Lawrence Livermore National Laboratory

Signal and Imaging Sciences Conference, Center for Advanced Signal and Imaging Sciences (CASIS),

Engineering Directorate

Model-Based Algorithms for Detecting Cable Damage from Time Domain Reflectometry Measurements

November 15-16, 2007

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Eng/NSED/Systems and Decision Sciences Section

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Auspices and Disclaimer

Auspices

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We Have an Interdisciplinary Team

- **Graham Thomas - ENG/MMED**
  - **Project Management**
  - **NDE, materials characterization**

- **Chris Robbins - ENG/NSED**
  - **Program Management**
  - **Data acquisition, hardware, signal processing software, NDE**

- **Grace Clark - ENG/NSED**
  - **Image/signal processing, target/pattern recognition, sensor data fusion, NDE**

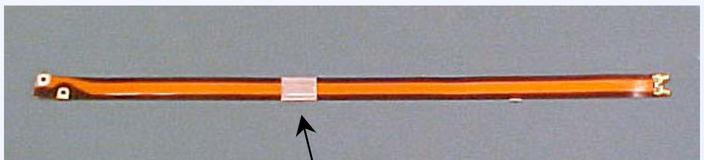
- **Katherine Wade - ENG/NSED**
  - **Signal processing software and testing**

Agenda

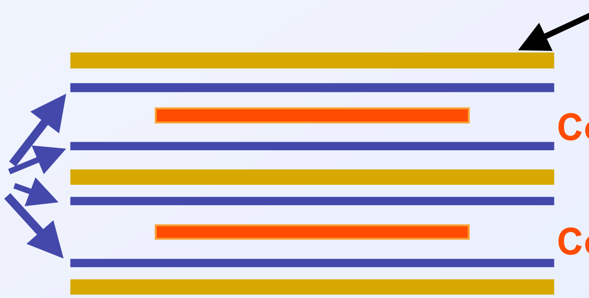
- **Introduction**
  - **- The Cable Damage Detection Problem**
  - **- This is work in progress**
- **Technical Approach -** ***Model-Based Damage Detection***
- **Damage Detection Processing Results**
  - **- Real Measurements, Artificial Damage** ***- Not reported here***
  - **- Real measurements, real damage**
  - **- Performance Measurements**
    - ***- ROC Curves, Confidence Intervals***
- **Discussion and Plans**

We Are Testing Two-Conductor Flat Cables With Kapton Insulation - For Dielectric Anomalies

Two-Conductor Flat Cable
With Kapton Insulation



Foil Simulating a Capacitive Discontinuity (Damage)



Kapton Dielectric

Adhesive

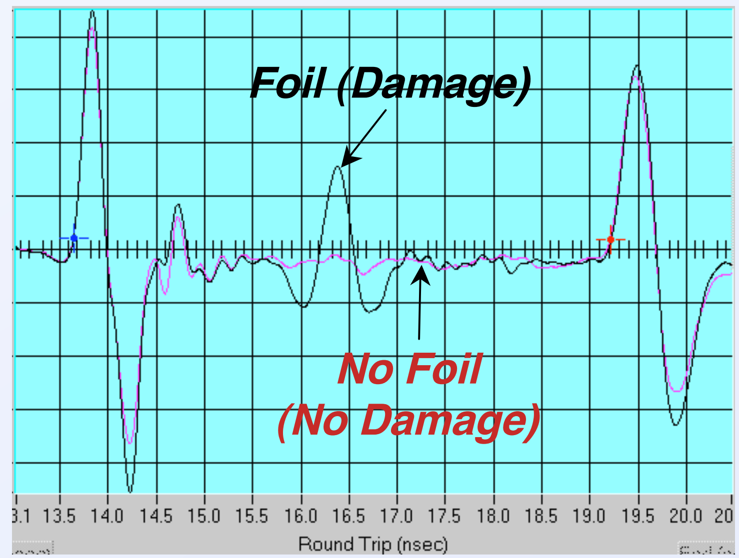
Copper foil

Kapton

Copper foil

Kapton

Red TDR Signal => Good Cable
Black TDR Signal => Damaged Cable



Expected Damage Types:

- Compressions
- Punctures
- Short Circuits
- Open Circuits

The Technical Challenges/Issues are Difficult, But We Do Not Know Yet *Exactly* How *Difficult*

- **We have access to only one end of the cable**
- **We cannot "Hi-Pot" the cables in place**
- **We have no exemplars of "real" damaged cables**
  - We must "insult" them artificially
- **We have no archive signals from the cables "As-Built"**
  - Only a "typical" signal for an undamaged cable
- **Small sample size**
  - Small number of available cables for "insulting" (~ 60)
  - Obviates using supervised learning pattern recognition algorithms
  - Makes it difficult to create ensembles for building ROC curves
- **Repeatability of Measurements** ***(A VERY IMPORTANT ISSUE)***
  - Single cable - Test to test *[Apparently solved to first order]*
  - Cable to cable *[Under current investigation - OK to first order]*
- **The signal shape changes significantly with the cable environment**
  - We are building 2D and 3D "Mockups"

The Key Hardware Component is the
Pulse Insersion Unit (PIU)

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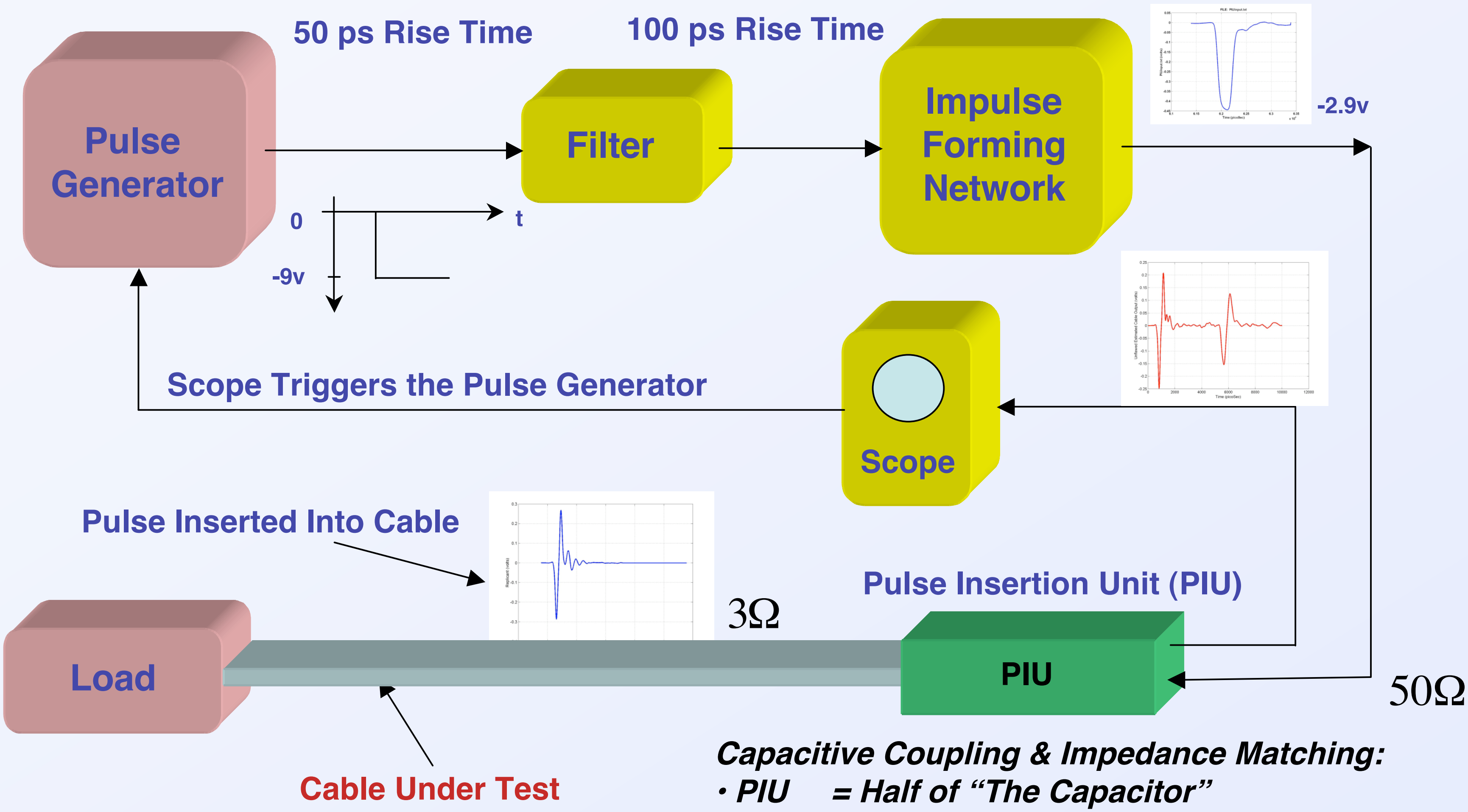

Capacitive Coupling & Impedance Matching:
- ***PIU = Half of "The Capacitor"***
- ***Cable = Half of "The Capacitor"***

Our Focus is on *a Binary Detection Decision (Yes/No),* NOT Failure Mode Classification or "Reliability"

Three Possible Hierarchical Decision Levels:

1. ***Detection:***
   - ***Decide whether or not an abnormality in the cable TDR response exists (yes or no)***
   - ***Assume that an abnormal TDR response implies a flaw in the cable***

2. ***Flaw or Failure Mode Classification:***
   - ***Classify the type of failure mode or flaw detected, from among a fixed set of possible modes***

3. ***Final Decision:***
   - ***Using all of the information from the measurements and the previous two steps (fusion), decide whether the cable is "reliable or not reliable"***

The Model-Based Damage Detection Approach: *Detect a Model Mismatch if Damage is Present*

- **Exploit the fact that the TDR measurements are reasonably repeatable.**

- **Build a forward model of the dynamic system (cable) for the case in which *NO DAMAGE* exists**

- **Whiteness Testing on the *Innovations (Errors):***
  Estimate the output of the actual system using measurements from a dynamic test.

  - If *no damage* exists, the model will match the measurements, so the "innovations" (errors) will be *statistically white*.

  - If a *damage* exists, the model will not match the measurements, so the "innovations" (errors) will *not be statistically white.*

- **Weighted Sum Square Residuals (WSSR) Test:**
  The WSSR provides a single metric for the model mismatch

Step #1: System Identification to Estimate the Dynamic Model of the *Undamaged Cable*

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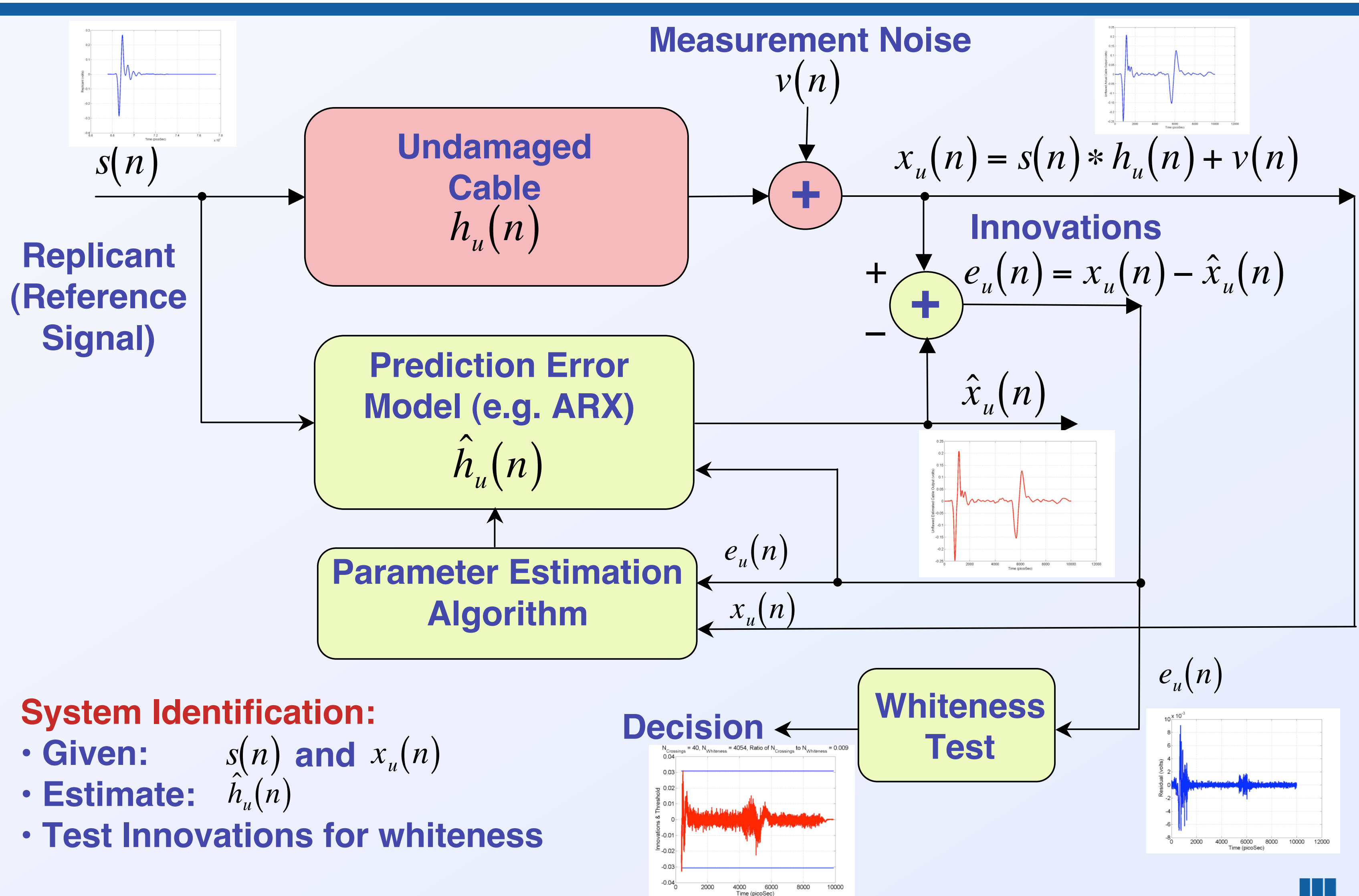
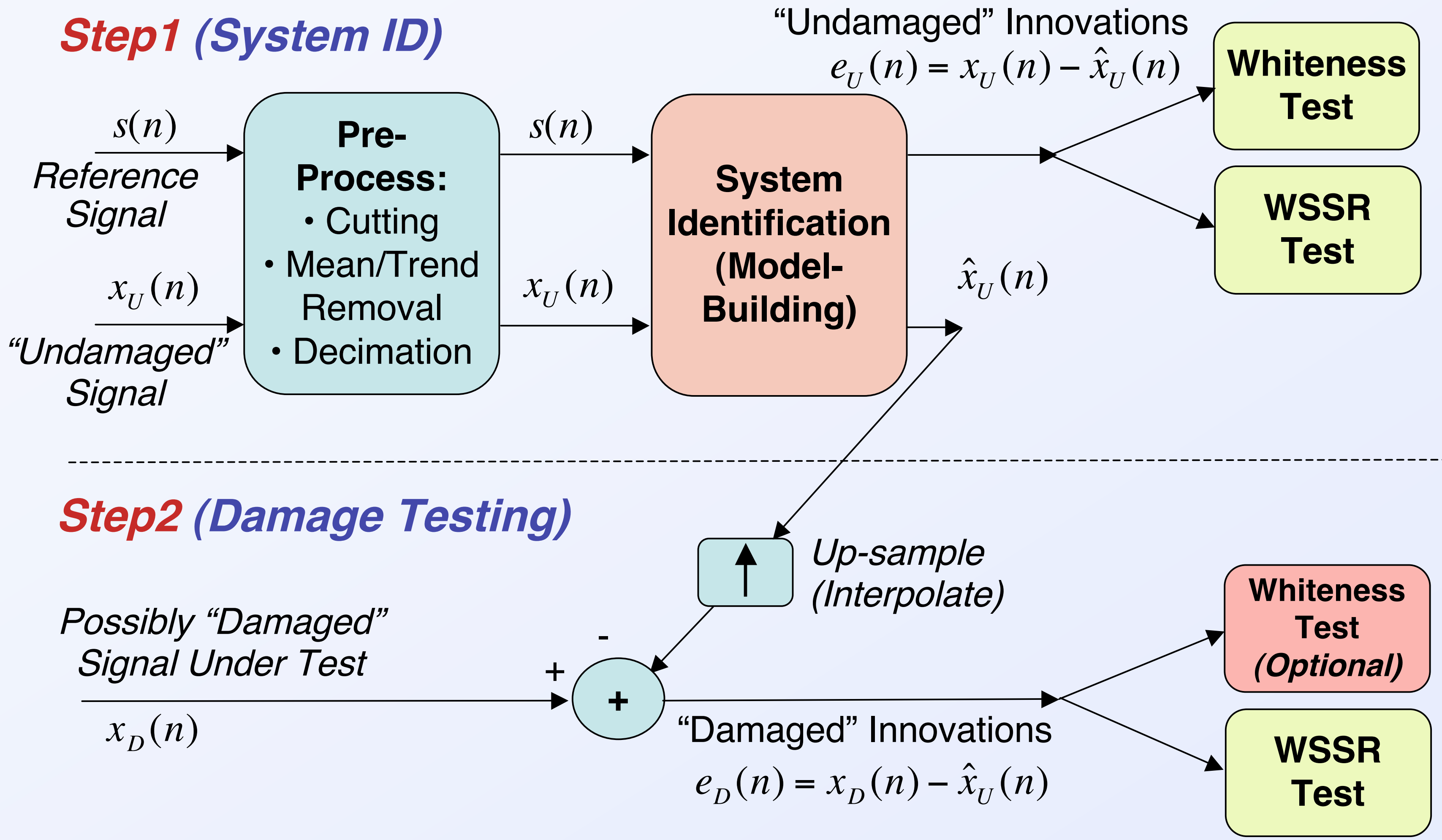


System Identification:

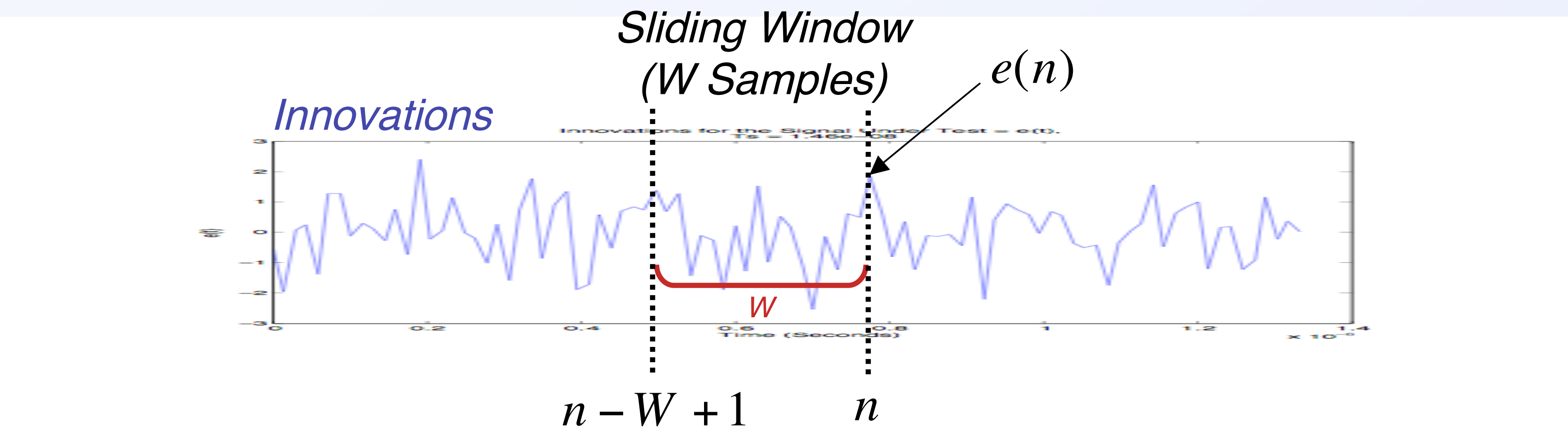
- Given: $s(n)$ and $x_u(n)$
- Estimate: $\hat{h}_u(n)$
- Test Innovations for whiteness

Step1 (System ID) is Done *"Offline"*
Step2 (Damage Testing) is Done *"Online"*



Scalar WSSR is Calculated Using a Sliding Window Over the Innovations Sequence $e(n)$

WSSR = "Weighted Sum Squared Residuals"



$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \quad \text{for } n \geq W$$

WSSR is a useful test statistic for detecting an abrupt change, or "jump" in the innovations

The Scalar WSSR Confidence Interval Threshold is Parameterized by *the Window Length W*

Summary of the WSSR Test for Significance $\alpha = .05$:

$$\gamma(n) = \sum_{j=n-W+1}^{n} \frac{e^2(j)}{V(j)}, \quad \text{for } n \geq W$$

$$V(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} \left[e^2(j) - \bar{e}(j)\right]^2, \quad \text{for } n \geq W$$

$$\bar{e}(n) = \frac{1}{W} \sum_{j=n-W+1}^{n} e(j), \quad \text{for } n \geq W$$

$$\tau = W + 1.96\sqrt{2W}$$

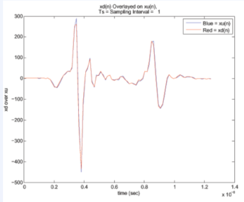
$$\text{If } \gamma(n) \underset{< H_0}{\overset{\geq H_1}{}} \tau, \quad (\tau = \text{Decision Threshold})$$

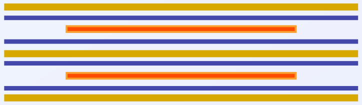
In practice, we implement the WSSR test as follows:

- Let F_E = Fraction of samples of $\gamma(n)$ that exceed the threshold
- If $F_E \leq \alpha$, Declare H_0 is true (innovations are white, no jump)
- If $F_E > \alpha$, Declare H_1 is true (innovations are not white, jump)

We Acquired an Ensemble of Real Signals for Processing

The PIU was never disconnected between acquisitions   ***Experiment E1: Data from 2_13_07***

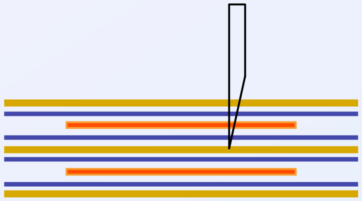




UNDAMAGED

Reference Signals *(Undamaged):*

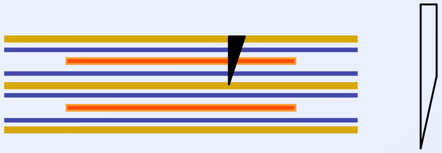
refa, refb, refc



MINOR DAMAGE

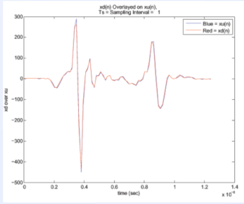
Minor Damage *(pin hole, knife present, no short):*

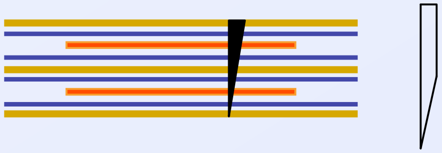
minor1a, minor1b, minor1c



Minor Damage *(pin hole, knife removed, no short):*

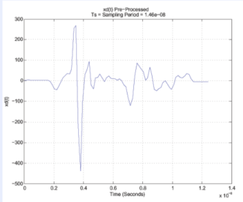
minor2a, minor2b, minor2c

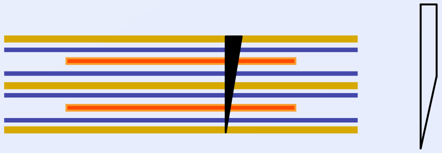




Minor Damage *(pin hole, knife removed, cable rubbed to remove short):*

minor3a, minor3b, minor3c





MAJOR DAMAGE

Major Damage *(pin hole, knife removed, conductors shorted):*

major1a, major1b, major1c

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Experiment 1: System Identification Results

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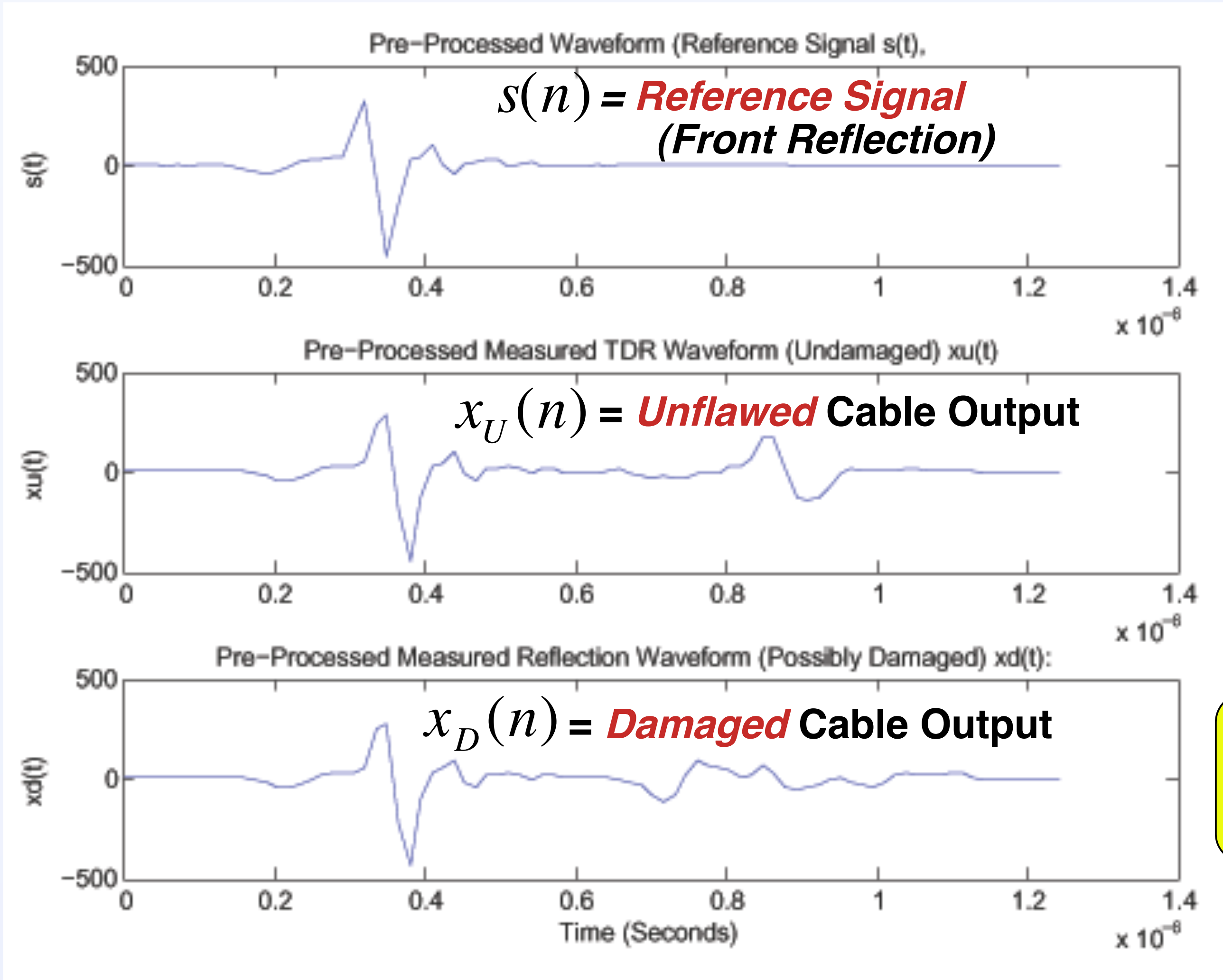
E1_s_xu_xdC.pdf

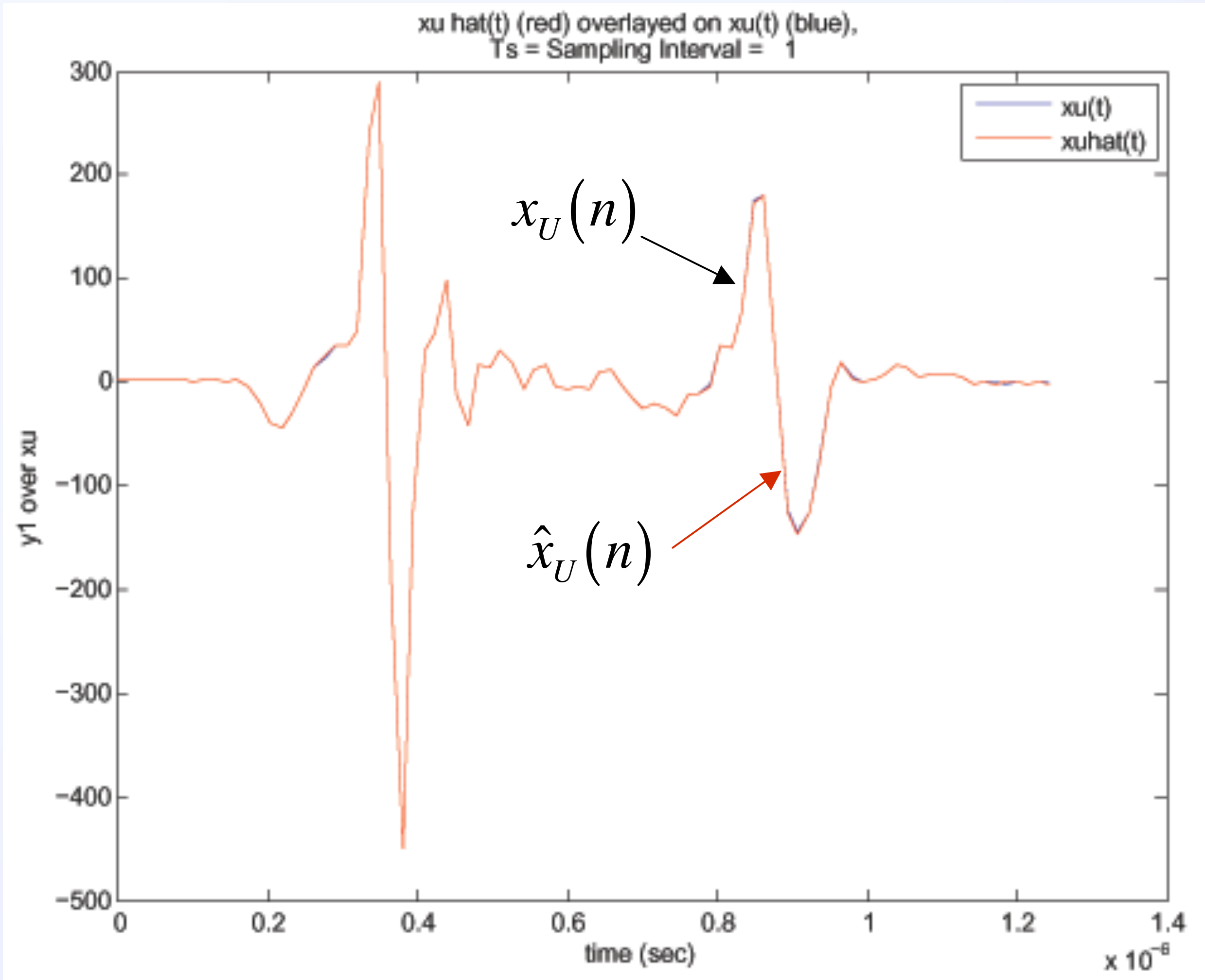
System Identification: Preprocessed Signals



Example: Major Damage

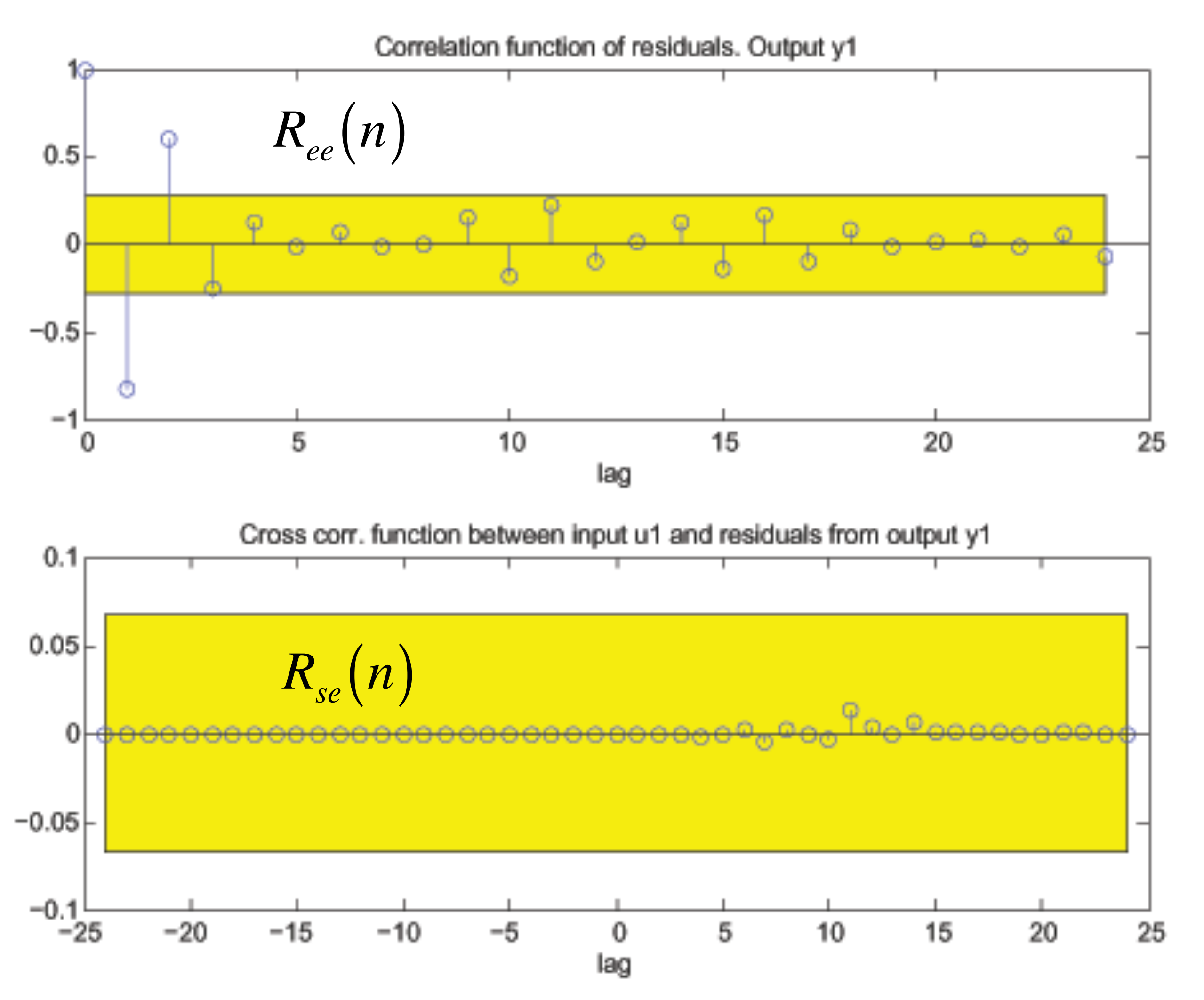
E1_xuhat_xuC.pdf

System Identification: *The Model Fit is Good*



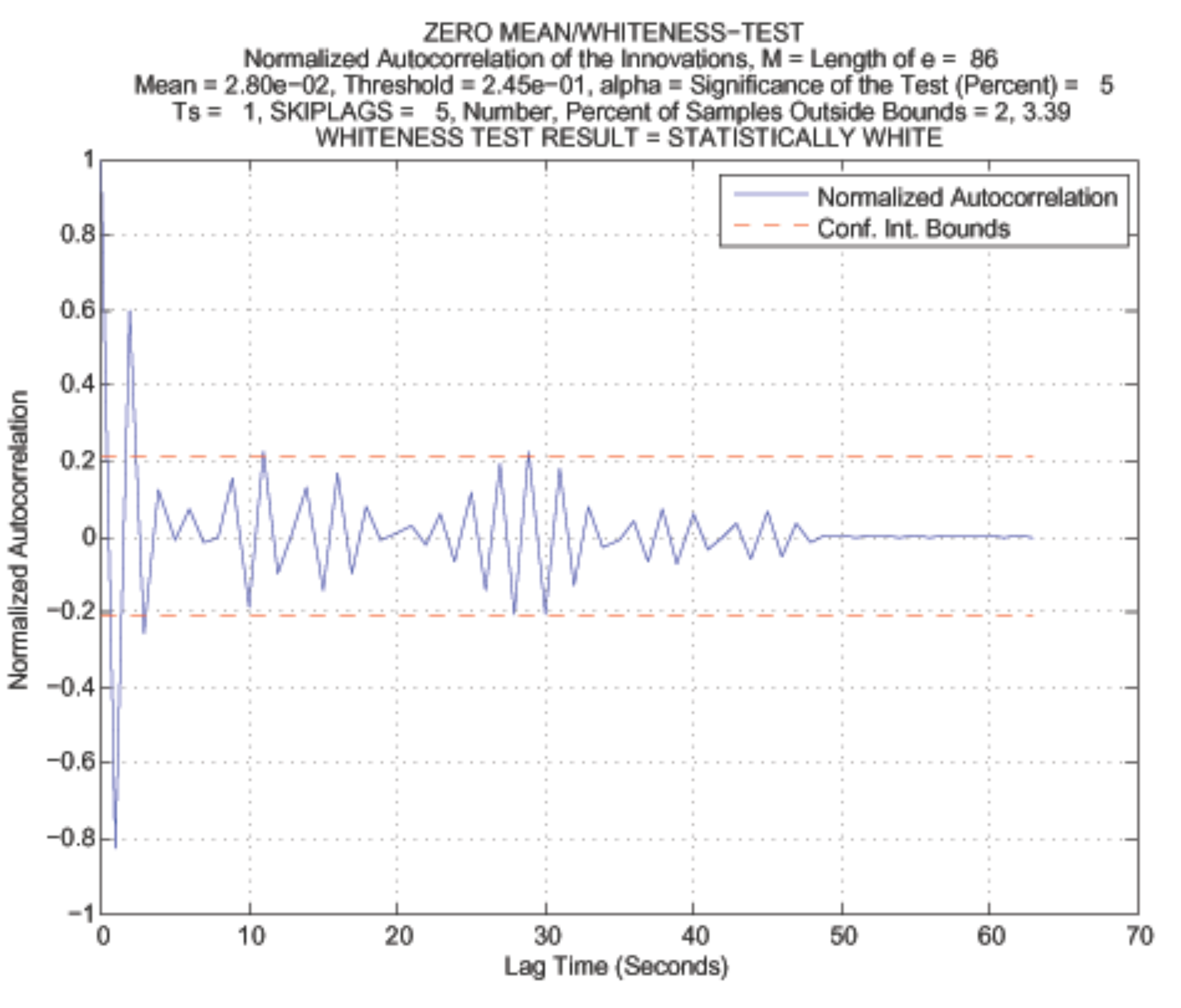
E1_Ree_Rxy1C.pdf

System Identification: *Correlation Tests are Satisfactory*



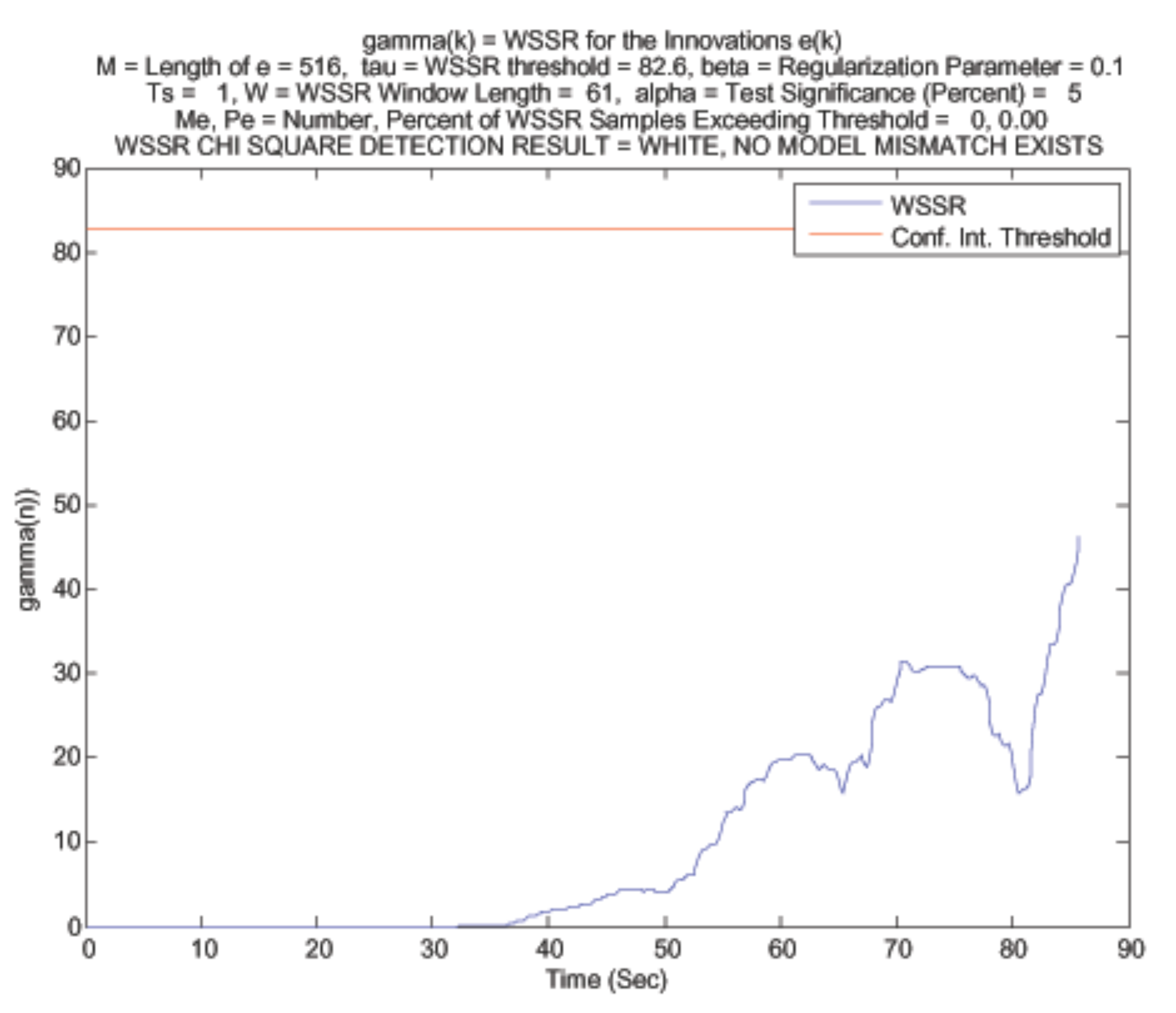
E1_WT_euC.pdf

System Identification Whiteness Test Result = ***White***



E1_WSSR_eu(61)C.pdf

System Identification WSSR Test Result = *No Model Mismatch!*



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Experiment 1:
"Minor3" Damage

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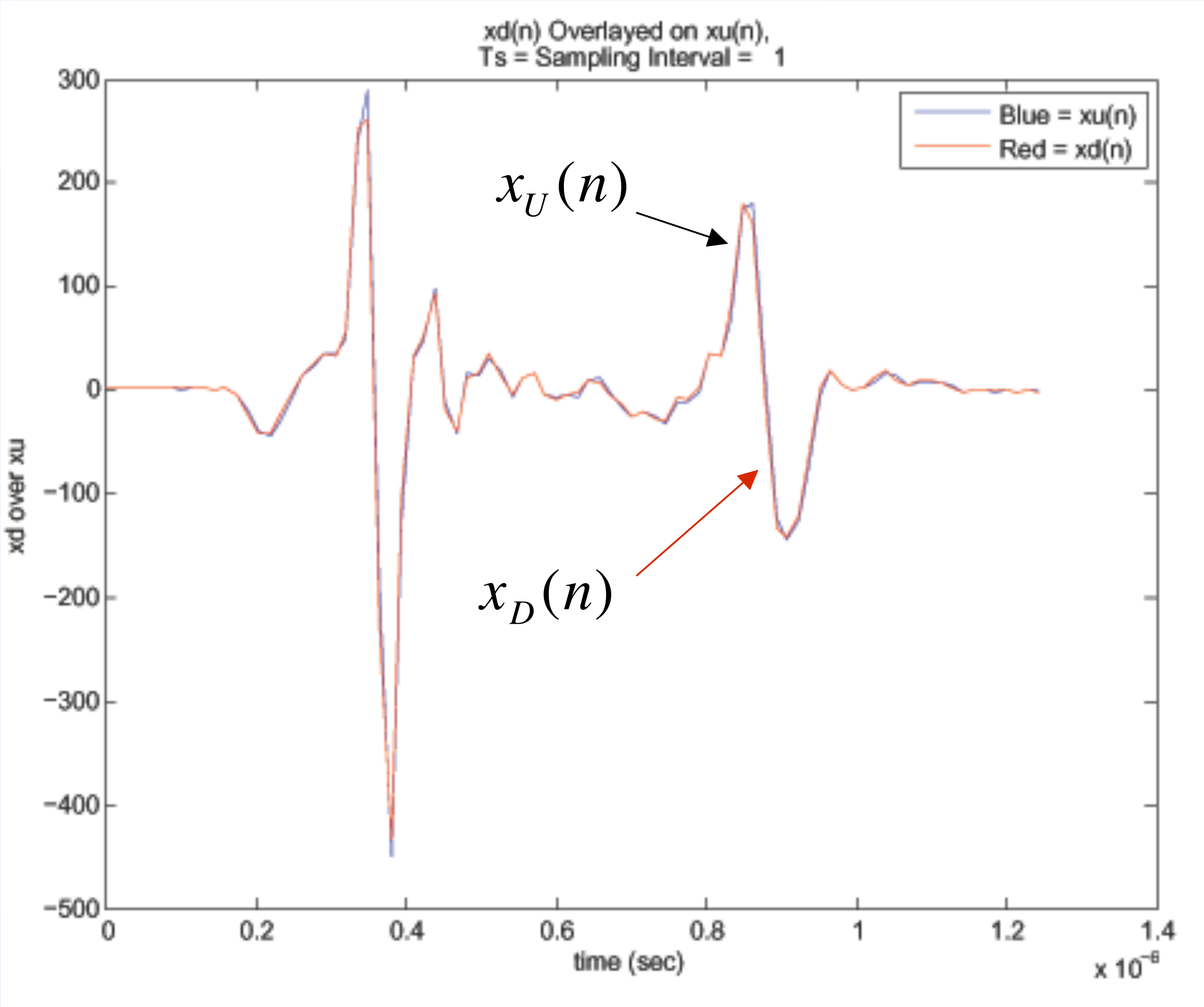
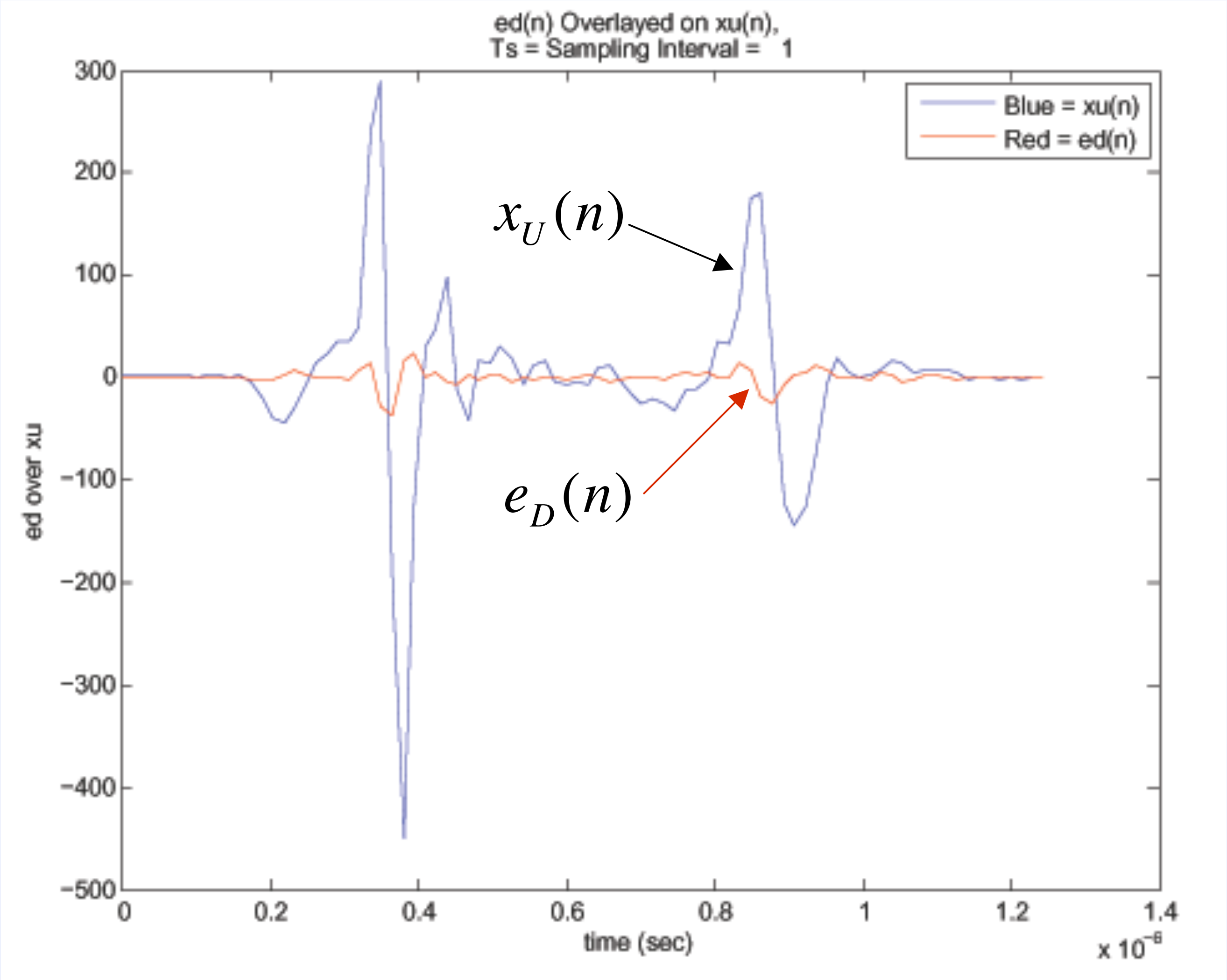
E1_xd_m3a_xuC.pdf

"Minor3 Damage": *Damage Is Difficult to Distinguish Visually*



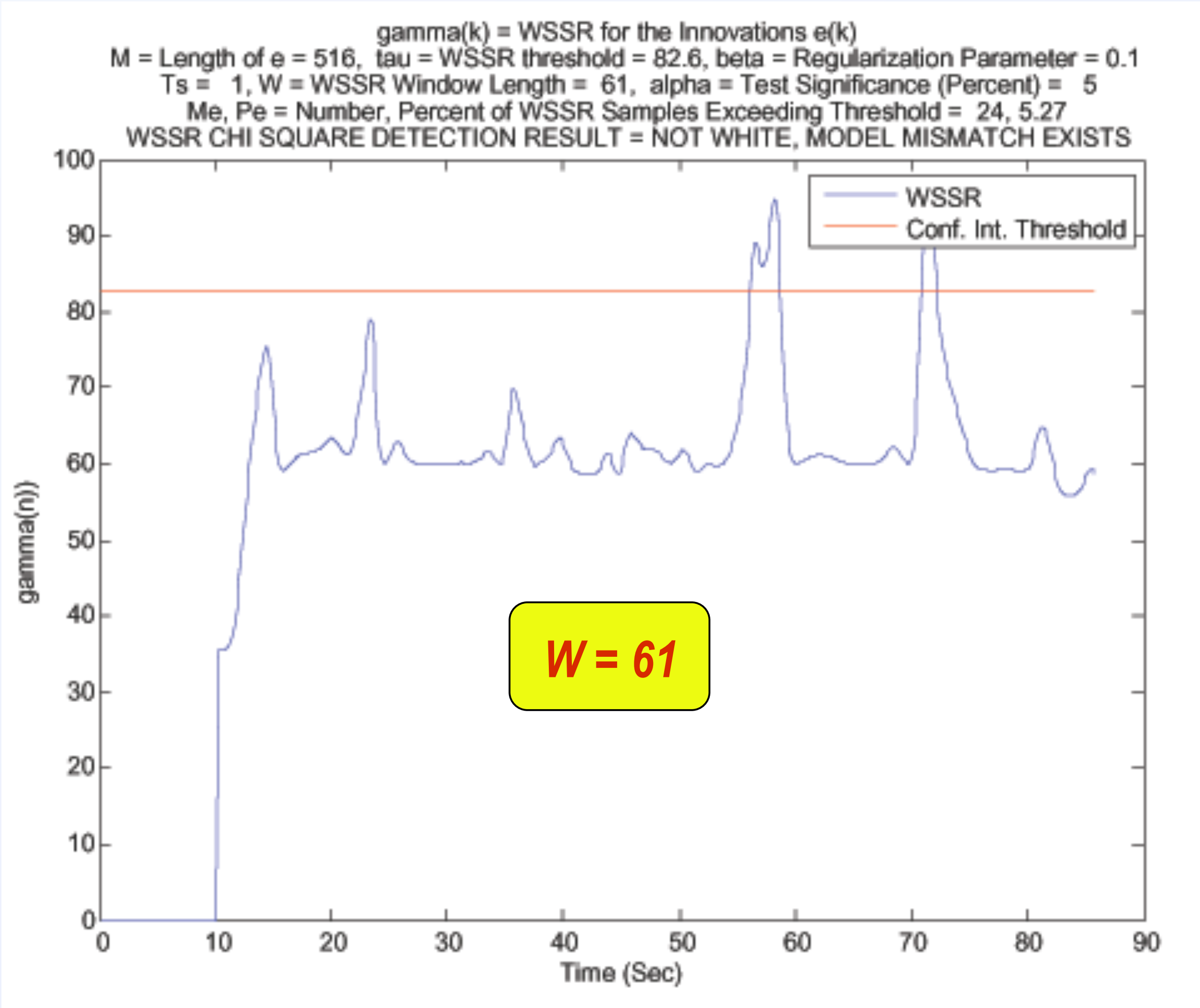
E1_ed_m3a_xuC.pdf

Minor3 Damage: *The Innovations are Small, But Correlated*



E1_WSSR_ed_m3a_(61)C.pdf

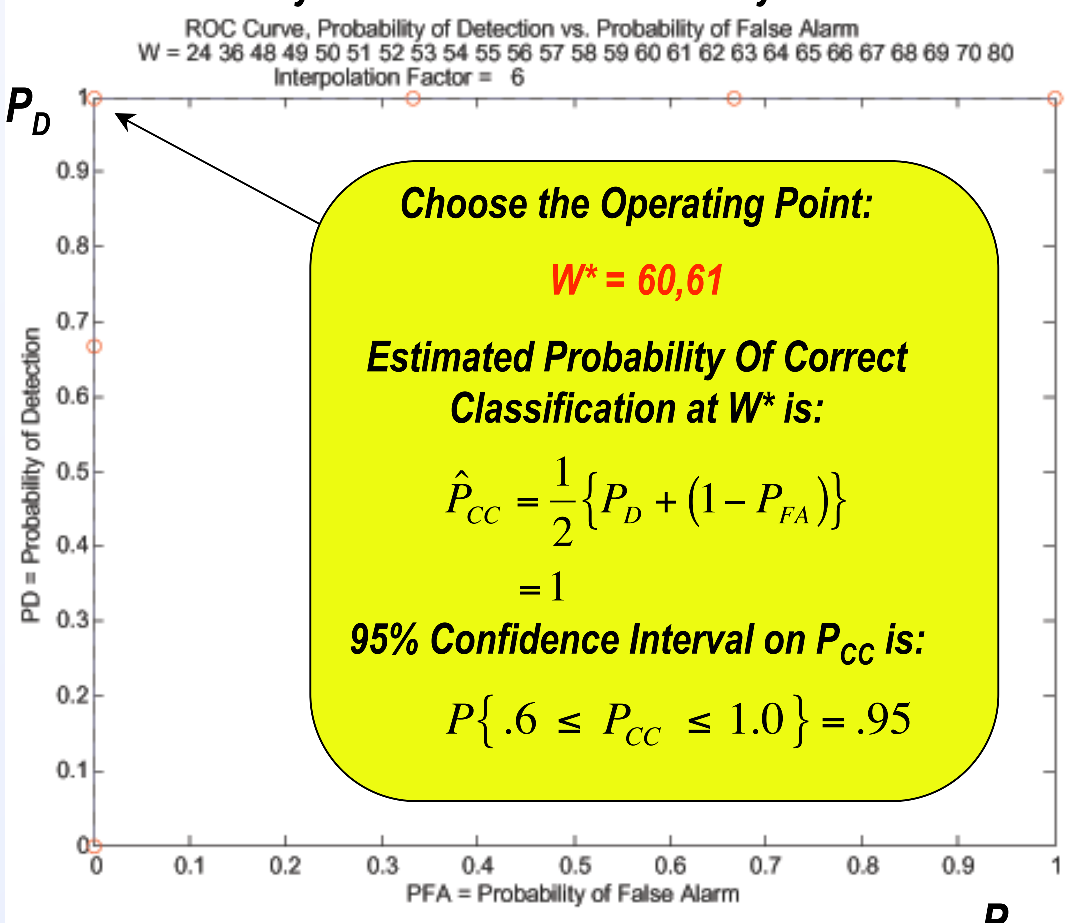
"Minor3 Damage" WSSR Result = *Model Mismatch!*



Minor3a,b,c Damage
Receiver Operating Characteristic (ROC) Curve = Perfect

W	P_{FA}	P_D
24	1	1
36	0.66667	1
48	0.66667	1
49	0.66667	1
50	0.66667	1
51	0.66667	1
52	0.66667	1
53	0.66667	1
54	0.66667	1
55	0.66667	1
56	0.33333	1
57	0.33333	1
58	0.33333	1
59	0.33333	1
60	0	1
61	0	1
62	0	0.66667
70	0	0
80	0	0

Probability of Detection vs. Probability of False Alarm



Choose the Operating Point:

W* = 60,61

Estimated Probability Of Correct Classification at W* is:

$$\hat{P}_{CC} = \frac{1}{2}\left\{P_D + \left(1 - P_{FA}\right)\right\}$$
$$= 1$$

95% Confidence Interval on P_{CC} is:

$$P\left\{.6 \leq P_{CC} \leq 1.0\right\} = .95$$

Conclusions & Future Work

- **The damage effects are somewhat distributed about the signal**
  - They are not necessarily localized in time/space
  - This gives *added value* to the model-based approach because it does not rely on localized damage effects

- **Tests with real data validate the algorithms**
  - ***"Minor3" and "Major" Damage* give perfect ROC curves**
  - ***"Minor1" and "Minor2"* Damage give suboptimal ROC Curves**

Future Work:

- **Performance Tests using our *new Pulse Insertion Unit (PIU)***
- **More repeatability studies:**
  - **Measurement-to-measurement for one cable**
  - **Cable-to-cable**
- **Cable "Insult Studies" with various types of damage**
- **Experiments in realistic cable environments *- 2D Mockup, 3D Mockup***
- **Build and test GUI's**
- **Use algorithms with other applications**

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Contingency VG's

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Step #2: Compare the Responses of the Undamaged and Damaged Cables ==> *Damage Detection*

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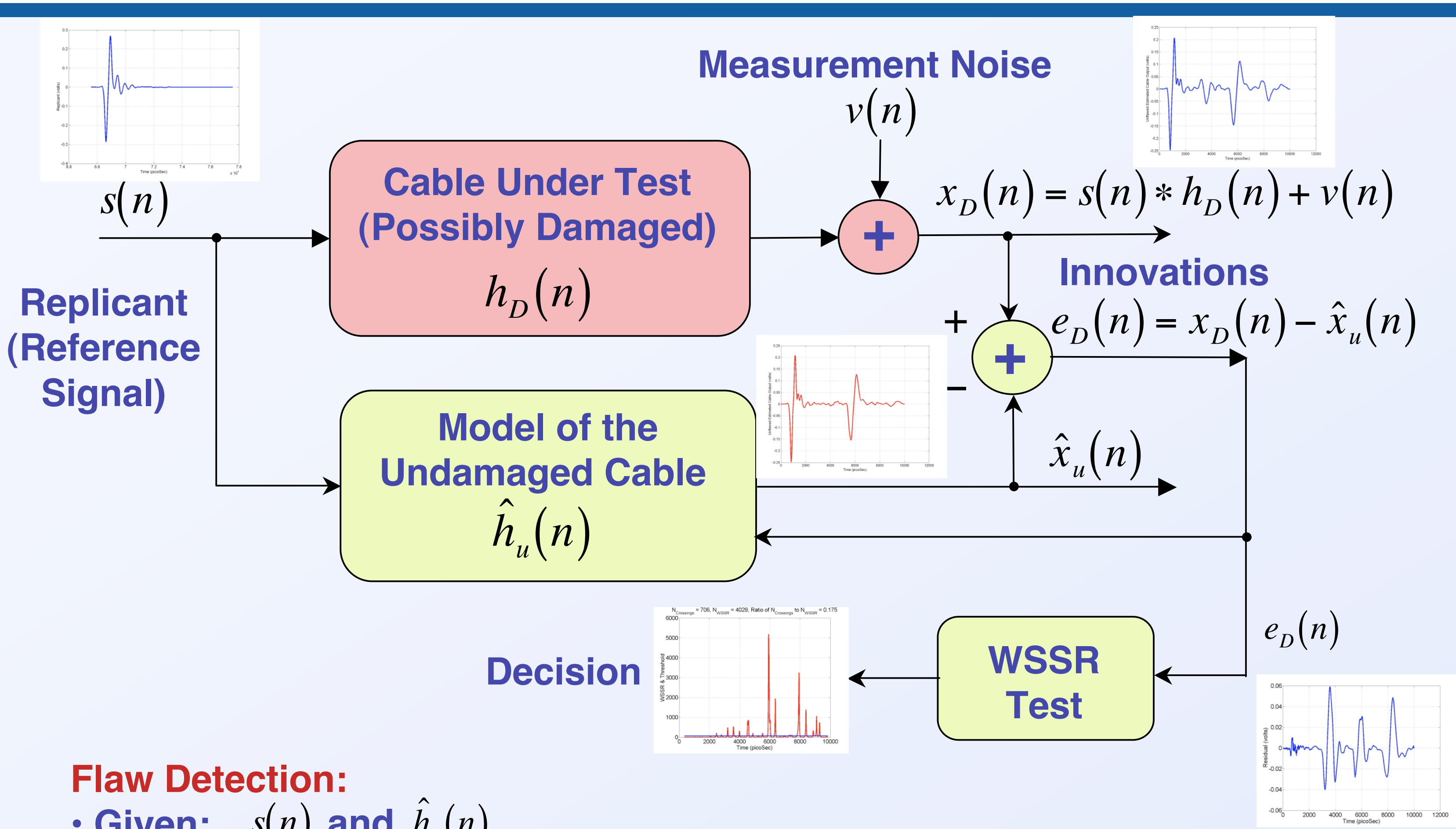
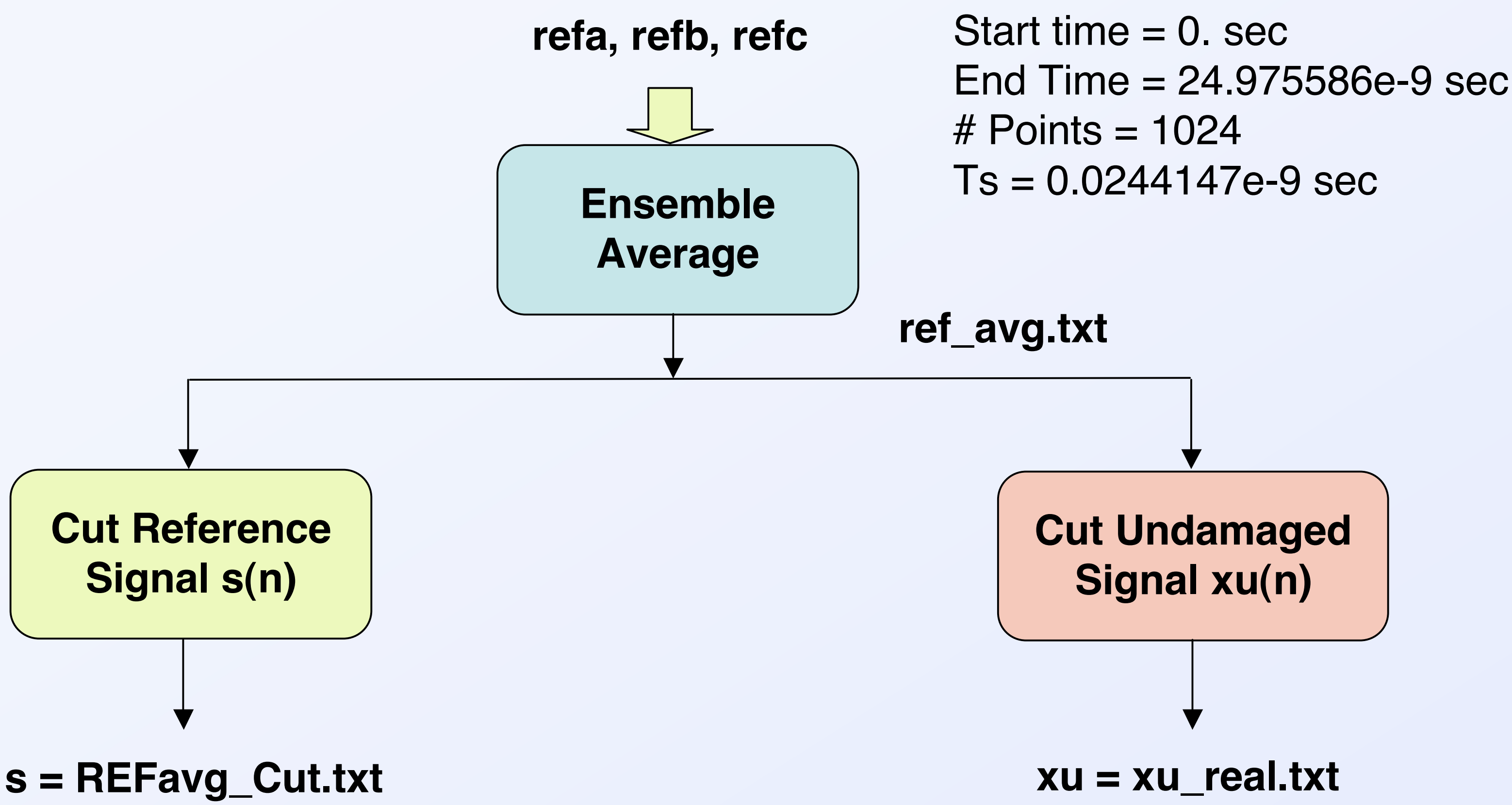


Flaw Detection:

- **Given:** $s(n)$ **and** $\hat{h}_u(n)$
- **Detect flaws by testing the innovations (nonstationary) for whiteness using WSSR (Weighted Sum Squared Residuals) over a moving window**

E1: “Undamaged”Signals Were Cut for
Step1: System Identification



The "Damage Signals" Were Cut for
Step1: Damage Testing

Suboptimal Detection Results for Minor1 and Minor2 Damage

Perfect Detection Results for Minor3 and Major Damage

Minor1a-c	Minor2a-c	Minor3a-c	Major1a-c
Cut	Cut	Cut	Cut
xd_m1a.txt	xd_m2a.txt	xd_m3a.txt	xd_MM1a.txt
xd_m1b.txt	xd_m2b.txt	xd_m3b.txt	xd_MM1b.txt
xd_m1c.txt	xd_m2c.txt	xd_m3c.txt	xd_MM1c.txt

Processing Details for the Signals in Red are shown in this presentation

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Experiment 1:
Major Damage

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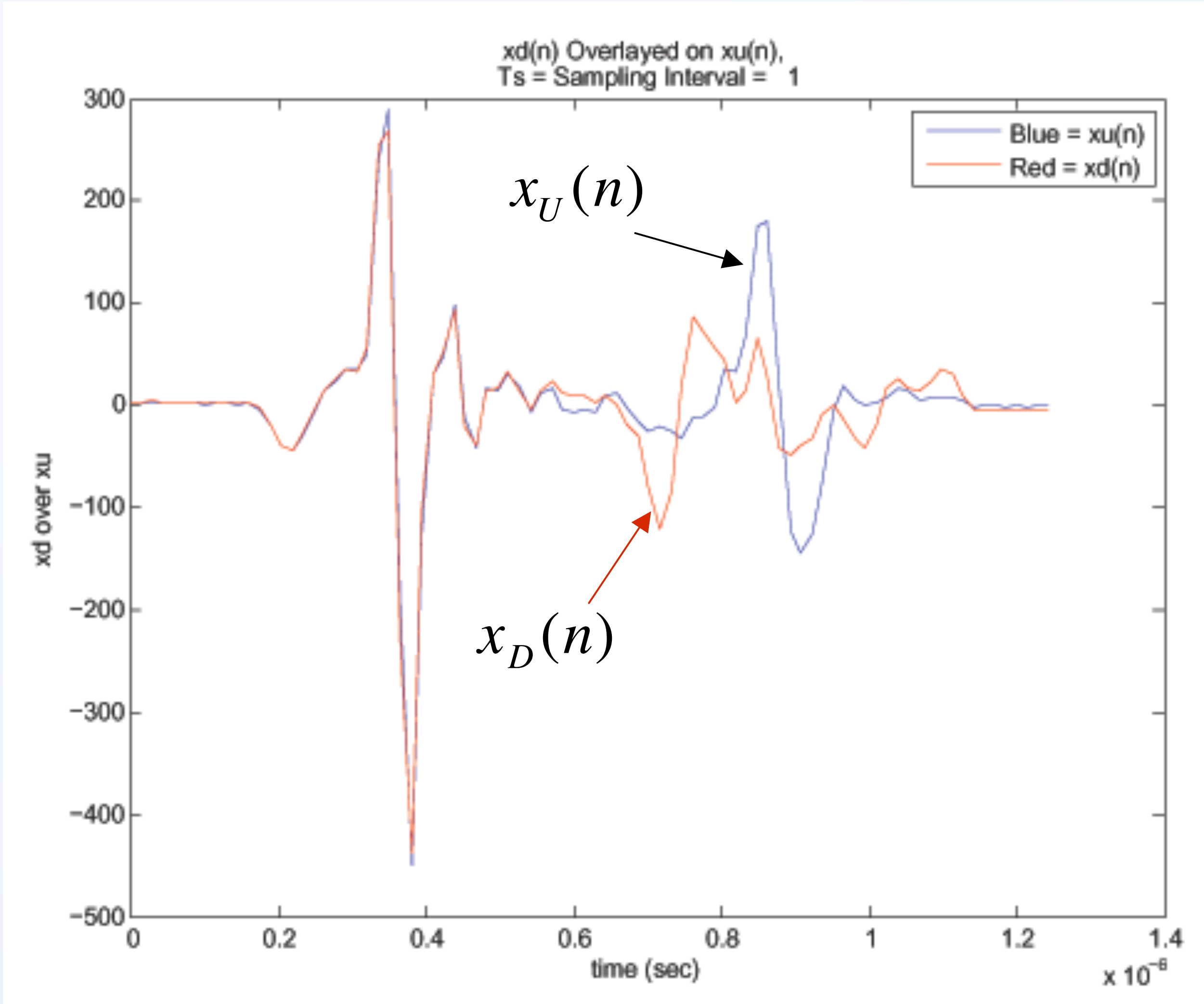
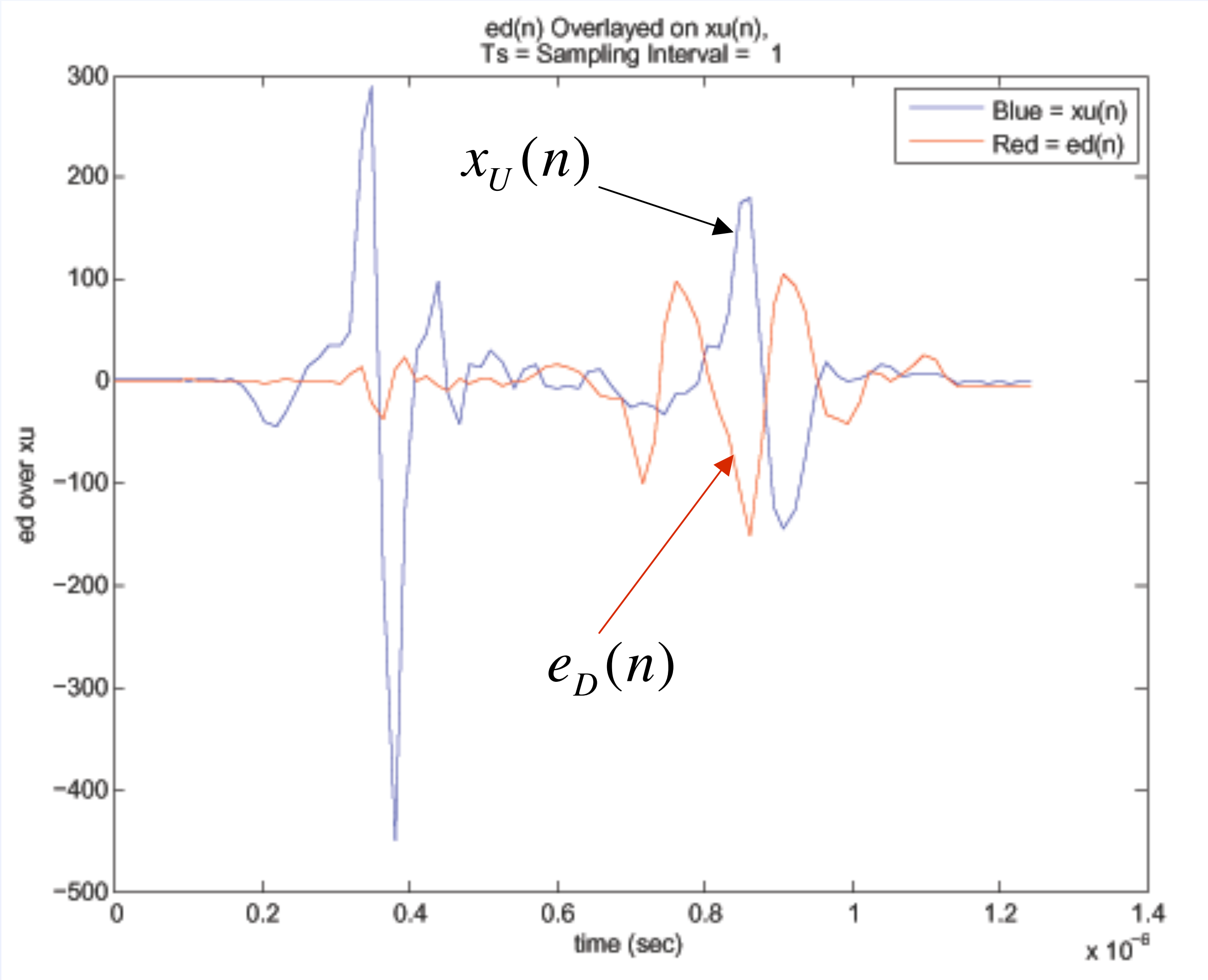
E1_xd_MM1a_xuC.pdf

"Major Damage" Signal *Shows Obvious Damage*

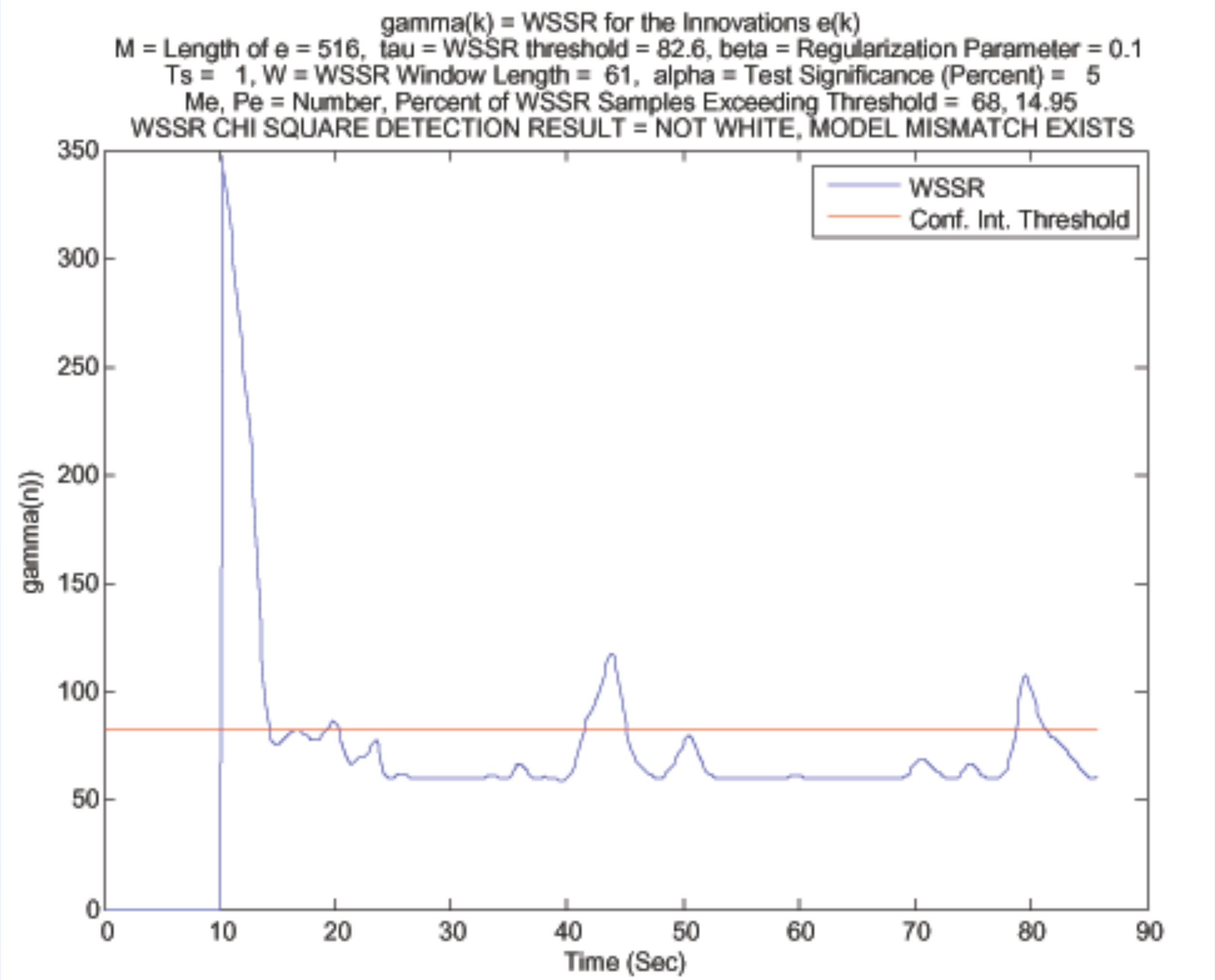


E1_ed_MM1a_xu.pdf

"Major Damage" Innovations *Are Large and Correlated*



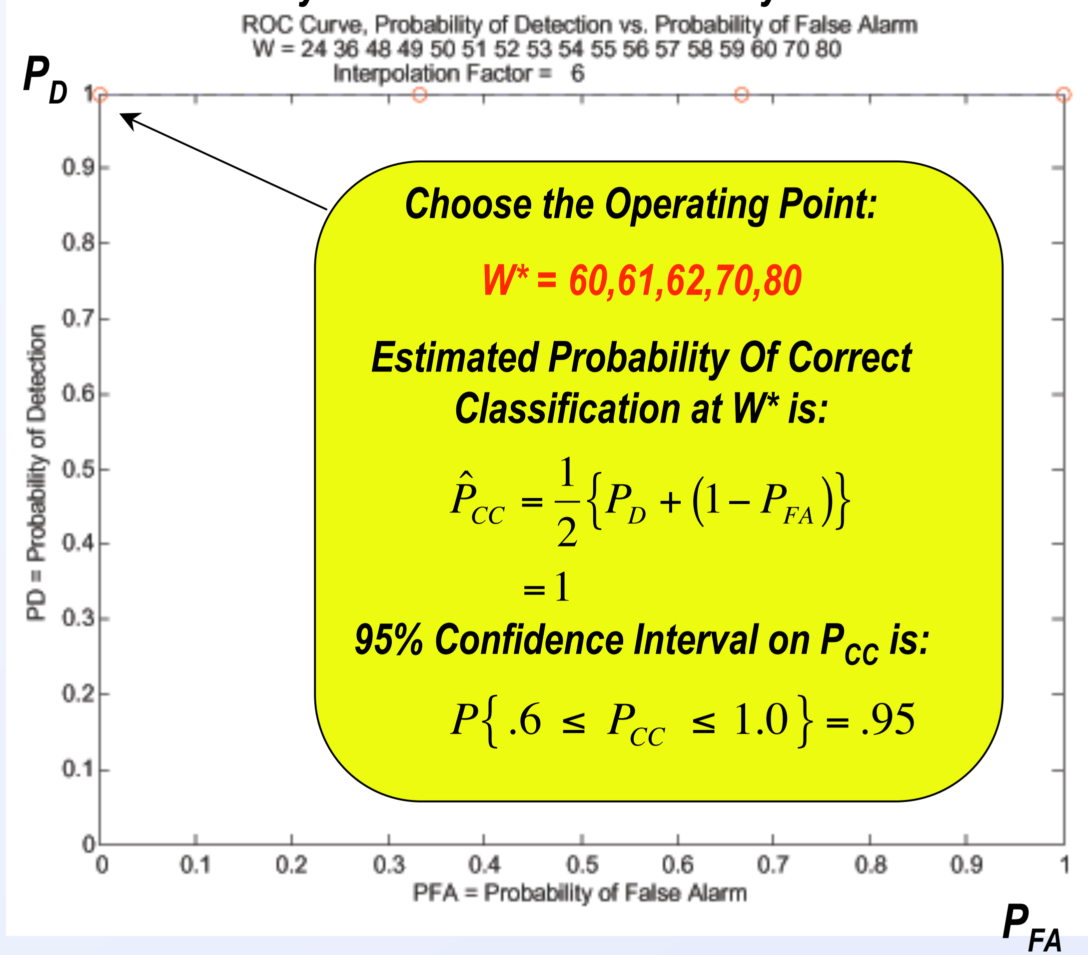
"Major Damage" WSSR Test Result = Model Mismatch



Major Damage:
Receiver Operating Characteristic (ROC) Curve = Perfect

W	P_{FA}	P_D
24	1	1
36	0.66667	1
48	0.66667	1
49	0.66667	1
50	0.66667	1
51	0.66667	1
52	0.66667	1
53	0.66667	1
54	0.66667	1
55	0.66667	1
56	0.33333	1
57	0.33333	1
58	0.33333	1
59	0.33333	1
60	0	1
61	0	1
62	0	1
70	0	1
80	0	1

Probability of Detection vs. Probability of False Alarm



Choose the Operating Point:

W* = 60,61,62,70,80

Estimated Probability Of Correct Classification at W* is:

$$\hat{P}_{CC} = \frac{1}{2}\left\{P_D + \left(1 - P_{FA}\right)\right\}$$
$$= 1$$

95% Confidence Interval on P_{CC} is:

$$P\left\{.6 \le P_{CC} \le 1.0\right\} = .95$$

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Experiment 1:
ROC Curves for Minor1,Minor2, and All 12 Damge Signals

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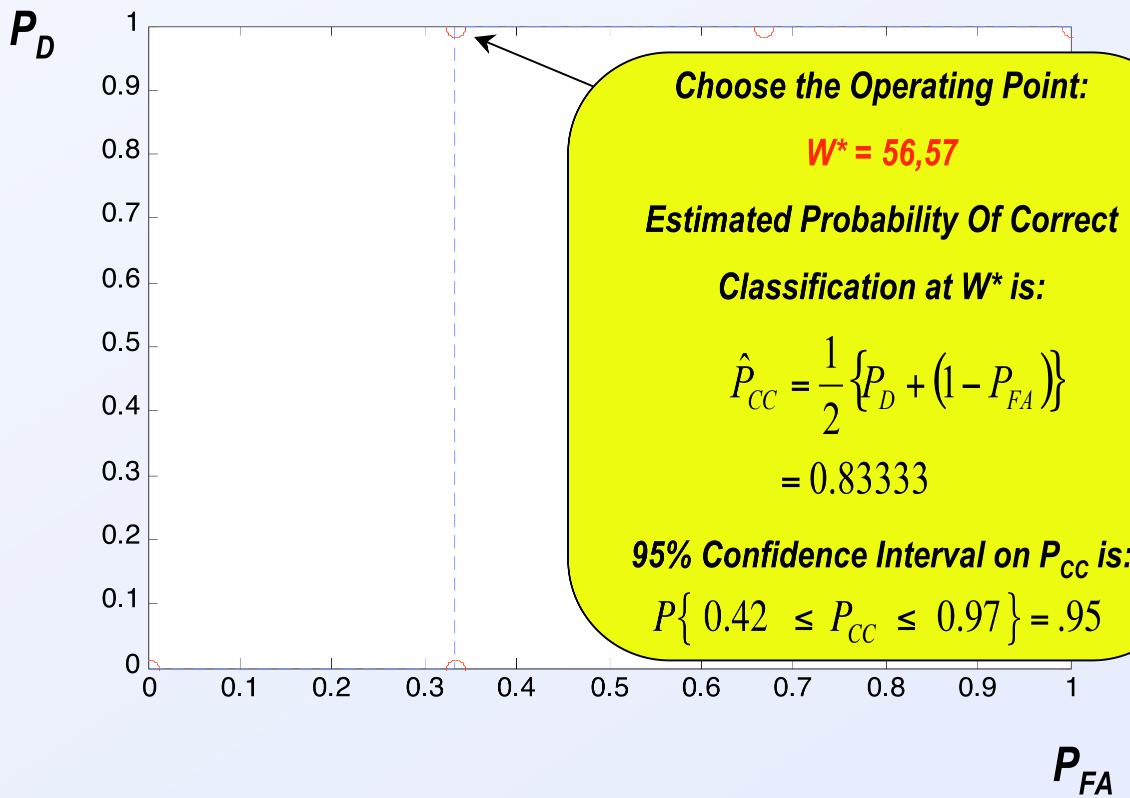
Minor1a,b,c Damage

Receiver Operating Characteristic (ROC) Curve

W	P_{FA}	P_D
24	1	1
36	1	0.66667
48	1	0.66667
49	1	0.66667
50	1	0.66667
55	1	0.66667
56	1	0.33333
57	1	0.33333
58	0	0.33333
59	0	0.33333
60	0	0
61	0	0
62	0	0
63	0	0
64	0	0
65	0	0
70	0	0
80	0	0

Probability of Detection vs. Probability of False Alarm



Choose the Operating Point:

W* = 56,57

Estimated Probability Of Correct Classification at W* is:

$$\hat{P}_{CC} = \frac{1}{2}\left\{P_D + \left(1 - P_{FA}\right)\right\}$$

$$= 0.83333$$

95% Confidence Interval on P_{CC} is:

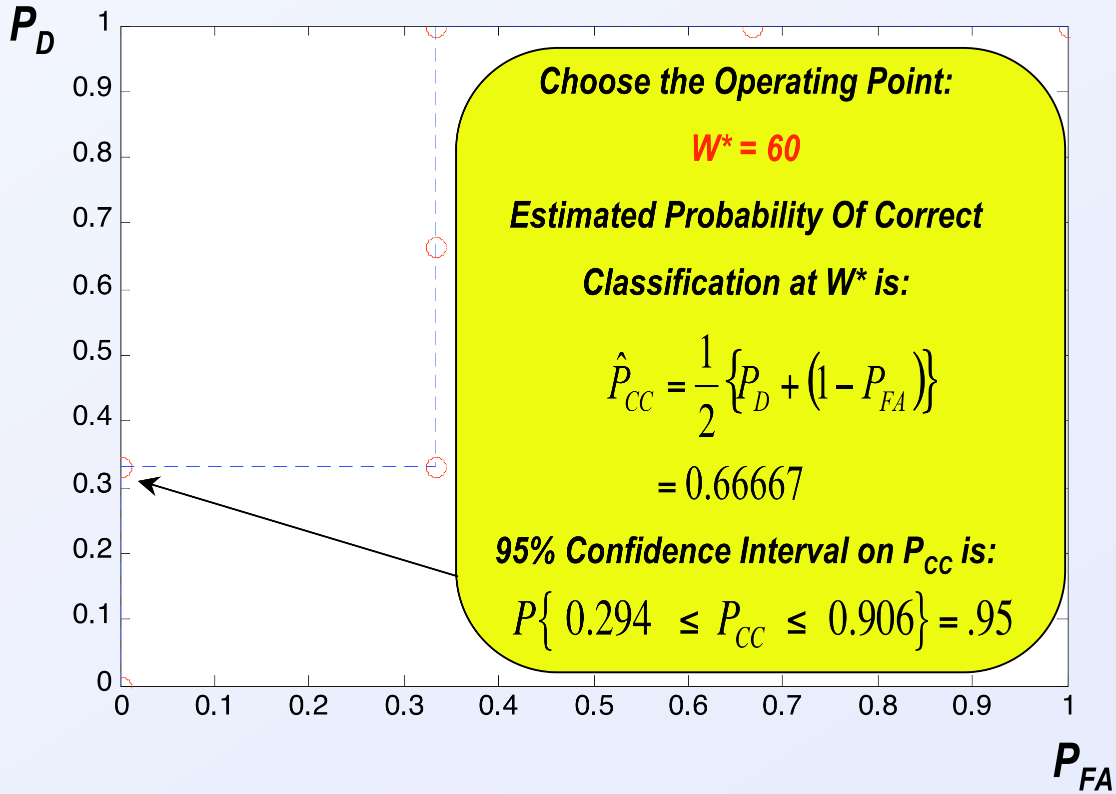
$$P\left\{\, 0.42 \;\le P_{CC} \le\; 0.97 \right\} = .95$$

Minor2a,b,c Damage

Receiver Operating Characteristic (ROC) Curve

W	P_{FA}	P_D
24	1	1
36	1	0.66667
48	1	0.66667
49	1	0.66667
50	1	0.66667
55	1	0.66667
56	1	0.33333
57	1	0.33333
58	0.66667	0.33333
59	0.33333	0.33333
60	0.33333	0
61	0	0
62	0	0
63	0	0
64	0	0
65	0	0
70	0	0
80	0	0

Probability of Detection vs. Probability of False Alarm



All 12 Signals: Minor1a,b,c, Minor2a,b,c, Minor3a,b,c, Majora,b,c

Receiver Operating Characteristic (ROC) Curve

W	P_{FA}	P_D
24	1	1
36	1	0.66667
48	1	0.66667
49	1	0.66667
50	1	0.66667
55	1	0.66667
56	1	0.33333
57	1	0.33333
58	0.66667	0.33333
59	0.58333	0.33333
60	0.58333	0
61	0.5	0
62	0.41667	0
63	0.25	0
64	0.25	0
65	0.25	0
70	0.25	0
80	0.25	0

Probability of Detection vs. Probability of False Alarm