# The Use of Probabilistic Reasoning to Improve Least Squares Based Gas Path Diagnostics

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# The Use of Probabilistic Reasoning to Improve Least Squares Based Gas Path Diagnostics

- The problem of Gas Path fault diagnosis
- Overall diagnostic procedure
  - o Least squares based gas path method
  - o Statistical Processing for diagnosis improvement
  - o Fault isolation criteria
- Implementation on a turbofan engine
- Summary - Conclusions

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# The problem of Gas Path fault diagnosis

**Measurements of thermodynamic nature (*Y*)**
**(pressures, temperatures, shaft speeds etc.)**

$$\bar{Y} = g(\bar{f})$$

**Isolate faulty engine components, represented by health parameters (*f*)**
**(flow capacities, efficiency factors etc.)**

- **Measurements inaccuracies**
- **Lack of measurements**
- **System of equations non-invertible**
- **Health parameters estimation**

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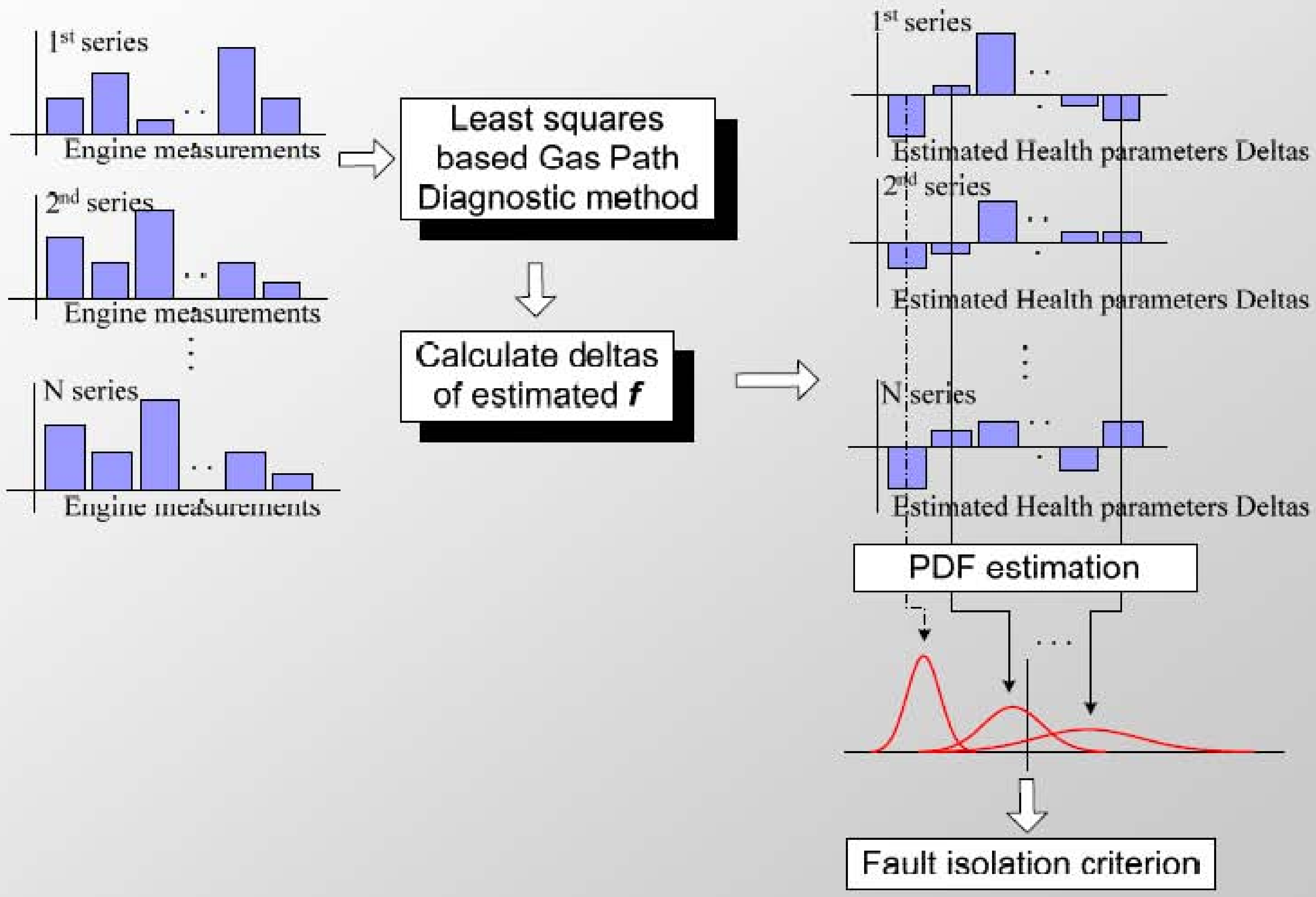
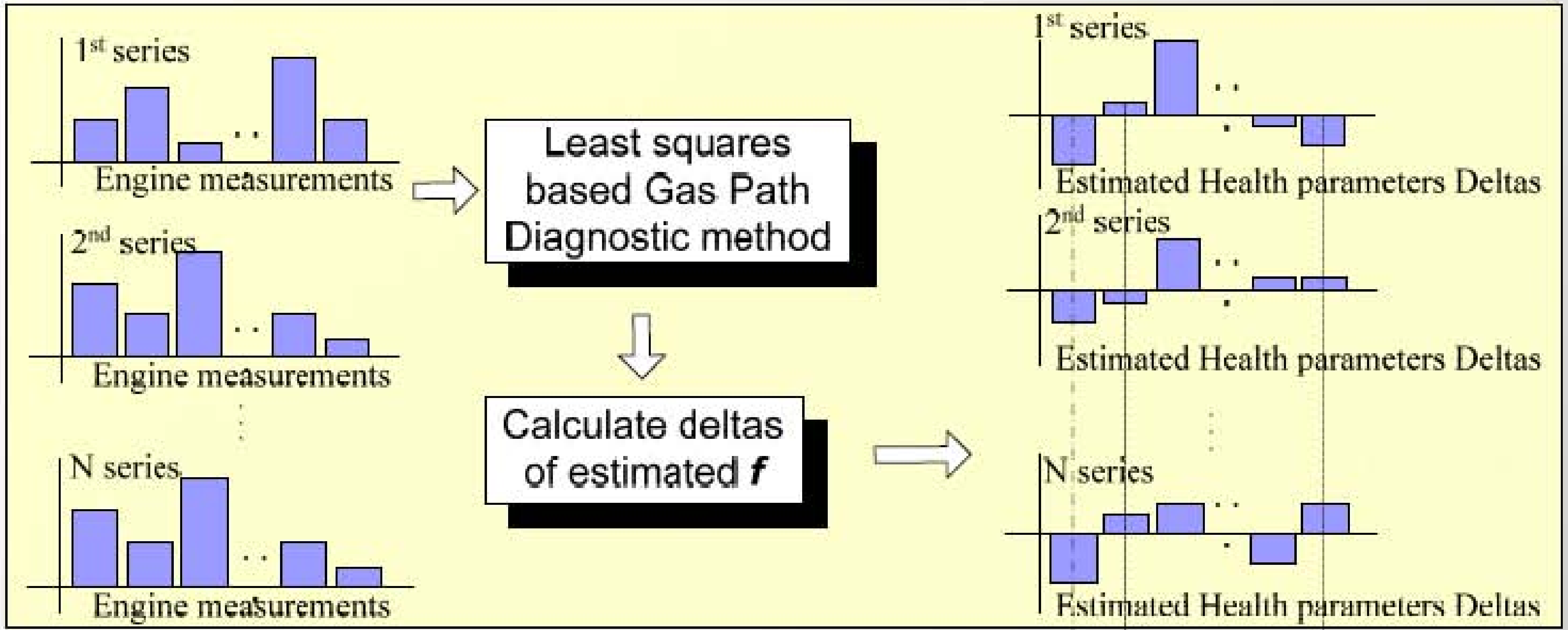
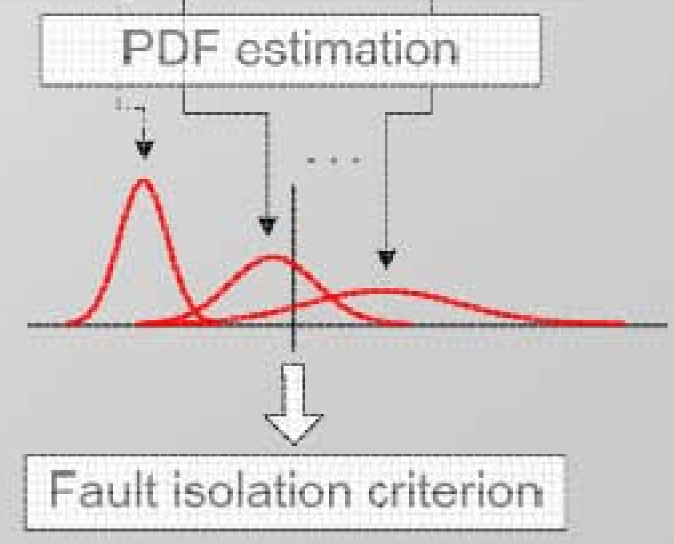
# Overall diagnostic procedure



# Overall diagnostic procedure

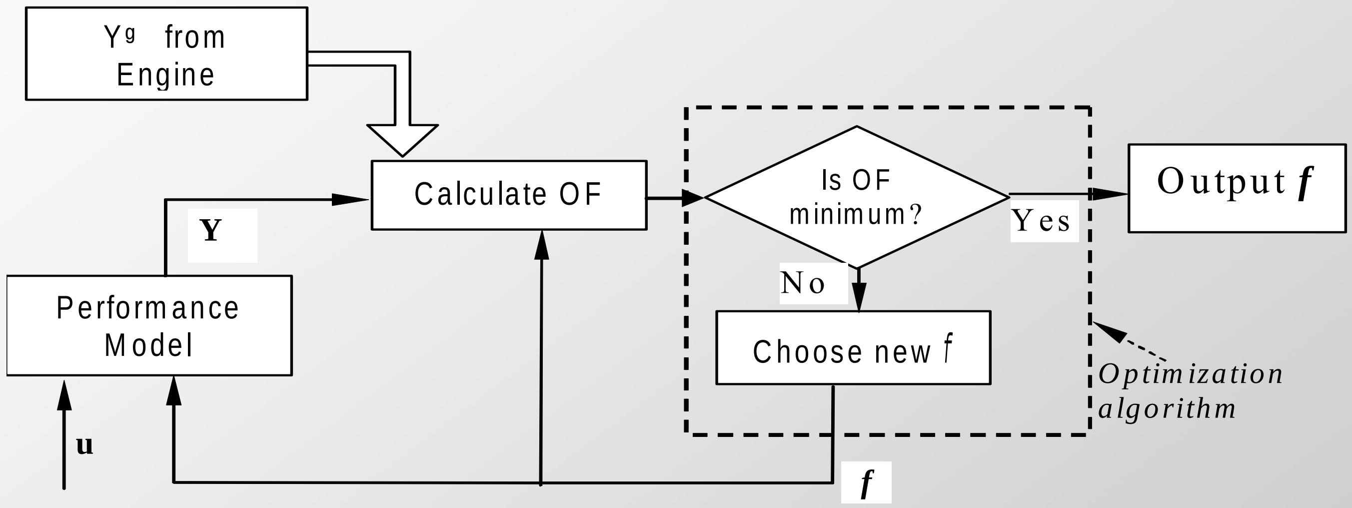



**Least squares based**
**Gas Path method for**
**health parameter estimation**

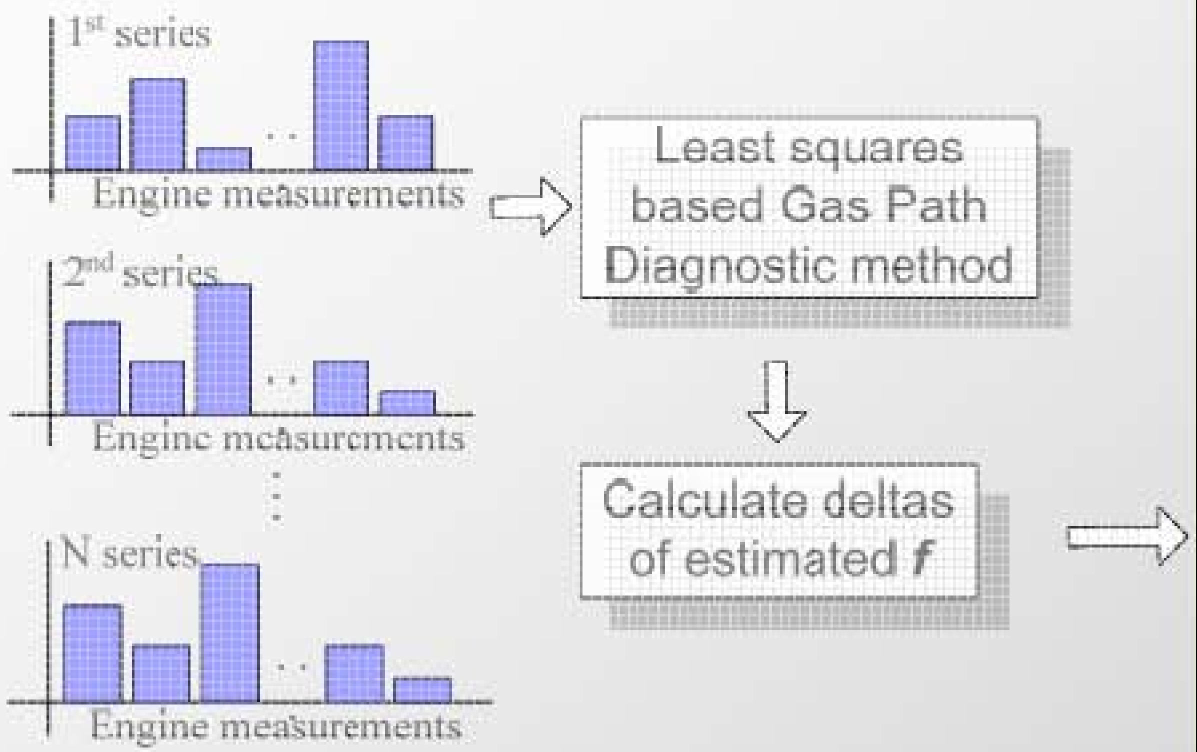
# Least Squares Based Gas Path diagnostic method

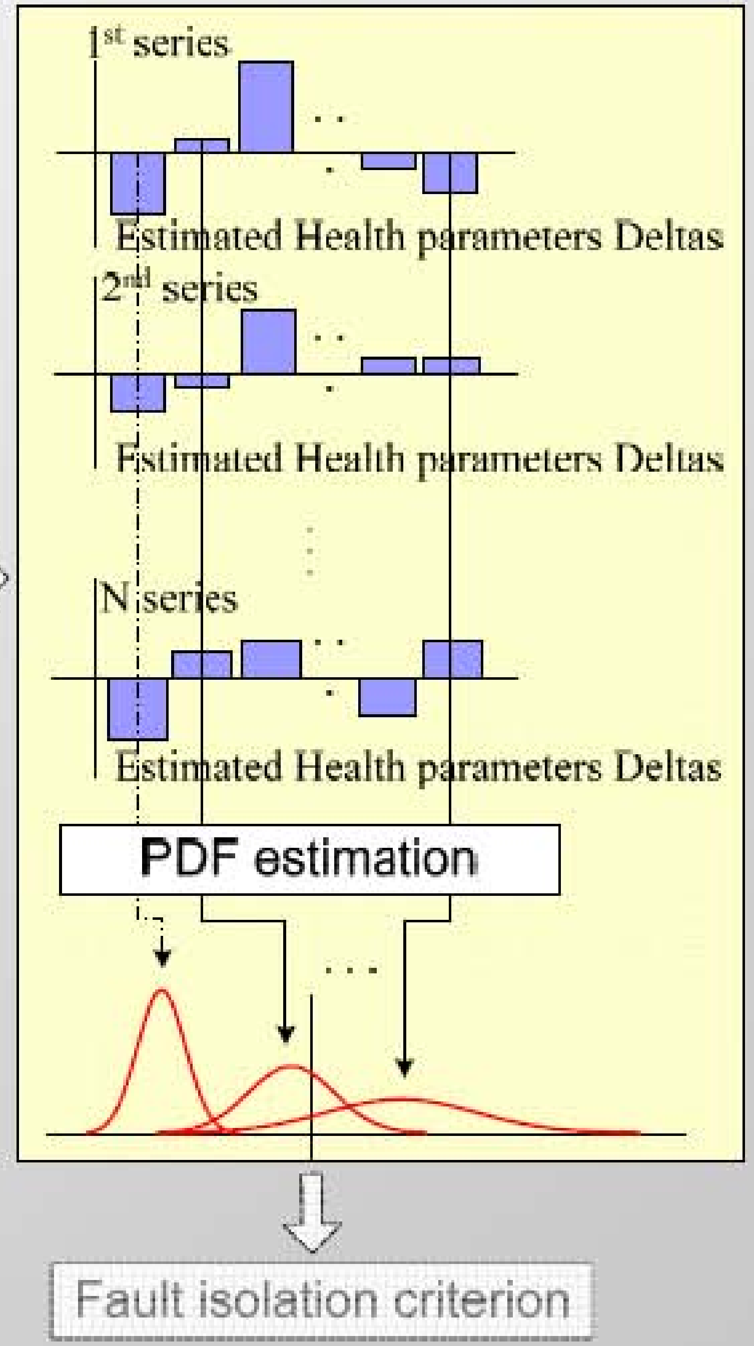
## Health parameter estimation through the minimization of appropriate objective function (OF)




$$OF = \sum_{i=1}^{M}\left[\frac{Y_i - Y_i^g}{Y_i^g \sigma_{Y_i}}\right]^2 + C_A \cdot \sum_{j=1}^{N}\left|\frac{f_j - f_j^r}{f_j^r \sigma_{f_j}}\right| + C_S \cdot \sum_{j=1}^{N}\left[\frac{f_j - f_j^r}{f_j^r \sigma_{f_j}}\right]^2$$

# Overall diagnostic procedure



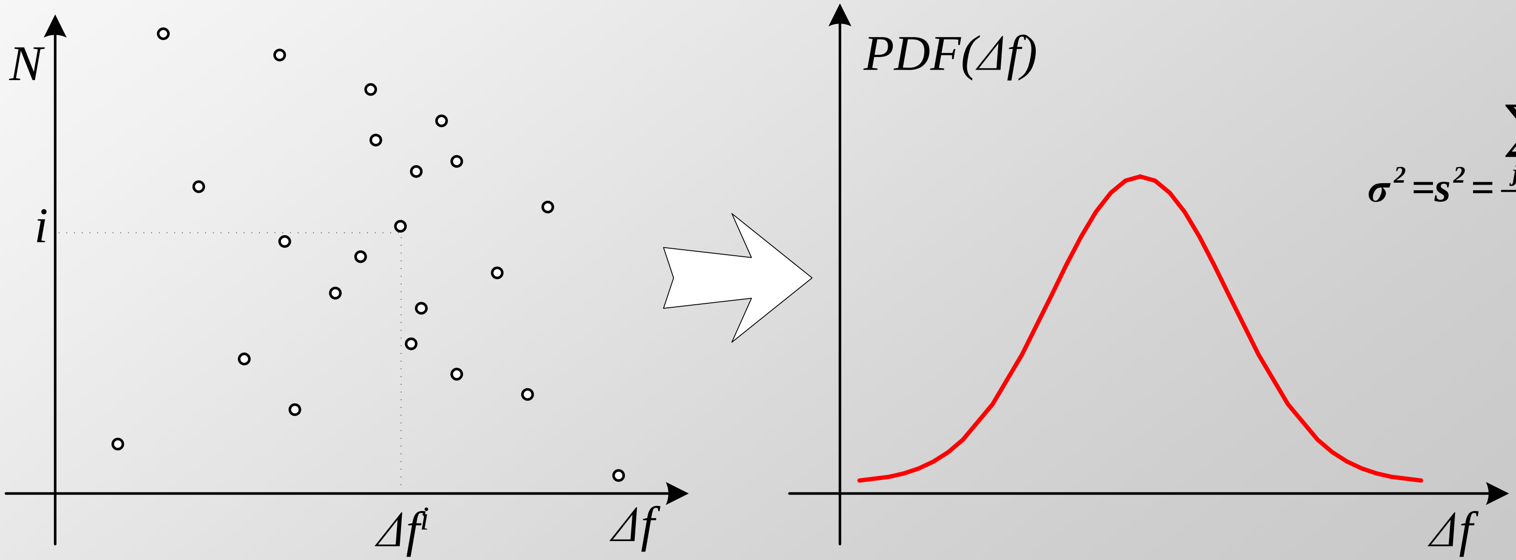




**Probability Density Function Estimation**

# Estimation of the Probability Density Function (PDF)

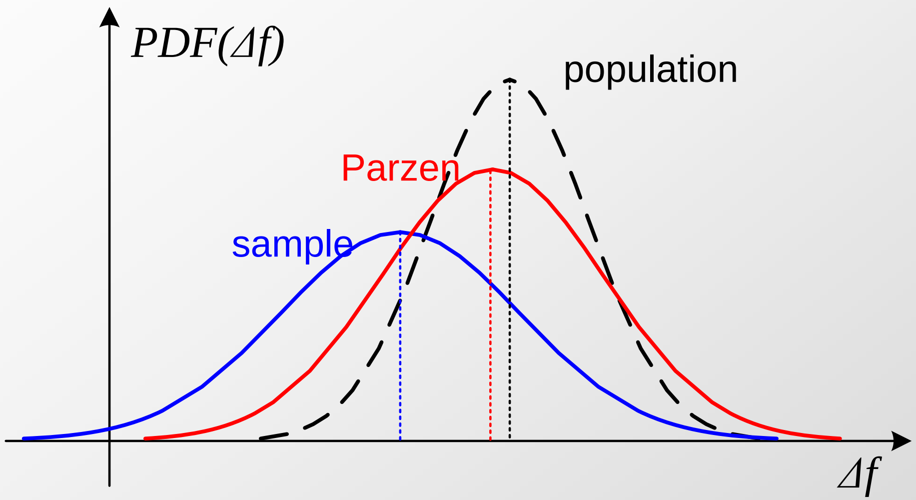
## PDF reproduction through the use of Parzen approximation

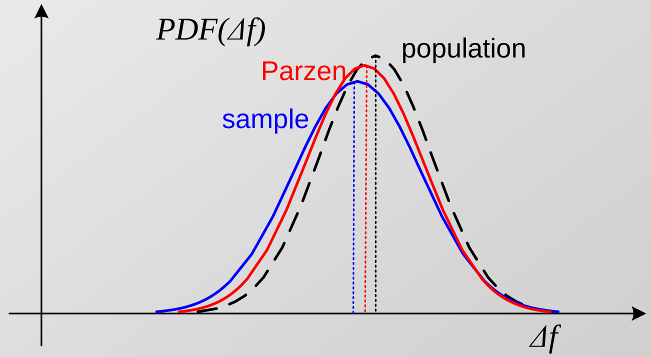
$$PDF(\Delta f)=\frac{1}{N}\cdot\sum_{j=1}^{N}\frac{1}{\sigma\sqrt{2\pi}}\cdot exp\left(-\frac{\left(\Delta f-\Delta f^{\,j}\right)^{2}}{2\sigma^{2}}\right)$$




$$\sigma^{2}=s^{2}=\frac{\sum_{j=1}^{N}\Delta f^{\,j2}}{N-1}$$

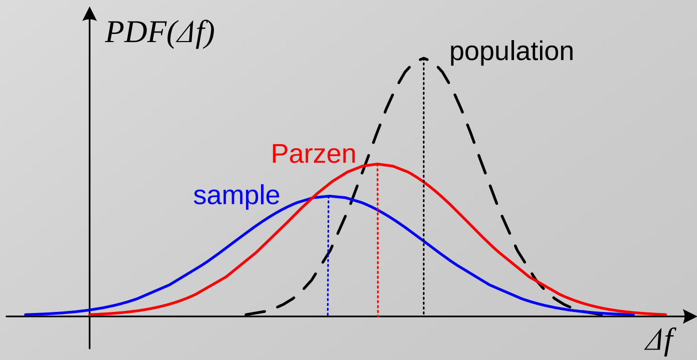
# The effectiveness of Parzen estimation



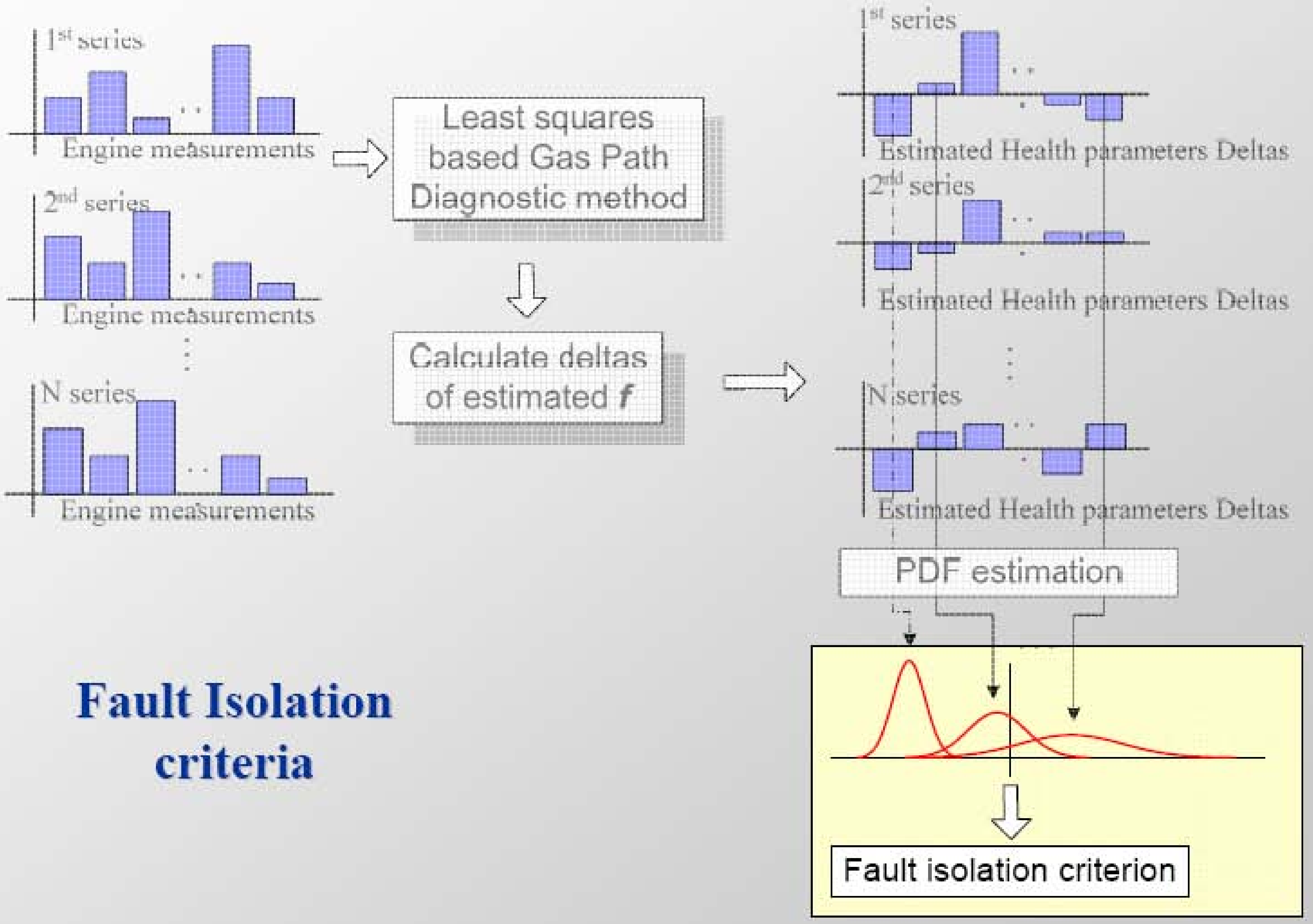

**Good sample**

**The Parzen approximation leads to a better estimation of the population distribution**



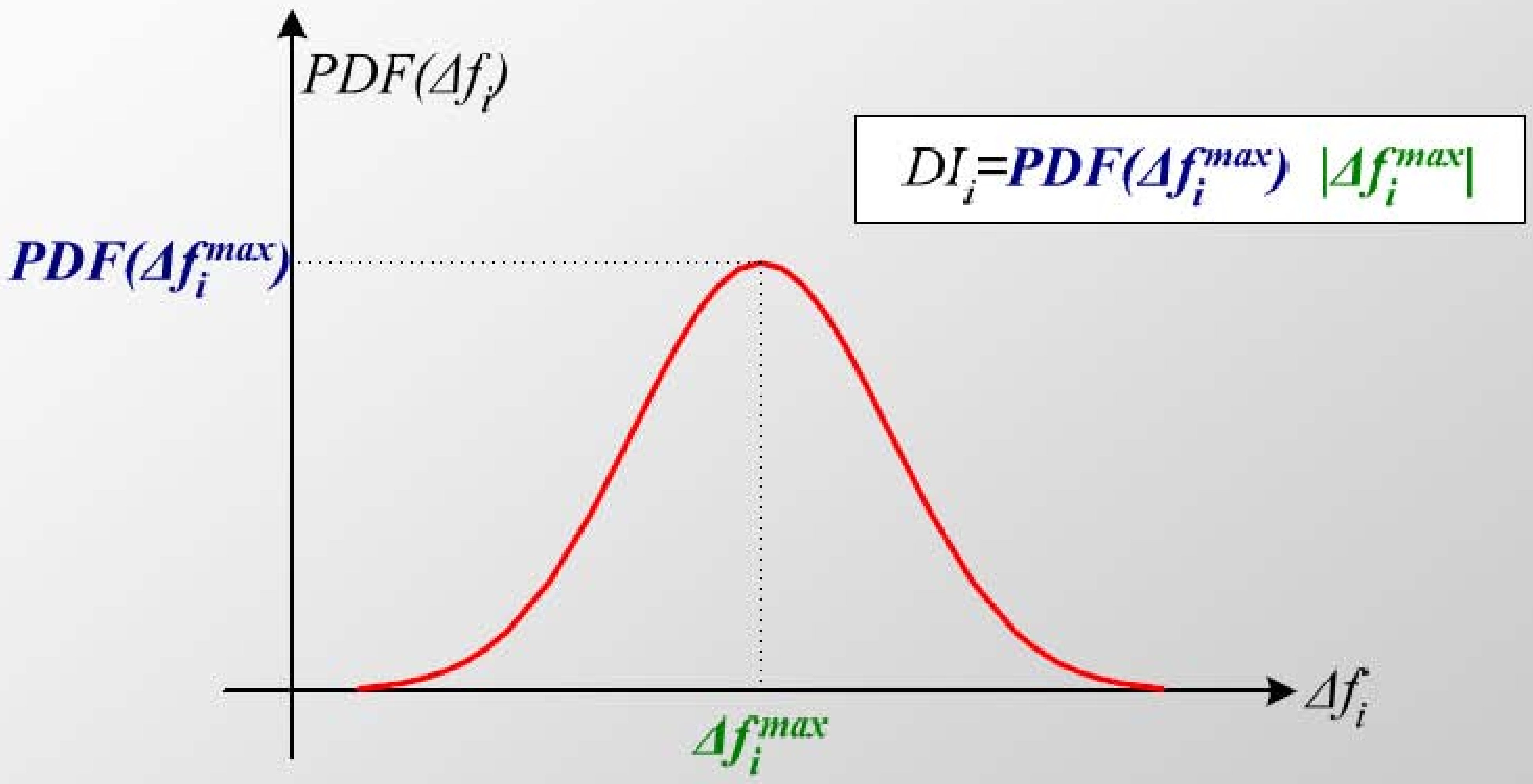

**Poor sample**

# Overall diagnostic procedure



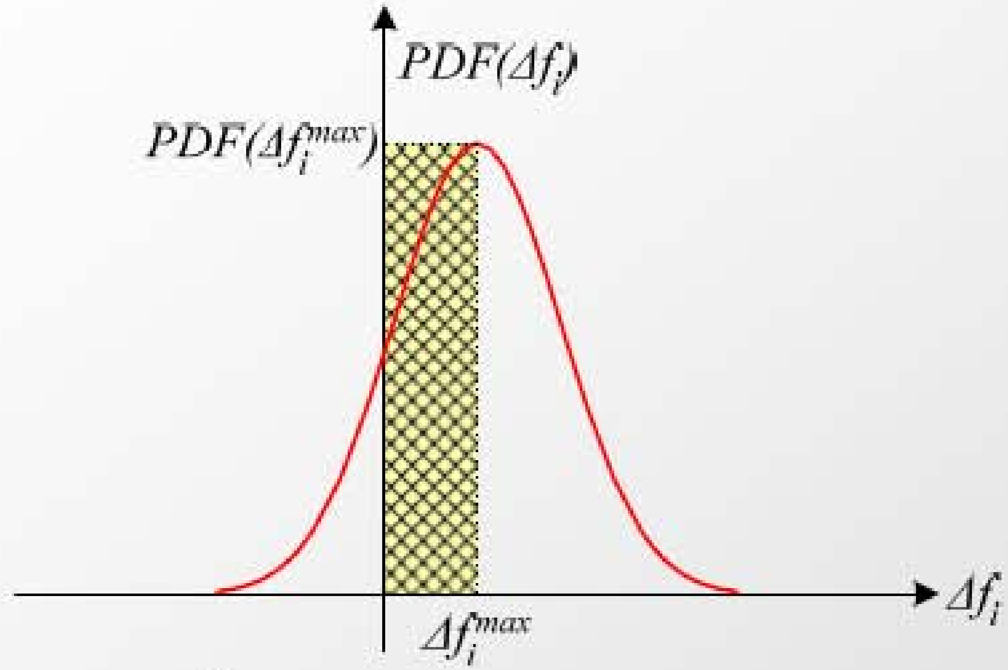

**Fault Isolation criteria**

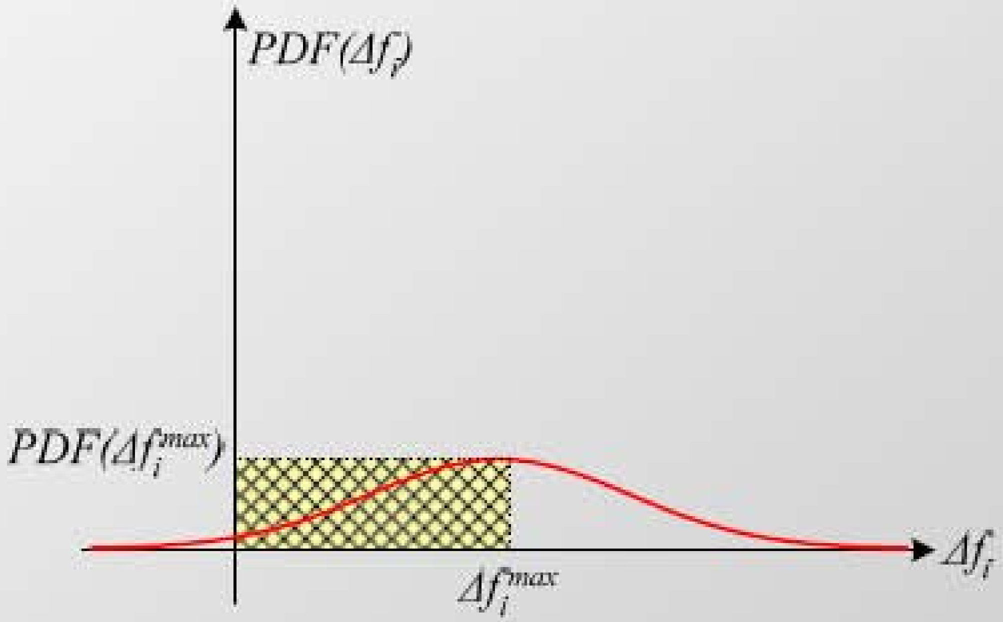
# Fault isolation criterion

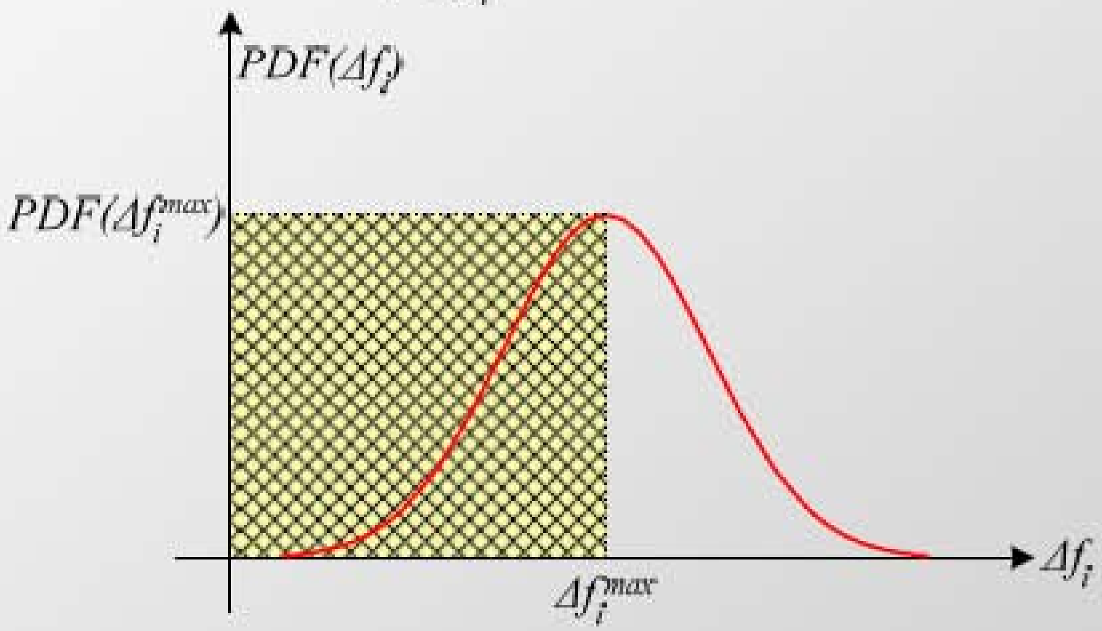



**DI values are representative of the current health condition of engine components**

# Fault isolation criterion



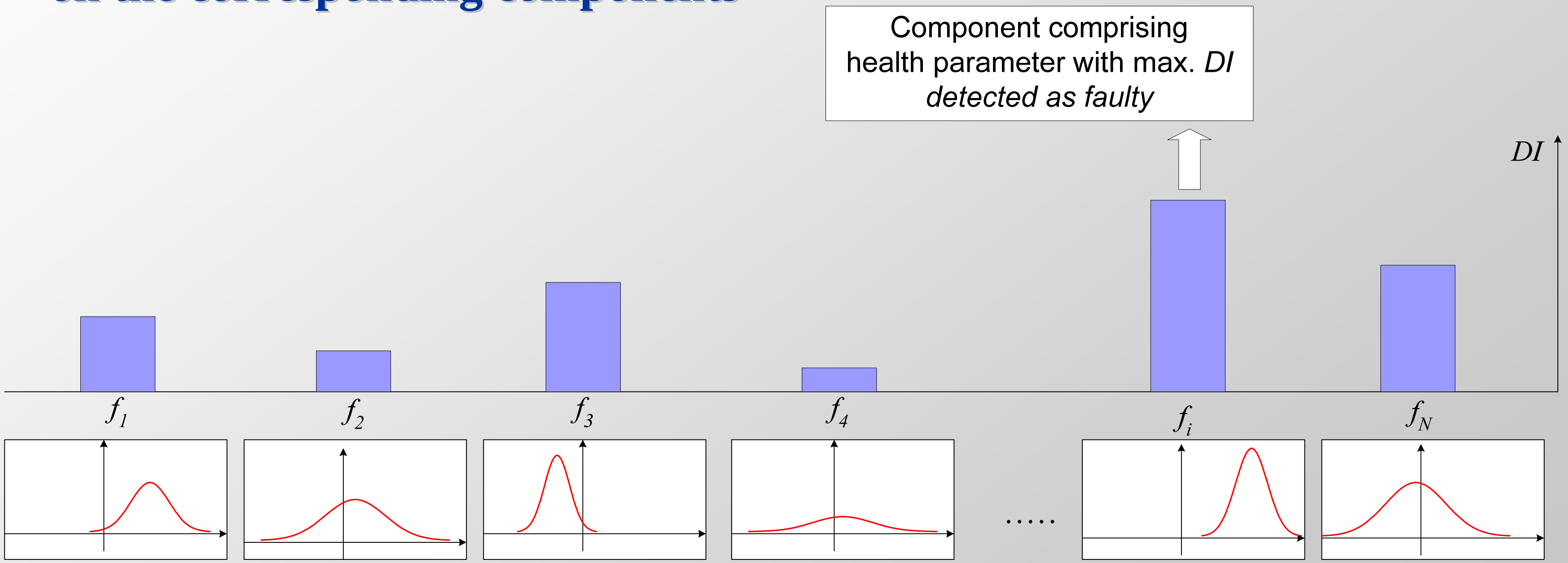




**Large DI value indicate the presence of fault on the corresponding components**

# Fault isolation criterion

**Large DI value are indicative of the presence of fault on the corresponding components**



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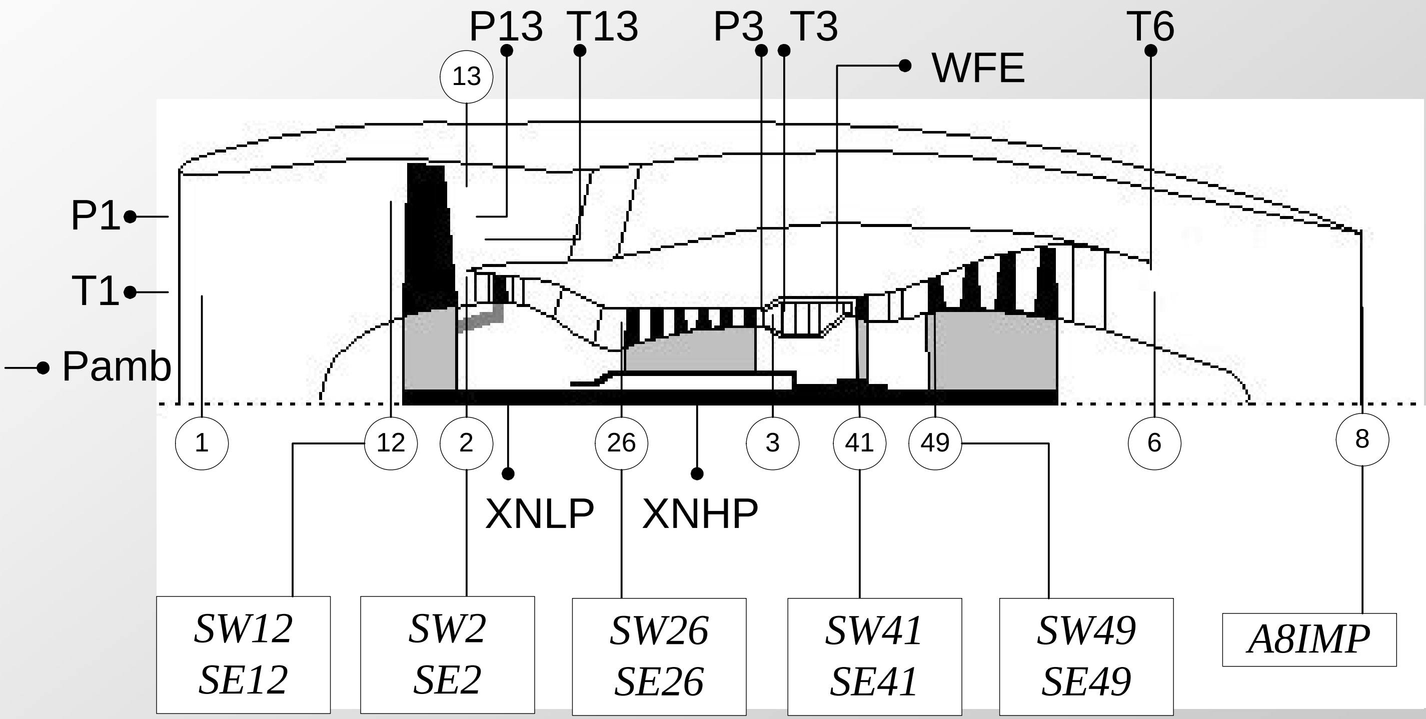
# Application to a benchmark case

## Detect health parameters that may deviate due to component faults




High-by-Pass ratio, partially mixed, turbofan engine used as a test case

# Examined fault cases

| Fault Case | Health parameters deviation | Affected components |
|---|---|---|
| A | ΔSW2=-0.7%, ΔSE2=-0.4%, ΔSW12=-1%, ΔSE12=-0.5% | LPC |
| B | ΔSE12=-1% | |
| C | ΔSW26=-1%, ΔSE26=-0.7% | HPC |
| D | ΔSE26=-1% | |
| E | ΔSW26=-1% | |
| F | ΔSW4=+1% | HPT |
| G | ΔSW4=-1%, ΔSE4=-1% | |
| H | ΔSE4=-1% | |
| I | ΔSE45=-1% | LPT |
| J | ΔSW45=-1%, ΔSE45=-0.4% | |
| K | ΔSW45=-1% | |
| L | ΔSW45=+1%, ΔSE45=-0.6% | |
| M | ΔA8imp=+1% | NOZZLE |
| N | ΔA8imp=-1% | |
| O | ΔA8imp=+2% | |

**A series of 50 measurements available for each fault case**

# Procedure evaluation on the benchmark fault cases

## Normalized values of DI of the health parameters

| fault cases | SW12 | SE12 | SW2 | SE2 | SW26 | SE26 | SW41 | SE41 | SW49 | SE49 | A8IMP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1.0 | 0.4 | 0.1 | 0.3 | 0.5 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| B | 0.1 | 1.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| C | 0.0 | 0.0 | 0.2 | 1.0 | 0.1 | 0.4 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| D | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| E | 0.2 | 0.4 | 0.2 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 |
| F | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| G | 0.3 | 0.0 | 0.1 | 0.1 | 0.2 | 0.0 | 1.0 | 0.4 | 0.4 | 0.5 | 0.3 |
| H | 0.3 | 0.3 | 0.4 | 0.1 | 0.2 | 0.1 | 0.0 | 1.0 | 0.6 | 0.5 | 0.7 |
| I | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 1.0 | 0.0 |
| J | 0.1 | 0.3 | 0.8 | 0.5 | 0.2 | 0.1 | 0.1 | 1.0 | 0.3 | 0.2 | 0.3 |
| K | 0.4 | 0.3 | 0.4 | 0.2 | 0.4 | 0.1 | 0.1 | 0.1 | 1.0 | 0.1 | 0.4 |
| L | 0.4 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.3 | 0.0 |
| M | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| N | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| O | 0.3 | 0.4 | 0.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 1.0 |

# Procedure evaluation on the benchmark fault cases

## Evaluation using the multipoint diagnostic approach

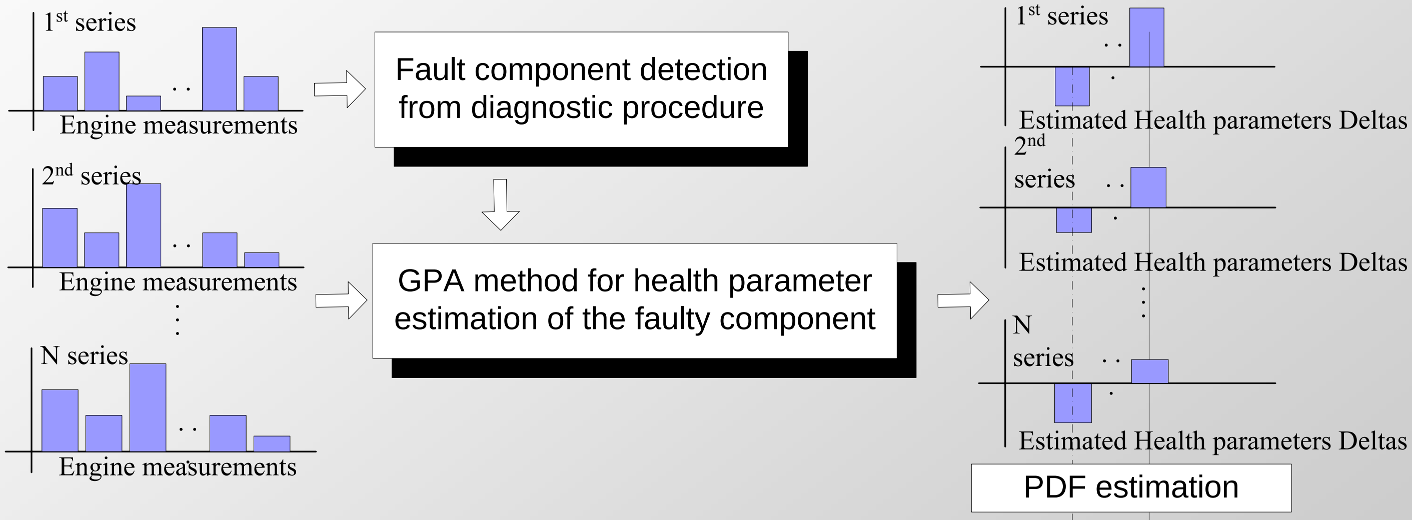
| fault cases | SW12 | SE12 | SW2 | SE2 | SW26 | SE26 | SW41 | SE41 | SW49 | SE49 | A8IMP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1.0 | 0.7 | 0.6 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.2 | 0.0 | 0.3 |
| B | 0.2 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 |
| C | 0.0 | 0.1 | 0.0 | 0.4 | 1.0 | 0.9 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 |
| D | 0.2 | 0.0 | 0.0 | 0.1 | 0.0 | 1.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 |
| E | 0.2 | 0.0 | 0.1 | 0.3 | 1.0 | 0.1 | 0.1 | 0.0 | 0.1 | 0.2 | 0.2 |
| F | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 1.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| G | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 0.1 | 0.9 | 1.0 | 0.0 | 0.1 | 0.0 |
| H | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.1 | 1.0 | 0.1 | 0.0 | 0.1 |
| I | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 1.0 | 0.0 |
| J | 0.1 | 0.0 | 0.0 | 0.4 | 0.0 | 0.2 | 0.1 | 0.1 | 0.4 | 1.0 | 0.0 |
| K | 0.6 | 0.0 | 0.2 | 0.8 | 0.0 | 0.5 | 0.3 | 0.3 | 1.0 | 0.5 | 0.5 |
| L | 0.0 | 0.0 | 0.1 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.4 | 1.0 | 0.0 |
| M | 1.0 | 0.0 | 0.0 | 0.6 | 0.0 | 0.1 | 0.3 | 0.1 | 0.4 | 0.3 | 0.7 |
| N | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |
| O | 0.1 | 0.0 | 0.0 | 0.3 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.2 | 1.0 |

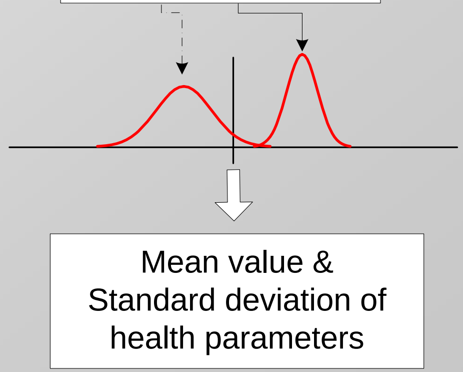
# Procedure evaluation on the benchmark fault cases

## Evaluation using the sample characteristics: $DI_i = \frac{\mu_{\Delta fi}}{\sigma_{\Delta fi}}$

| fault cases | SW12 | SE12 | SW2 | SE2 | SW26 | SE26 | SW41 | SE41 | SW49 | SE49 | A8IMP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1.0 | 0.8 | 0.6 | 0.1 | 0.0 | 0.3 | 0.4 | 0.0 | 0.3 | 0.1 | 0.4 |
| B | 0.2 | 1.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | 0.2 | 0.1 | 0.2 |
| C | 0.0 | 0.3 | 0.1 | 0.4 | 0.9 | 1.0 | 0.1 | 0.4 | 0.1 | 0.4 | 0.0 |
| D | 0.2 | 0.0 | 0.1 | 0.2 | 0.0 | 1.0 | 0.3 | 0.1 | 0.2 | 0.2 | 0.2 |
| E | 0.5 | 0.1 | 0.3 | 0.6 | 1.0 | 0.4 | 0.5 | 0.4 | 0.2 | 0.7 | 0.4 |
| F | 0.2 | 0.1 | 0.0 | 0.2 | 0.0 | 0.1 | 1.0 | 0.1 | 0.2 | 0.2 | 0.2 |
| G | 0.1 | 0.1 | 0.1 | 0.3 | 0.2 | 0.2 | 0.7 | 1.0 | 0.0 | 0.2 | 0.1 |
| H | 0.2 | 0.0 | 0.0 | 0.2 | 0.1 | 0.2 | 0.2 | 1.0 | 0.1 | 0.1 | 0.2 |
| I | 0.0 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.0 | 0.2 | 0.1 | 1.0 | 0.0 |
| J | 0.1 | 0.1 | 0.0 | 0.4 | 0.1 | 0.3 | 0.2 | 0.3 | 0.4 | 1.0 | 0.1 |
| K | 0.3 | 0.0 | 0.2 | 0.4 | 0.1 | 0.4 | 0.3 | 0.3 | 0.4 | 1.0 | 0.3 |
| L | 0.1 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.0 | 0.3 | 0.6 | 1.0 | 0.1 |
| M | 1.0 | 0.0 | 0.2 | 0.6 | 0.1 | 0.4 | 0.8 | 0.3 | 0.6 | 0.7 | 0.8 |
| N | 0.2 | 0.1 | 0.1 | 0.3 | 0.1 | 0.3 | 0.2 | 0.2 | 0.1 | 0.2 | 1.0 |
| O | 0.2 | 0.0 | 0.0 | 0.4 | 0.2 | 0.3 | 0.2 | 0.4 | 0.0 | 0.4 | 1.0 |

# Diagnosis improvement-refinement

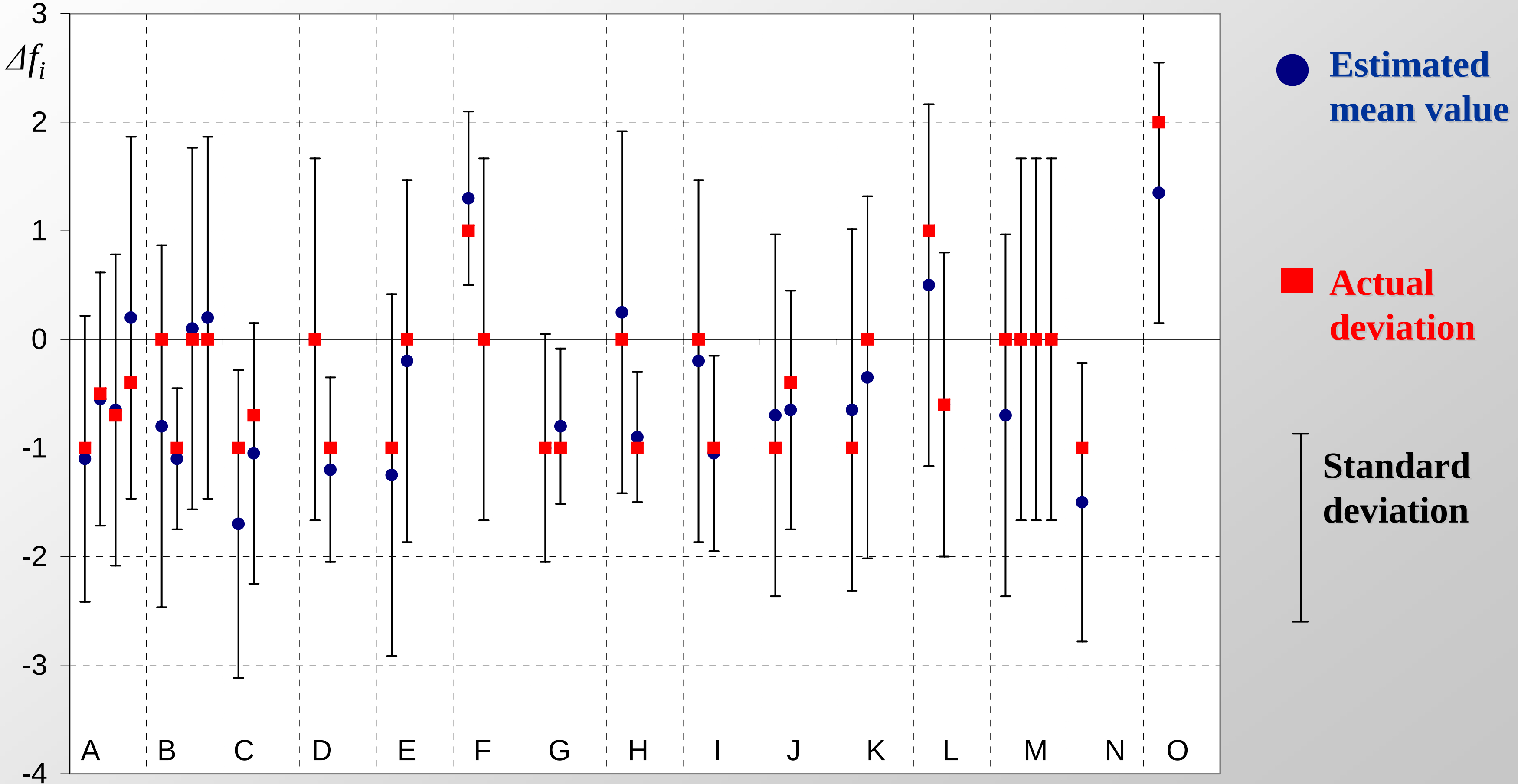



**Estimation of the actual deviation of the health parameters deviation through a two-step application of the diagnostic procedure**

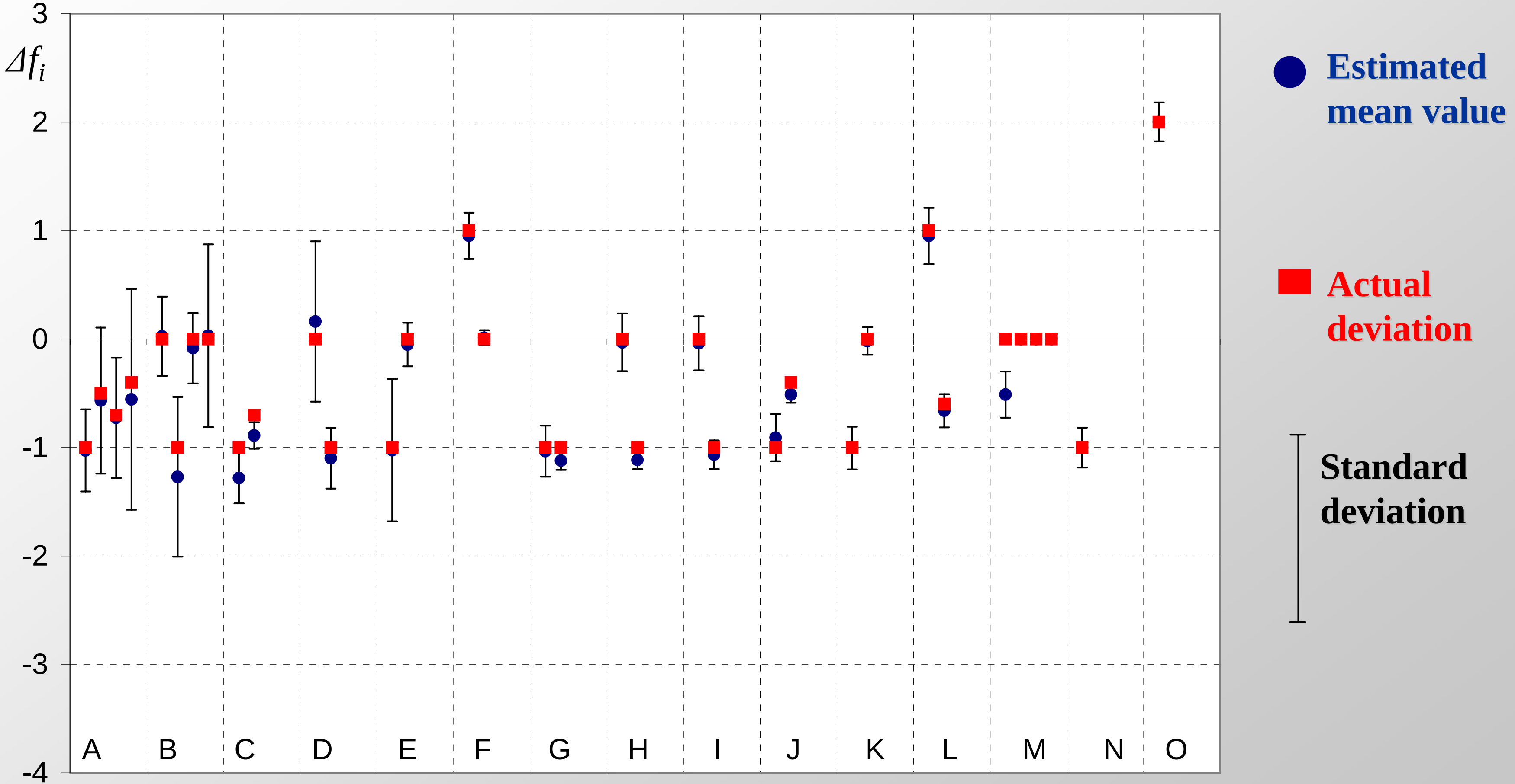
# Diagnosis improvement-refinement

## Application on the benchmark fault cases (1st pass)



# Diagnosis improvement-refinement

## Application on the benchmark fault cases (2nd pass)



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# Summary - Conclusions

- **A combination of least squares based Gas Path methods with a PDF estimator allows efficient fault detection**
- **Comparison with previous approaches demonstrated that the PDF estimator can improve the effectiveness of Gas Path diagnostic methods**
- **A two-step application of the proposed procedure can lead to a quite accurate estimation of the health parameters**
- **The proposed procedure can be applied using any diagnostic method that allows health parameters estimation**