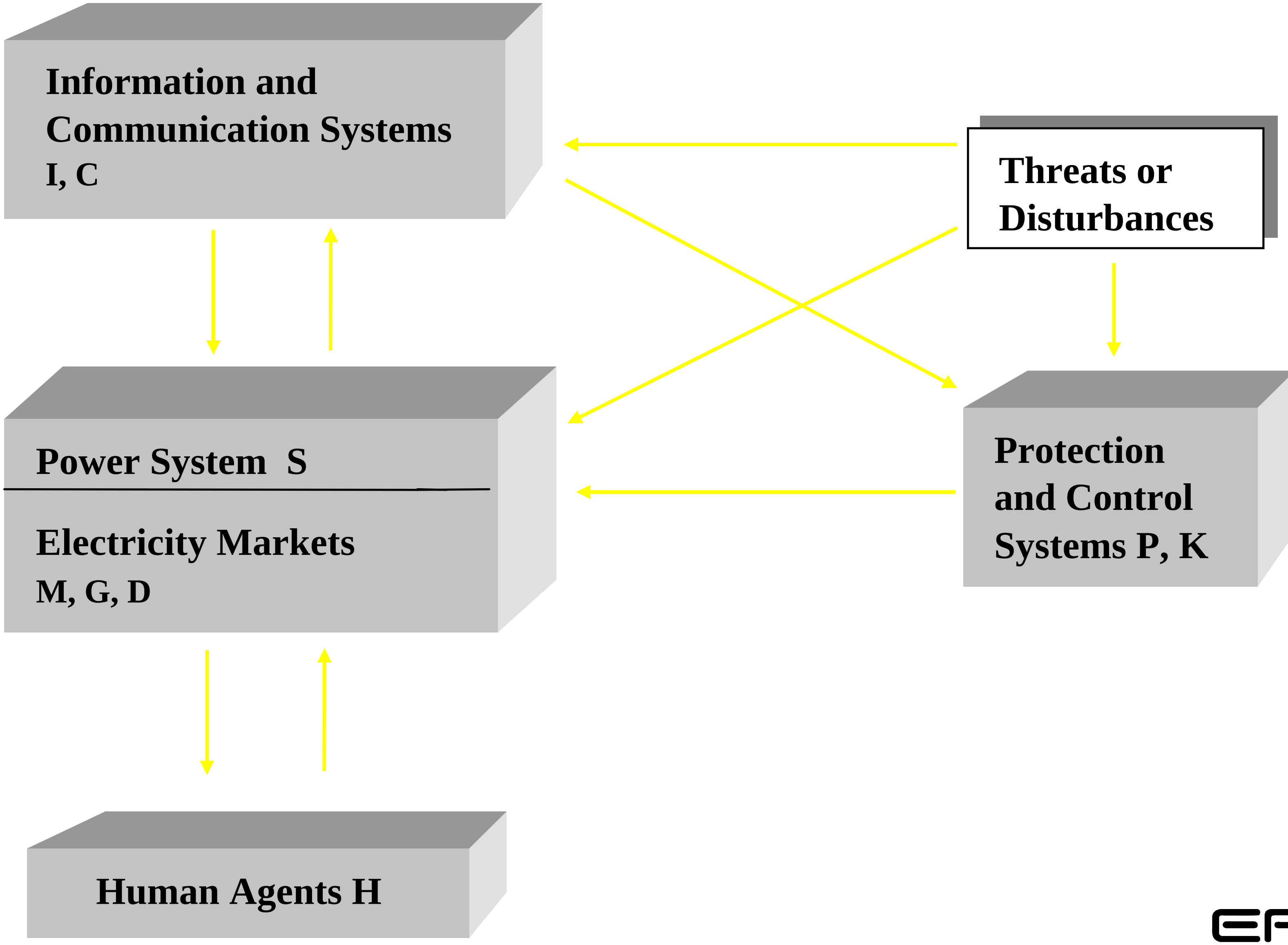
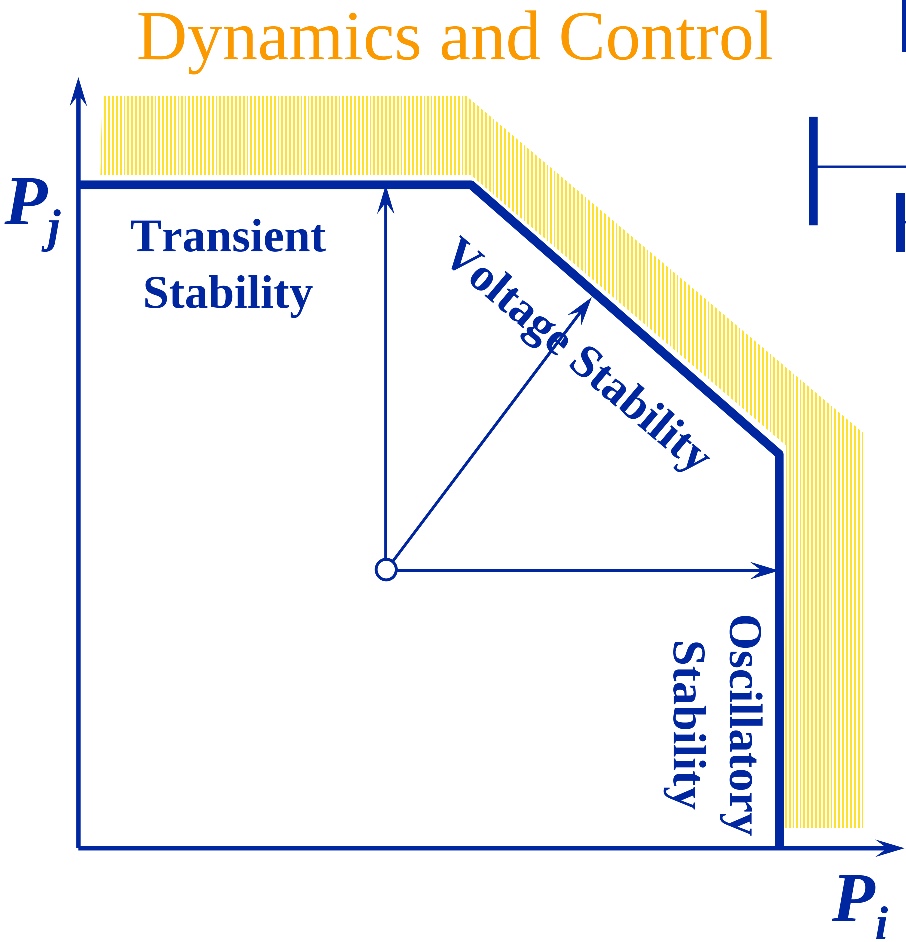
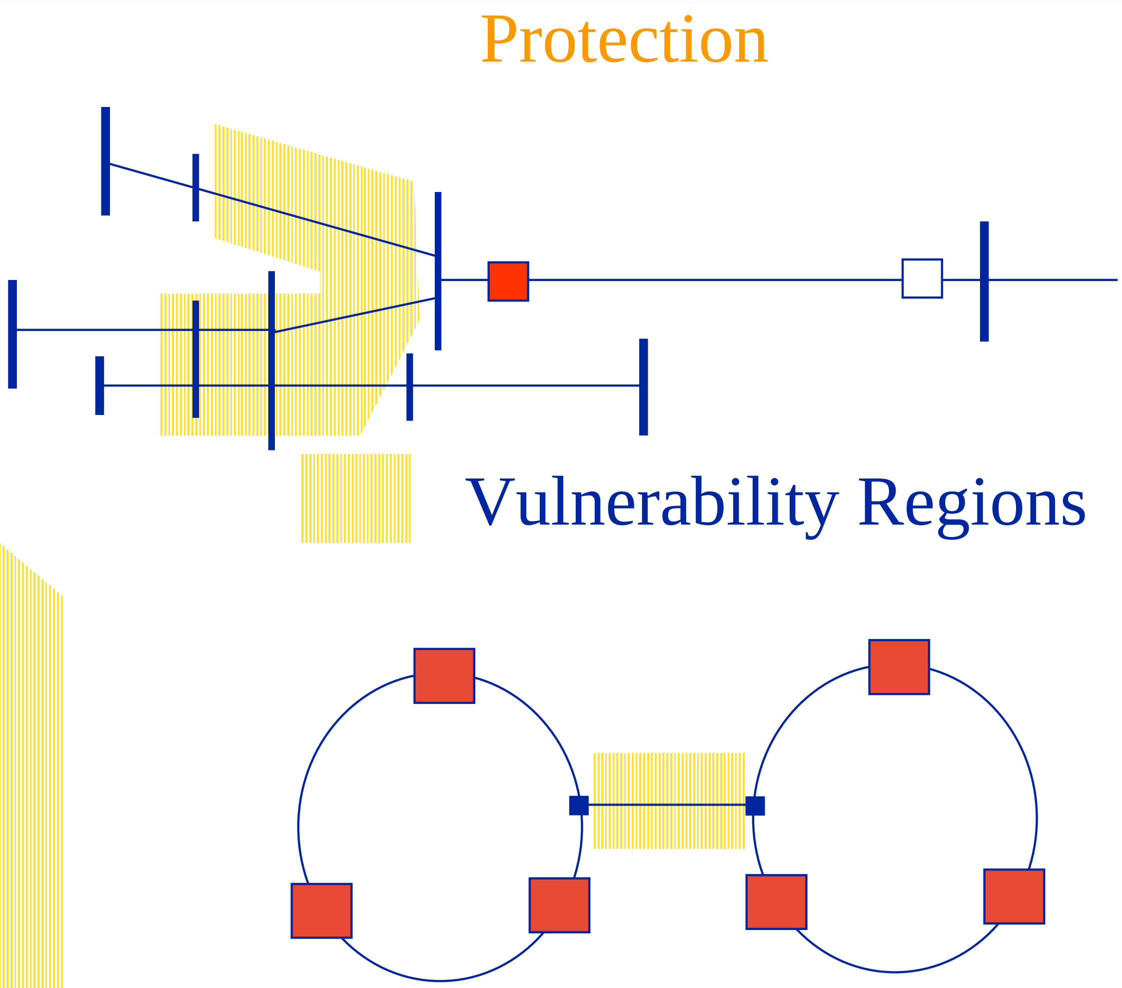
Integrated Protection and Control



Vulnerability Indices



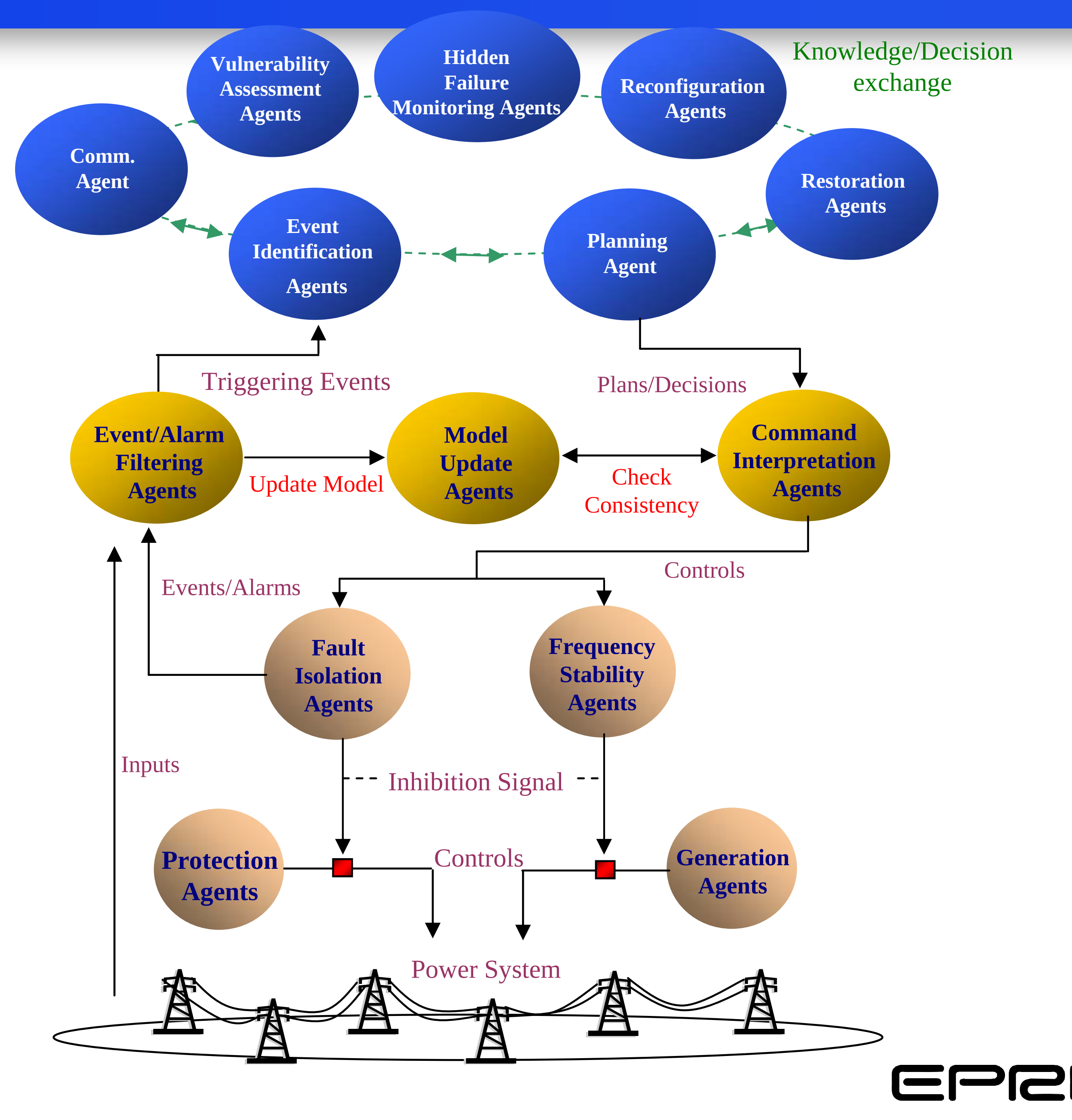


Integrated Infrastructure Protection and Control via Multi-Agent Systems

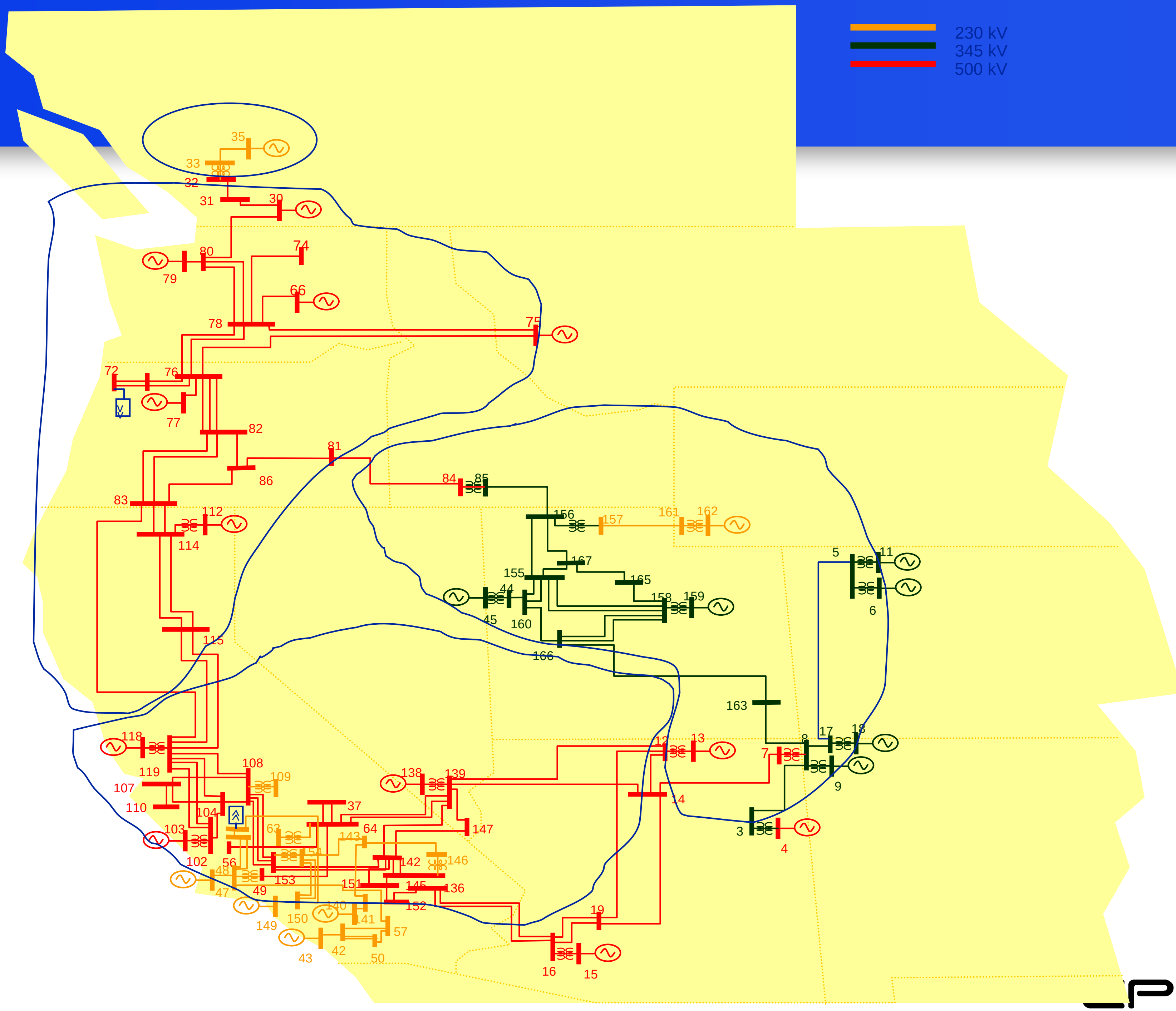
DELIBERATIVE LAYER

COORDINATION LAYER

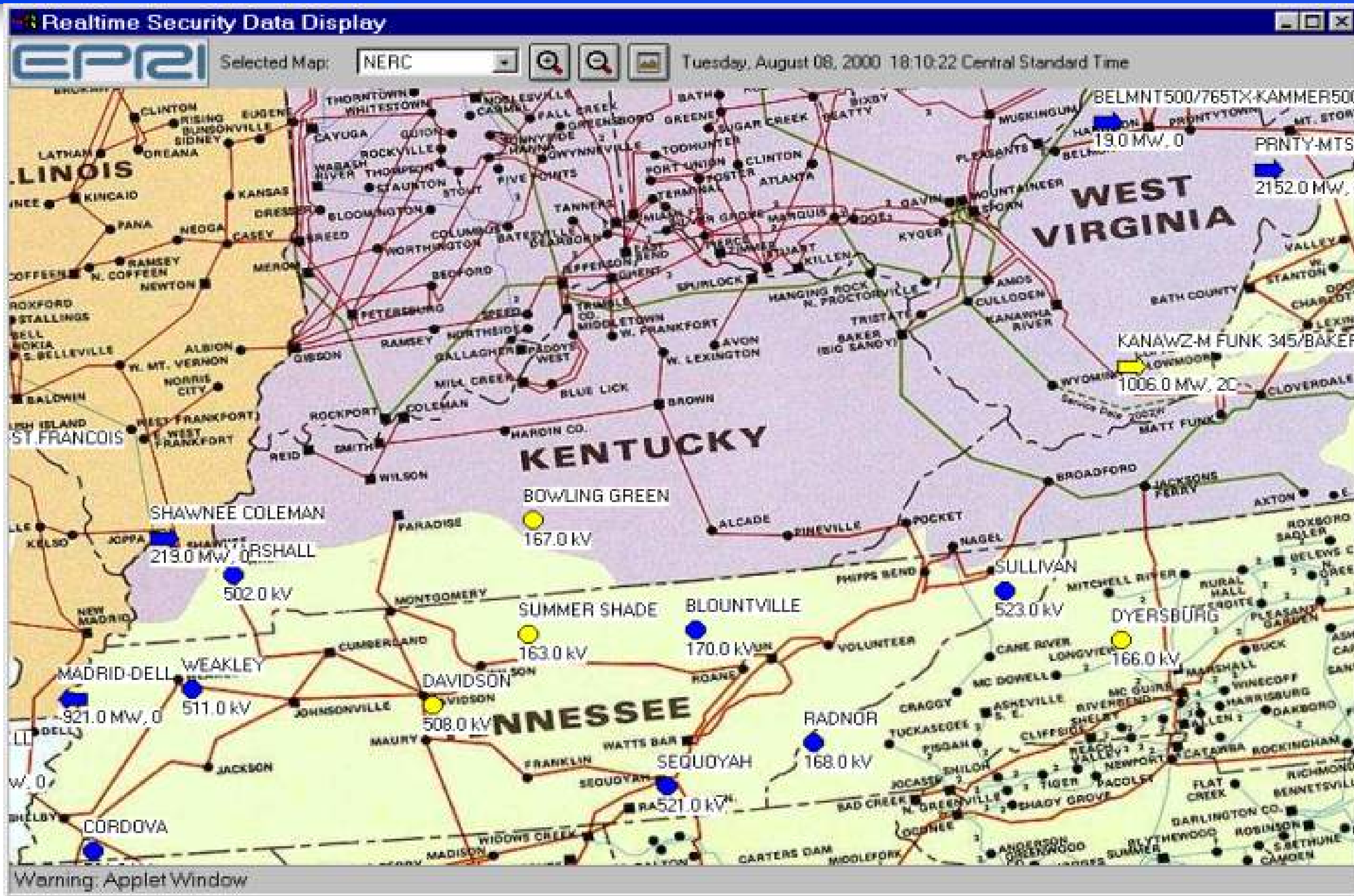
REACTIVE LAYER



Intelligent Adaptive Islanding



EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)



Infrastructure Security R&D: Response to 9/11

- **Impact:** Our security, quality of life, national and international economy
- **Response:** *An integrated & coordinated program for meeting the security needs of the electric industry*
- Focused R&D involving end-to-end:
  - Risk assessment & management
  - Prevention, Mitigation & Recovery
- Customer Support Initiatives
  - Vulnerability Assessments
  - Regional information sharing programs
  - Procedures development support

Contacts: Dr. Massoud Amin & Dr. Karl Stahlkopf

EPRI

Aftermath of 9/11: Steps Toward Ensuring Security

- EPRI's *Electricity Infrastructure Security Assessment* considers six broad areas:
  - System-Wide Vulnerability Assessment
  - Grid Security
  - Cyber and Communications Threats
  - Distribution System, Disaster Mitigation and Recovery
  - Generation/Environment
  - Power Markets

EPRI

EPRI's *Electricity Infrastructure Security Assessment*

- Two volumes:
  - Vol 1: out to 18 months
  - Vol 2: 18 months to 5 years
- Purpose
  - To provide a preliminary assessment by EPRI of potential terrorist threats to the electricity system, along with some suggested countermeasures
- Emphasis
  - How advanced technologies can be used to protect critical infrastructures
  - Physical security issues are left to individual utilities

Bigger picture: Research challenges to develop fundamental solutions…

- Development of advanced C3 (Computers, Communications, & Control) networks overlay the power network,
- Knowing what is happening- Satellite-based WAMS
- Understanding what constitutes a problem- Dynamic Stability Analysis, visualization tools
- Understanding the "true" dynamics soon enough to do something about it- Faster analysis, look-ahead simulation,...
- Determining what actions could solve the problem- Contingency plans, and risk management
- Implementing the solution- Control devices/systems; alternate path options

… require basic research to develop fundamental solutions…

- Intelligent sensors as elements in real-time data base; sensor interface to multi-resolutional models? Metrics?
- Increased dependence on information systems (e.g., software as the glue among various subsystems/tasks)
- Dependability/robustness is the key; V&V remains a big challenge
- Effect of market structures, distributed generation, other new features on above issues
- Designing/Evolving a robust system - Complexity, distributed sensing, control and adaptation

"... not to sell light bulbs, but to create a network of technologies and services that provide illumination..."

The Energy Web:

"The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming - and interconnected with everything else."

-- Wired Magazine, July 2001

http://www.wired.com/wired/archive/9.07/juice.html