Integrated Architecture for Aircraft Engine Performance Monitoring and Fault Diagnostics: Engine Test Results

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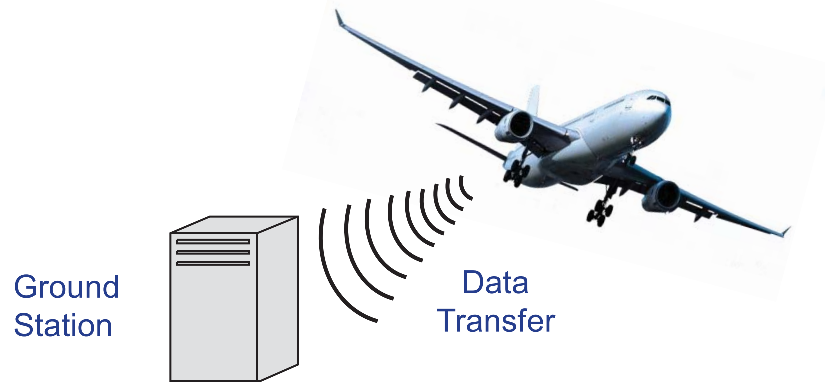
Overview

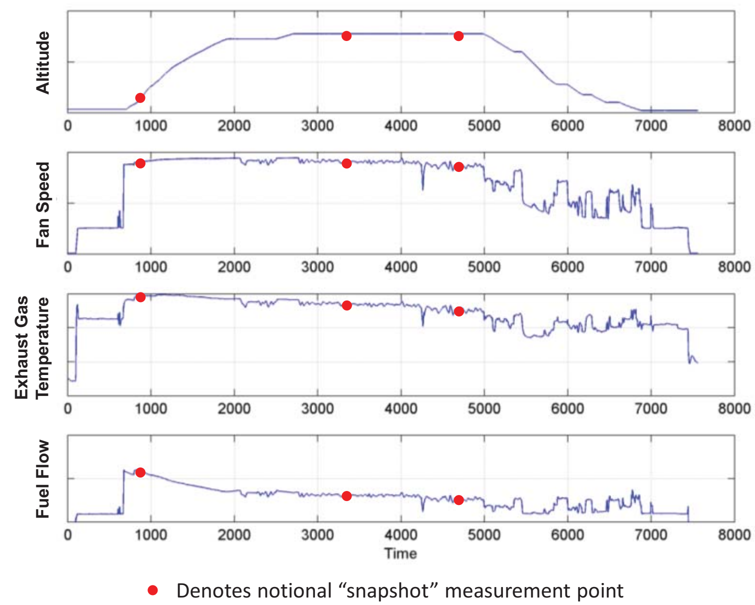
- Background
- Architecture
- Application
- Results
- Conclusion

Background – aircraft engine performance trend monitoring and gas path fault diagnostics

- Conventional Approach:
  - Ground-based
  - Processing of "snapshot" measurements post-flight
  - Enables estimation and trending of engine performance and gas path fault diagnostics
  - Early diagnosis of incipient fault conditions with minimal latency can be challenging

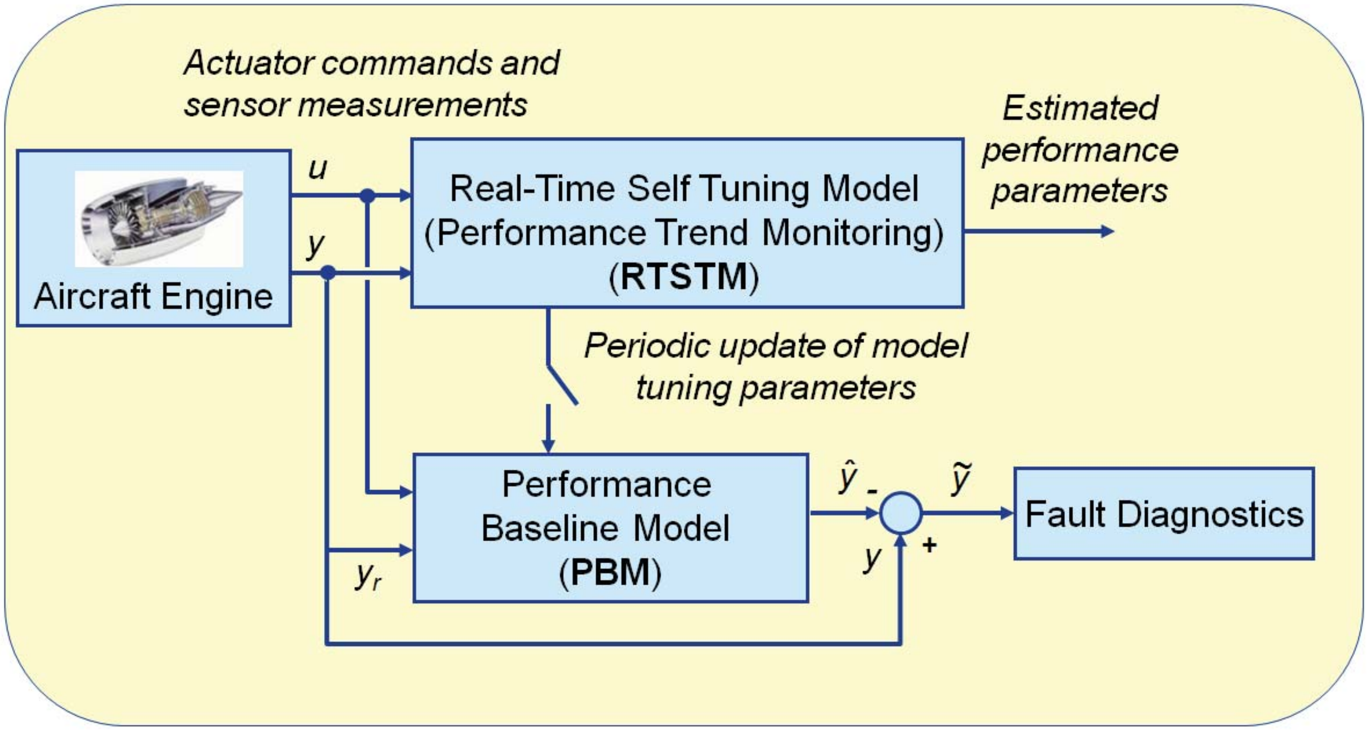
- Emerging Approach:
  - Advances in on-board processing and flight data recording capabilities are enabling new diagnostic approaches
  - Acquisition of full-flight streaming/continuous measurement data now possible
  - Requires new approaches to analyze expanded quantity and format of data





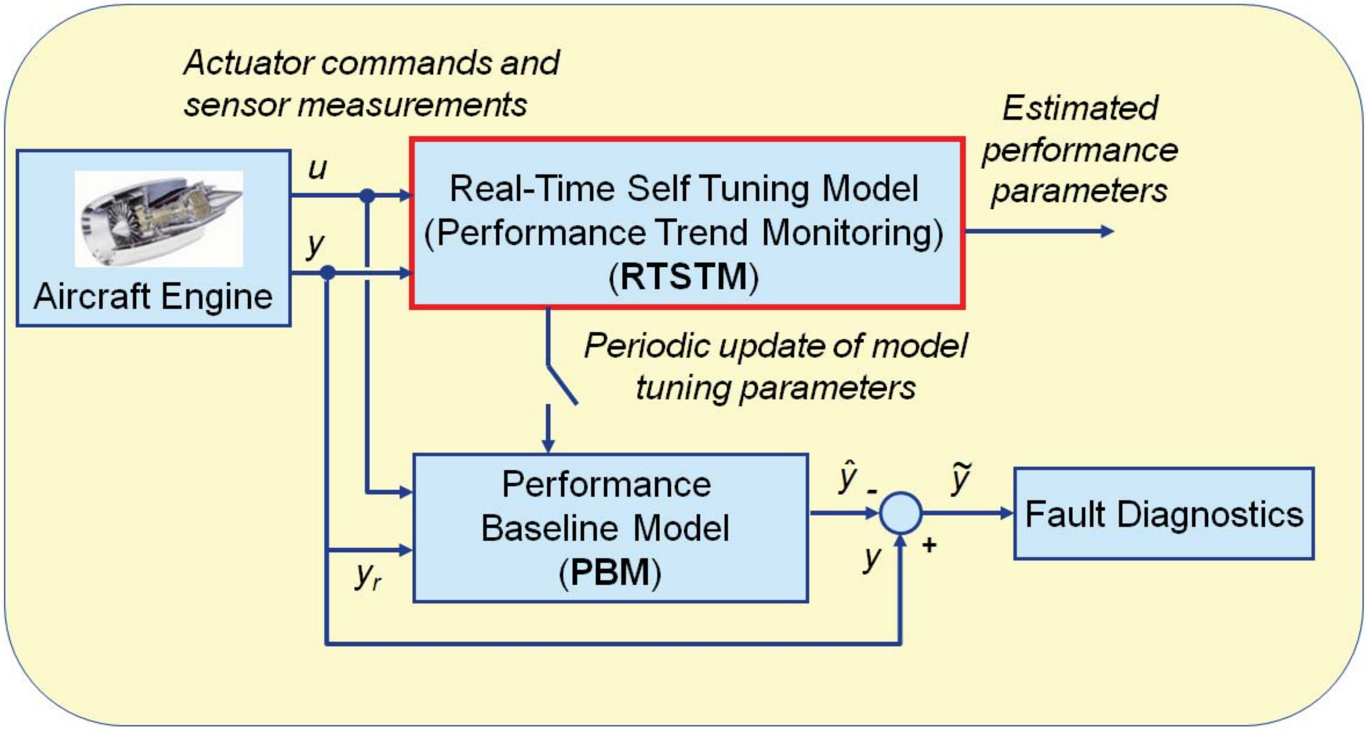
Example Aircraft Engine Flight Data

Architecture for Engine Performance Monitoring and Fault Diagnostics



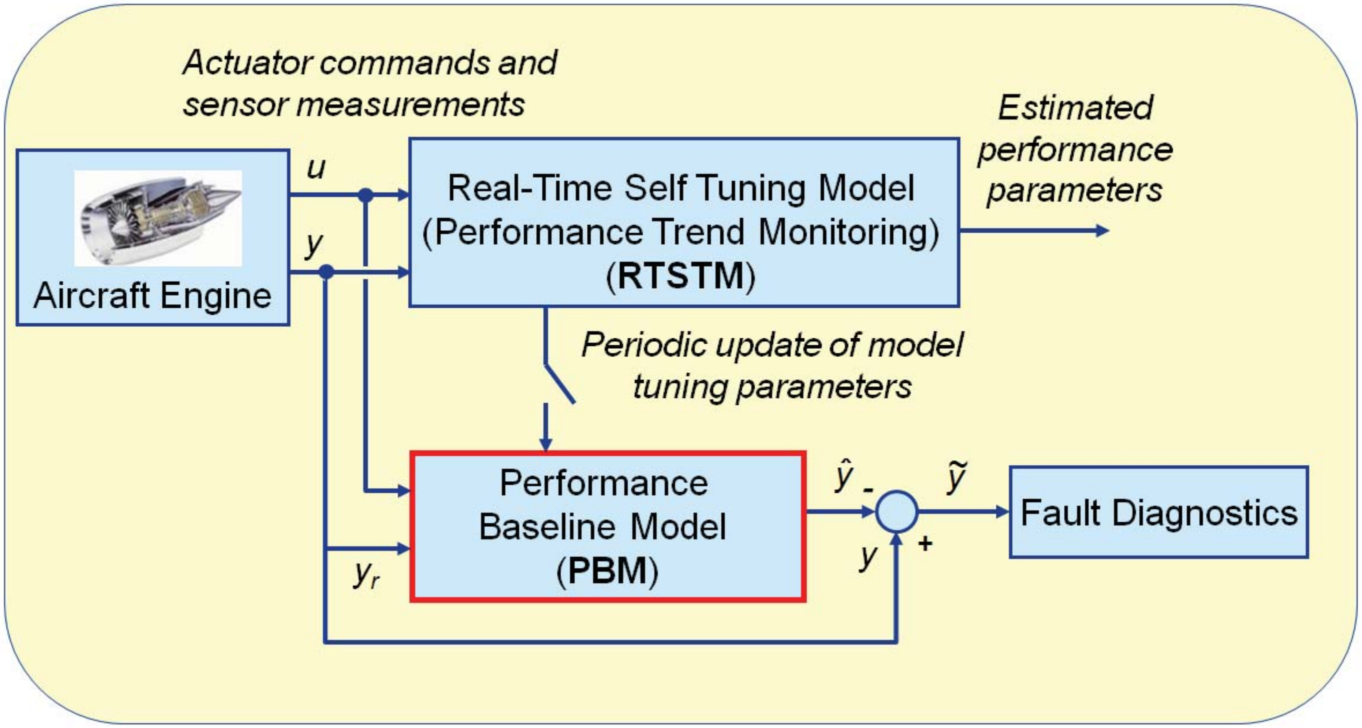
- Designed for processing real-time continuous (streaming) engine measurement data to provide:
  - Estimation and trending of deterioration-induced engine performance changes
  - Detection and isolation of gas path system faults

Real-Time Self Tuning Model



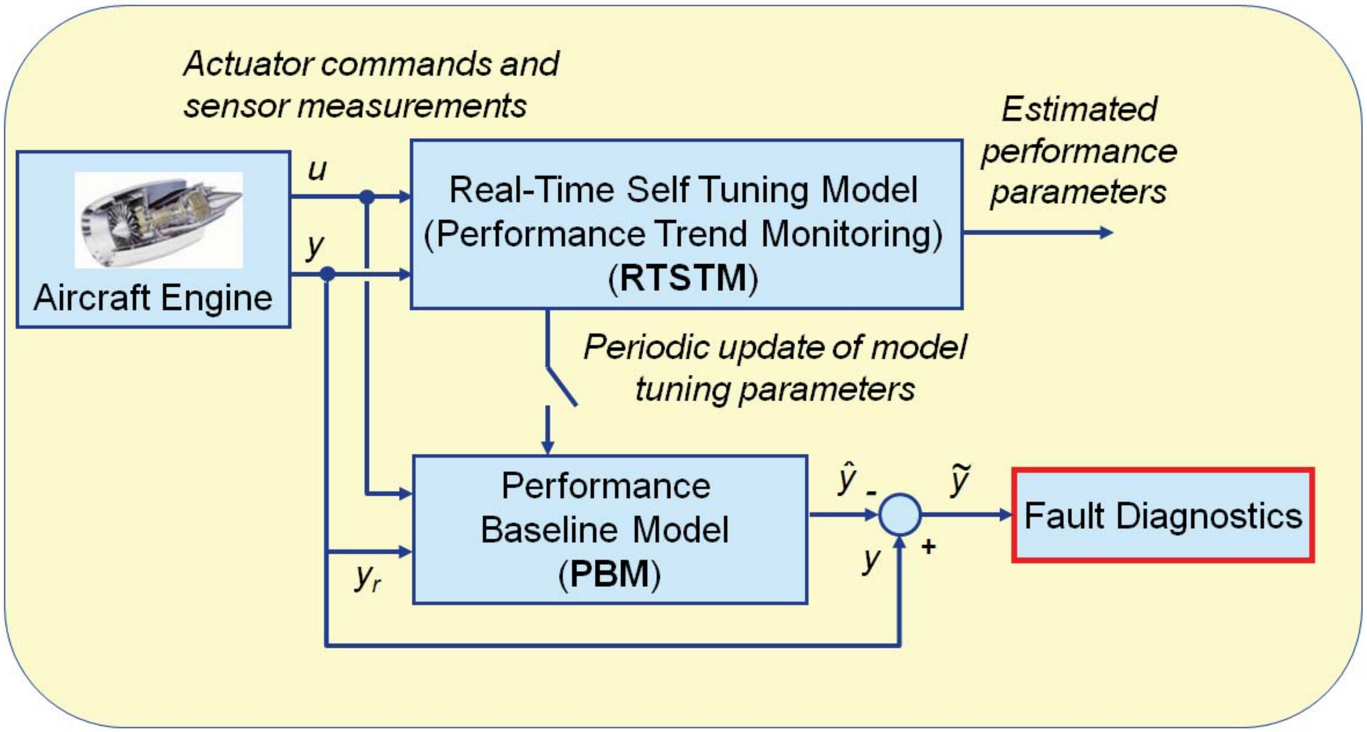
- Self-tuning piecewise linear Kalman filter design
- Applies NASA-developed optimal tuner selection
  - Application for underdetermined estimation problems
  - Minimizes mean squared estimation error in parameters of interest
- Provides real-time estimates of unmeasured engine performance parameters

Performance Baseline Model



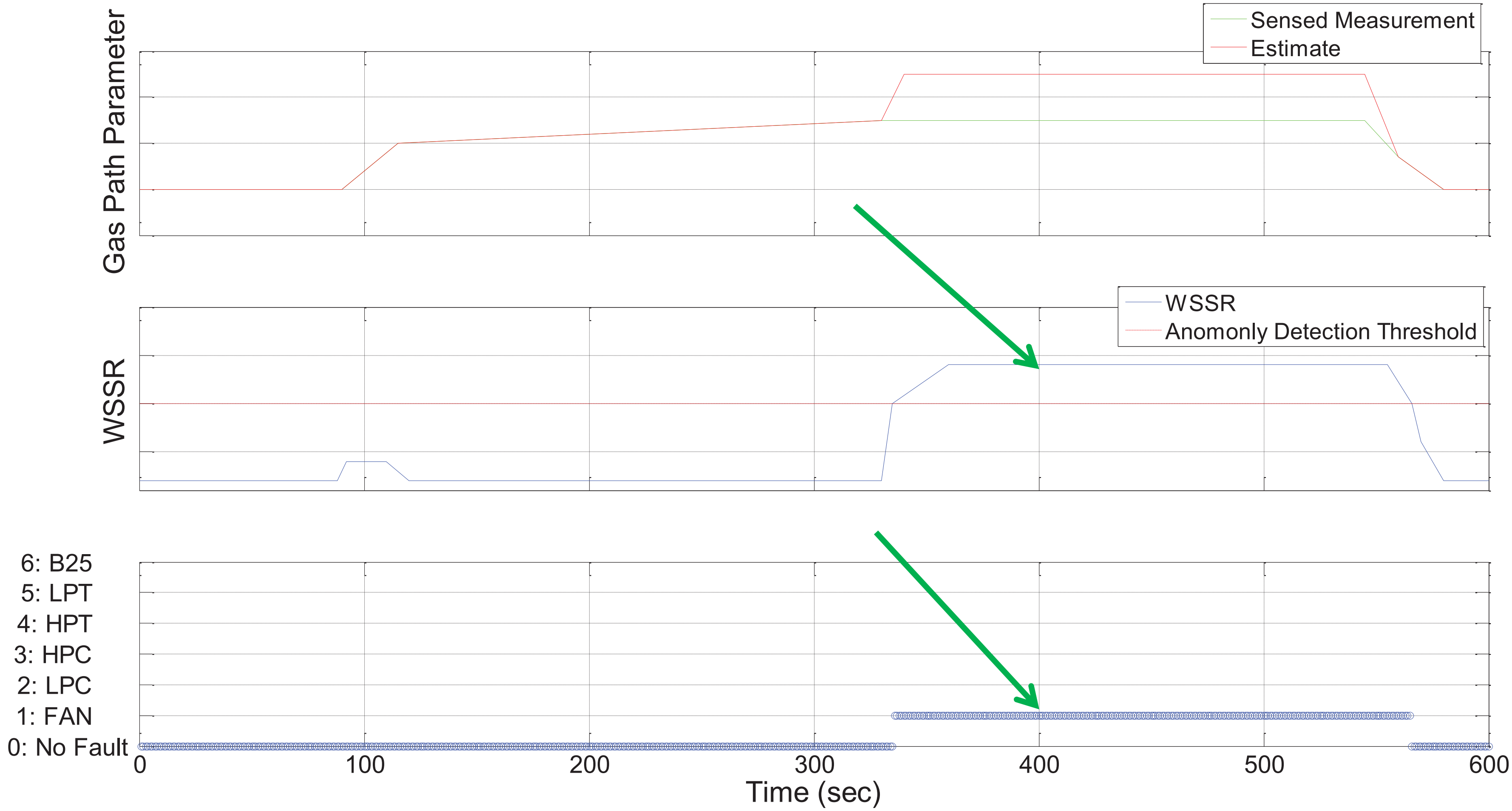
- Piecewise linear state space model design, open-loop with inputs:
  - Actuator commands, *u.*
  - Power reference parameter, y_r, which is used to improve model-to-engine tracking capability.
  - Periodic model tuning parameter updates from RTSTM to account for gradual degradation effects.
- PBM provides a baseline of recent engine performance

Fault Diagnostics



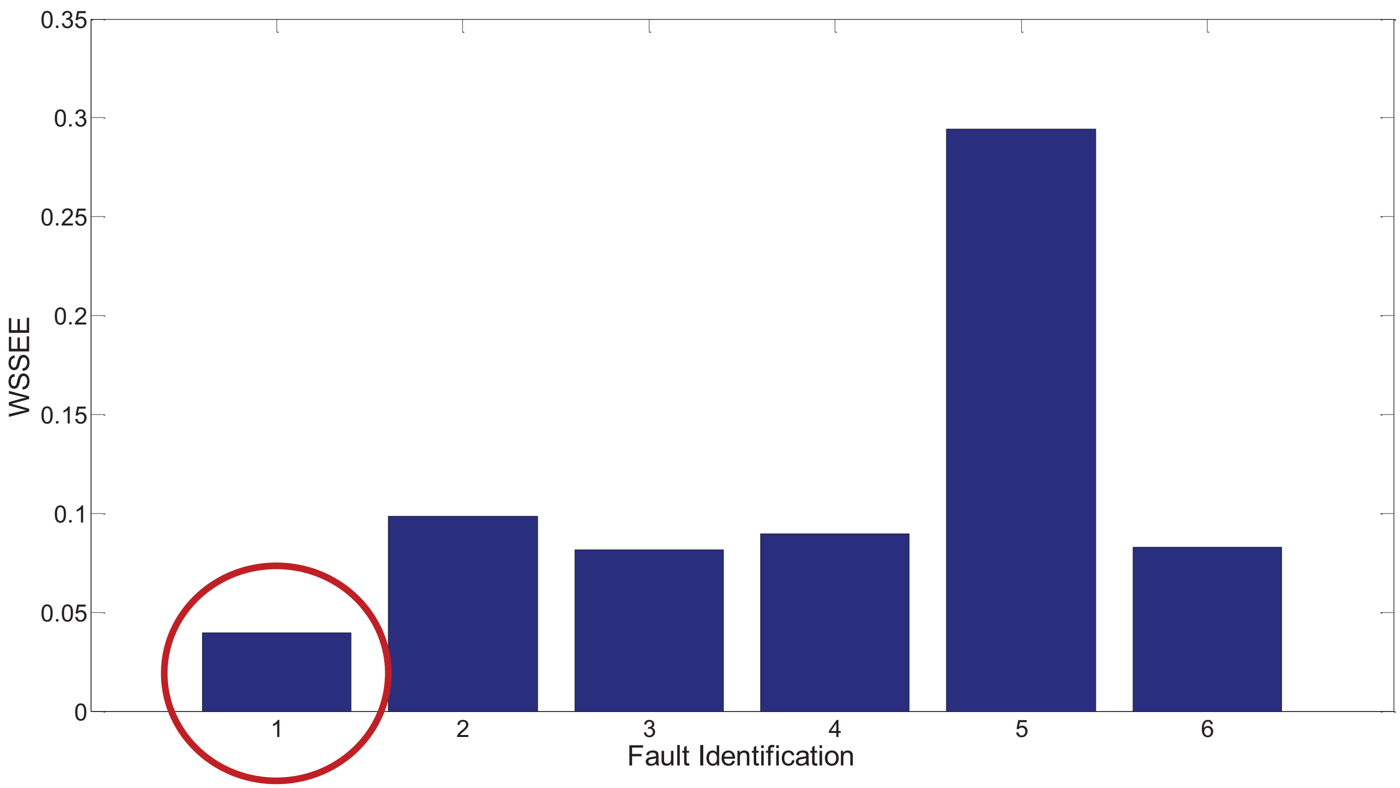
- Monitors residuals between sensed engine outputs and PBM estimated outputs
- Fault detection is performed by calculating and monitoring a weighted sum of squared residuals *(WSSR)* signal. $WSSR = \tilde{y}^T R^{-1} \tilde{y}$
- Upon fault detection, fault classification is performed by identifying the candidate fault signature that most closely matched the observed residual in a weighted least squares sense. $WSSEE_j = \left(\tilde{y} - \hat{\tilde{y}}_j\right)^T R^{-1} \left(\tilde{y} - \hat{\tilde{y}}_j\right)$

Fault Diagnostics



At each time sample a new *WSSR* and *WSSEE* are calculated

Fault Diagnostics



The smallest *WSSEE* value is classified as the fault type.

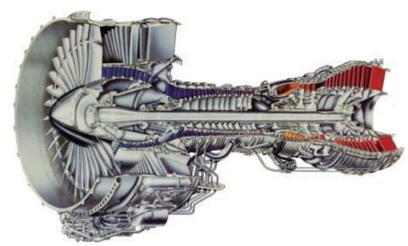
Application Example: Analysis of Vehicle Integrated Propulsion Research (VIPR) Engine Test Data

- VIPR is a series of ground-based, on-wing engine tests to mature engine health management sensors and algorithms
  - Ongoing at NASA Armstrong / Edwards Air Force Base
  - Partners include NASA, US Air Force, Pratt & Whitney, and others

- Test vehicle:
  - Boeing C-17 Globemaster III
  - Equipped with Pratt & Whitney F117 high-bypass turbofan engines

- VIPR ground tests include:
  - A series of nominal and seeded faulted engine test cases
    - Faults include station 2.5 bleed valve and 14th stage bleed valve faults
  - Data collected over a range of engine power settings including steady-state and transient operating conditions

Boeing C-17 Globemaster III



Pratt & Whitney F117 Turbofan Engine

Model-Based Gas Path Diagnostic Architecture

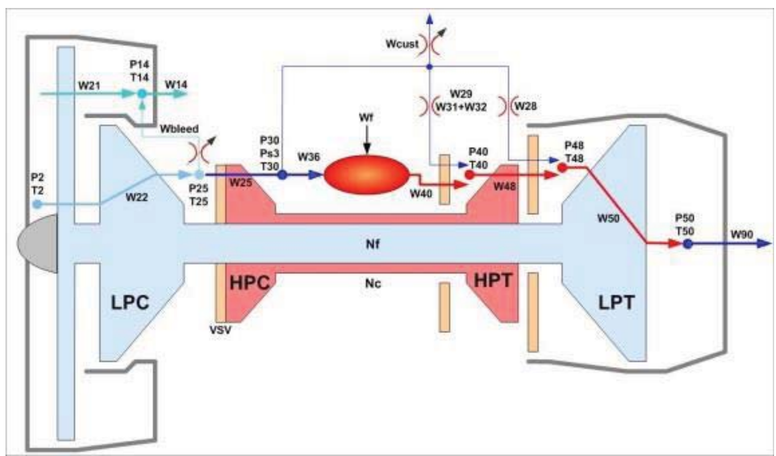
- Architecture Designed Based on NASA C-MAPSS40k Engine Model

Gas Path Sensor Measurements

Symbol	Description
N1	fan speed
N2	core speed
P25	low pressure compressor exit total pressure
T25	low pressure compressor exit total temperature
Ps3	high pressure compressor exit static pressure
T35	high pressure compressor exit total temperature
P5	low pressure turbine exit total pressure
T5	low pressure turbine exit total temperature

Actuator Commands

Symbol	Description
Wf	fuel flow
VSV	variable stator vanes
BLD25	station 2.5 bleed valve



Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)

Model-Based Gas Path Diagnostic Architecture

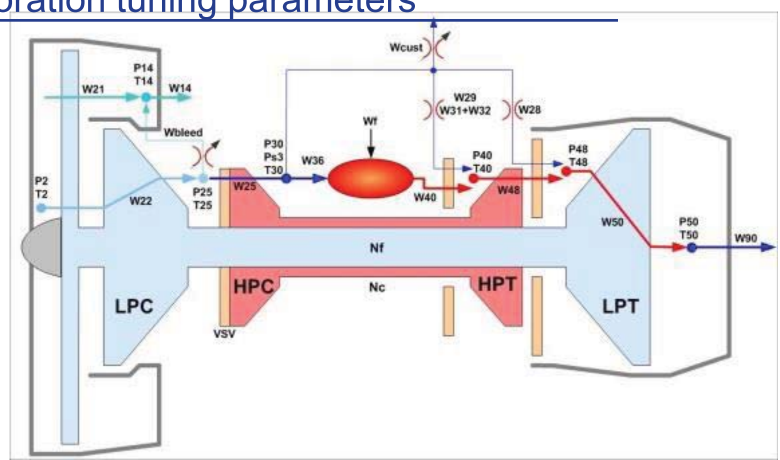
- Architecture Designed Based on NASA C-MAPSS40k Engine Model

PBM Estimated Parameters

Description
6 state variables (1 rotor speeds, 5 metal temperatures)
8 engine sensors (2 rotor speeds, 3 pressure and 3 temperature)
6 engine performance deterioration tuning parameters

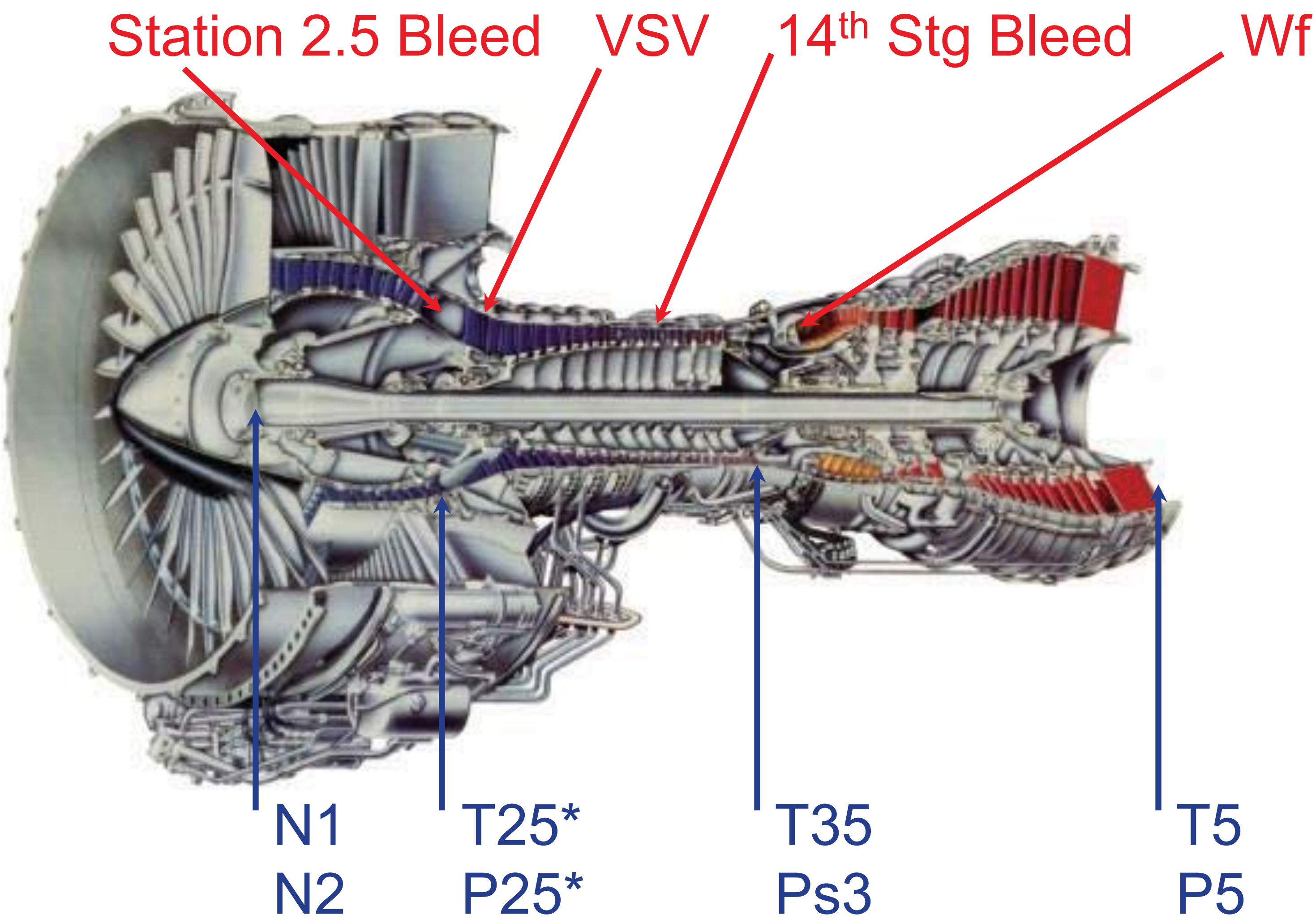
RTSTM Kalman Filter Estimated Parameters

Description
7 state variables (2 rotor speeds, 5 metal temperatures)
8 engine sensors (2 rotor speeds, 3 pressure and 3 temperature)
6 engine performance deterioration tuning parameters



Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)

Engine Sensors and Commands Considered in this Study

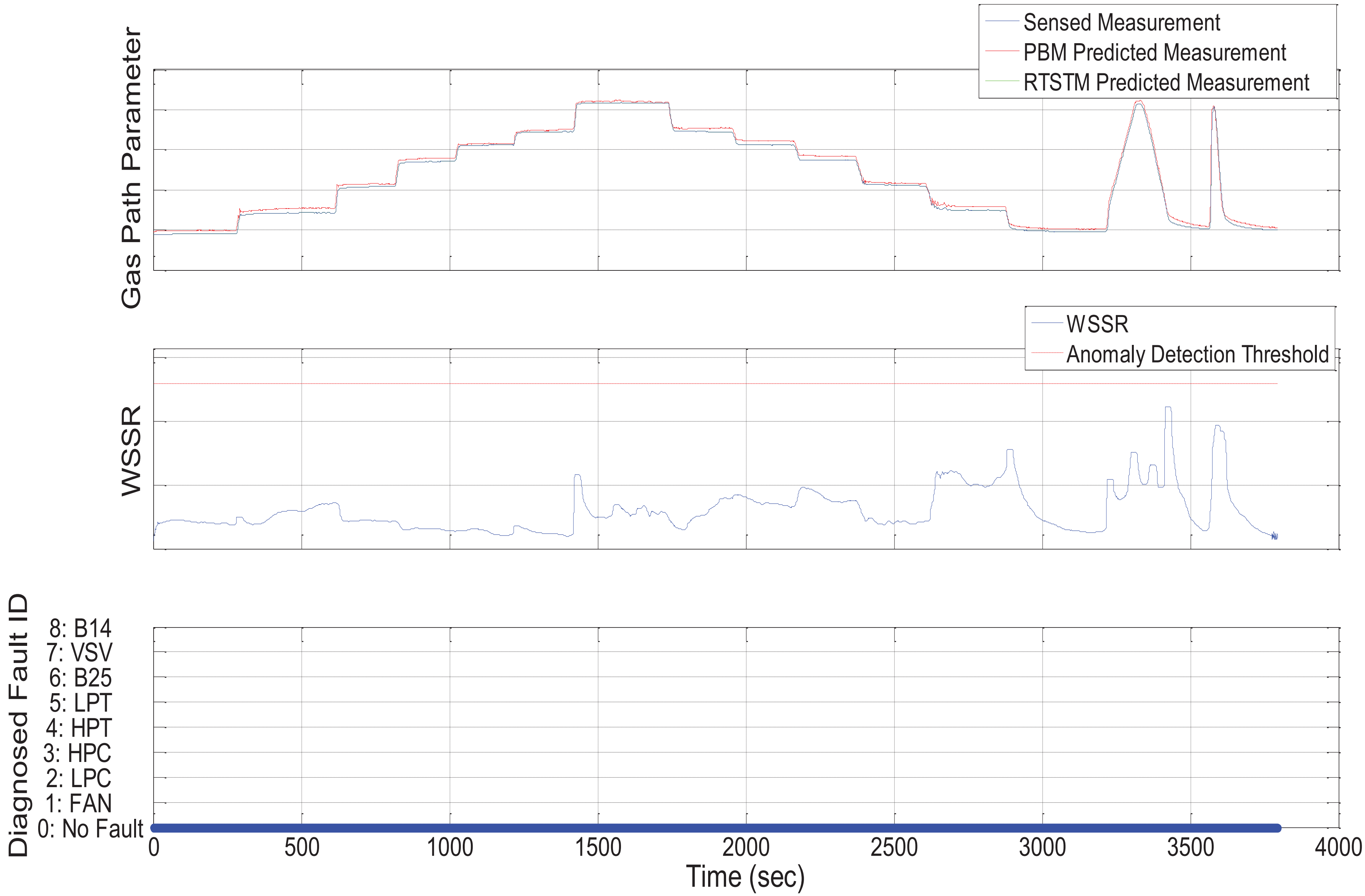


*Sensors unique to VIPR II tests

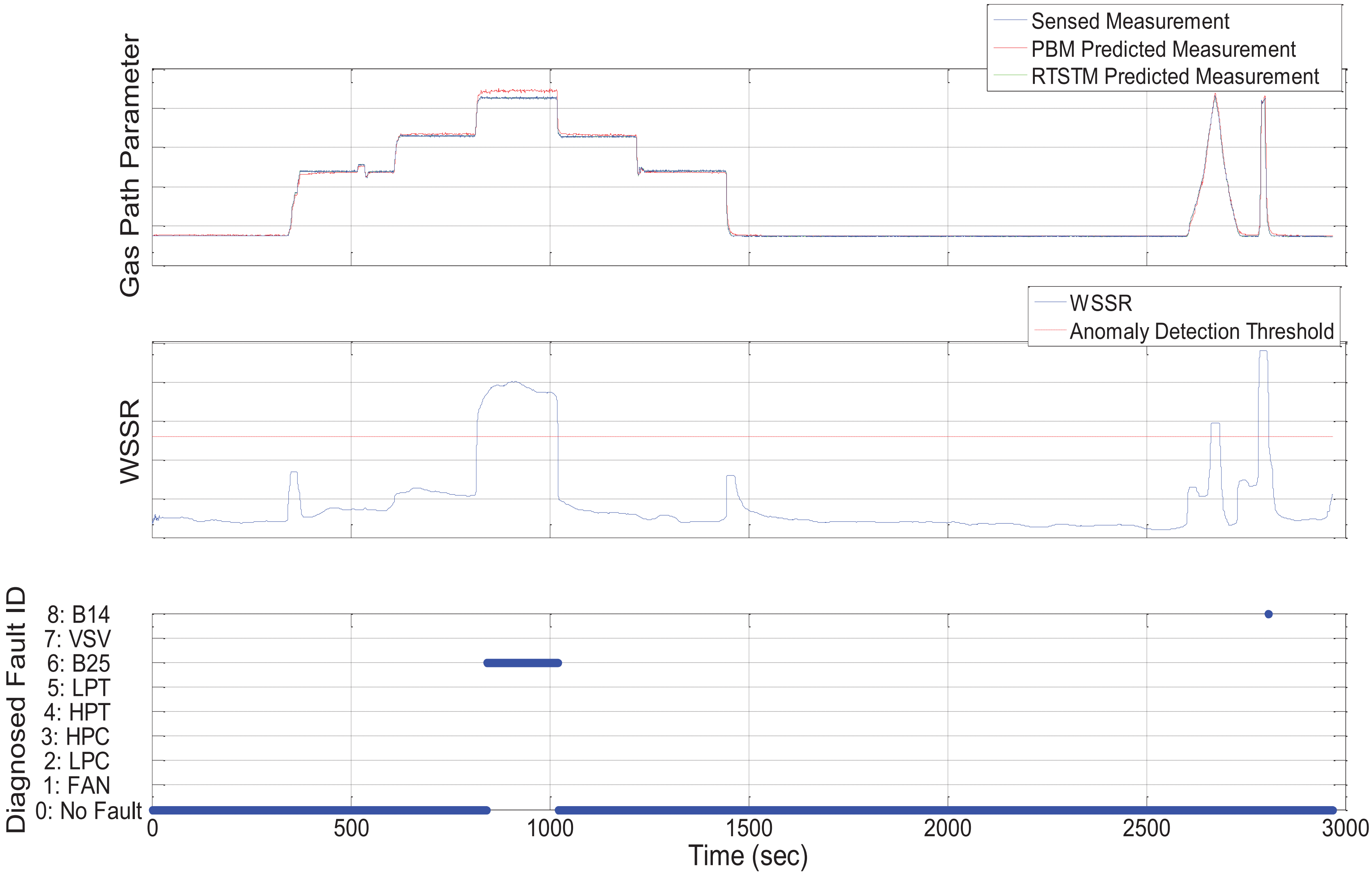
Fault Types

Fault Index	Fault Types
1	Fan
2	Low Pressure Compressor
3	High Pressure Compressor
4	High Pressure Turbine
5	Low Pressure Turbine
6	Station 2.5 Bleed Valve
7	Variable Stator Vane
8	14^{th} Stage Bleed Valve

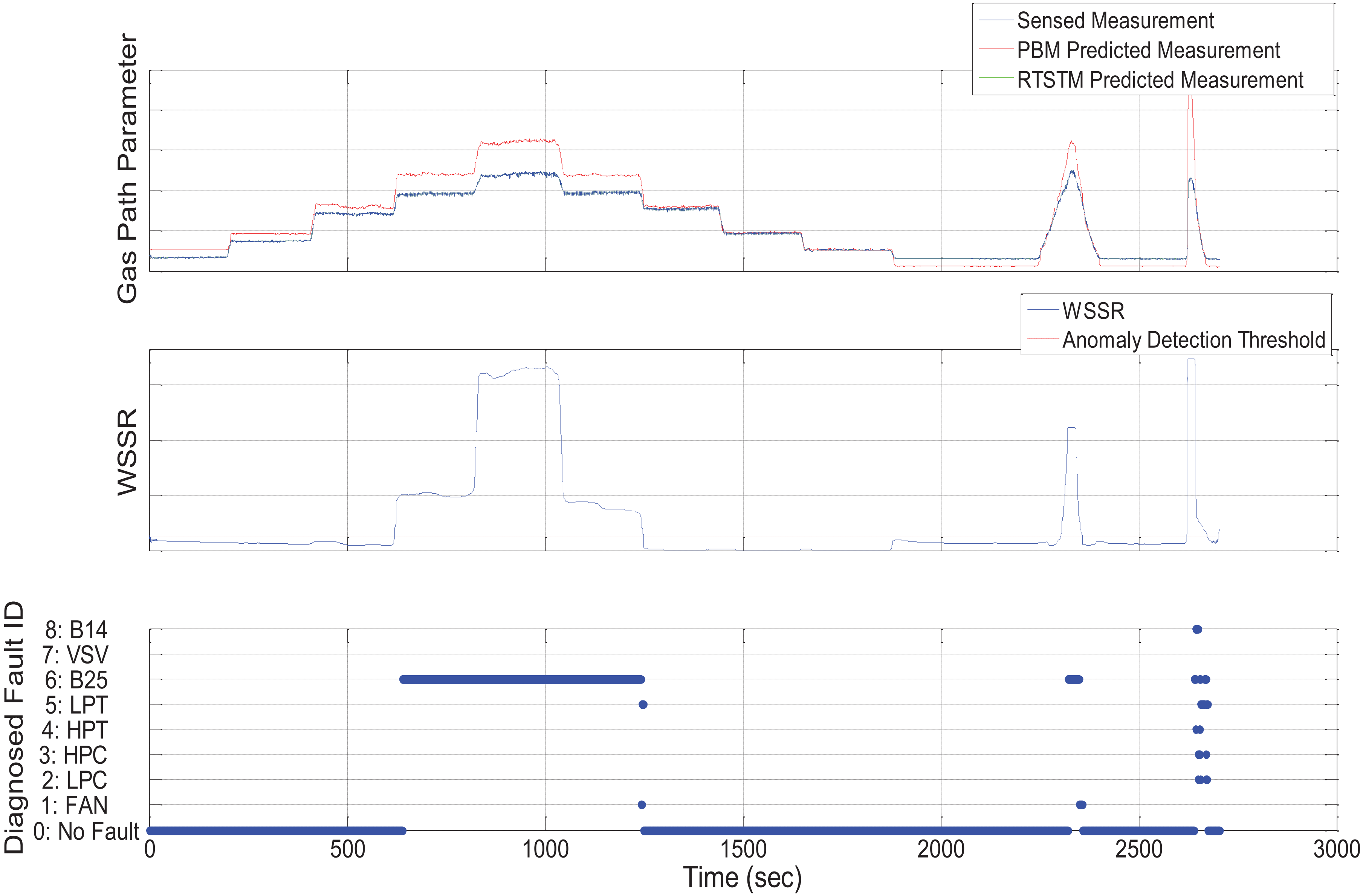
VIPR I Baseline Results



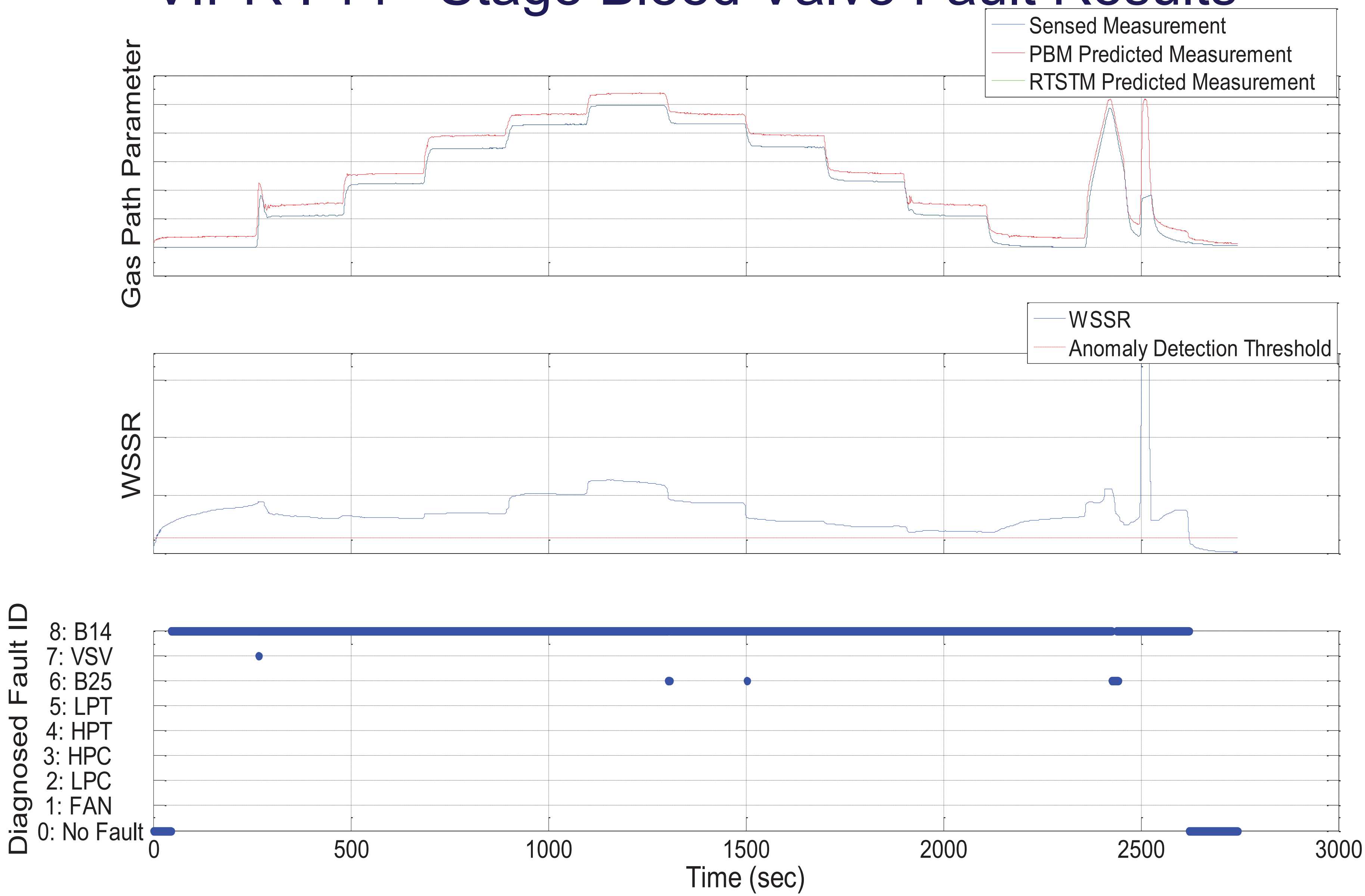
VIPR I Station 2.5 Bleed Valve Fault Results



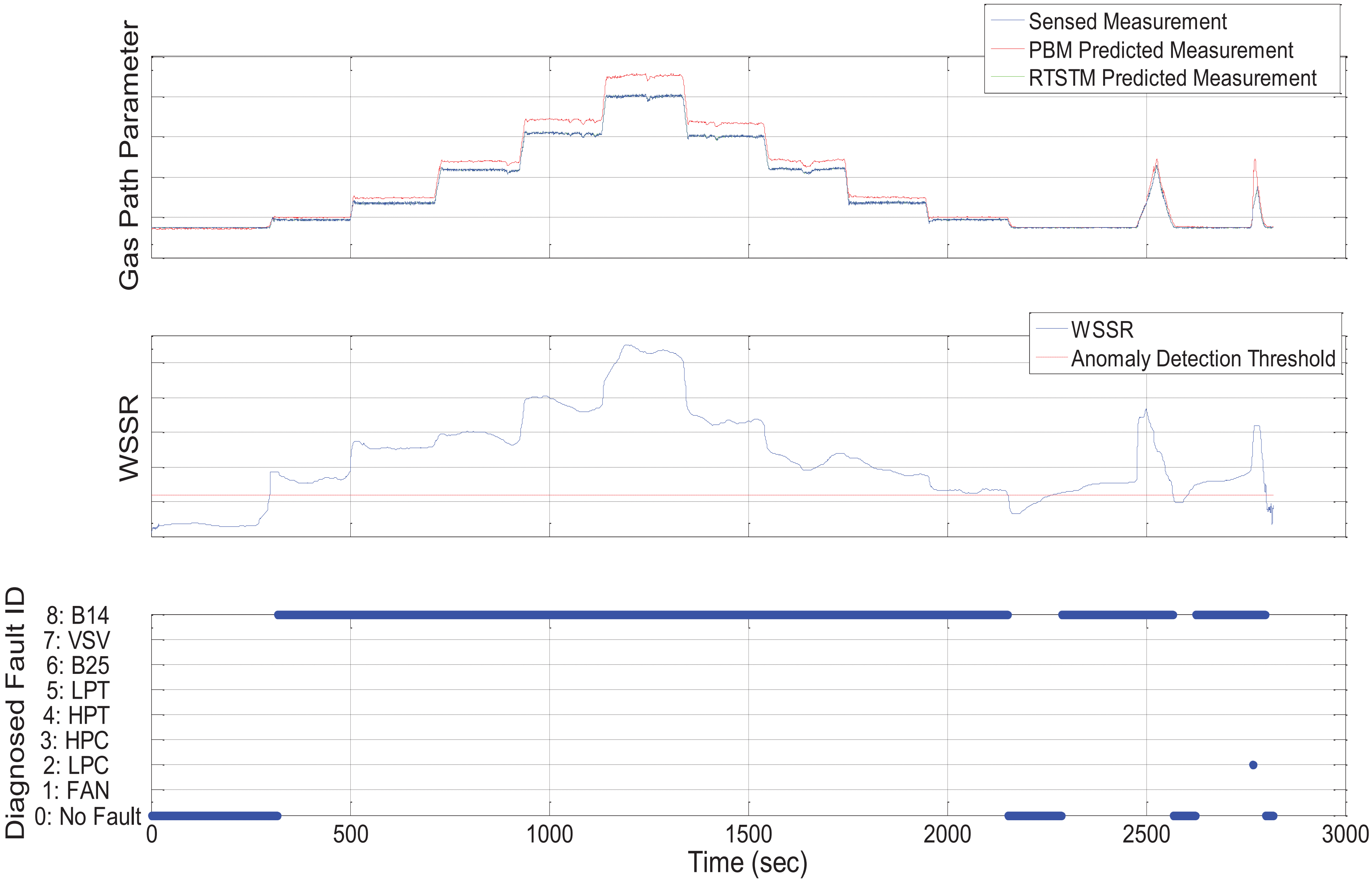
VIPR II Station 2.5 Bleed Valve Fault Results



VIPR I 14th Stage Bleed Valve Fault Results



VIPR II 14th Stage Bleed Valve Fault Results



Conclusion

- Architecture was found to provide reliable steady-state fault detection and isolation
- Addition of station 2.5 sensor provided fault detection at lower power settings
- Future work will include improved matching of model to engine dynamics
- The architecture's ability to estimate deteriorated engine performance will be evaluated during the follow on VIPR III test

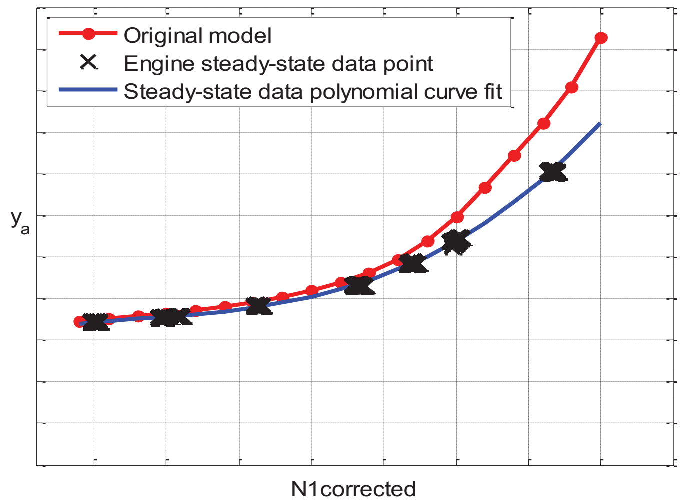
Acknowledgments

Research conducted under the Vehicle Systems Safety Technologies Project of NASA's Aviation Safety Program

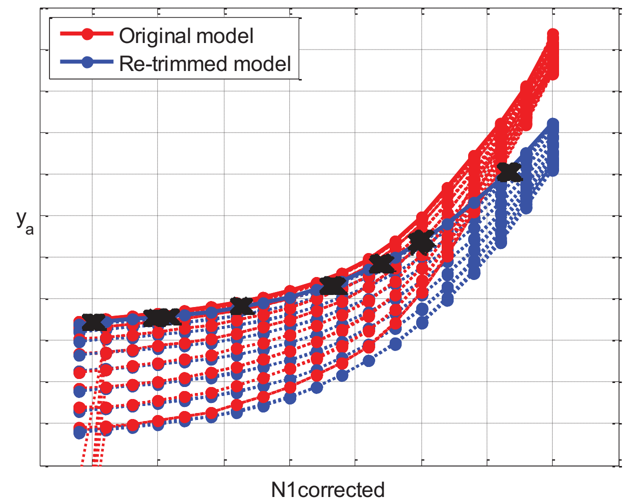
Backup Slides

Model-Based Gas Path Diagnostic Architecture Enhancements

- Model-based gas path diagnostic architecture designed based on NASA C-MAPSS40k model.
- Model updates were necessary due to notable mismatch between F117 engine and C-MAPSS40k model:
  - Re-trimmed piecewise linear model to match F117 engine performance
  - Updated model thermocouple dynamics



Original model and polynomial curve fit through acquired steady-state data (parameter y_a)



Original and re-trimmed PWLM (parameter y_a)

Equations

Measurement residuals: $\tilde{y} = y - \hat{y}$

Weighted sum of squared residuals: $WSSR = \tilde{y}^T R^{-1} \tilde{y}$

Theoretical sensor residual: $\tilde{y} = Hm$

Fault influence matrix: $H_{i,j} = \left[\frac{\tilde{y}_i}{m_j} \right]$

Estimated fault magnitude: $\hat{m}_j = \left(H_j^T R^{-1} H_j \right)^{-1} H_j^T R^{-1} \tilde{y}$

Estimated sensor residual: $\hat{\tilde{y}}_j = H_j \hat{m}_j$

Weighted sum of squared estimated error: $WSSEE_j = \left(\tilde{y} - \hat{\tilde{y}}_j \right)^T R^{-1} \left(\tilde{y} - \hat{\tilde{y}}_j \right)$

VIPR II Baseline Results