Using Wavelets to Analyze Random Telegraph Signal Noise

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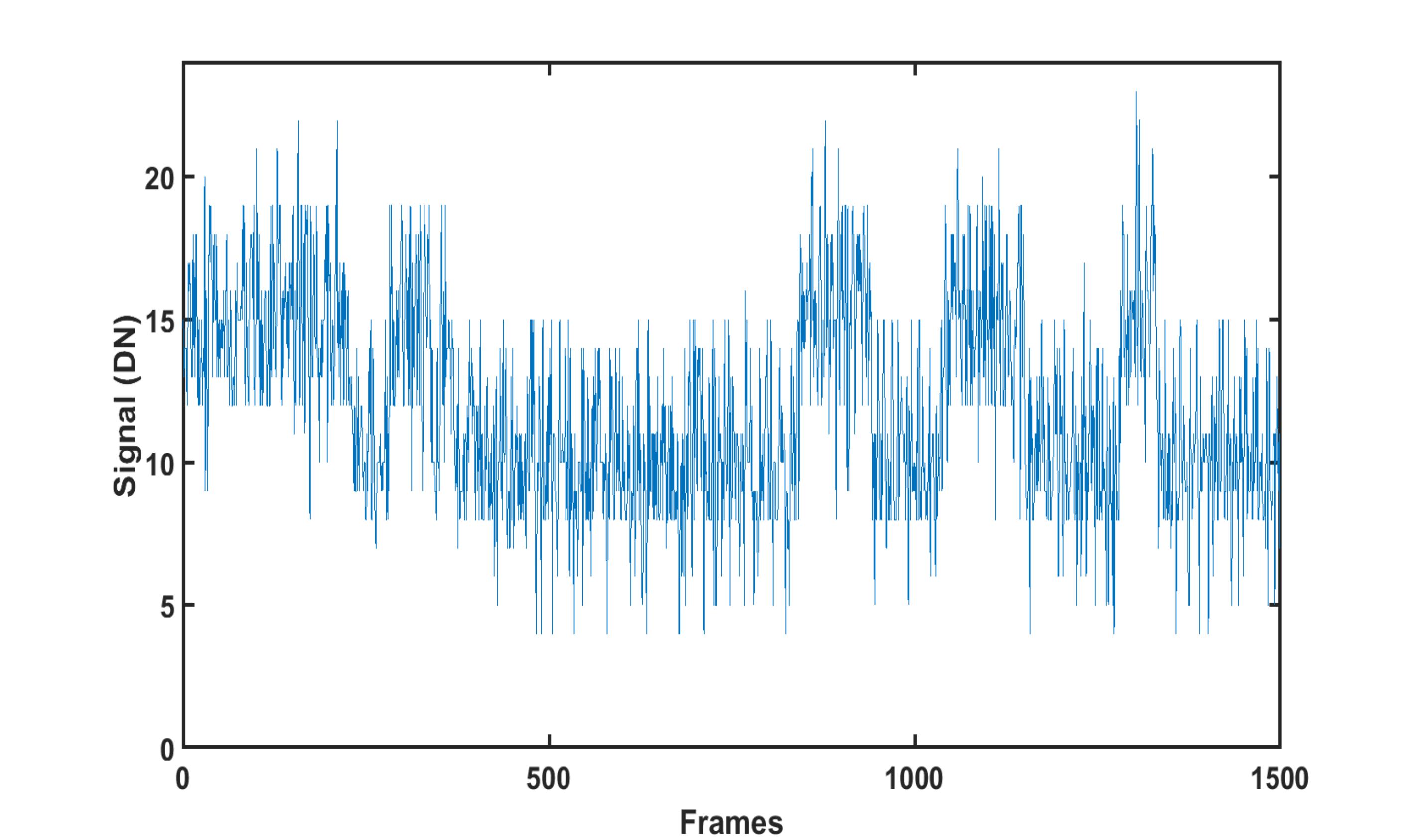
RTS Noise - Overview

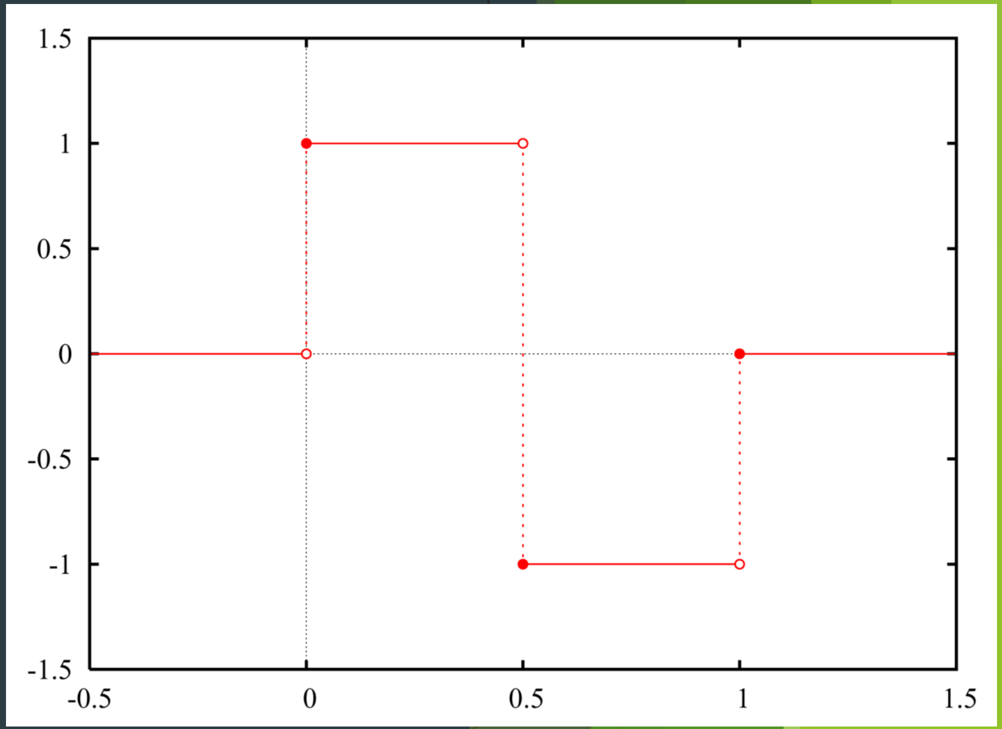
- Observed in CCD and CMOS architectures
- Defined by discrete changes in signal level (blinking pixels)
- Stochastic process with Poisson distributed state lifetimes
- Characterized by similar lifetimes



The Haar Wavelet & Discrete Wavelet Transform

- An orthonormal basis set developed by Alfred Haar in 1909
- Left largely in obscurity until DeBauchies pioneering work constructing and using wavelets for digital signal processing and analysis

- DWT Useful for edge detection applications
- Acts like a microscope, signals analyzed at a variety of scales



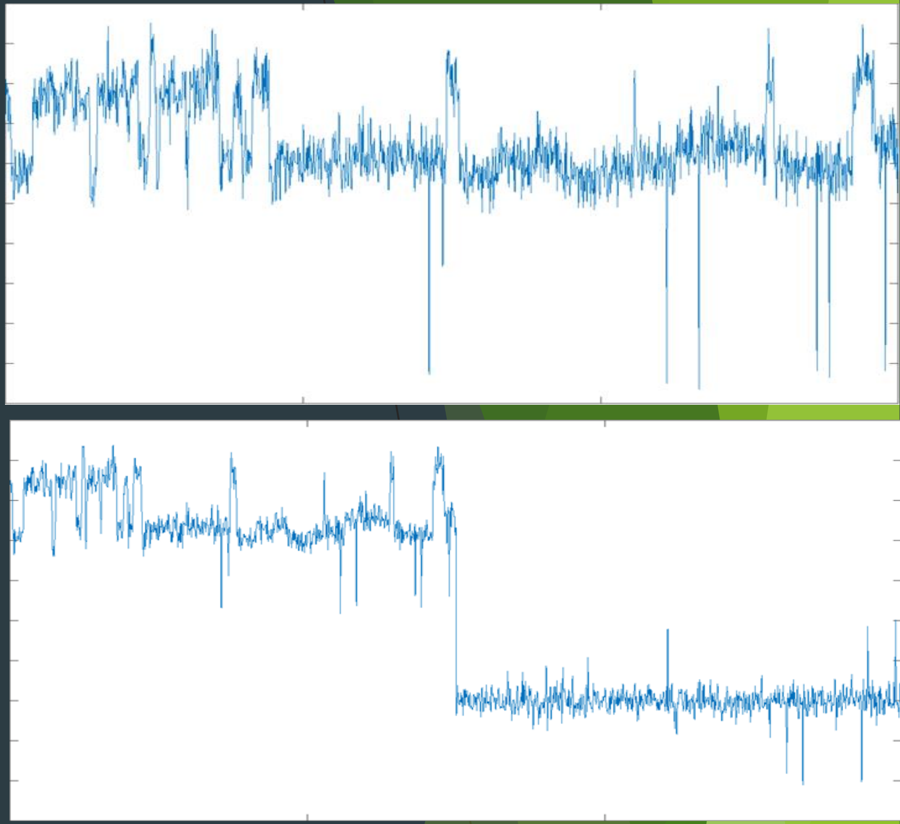
Experimental Parameters for radiation effects in Si image sensors

- COTS Omnivision OV5647
- Raw frames taken using a Raspberry Pi 3
- Five sensors irradiated with a continuum of high energy γ and x-rays (peak - $2MeV$)
- 1500 frames taken at 0.05 frames/s
  - ~ 8.3 hours total measurement time
- Frames taken in dark at 23°C

Absorbed Ionizing Dose (rad - Si)
500
2,500
5,000
10,000
25,000

Haar Wavelet Analysis – DWT

- Consider a digital signal $\mathbf{f} = (f_1, f_2, f_3, \dots f_N)$
- The discrete wavelet transform (DWT) breaks f into two 'daughter' series of length $\mathrm{N}/2$
  - Trend Series Members
    - $a_m = \frac{f_{2m-1}+f_{2m}}{\sqrt{2}} \qquad 1 < m \leq N/2$
  - Details Series Members
    - $d_m = \frac{f_{2m-1}-f_{2m}}{\sqrt{2}} \qquad 1 < \; m \leq N/2$



J. S. Walker, A Primer on Wavelets and their Scientific Applications. Boca Raton [Fla.]: Chapman & Hall/CRC, 2nd ed., 2008.

Haar Wavelet Analysis – DWT (cont.)

- The DWT is similar to a microscope because it is repeatable
  - The trend series is treated as the new ‘mother’ signal

- Each time a subsequent transform is performed the ‘daughter’ series are of half size
  - The new ‘daughter’ series represent twice as many values from the original signal

Wavelet Operators – Trends Series

- $\mathbf{V}_1^1 = \frac{1}{\sqrt{2}}(1,1,0,0,0,\ldots); \; \mathbf{V}_2^1 = \frac{1}{\sqrt{2}}(0,0,1,1,0,\ldots)$

$$a_1 = \frac{f_1+f_2}{\sqrt{2}} = \mathbf{f}\cdot\mathbf{V}_1^1; \;\; a_2 = \frac{f_3+f_4}{\sqrt{2}} = \mathbf{f}\cdot\mathbf{V}_2^1$$

$$a_m = \frac{f_{2m-1}+f_{2m}}{\sqrt{2}} = \mathbf{f}\cdot\mathbf{V}_m^1$$

Wavelet Operators – Details Series

- $\mathbf{W}_1^1 = \frac{1}{\sqrt{2}}(1, -1, 0, 0, 0, \dots), \ \mathbf{W}_2^1 = \frac{1}{\sqrt{2}}(0, 0, 1, -1, 0, \dots)$

$$d_1 = \frac{f_1 - f_2}{\sqrt{2}} = \mathbf{f} \cdot \mathbf{W}_1^1; \quad d_2 = \frac{f_3 - f_4}{\sqrt{2}} = \mathbf{f} \cdot \mathbf{W}_2^1$$

$$d_m = \frac{f_{2m-1} - f_{2m}}{\sqrt{2}} = \mathbf{f} \cdot \mathbf{W}_m^1$$

The Inverse Transform

$$\mathbf{f} = \left(\frac{a_1 + d_1}{\sqrt{2}}, \frac{a_1 - d_1}{\sqrt{2}}, \ldots \frac{a_{\frac{N}{2}} + d_{\frac{N}{2}}}{\sqrt{2}}, \frac{a_{\frac{N}{2}} - d_{\frac{N}{2}}}{\sqrt{2}}\right)$$

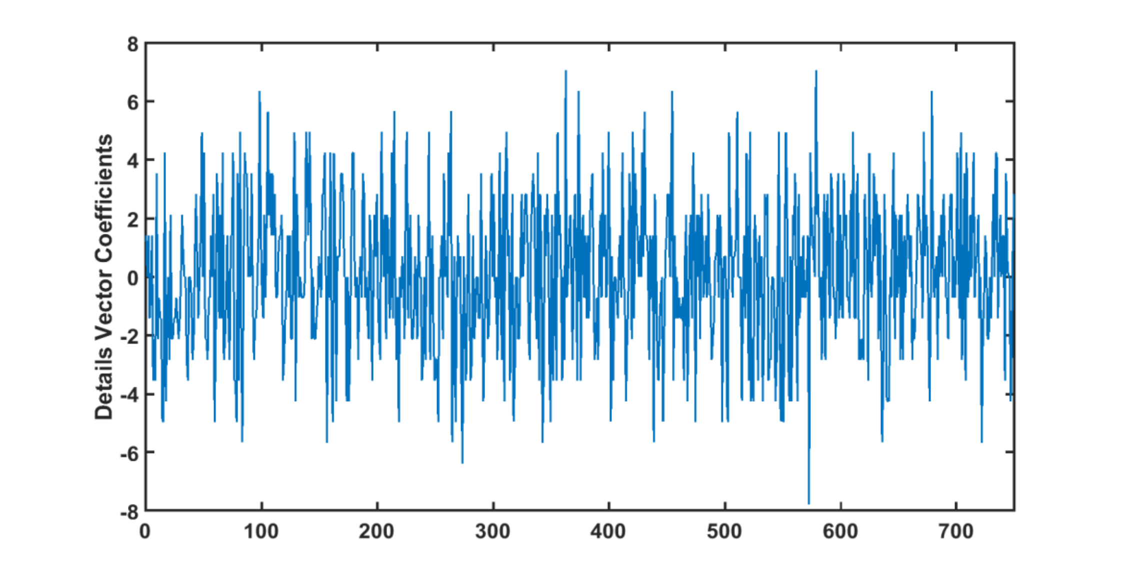
DWT – Denoising

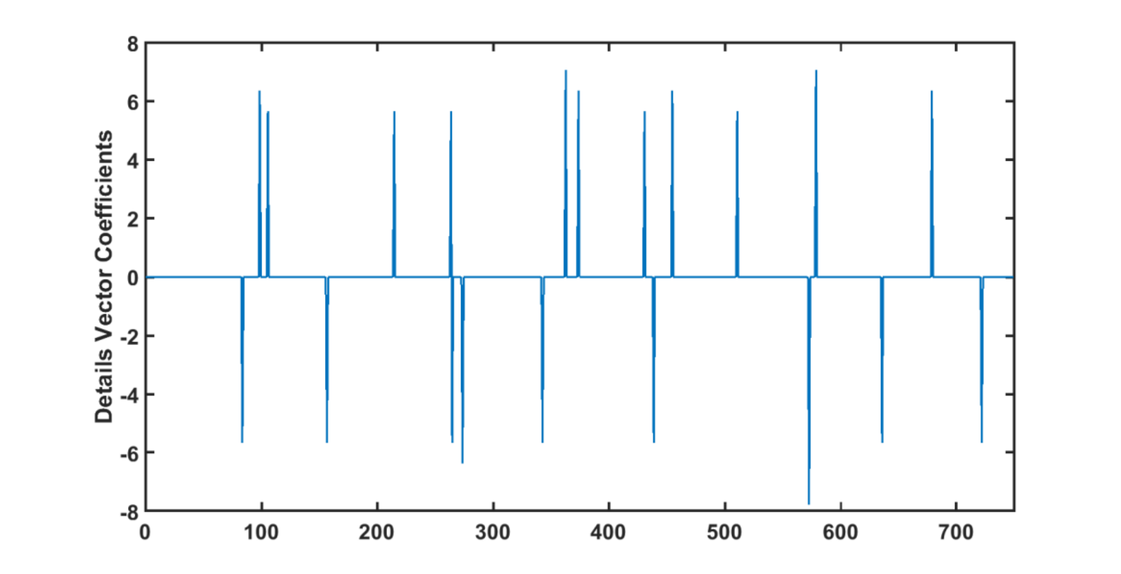
- White noise is suppressed by thresholding the details series
  - Similar to a high-pass/low-pass filter
  - Based on magnitude rather than frequency
- The threshold is statistically derived

$$\mathrm{T} = \hat{\sigma}\sqrt{2\log(n)}$$

- T is the universal threshold derived by Donoho and Johnstone†
- Values below the threshold are set to zero

† G. P. Nason, "Choice of the threshold parameter in wavelet function estimation," Wavelets and statistics, vol. 103, pp. 261–280, 1995.



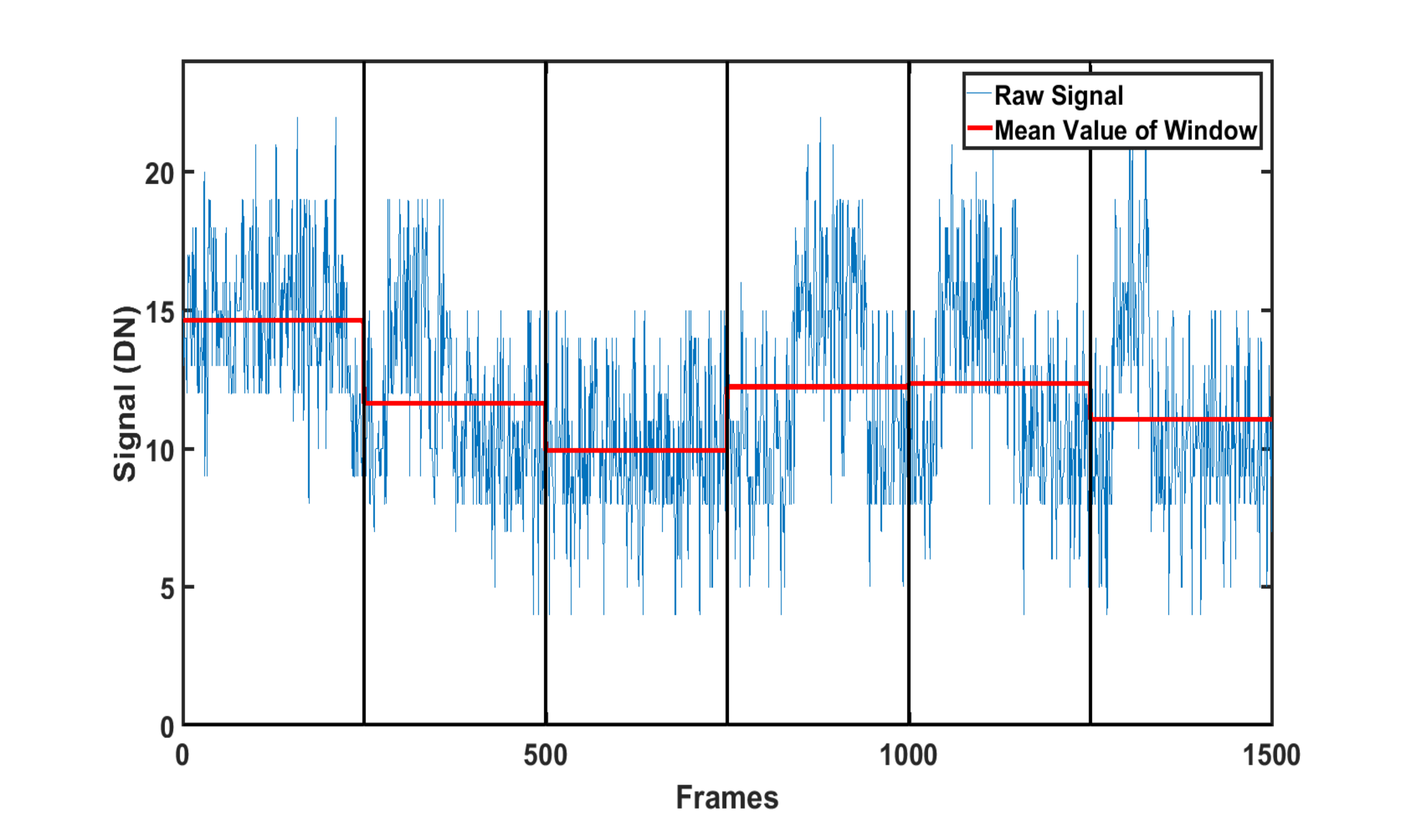


Approximation Signal Construction

- The goal is to remove all noise from the signal except for the RTS transitions
- The DWT is performed seven times and thresholded at every iteration
- The chosen threshold is designed be highly discriminatory to prevent false positive detections
- A temporal screen is implemented to remove contributions from single events like cosmic rays

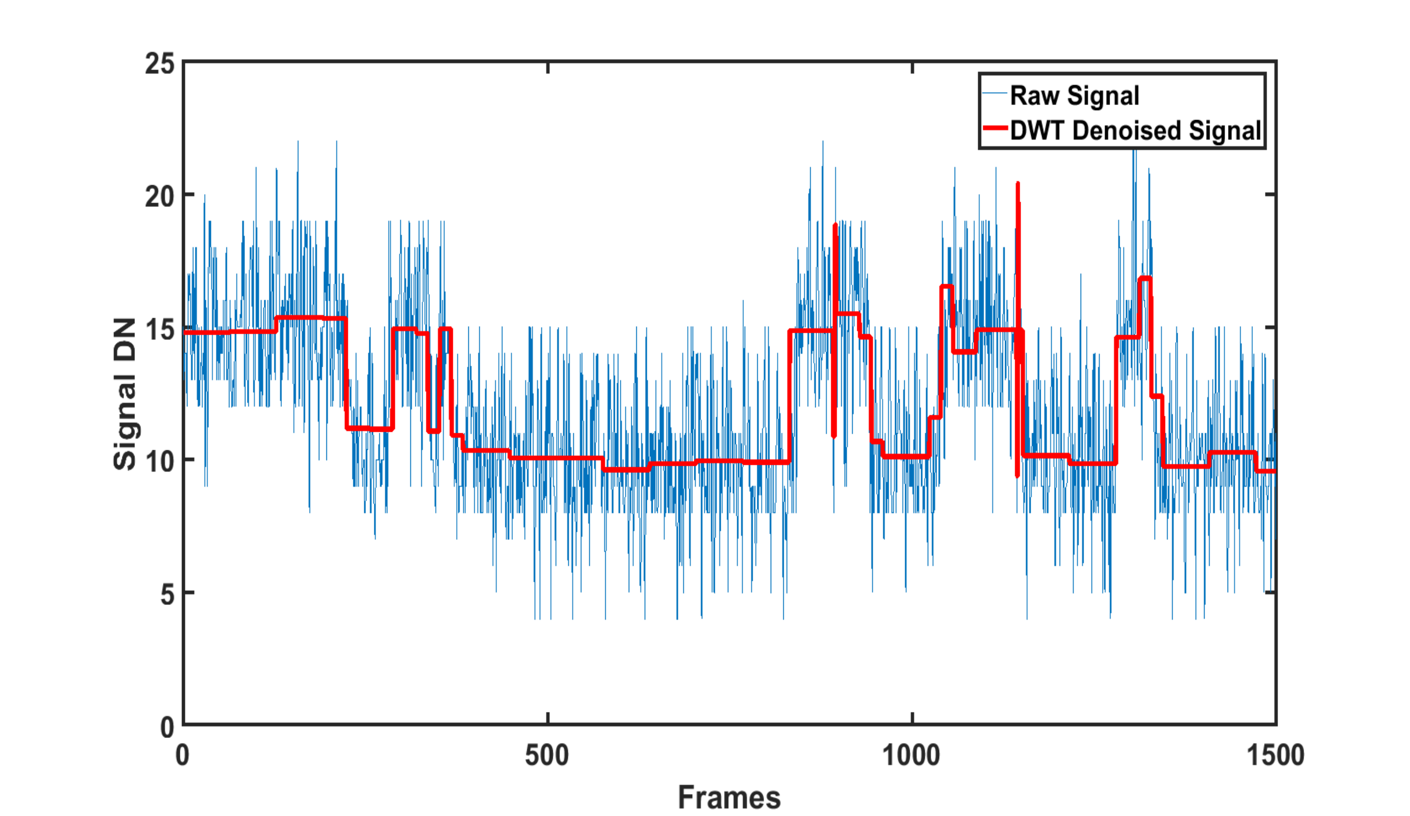
Approximation Signal Construction Stage 1: Window Comparison

- Cut signal into six windows
- Compare the mean of a window to the previous two
- If any difference is greater than the standard deviation of the noise σ_r the signal progresses as an RTS candidate
- Crude, but highly effective and discriminatory



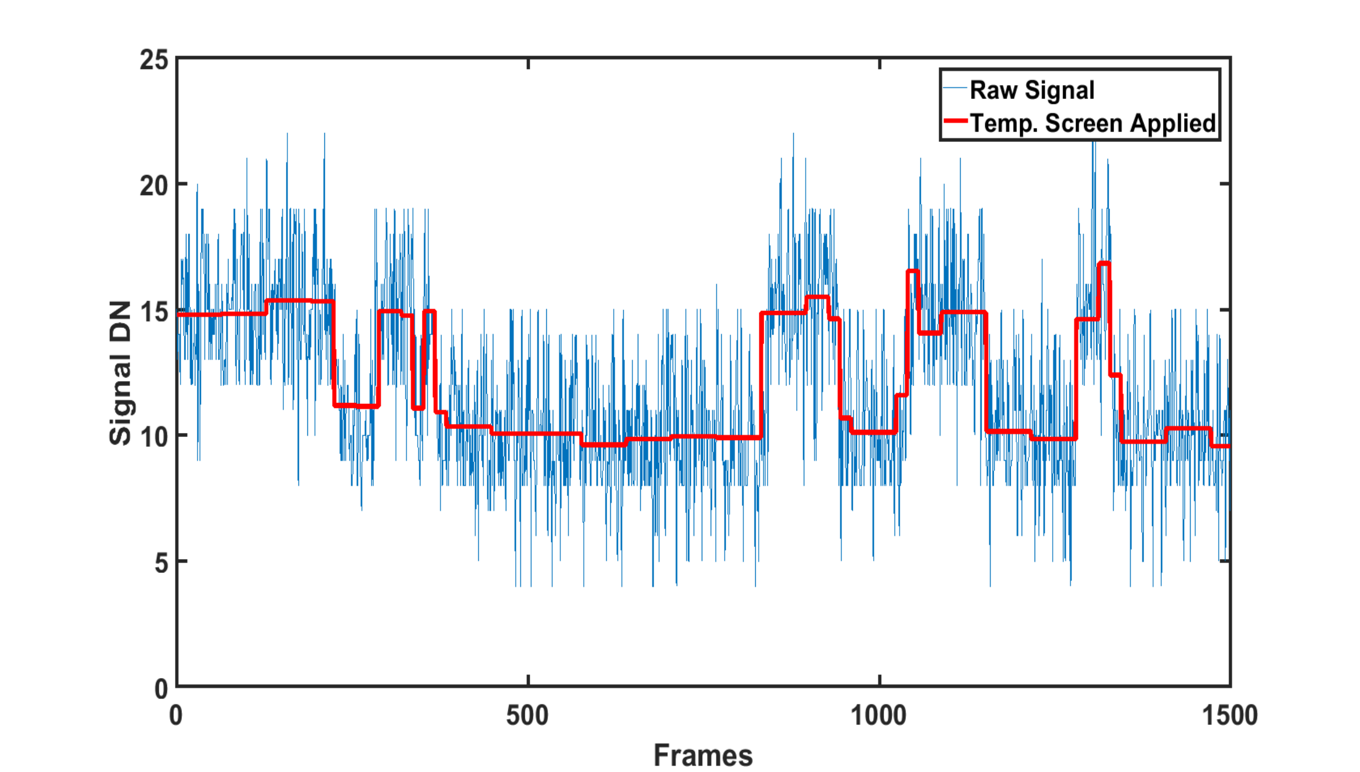
Approximation Signal Construction Stage 2: DWT Denoising

- The signal is run through the DWT denoising method as described previously
- The white noise is greatly reduced, but a few transients remain



Approximation Signal Construction Stage 3: Temporal Screen

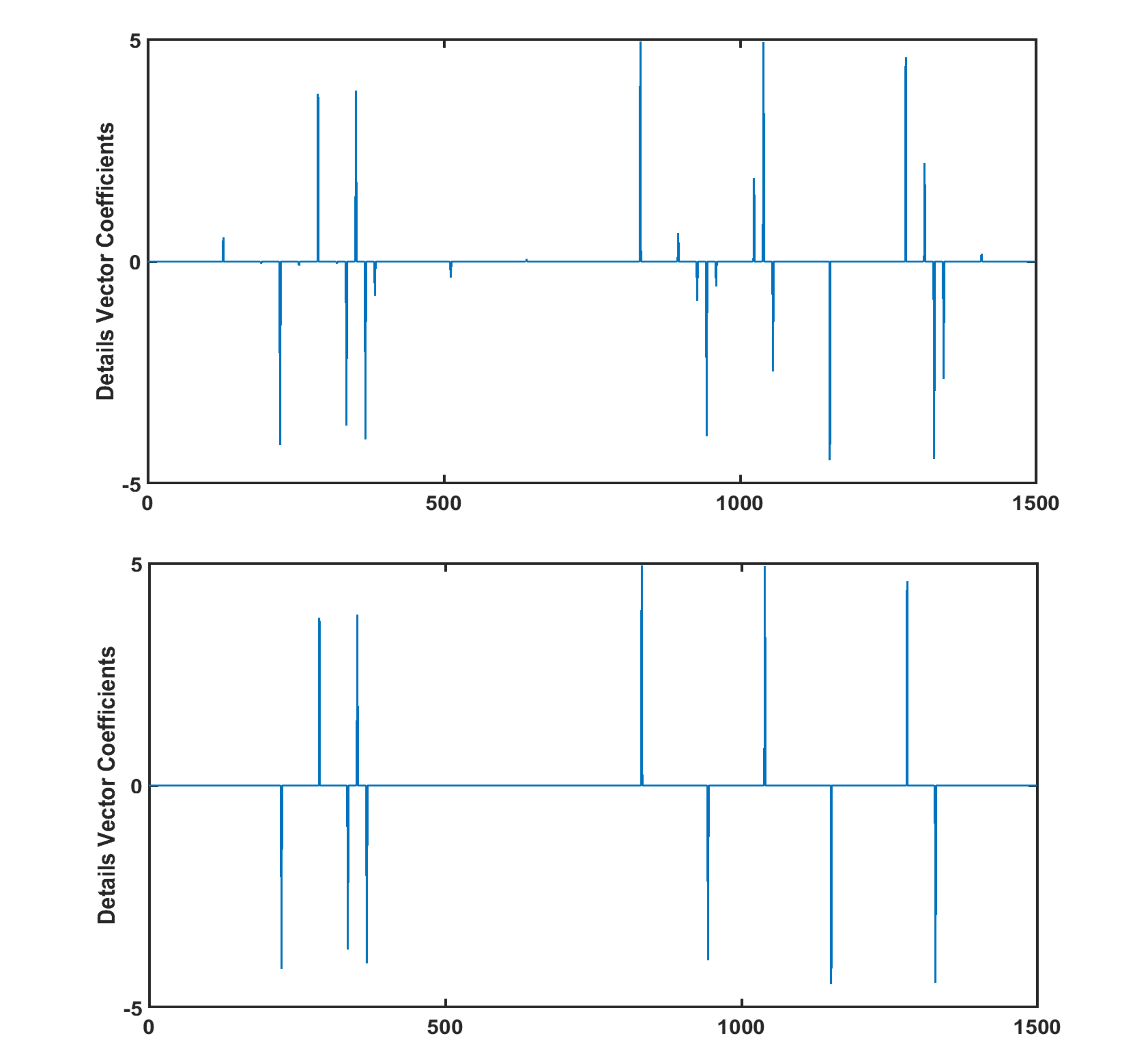
- To remove transients, a simple running comparison is implemented to verify the stability of a transition
- When a change in magnitude happens at frame k, its value is compared to the next l frames where $l = 10$
- If the value is unchanged the transition is considered stable and left alone
- If the value changes is considered a transient, and is changed to the value at frame $k - 1$



Approximation Signal Construction Stage 4: A Second Thresholding

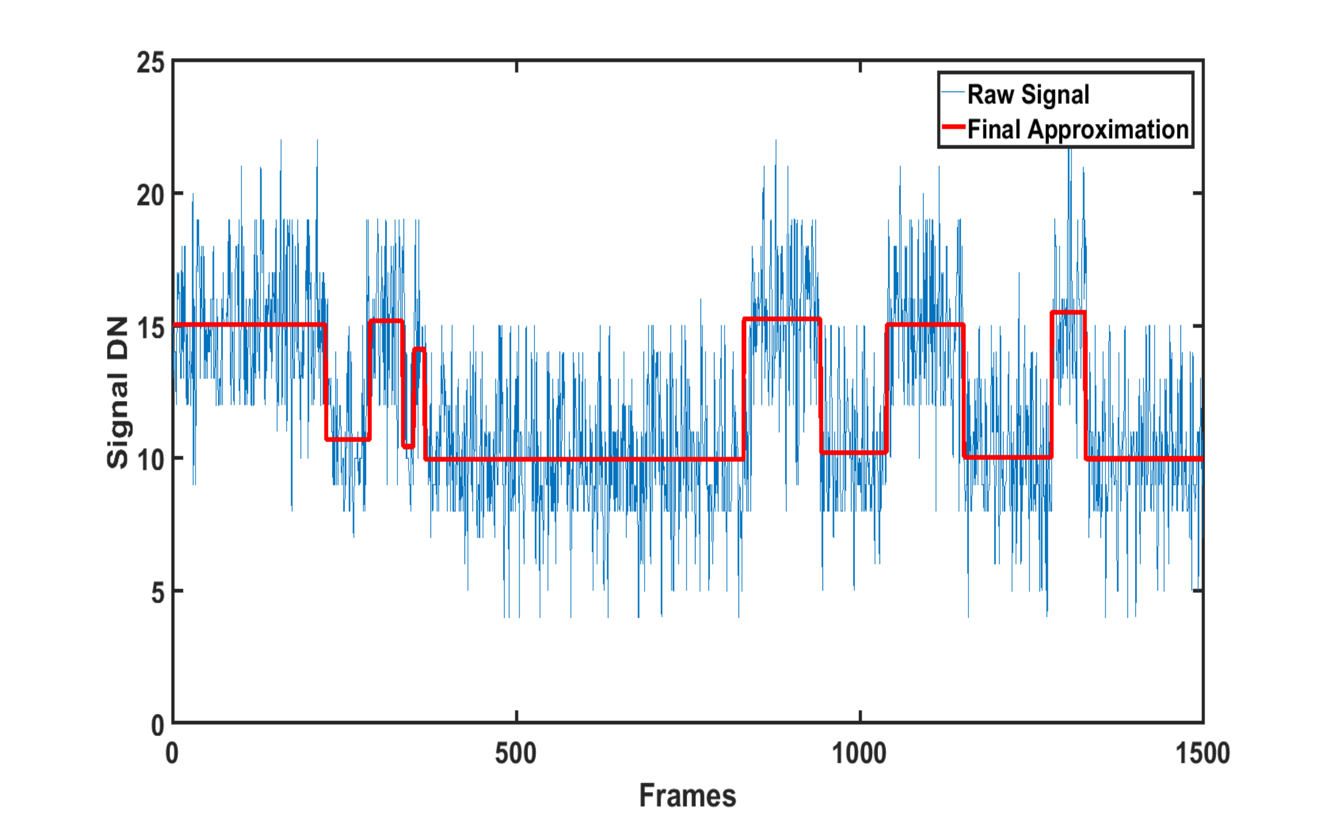
- Nearly all of the white noise is removed, but a few small changes remain
- A new details series is creating by subtracting each frame value by the previous frame value
- The new details series s is of $N - 1$ where N is the size of the original signal
- Because the noise is already suppressed, the threshold need not be so discriminatory, as such

$$T_s = s_{MAX} * u_{0.75}$$



Approximation Signal Construction Stage 5: Final Reconstruction

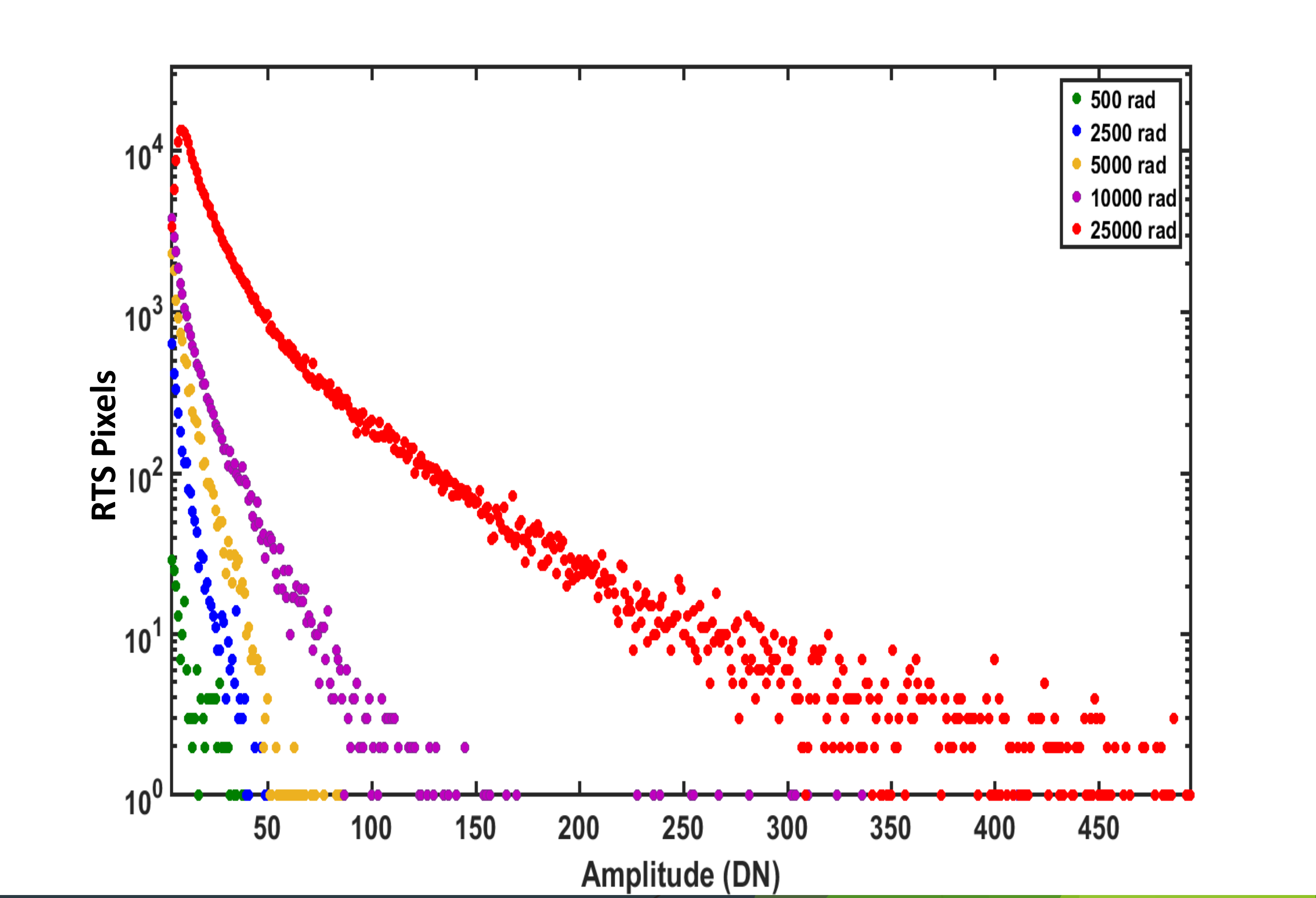
- The final approximation is created by applying the mean of the original signal to the segments between the remaining non-zero values of the latest details series
- With the new approximation complete the RTS amplitudes and time constants can be gathered easily for analysis



Results – Maximum Amplitudes

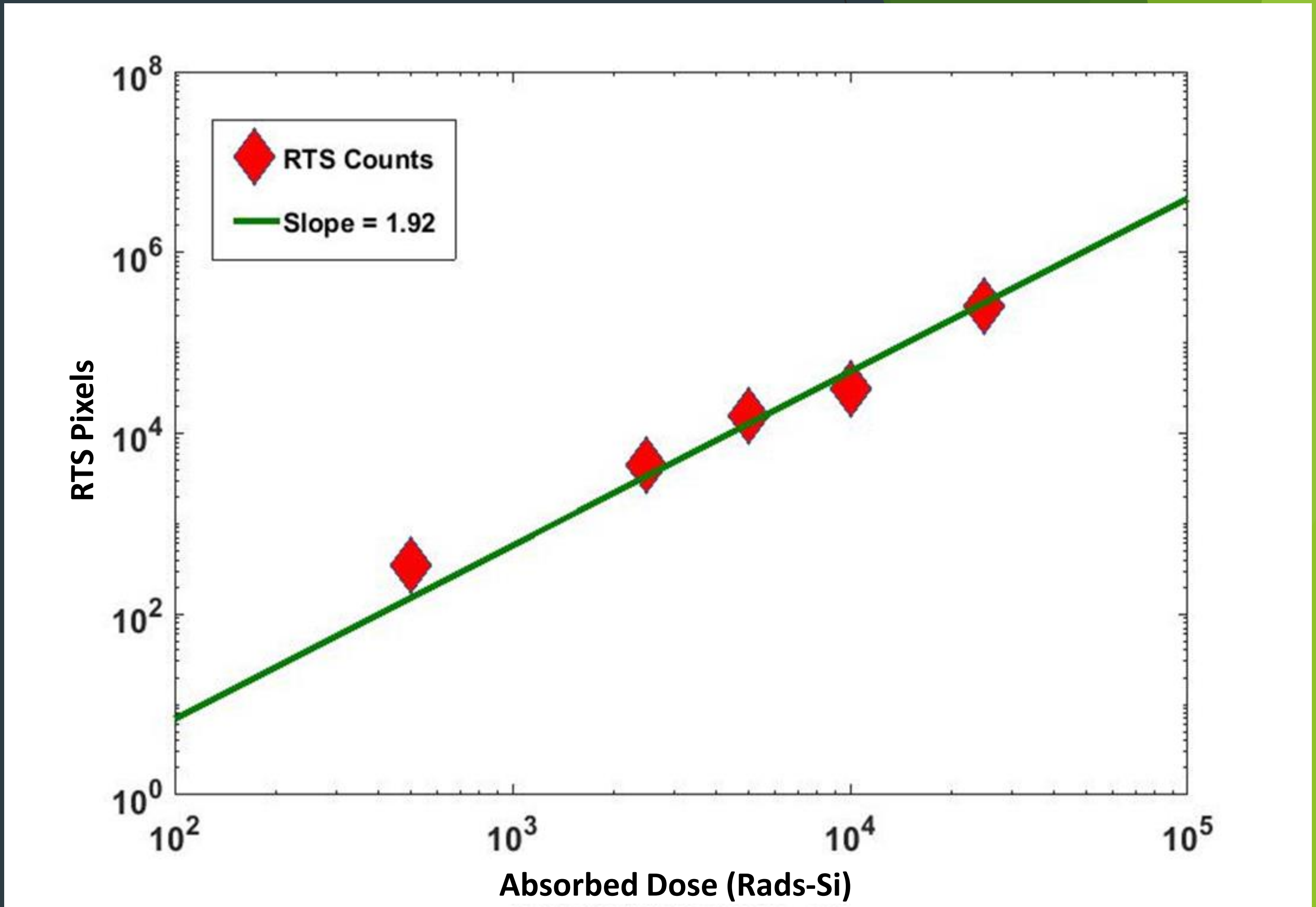
- Similar shape of curves indicates that higher doses increase the likelihood of creating an RTS center, but the amplitude probability for a center is set

- No correlation seen between RTS amplitude and time constants



Results – Second-Order Defect Generation

- The number of RTS centers increases ~quadratically with absorbed dose
- This indicates that the particular defect responsible for this RTS noise is of second-order



Thank You

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- My labmates: Justin Dunlap, Bahar Ajdari, Joe Niederriter, Paul DeStefano, and Denis Heidtmann

Results – State Lifetimes

- Lifetimes are calculated by averaging the time spent in the high or low states
- Both high and low states display an exponential distribution
- The low state time constant distribution is slightly flatter than the high state, indicating that the low state is the more stable of the two