PNNL-SA-121634

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

Pradeep Ramuhalli, Ramakrishna Tipireddy, Megan Lerchen

Pacific Northwest National Laboratory

Jamie Coble, Anjali Nair, Samuel Boring

University of Tennessee Knoxville

Brent Shumaker, Hash Hashemian

Analysis and Measurement Services

October 12-13, 2016

Project Overview

- **Goal: Develop and evaluate a standardized framework for next-generation online monitoring applicable to current and future nuclear systems**

- **Participants:**
  - PNNL (Pradeep Ramuhalli, Ramakrishna Tipireddy, Megan Lerchen)
  - University of Tennessee Knoxville (Jamie Coble, Anjali Nair, Sam Boring)
  - AMS (Brent Shumaker)

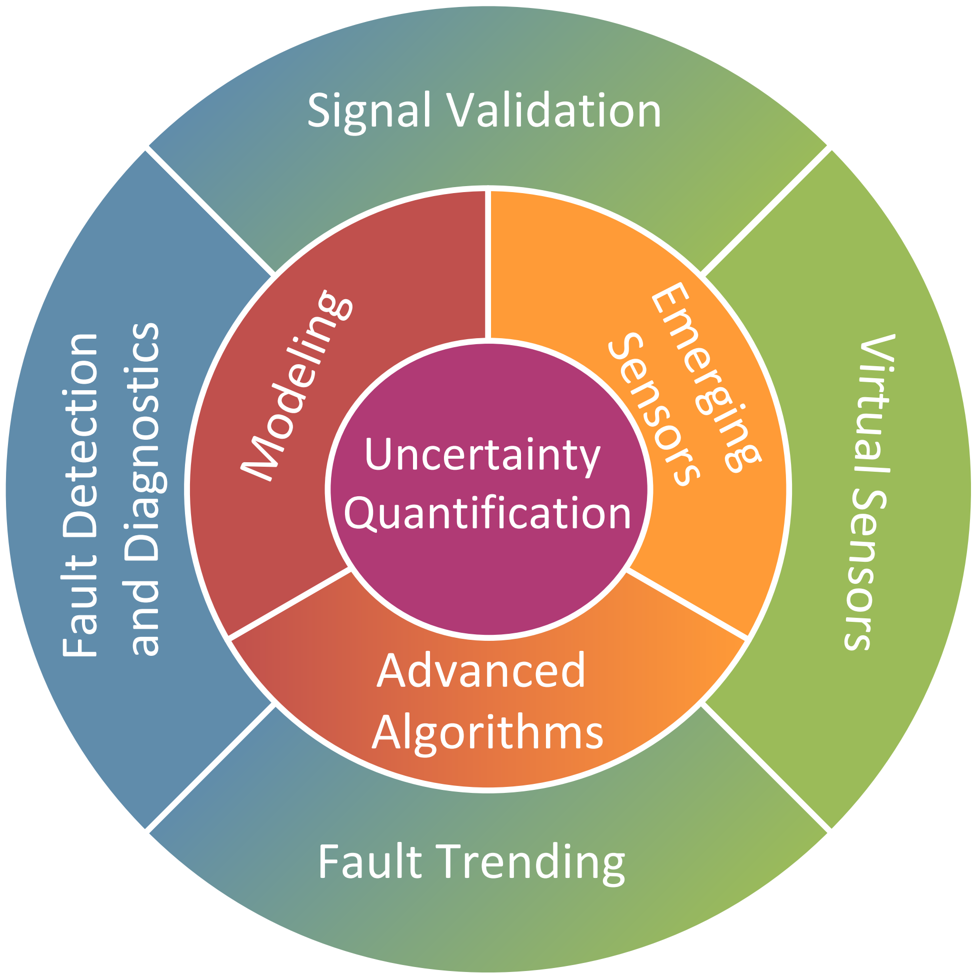
- **Schedule**
  - Three years (FY 2015 – FY 2017)

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Objectives

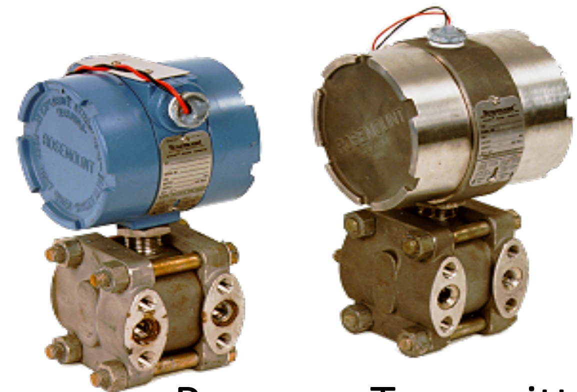
- **Develop next-generation online monitoring applicable to current and future nuclear systems**
  - Apply data-driven UQ to develop methods for real-time calibration assessment and signal validation
  - Robust virtual sensors to augment available plant information
  - Technologies for automated sensor response-time monitoring
  - Considerations for emerging I&C technologies



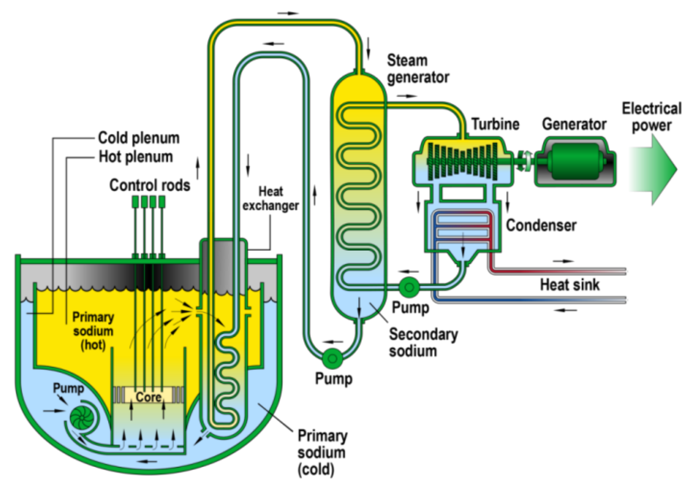
Project Background

- **Measurement reliability key to safe, economic and secure operation of nuclear systems**
  - Interval-based recalibration used to assure reliability

- **Current practices have several drawbacks**
  - Time consuming and expensive
  - Sensor calibration assessed infrequently
  - Contributes to unnecessary radiological dose
  - Unnecessary maintenance may damage healthy sensors
  - Potential for limited opportunities for maintenance in future nuclear systems
  - Different failure mechanisms for next-generation sensors and I&C



Pressure Transmitters



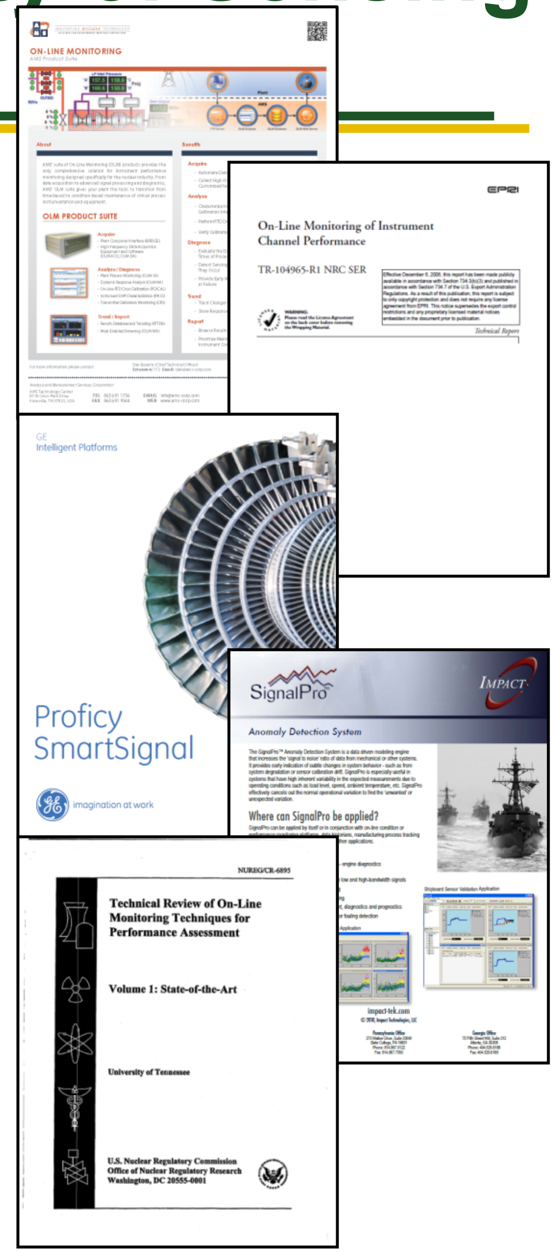
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Sensor Performance Monitoring can Improve Reliability of Sensing

- **Online monitoring (OLM) supports condition-based calibration of key instrumentation**

- **OLM technologies can**
  - Temporarily accommodate limited sensor failure
  - Provide indications for measurements that cannot be made (virtual sensors)
  - Ensure reliability of next-generation sensors and instrumentation through formal methods for uncertainty quantification
  - Support extended sensor calibration cycles and reduce or eliminate TS-required periodic recalibration



U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Technology Impact

- **Framework for next generation OLM that enables**
  - Recalibration needs assessment for dynamic and steady-state operation
  - Short-term operation with a limited number of failing sensors, through the use of virtual sensor technology
  - Ability to derive plant information that currently cannot be measured using virtual sensors
  - Monitoring and detection of degradation in sensor response time
  - Predictive (over short-term) assessment of sensor failure
  - OLM framework for emerging I&C technologies

- **Supports DOE-NE research objectives***
  - Improve reliability, sustain safety and extend life of current reactors
  - Improve affordability of new reactors

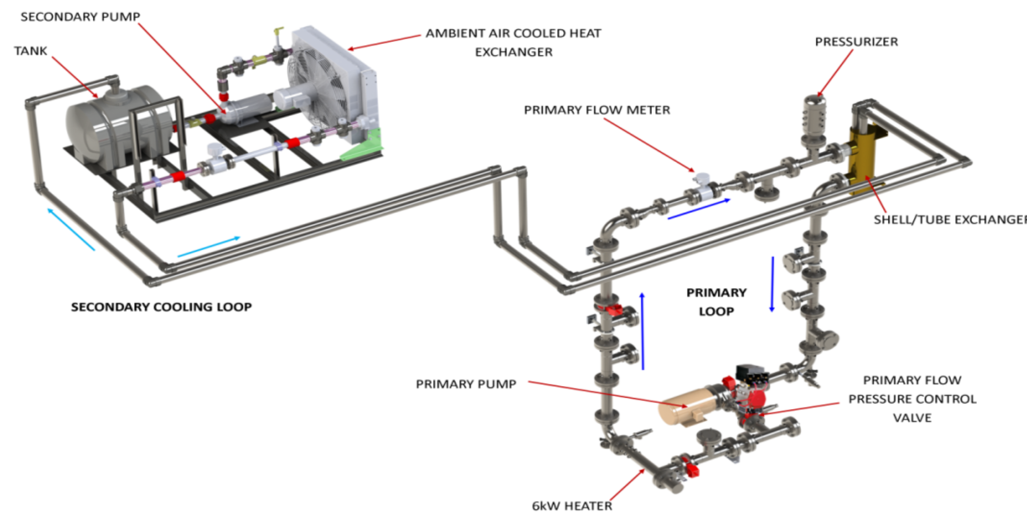
**Nuclear Energy Research and Development Roadmap, April 2010*

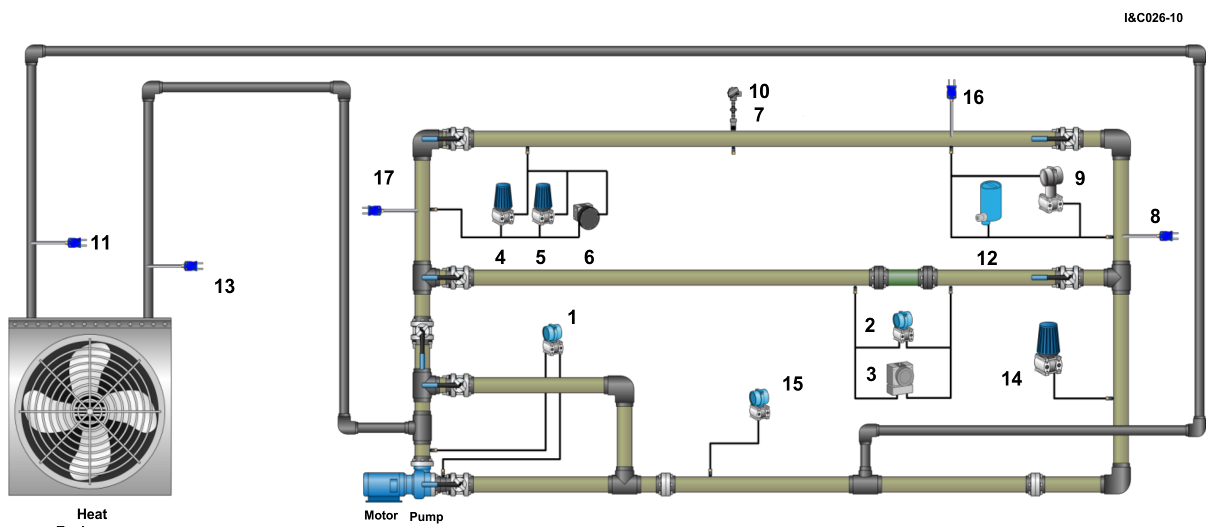
Research Tasks

- **Signal validation and virtual sensors**
  - Evaluate how uncertainty drives minimum detection limits and acceptance criteria
  - Estimate expected measurement values (and associated uncertainties) for replacing faulted sensors
  - Evaluate the effect of using virtual sensors on OLM and OLM uncertainty
  - Develop guidelines for condition-based sensor recalibration
- **Assess impacts of next generation sensors and instrumentation**
  - Requirements definition for OLM in next generation I&C
  - Gaps assessment: Map algorithms (from other tasks) to requirements
- **Response time OLM**
  - Acceptance criteria development
  - Adapt research in signal validation for response time OLM
- **Verification and validation based on data from a suitable test-bed or operating plant**

Testbeds Simulate Heat Exchanger Operations

- **Simple heat exchanger loop**
- **Sensor and instrumentation models coupled to loop model**
- **Prescribed uncertainty levels to directly study effects on sensed values and OLM results**
  - Normal and anomalous conditions

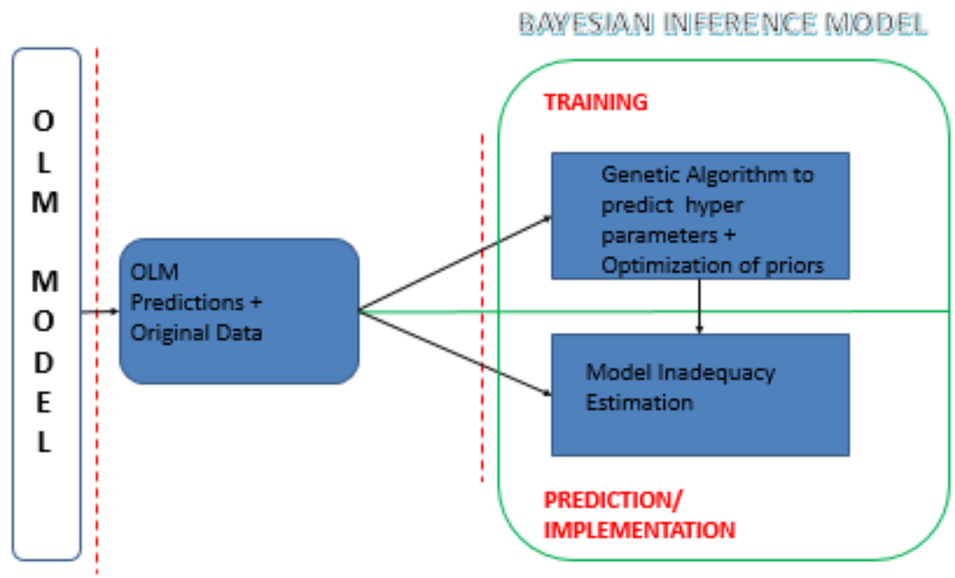




ITEM	ID	SENSOR TYPE	MANUFACTURER
1	FT-4-1	DIFFERENTIAL PRESSURE	ROSEMOUNT
2	FT-3-1	DIFFERENTIAL PRESSURE (SMART)	ROSEMOUNT
3	FT-3-2	DIFFERENTIAL PRESSURE	BARTON
4	FT-1-1	DIFFERENTIAL PRESSURE	FOXBORO
5	FT-1-2	DIFFERENTIAL PRESSURE	FOXBORO
6	FT-1-4	DIFFERENTIAL PRESSURE (SMART)	BARTON
7	TE-1-2	RTD (SMART)	ROSEMOUNT
8	TC-2-1	THERMOCOUPLE TYPE-J (SMART)	ROSEMOUNT
9	FT-2-1	DIFFERENTIAL PRESSURE	SCHLUMBERGER
10	CTRL-TEMP	RTD (SMART)	ROSEMOUNT
11	TC-HX-OUT	THERMOCOUPLE TYPE-J	OMEGA
12	FT-2-3	DIFFERENTIAL PRESSURE	HONEYWELL
13	TC-HX-IN	THERMOCOUPLE TYPE-J	OMEGA
14	CTRL-PSR	GAUGE PRESSURE	FOXBORO
15	PT-2	GAUGE PRESSURE	ROSEMOUNT
16	TC-LOOP-FAR	THERMOCOUPLE TYPE-E	OMEGA
17	TC-PUMP-OUT	THERMOCOUPLE TYPE-K	OMEGA

Signal Validation using Bayesian Inference Model

- **Uncertainty quantification of OLM residuals**
- **Focus on differentiability of errors of interest, such as model inadequacy and instrument errors**
  - Model inadequacy is assumed stationary across time and operating conditions
- **Bayesian inference and Gaussian process models applied for predicting model inadequacy values**
- **Model trained and tested using Nuclear coolant data and the flow loop data collected by AMS**
  - Normal and anomalous conditions

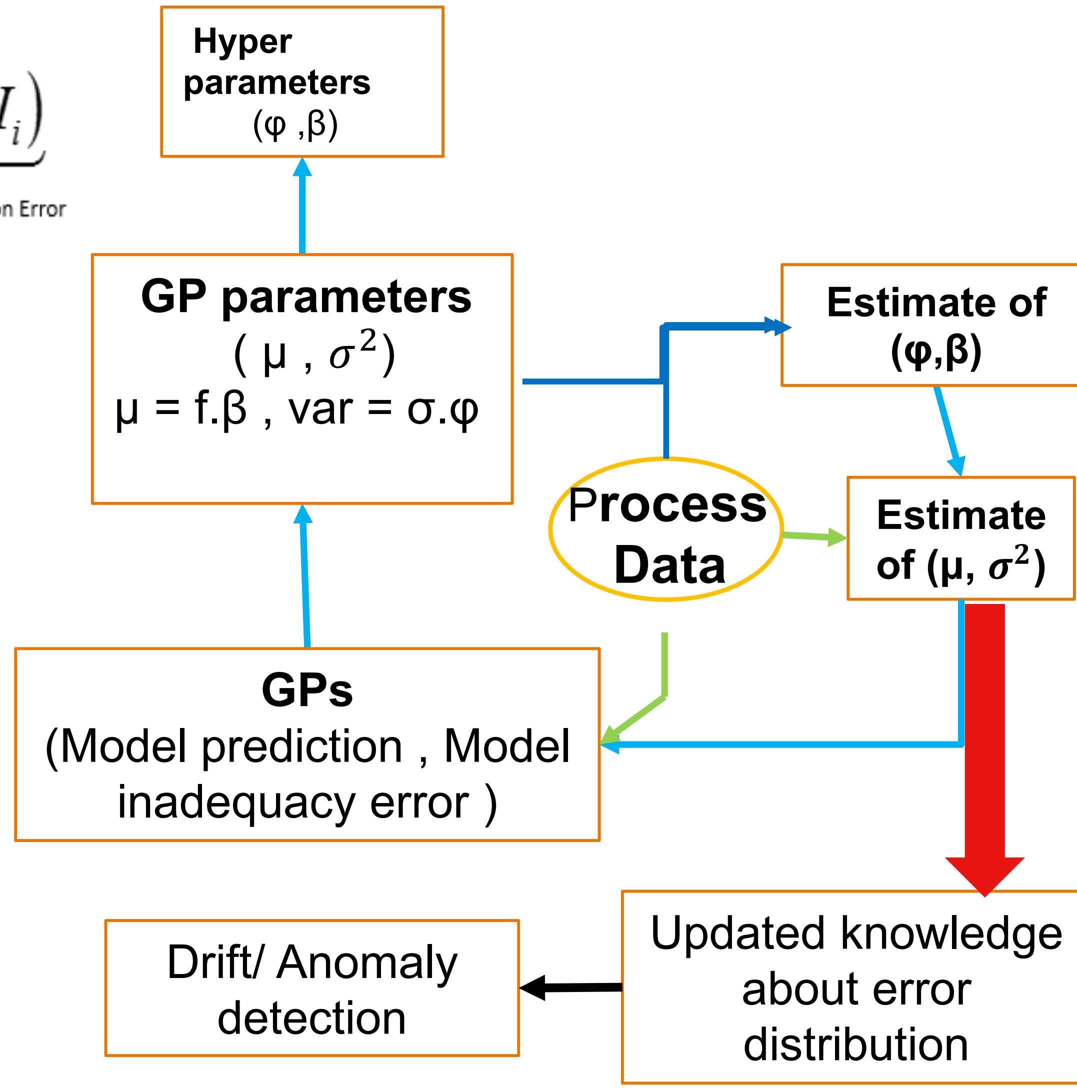


Model process overview

$$r(z_i,\omega_i)=\underbrace{\underbrace{y(z_i,\omega_i)}_{\text{Predictive Model}}}_{\textbf{GP 1}}-\overbrace{z_i}^{\text{Observation /Data}}=\underbrace{\underbrace{\delta(z_i,\omega_i)}_{\text{Model Inadequacy}}}_{\textbf{GP 2}}+\overbrace{e_i}^{\text{Observational Error}}+\underbrace{\rho\eta(\Delta t_i,I_i)}_{\text{Sensor Degradation Error}}$$

On the basis of the defined priors in the form of GP1 and GP2 , the Bayesian inference model is implemented

The distribution of interest : the model inadequacy is updated using data and various parameter estimates. This is used to bound the error and uncertainty of the prediction



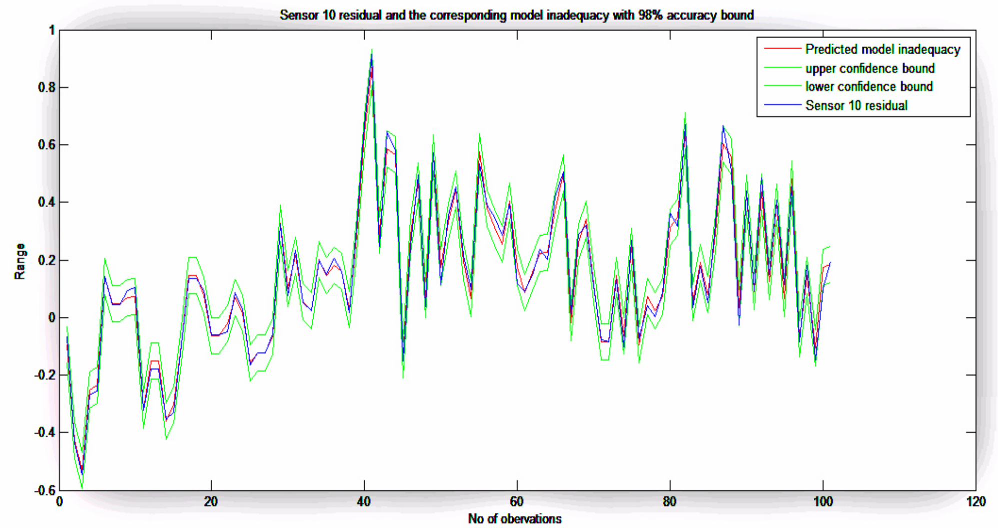
APPLICATION

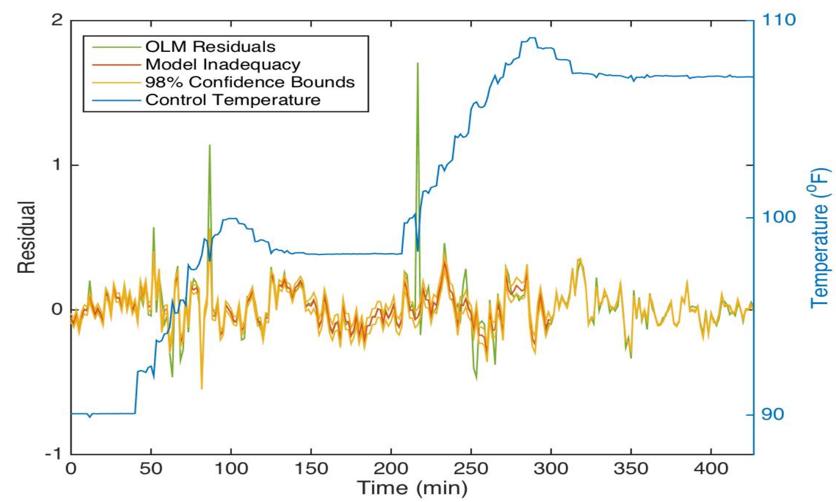
Results

- **Current model inadequacy predictions meets the model assumptions under normal steady state and transient conditions**

- **Evaluating performance under faulted conditions**
  - Current system performance is not sufficiently robust to faults

- **Future work will integrate with forced flow loop data and models at UTK**

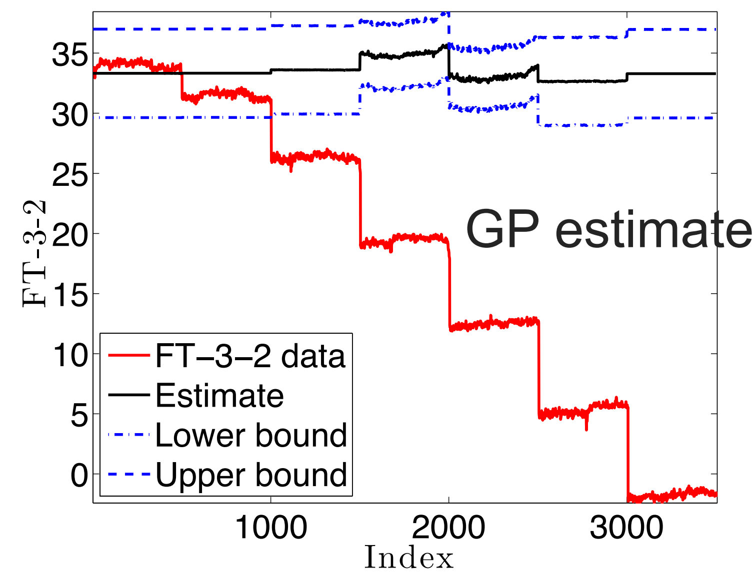


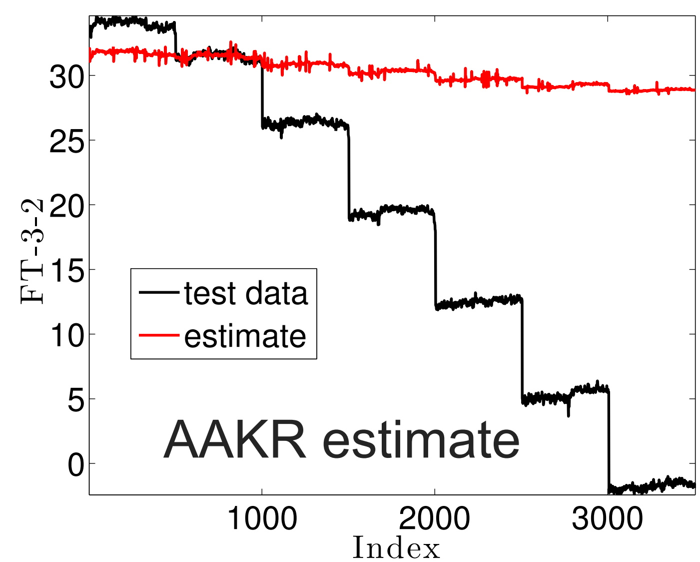


Virtual Sensing

Data-driven virtual sensor models

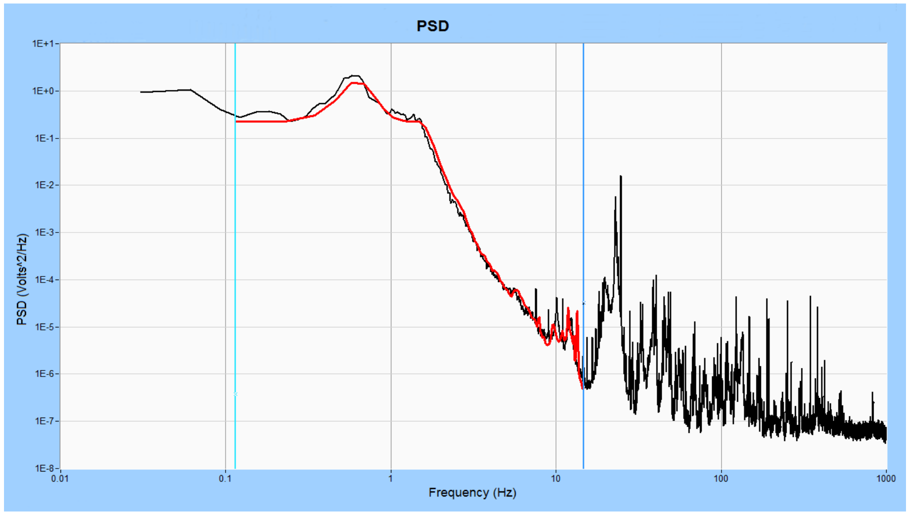
- Models used for fault detection are often applicable for virtual sensing
  - Each model has pros and cons relative to virtual sensing
- Models sensitive to training data used to derive parameters
  - Data sets must include fault data to allow for robust prediction by some models
- Alternative independent variables may enable more robust estimates at the expense of robust fault detection
  - Currently being evaluated





Sensor Response OLM

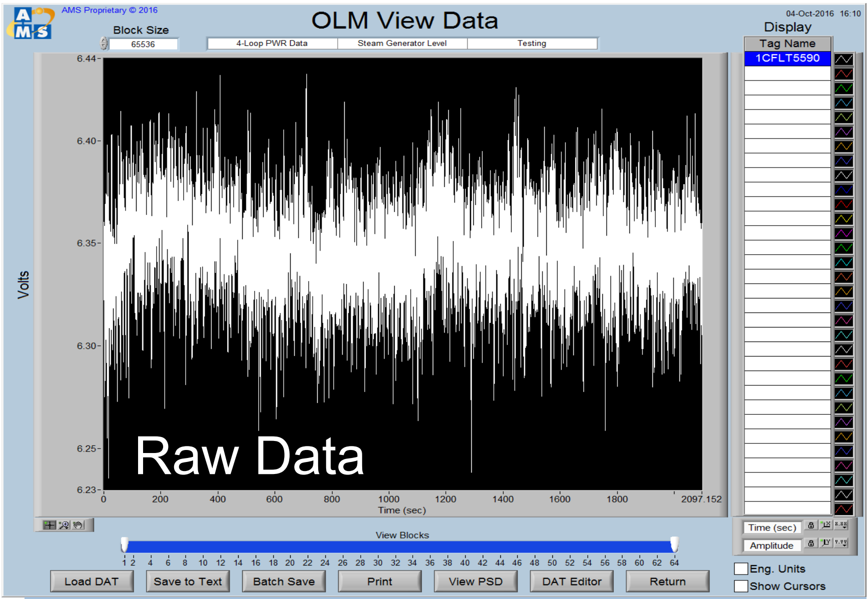
- **Automated Sensor Response OLM**
  - Dynamic response is a key indicator of sensor system performance and health
  - Traditional noise analysis methodology relies on knowledge from experienced engineers
  - Expert knowledge will be combined with automated analysis tools to provide accurate and repeatable sensor response results that can be integrated with other OLM analysis techniques
- **Noise Testing and Algorithm Development**
  - Acquire high-frequency noise data on nuclear-grade transmitters in the test loop
  - Simulate voids, leakages, and sensing line blockages to facilitate the development of robust sensor response evaluation and diagnostic algorithms

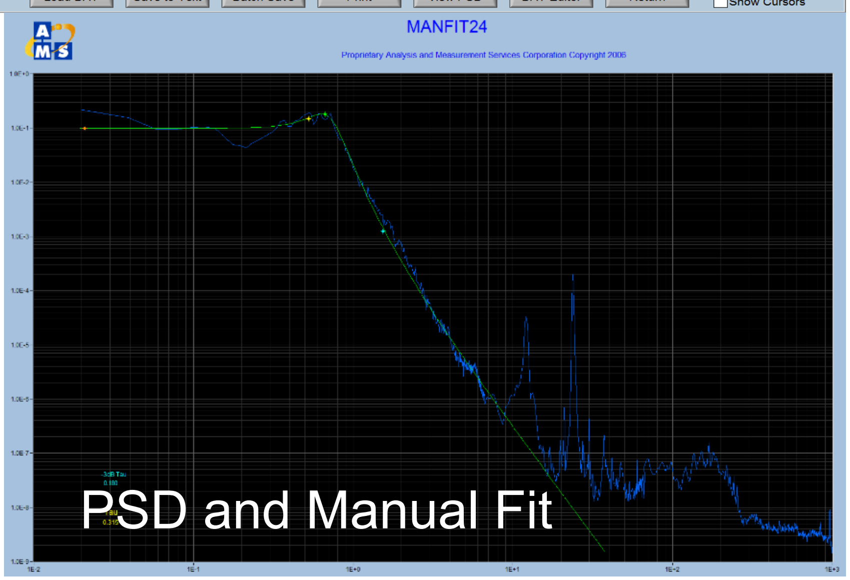


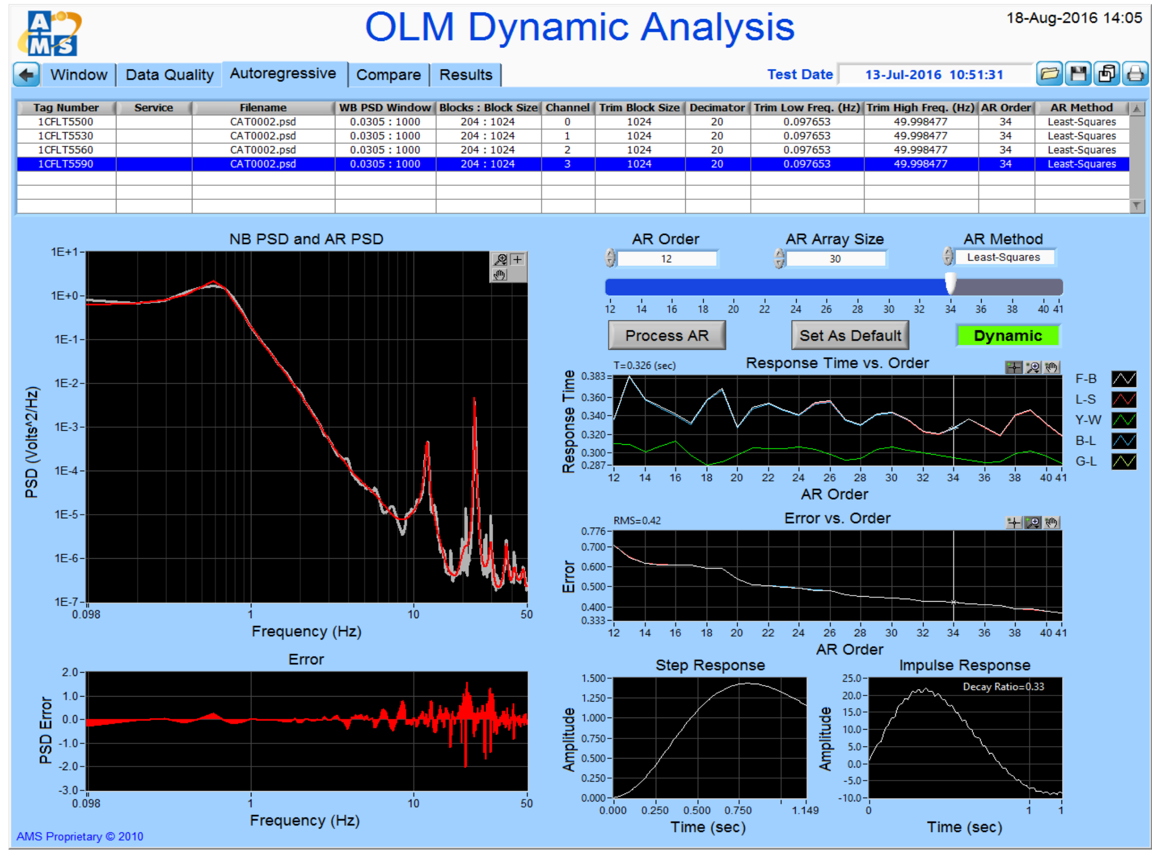
Noise Analysis for Actual Plant Data

- Data recorded from 4 protection sets, 44 sensors
- 35 minutes of data per protection set, 2000 S/sec
- RCS Flow and SG Level – 28 transmitters
- Pressurizer Pressure and Steam Pressure – 16 transmitters
- Noise data converted to spectrums
- Data and spectrums analyzed using existing methods
- AR models created and evaluated
- Results compared

Example of Steam Generator Level Data







Automated Model Fitting and Analysis

Automated Response Time Evaluation: DP Transmitters

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Item #	Service	Tag	Auto AR (sec)	Manual (sec)	ΔT (sec)
1	RCS Flow	RCFT-001	0.27	0.29	-0.02
2		RCFT-002	0.31	0.31	0.00
3		RCFT-003	0.30	0.28	0.02
4		RCFT-004	0.36	0.34	0.02
5		RCFT-005	0.28	0.27	0.01
6		RCFT-006	0.29	0.28	0.01
7		RCFT-007	0.22	0.23	-0.01
8		RCFT-008	0.26	0.26	0.00
9		RCFT-009	0.24	0.22	0.02
10		RCFT-010	0.23	0.2	0.03
11		RCFT-011	0.24	0.2	0.04
12		RCFT-012	0.26	0.25	0.01
13	SG Level	SGLT-001	0.57	0.62	-0.05
14		SGLT-002	0.41	0.41	0.00
15		SGLT-003	0.39	0.37	0.02
16		SGLT-004	0.35	0.36	-0.01
17		SGLT-005	0.42	0.43	-0.01
18		SGLT-006	0.34	0.33	0.01
19		SGLT-007	0.34	0.3	0.04
20		SGLT-008	0.38	0.33	0.05
21		SGLT-009	0.41	0.39	0.02
22		SGLT-010	0.37	0.39	-0.02
23		SGLT-011	0.44	0.42	0.02
24		SGLT-012	0.41	0.41	0.00
25		SGLT-013	0.34	0.33	0.01
26		SGLT-014	0.34	0.33	0.01
27		SGLT-015	0.42	0.42	0.00
28		SGLT-016	0.38	0.35	0.03

DP Transmitters

Item #	Service	Tag	Auto AR (sec)	Manual (sec)	ΔT (sec)
1	Pzr Pressure	PZPT-001	0.37	0.38	-0.01
2		PZPT-002	0.54	0.55	-0.01
3		PZPT-003	0.40	0.43	-0.03
4		PZPT-004	0.44	0.44	0.00
5	Steam Pressure	MSPT-001	0.06	0.07	-0.01
6		MSPT-002	0.07	0.08	-0.01
7		MSPT-003	0.06	0.08	-0.02
8		MSPT-004	0.07	0.07	0.00
9		MSPT-005	0.06	0.08	-0.02
10		MSPT-006	0.03	0.04	-0.01
11		MSPT-007	0.10	0.08	0.02
12		MSPT-008	0.13	0.11	0.02
13		MSPT-009	0.08	0.08	0.00
14		MSPT-010	0.08	0.08	0.00
15		MSPT-011	0.09	0.09	0.00
16		MSPT-012	0.07	0.07	0.00

Pressure Transmitters

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Accomplishments

- **Implemented and evaluated initial approaches under each task**
  - Signal validation, virtual sensing, response time monitoring
- **Integration activities begun**
- **Updates on research status in FY16 (PNNL-25382 , PNNL-25104, PNNL-24702)**
- **Journal/Conference papers and presentations**
  - Nair, A, and JB Coble, "A High Confidence Signal Validation Technique for Sensor Calibration Assessment in Nuclear Power Systems." 2015 ANS Winter Meeting and Technology Expo. November 7-12, 2015: Washington, DC.
  - Nair, A, S Boring, JB Coble, "High Accuracy Signal Validation Framework for Sensor Calibration Assessment in NPPs." 2016 ANS Winter Meeting and Technology Expo. November 6-10, 2016: Las Vegas, NV.
  - Nair, Anjali Muraleedharan, "Bayesian Framework for High Confidence Signal Validation for Online Monitoring Systems in Nuclear Power Plants. " Master's Thesis, University of Tennessee, 2016. http://trace.tennessee.edu/utk_gradthes/4060
  - Tipireddy R, ME Lerchen, and P Ramuhalli. 2016. "Virtual sensors for robust on-line monitoring (OLM) and Diagnostics." Submitted to International Conference on Prognostics and Health Management (IEEE PHM2016).
  - Tipireddy R, ME Lerchen, and P Ramuhalli. 2016. "Methodologies for Virtual Sensing in nuclear plant on-line monitoring." In preparation, for submission to IEEE Trans. Rel.

Next Steps

- **Signal validation**
  - Complete implementation and testing of sensor status and fault diagnostics using data-driven UQ
  - Input to advanced monitoring/control algorithms
- **Virtual sensing**
  - Alternate algorithms for virtual sensing
  - Uncertainty must account for spillover of faulty reading into estimate
  - Number of allowed virtual sensors, and duration of applicability to be determined
- **Response time OLM**
  - Implement and verify algorithms for noise analysis
- **OLM requirements using emerging I&C technologies**
- **Verification and validation of algorithms using data from test-beds as well as data from operating plants**

Conclusion

- **Research focused on addressing high-impact technical gaps to developing a standardized framework for robust next-generation online monitoring**
- **Outcomes enable**
  - Extended calibration intervals and relief of even limited periodic assessment requirements
  - Assessment of sensor measurement accuracy with high confidence
  - Derived values for desired parameters that cannot be directly measured
- **Outcomes support**
  - Improved reliability and economics for current and future nuclear systems
  - Deployment of advanced sensors (ultrasonic, fiber optic, etc.) and instrumentation (digital I&C, wireless, etc.)