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Fusing Models and Data for a Dynamic Paradigm of Power Grid Operations

ASCR Project: Advanced Kalman Filter for Real-Time Responsiveness in Complex Systems

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Challenges in Future Power Grid Operations
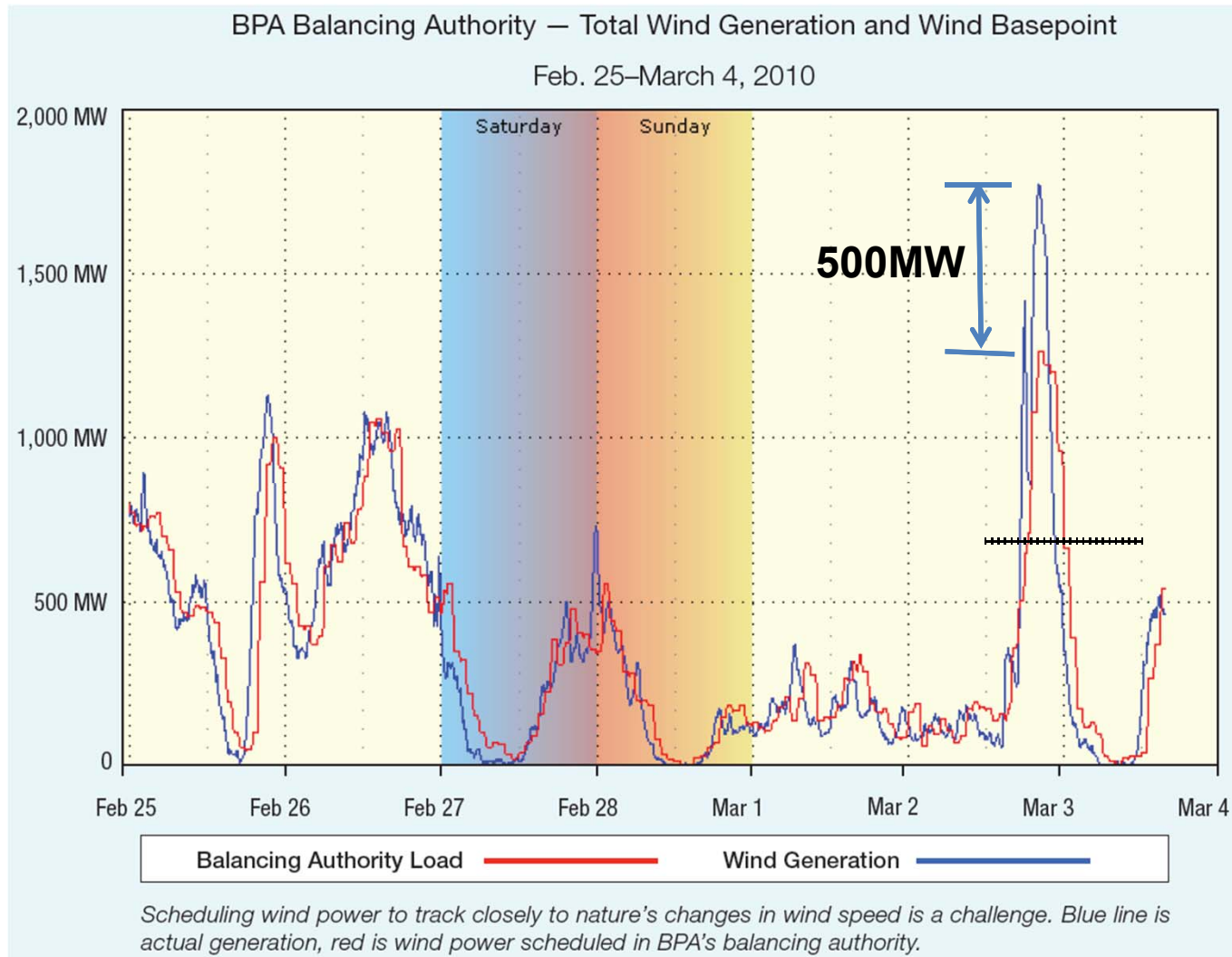## "Grid evolution meets information revolution"

▶ **Grid Evolution** – stochastic & dynamic

- ■ Generation: intermittent renewable energy, distributed generation,
- ■ Demand: smart loads, plug-in hybrids,
- ■ Other: storage, new market design/incentives

▶ **Information Revolution** – data rich but information scarce

- ■ Large number of phasor measurement units and smart meters
- ■ Requirements of cyber security
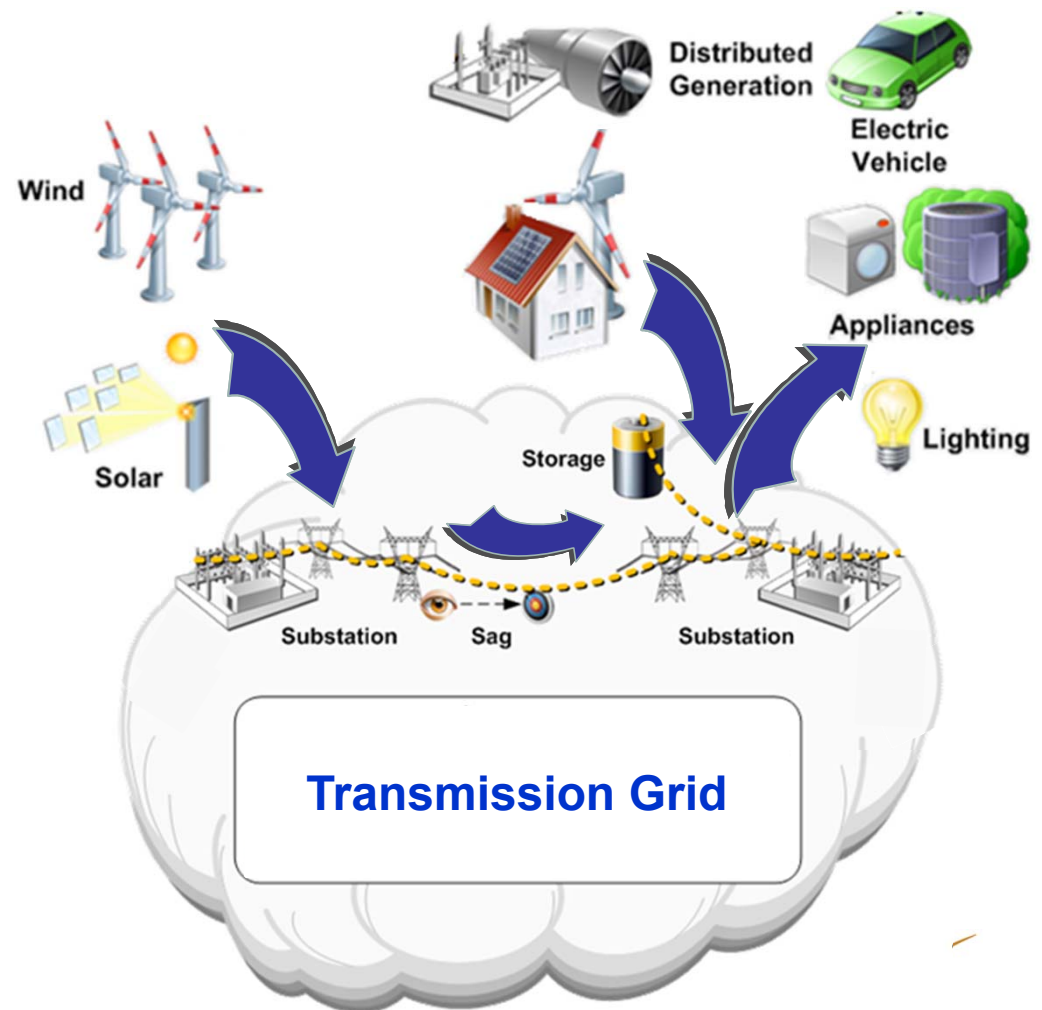
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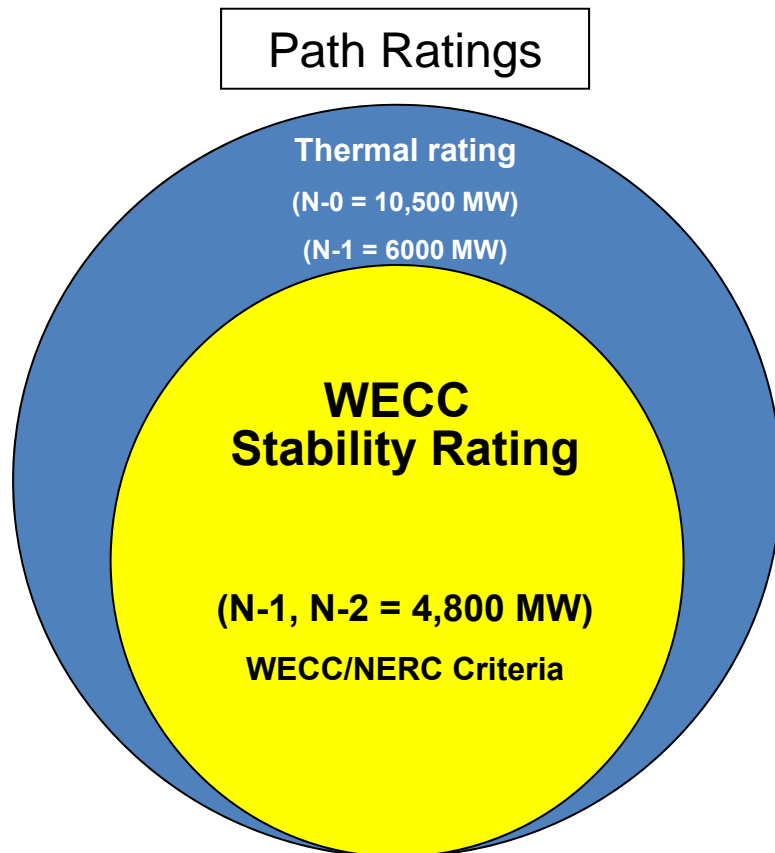NATIONAL LABORATORY

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Mitigate Intermittency of Renewable Energy

BPA Balancing Authority — Total Wind Generation and Wind Basepoint
Feb. 25–March 4, 2010

Scheduling wind power to track closely to nature's changes in wind speed is a challenge. Blue line is actual generation, red is wind power scheduled in BPA's balancing authority.

Source: BPA Fact Sheet, "BPA's wind power efforts surge forward", March 2010

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Enable Real-time Rating for Better Asset Utilization

Transfer Capacity Example – California Oregon Intertie (COI)

Path Ratings
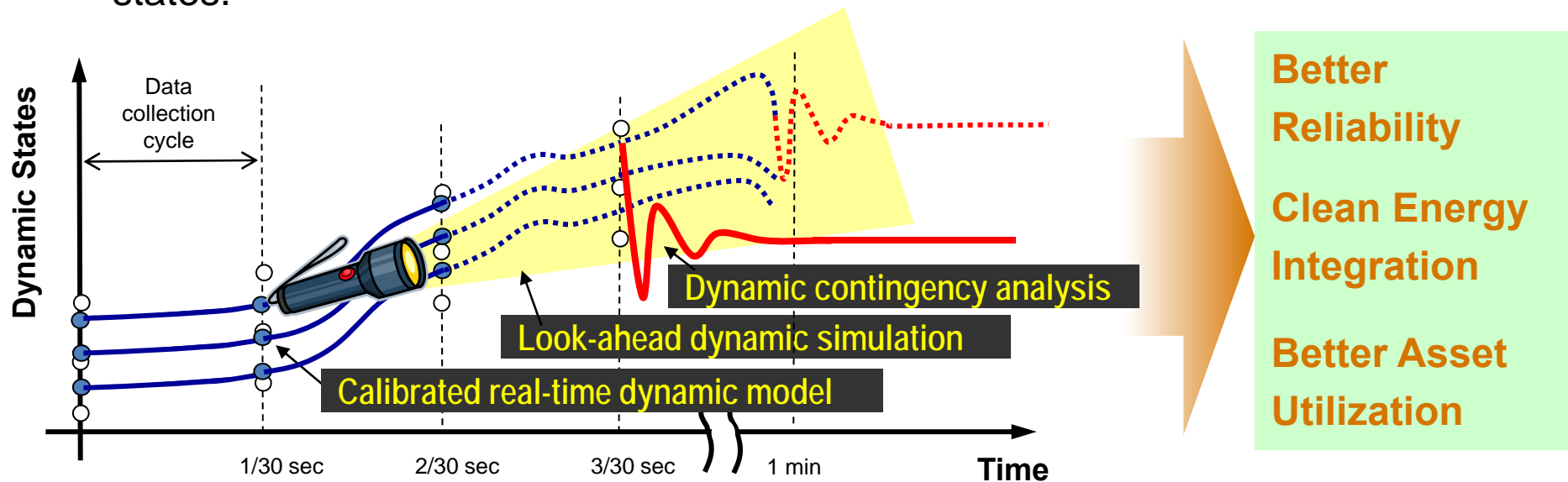
U75, U90 and U(Limit)

Thermal rating
(N-0 = 10,500 MW)
(N-1 = 6000 MW)

**WECC
Stability Rating**

(N-1, N-2 = 4,800 MW)

WECC/NERC Criteria

U75 – % of time flow exceeds 75% of OTC *(3,600 MW for COI)*

U90 - % of time flow exceeds 90% of OTC (4,320 MW for COI)

U(Limit) - % of time flow reaches 100% of OTC *(4,800 MW for COI)*

% of Time

75%   90%   100%

% of OTC

Source : Western interconnection 2006 congestion management study

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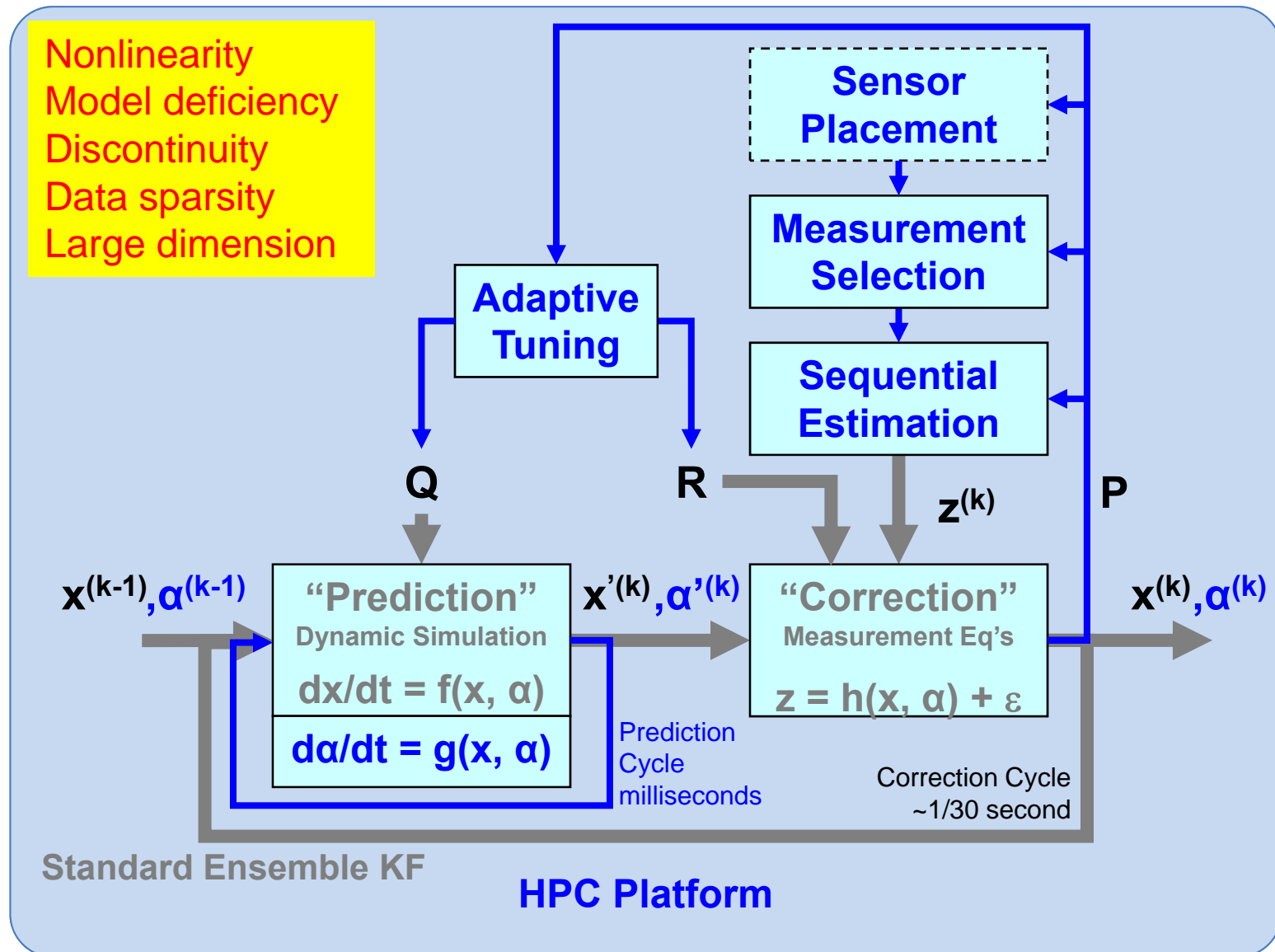
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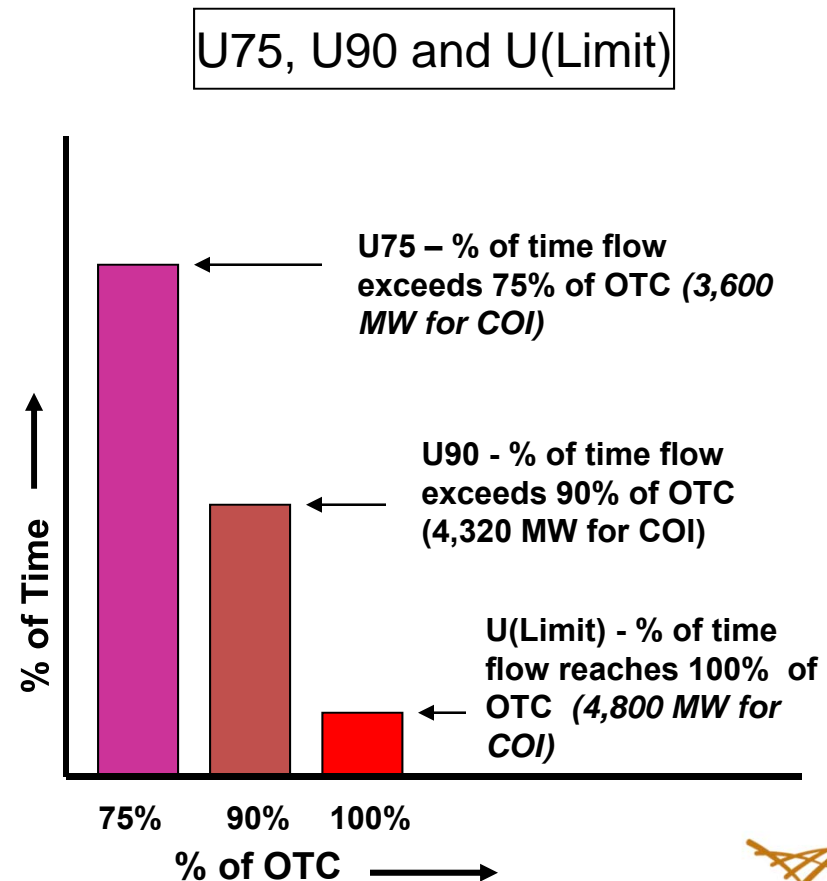
Dynamic Paradigm of Power Grid Operations

▶ **National Driver**: Clean and Efficient Power Grid as well as being affordable, reliable, and secure ➜ Operation: static & slow to dynamic & fast.

▶ **Technical Approach**: combine model prediction and measurement observations to determine where we are, where we are going, and what-ifs.

- ■ Fuse models and data with nonlinearity, discontinuity, model deficiency, and data sparsity.
- ■ Develop Advanced Kalman Filter and HPC codes to estimate states and models
- ■ Solve a large number of ODE systems to predict future states and alternative states.

Advanced Kalman Filter for Complex Systems

Nonlinearity
Model deficiency
Discontinuity
Data sparsity
Large dimension

Sensor Placement

Measurement Selection

Sequential Estimation

Adaptive Tuning

Q

R

$z^{(k)}$

P

$x^{(k-1)}, \alpha^{(k-1)}$

"Prediction"
Dynamic Simulation

$$dx/dt = f(x, \alpha)$$

$$d\alpha/dt = g(x, \alpha)$$

$x'^{(k)}, \alpha'^{(k)}$

"Correction"
Measurement Eq's

$$z = h(x, \alpha) + \varepsilon$$

$x^{(k)}, \alpha^{(k)}$

Prediction Cycle milliseconds

Correction Cycle ~1/30 second

Standard Ensemble KF

HPC Platform

Advances from Standard Ensemble Kalman Filter

Optimal sensor placement

$$P^\infty = \lim_{k \to \infty} E[(x_k - \hat{x}_k)(x_k - \hat{x}_k)^T]$$

$$\min_{loc(z)}\left(P^\infty\right)$$

Adaptive tuning

$$S_k = HP_k^- H^T + R$$
$$T_k = RS_k^{-1}R$$
$$Q_k = f(T_k)$$
$$R_k = f(T_k)$$

Prediction

Parameter calibration

$$x_k = [x_k \quad \alpha_k]$$

$$q_i \sim normal(0, Q_k)$$

$$\hat{X}_{k-1} = [\hat{x}_{k-1} + q_1 \quad \hat{x}_{k-1} + q_2 \quad \cdots \quad \hat{x}_{k-1} + q_N]$$

$$X_k^- = \hat{X}_{k-1} + f(\hat{X}_{k-1}, Y_{k-1}, 0)\Delta t$$

$$X_a^- = X_k^- - mean(X_k^-)$$

Multi-step prediction

$$Repeat\ prediction\ steps$$

Correction

$$Z_a^- = h(X_k^-, 0) - mean(h(X_k^-, 0))$$

$$r_i \sim normal(0, R_k)$$

$$Z_k = [z_k + r_1 \quad z_k + r_2 \quad \cdots \quad z_k + r_N]$$

$$P_k^- H_k^T = \frac{1}{N-1} Z_a^-(X_a^-)^T \quad H_k P_k^- H_k^T = \frac{1}{N-1} Z_a^-(Z_a^-)^T$$

Measurement selection

$$z_k \leftarrow C^T z_k, \quad \max_C tr\left\{ \frac{C^T H \hat{P}_k^- \hat{P}_k^- H^T C}{C^T(H\hat{P}_k^- H^T + \hat{R})C} \right\}$$

Sequential estimation

$$P^- = U \cdot D \cdot U^T$$
$$H' = HU$$
$$r_1 = [\frac{H_{11}'^2}{R_{11}} \quad \frac{H_{21}'^2}{R_{22}} \quad \frac{H_{31}'^2}{R_{33}} \cdots \frac{H_{m1}'^2}{R_{mm}}]^T$$
$$Select\ top\ z_k\ per\ r\ ranking$$

$$K_k = (P_k^- H_k^T)(H_k P_k^- H_k^T + R_k)^{-1}$$

$$\tilde{X}_k = X_k^- + K_k(Z_k - h(X_k^-, 0))$$

Note: equations simplified for illustration purposes.

Estimation Performance – estimation accuracy

► Excellent tracking with realistic evaluation conditions

■ 3% measurement noise; 40 ms measurement cycle; 10 ms model prediction cycle; 20% parameter errors; unknown topology change; unknown initial states.

Blue tracking red is the goal

100% is the goal
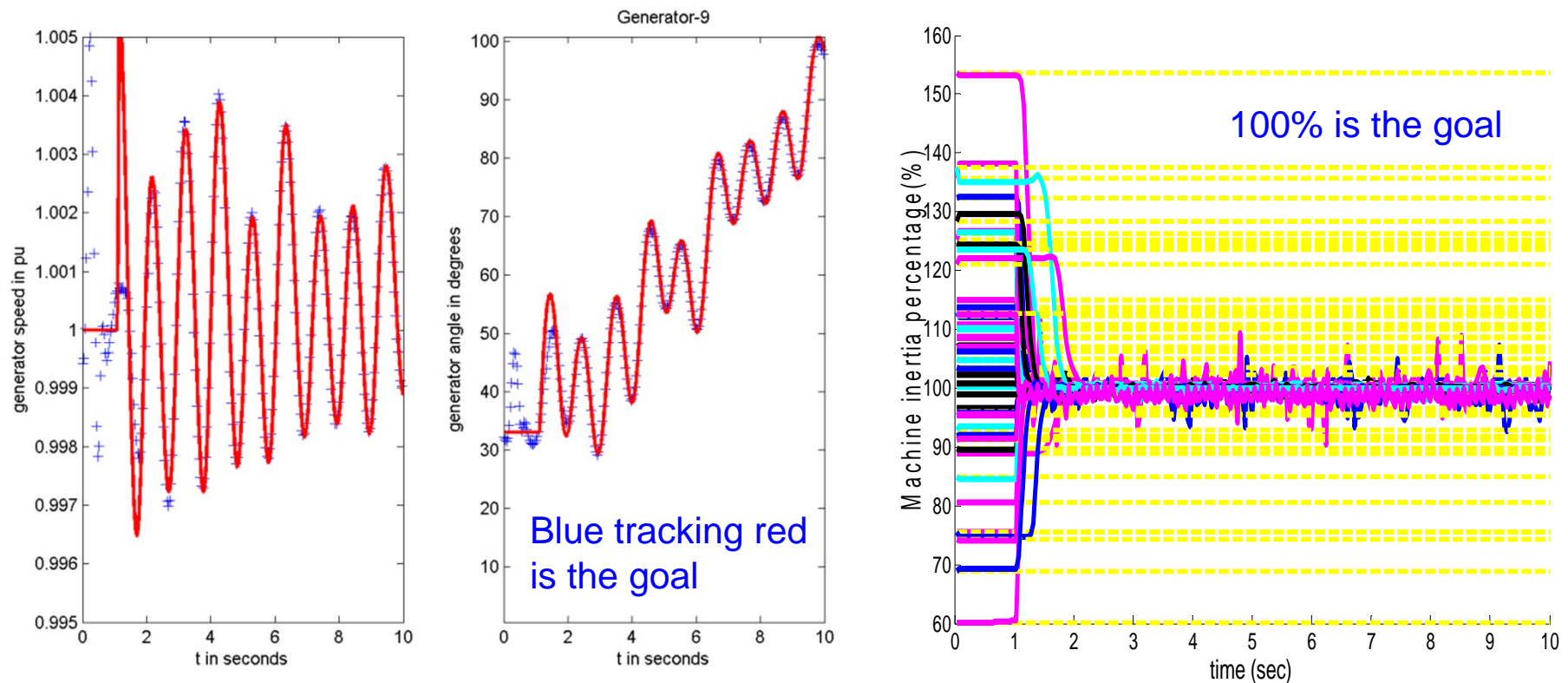
Estimation Performance – measurement handling

▶ Measurement selection

- Pseudo inverse test: 1000 measurements, 50 states

|	No selection	With selection				
Measurements	1000	100	50	25	12	6
Time	7.82 sec	1.31 sec	0.60 sec	0.52 sec	0.53 sec	0.58 sec
Rel Accuracy	100%	100%	100%	59%	32%	17%

▶ Sequential estimation

- Trade-off between computation time and number of measurements

- Sequential estimation maximizes estimation quality with available computing resources

- Choose measurements with most "value" – largest *sensitivity-to-uncertainty* ratio

Sequential Estimation
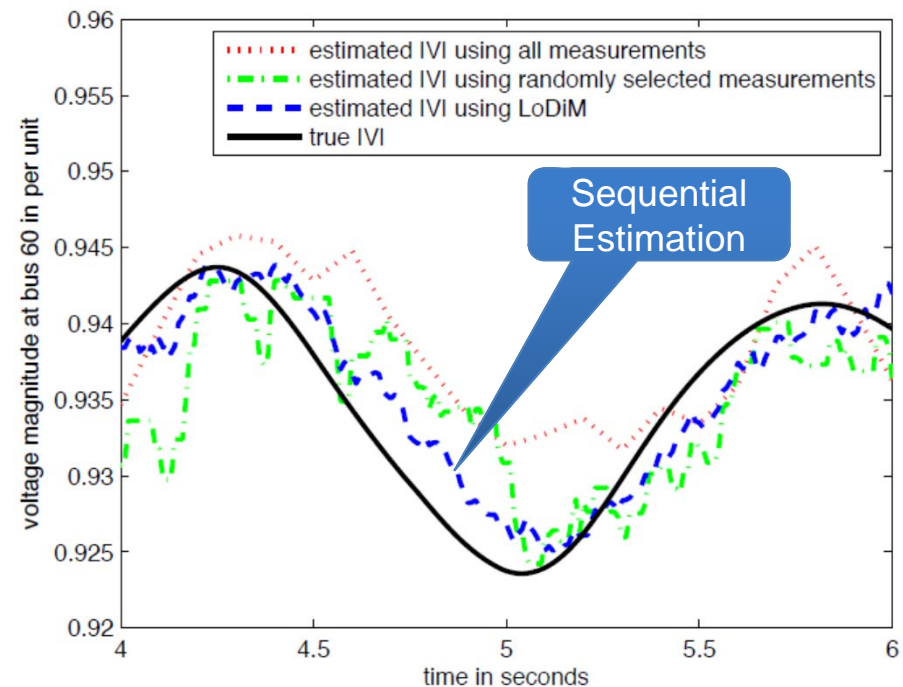
Computational Performance – scalability

► Current codes scale to ~1000 cores

► Rate-limiting step is some dense matrix multiplies and a Cholesky decomposition

► A peta-scale problem

  ■ Western US power grid: 16072 Buses, 2361 Generators →1.7*10^{13} flops

  ■ To complete each step in 0.03 sec → 0.6 Petaflops/sec (ideal)

  ■ Data movement limits efficiency to <10% → >6 PF

16072 bus, 2361 Gen System (WECC)

16072 bus, 2361 Gen System (WECC)
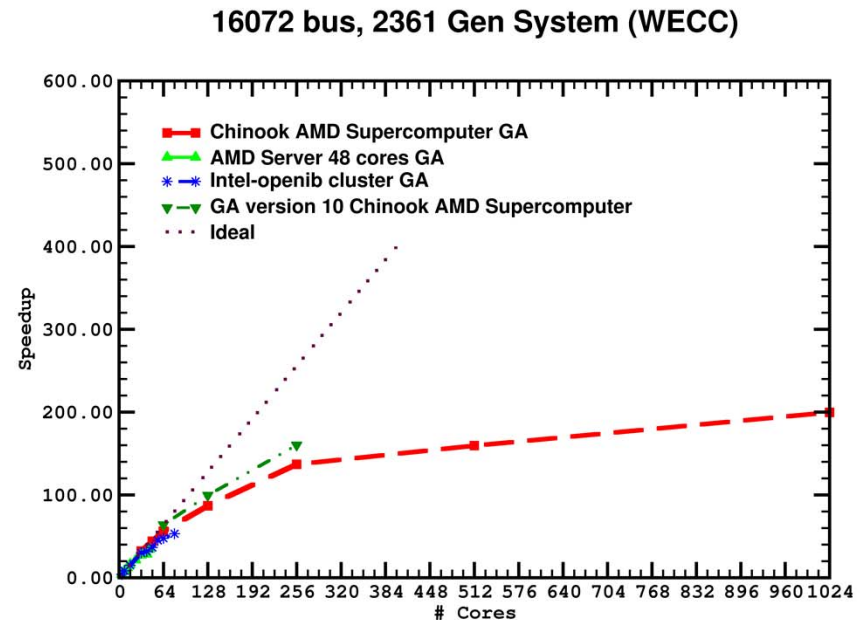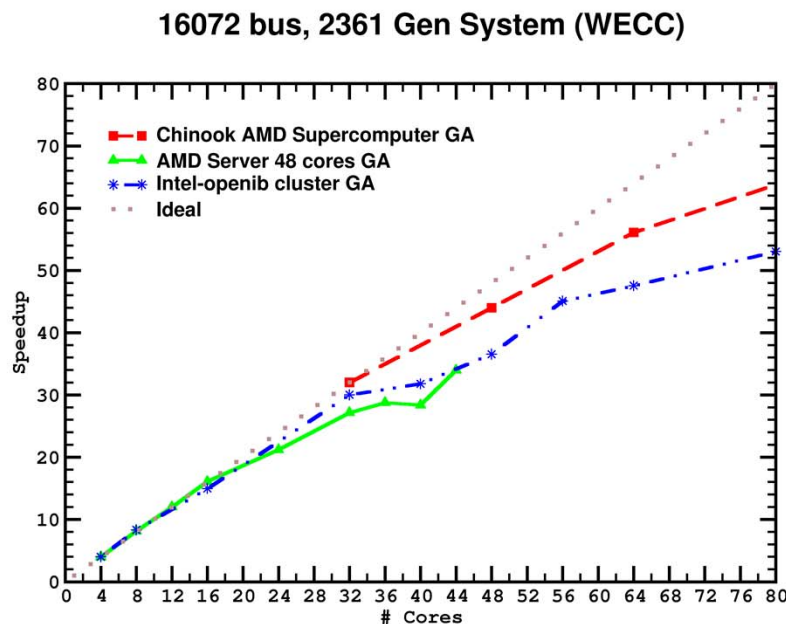
Synergetic Work – look-ahead dynamic simulation

▶ ODEs: achieved 14x speed-up for a 400 machine system.

▶ Speed-up performance is expected to be better with larger system sizes (e.g. WECC has 3000 generator).

▶ Promising for look-ahead capabilities.

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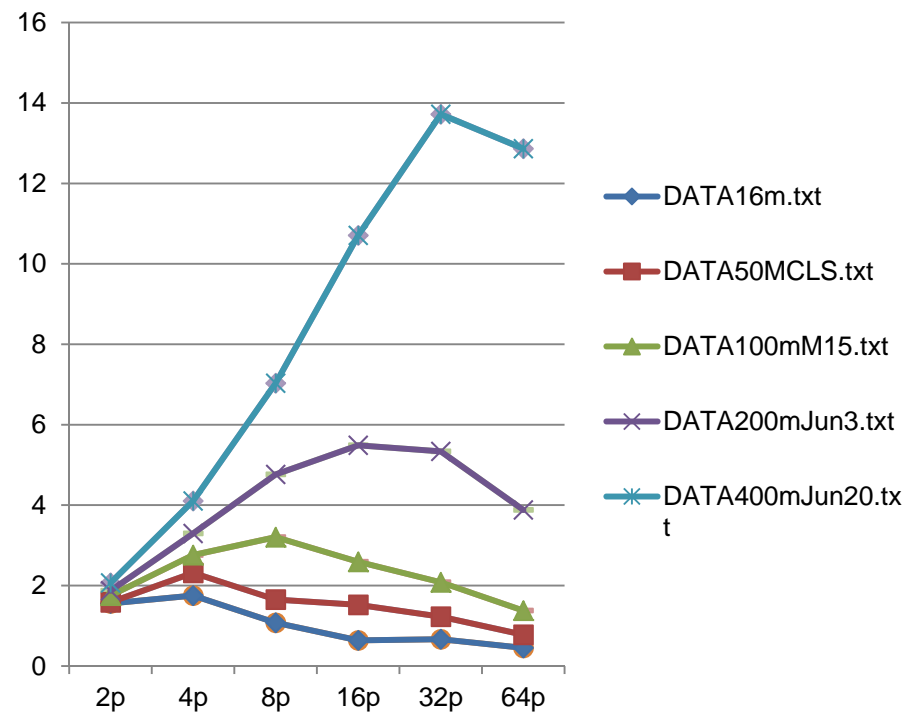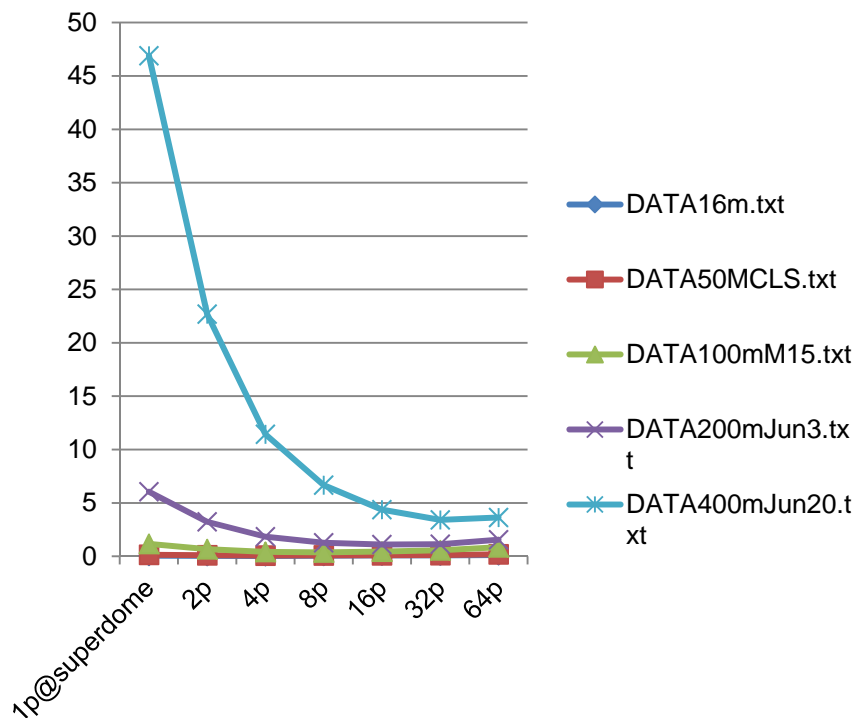
Synergetic Work – dynamic contingency analysis

► A large set of ODEs

► Computational challenge is load balancing – dynamic load balancing vs. static load balancing

► Results on steady-state contingency analysis shows a promising path forward
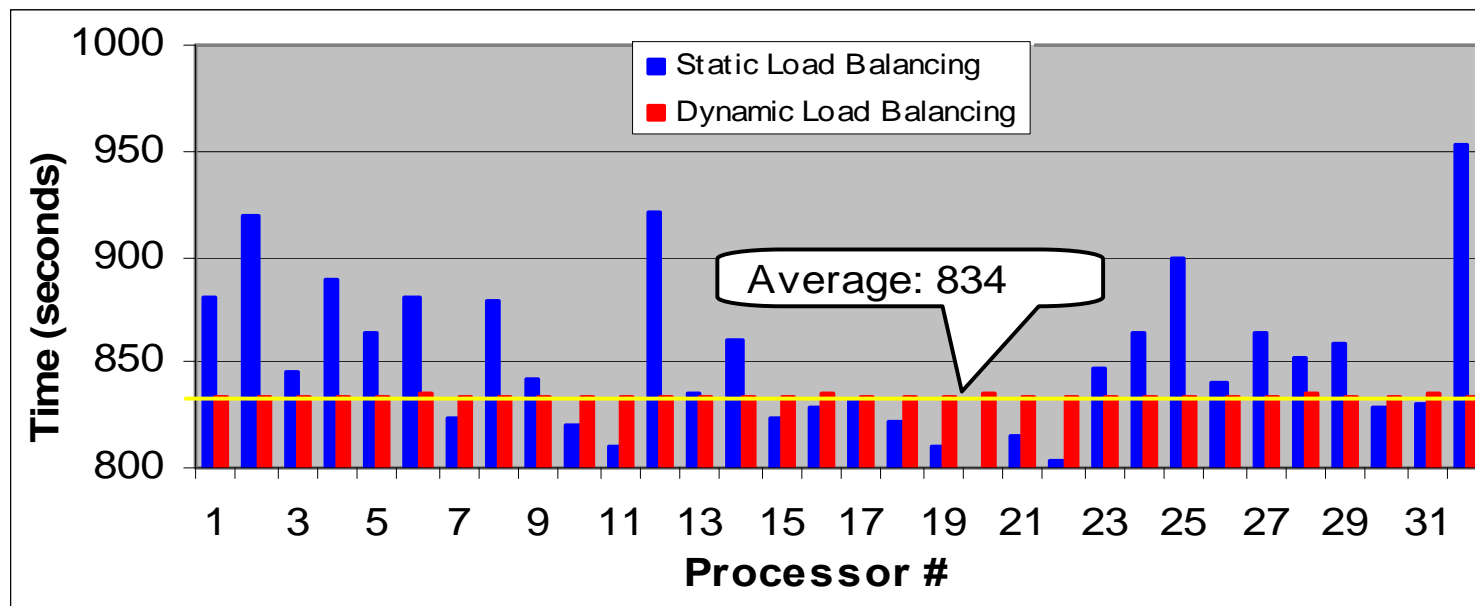
Next Steps

► Within the current project:

- Refine the Advanced Kalman Filter algorithm and mathematics
- Scale to 10,000-100,000 cores
- Demonstrate value with integrated testing of developed algorithms

► Remaining challenges – beyond the current project :

- Develop real-time HPC platform: hardware and software stacks
- Solve a large set of high-dimension ODEs in real time
  - Look-ahead dynamic simulation
  - Dynamic contingency analysis
- Integrate technical elements for the dynamic grid operation paradigm

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Summary

- ► Grid operations: from static & slow to dynamic & fast ← grid evolution meeting information revolution.
  - ■ Enabling technologies are computation advancement and data development
- ► Advanced Kalman Filter has been developed to fuse models and data to determine where we are – foundation for a dynamic paradigm of grid operation
- ► Excellent estimation accuracy and computational performance have been demonstrated with tests using power grid models and data.
- ► An integrated platform and software package are being developed for the dynamic operation paradigm – where we are, where we are going, and what-ifs.

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Questions?

Please come visit our posters:

Monday 3:15PM
- Poster #18: Zhenyu Huang, "Fusing Models and Data for a Dynamic Paradigm of Power Grid Operations"
- Poster #08: Jinghe Zhang, "Adaptable Kalman Filtering for Robust Power System State Tracking"

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