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Cable Damage Detection Algorithms for Time Domain Reflectometry Signals

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Cable Damage Detection Algorithms for Time Domain Reflectometry Signals

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Auspices and Disclaimer

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Disclaimer

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
- Paul Sousa - ENG
  - Laboratory technician, data acquisition

Agenda

- **Introduction**
  - **- The Cable Damage Detection Problem**
  - **- This is work in progress**

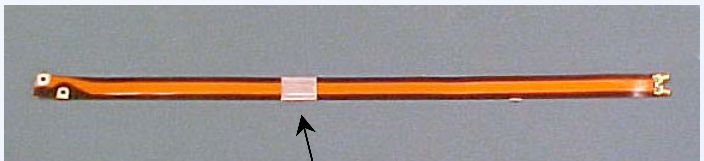
- **Technical Approach -** ***Model-Based Damage Detection***

- **Damage Detection Processing Results**
  - **- Real Measurements, Artificial Damage** ***- Reported Earlier***
  - **- Real measurements, real damage**
  - **- Performance Measurements**
    - ***- ROC Curves, Confidence Intervals***

- **Discussion and Plans**

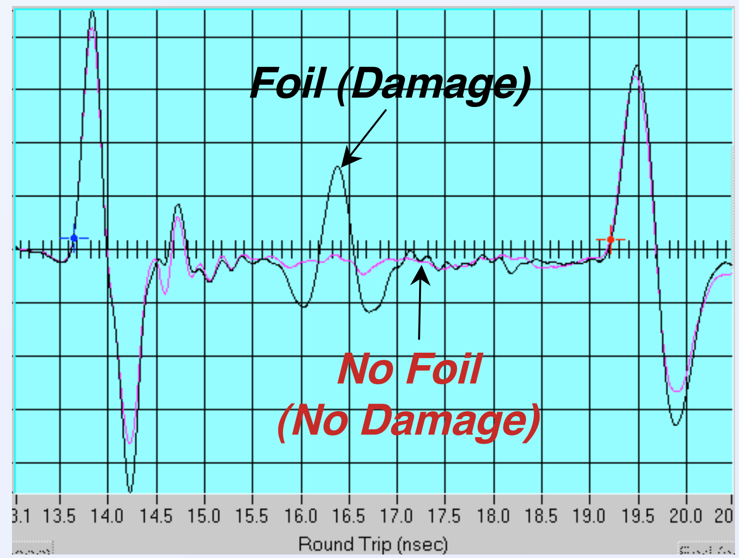
We Are Testing Two-Conductor Flat Cables With Kapton Insulation - For Dielectric Anomalies

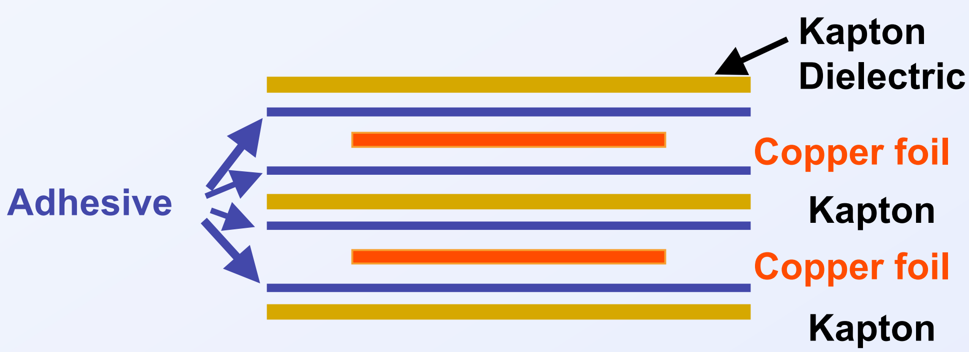
Two-Conductor Flat Cable
With Kapton Insulation



Foil Simulating a Capacitive Discontinuity (Damage)

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





Expected Damage Types:

- ***Compressions***
- ***Punctures***
- ***Short Circuits***
- ***Open Circuits***

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

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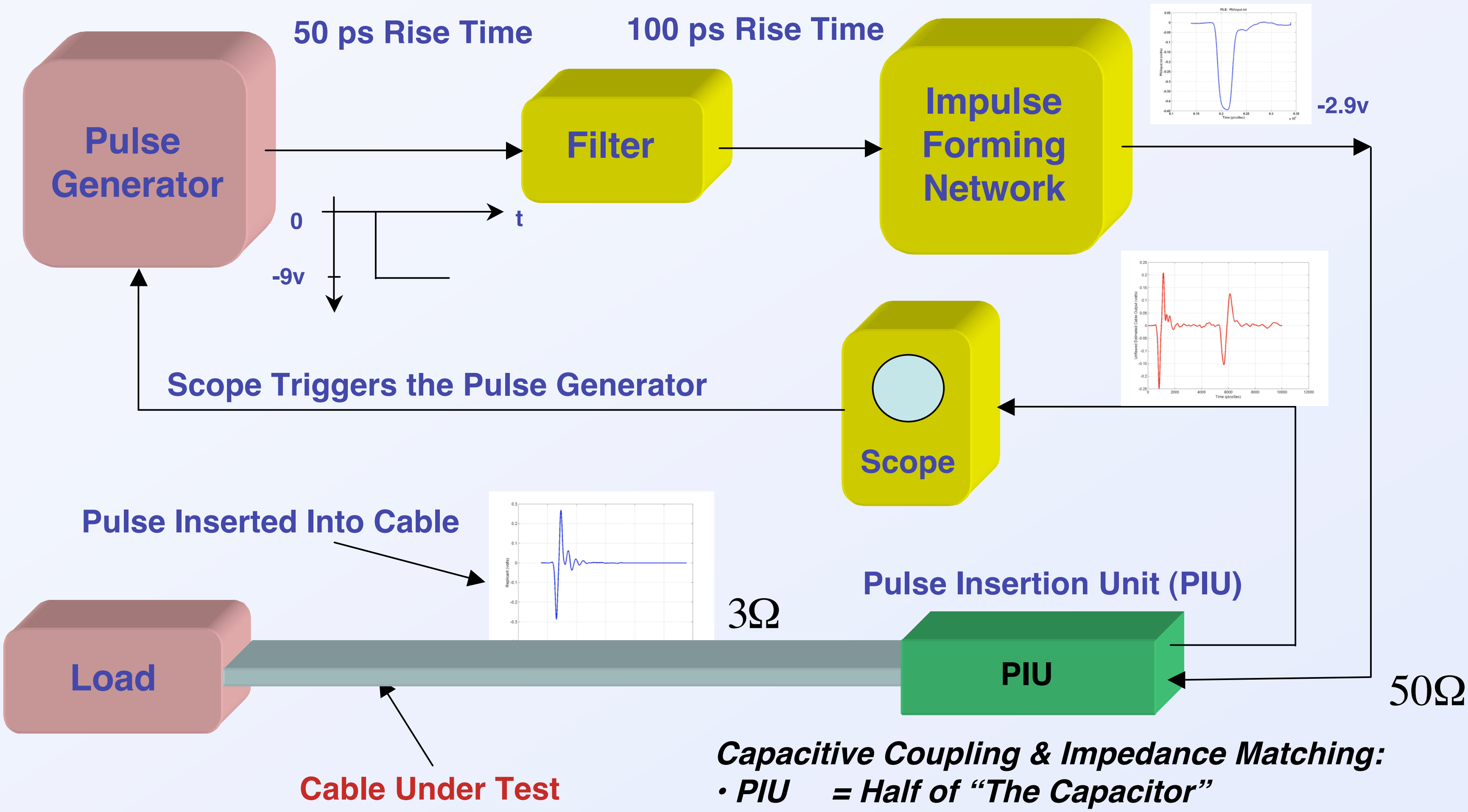


Capacitive Coupling & Impedance Matching:
- ***PIU = Half of "The Capacitor"***
- ***Cable = Half of "The Capacitor"***

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 *[Solved after lots of hard work]*

- **The signal shape changes significantly with the cable environment**
  - We have 2D and 3D "Mockups"

Repeatability: Use a Confidence Interval About the Mean

[Small Sample Size Case (M < 30)]

If the *test statistic* $\mu(\mathrm{t})$ is Gaussian distributed,
then the *95% confidence interval* estimate of the test statistic for small *sample size (M < 30)* is:

$$P\left\{\bar{z}(t)-\frac{bS(t)}{\sqrt{M-1}} < \mu(t) < \bar{z}(t)+\frac{bS(t)}{\sqrt{M-1}}\right\}=1-\alpha=.95$$

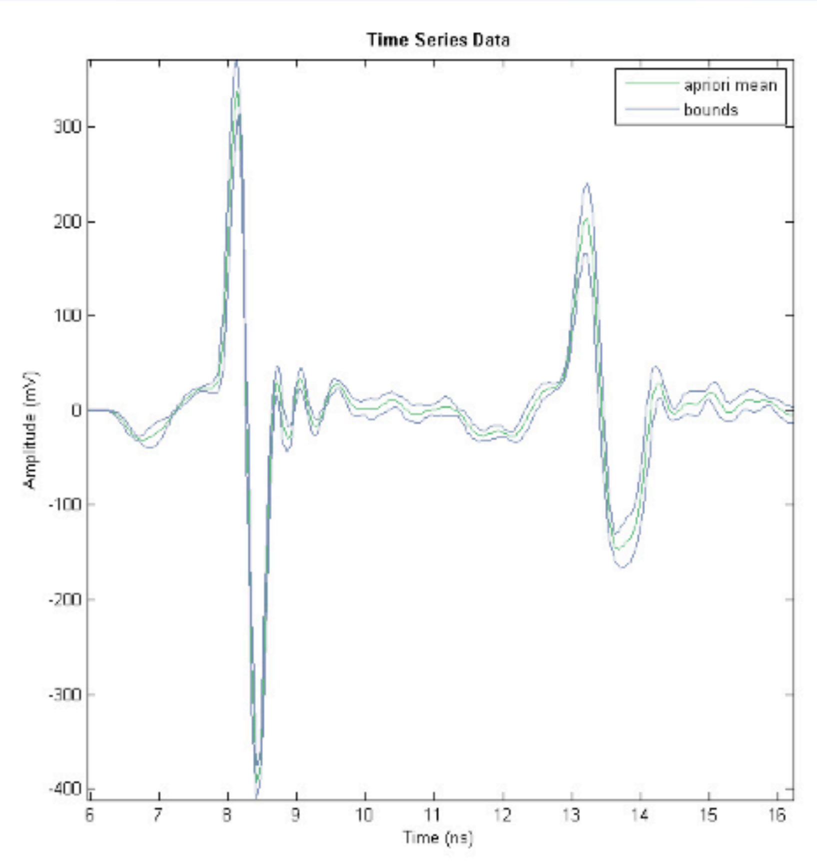
$$\alpha = \text{Significance Level} = .05$$

"With confidence 95%, the test statistic lies between the lower bound and the upper bound."

Note: For this case, we must use the Student's t distribution to compute the bounds.

*Note: b is a constant that depends on the sample size M.
For M < 30, choose b from a "Student's t table."*

We Plot the Ensemble Sample Mean Signal and its Confidence Interval Bounds about the Mean



- Let $F =$ Fraction of samples of mean that exceed the threshold
- If $F \leq \alpha$, Declare *Signal Ensemble is repeatable*
- If $F > \alpha$, Declare *Signal Ensemble is not repeatable*

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

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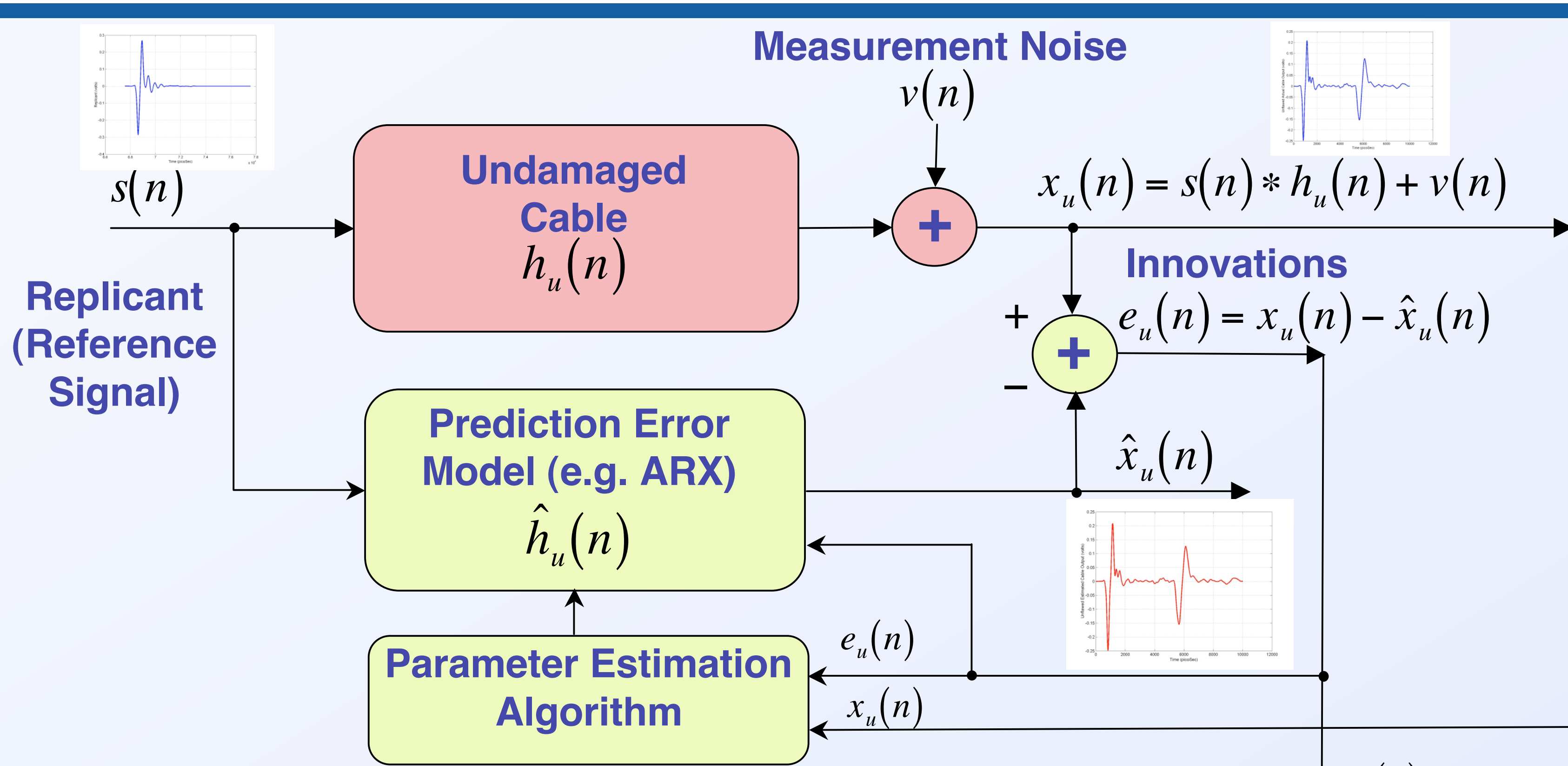
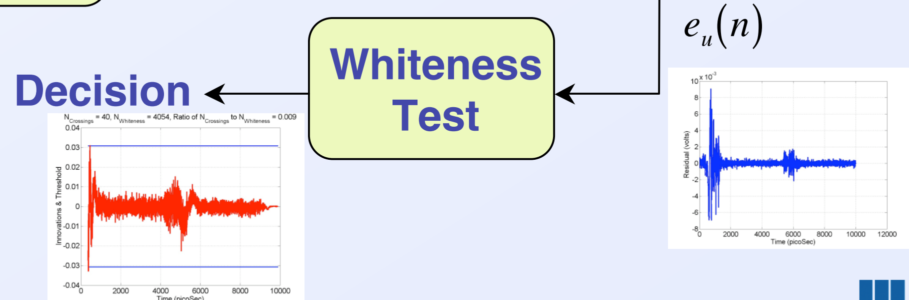
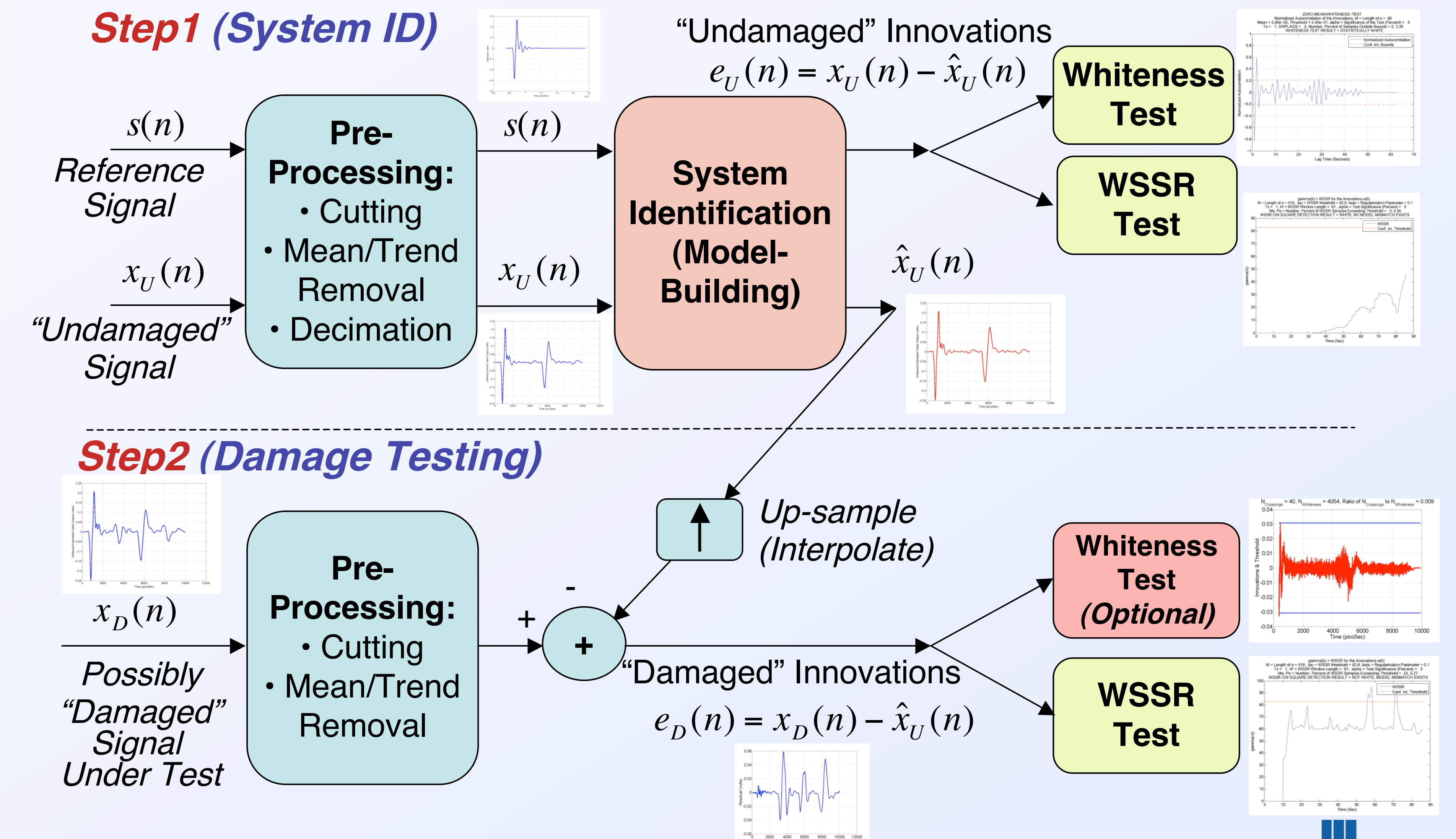




System Identification:

- 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"*



The Form of the Linear System Model Used is "ARX"
= *"Auto-Regressive with Exogenous Input"*

$$y(t) = \frac{B(q^{-1})}{A(q^{-1})} u(t - nk) + \frac{1}{A(q^{-1})} e(t)$$

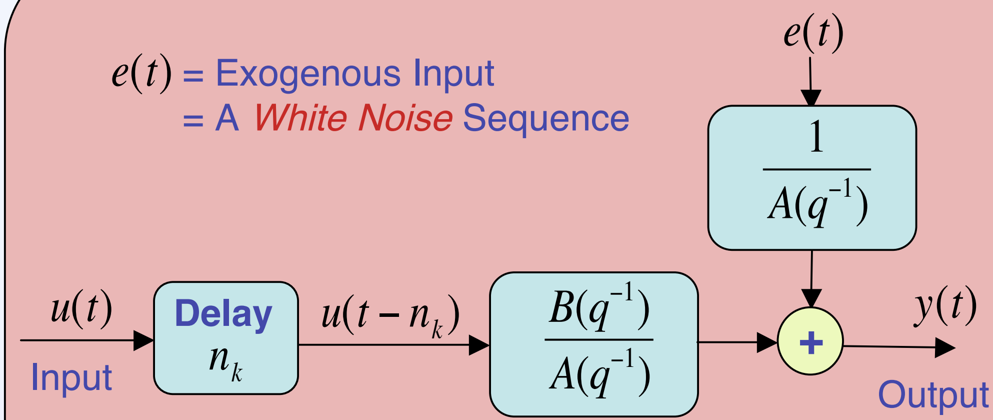
Where:

$$A(q) = 1 + a_1 q^{-1} + a_2 q^{-2} \cdots + a_{N_a} q^{-N_a}$$

$$B(q) = b_0 + b_1 q^{-1} + b_2 q^{-2} \cdots + b_{N_b} q^{-N_b}$$

$$q^{-1} = \text{Delay Operator}$$

$e(t)$ = Exogenous Input
= A *White Noise* Sequence



The model parameters are estimated using a least squares algorithm:
- Solve an over-determined set of linear equations
- Solve using QR factorization algorithm
- The regression matrix is formed so that only measured quantities are used (no fill-out with zeros).

Scalar WSSR (Weighted Sum Squared Residuals) Test

For a Scalar Measurement (p = 1)

Given the innovations signal $e(n)$

We define the scalar WSSR test statistic at time index n:

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

Note: We estimate WSSR over a finite sliding window of length W samples.

Where:

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

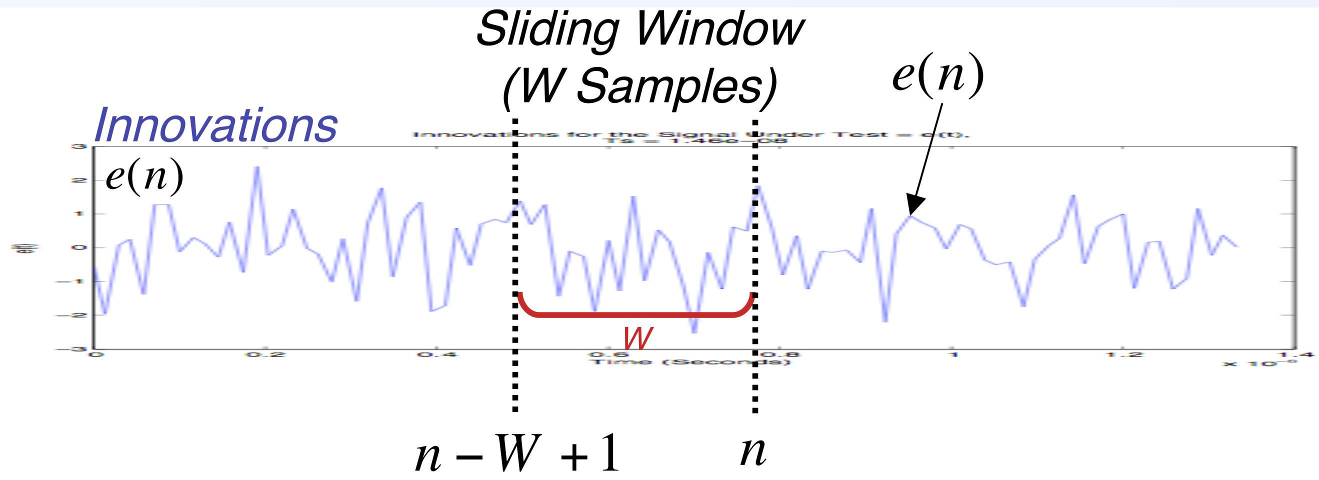
Sample variance over the sliding window

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

Sample mean over the sliding window

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 $\alpha = .05$:

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

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

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

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

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

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)

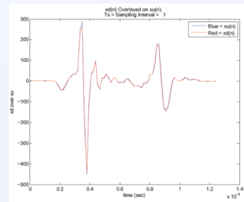
We Acquired an Ensemble of Real Signals for Processing

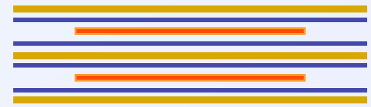
The PIU was never disconnected between acquisitions *Experiment E1: Data from 2_13_07*

UNDAMAGED

Reference Signals *(Undamaged):*

refa, refb, refc

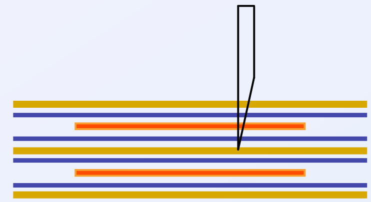




MINOR DAMAGE

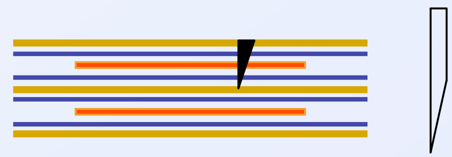
Minor Damage *(pin hole, knife present, no short):*

minor1a, minor1b, minor1c



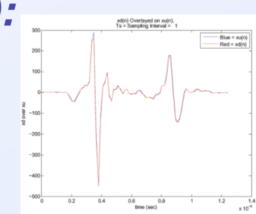
Minor Damage *(pin hole, knife removed, no short):*

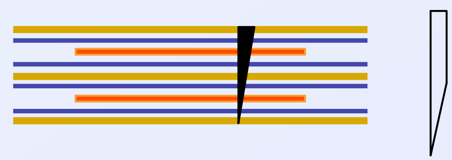
minor2a, minor2b, minor2c



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

minor3a, minor3b, minor3c

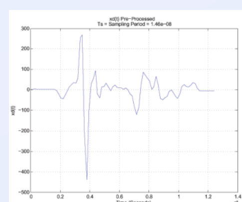


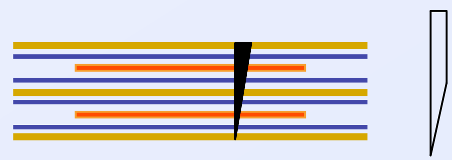


MAJOR DAMAGE

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

major1a, major1b, major1c





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Experiment 1:
System Identification Results

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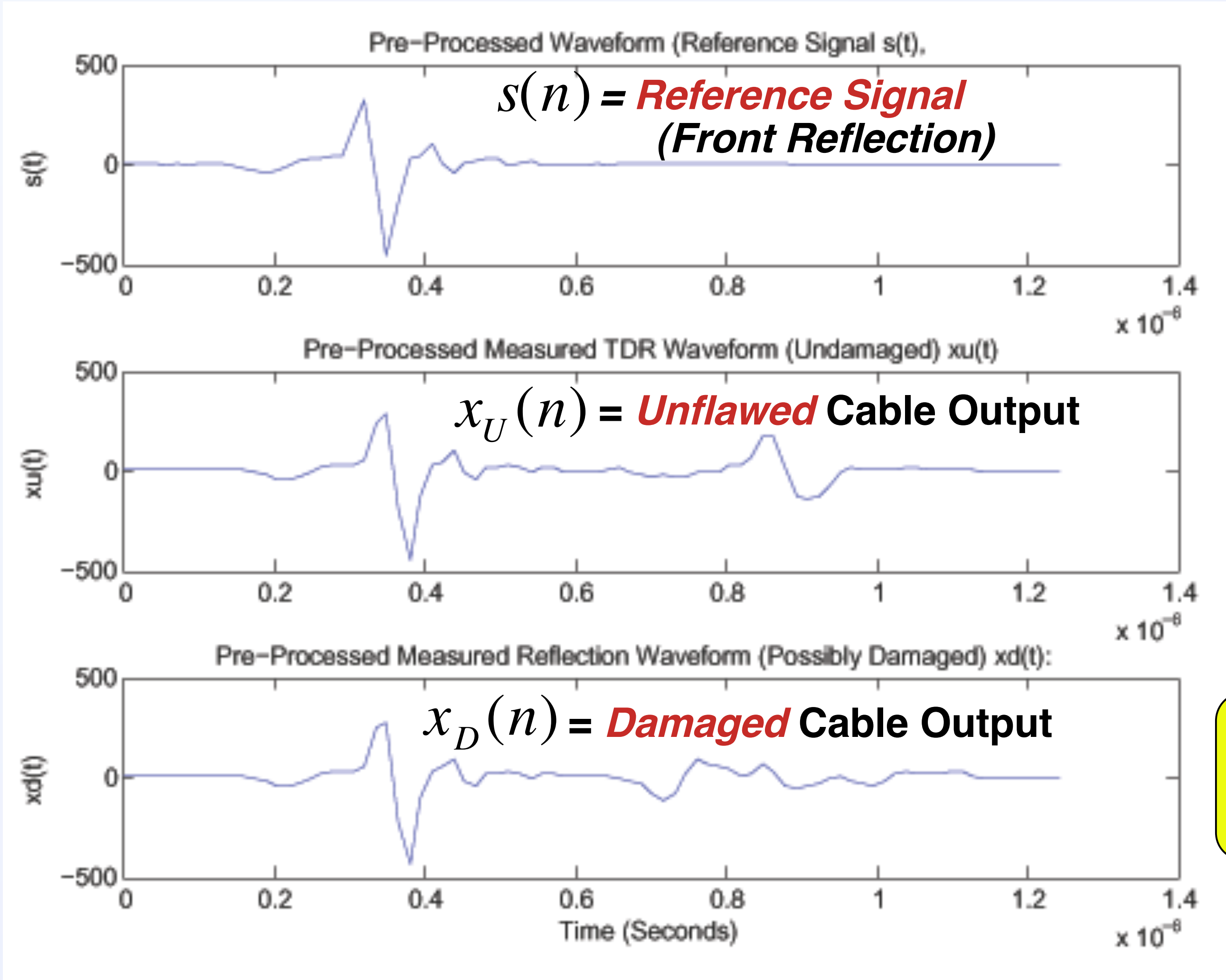
E1_s_xu_xdC.pdf

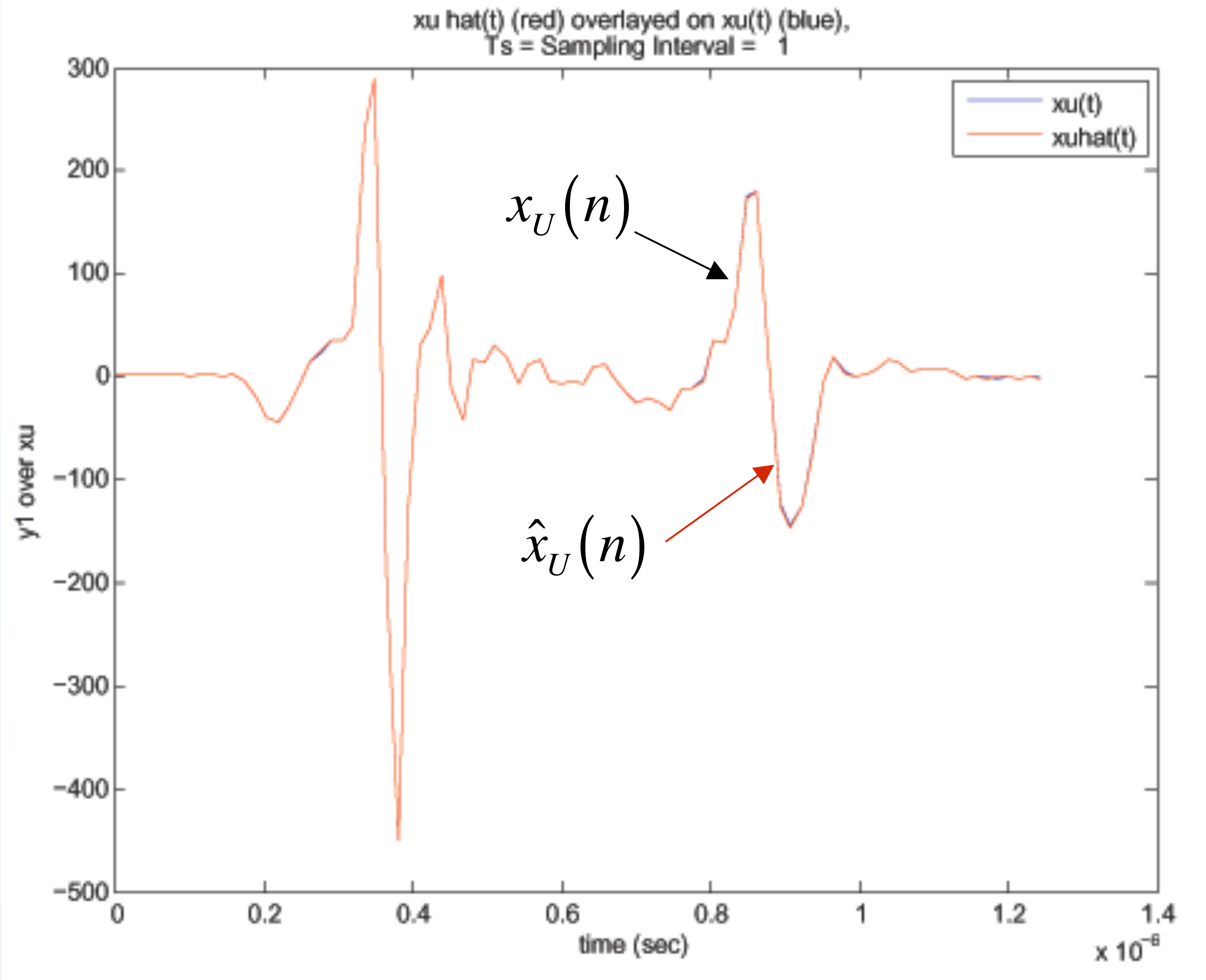
System Identification: Preprocessed Signals



Example: Major Damage

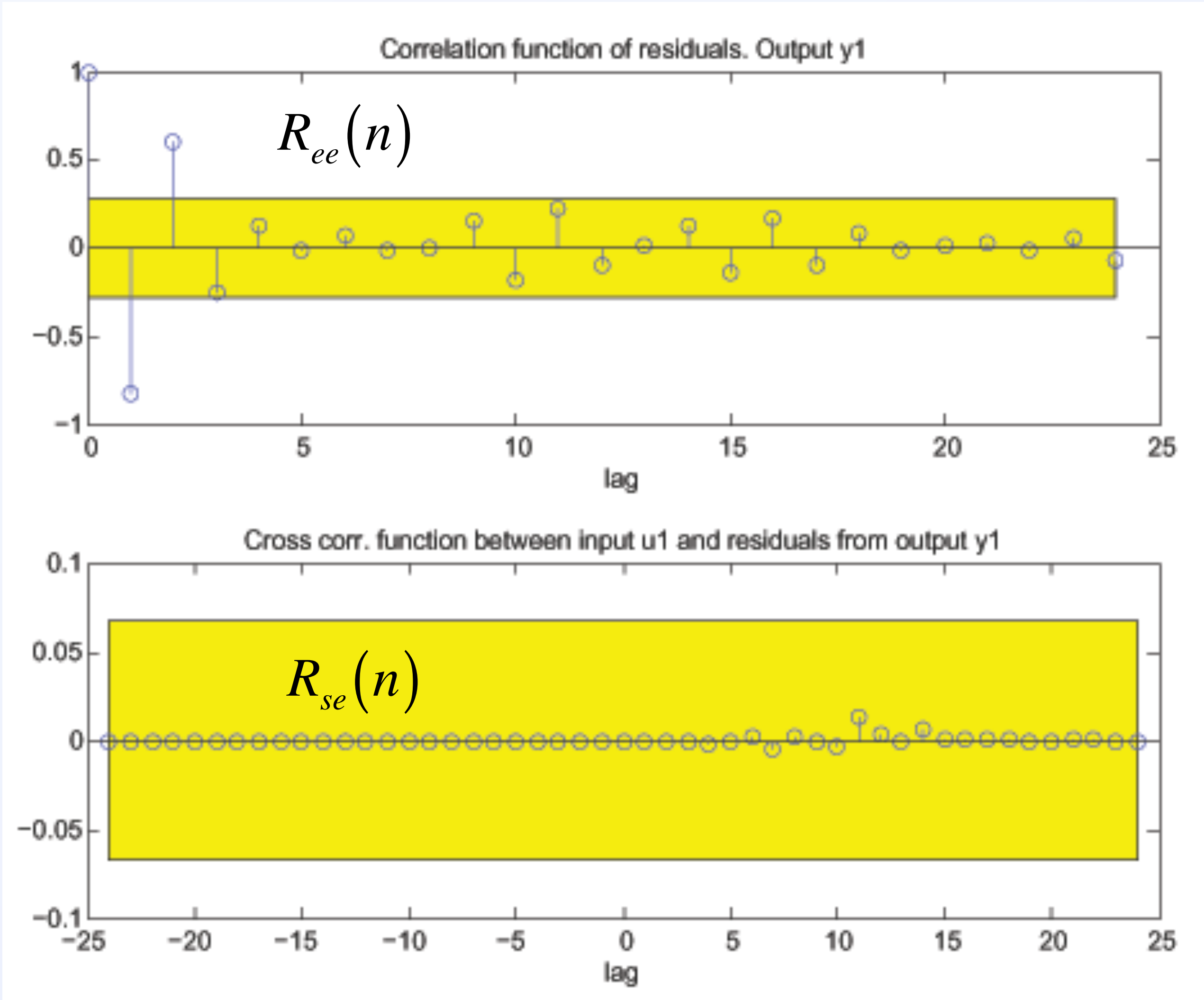
E1_xuhat_xuC.pdf

System Identification: *The Model Fit is Good*



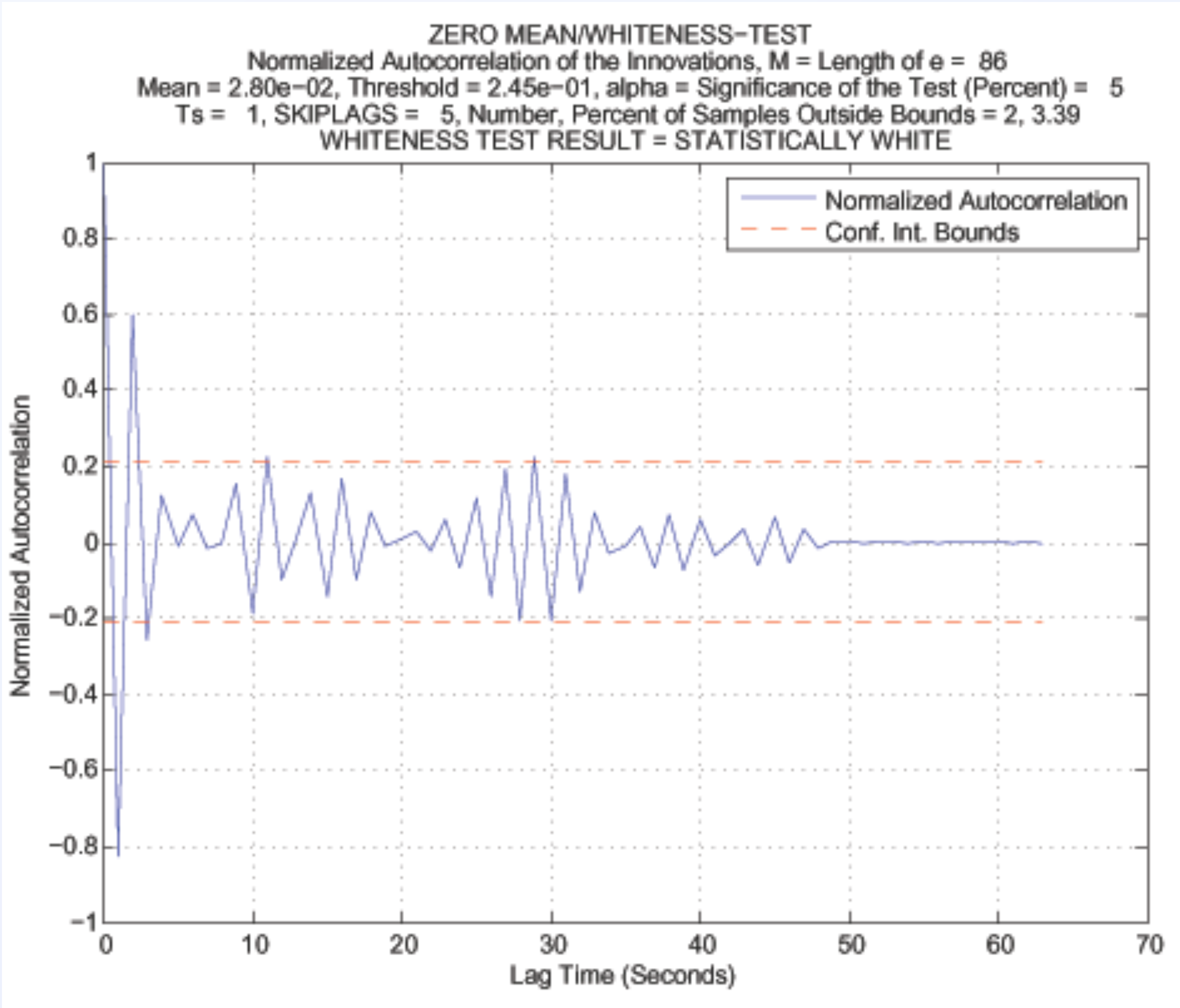
E1_Ree_Rxy1C.pdf

System Identification: *Correlation Tests are Satisfactory*



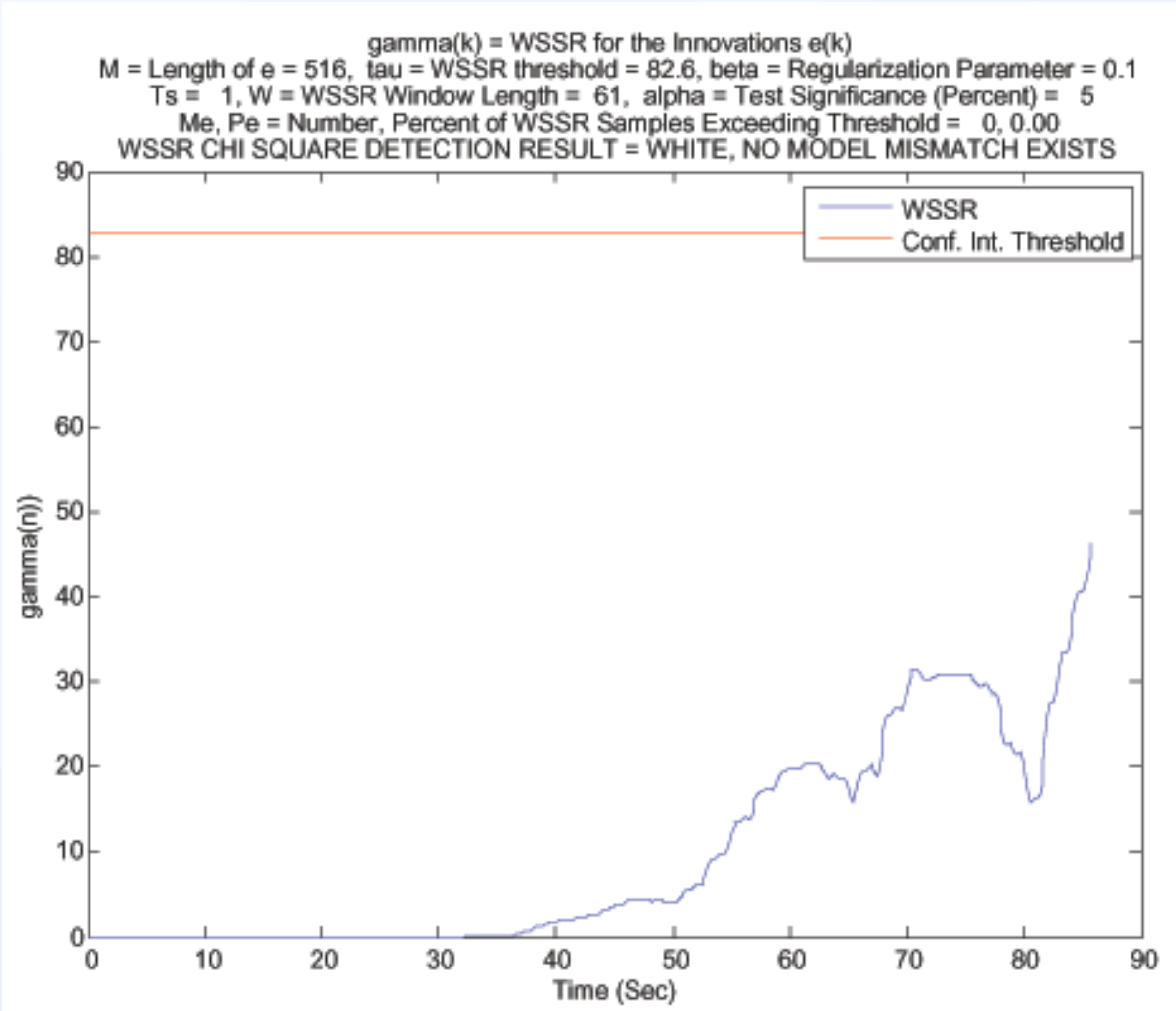
E1_WT_euC.pdf

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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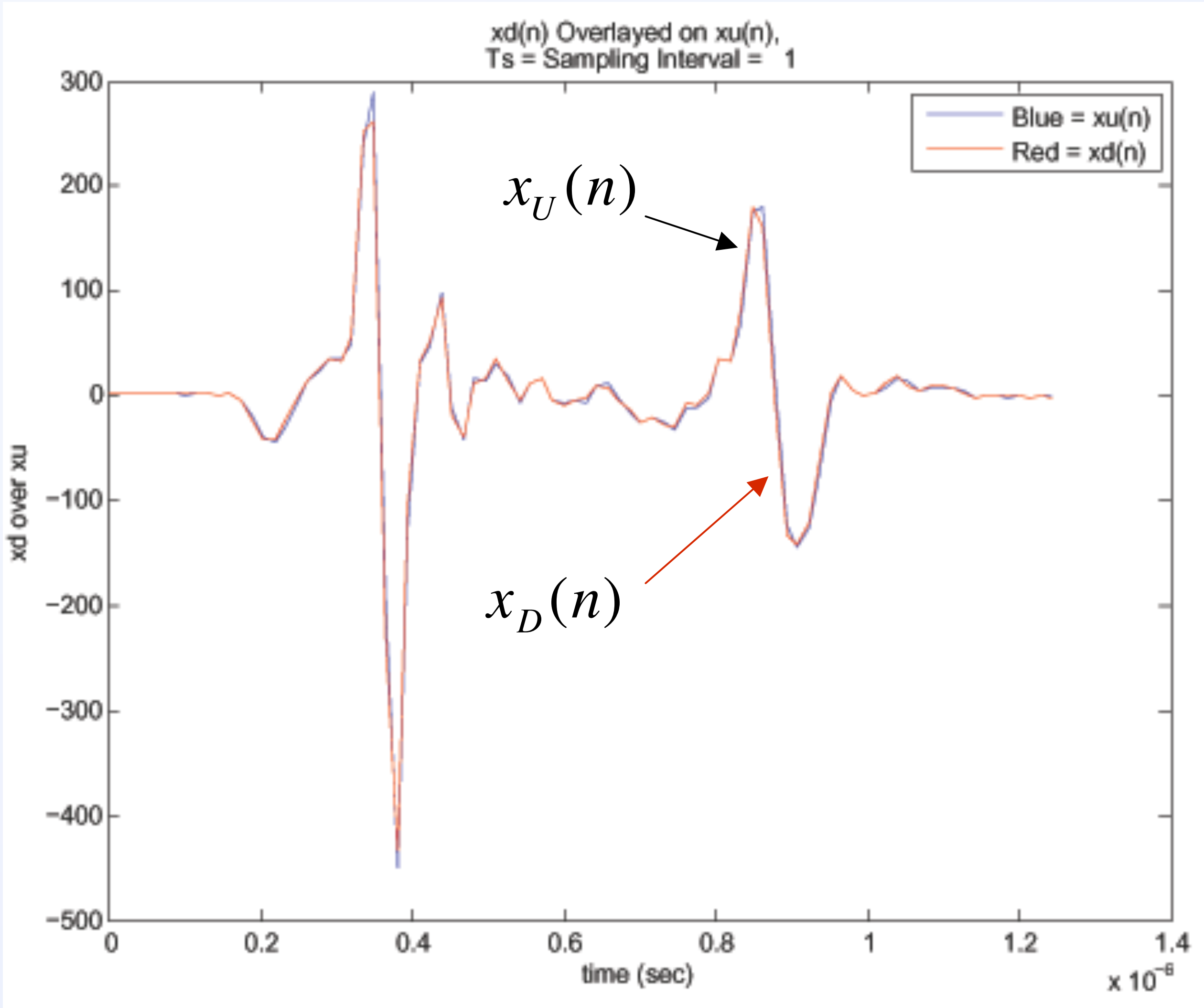
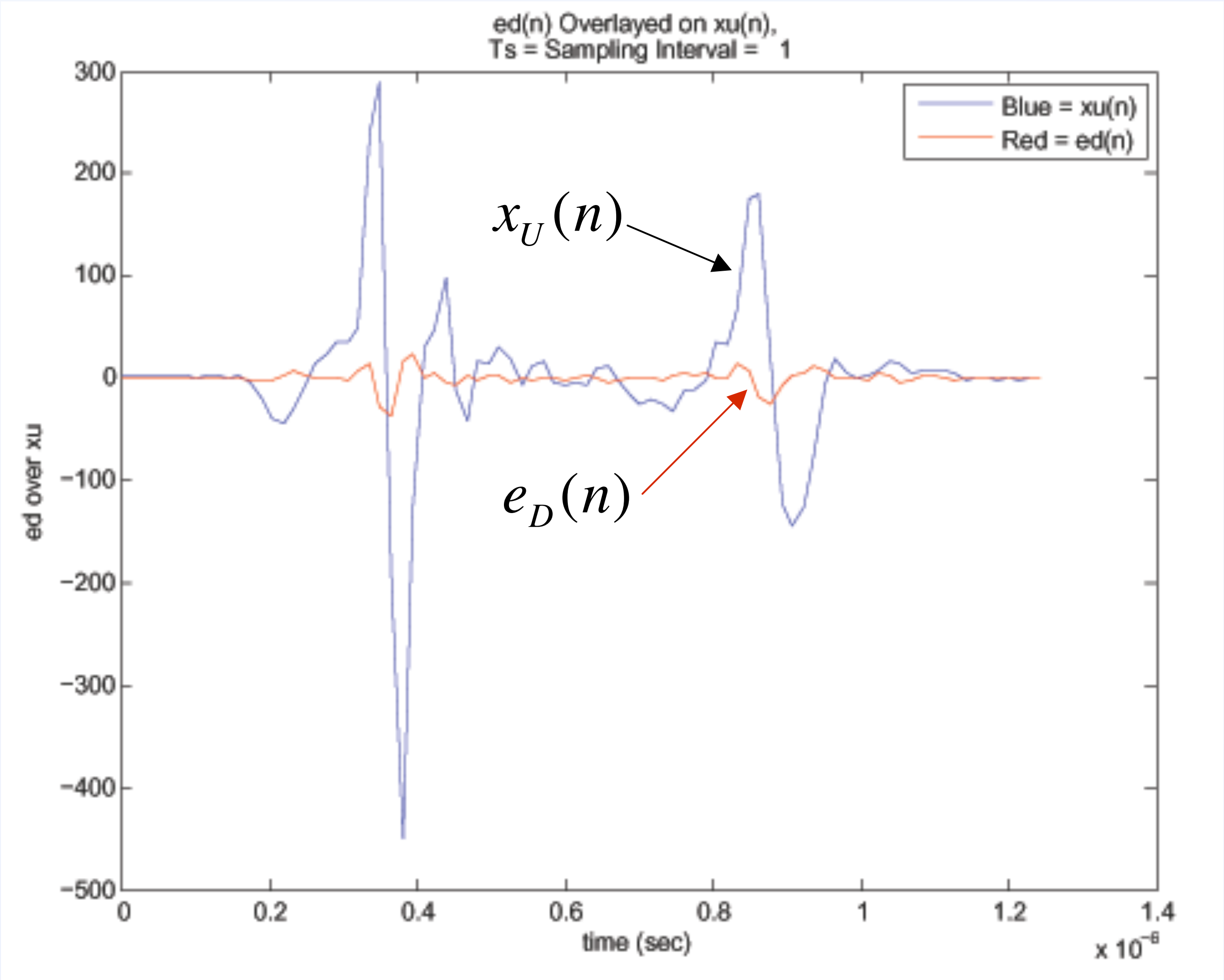
E1_xd_m3a_xuC.pdf

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



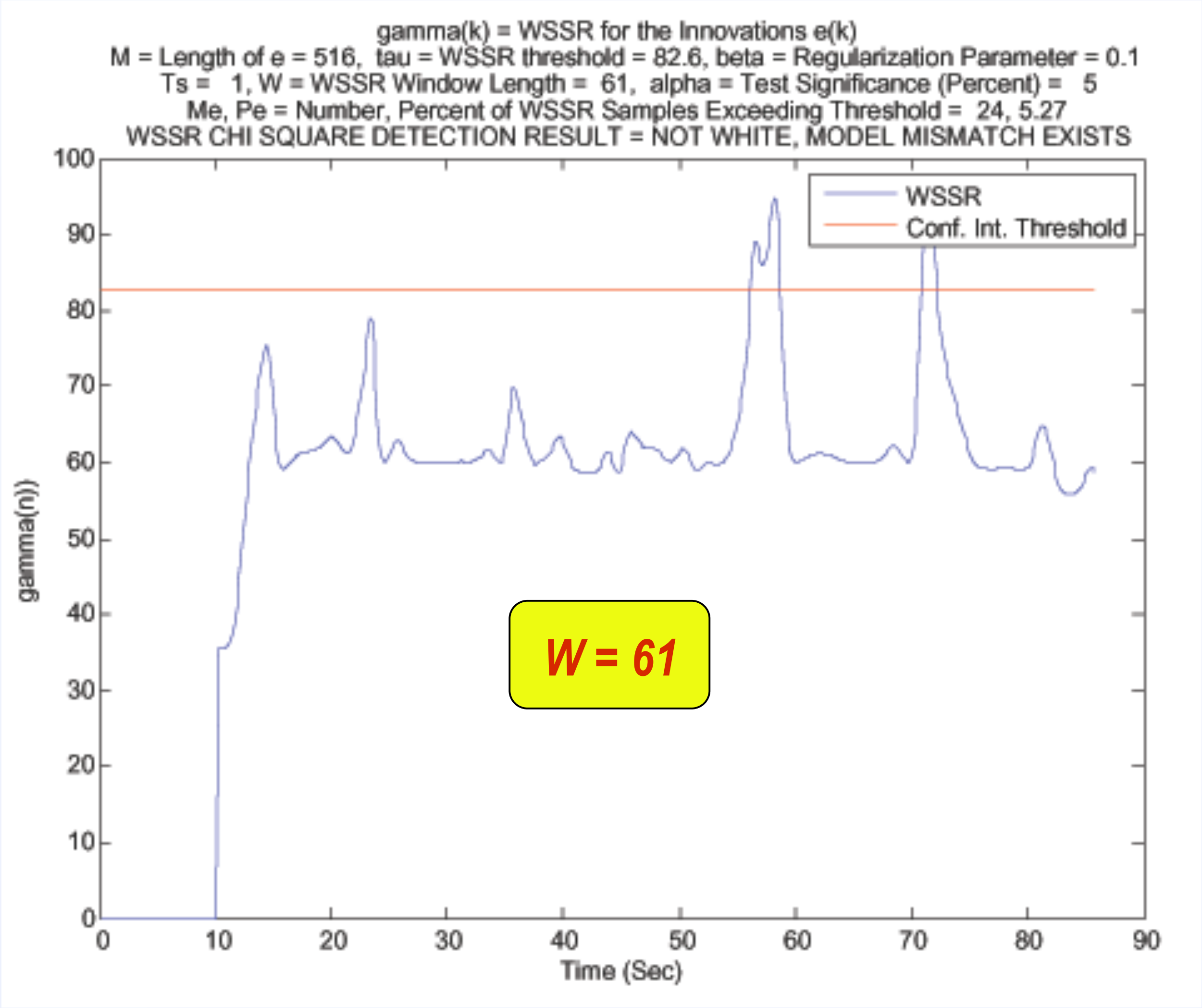
E1_ed_m3a_xuC.pdf

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



E1_WSSR_ed_m3a_(61)C.pdf

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

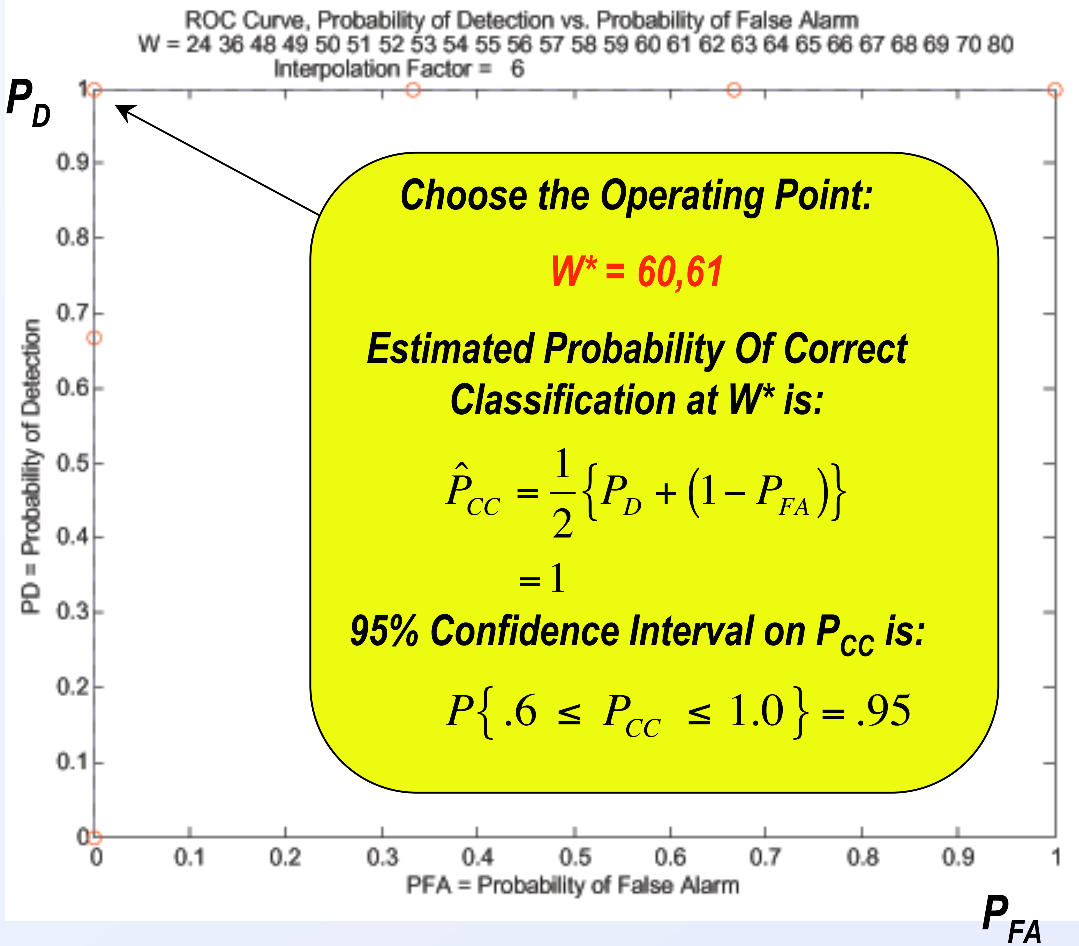


Minor3a,b,c Damage

Receiver Operating Characteristic (ROC) Curve = Ideal

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:

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

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Experiment 5b: Obvious Damage

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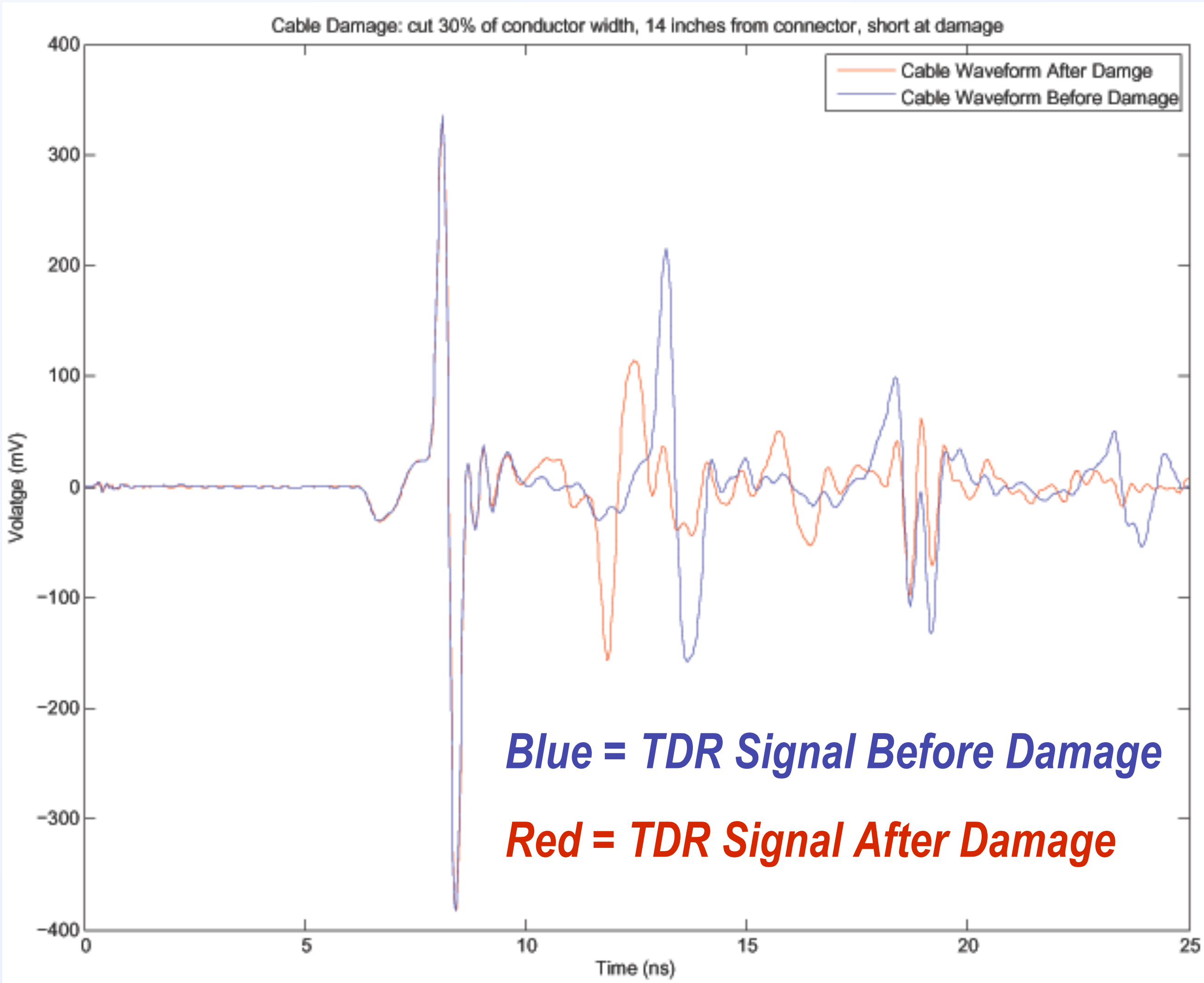
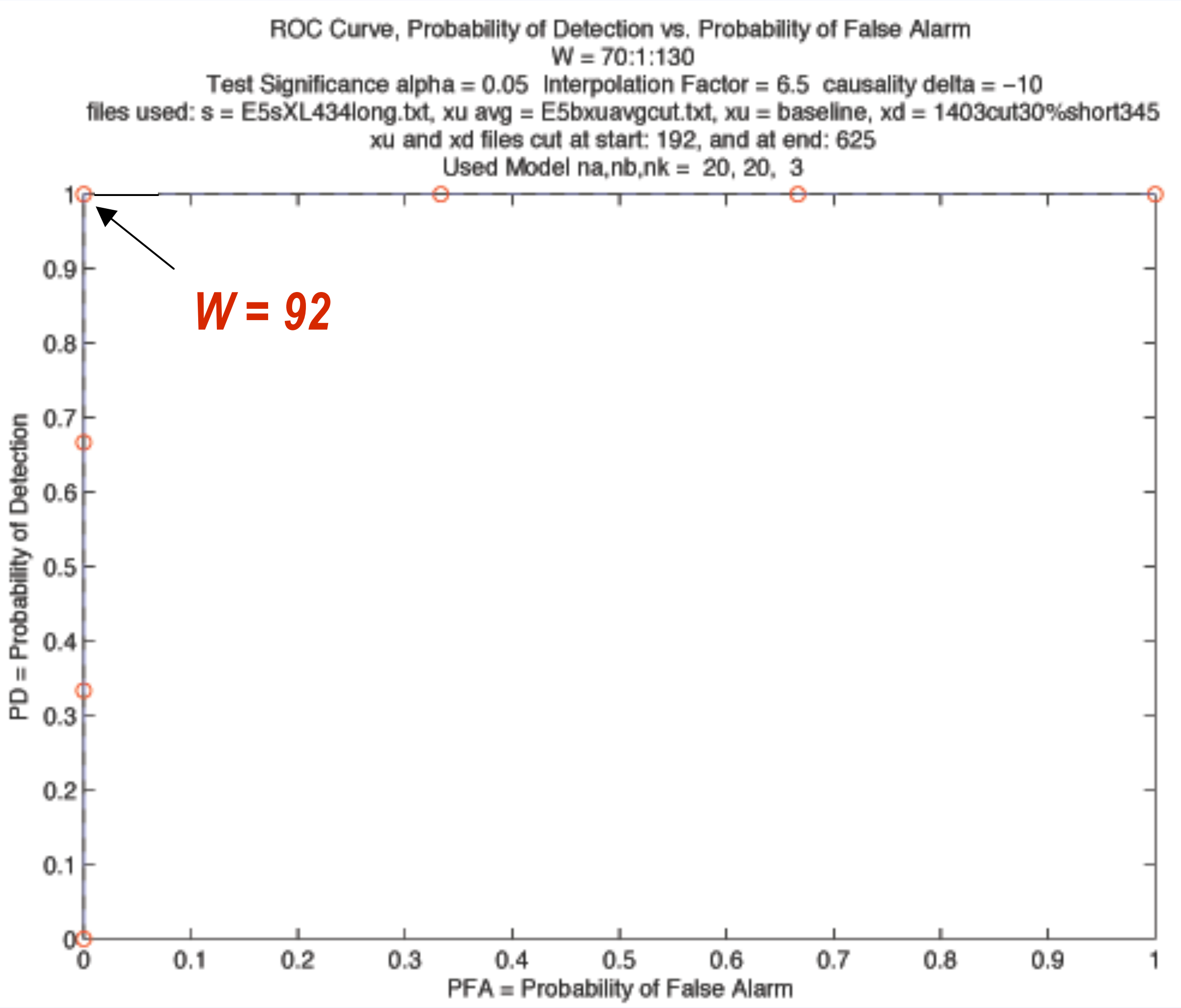
Exp. (1)E5b: Obvious Damage
Cut 30% of Conductor Width, 14 in from connector, cable shorted



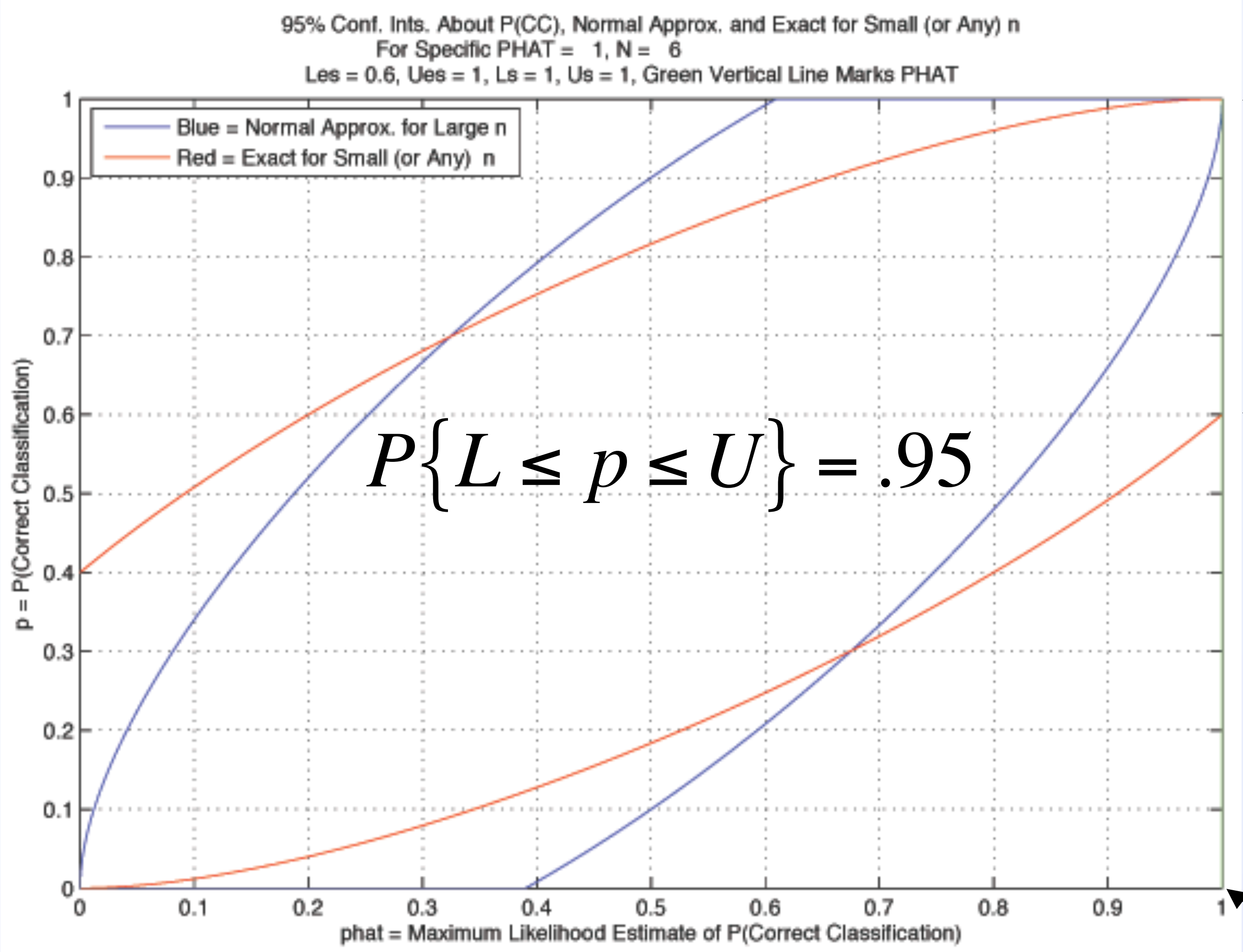
Exp. (1)E5b: Obvious Damage, ROC Curve is Ideal
Cut 30% of Conductor Width, 14 in from connector, cable shorted



Exp. (1)E5b: Obvious Damage, Confidence Interval on P(CC)

Cut 30% of Conductor Width, 14 in from connector, cable shorted

True P(CC) from Theory



$$P\{L \le p \le U\} = .95$$

Upper Bound U = 1

Lower Bound L = .6

$$\hat{p} = 1$$

Estimated P(CC) from Contingency Table

Conclusions & Future Work

- **Tests with real data validate the algorithms:**
  - *Earlier tests with cables on a work bench*
    - *Cable not removed between measurements*
  - *Recent tests with cables in the 2D mockup fixture*
    - *Cable removed between measurements*
  - *Can sometimes detect damage that is not obvious by visual inspection*

- **The most difficult issues have been:**
  - *Repeatability of the TDR measurements in the 2D fixture*
    Extensive work was required to achieve repeatability

Future Work:

- *Cable "Insult Studies" with more damage types*
- *Tune the adjustable algorithm parameters for best performance*
  - *Interpolation factors, significance of tests, etc.*
- *Experiments in realistic cable environments - 3D Mockup*
- *Use algorithms with other applications - Other systems, optical cables*