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High-Performance Computing for Real-Time Detection of Large-Scale Power Grid Disruptions

Mohammed Olama
Oak Ridge National Laboratory

Kyle Spafford
Oak Ridge National Laboratory

Olufemi Omitaomu
Oak Ridge National Laboratory

James Nutaro
Oak Ridge National Laboratory

Supriya Chinthavali
Oak Ridge National Laboratory

See next page for additional authors

Authors
Mohammed Olama, Kyle Spafford, Olufemi Omitaomu, James Nutaro, Supriya Chinthavali, and Steven Fernandez

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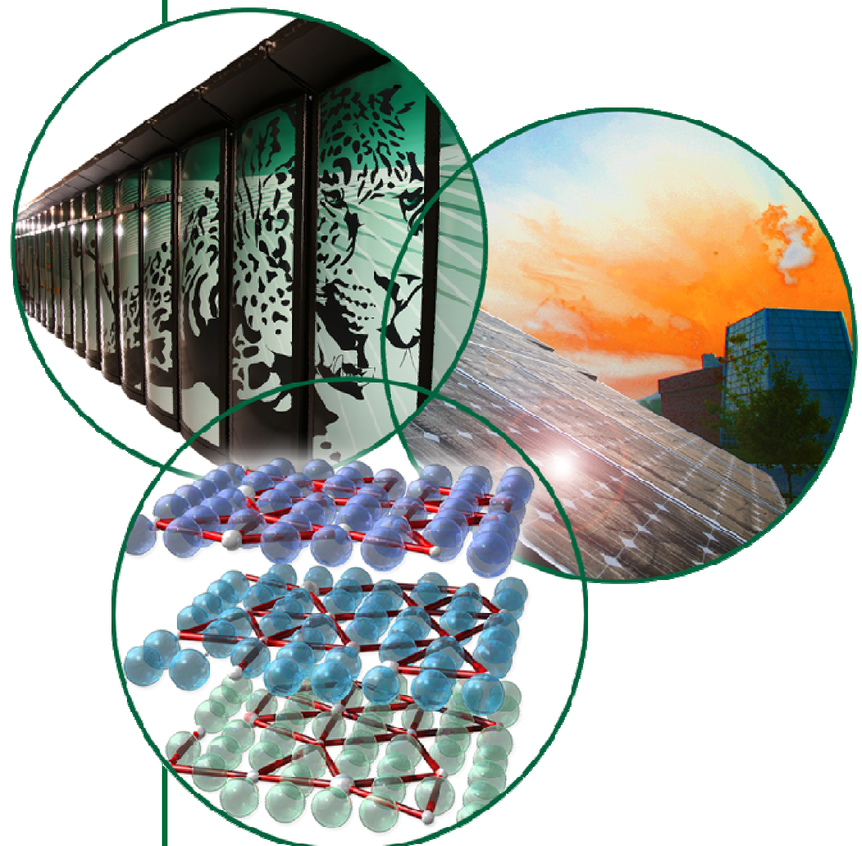


Modeling, Simulation and Optimization for the 21st Century Electric Power Grid
Oct. 22, 2012

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

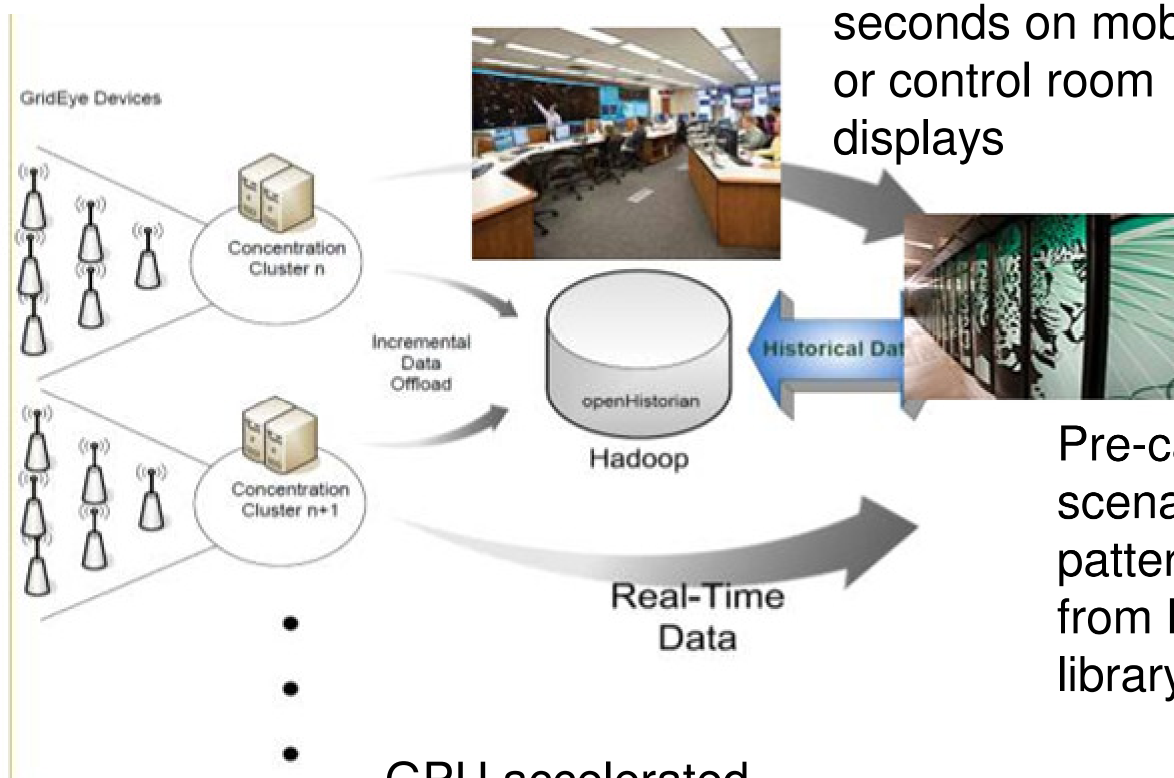
Objectives

- Use HPC to analyze sensor data for real time grid monitoring, prediction, and operation
- Manage vast amount of sensor data
  - Algorithms to dynamically identify and communicate relevant data
  - Data management with provenance
  - Secure data sharing, storage, archiving
- Actionable information analysis
  - Real-time integration and analysis of terabytes of sensor data
  - Deliver appropriate data to data-driven simulators

Overview

Display to decision makers within 2-4 seconds on mobile or control room displays

Detectors sense event within one second of event

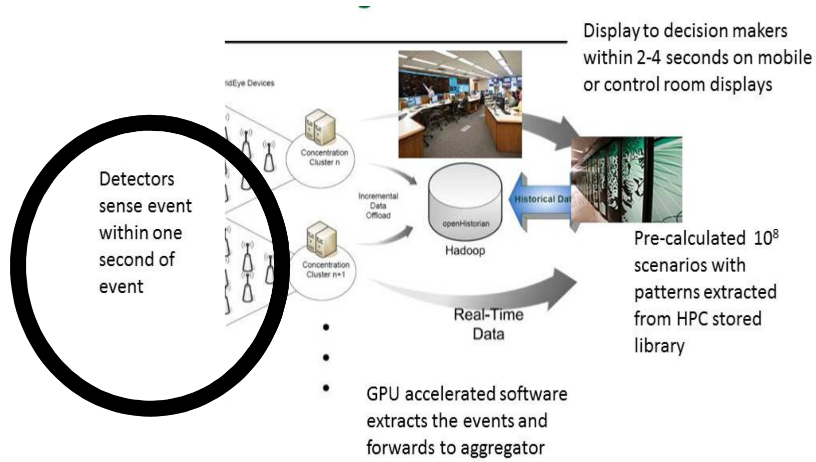


Pre-calculated 10^8 scenarios with patterns extracted from HPC stored library

GPU accelerated software extracts the events and forwards to aggregator

Measuring Frequency Transients

- **Frequency measurement system developed to provide real-time measurements of frequency transients. The new sensor has the following characteristics:**



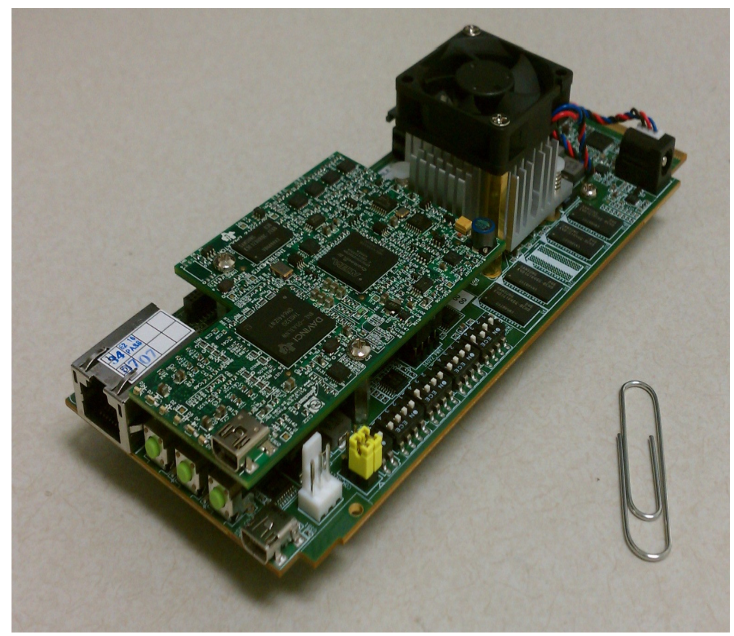
a) Cyber-security using hardware-accelerated cryptography

b) Producing a symbol rate of 8000 measurements per second

c) Providing at that rate, average frequency with a sensitivity of 25mHz within 80ms

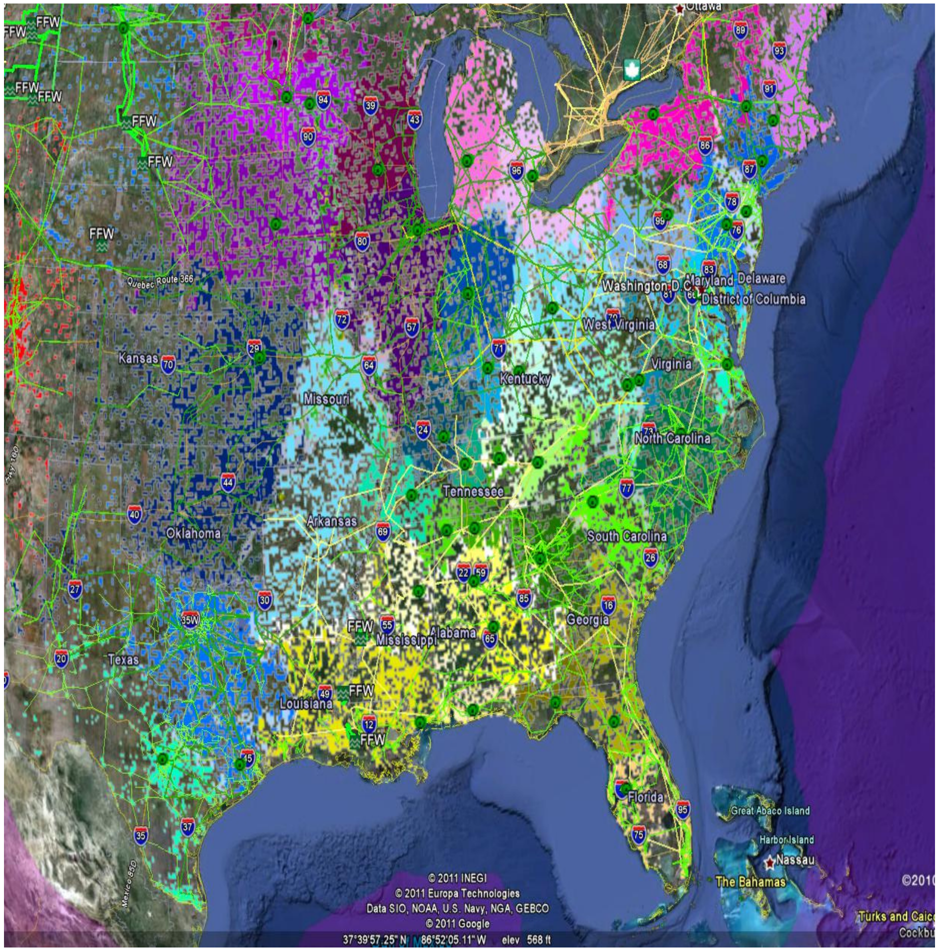
d) Employing a timing system to accurately time-stamp using VLF broadcast time-code signals and the IEEE 1588 precision time protocol standard

e) System cost less than $1000 per copy



The Research Data Set

- A research data set of **frequency disturbances for the Eastern Interconnection (EI)** was created that was 2 TB in size based on **empirical measurements** during a trip of the Cook Nuclear Power Plant
- This data set granularly defined the inter-oscillatory areas and demonstrated that 83 locations could cover the Eastern Interconnection and defined the size of the data streams would be **on the order of TB/hr**

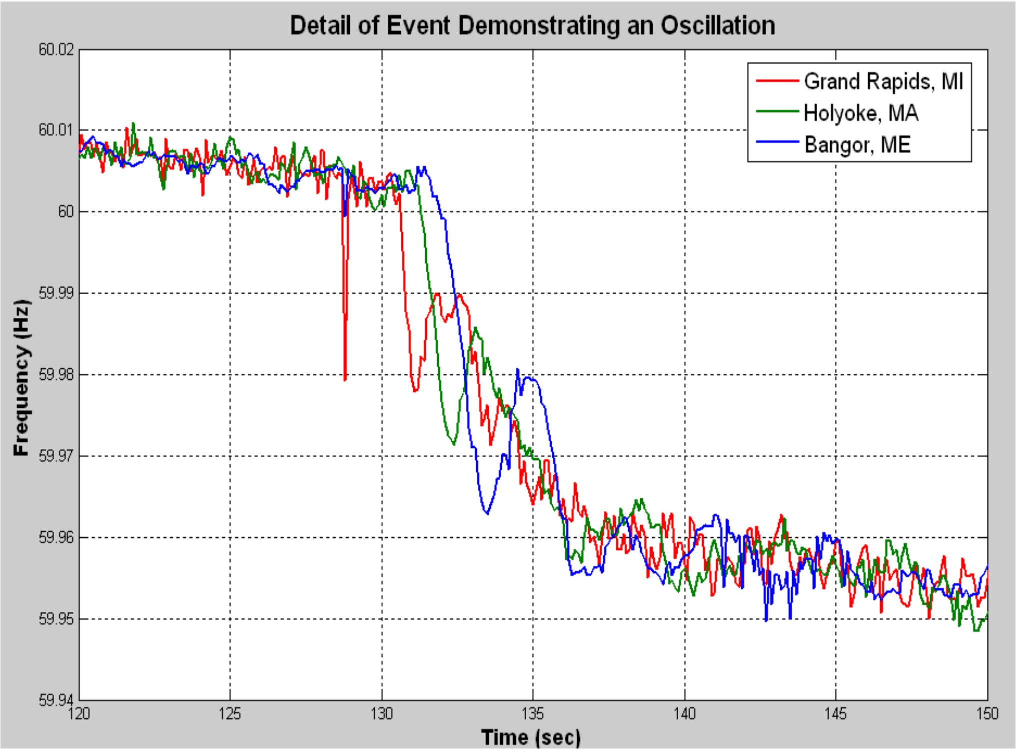


High Speed Frequency Data Streams - Events

- Imbalance of generation and load can cause sudden frequency changes within the system
- These “events” include scenarios such as:
  - Generator Trip
  - Load Rejection
  - Line Trip
  - Oscillations
- The two real-time goals are
  - Detecting the occurrence of events
  - Identifying root cause based on simulation

Event Detection

- Goal: Use frequency signatures after an event such as a generator trip to locate the event origin.
- How is frequency based event analysis useful?
  - Provide the approximate location of events in real time
  - Other metrics like event type and trip amount (MW loss) can be extracted



Event Extraction Algorithm

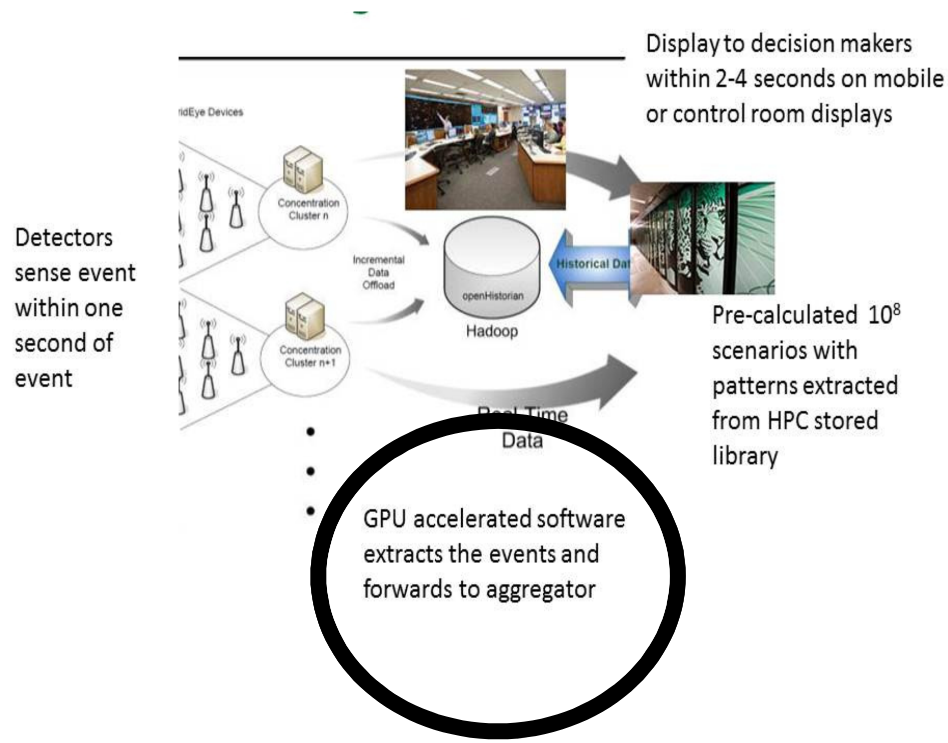
- **Developed an Event Extraction Algorithm GPU Accelerated Event Detection Algorithm (GAEDA), that**

(a) Converts a multi-dimensional sequence into a univariate time series using the singular value decomposition (SVD) method

(b) Applies anomaly detection techniques for univariate time series.

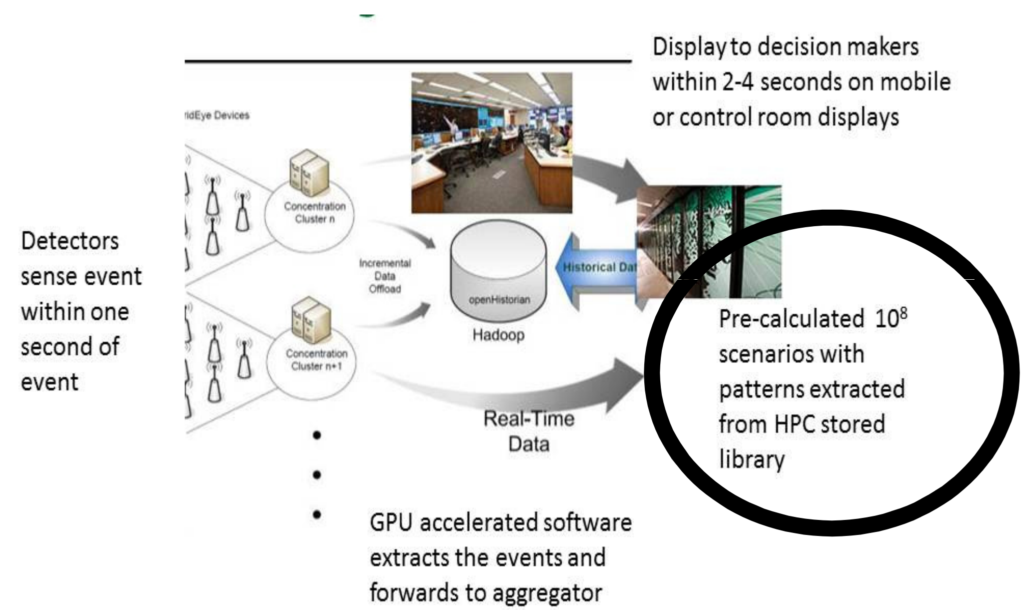
(c) Is scalable to big datasets by adopting techniques from perturbation theory for incremental SVD analysis.

(d) Accounts for nonlinear dependencies.

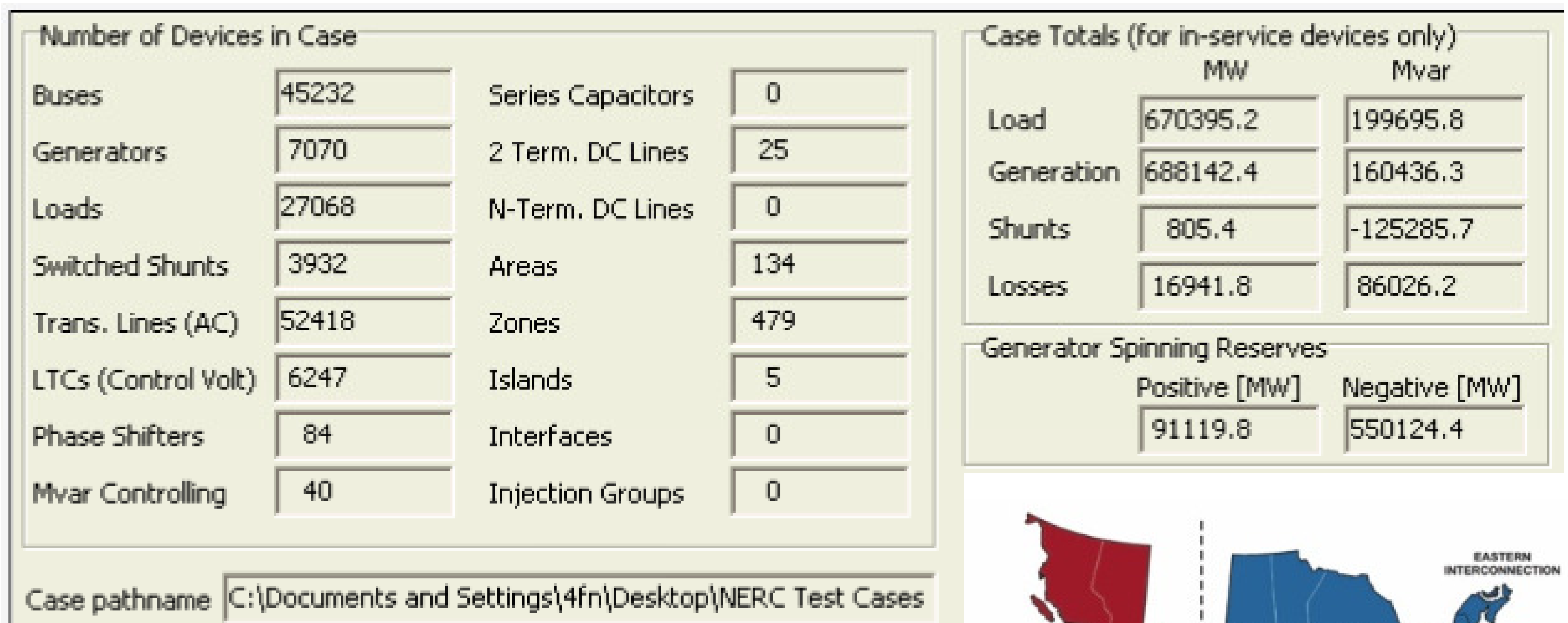


Event Detection Scheme: Rapid Extraction of Disruption Signatures for Many Core GPU Architecture

- Building a library of all possible (detectable) contingencies and there frequency signatures using PF simulations
- Searching and comparing current sensor data to simulated signatures
- Detecting the most probable event(s)



The Eastern Interconnect



Number of Devices in Case

Buses	45232	Series Capacitors	0
Generators	7070	2 Term. DC Lines	25
Loads	27068	N-Term. DC Lines	0
Switched Shunts	3932	Areas	134
Trans. Lines (AC)	52418	Zones	479
LTCs (Control Volt)	6247	Islands	5
Phase Shifters	84	Interfaces	0
Mvar Controlling	40	Injection Groups	0

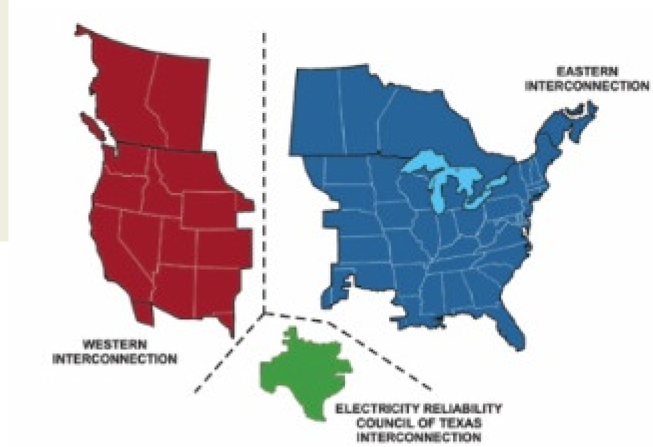
Case Totals (for in-service devices only)

	MW	Mvar
Load	670395.2	199695.8
Generation	688142.4	160436.3
Shunts	805.4	-125285.7
Losses	16941.8	86026.2

Generator Spinning Reserves

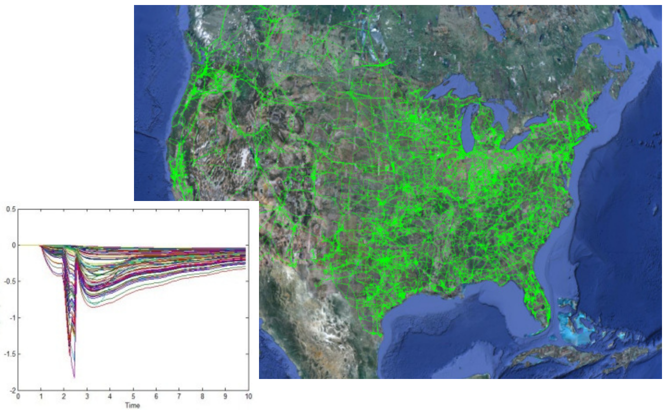
Positive [MW]	Negative [MW]
91119.8	550124.4

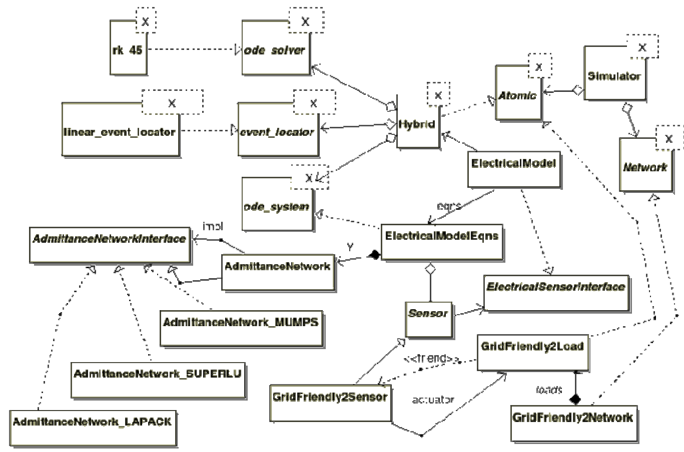
Case pathname C:\Documents and Settings\4fn\Desktop\NERC Test Cases

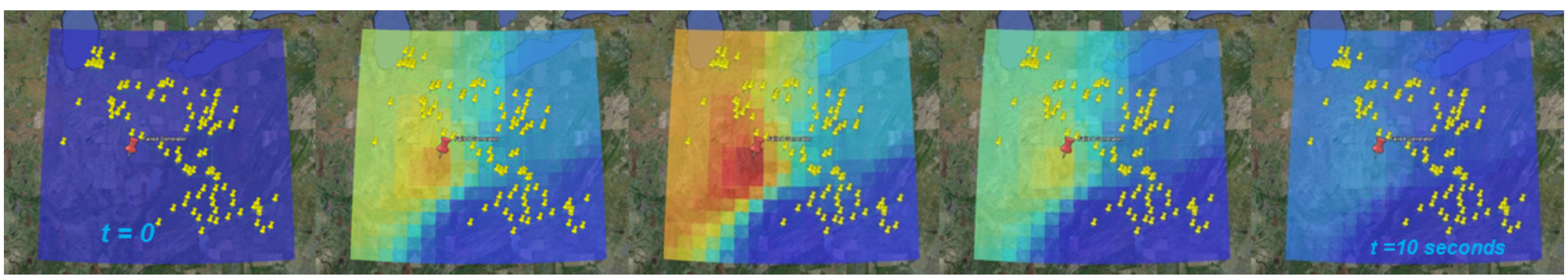


Toolkit for Hybrid Modeling and Evaluation (THYME) of Electric Power Systems

ORNL's THYME





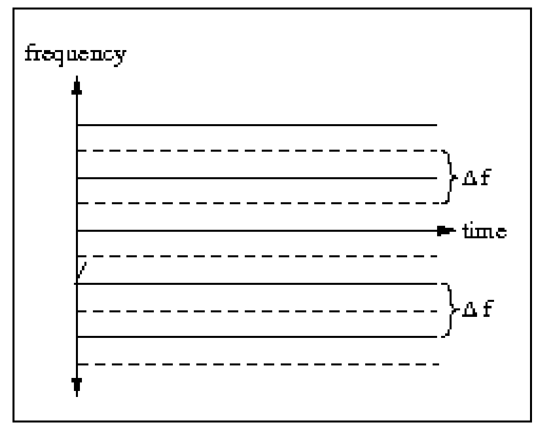


Dynamic models simulate frequency oscillations in the electric transmission system after an outage - A source for understanding electric grid state.

Reference: J. Nutaro, P.T. Kuruganti, L. Miller, S. Mullen, and M. Shankar, published in the Proceedings of the Power Engineering Society's General Meeting, pp.1-8, June 2007.

Accurate modeling of frequency sensors at loads

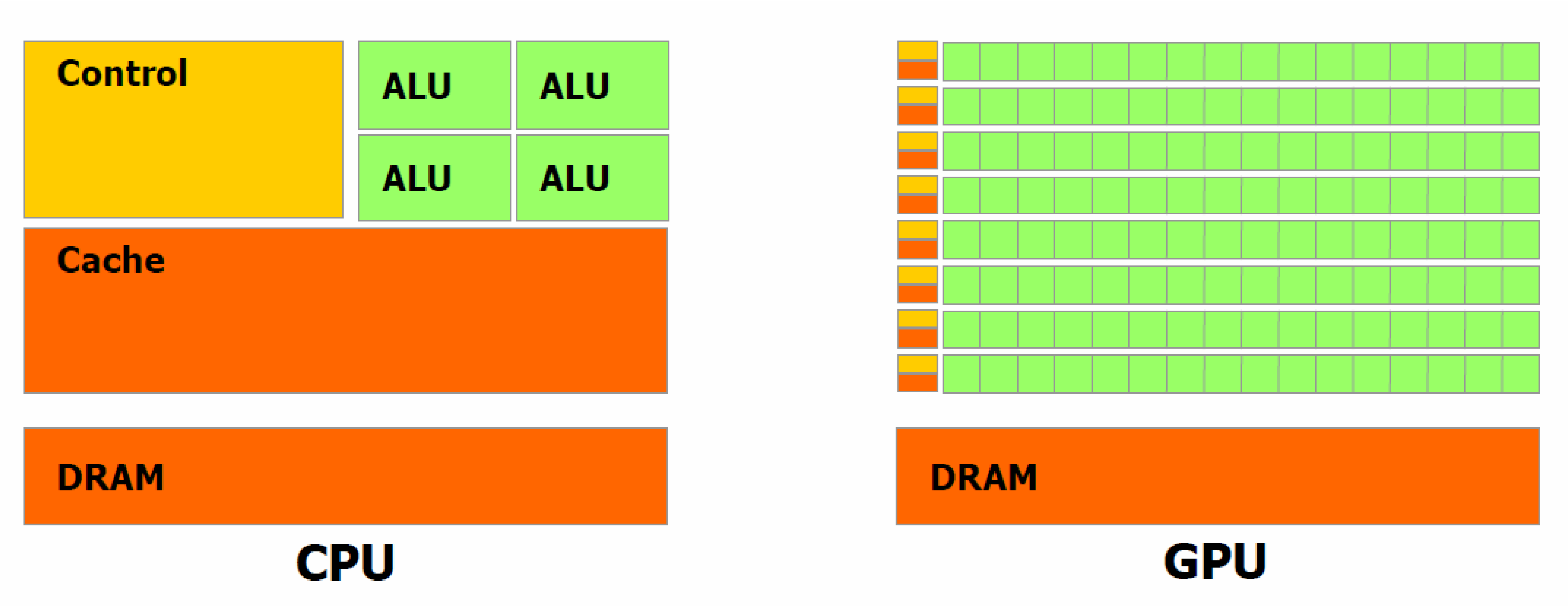
- Novel method for removing numerical artifacts from simulated system frequencies at electrical loads
  - Nutaro, J.; Protopopescu, V.; "Calculating Frequency at Loads in Simulations of Electro-Mechanical Transients," IEEE Transactions on Smart Grid, vol.3, no.1, pp.233-240, March 2012



- Discrete event models of digital sensors
  - Precise calculation of detection thresholds
  - Simulation of IP-based communication network for streaming sensor data

It's close to the ideal case for a GPU!

- With less resources spent on cache, GPUs are more **efficient** for parallel problems with small working sets



Advantages of GPUs

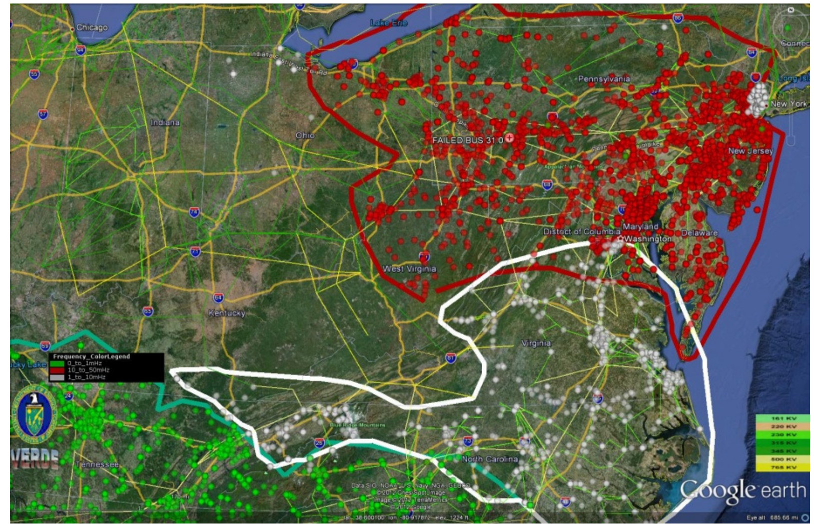
- **Why GPUs?**
  - **Less resources spent on cache**
  - **Inexpensive**
  - **Energy Efficient**
  - **Horizontal Scaling (proportional increase in sensors and GPUs)**
  - **Also useful for fast compression of sensor data: 75 GB/s @ 1.25x compression ratio**
    - M. A. O'Neil and M. Burtscher. **Floating-Point Data Compression at 75 Gb/s on a GPU**. *Fourth Workshop on General Purpose Processing on Graphics Processing Units* (GPGPU-4). Newport Beach, CA. March 2011.

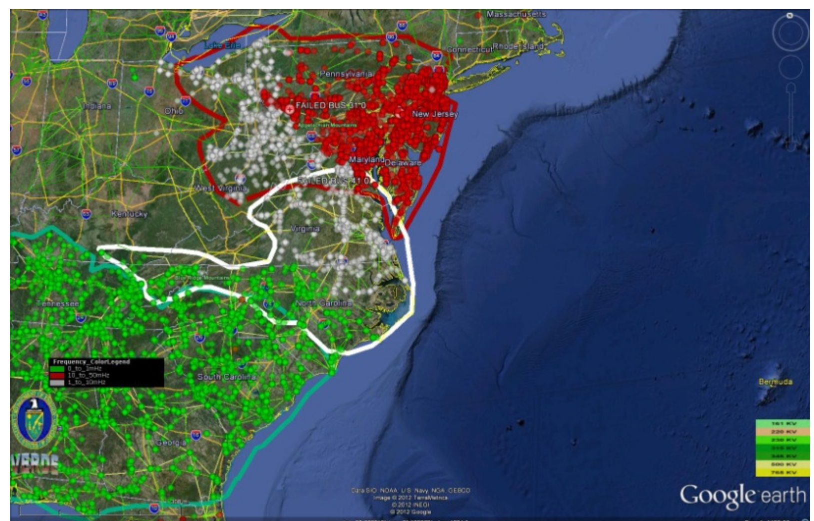
Event Detection Scheme

- The THYME framework was used to perform a full set of (N-1) contingencies (roughly 60K) operating on ORNL's Keeneland cluster, which is a 200 Teraflop high performance computer, producing roughly 5GB of signatures
- These simulations solve for the frequency depression at each of the 60K elements and match to the pattern of depression to identify the lost component or components
- Each GPU can compare\search this data at a rate of 1.5MM signatures per second
- This process populates data base searchable within the 2-4 second decision loop

Demonstration of Development of Models on Keeneland

- Each event within an N-1 contingency calculation creates **patterns** to allow retrieval from an archive of 10 billion contingencies within a 2000 msec decision loop – This still **limits cases to N-4**.
- An approach presents itself to apply heuristics to further extend libraries beyond the N-4 contingency levels.
- After analyzing the EI simulation results for the N-1 data set, there are about **4% cases** have frequency depressions that exceed 8 mHz.



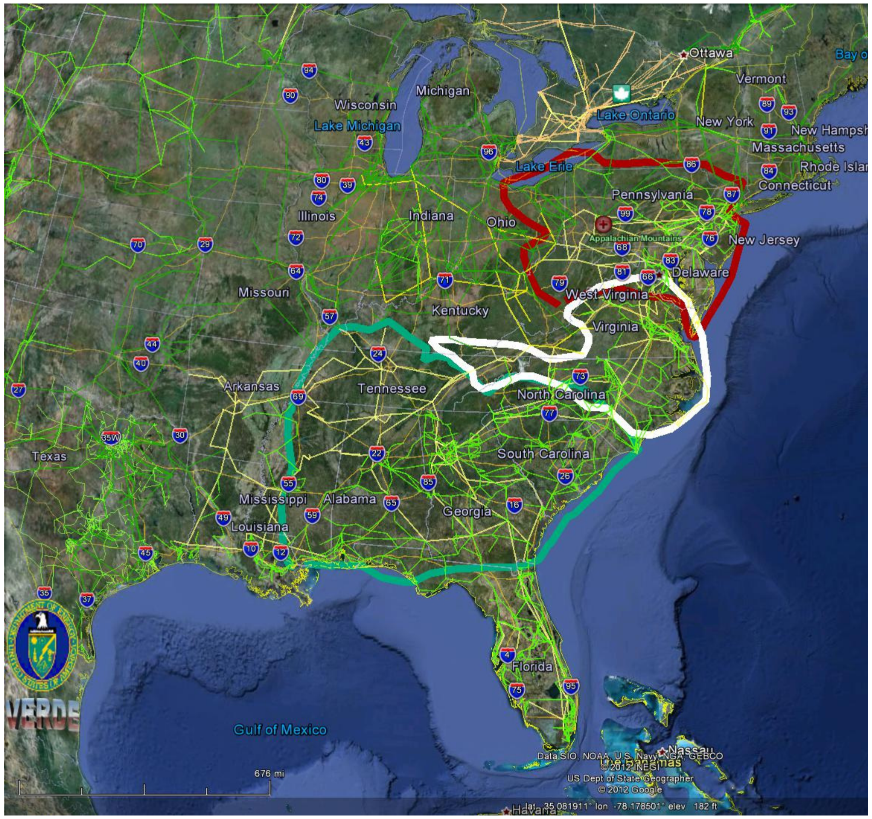


Architecture Summary Table

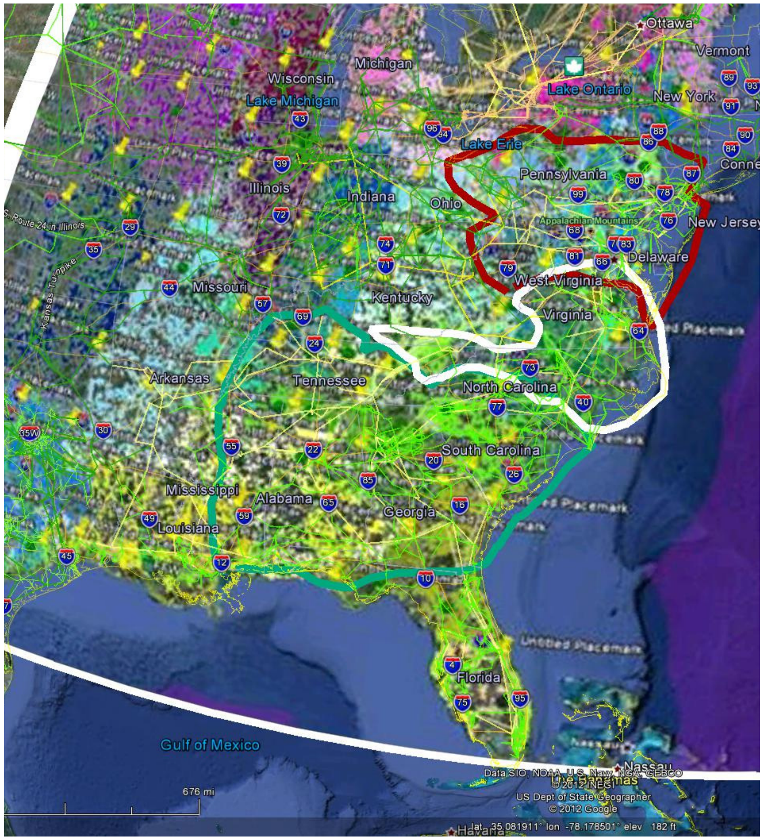
- The demonstration illustrated the ability to search up to N-10 contingencies within the 2-4 second decision loop

Task	Requirement	Prototype Solution
Event Detection	Process 2TB/hr sensor data in real-time	GAEDA, 1.2 GB/s
Signature Search	Search all simulated scenarios in 2000ms	GAEDA, 1.5MM sig/s
Scenario Library	Exponential number of PG simulations	THYME on Keeneland, 58k simulations
Sensor Data Archive	Store 7.01 PB data	220 Node Hadoop Cluster

Comparison of Cook NPP 2009 Trip Inter-oscillatory areas and HPC Modeling Results

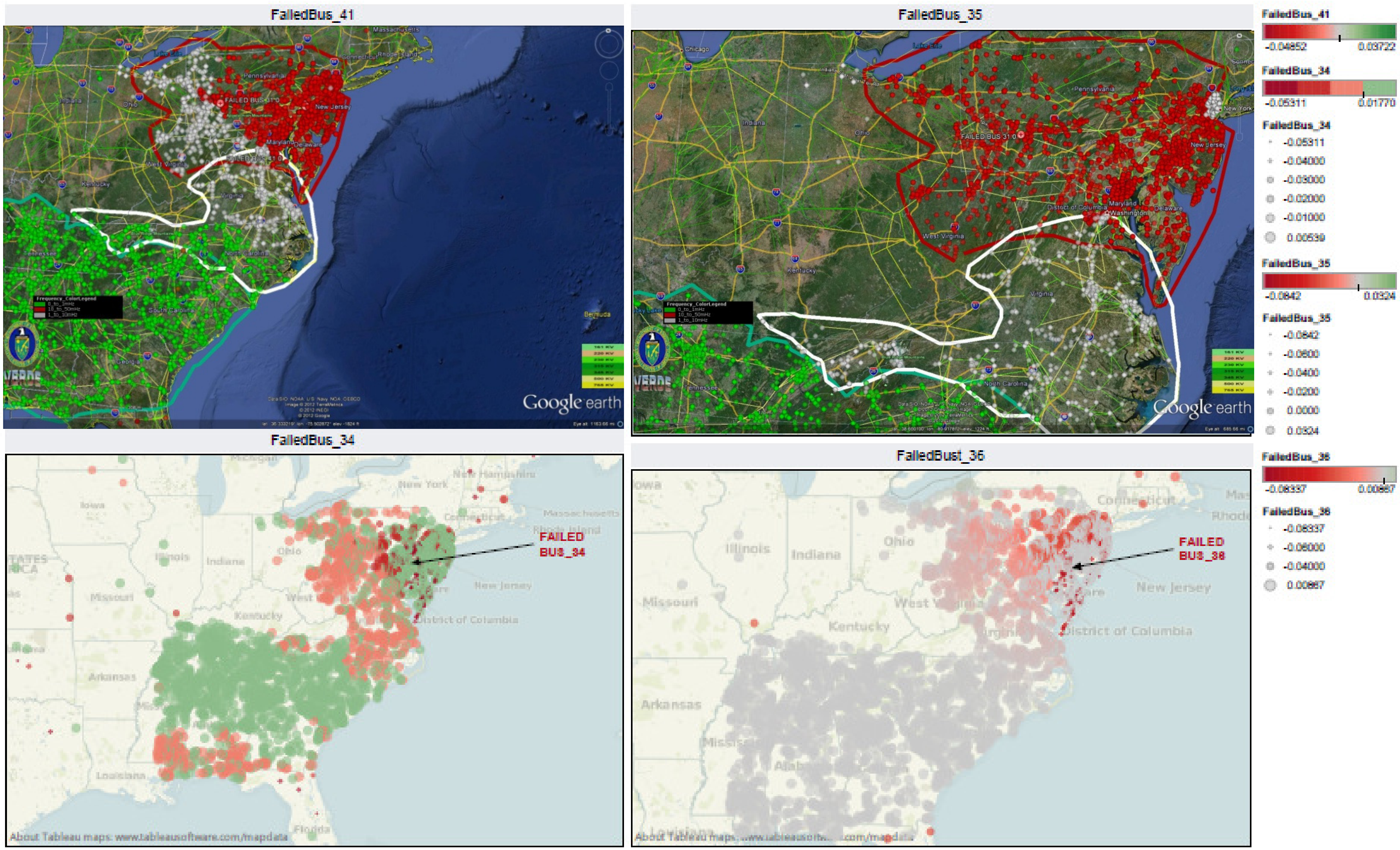


Modeling Based Inter-oscillatory Areas



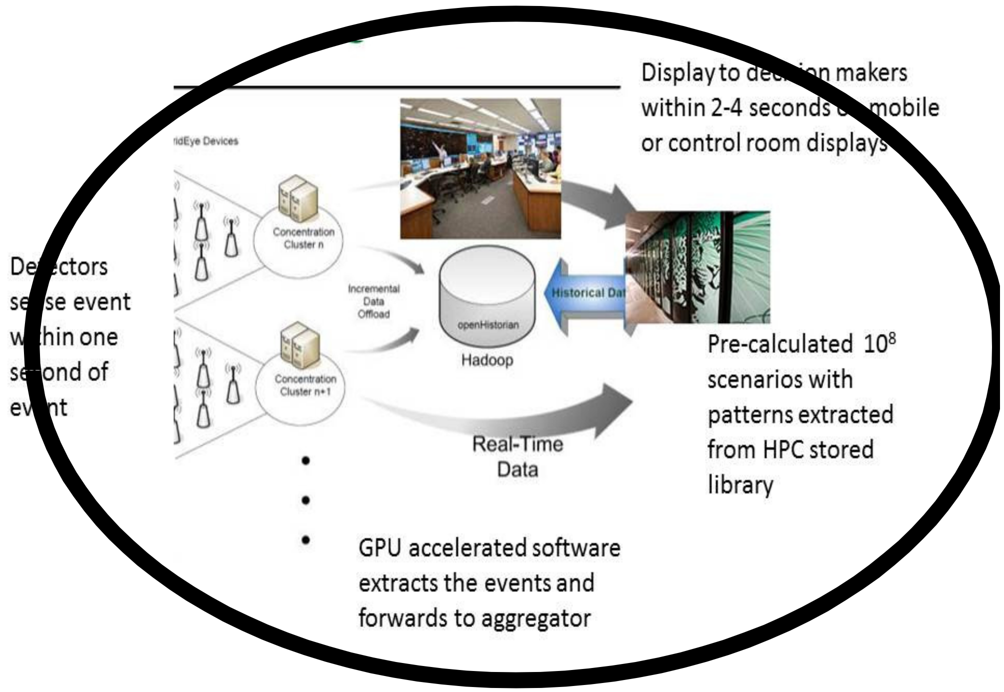
Sampler locations and 2009 empirically derived inter-oscillatory service areas

Patterns of Frequency Propagation and Identification of Failed Buses can be Detected and Presented to Decision Makers on Tablet Platforms within 2-4 second Response Times



Integration of Complete Concept and Demonstration

- The pipeline from the research data set through extraction of the events though searching a 10 million tuple data set to identify potential component results to presenting the search results to a mobile device was accomplished within 1.8 seconds



Electricity that is Always There

1. Sensor displays provide early warning of disruptions and start predictive models to identify possible scenarios

4. Failures, natural or man-made, are forecast or assessed in real-time so response and repairs can be pre-staged or dispatched in real-time

2. Petascale simulations generate scenario libraries that are rapidly searched and closest matches presented within two seconds

3. Operators are updated on emerging disruptions automatically without manually calling the field or other utilities

5. Renewables, micro-grid Islands, and distributed generation can be controlled with new protocols and techniques to handle unanticipated demands


Questions?