Advanced Antenna Measurement Techniques Using Time Domain Transformation

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Time Domain Gating is widely used as a **black box** function in commercial VNAs, yet few understand it well

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What will we show?

- Understand how VNA performs time domain transform and gating.
- Understand the nuances of the different parameters, and their effects on time domain gating.
- Discuss gating band edge errors, mitigation techniques and limitations of the post-gate renormalization used in a VNA.

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Background on Frequency/Time

- Vector antenna responses can be Inverse Fourier transformed to time domain. This is a function in commercial Vector Network Analyzers (VNA).
- Time Domain and frequency domain are in reciprocal space. We can transform (via forward and inverse Fourier Transform) from one to the other without any loss of information. They are two ways of viewing the same information.

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Time ⟷ Frequency

Fourier Transform and Inverse Fourier Transform– converts between frequency domain function and a time domain function

	FT	DFT
$time \overset{\boldsymbol{F}}{\Rightarrow} freq$	$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-i2\pi ft}\, dt$	$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{2\pi i}{N}kn}$
$freq \overset{\boldsymbol{F^{-1}}}{\Longrightarrow} time$	$x(t) = \int_{-\infty}^{\infty} X(f)\, e^{i2\pi ft}\, df$	$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k \cdot e^{\frac{2\pi i}{N}kn}$

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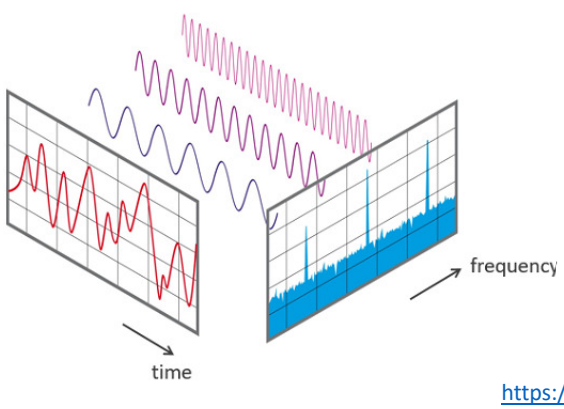
Two views of the same function



Source: wikipedia

https://tex.stackexchange.com/questions/127375/replicate-the-fourier-transform-time-frequency-domains-correspondence-illustrati?noredirect=1&lq=1

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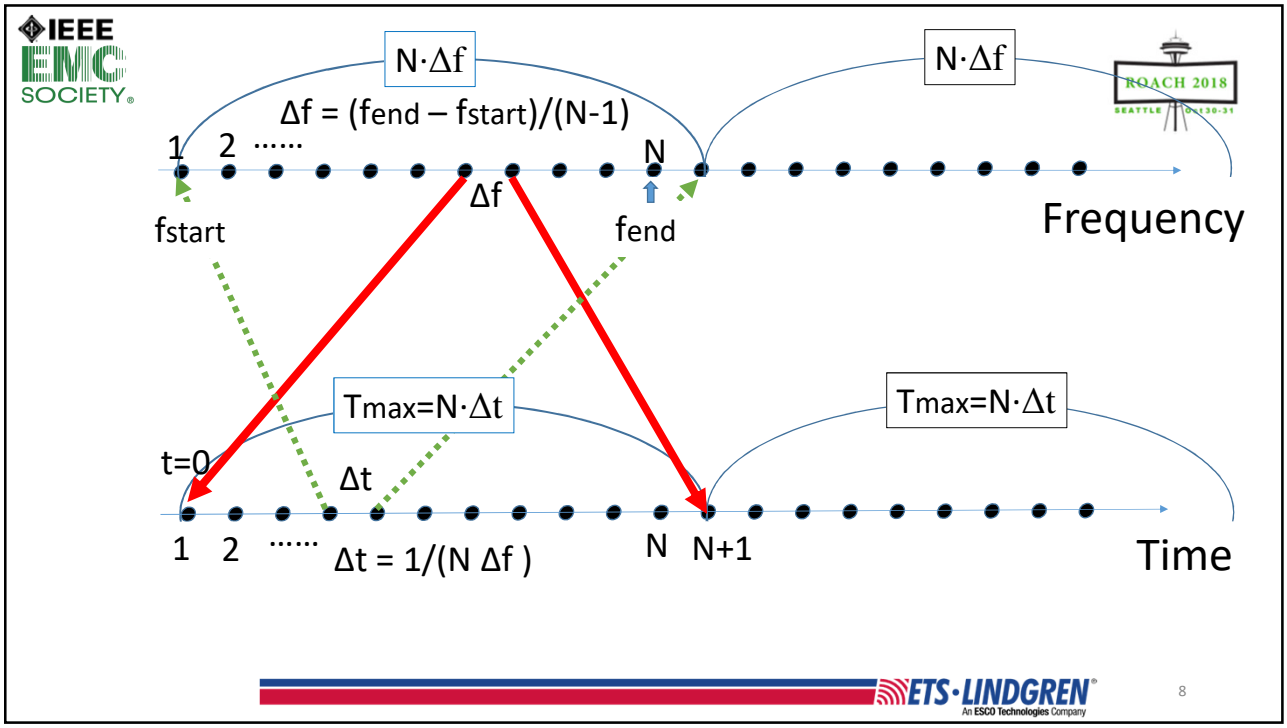
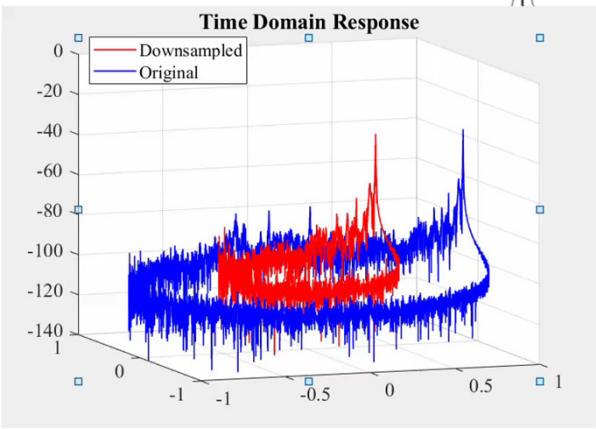
The Cost of Discretization

- Taking **discrete** samples makes the transformed domain **periodic**
- The finer the discretization, the longer the period in the other domain



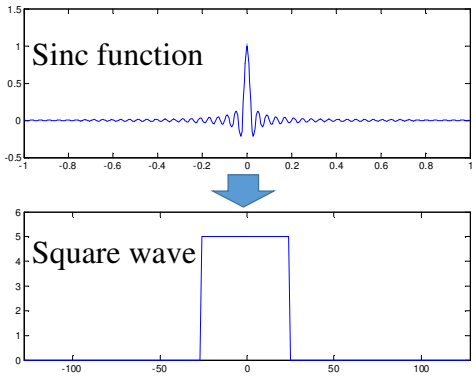
TD view – dealing with Alias

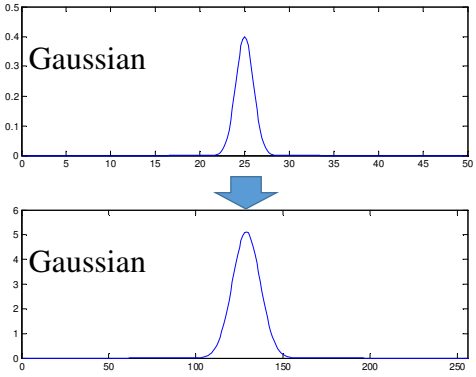
- Alias: next period (because of discretization) showing up
- Time Period=1/Δf.
- To enlarge the alias-free range (bigger cylinder) -> increase the density, i.e., more frequency points
- Example: 1601 points, 1-11 GHz, the alias free range is T≈(1601-1)/10GHz=160 ns or 48 m in free space



Discrete in one domain = periodic in the other domain

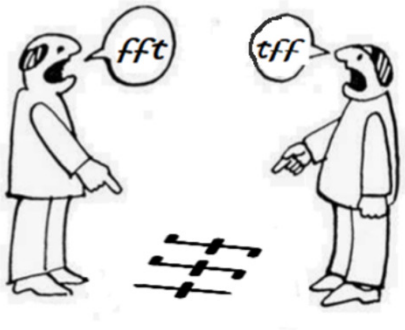
Useful Fourier Transform Pairs



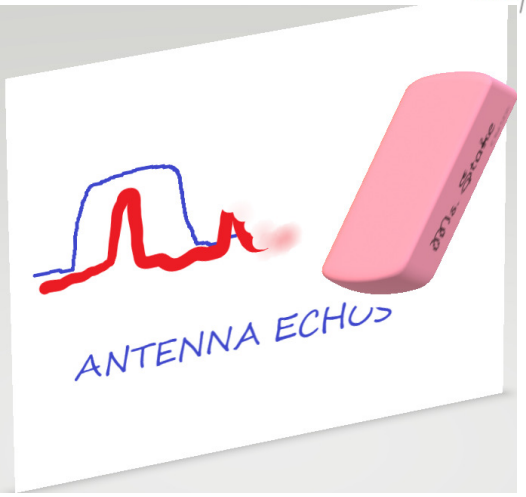


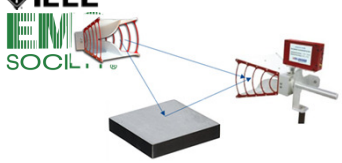
Do more with the transform

- If all we are doing is to transform data back and forth between the two domains, we have not gained any improvements in the data, except maybe some insights in how signal travels between antennas.



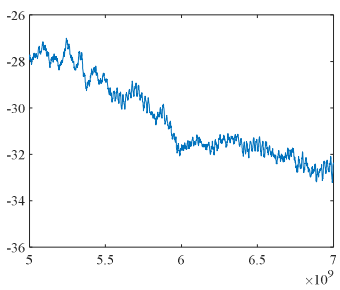
- Time gating can be thought of as a bandpass filter in time. This allows us to look at only a portion of time selectively. We can then transform back to frequency domain, and view the frequency data for the selected signal .



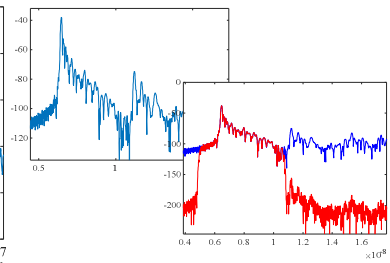


A Conceptual View of Gating

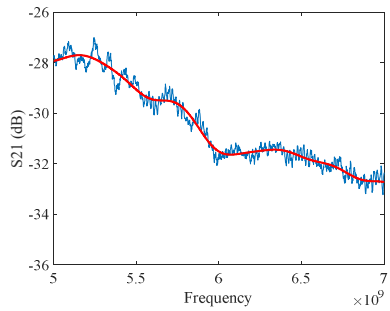
Measure S21(f) → Transform to TD → Apply Gating → Transform to FD → Gated S21(f)



Frequency domain



Time domain



Frequency domain

Considerations in Actual Gating

- We presented a conceptual representation of gating in 3 steps:

FD->TD → Multiply Gate → TD->FD

- Actual gating process is more nuanced
  - Chirp-Z vs. FFT, and aliases
  - Windowing
  - Time domain resolution
  - Gating in the frequency domain
  - Gate design
  - Edge effect mitigation

Gating via Convolution

- Convolution in time domain = multiplication in frequency domain

or vice versa

- Multiplication in time = convolution in the frequency domain
  - Time domain gating = $\boldsymbol{F}[x(t) \cdot g(t)] = X(f) * G(f)$
    where $x(t) = \boldsymbol{F}^{-1}[X(f)]$, $\quad G(f) = \boldsymbol{F}[g(t)]$

- <u>Time domain Gating = convolution of data with gate kernel directly in the frequency domain</u>

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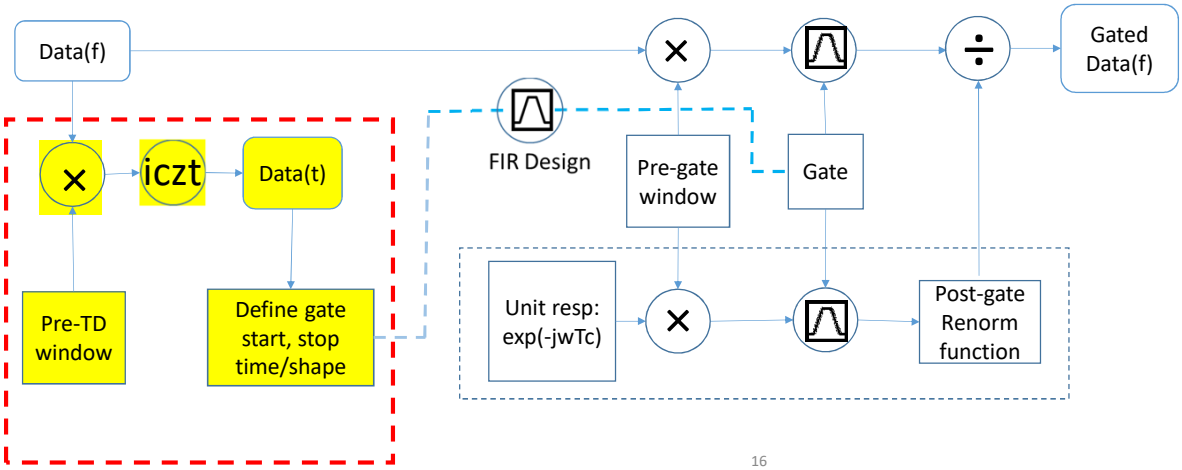
First Step of Gating: take the data to TD



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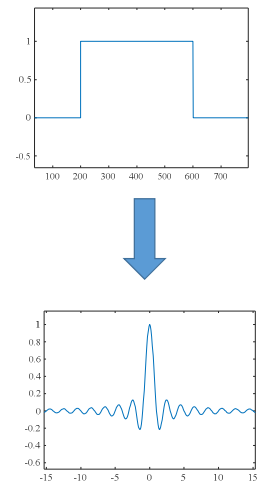
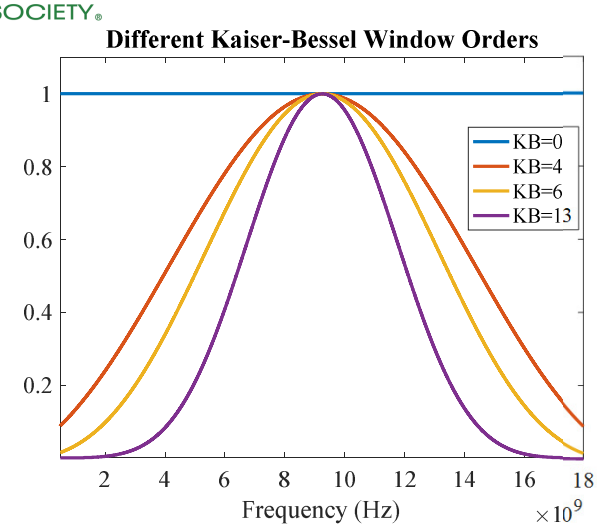
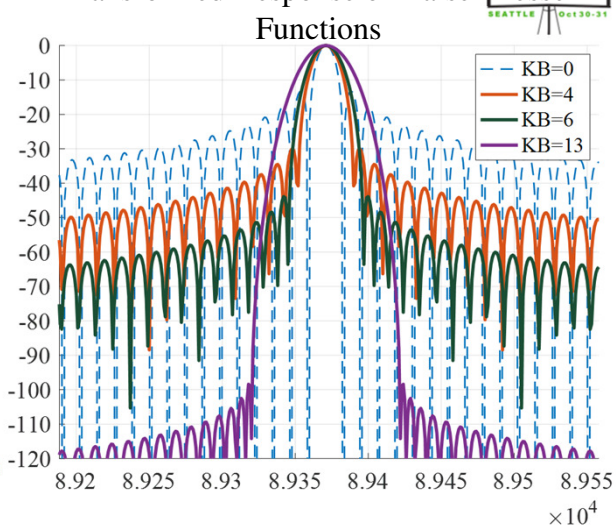
Pre-TD Windowing

- Rectangular function transforms to a *sinc* function.
- $S_{21}(f)$ data typically does not taper to zero at the two frequency ends. If directly transformed, it results in ringing in the time domain. The artifacts can obscure the viewing, thus our ability to identify real responses.
- Windowing is to multiply the frequency domain data (before transformation) with a tapering function.





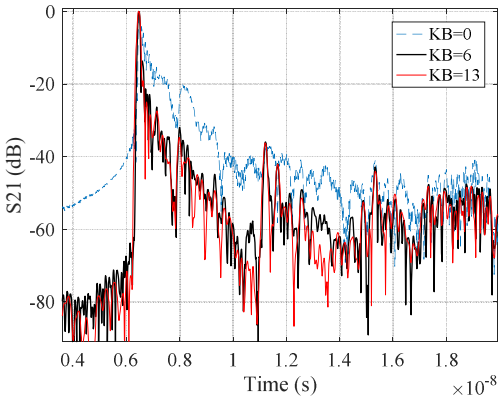


Kaiser-Bessel Windows with varying KB=πα

Changing Pre-TD Window in a VNA

- Pre-TD window function can be changed by end users,
- It is only used as an aid to select start and stop time - purely for viewing
- Don't be afraid to change! No effect on gating

Effects of Window on Time Domain View



- KB=0=>no window, equivalent to rectangular window
- KB level: tradeoff between main beam width vs. side lobe levels
- Default (KB=6) provides a good compromise for most applications

Chirp-Z/Inverse Chirp-Z Transform

- Chirp-Z (CZT) is a generalization of the discrete Fourier transform.
- Chirp-Z transform allows re-sampling: arbitrary start/stop points and density in the transform domain
- Often used to zoom into a region, CZT interpolates data (equivalent zero-padding) – it is essentially a *sinc* smoothing.

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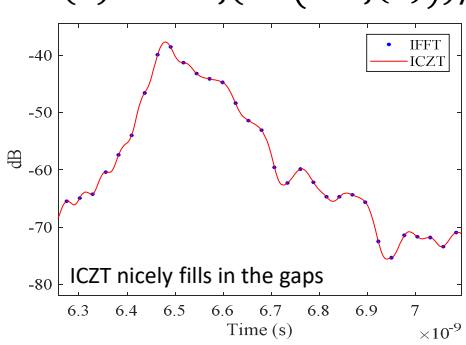
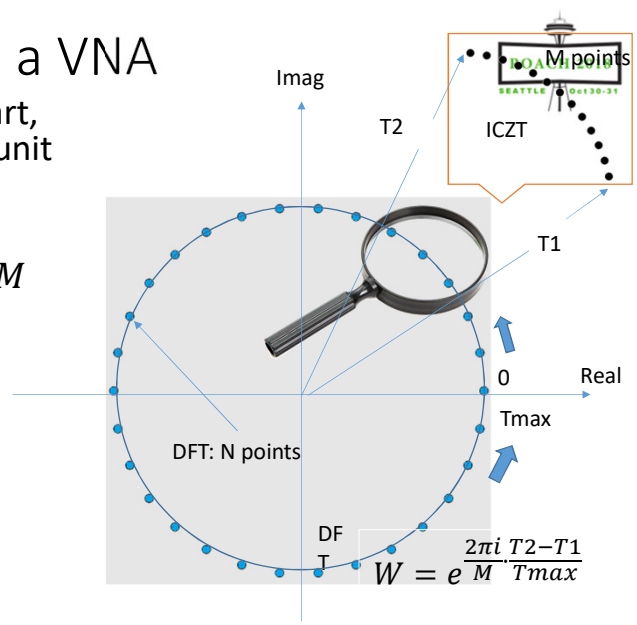
CZT in a VNA

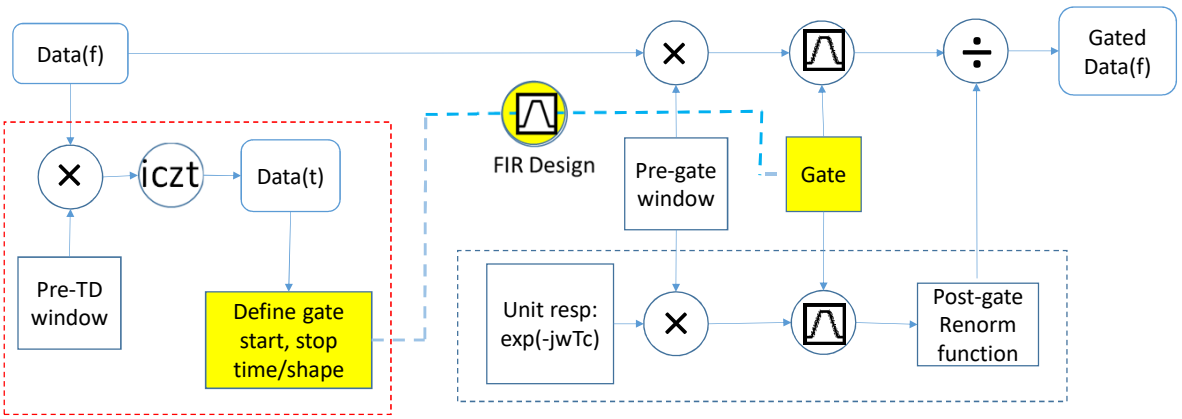
- CZT in a VNA allows arbitrary start, stop points and # points on the unit circle.
- For inverse (ICZT) On unit circle:
  $\mathrm{iczt}(x) = \mathrm{conj}(\mathrm{czt}(\mathrm{conj}(x)))/M$





$$W = e^{\frac{2\pi i}{M}\frac{T2-T1}{Tmax}}$$

Designing the Gate



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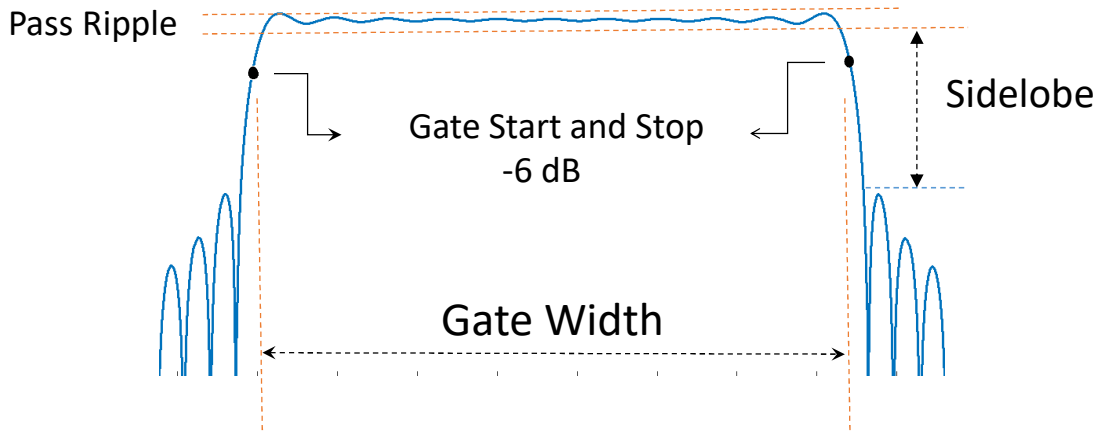
Time Gate is a Filter, done in TD

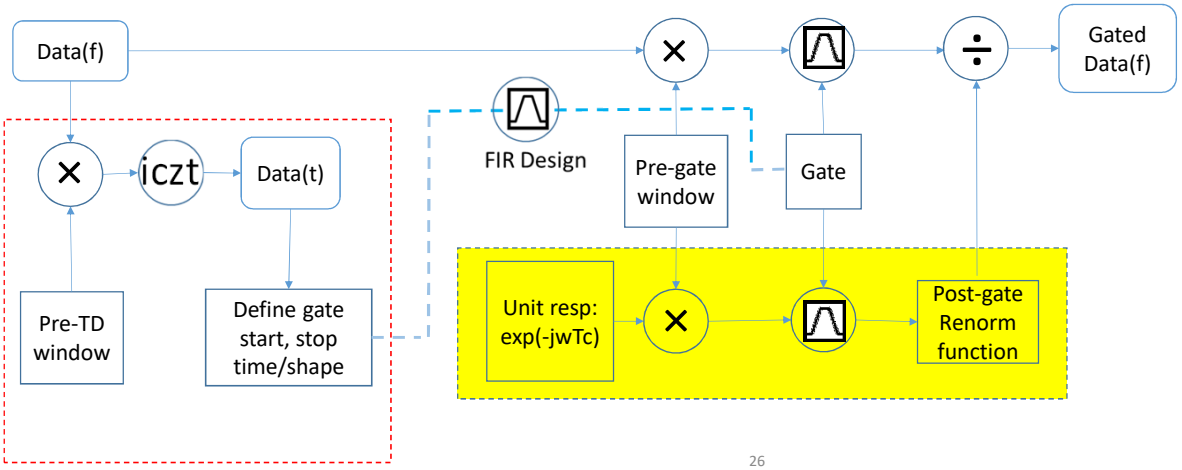
- Time gate is designed as a filter, in this case, a Kaiser windowed FIR filter.
  - Gate (f) is a sinc function, which is truncated, and windowed
- Based on the gate specification, the length of the filter, and shape of the Kaiser window (beta) is determined.

Illustration of Gate Shape



- Normal Gate/Wide Gate/Max Gate/Min Gate all refer to sidelobe/transition shape

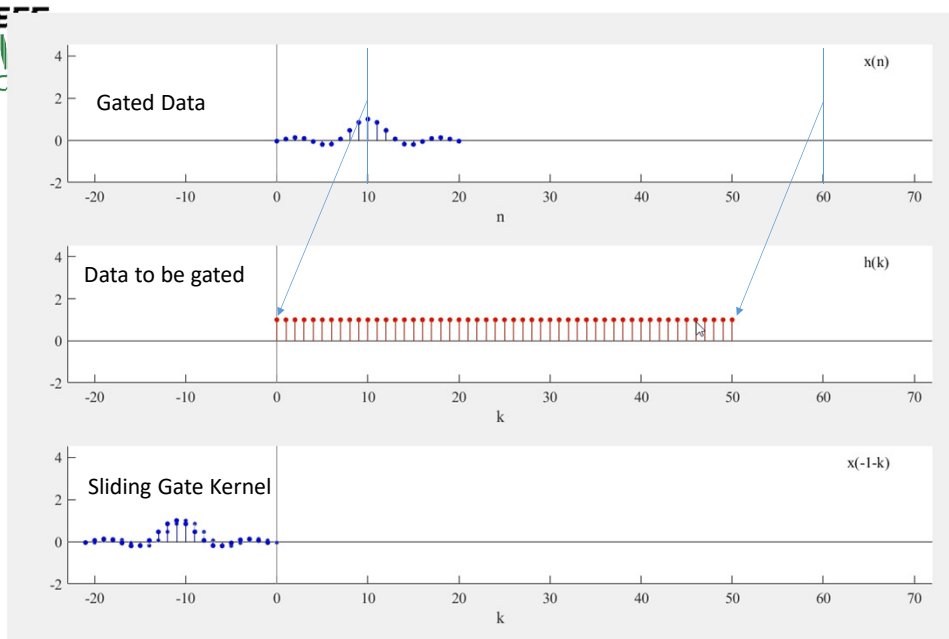
Edge Renormalization



Data at the Band Edges

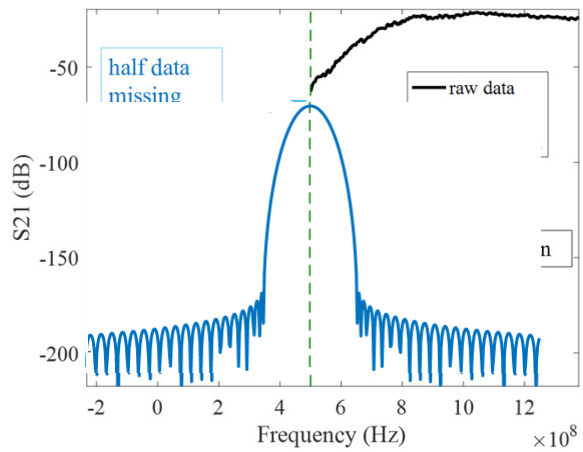
$$\boldsymbol{F}\big(\mathrm{data}(t)\cdot\mathrm{gate}(t)\big) = \mathrm{Data}(f) * G(f) = \sum_{j=-M/2}^{M/2} \mathrm{Data}(j)G(f-j)$$

- The convolution theorem provides an intuitive view of the effect of time gating.
- In the frequency domain, this can be viewed as the data being multiplied and summed by a flipped sliding gate kernel (Convolution!)



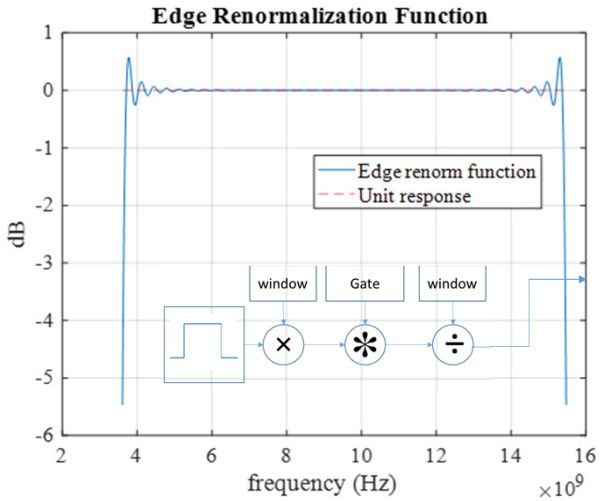
Causal Convolution
Shifts the result

We have a problem near the Edges!



- There will be a ~6 dB drop off for the gated data
- This edge effect is a distortion due to the time gate

Post-Gate Re-Normalization



- Consider processing a unit function, it will show the edge effect after gating, just like the raw data will
- Gated raw data will be divided by this renormalization function

Post Gate Renormalization

- Post Gate Renormalization makes two important assumptions
  - Edge effect on the unit (**flat**) function is similar to that on the raw data
  - Post gate renormalization assumes the time domain pulse is centered around the gate
- Violating either condition will result in edge errors.

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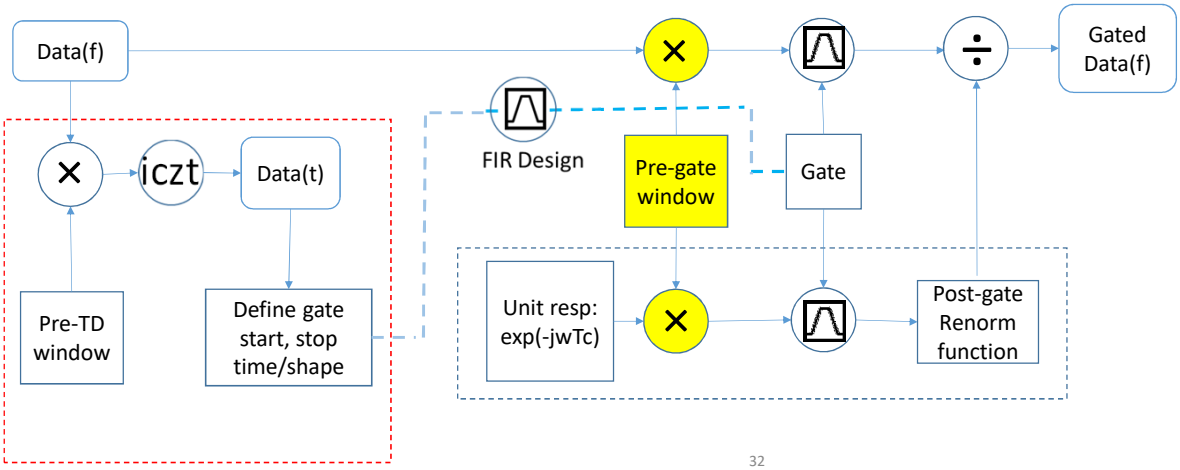
Pre-Gate Windowing



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Pre-Gate Window

- Pre-gate window: Window function before time domain gating is applied.
- Pre-gate window is to be distinguished from pre-TD window. (Recall pre-TD window is used "for viewing only").
  - Unlike pre-TD window, pre-gate window cannot be changed by the user in a VNA
  - Pre-gate window affects gating, while pre-TD window does not.

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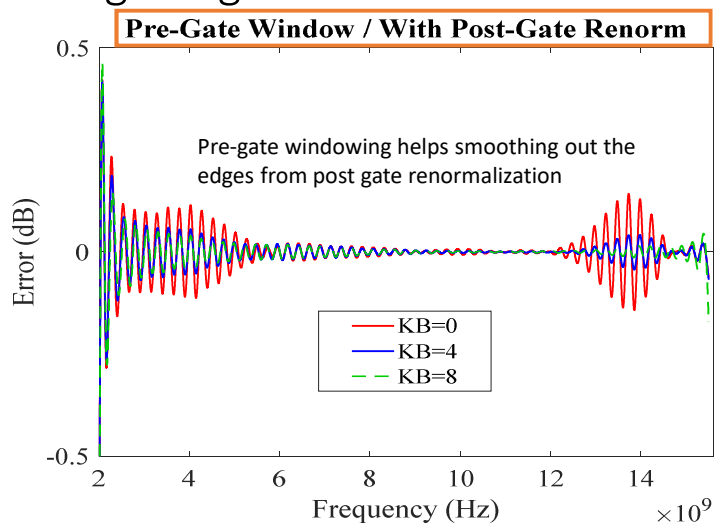
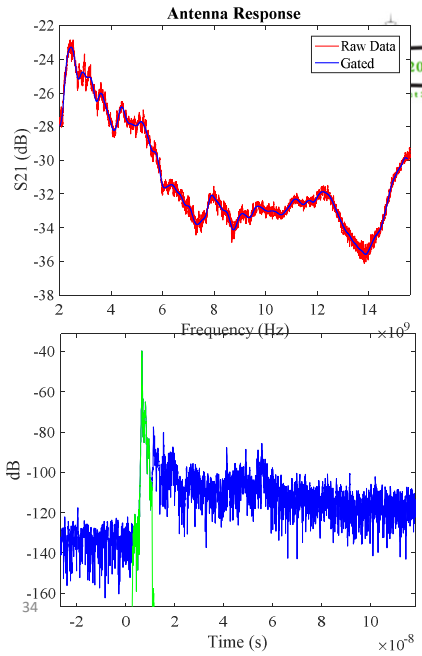
Pre-Gate Window: Smooth out the rough edges





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Gating –Don't make it convoluted

- Should we gate in FD via direct convolution?
- Or in TD through FFT (so called "Fast Convolution")?
- In most cases, fast convolution is magnitudes faster than direct convolution

Fast Convolution

$$X * Y = IFFT(FFT(X) \cdot FFT(Y))$$

circular convolution, so zero padding is needed to achieve linear convolution

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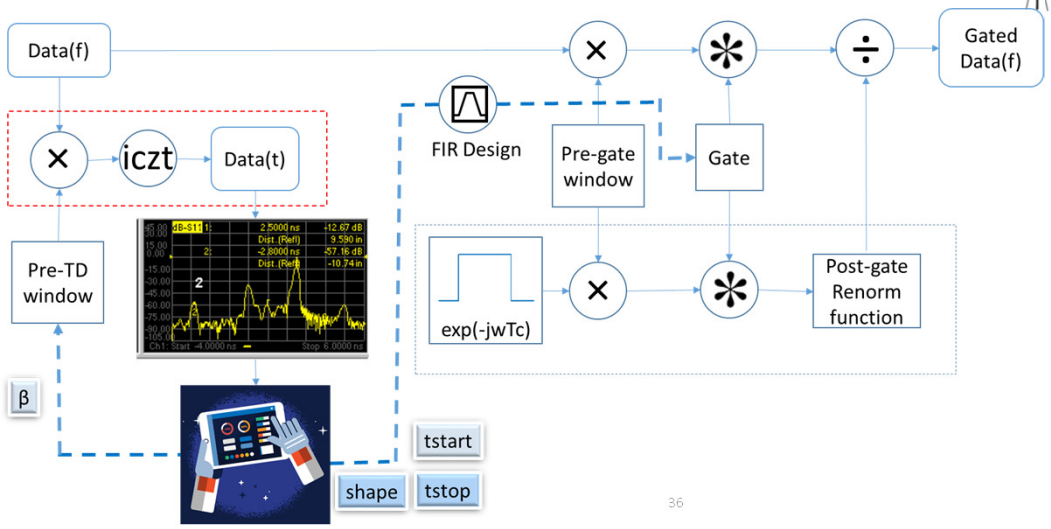
Putting it all together



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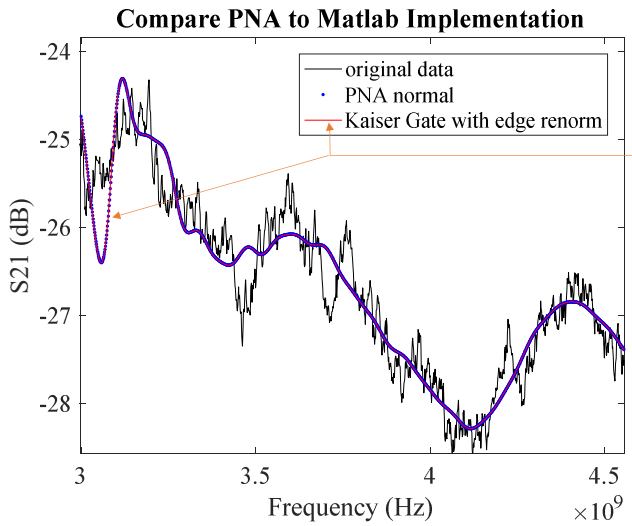
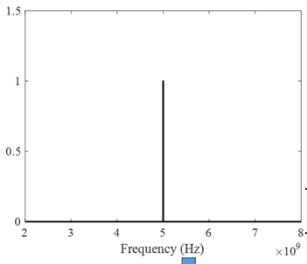
Validating the gating algorithm



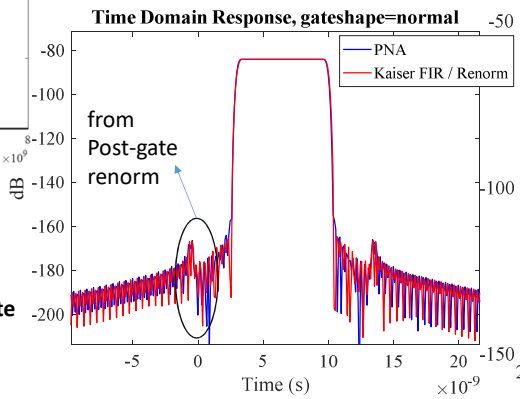
A matlab implementation can match results from a commercial VNA

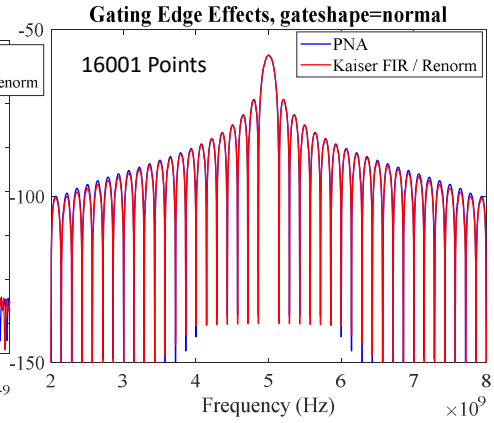
Example: gating a centered frequency spike



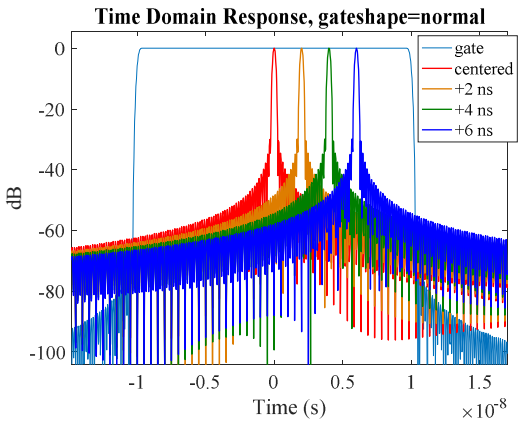
The result includes gating, pre-gate window and post-gate renormalization

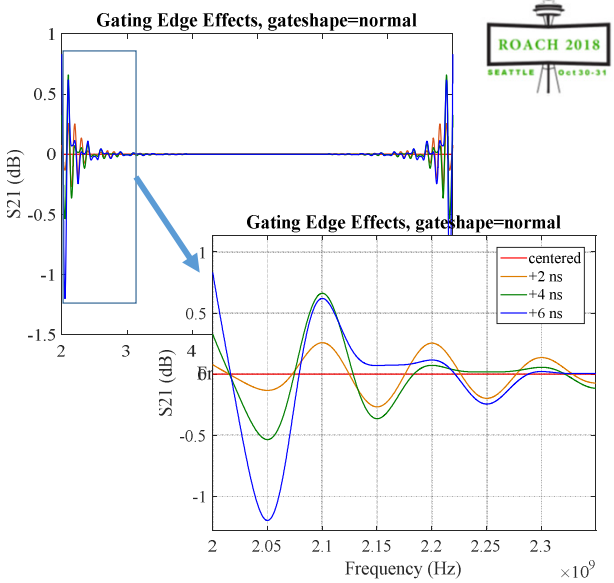
Again showing close match: Matlab (red) / VNA (blue)



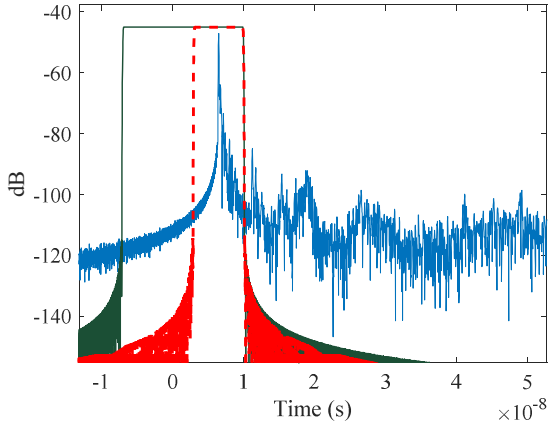


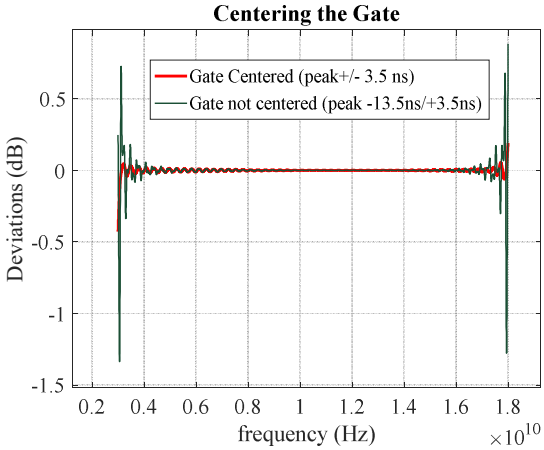
Gate Centering: Unit Response



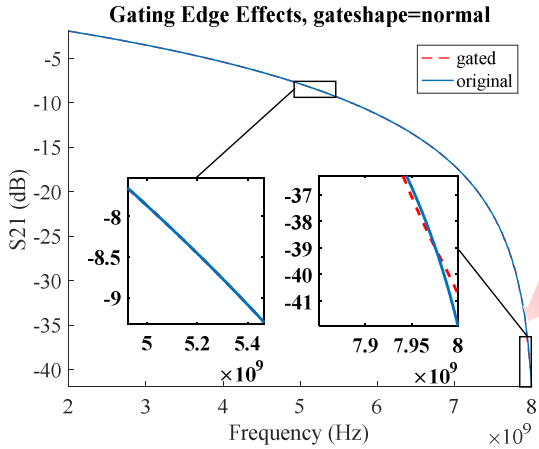


Gate Centering = smaller edge errors



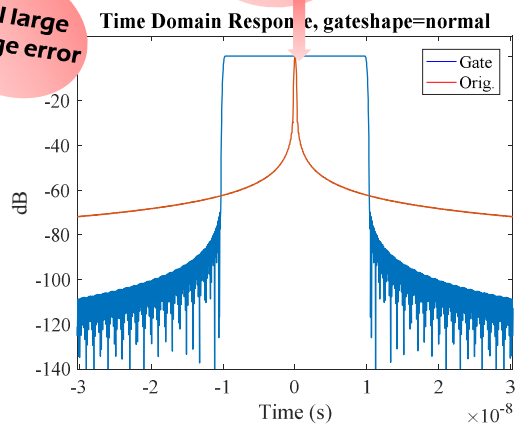


Non-flat responses – residuals after normalization

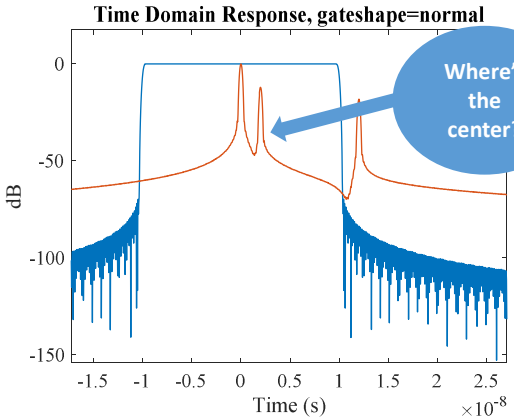


Still large Edge error

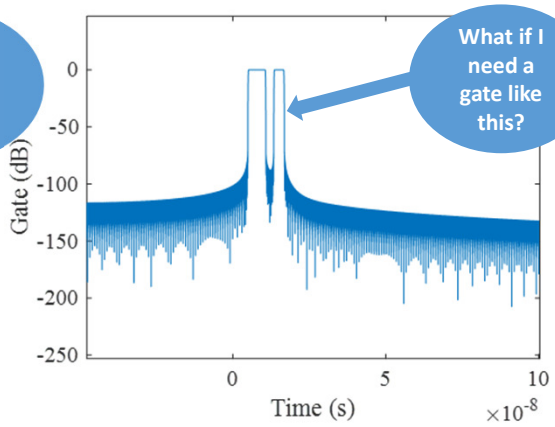
Gate Centered



Practical Issues with Gating



Where's the center?

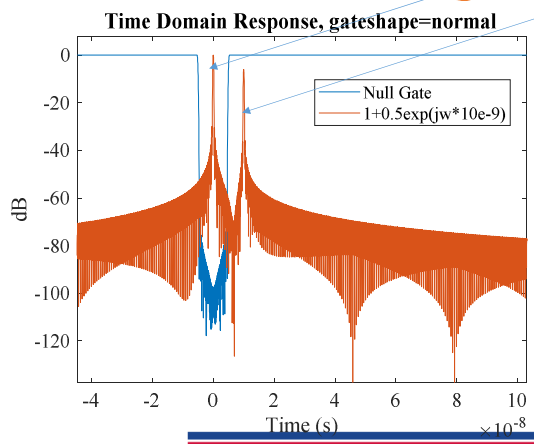


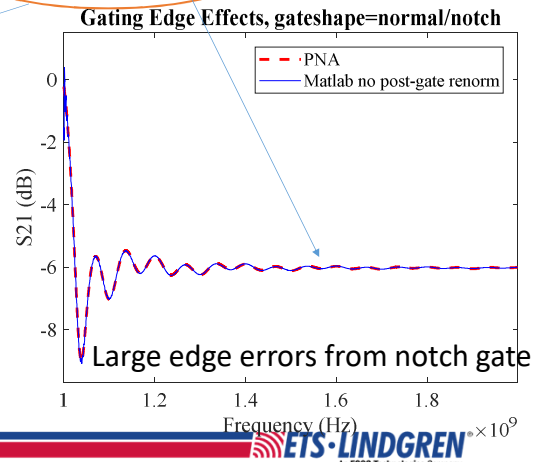
What if I need a gate like this?

Notch Gate – No Normalization Allowed

- Notch gate can't use post-gate renormalization

$$data = 1 + 0.5e^{-j\omega \cdot 10e-9}$$, 1-6 GHz, 16001 points

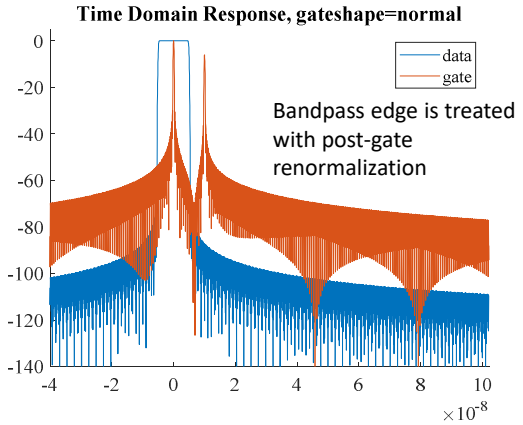


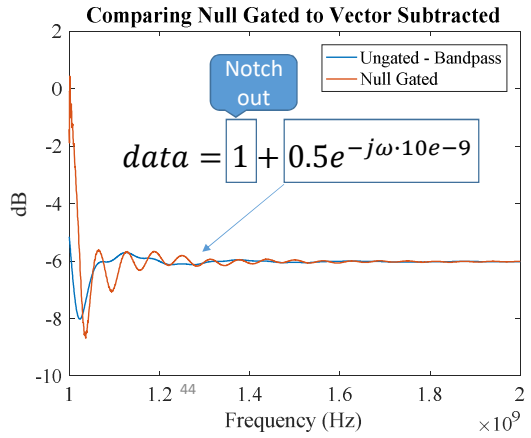


Large edge errors from notch gate

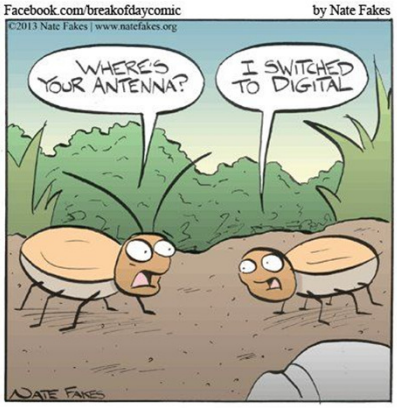
A Better Way to Notch (Null) Gate

- Use a bandpass gate instead:
  - Notch gated (f) = Ungated – Bandpass Gated (in vector)





Summary

- We demonstrated the inner workings of the time domain gating function in a network analyzer.
- Discussed the window function and gate design.
- Discussed edge effects due to time domain gating, and post-gate renormalization.
- We presented edge renormalization and its limitations in a vector network analyzer, and some tips on minimizing the effects.
- Refer to AMTA 2018 paper "*A Novel Approach to Reduce Band Edge Effects in Time Domain Gating using Spectrum Extrapolation*".

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