INTEGRATED VEHICLE HEALTH MANAGEMENT

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES): A Public Approach for Benchmarking Gas Path Diagnostic Methods

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Overview

- Recent technology reviews have revealed that while Engine Health Management (EHM) related research and development has increased significantly in recent years, there exists a fundamental inconsistency in defining and representing EHM problems.

- Currently many of the EHM solutions published in the open literature are applied to different platforms, with different levels of complexity, addressing different problems, and using different metrics for evaluating performance. As such it is difficult to perform a one-to-one comparison of candidate solutions.

- The ProDiMES propulsion gas path diagnostic benchmark problem and metrics have been constructed, and is proposed to serve as a standard benchmark, or theme problem, to facilitate the development and comparison of candidate propulsion gas path diagnostic methodologies.

Outline

- Background & Motivation
- Gas Path Diagnostic Benchmark Process
- Software Demonstration
- Future Schedule
- Summary

Background & Motivation

- NASA Glenn sponsored a survey of recent advancements in Engine Health Management (EHM) technologies (in 2004 with Scientific Monitoring Inc.)
- Survey results showed that EHM related R&D activities have increased significantly since late 1990's
- Survey also found that often …
  - Terminologies are different
  - Algorithms are different
  - Applications are different
  - Presentations are different
- → No basis of comparison
- Recommendation: Define and put forth a standardized process, with realistic complexity, to compare the merits of different EHM approaches

Approach

- Participants are provided (free of charge)…
  - A common toolset / environment to enable the independent development, evaluation and benchmarking of gas path diagnostic methods. This includes all types of diagnostic methods:
    - Data driven (empirical) methods
    - Analytical (model-based) methods
    - Hybrid or fused methods
  - Identical blind test cases to facilitate a one-to-one comparison of techniques developed by various participants

- Participants are expected to provide …
  - Diagnostic assessments based on the provided blind test cases
    - Participants will receive their blind test case diagnostic results, plus the anonymous results of other participants
  - Participation in follow-on workshop to share results and lessons learned

- Benefits of participation …
  - Access to a common gas path diagnostic theme problem
  - Results from a broad comparative study of candidate gas path diagnostic methods developed by multiple participants

Key Decision Points

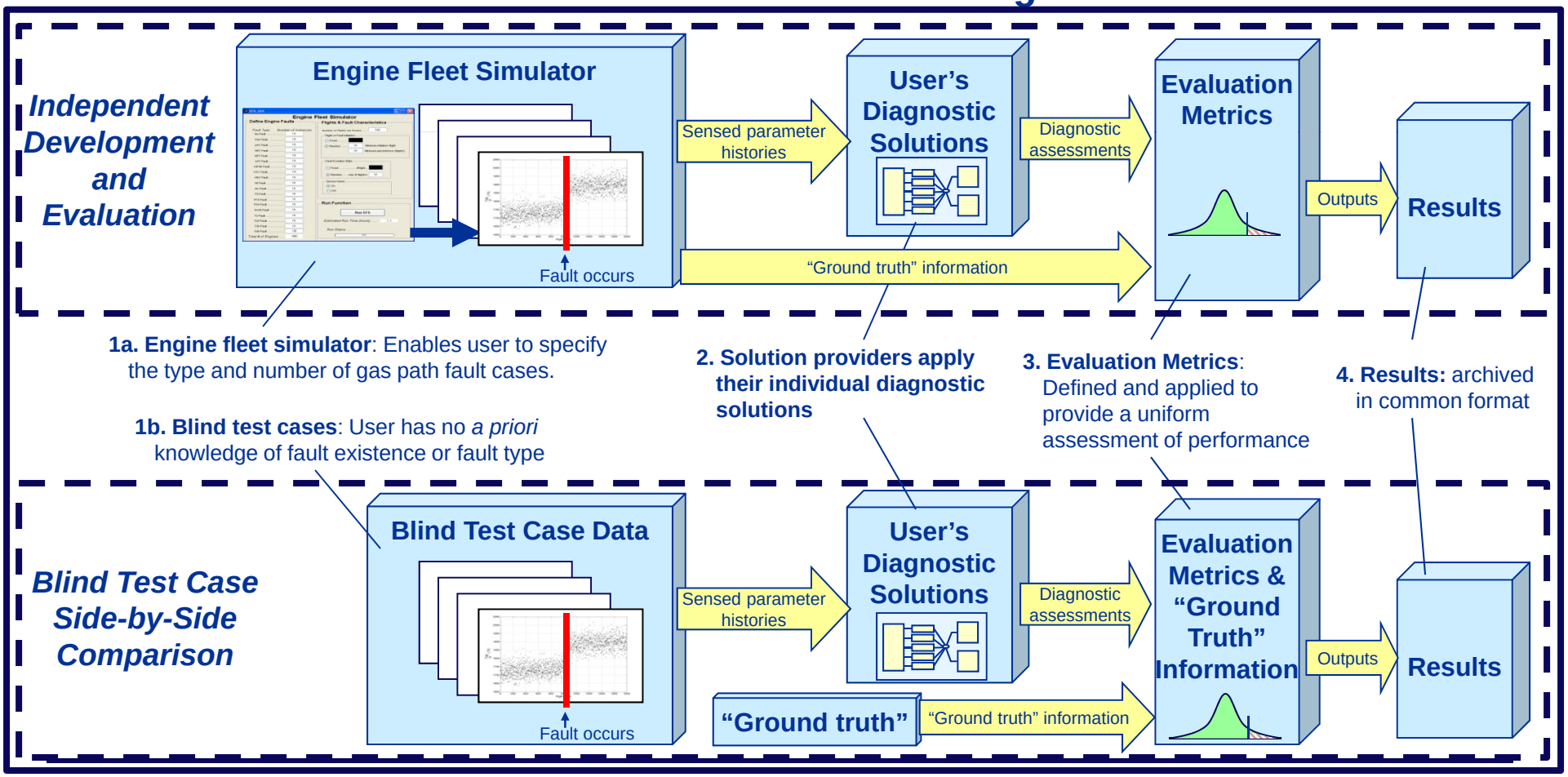
- Decided to specifically focus on ground-based diagnostics
  - Processing “snap-shot” measurements collected from each engine, each flight, with realistic operating condition variations.
- Implemented in Matlab software. Produces simulated data using a generic turbofan engine model:
  - Cons:
    - Does not capture all of the nuances inherent in actual engine data
  - Pros:
    - Avoids ITAR and proprietary issues
    - Provides unambiguous “ground-truth” state knowledge
    - Enables significant quantities of test and evaluation data to be generated
- Provides an initial assessment of diagnostic methods
  - It is readily acknowledged that additional development and maturation would be required to mature any technology to the level of practical implementation
- It is not intended to formulate this as a competition
  - The generally positive intent is to provide an environment that will truly facilitate the development, evaluation and sharing of EHM capabilities and ideas

ProDiMES
Diagnostic Benchmarking Process

ProDiMES Diagnostic Benchmarking Process

ProDiMES enables independent development & evaluation and a blind test case comparison

ProDiMES Public Benchmarking Process

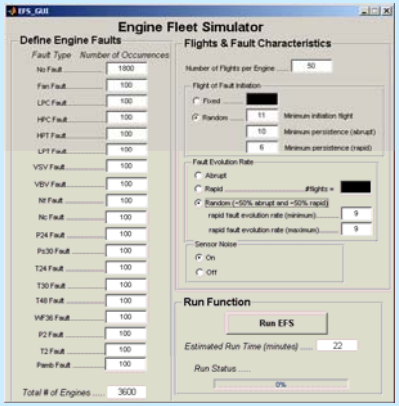


Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

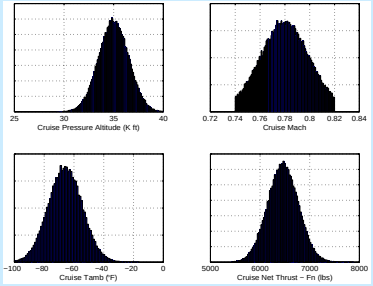
Engine Fleet Simulator

- Engine Fleet Simulator (EFS) Includes:
  - Graphical User Interface: Allows end user to select the number of engines in the fleet, flights per engine, instances of each fault type, flight of fault occurrence, and fault evolution rates.
  - Case Generator: Applies random engine operating conditions, deterioration profiles, and fault magnitudes
  - Commercial Modular Aero-Propulsion System Simulation Steady-State (C-MAPSS SS)

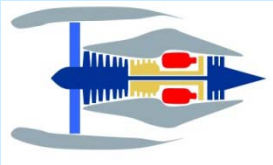
User Interface



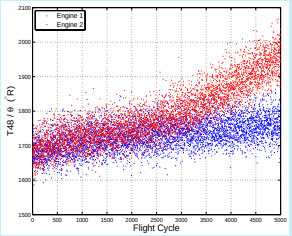
Case Generator



C-MAPSS SS Steady-State Engine Model



Parameter Histories



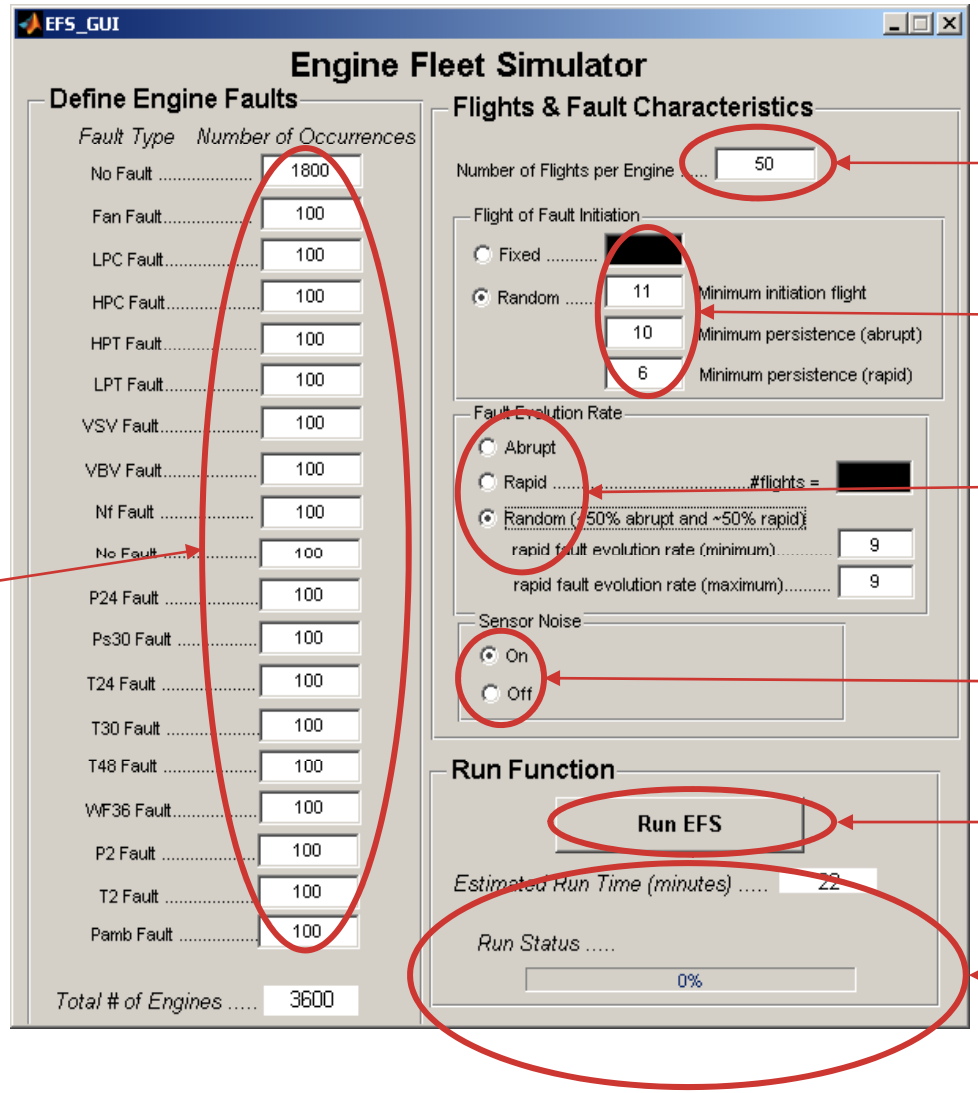
Engine Fleet Simulator Architecture

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

EFS - Graphical User Interface

Specifies the number of engines and number of instances of each no-fault, and fault type

- 18 different fault types
- Individual engines can experience no more than a single fault



Number of flights each engine experiences

Flight of fault initiation (fixed or random)

Fault evolution rate (abrupt, rapid or random)

Sensor noise (on / off)

Initiates EFS Run

Estimates run time, and provides run status

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

EFS - Case Generator

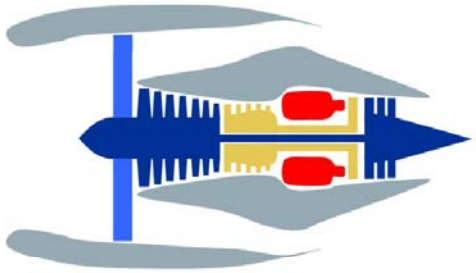
Case Generator – Randomly assigns the following information for each engine in the fleet based upon defined distributions:

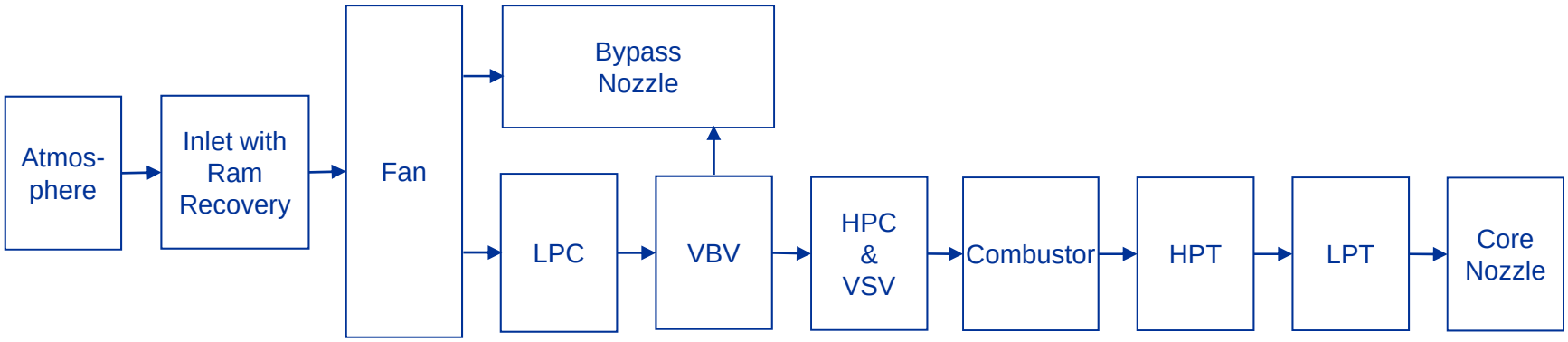
- Performance deterioration profile as a function of flight cycles (approximated from NASA Contractor reports)
- Variations in Takeoff and Cruise operating conditions each flight
- Sensor measurement non-repeatability effects
- Fault manifestations exhibit random variation in …
  - Magnitude
  - Evolution rate (if selected to occur randomly)
  - Flight of fault occurrence (if selected to occur randomly)

C-MAPSS Steady State Engine Model

Commercial Modular Aero-Propulsion System Simulation Steady-State (C-MAPSS SS):

- NASA developed generic non-linear, component level, engine model representative of a large commercial turbofan
- Coded in Matlab
- A steady-state version of C-MAPSS is used within the EFS:
  - No closed loop control logic, or transient operating capability
  - Logic is applied to ensure operating limits are not violated
  - Steady-state solver balances engine to specified operating point
  - Captures coupled fault effects (e.g. a corrected rotor speed sensor fault will result in mis-scheduled variable geometry).
- Produces 11 sensed outputs
  - 3 aircraft parameters (Pamb, P2, T2)
  - 8 engine measurements (Nf, Nc, P24, Ps30, T24, T30, T48, Wf36)

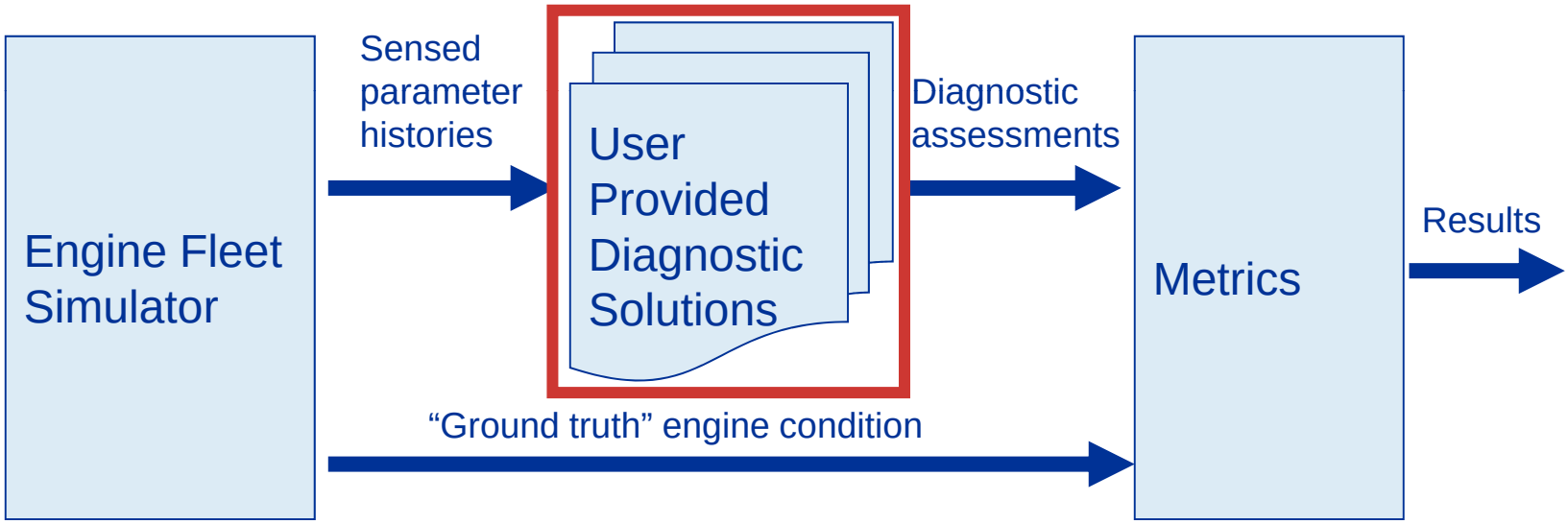




C-MAPSS SS Engine Model Block Diagram

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

ProDiMES Diagnostic Benchmarking Process



Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

User Provided Diagnostic Solutions

Participants have the capability to develop data driven, or analytical diagnostic solutions:

- Data-driven solutions: The Engine Fleet Simulator is designed to provide participants the flexibility to generate data of the desired type and quantity
- Analytical Solutions: Participants will be provided access to the C-MAPSS SS engine model to facilitate the development of analytical diagnostic methods

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

User Provided Diagnostic Solutions

Available Information (stored in Matlab format):

Sensed Parameter Histories:

- 11 sensed values collected from each engine, each flight, at takeoff & cruise

Note: Diagnosis is to be solely based on sensed information collected at, and prior to, the current flight. Although future flight sensed information is available, it is not to be used for diagnosis

Ground truth fault information including:

- Fault type
- flight of fault initiation
- fault evolution rate

Note: Ground truth fault information is available for development, training and evaluation purposes …but is not to be used for diagnosis.

User Provided Diagnostic Solution

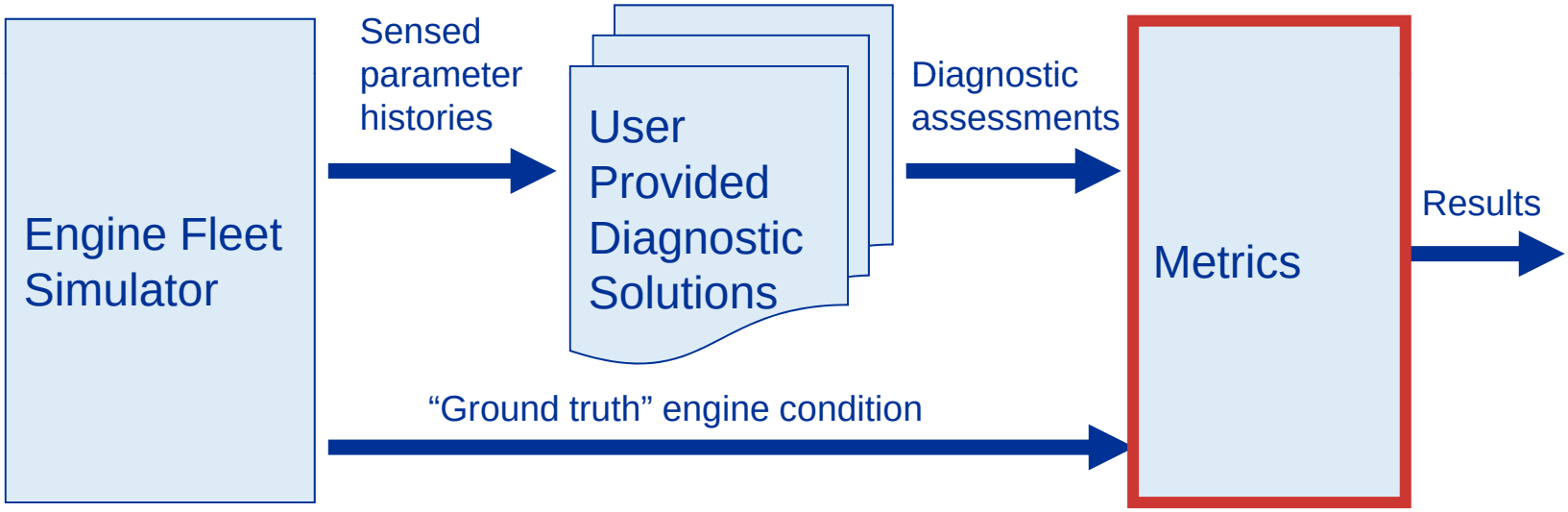
Required Solution (stored in Matlab format):

Diagnostic assessment for each engine, each flight consisting of the "Fault ID"

Target false alarm rate is once per 1000 flights

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

ProDiMES Diagnostic Benchmarking Process

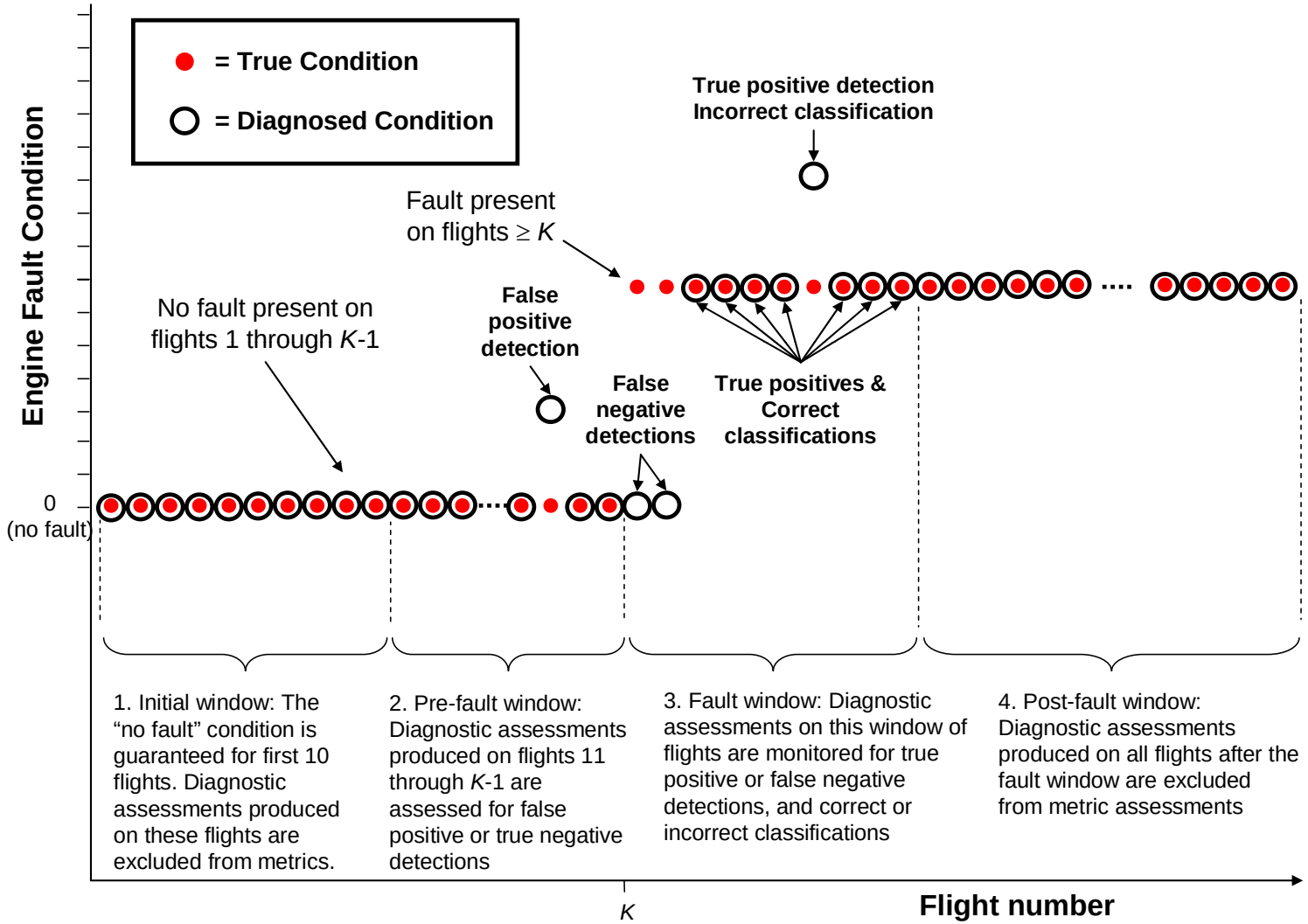


Metrics

- Defined to assess:
  - Fault detection performance
    - True positives
    - True negatives
    - False negatives (missed detections)
    - False positives (false alarms)
  - Fault classification performance
    - Correct classification rate
    - Kappa Coefficient
  - Diagnostic latency
    - Number of flights required to diagnose a fault
- A provided Matlab routine automatically evaluates performance against the defined metrics, and archives results to a Microsoft Excel spreadsheet by …
  - Fault type
  - Fault evolution rate (abrupt or rapid)
  - Fault magnitude (small, medium, large)

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Metrics (cont.)



Diagnostic window partitioning of engine flight history

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Metrics (cont.)

Detection Decision Matrix

		Predicted State	
		Fault	**No Fault**
True State	**Fault**	*True Positives*	*False Negatives (missed detections)*
	No Fault	*False Positives (false alarms)*	*True Negatives*

True Positive Rate →

$$\text{TPR} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Negatives}} \cdot 100\%$$

False Positive Rate →

$$\text{FPR} = \frac{\text{False Positives}}{\text{False Positives} + \text{True Negatives}} \cdot 100\%$$

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Metrics (cont.)

Classification Confusion Matrix

		Predicted State			
		Fault 1	**Fault 2**	**. . .**	**Fault n**
True State	**Fault 1**	C_{11}	C_{12}	. . .	C_{1n}
	Fault 2	C_{21}	C_{22}	. . .	C_{2n}
	:	:	:	. . .	:
	Fault n	C_{n1}	C_{n2}	. . .	C_{nn}

Percent Correct Classification Rate → $$PCC_p = \frac{C_{pp}}{\sum_{q=1}^{n} C_{pq}} \cdot 100\%$$

Metrics (cont.)

Kappa Coefficient – Measure of an algorithm's ability to correctly classify a fault, which takes into account the expected number of correct classifications occurring by chance. It can be calculated from the elements of a Confusion Matrix as follows:

Kappa Coefficient →

$$\kappa = \frac{N(\text{correctly classified}) - N(\text{expected correct by chance})}{N(\text{total}) - N(\text{expected correct by chance})}$$

where

$$N(\text{correctly classified}) = \sum_{p=1}^{n} C_{pp}$$

$$N(\text{total}) = \sum_{p=1}^{n} \sum_{q=1}^{n} C_{pq}$$

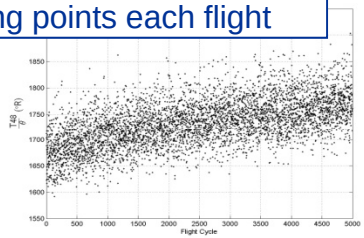
$$N(\text{expected correct by chance}) = \sum_{p=1}^{n} \left\{ \sum_{q=1}^{n} \frac{C_{pq}}{N(\text{total})} \cdot \sum_{q=1}^{n} C_{qp} \right\}$$

Example Diagnostic Solution

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Example Diagnostic Solution

"Snap-shot" parameter histories collected at discrete operating points each flight



Parameter Correction:
Accounts for variation in ambient conditions at the engine inlet

$$N1_C = \frac{N1}{\sqrt{\theta}}$$

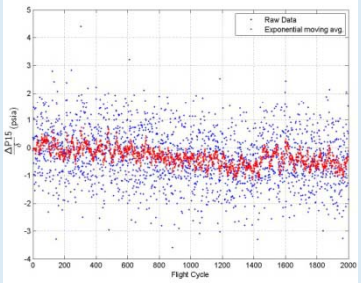
$$Wf_c = \frac{Wf}{\sqrt{\theta}\delta}$$

1. Trend Monitoring:
Monitors trends in engine performance "deltas" relative to established baseline

sensed parameters y → (+)

engine operating conditions → fleet average engine model → baseline engine parameters $y_{baseline}$ → (-)

Δy → exponential moving average → Δy_{ema}

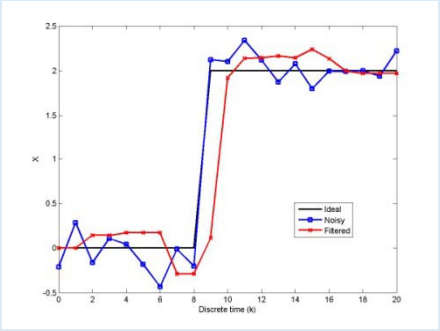


2. Event Detection:
Rapid/abrupt trend shift detection logic

Δy_{ema} → difference calculation → $\Delta\Delta y_{ema}$ → detect threshold exceeded ?

yes → single fault isolator → record fault type, & flight of detection

no → record no-fault found



3. Fault Isolation:
Identifies & ranks most plausible root causes for fault

$$e_n = \left[\sum_{i=1}^{m}\left(\frac{\Delta\Delta_k(i) - \Delta\Delta_k^*(i)}{\sigma_k}\right)^2\right]^{\frac{1}{2}}$$

Blind Test Case Data

Blind Test Case Data

- Includes data from approximately 10,000 engines
- 50 flights of data are provided for each engine
- Both abrupt and rapid fault types are included in the blind test cases
- A target false positive detection rate (false alarm rate) of once per 1,000 flights is specified
- Participants are to submit their blind test case diagnostic assessments to NASA.
- NASA will evaluate results against the metrics routine
- Participants will receive their own results, plus the anonymous results of other participants

Software Demonstration

Future Schedule

ProDiMES Schedule

- ProDiMES released through the NASA GRC Software Repository (August 2009) **(https://technology.grc.nasa.gov/software/)**

- Release includes:
  - Software Usage Agreement (must be signed prior to gaining access to the software)
  - Matlab software for independent development and evaluation
  - Identical blind test cases

- Individual development & evaluation (August 2009 – Spring 2011)

- Blind test case results evaluated (Spring 2011)
  - Participants will receive their own results, plus the anonymous results of other participants

- Hold NASA workshop to disseminate results and lessons learned (Spring 2011)

Important! Users are not to publicly disseminate ProDiMES results prior to the workshop!

- For future ProDiMES schedule updates please visit the website: www.grc.nasa.gov/WWW/cdtb/software/ehmbenchmark.html

Summary

- A public process for benchmarking gas path diagnostic methodologies is proposed
  - Allows end user's to independently develop and evaluate candidate gas path diagnostic methods
  - Automatically assesses diagnostic performance against a defined set of metrics
  - Identical blind test cases to be provided to enable a one-to-one comparison of candidate approaches

- For additional details and updates:
  - Contact: Don Simon (1-216-433-3740); Donald.L.Simon@nasa.gov
  - To request ProDiMES visit the website: https://technology.grc.nasa.gov/software/
  - For schedule updates visit the website: www.grc.nasa.gov/WWW/cdtb/software/ehmbenchmark.html