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

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

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November 17-18, 2005

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

# Disclaimer and Auspices Statements



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# We Have an Interdisciplinary Team

- **Graham Thomas - ME/MMED, NDE Group Leader for Ultrasonics/Acoustics**
  - **- NDE, materials characterization**
  - **- Project Management**

- **Grace Clark - EE/EETD**
  - **- Image/signal processing, automatic target/pattern recognition (ATR), sensor data fusion, NDE**

- **Chris Robbins - EE/DSED**
  - **- Data acquisition, hardware**

- **Eric Breitfeller - EE/DSED**
  - **- Signal processing, software**

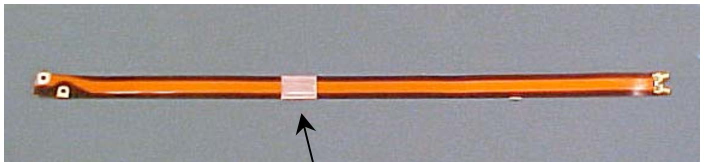
- **Rex Morey - EE/DSED (Retired)**
  - **- Time Domain Reflectometry**

# Agenda

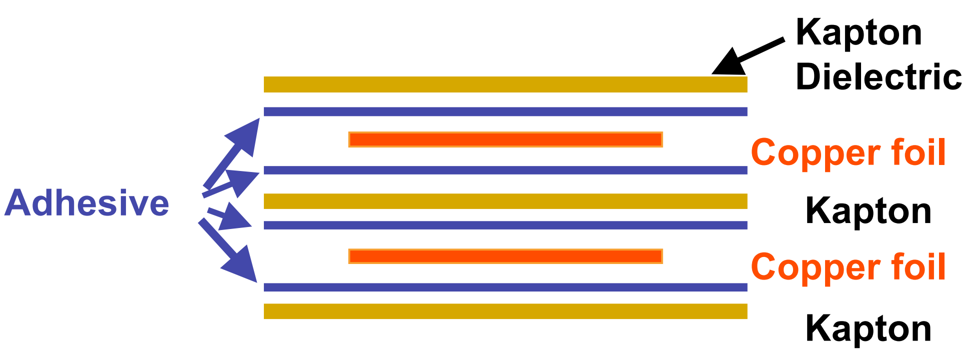
- **Introduction and Problem Definition** ***- Work in Progress***
- **Technical Approach**
- **Model-Based Flaw Detection Results**
- **Discussion**

# We Are Testing Two-Conductor Flat Cables With Kapton Insulation

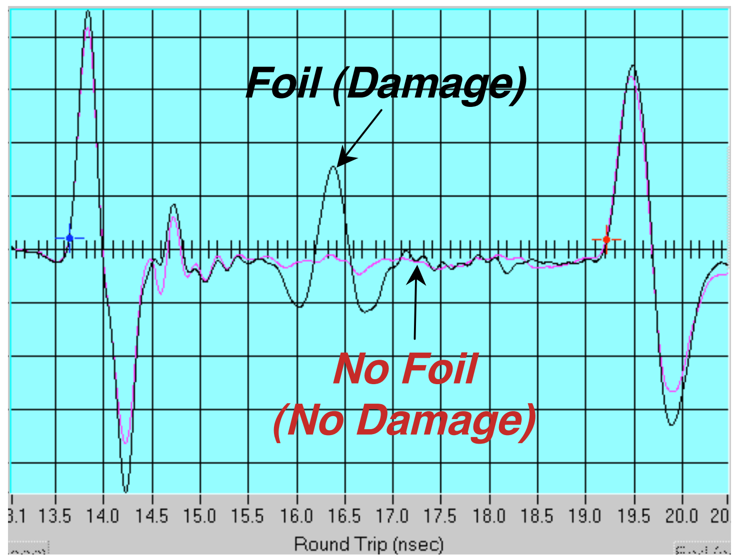
**Two-Conductor Flat Cable**
**With Kapton Insulation**



**Foil Simulating a Capacitive Discontinuity (Damage)**




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



# Benchtop Experiments (w/No Device "Mockup):"
## *Connections Create Some Variability*

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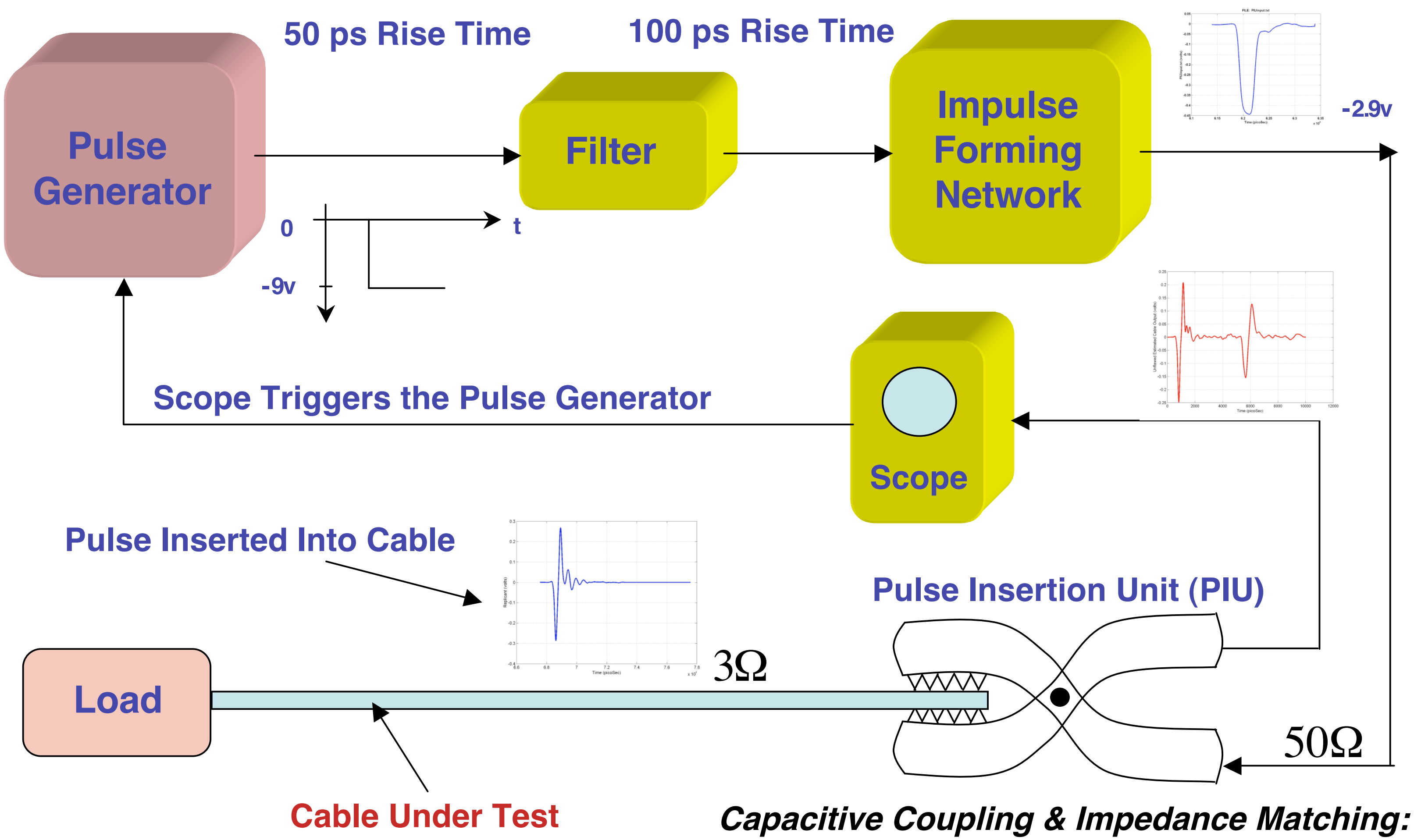



***Capacitive Coupling & Impedance Matching:***
- ***PIU = Half of "The Capacitor"***
- ***Cable = Half of "The Capacitor"***

# Proposed Decision-Making Protocol (Using TDR Measurements):

*Use a Three-Step Hierarchical Decision Scheme:*

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"***

# Model-Based Detection:
## *Detect a Model Mismatch if a Flaw 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 FLAW* exists**

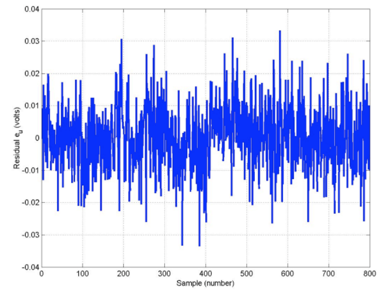
- **Whiteness Testing on the *Innovations (Errors):***
  **Estimate the output of the actual system using measurements from a dynamic test.**

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

# Let Us Define a "White Noise" Sequence $x(t)$

**Given a stochastic process $x(t)$**



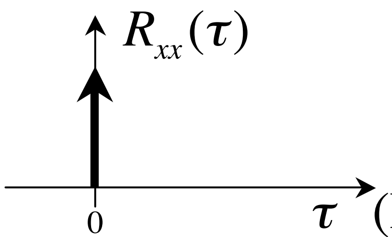
**x(t) is "white" when:**

**Autocorrelation (Time Domain)**

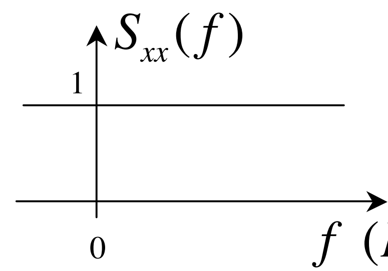
$$R_{xx}(\tau) = E\{x(t)x(t+\tau)\}$$
$$= \delta(\tau)$$
$$= \begin{cases} 1, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}$$

**Power Spectral Density (Frequency Domain)**

$$S_{xx}(f) = F\{R_{xx}(\tau)\}$$
$$= 1$$
$$F\{\bullet\} = \text{Fourier Transform}$$

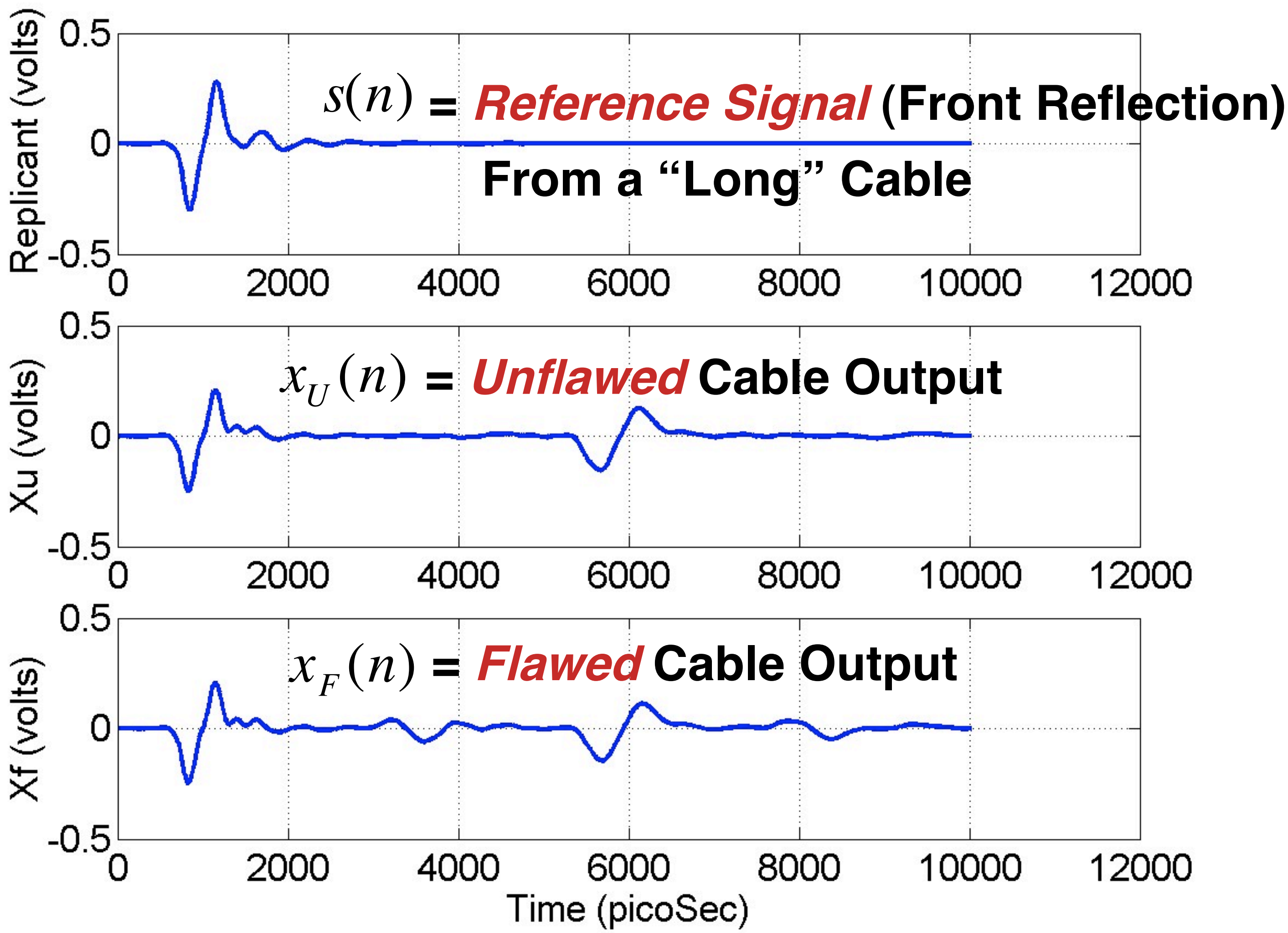



$F\{\bullet\}$ $\Longleftrightarrow$



# Experiment Using Real Cable TDR Signals:
## Raw Measurements





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

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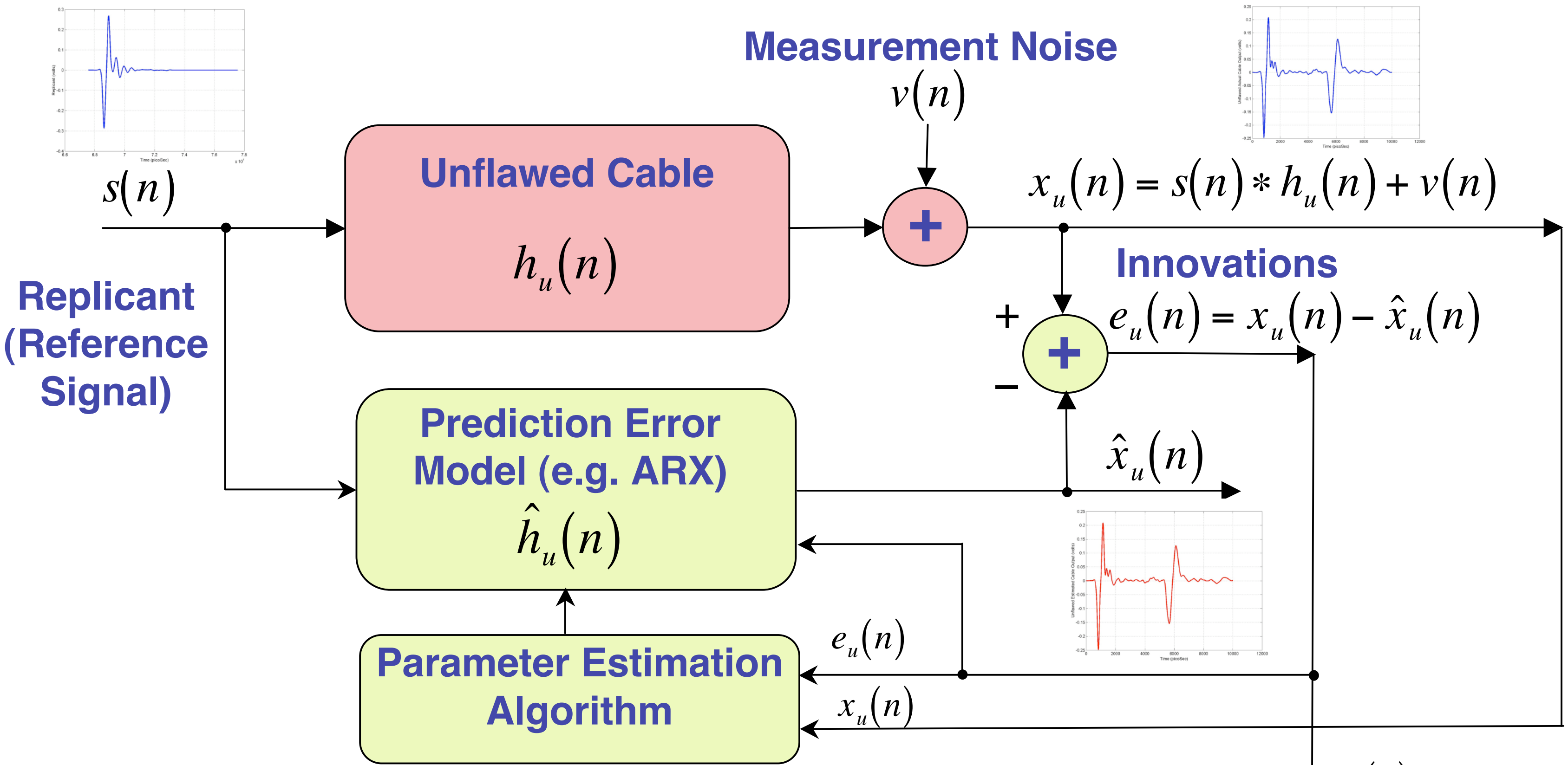
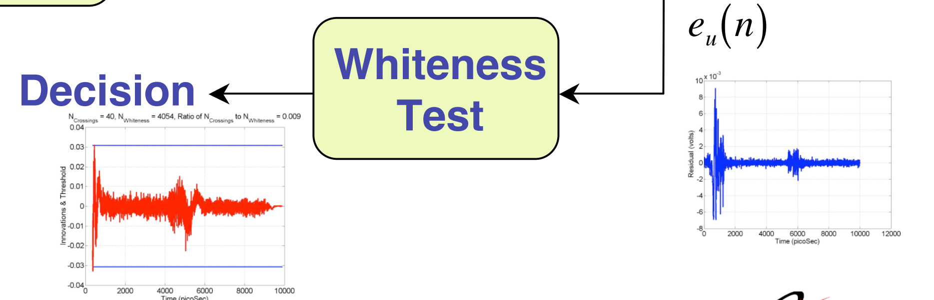
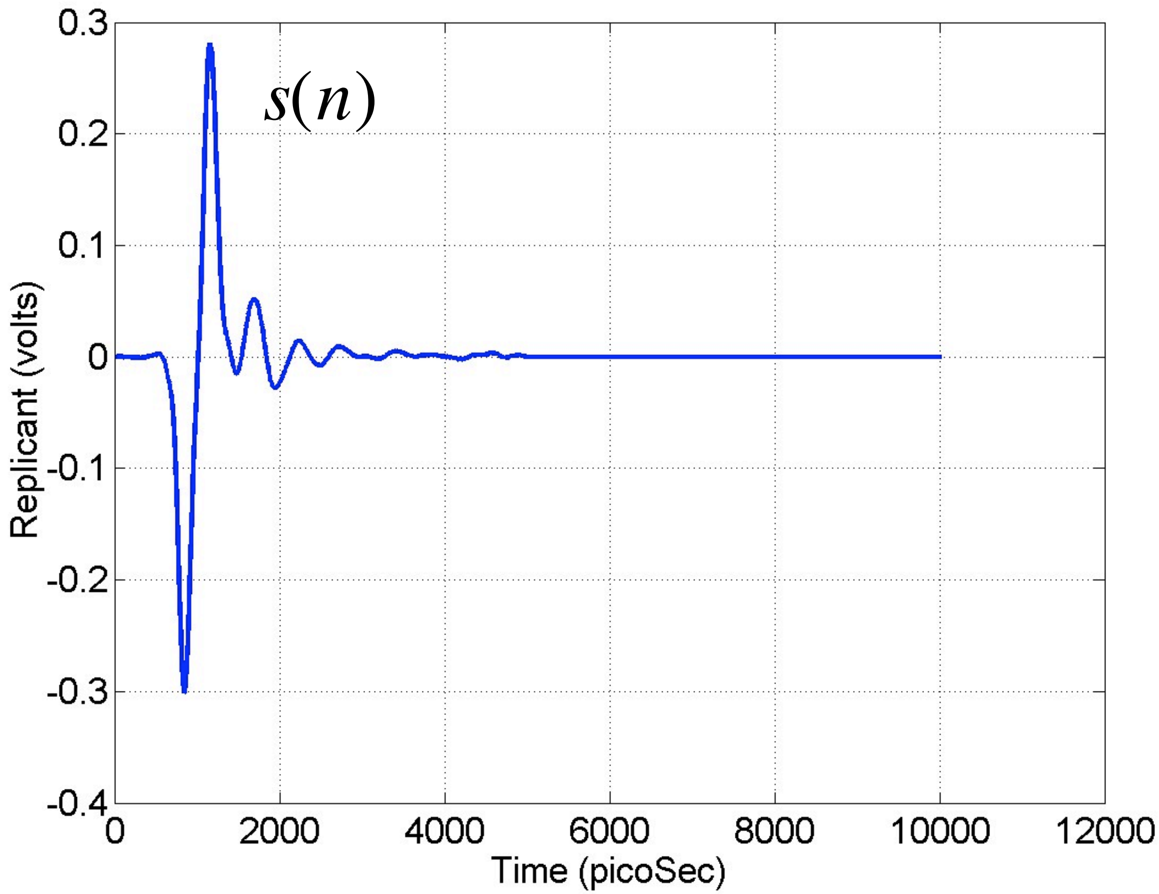


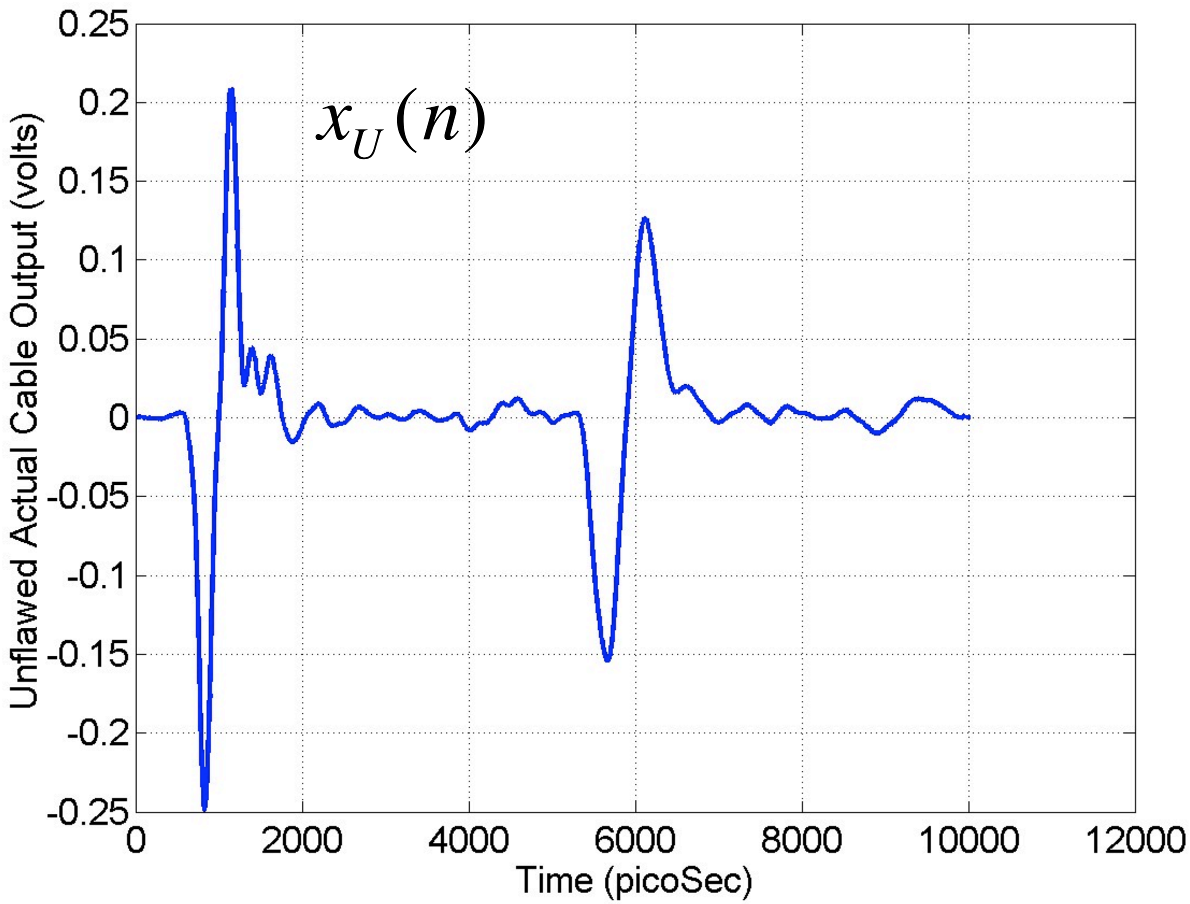

## System Identification:

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

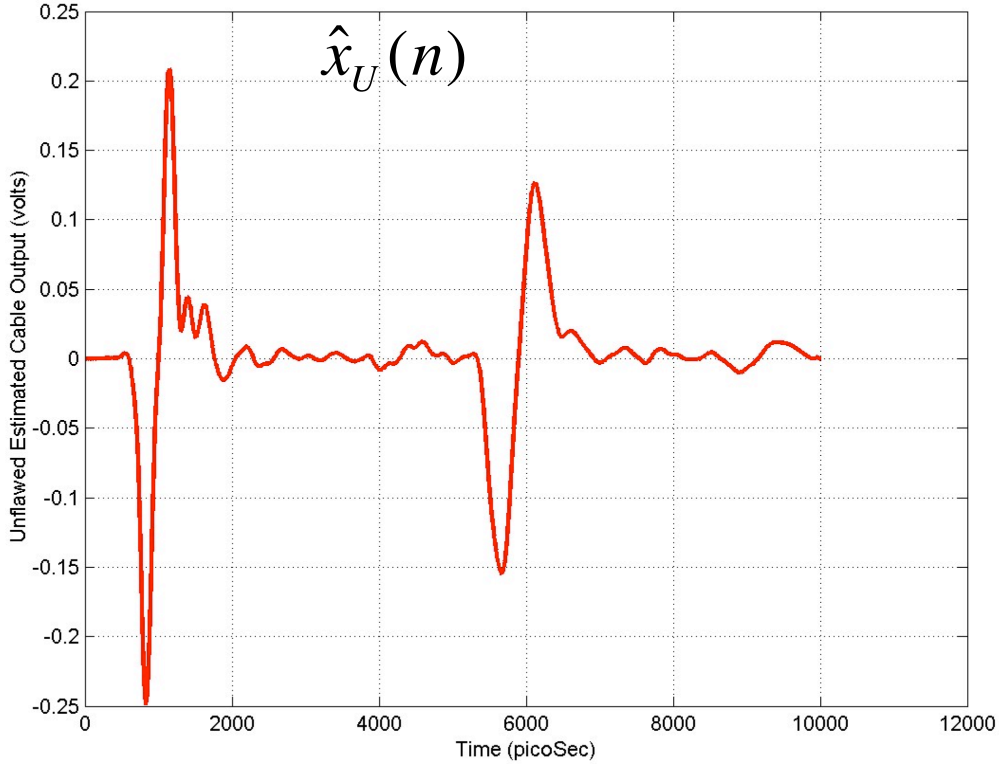
# $s(n)$ = *Reference Signal* (Front Reflection) From a "Long" Cable



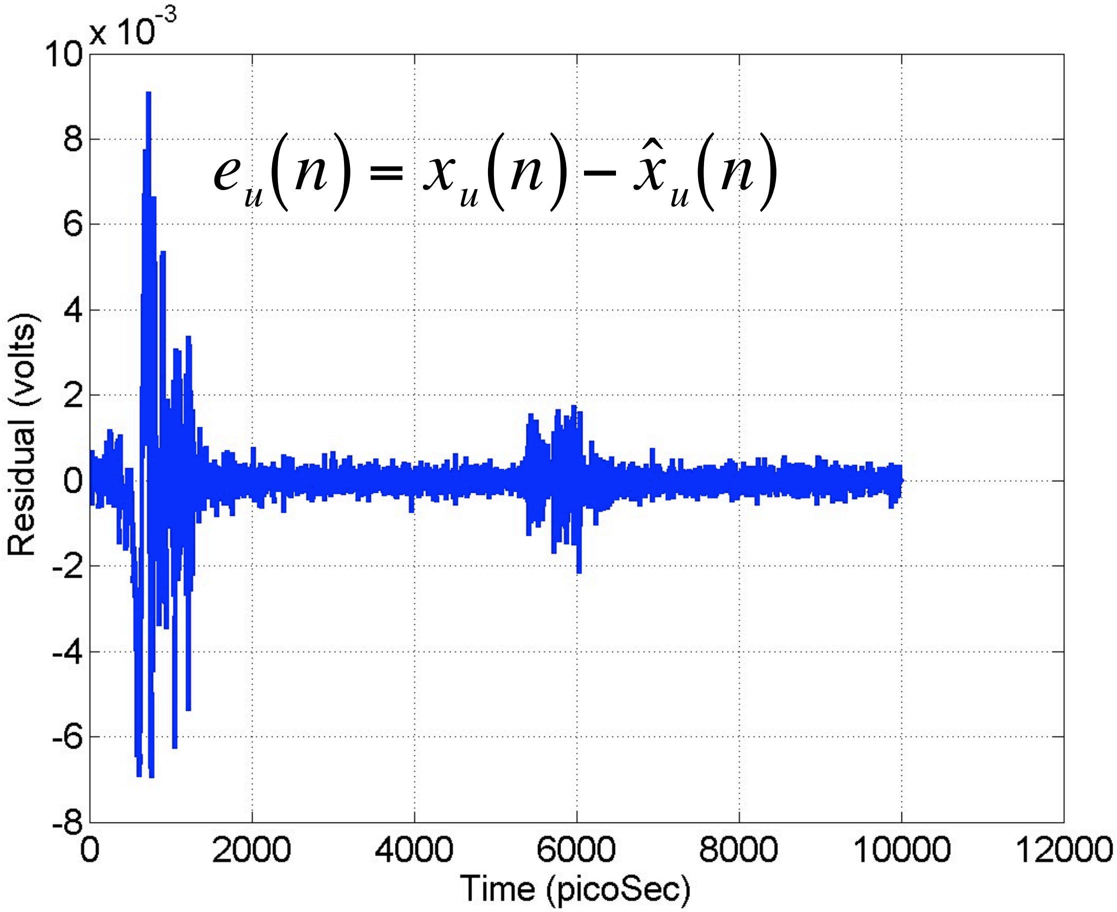
# Unflawed Case:
# $x_U(n)$ = *Unflawed* Cable Output



## Unflawed Case:
## $\hat{x}_U(n)$ = *Estimated* ***Unflawed*** **Cable Output**



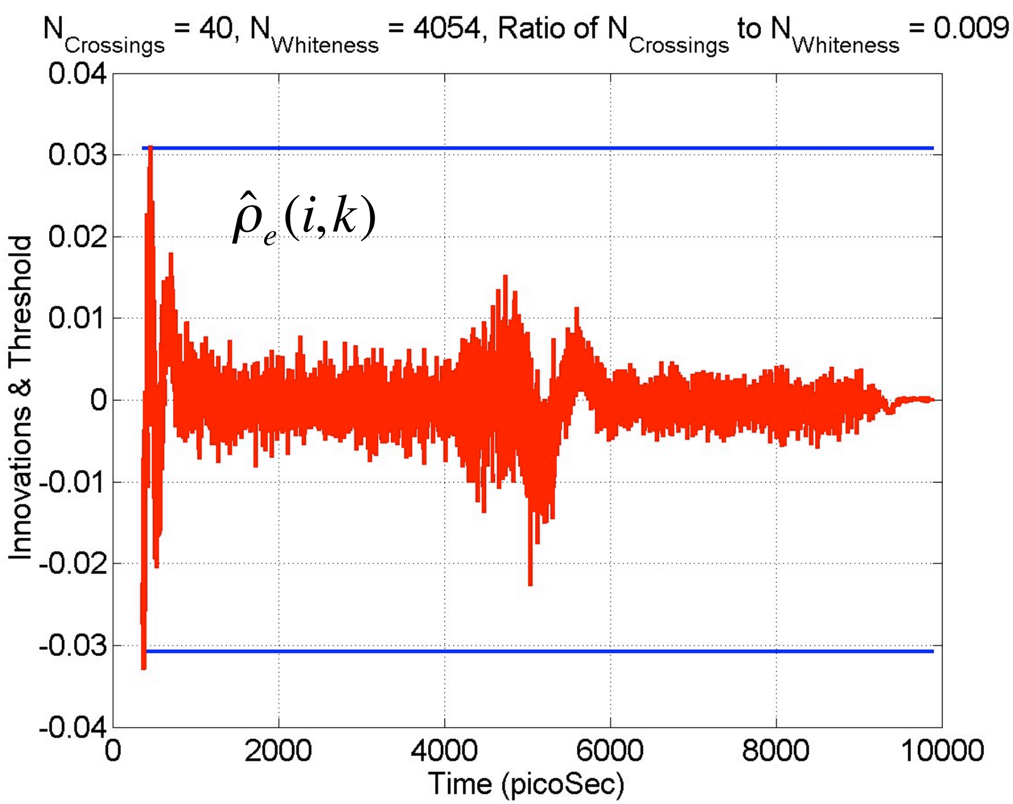
# Unflawed Case:
# Residual (or "Innovations")



# Unflawed Case:
# Whiteness Test on the Innovations



$$e_u(n) = x_u(n) - \hat{x}_u(n)$$ ***= Innovations***




The normalized auto-covariance $\hat{\rho}_e(i,k)$ of the innovations lies within the statistical confidence interval bounds (blue)

$\Longrightarrow$ Declare that the Innovations are "White"

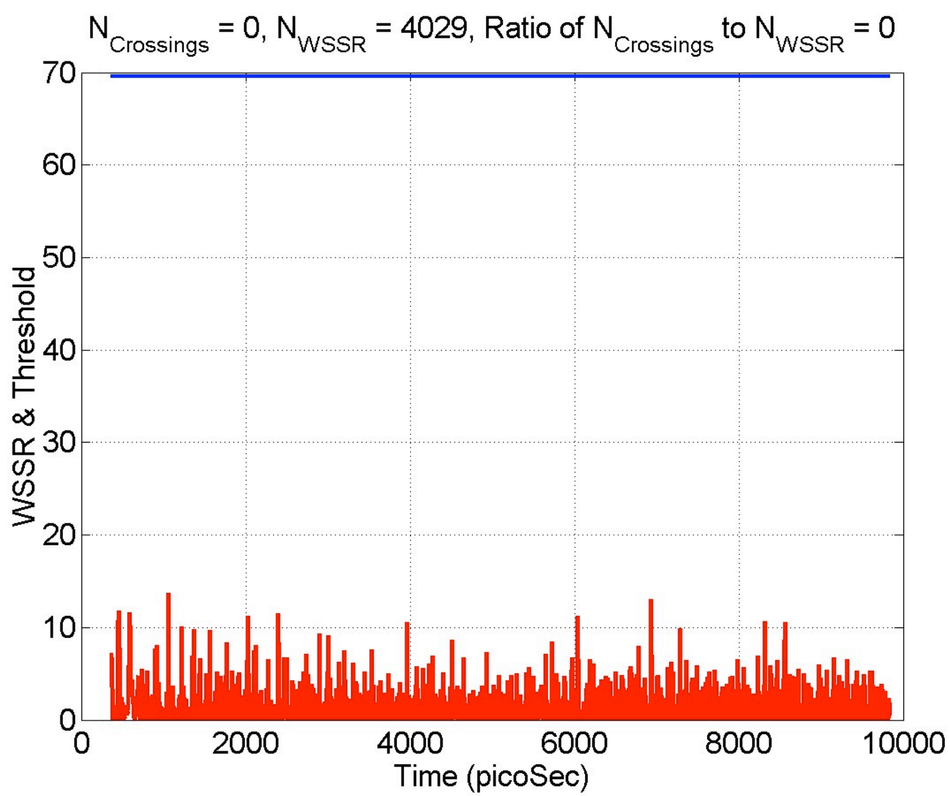
$\Longrightarrow$ There is no model mismatch

$\Longrightarrow$ ***The model is valid***

# Unflawed Case:
# WSSR Test for the Unflawed Case



$$\rho(l) = \sum_{k=l-N+1}^{l} \underline{e}^T(k) R_e^{-1}(k) \underline{e}(k) \quad \text{for } l \ge N \ \ \text{(scalar)}$$




**WSSR = Weighted Sum Squared Residuals**

The WSSR falls within the statistical bound (blue).

$\Longrightarrow$ There exists no model mismatch

$\Longrightarrow$ *The unflawed model is **Valid***

# Step #2: Compare the Responses of the Unflawed and Flawed Cables ==> *Flaw Detection*

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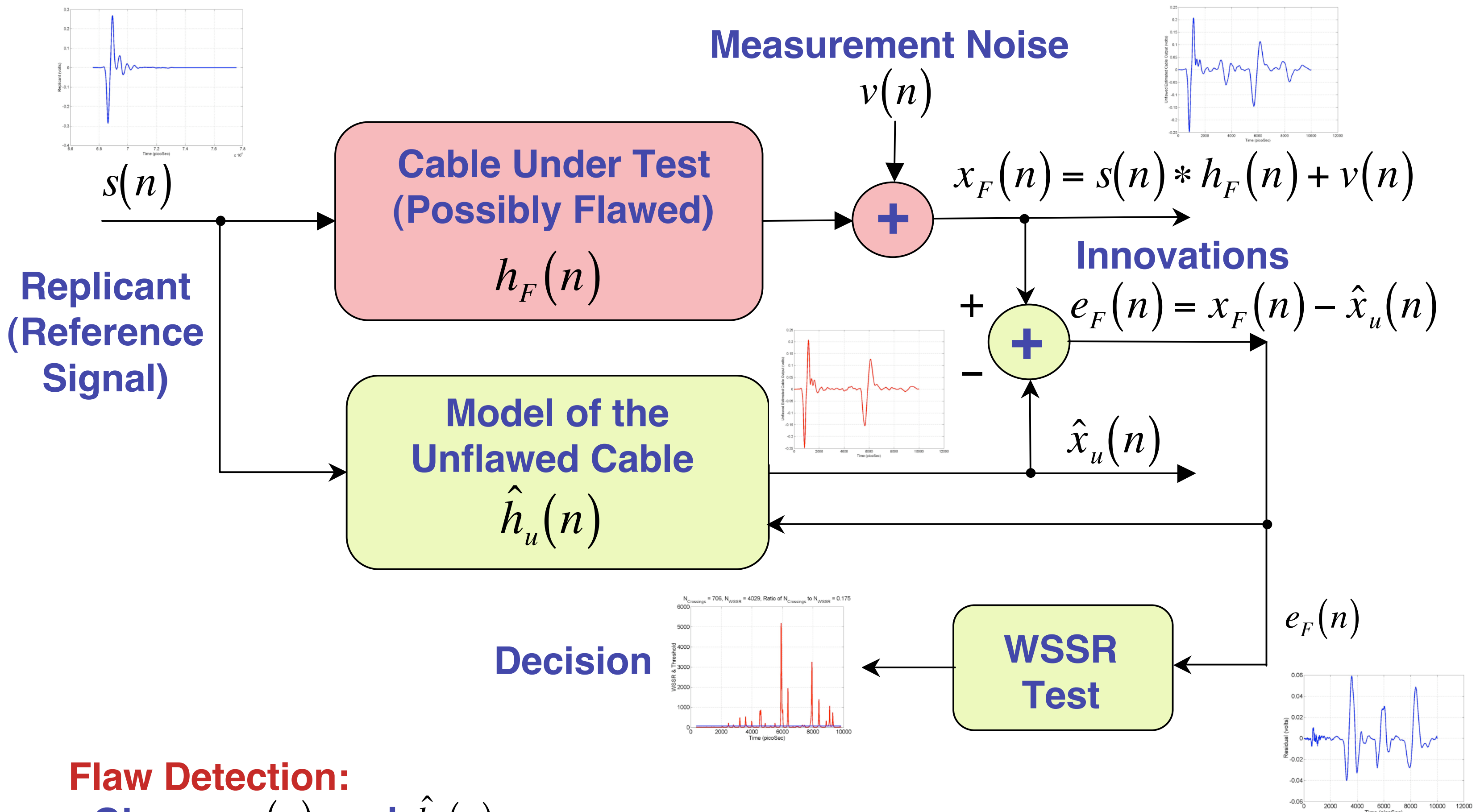
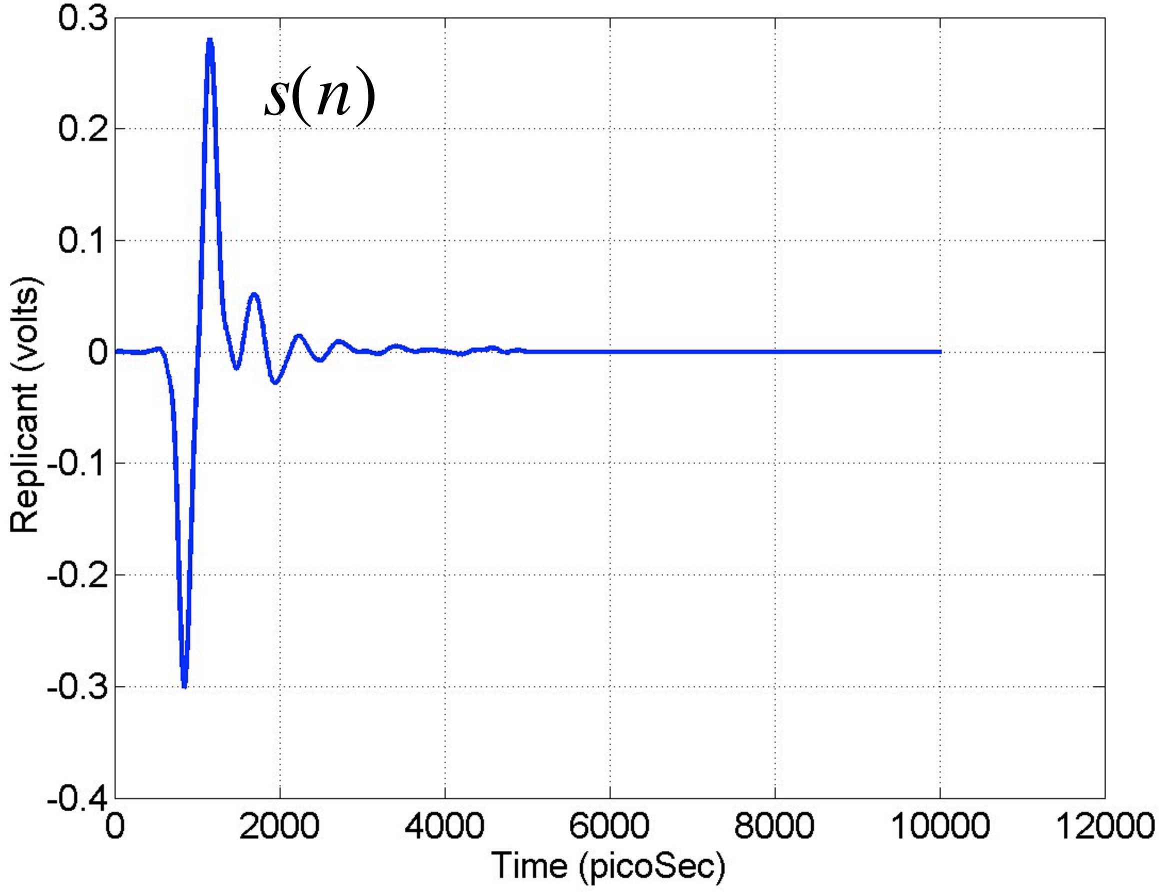



**Flaw Detection:**

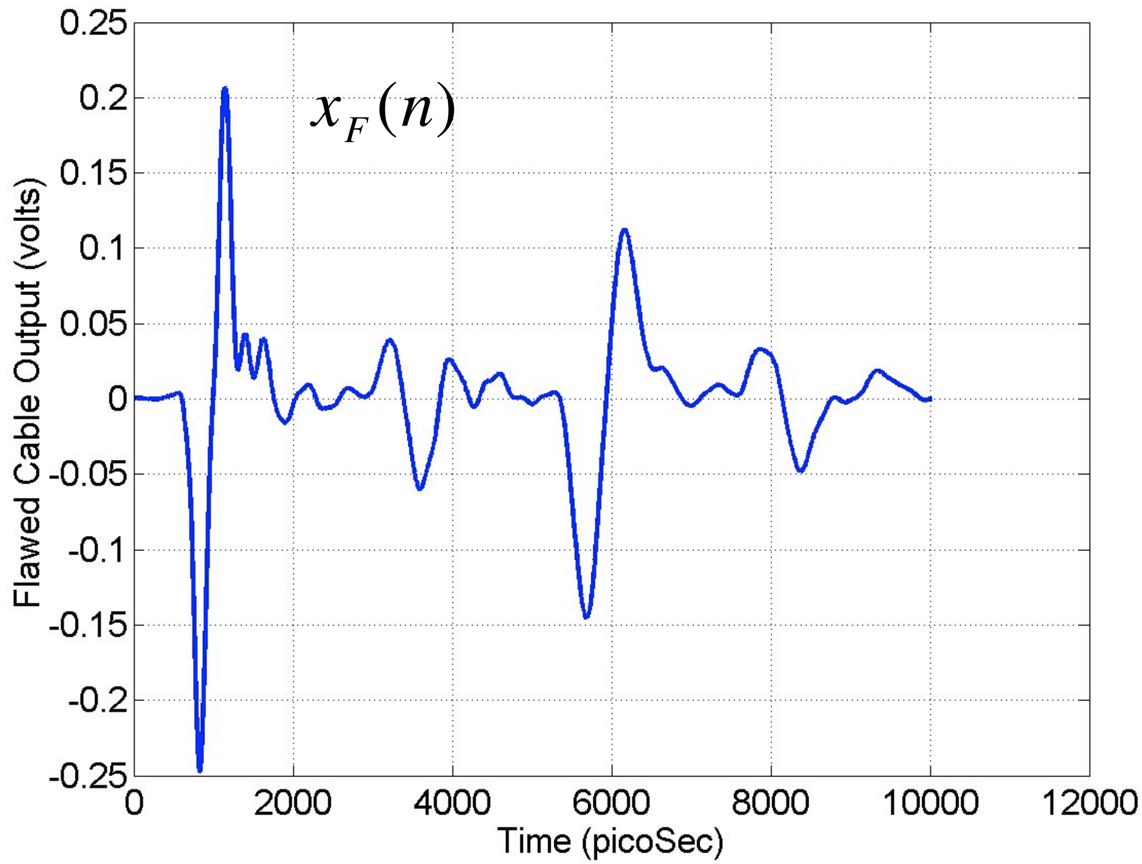
- **Given:** $s(n)$ **and** $\hat{h}_u(n)$
- **Detect flaws by testing the innovations (nonstationary) for whiteness using WSSR (Weighted Sum Squared Residuals) over a moving window**

# $s(n)$ = *Reference Signal* (Front Reflection) From a “Long” Cable



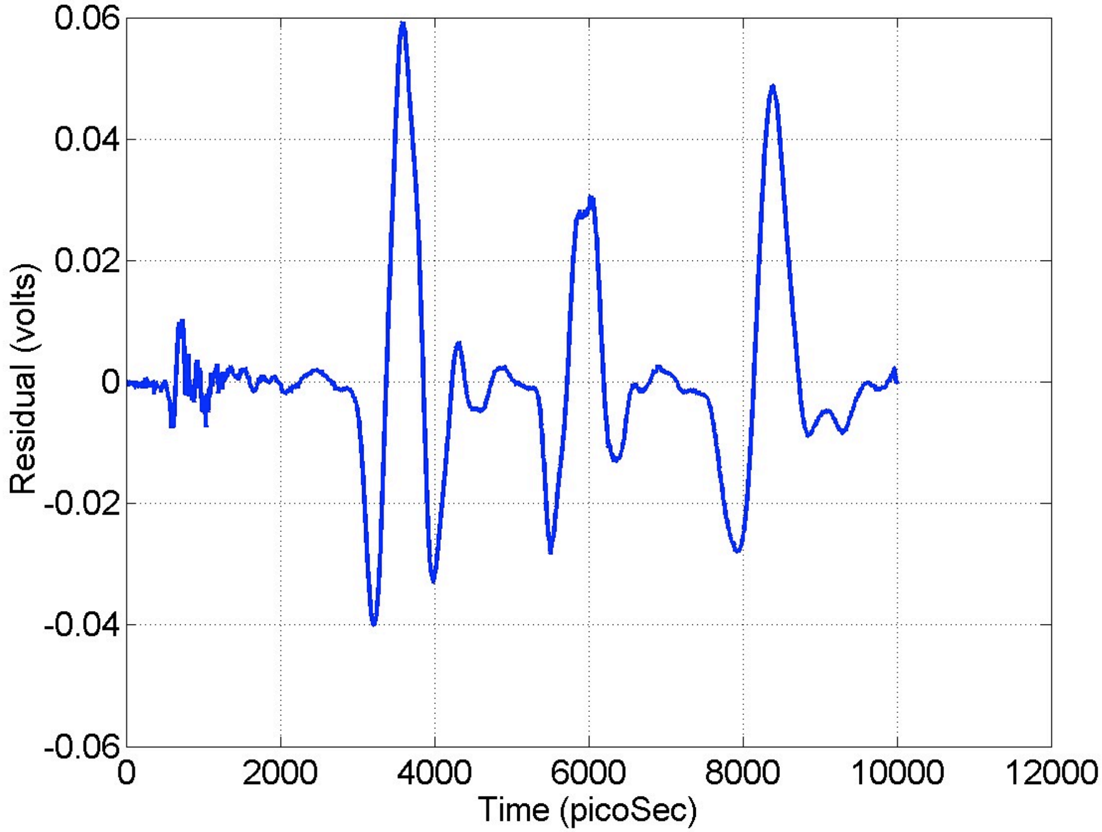
# Flawed Case:

# $x_F(n)$ = *Flawed* Cable Output



# Flawed Case:
# Residual (or "Innovations")

$$e_F(n) = x_F(n) - \hat{x}_u(n)$$ ***= Innovations***



# Flawed Case:
# Whiteness Test For the Flawed Case

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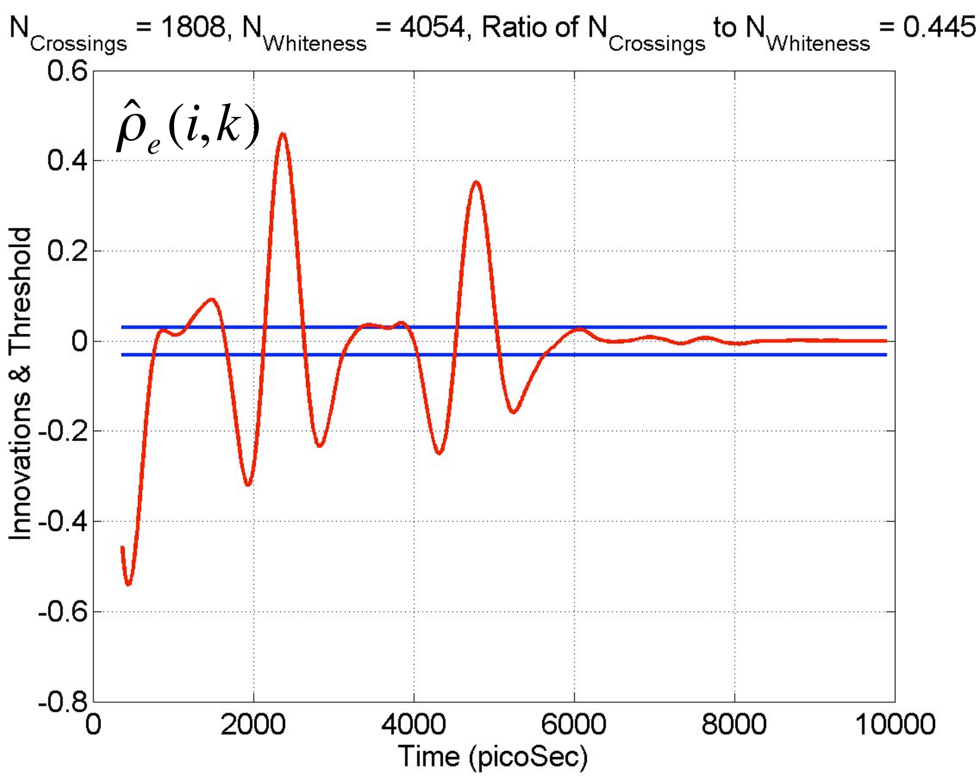
$$e_F(n) = x_F(n) - \hat{x}_u(n)$$ **= *Innovations***




The normalized auto-covariance $\hat{\rho}_e(i,k)$ of the innovations exceeds the statistical confidence interval bounds (blue)

$\Longrightarrow$ Declare that the Innovations are "Not White"

$\Longrightarrow$ There exists a model mismatch

$\Longrightarrow$ *The unflawed model is **NOT** Valid for this cable*

$\Longrightarrow$ ***An anomaly exists in the cable***

# Flawed Case:
# WSSR Test For the Flawed Case

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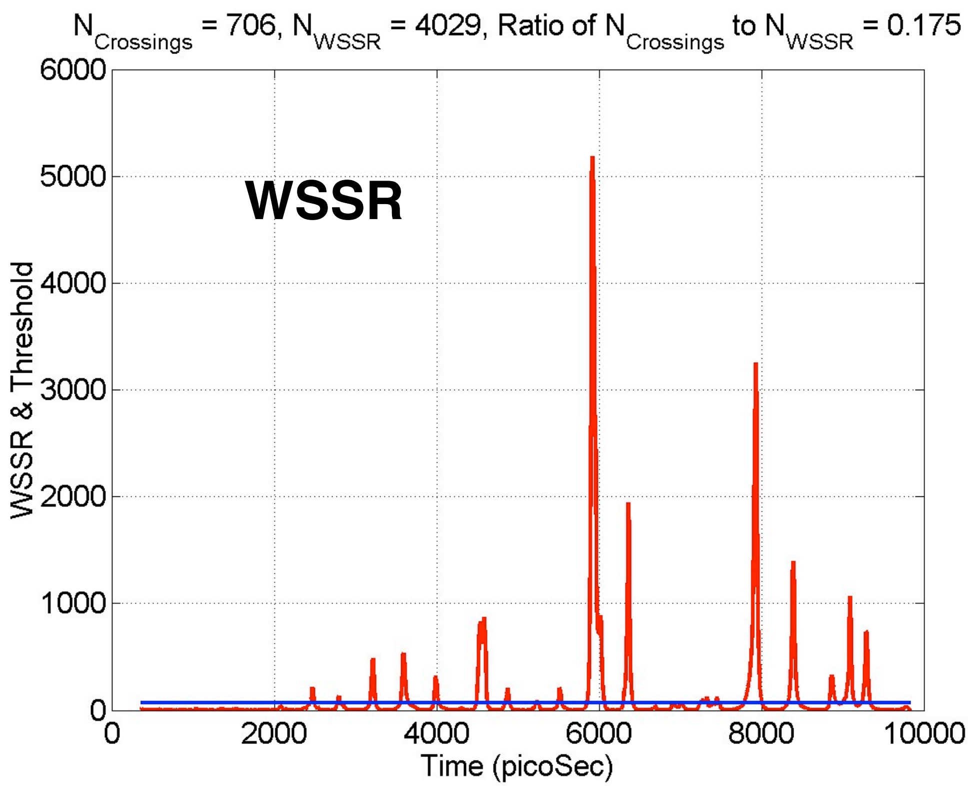
$$\rho(l) = \sum_{k=l-N+1}^{l} \underline{e}^{T}(k) R_e^{-1}(k) \underline{e}(k) \quad \text{for } l \geq N \ \text{(scalar)}$$

**WSSR = Weighted Sum Squared Residuals**




The WSSR exceeds the statistical bound (blue).

$\Longrightarrow$ There exists a model mismatch

$\Longrightarrow$ *The unflawed model is* ***NOT*** *Valid for this cable*

$\Longrightarrow$ ***An anomaly exists in the cable***

# **Discussion:** The Model-Based Approach Offers Advantageous Properties



- We can estimate the *LOCATION* of any detected anomaly.

- The algorithm is *robust* with respect to variations in the measured signals for various experimental scenarios:

  ==> If the TDR signals vary for various scenarios, we can model each case and test the cables effectively.

- This algorithm is very effective, even if we are given *only a single exemplar* of an unflawed cable signal.

# Discussion: Future Work:

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- Thorough repeatability studies:
  - Measurement-to-measurement for one cable
  - Cable-to-cable

- Given an ensemble of measurements,
  we can build more extensive performance measures:
  - Receiver Operating Characteristic (ROC) curves
    Probability of Detection
    vs. Probability of False Alarm
  - Statistical Confidence Interval about the estimated
    probability of correct classification

- Experiments in a cable environment (not just bench-top)

- Cable "insult" studies using estimated damage types