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Tools for Optimal Estimation of Hidden Trends in FDC

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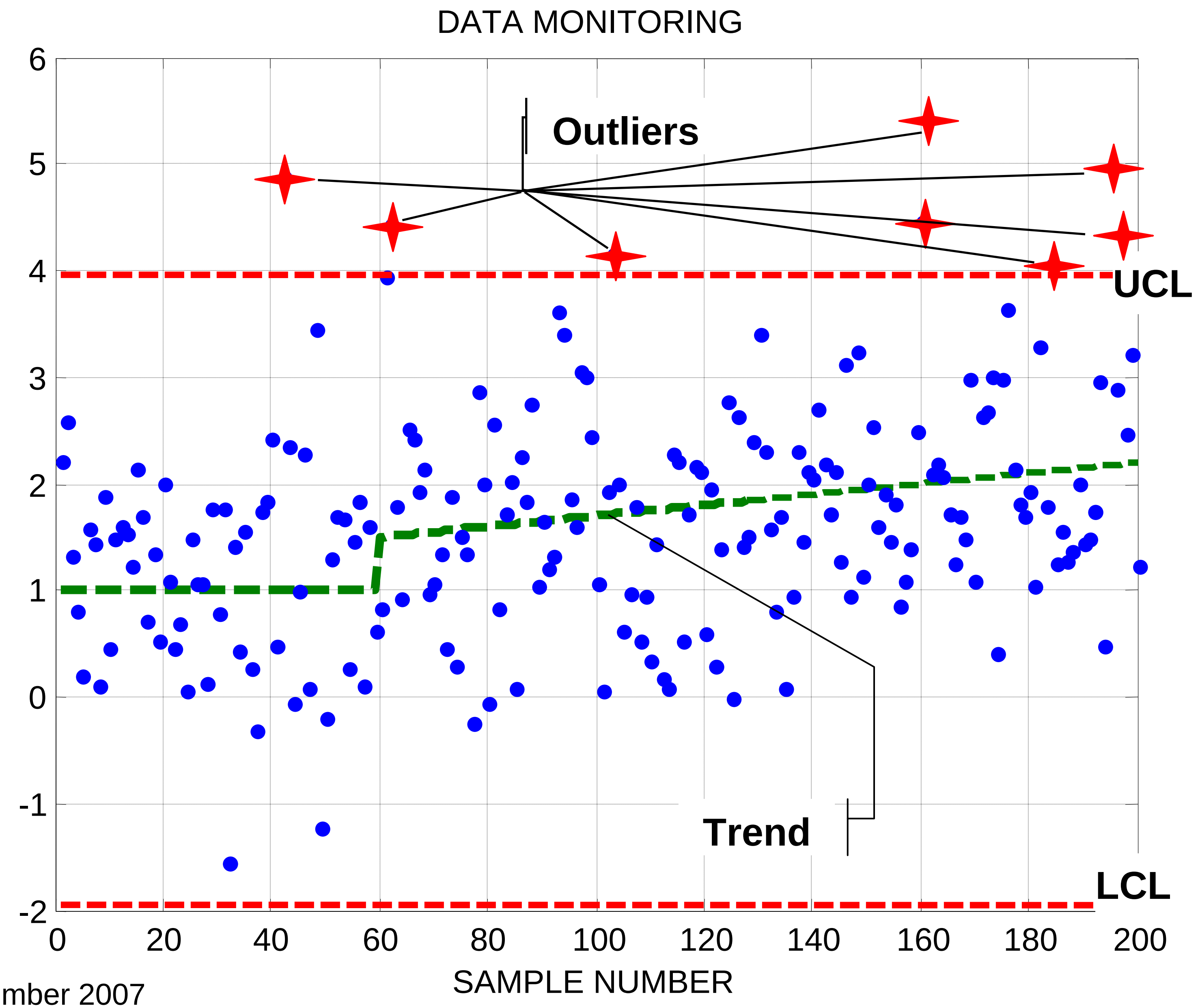


DATA MONITORING
Outliers
UCL
Trend
LCL
6
5
4
3
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160
180
200
SAMPLE NUMBER

Overview

- This talk presents:
  - Math formulation of the trending problem
  - Algorithms and tools for FDC

- Introduction
  - Where does this fit in industry practice?
    - SPC, APC, FDC…

State of the Art

SPC – Statistical Process Control

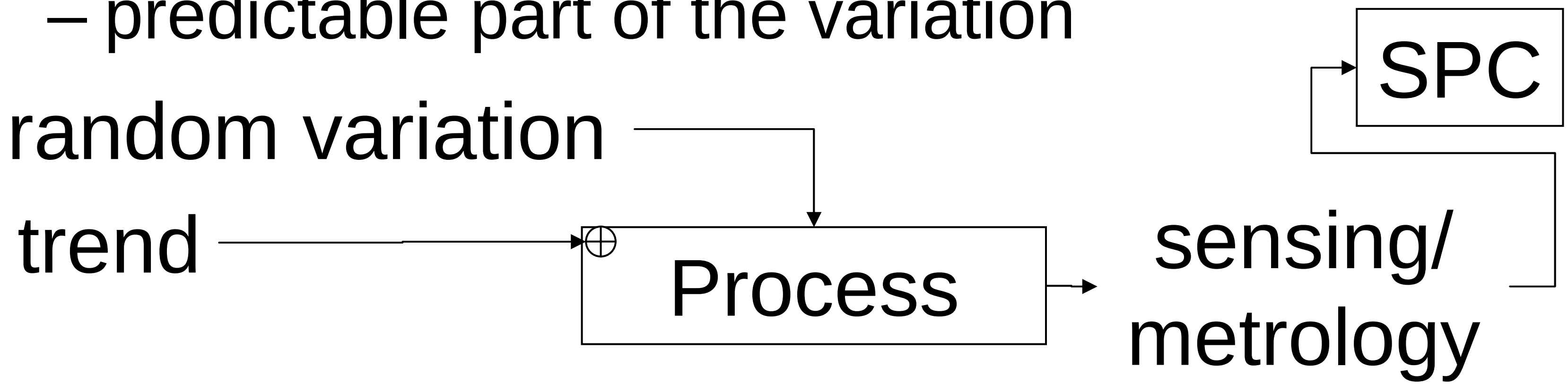
- SPC is used for 50-80 years
  - Shewart Chart
  - EWMA
  - CUSUM
- SPC operation
  - Watches for a change in the process
  - If an alarm, stop the process and troubleshoot

Multivariable SPC

- Is used for 20+ years
- Directionality of variation
  - PCA – Principal Component Analysis
- Multivariable statistics charts
  - T^2 and Q (=SPE)
- Detects a change in the process

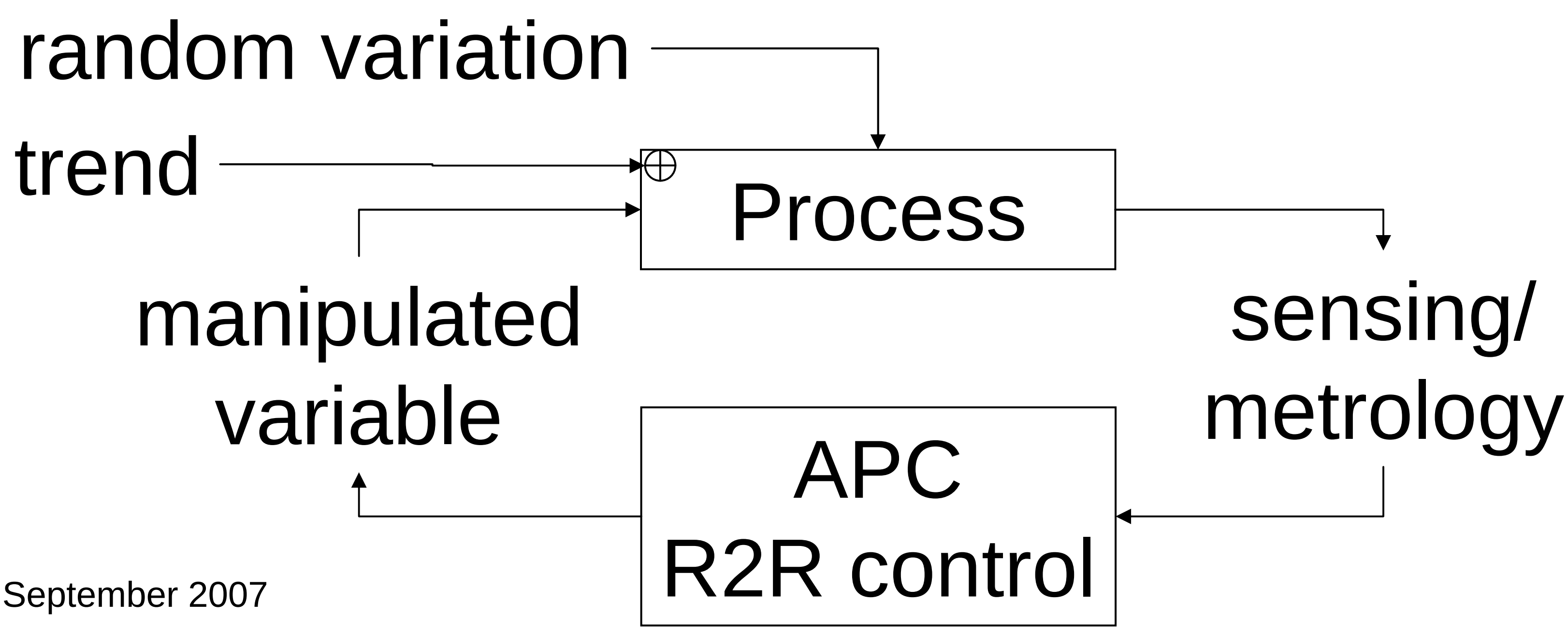
Process Variation in SPC

- Random variation
  - differs for each process run
  - unpredictable
- Trend and bias
  - same (or slowly varies) for each time sample
  - predictable part of the variation



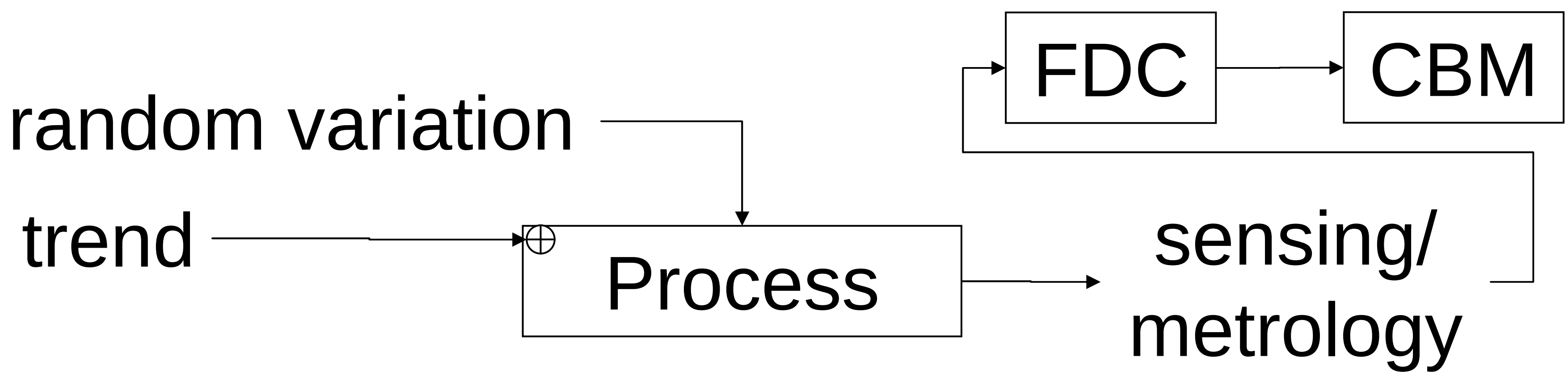
APC – Advanced Process Control

- Compensate the disturbance by feedback
- Takes care of the trend
- Continuous, automated update



FDC – Fault Detection & Classification

- FDC is the subject of this talk
- Estimates the trend and supports decisions
  - Automated troubleshooting, diagnostics
  - Condition based maintenance (CBM)



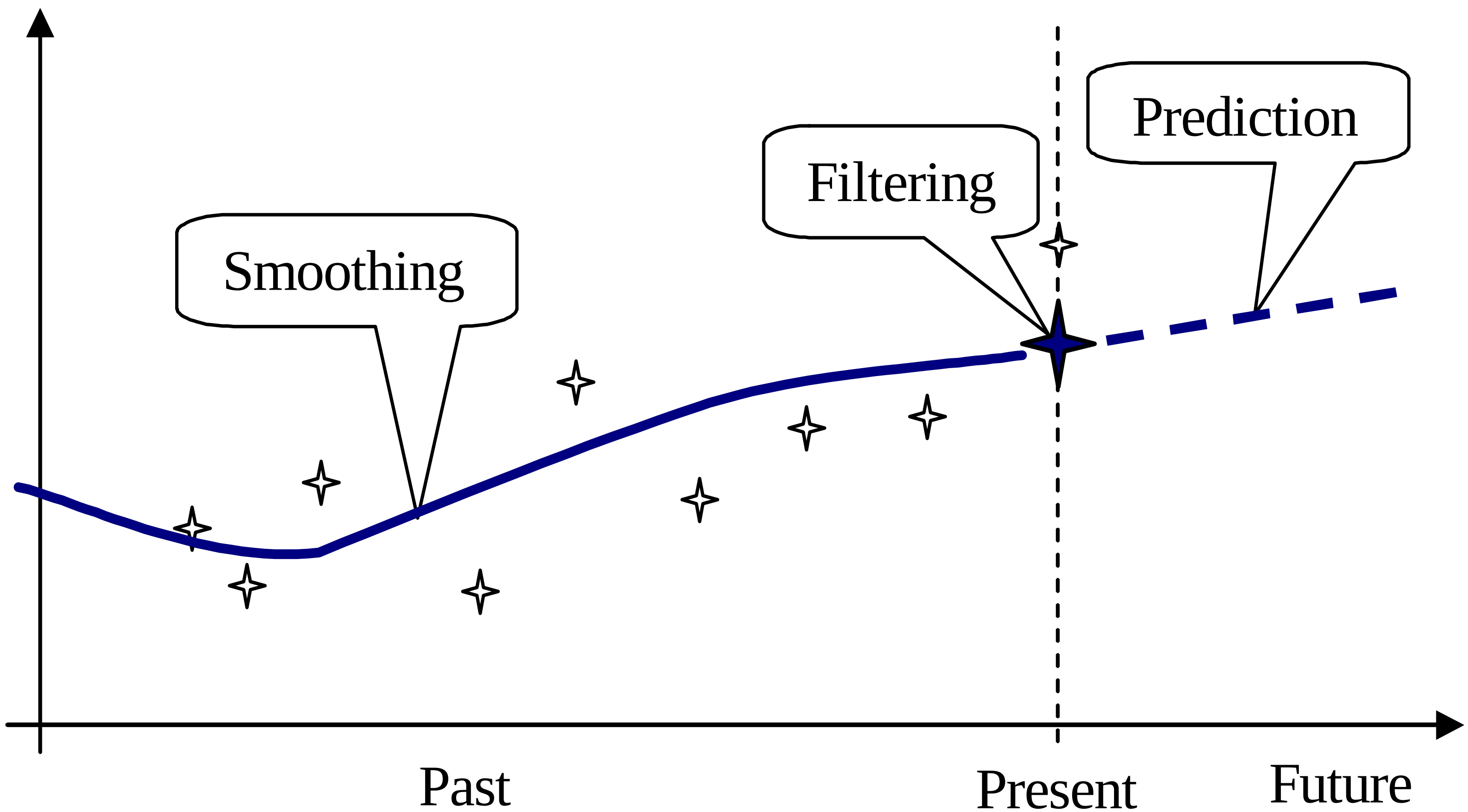
State of the Art in FDC

- Diagnostics, trending, prognostics, CBM
- Well established in process industries
  - refineries, pulp & paper
- Aerospace – Systems Health Management
  - commercial aviation, DoD, NASA
  - most advanced: jet engine monitoring
- IC manufacturing
  - emerging

Trending

Trending Functions

- What is trending?



Trend Estimation

- Data: $\{Y\} = \{y(1), \ldots, y(N)\}$ Observed data

  $\{X\} = \{x(1), \ldots, x(N)\}$ Underlying trend

- Bayesian estimation

$$P(\{X\} \mid \{Y\}) = P(\{Y\} \mid \{X\}) \cdot P(\{X\}) \cdot c \to \max$$

Observation model

Prior

- Random walk model of the trend

$$y(t) = x(t) + e(t) \longrightarrow P(\{Y\} \mid \{X\}) \qquad e \sim N(0, Q)$$

$$x(t+1) = x(t) + v(t) \longrightarrow P(\{X\}) \qquad v \sim N(0, R)$$

Trending Formulation

- Batch least squares; L2 prior

$$L = \frac{1}{2}\sum Q^{-1}\left[y(t) - x(t)\right]^2 + \frac{1}{2}\sum R^{-1}\left[x(t) - x(t-1)\right]^2 \rightarrow \min$$

Observation model

Prior

- Recursive filter version = Kalman filter
- Stationary Kalman filter = EWMA
- Why this is used in practice?
  - Conceptual and computational simplicity

Advanced Trending

- Laplacian or exponential process noise
  - describe jumps in the trend well; L1 prior
- Additional constraints
  - monotonicity: irreversible deterioration
  - positivity
- Could provide a better estimate
  - is the extra complexity worth it?

Optimization-based Estimation

- Quadratic Programming (QP)

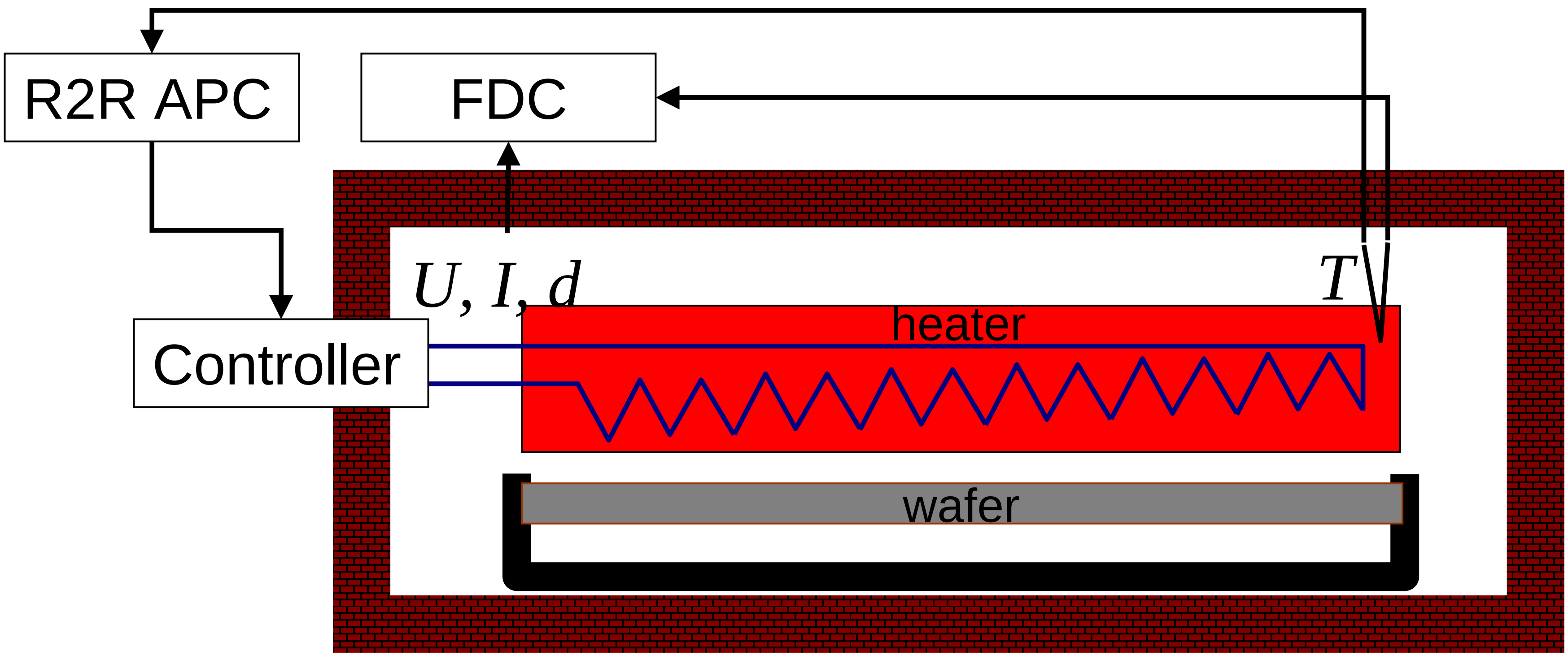
$$L = \frac{1}{2}\sum Q^{-1}\left[y(t) - x(t)\right]^2 + \sum R^{-1}\left|x(t) - x(t-1)\right| \rightarrow \min$$

$$x(t) \geq x(t-1)$$

- A convex constrained optimization problem
  - Can be solved efficiently and conveniently
  - Commercial solvers: 1K variables, in seconds
  - Specialized solvers: 1M variables, in minutes

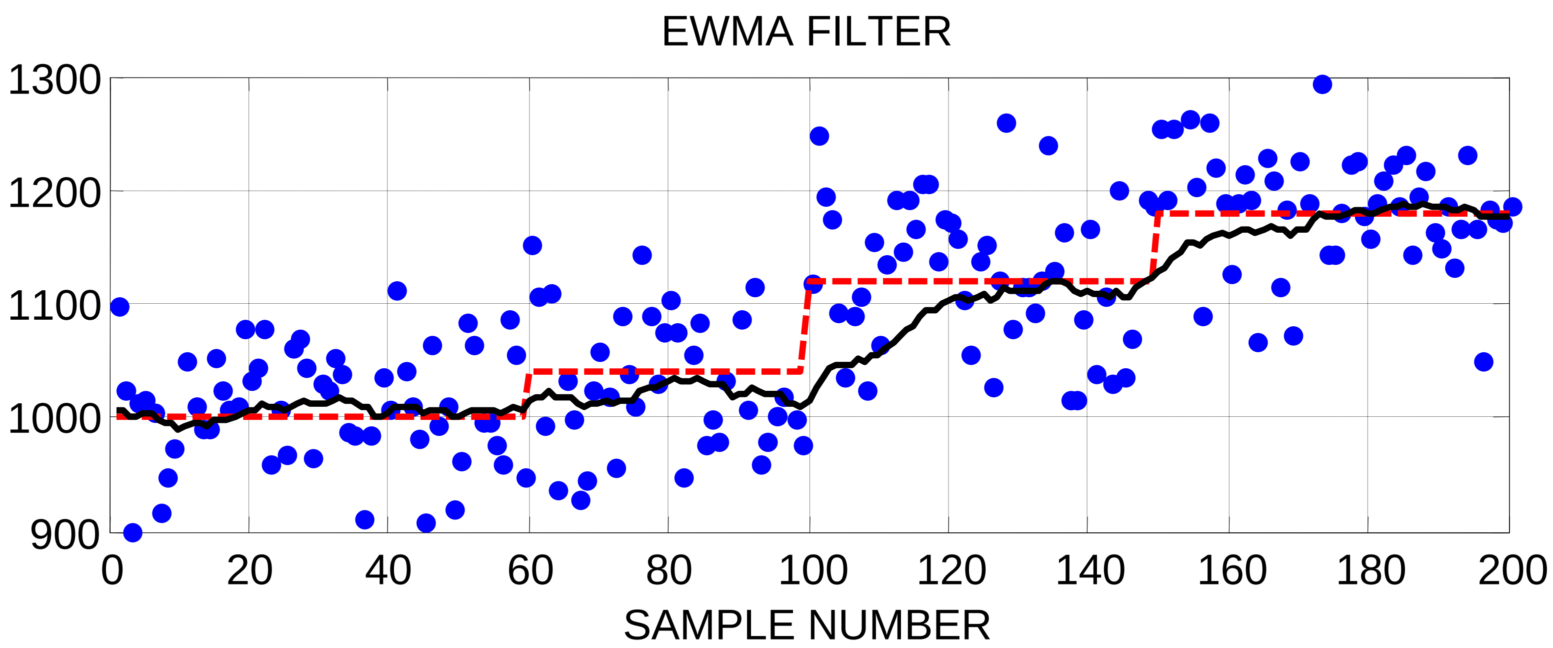
Heater Deterioration Example

- Post-exposure bake
- Increasing heater resistance

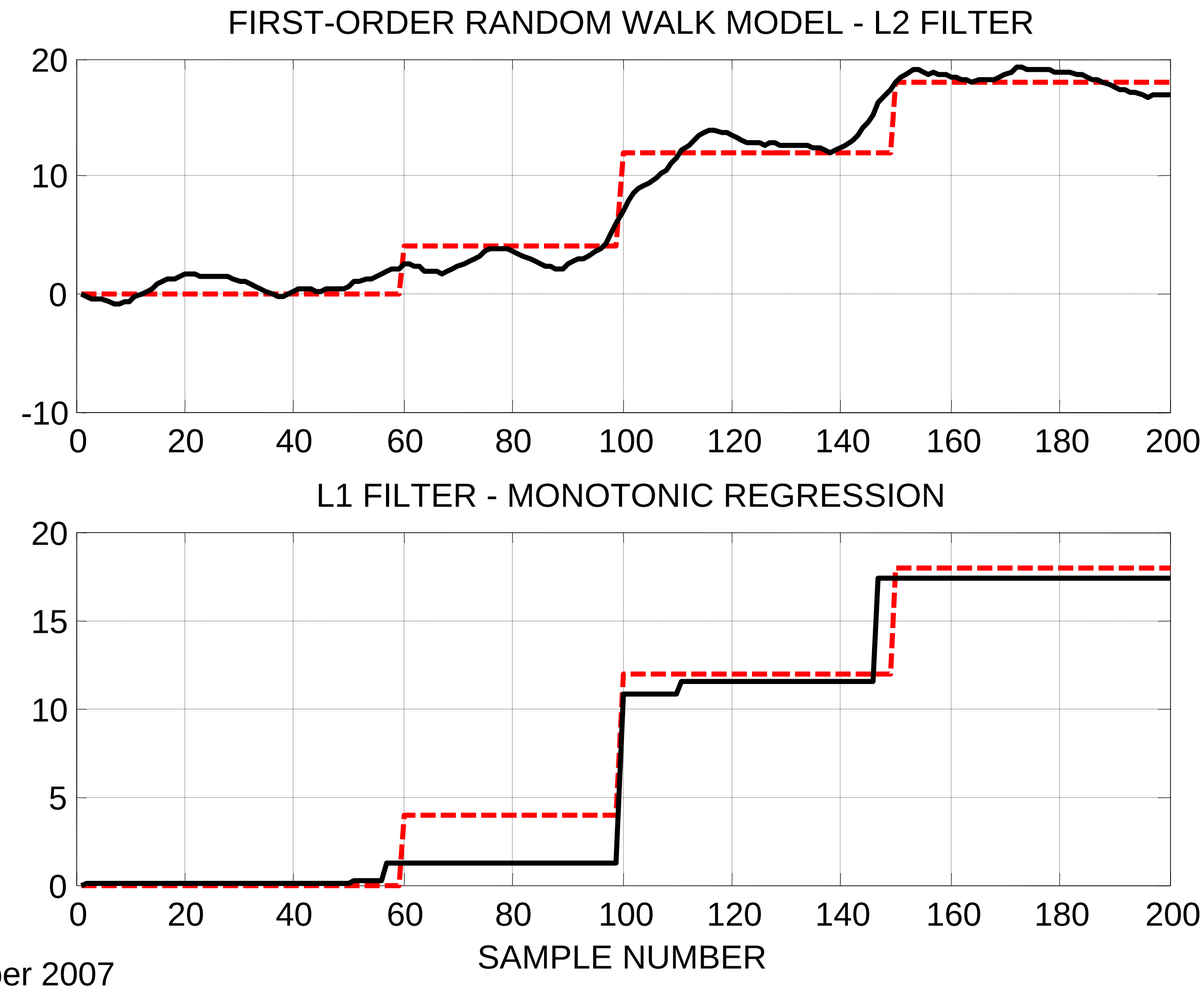


EWMA filter

- EWMA filter with $T=20$



Batch Regression: L2 and L1-Mono



Multivariable Trending

Multivariate Observation Model

$$Y(t) = S(t)\,f(t) + e(t)$$

- Multiple fault parameters
- Fault signatures $S(t)$ could come from empirical data or engineering analysis
- Goal: estimate hidden fault parameters $f(t)$
  - With prior models optimal estimation is a QP

Prior Models: Process

- Separate fault component models
- Random walk

$$f_k(t+1) = f_k(t) + \xi_k(t)$$

- Second-order random walk

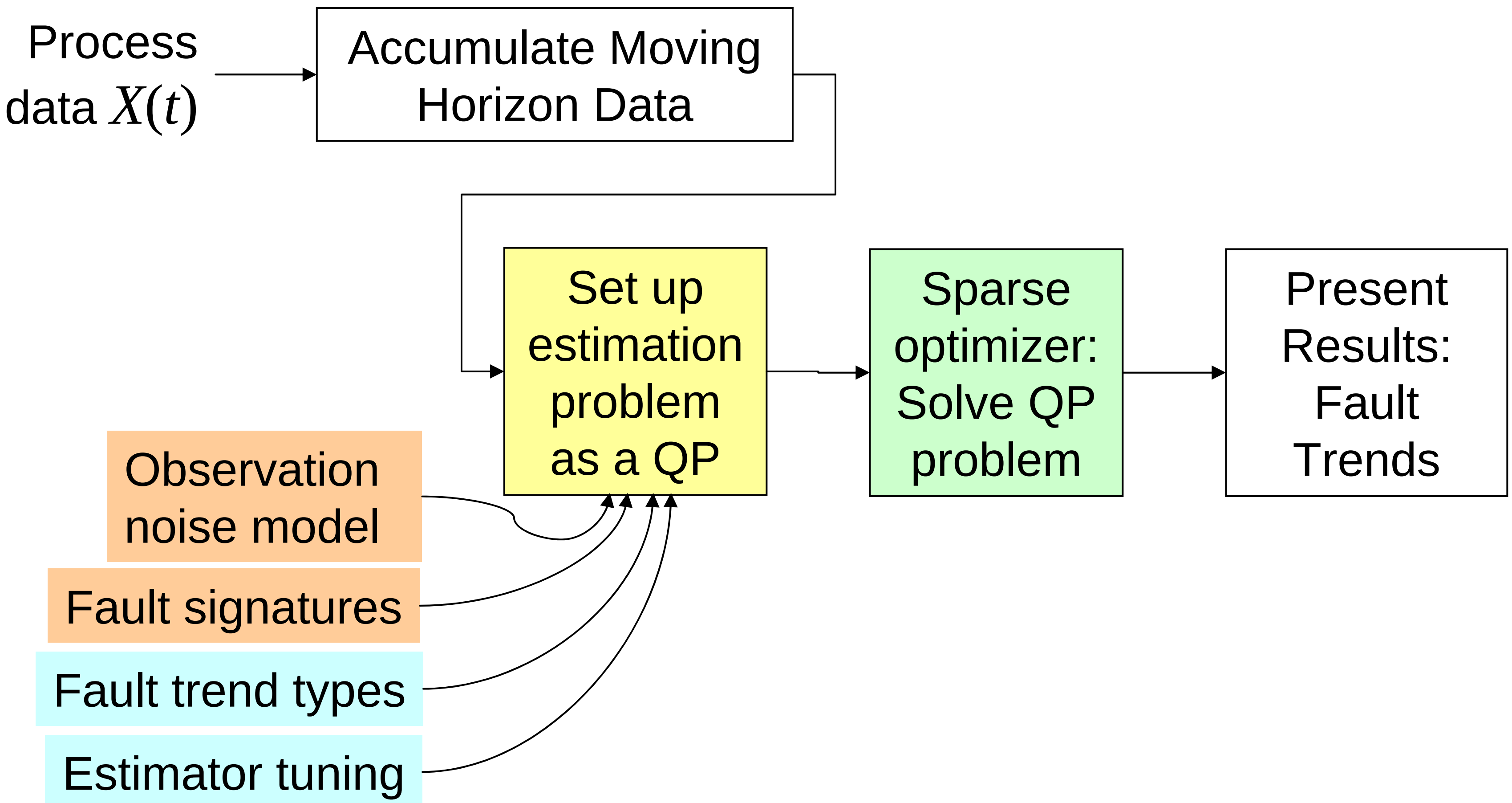
$$f_k(t+1) = f_k(t) + r_k(t) + \xi_k(t)$$

$$r_k(t+1) = r_k(t) + \eta_k(t)$$

Prior Models: Fault Types

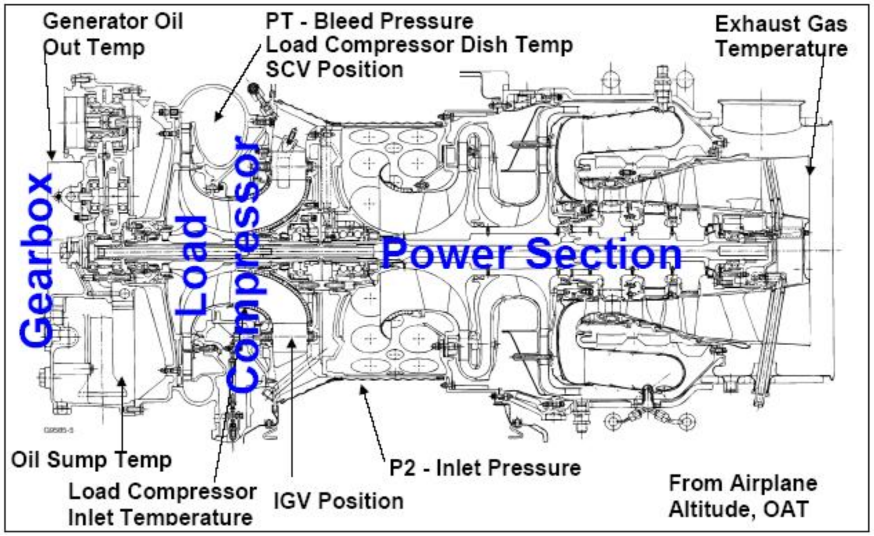
- Gaussian process noise model
  - Linear estimation (least mean squares)
- Laplacian process noise
  - Jumps (step changes) in the trend
- Exponential process noise
  - Irreversible deterioration
- Additional constraints
  - Positivity, upper bound

Estimation for FDC



Technology Applications

- Aircraft turbines
  - Deployed for a fleet



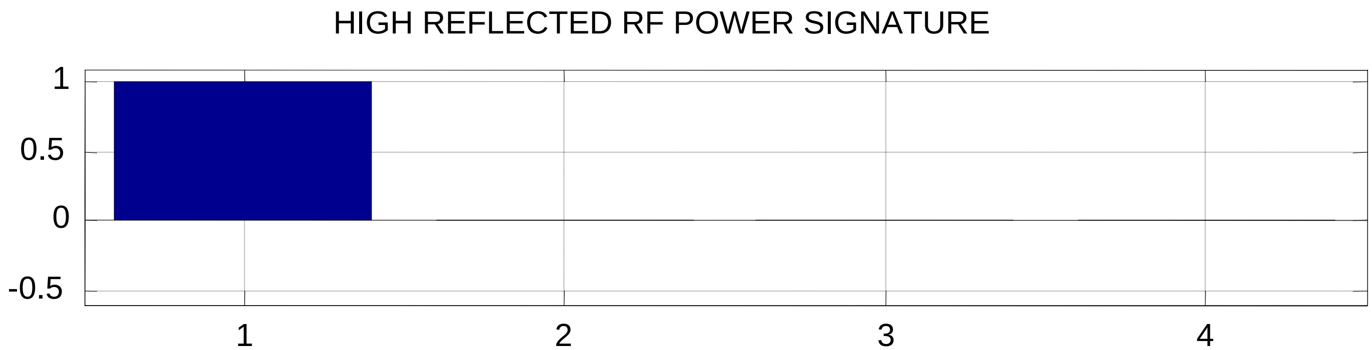
From IEEE CCA'02,'04

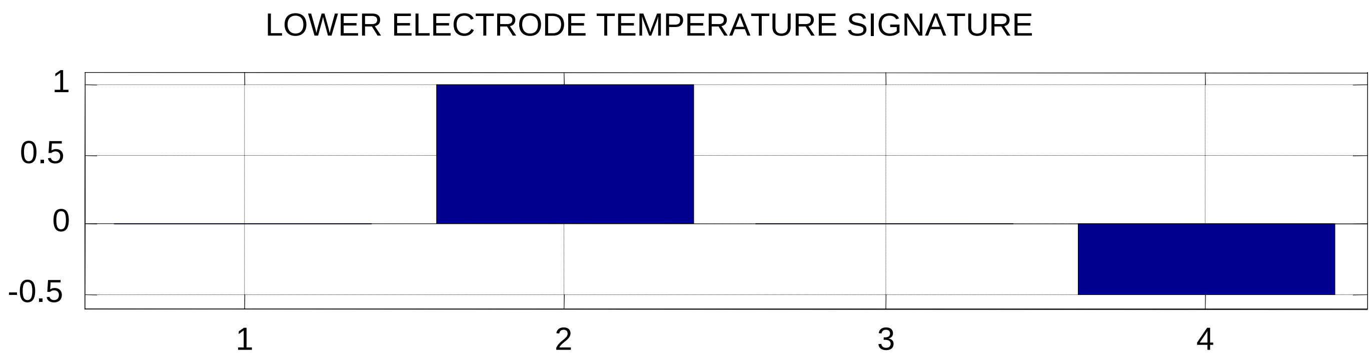
- NASA

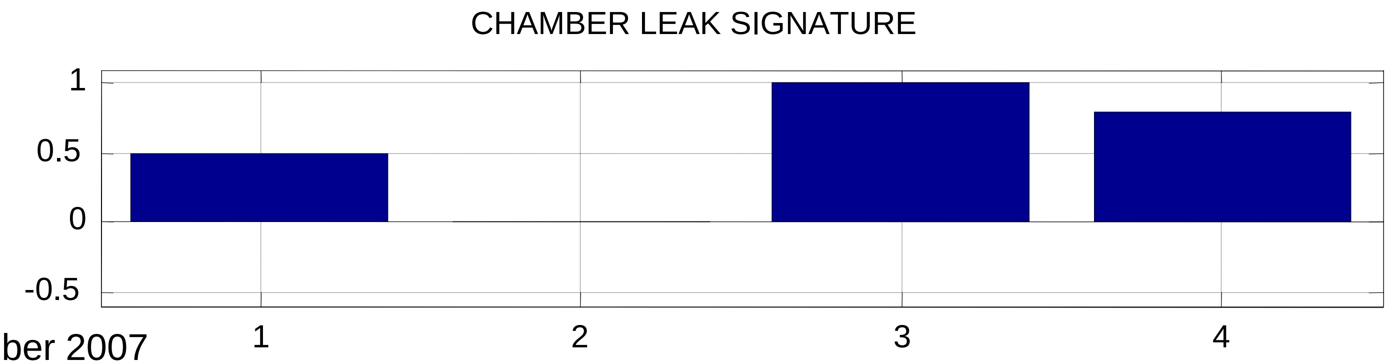
Etch Process Example

- Observed variables
  - RF Reflected Upper
  - Lower electrode cooling water temperature
  - Pressure control valve
  - Endpoint detector
- Faults
  - High reflected RF power
  - Drift in the lower electrode temperature
  - Chamber leak

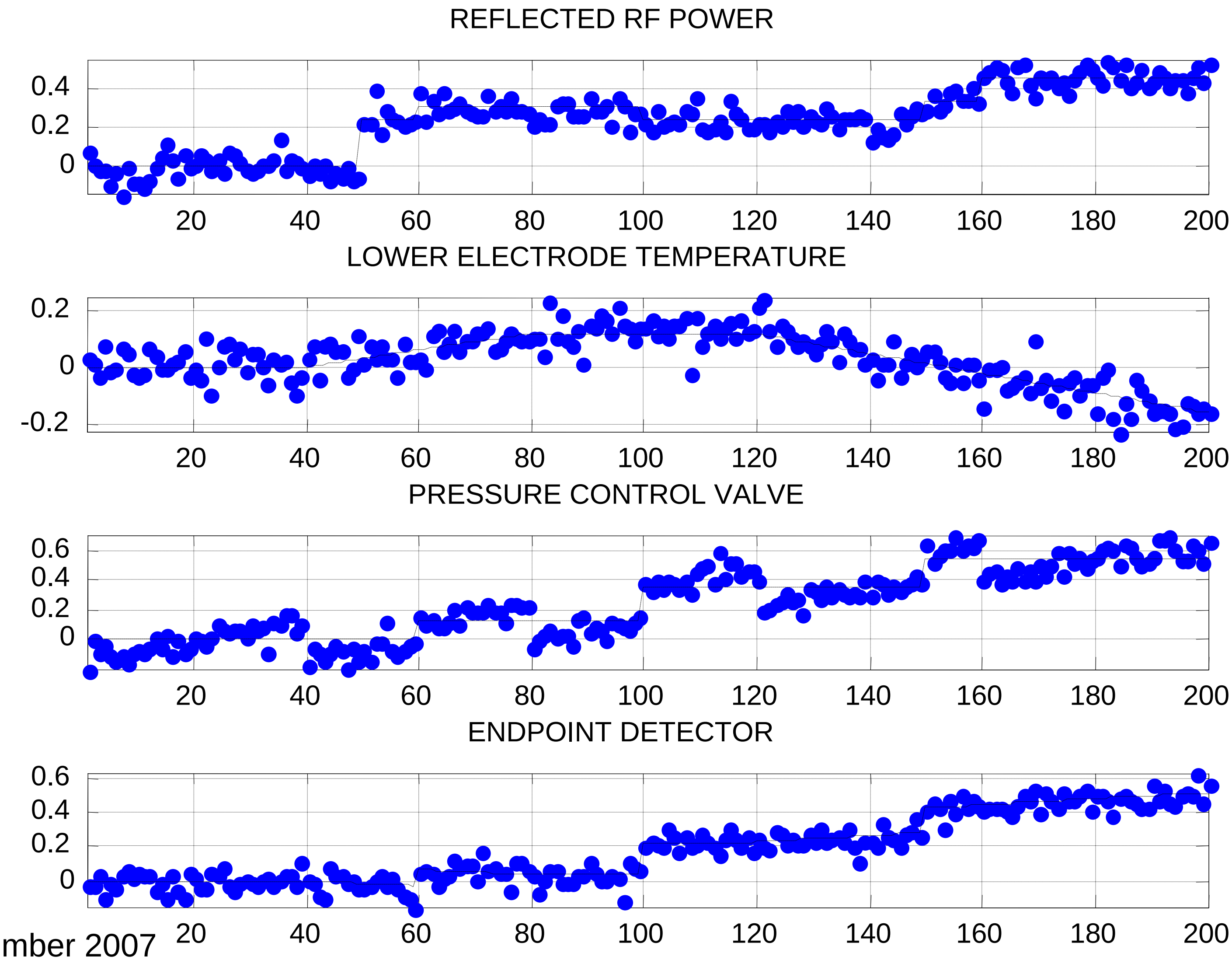
Etch Fault Signatures



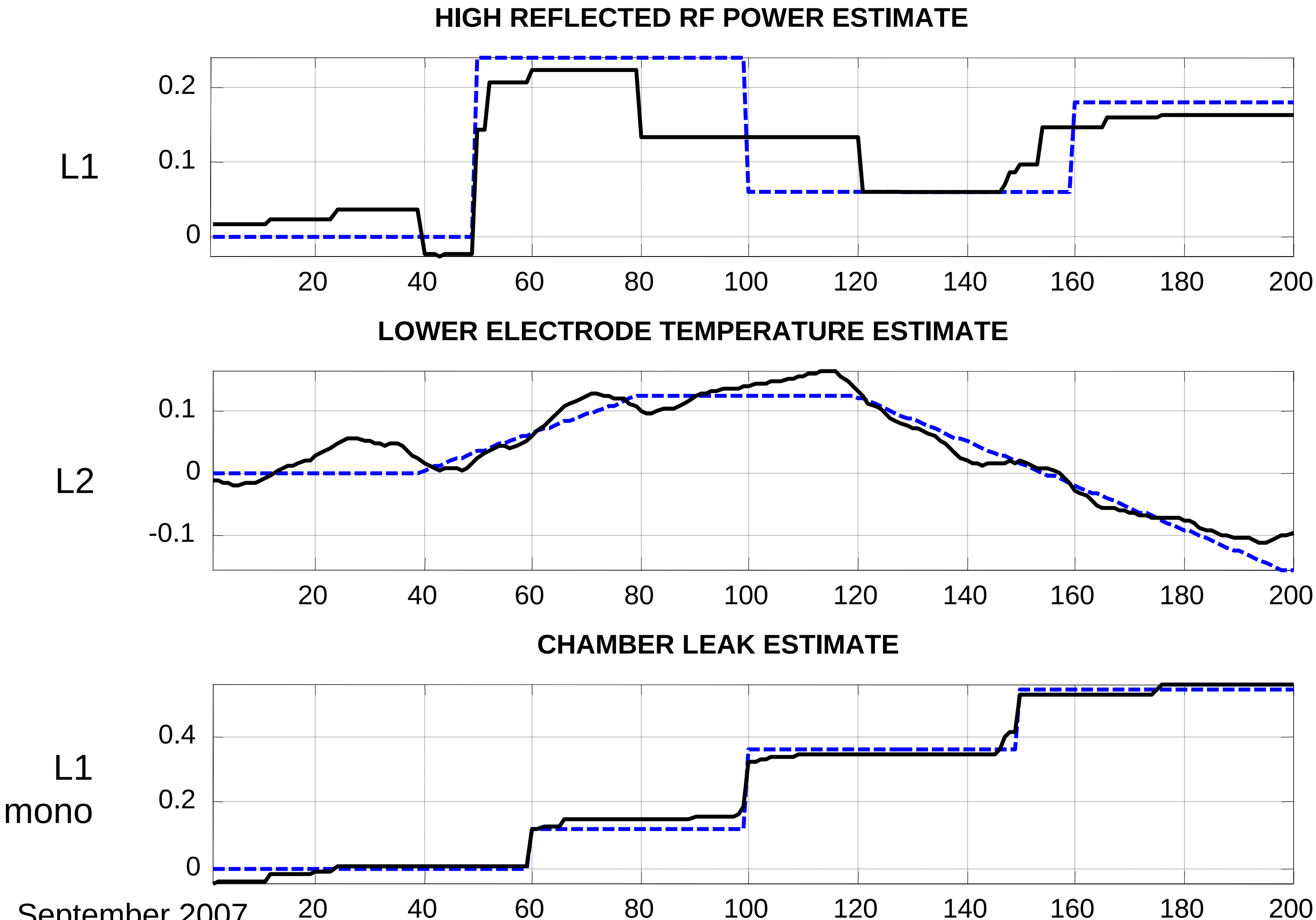




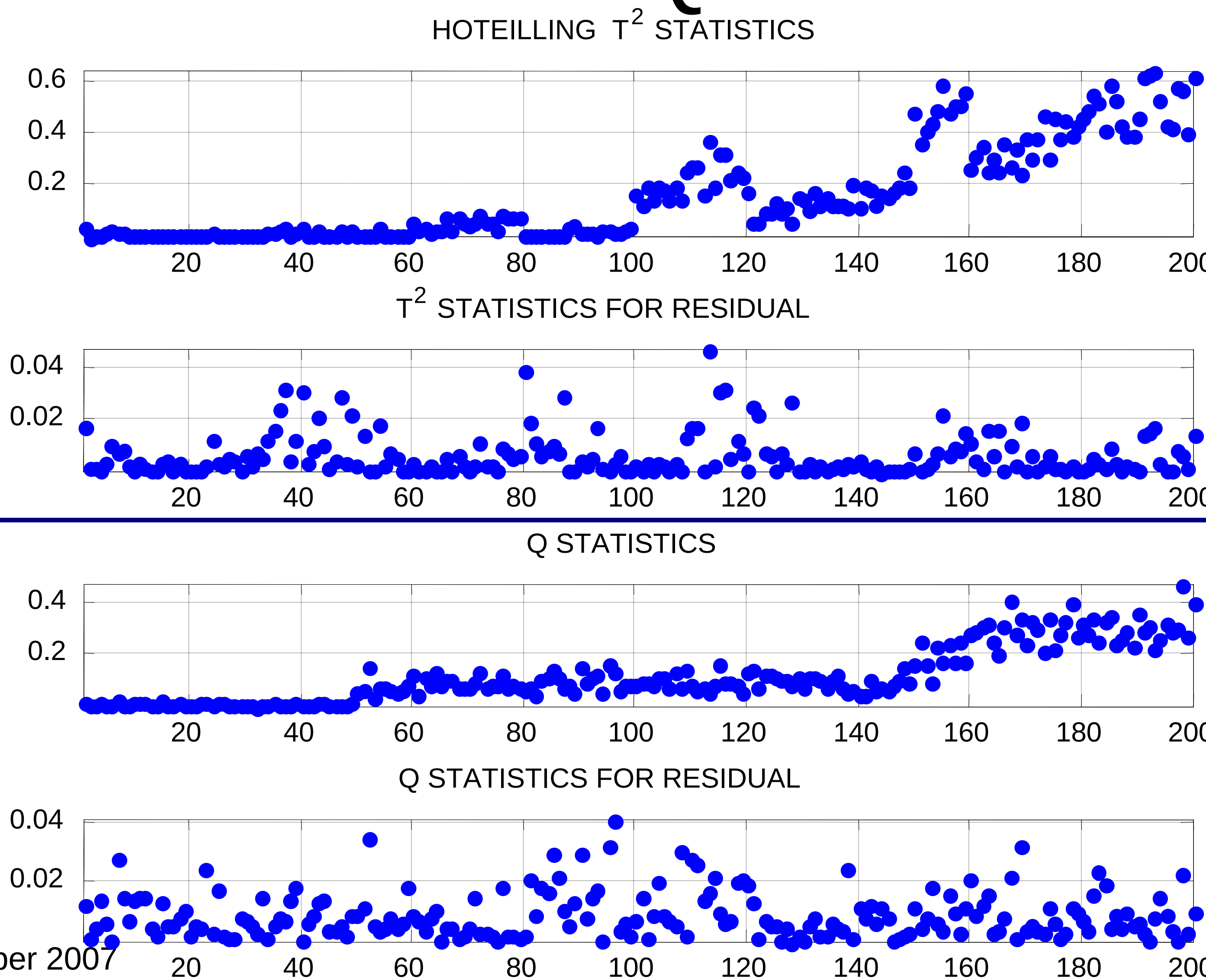
Etch Simulation Data



Fault Estimates



Etch T^2 and Q Statistics



T^2

Q

Conclusions

- Presented new and efficient algorithms
  - Optimal estimation of hidden trends
  - An extension of least-squares estimation
  - Based on solving QPs (standard software)
- Model-based algorithms
  - Fault signature models
  - Fault trend models (random walk, monotonic,...)
- Practical significance
  - Diagnostics, prognostics, CBM