Naval Information Warfare Center PACIFIC

A Comparison of Techniques for Non Data-Aided Carrier Tracking of Phase-Modulated Signals

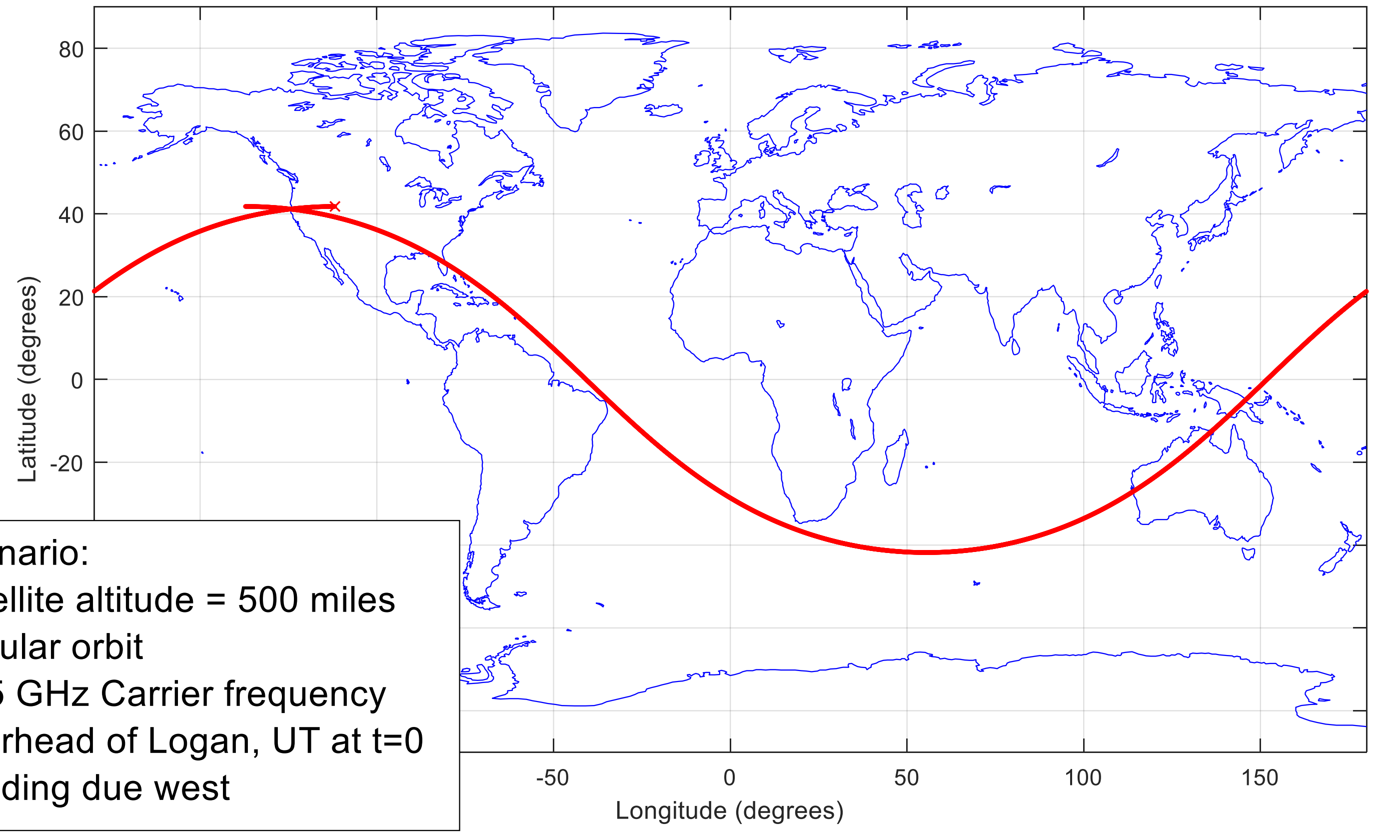
34th Annual Small Satellite Conference

Brendan Hill

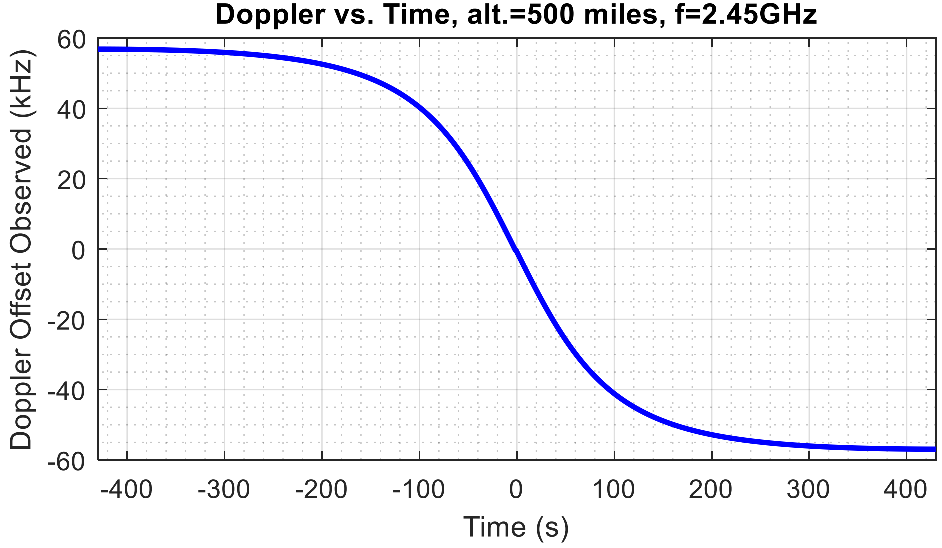
Nazia Mozaffar

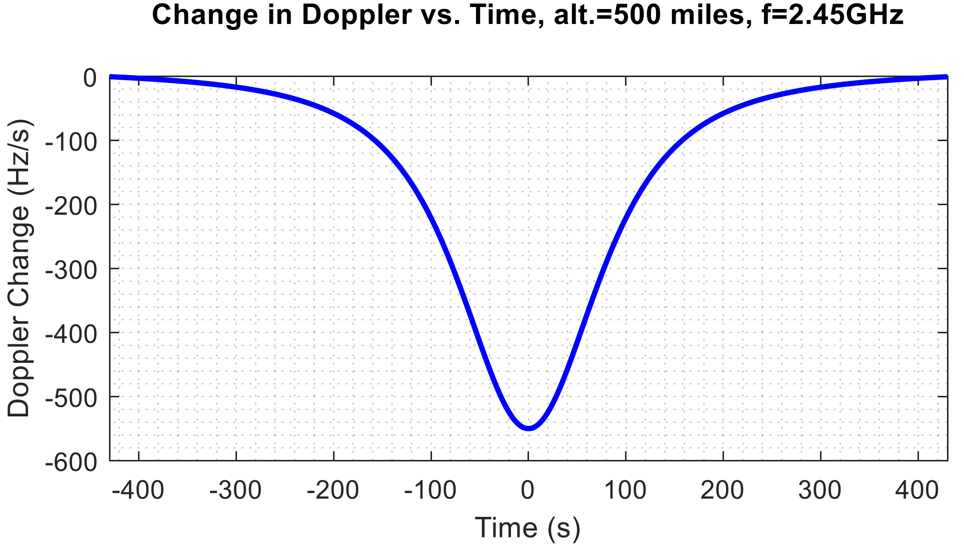
Salwan Damman

Doppler vs. Time During Satellite Overflight



Scenario:
Satellite altitude = 500 miles
Circular orbit
2.45 GHz Carrier frequency
Overhead of Logan, UT at t=0
Heading due west



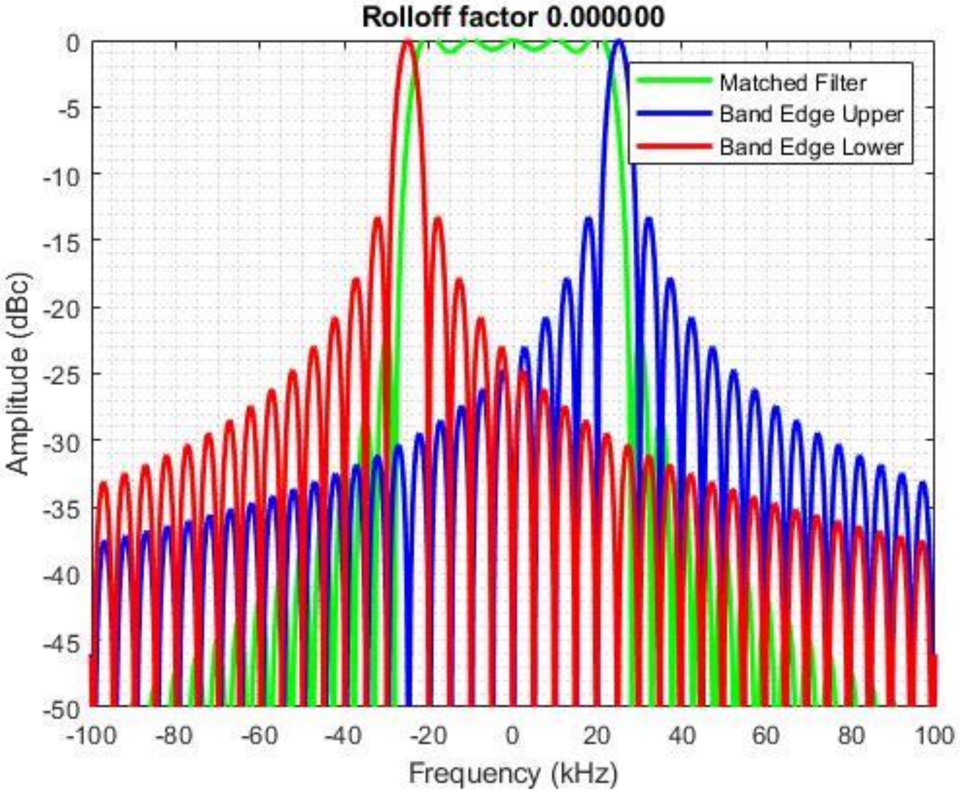


Problem: Satellite Observed Doppler vs. Time

- Scenario: 500-mile altitude satellite in circular orbit flying overhead Logan, UT at t=0 heading west, 2.45 GHz carrier frequency
- Desire maximum data transfer during limited overflight time
  - 14.5 minute overflight out of 1 hour 40 minute orbit time
- Doppler Changes with Time
  - Satellite's velocity 7.45km / s to stay in circular orbit
  - Doppler observed is proportional to component of velocity vector in direction between satellite and ground terminal
  - Peak Doppler Magnitude of 57kHz
  - Peak rate change of -550 Hz/s
- Terrestrial radios may not have been designed to handle large Doppler frequency offsets
- Desire techniques for detecting and tracking time-varying Doppler without demodulating the signal

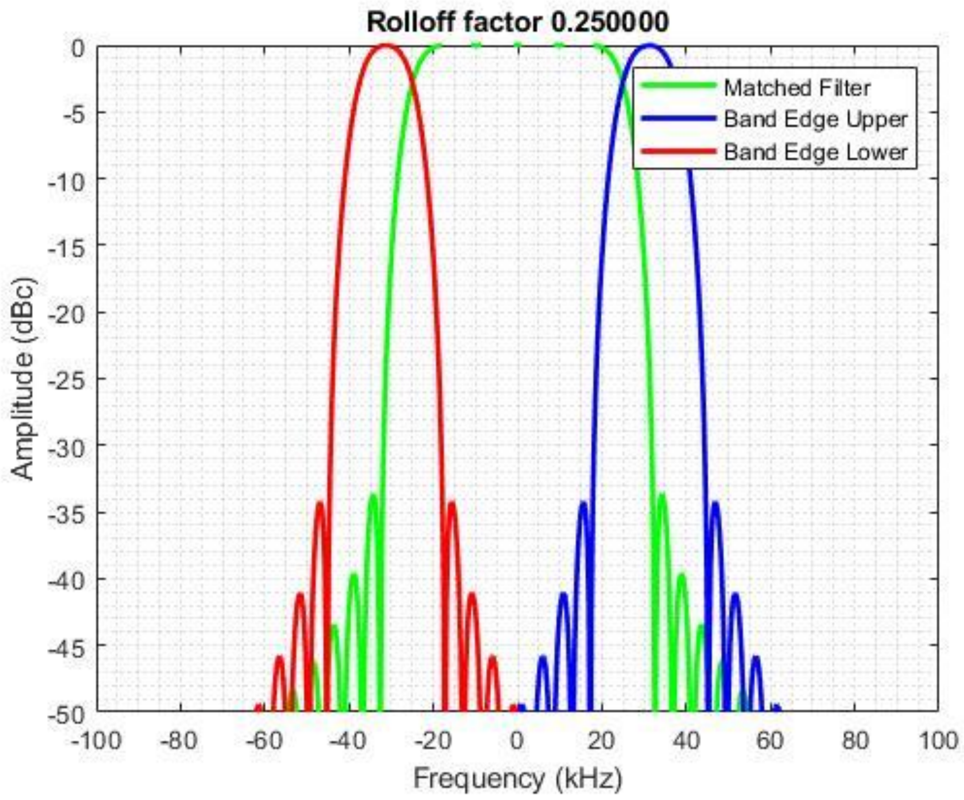
Band Edge Filters

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of shaping filter frequency response
  - Operate on excess bandwidth of signal
- Rolloff factor (α) determines excess bandwidth of signal
- Band edge filters are located at $\pm f_{sym} \cdot (1+\alpha)/2$, where f_{sym} is symbol rate
- As α increases, matched filter bandwidth increases, band edge filters' locations change



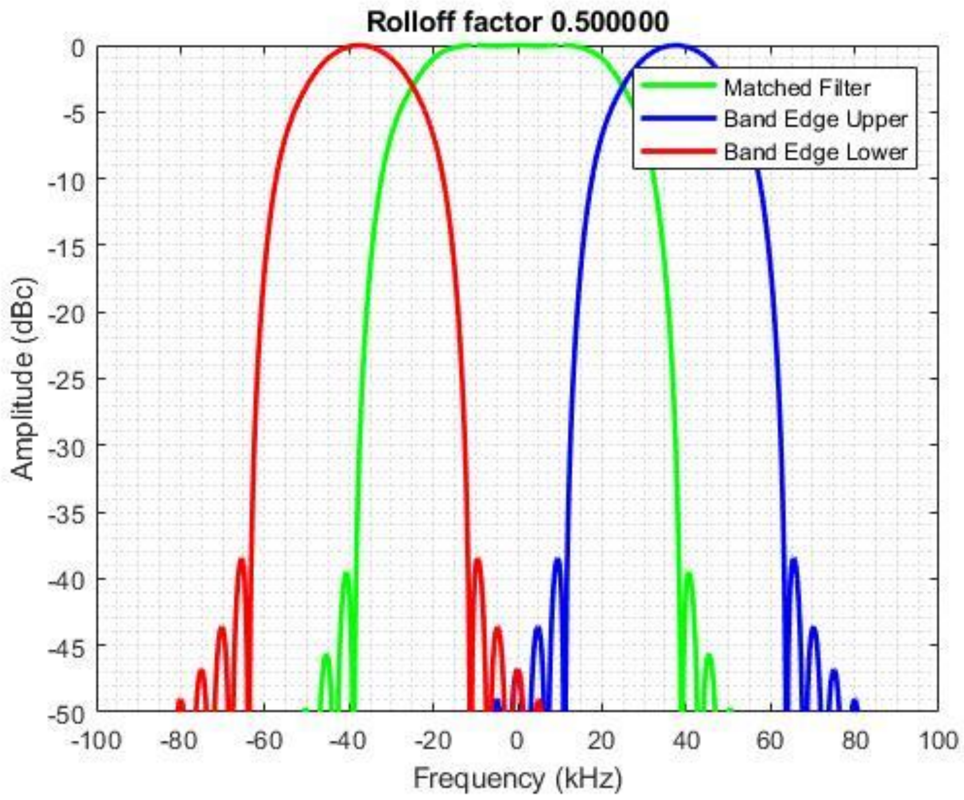
Band Edge Filters

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of shaping filter frequency response
  - Operate on excess bandwidth of signal
- Rolloff factor (α) determines excess bandwidth of signal
- Band edge filters are located at $\pm f_{sym} \cdot (1+\alpha)/2$, where f_{sym} is symbol rate
- As α increases, matched filter bandwidth increases, band edge filters' locations change



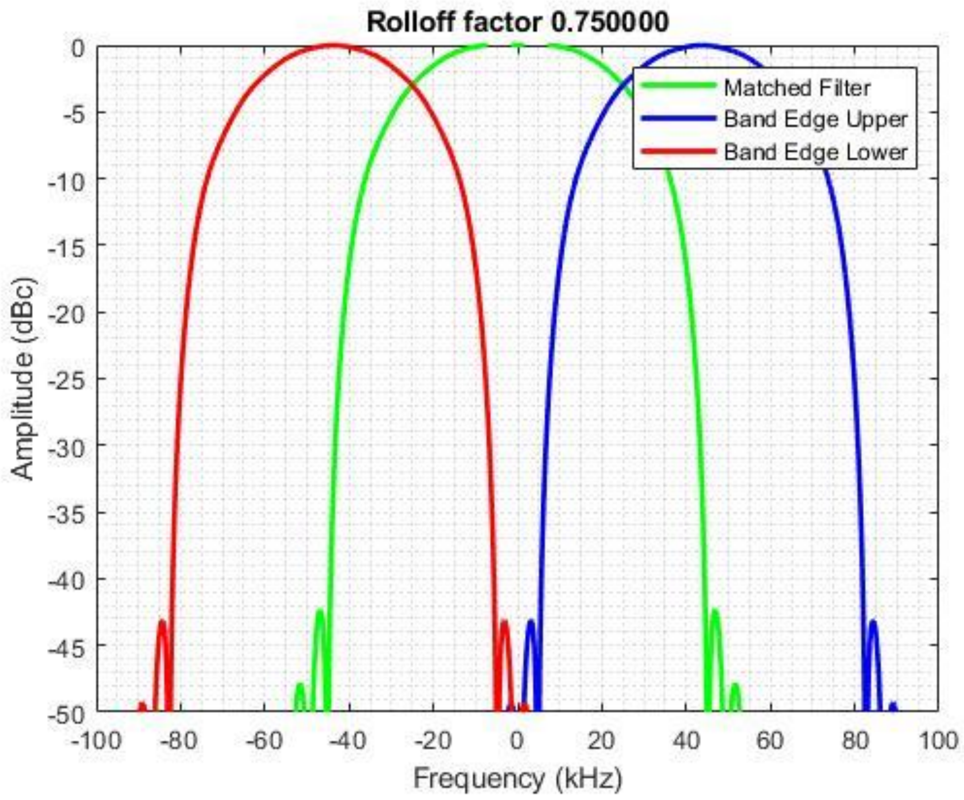
Band Edge Filters

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of shaping filter frequency response
  - Operate on excess bandwidth of signal
- Rolloff factor (α) determines excess bandwidth of signal
- Band edge filters are located at $\pm f_{sym} \cdot (1+\alpha)/2$, where f_{sym} is symbol rate
- As α increases, matched filter bandwidth increases, band edge filters' locations change



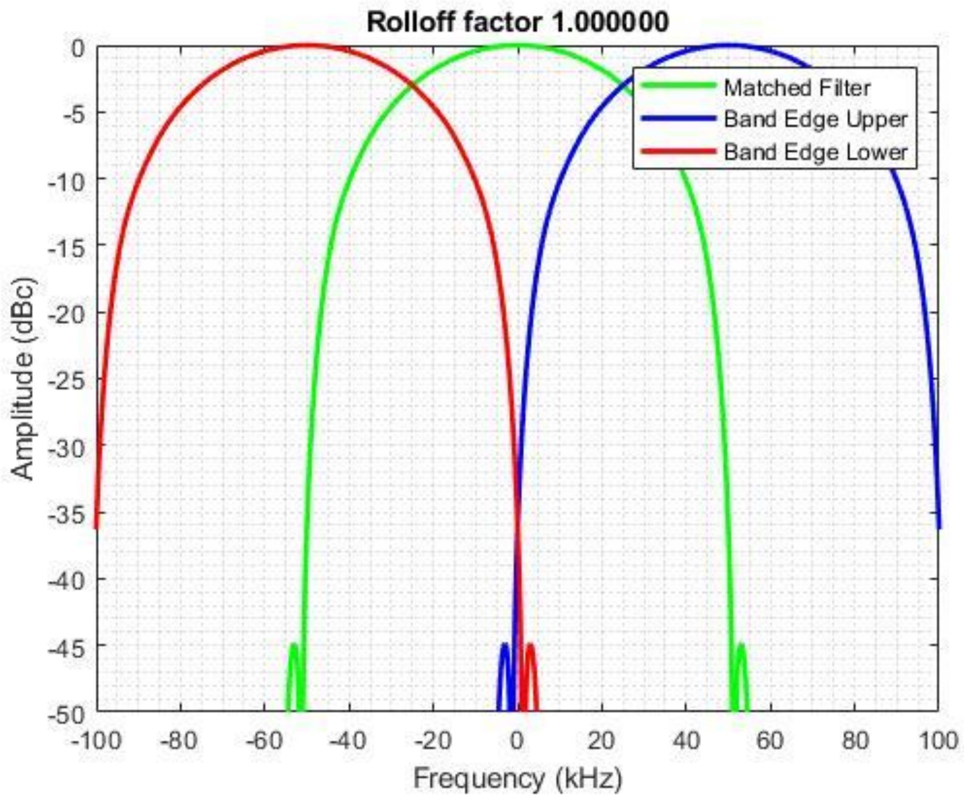
Band Edge Filters

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of shaping filter frequency response
  - Operate on excess bandwidth of signal
- Rolloff factor (α) determines excess bandwidth of signal
- Band edge filters are located at $\pm f_{sym} \cdot (1+\alpha)/2$, where f_{sym} is symbol rate
- As α increases, matched filter bandwidth increases, band edge filters' locations change

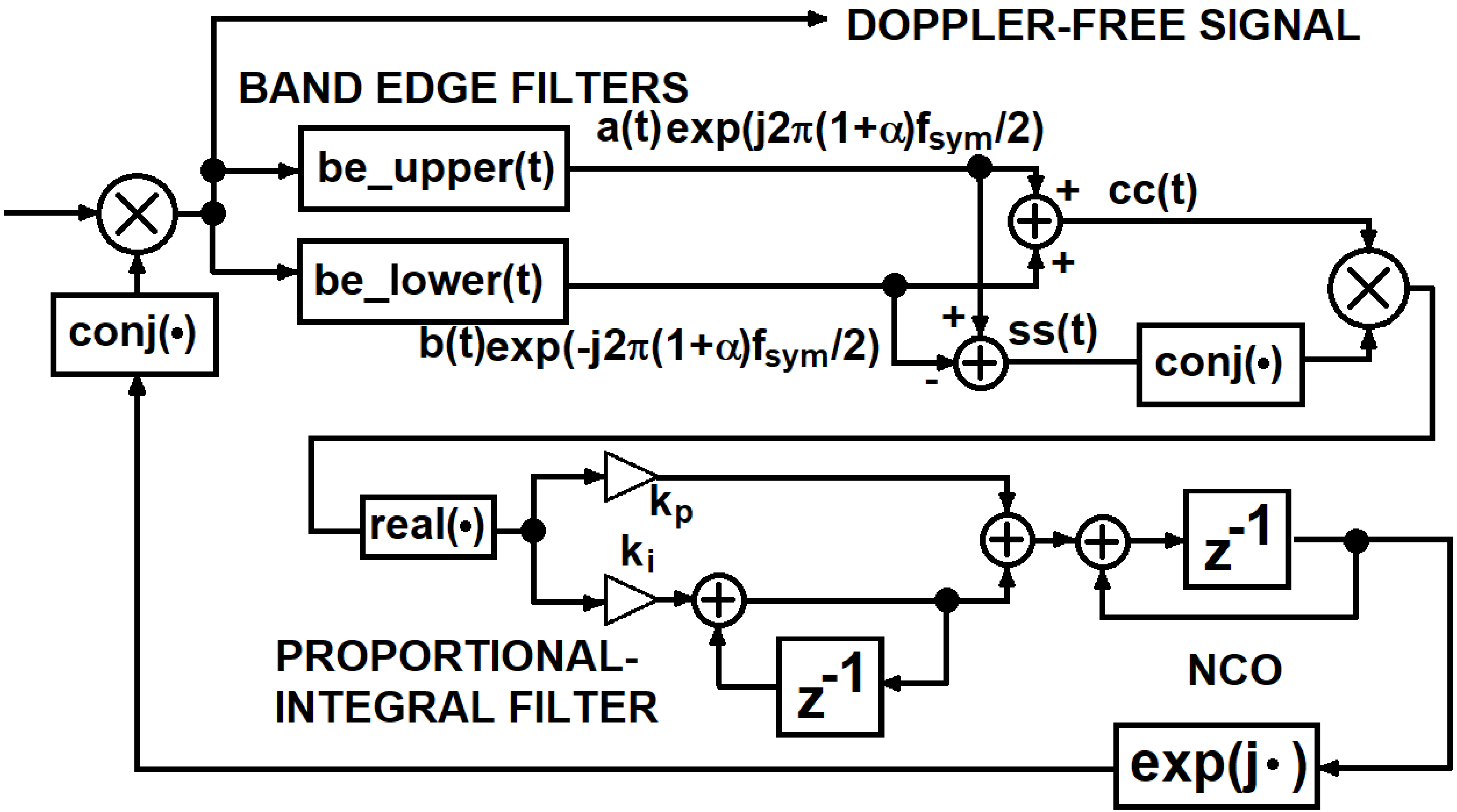


Band Edge Filters

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of shaping filter frequency response
  - Operate on excess bandwidth of signal
- Rolloff factor (α) determines excess bandwidth of signal
- Band edge filters are located at $\pm f_{sym} \cdot (1+\alpha)/2$, where f_{sym} is symbol rate
- As α increases, matched filter bandwidth increases, band edge filters' locations change

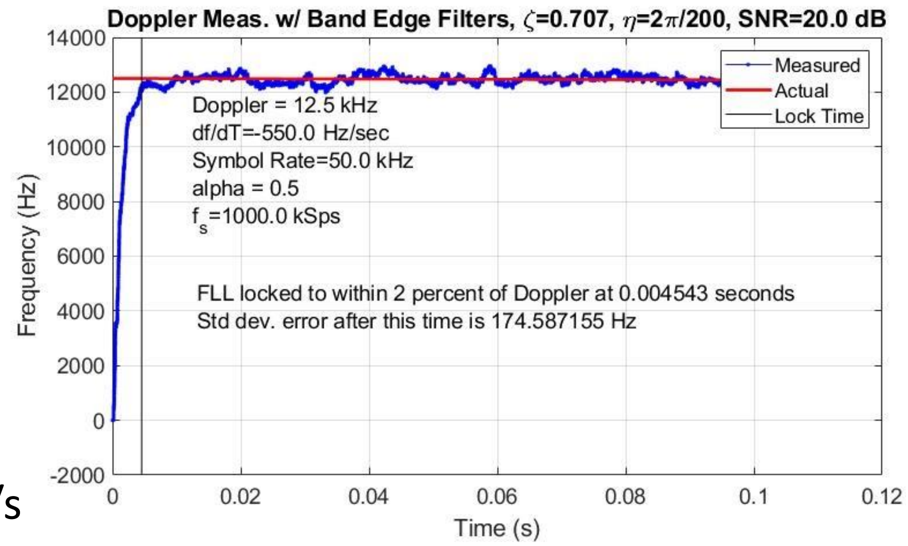


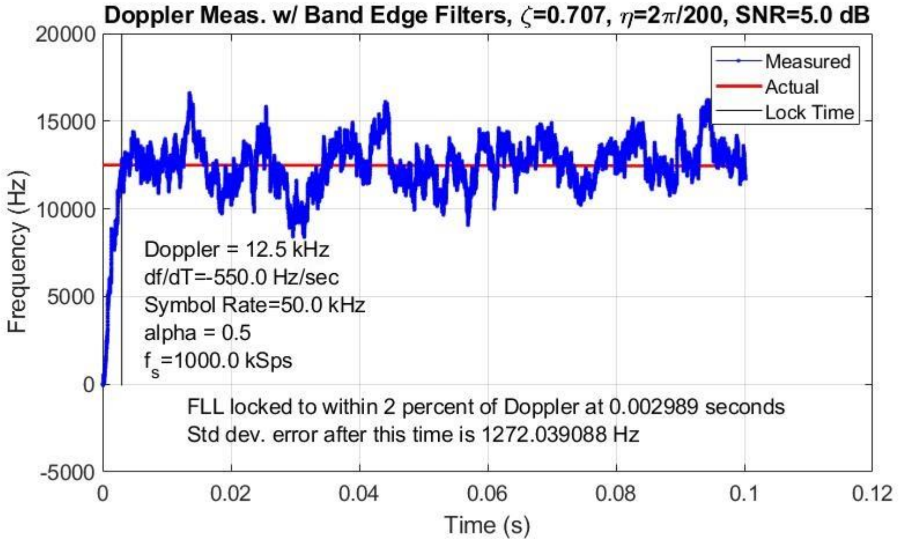
Band Edge Filter FLL Structure

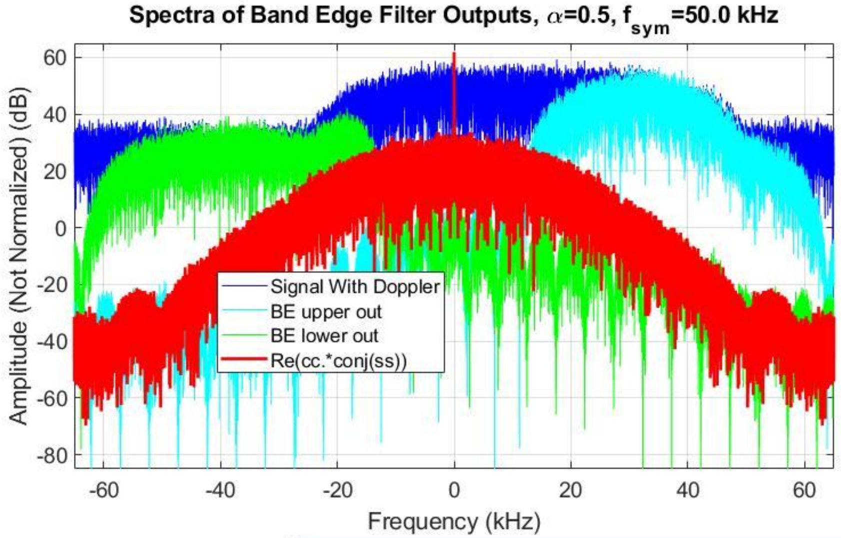


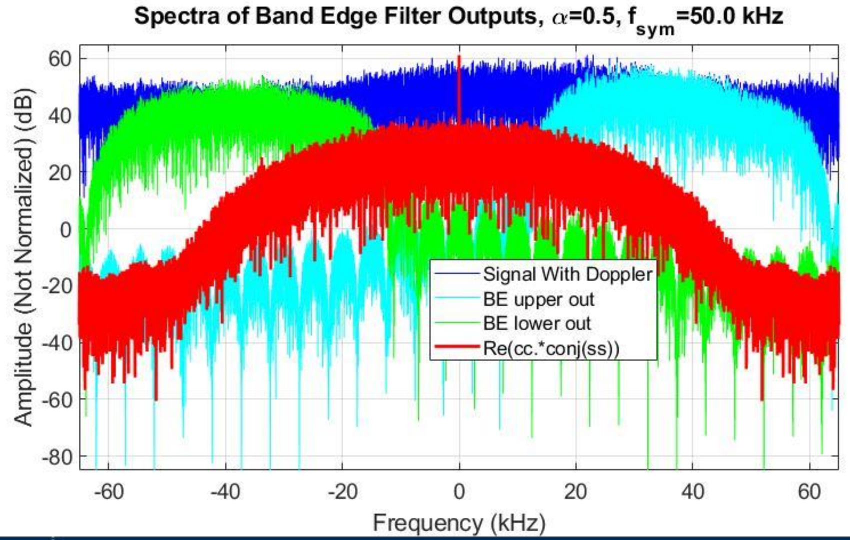
Performance of Band Edge FLL

BPSK modulation 50 kHz
1 MS/s sample rate
Initial Doppler = 12.5 kHz
Doppler change = -550 Hz/s
SNR = 20 dB on left
= 5 dB on right



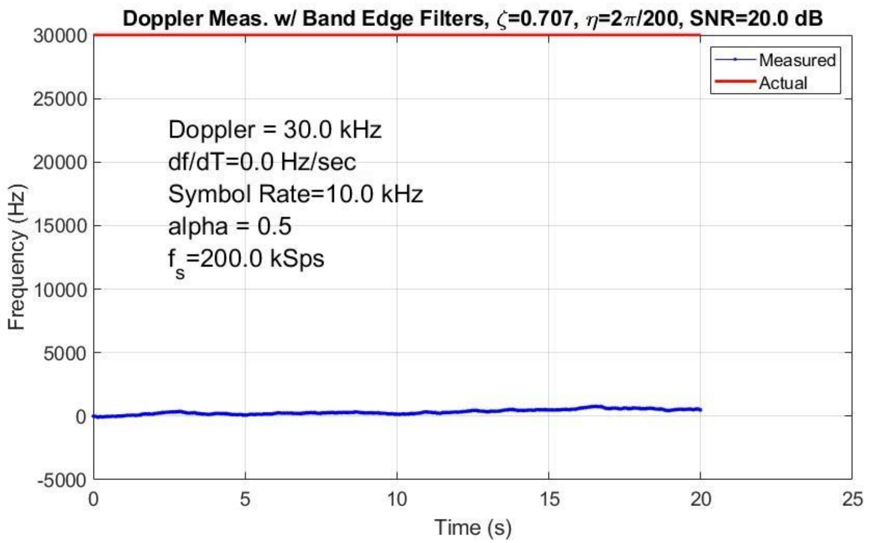


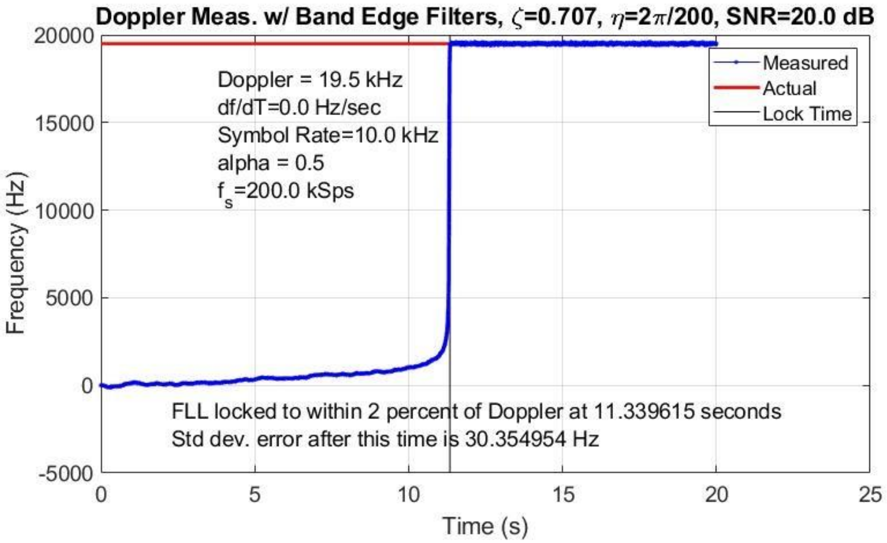


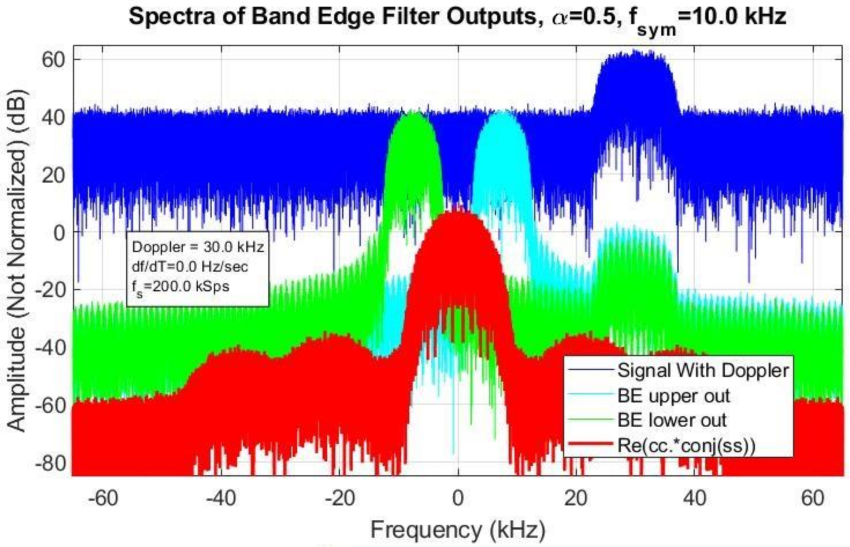


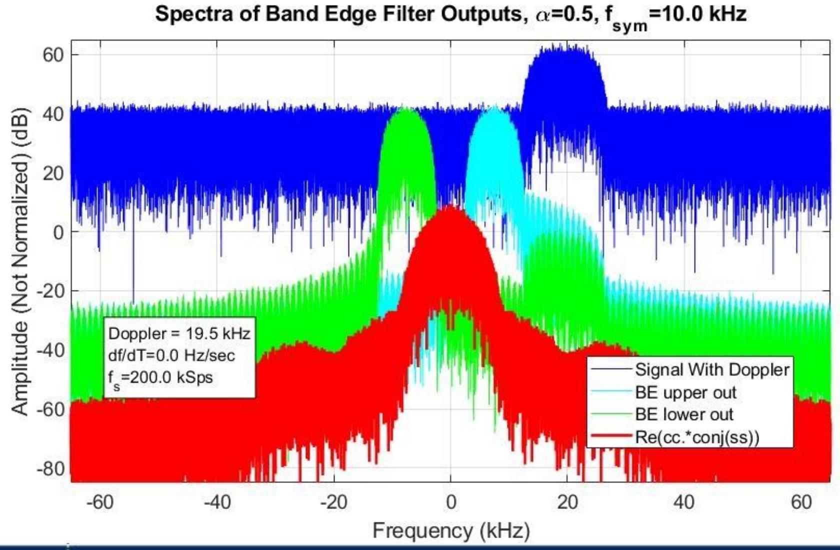
Problem with Band Edge FLL when Doppler Exceeds Modulation Bandwidth

BPSK modulation 10 kHz
200 kS/s sample rate
Doppler change = 0 Hz/s
SNR = 20 dB
Initial Doppler =
30 kHz left
19.5 kHz right







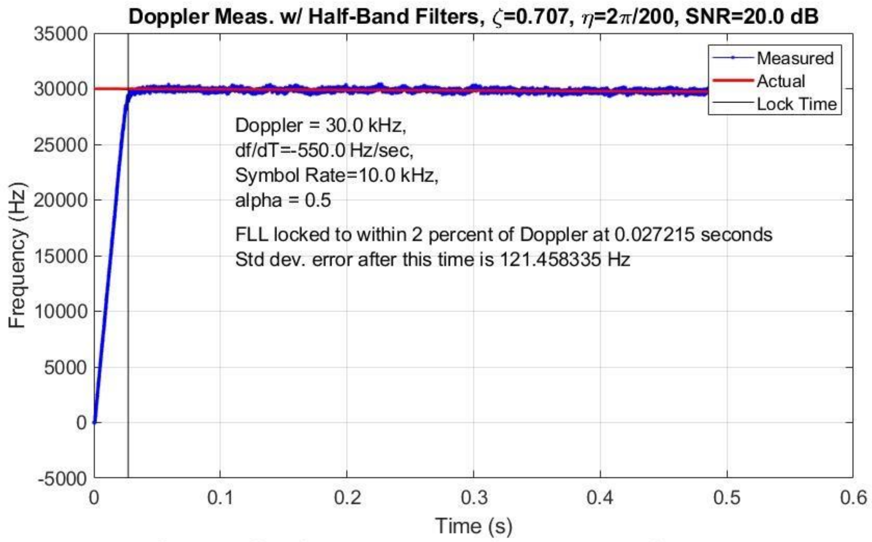


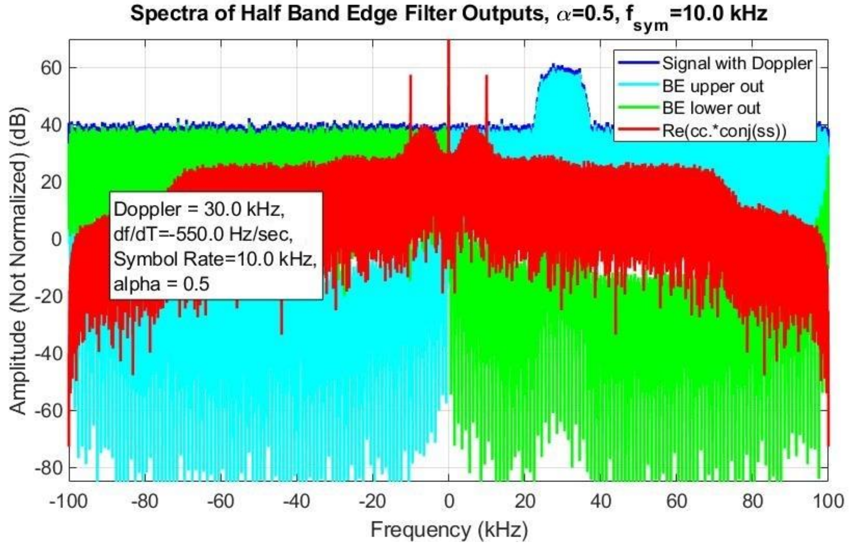
Band edge filters receive very little energy, preventing FLL from functioning properly

Naval Information Warfare Center PACIFIC

Fixing Problem with Half Band Filters

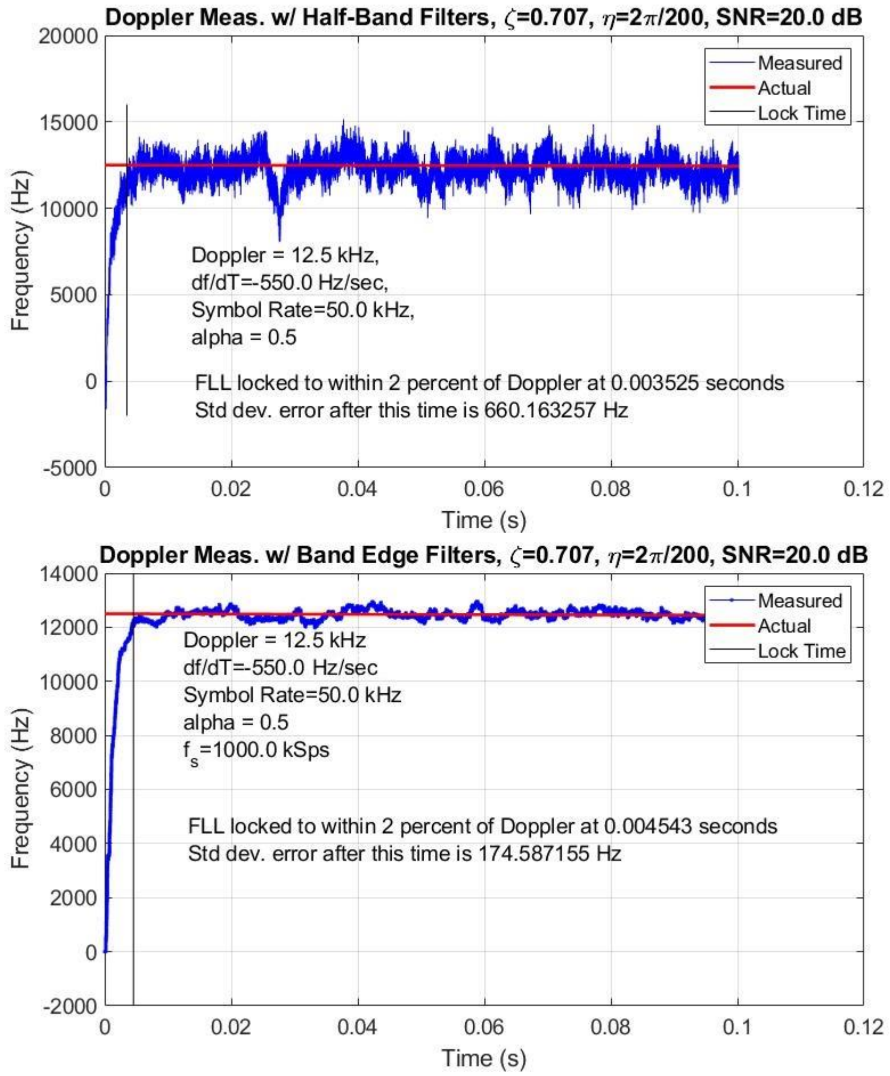
- Using Half Band filters as Band Edge Filters
- Filters will collect energy no matter the Doppler offset
- Able to acquire and track even when Doppler exceeds modulation bandwidth
    - BPSK signal with 10 kHz modulation
    - Doppler initially at 30 kHz,
    - Doppler changing by -550 Hz/s
    - Acquired in less than 30 ms
    - Standard deviation of freq. error 121Hz





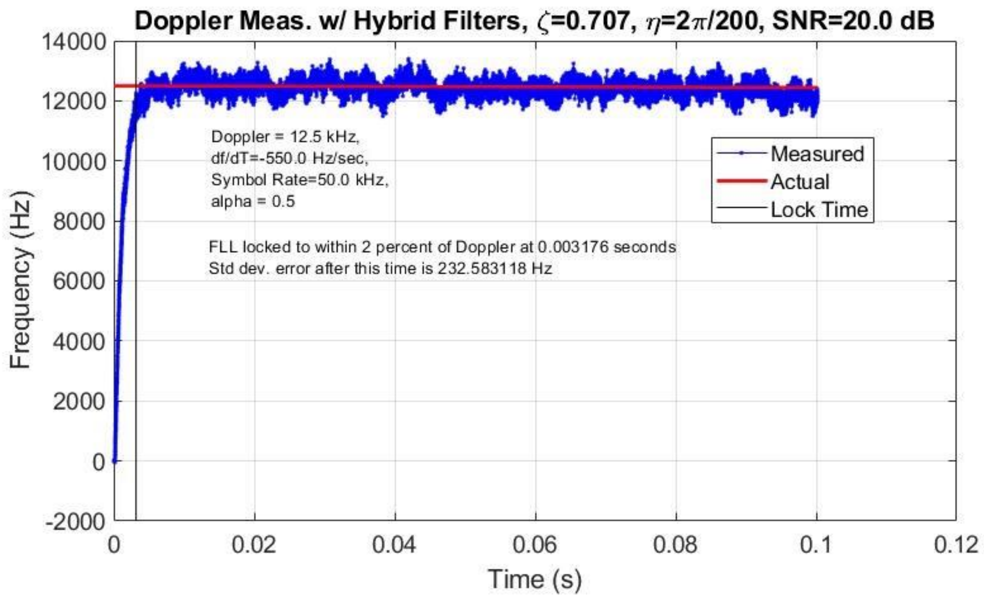
Half Band Filters vs. Optimum Filters when Doppler is within Modulation Bandwidth

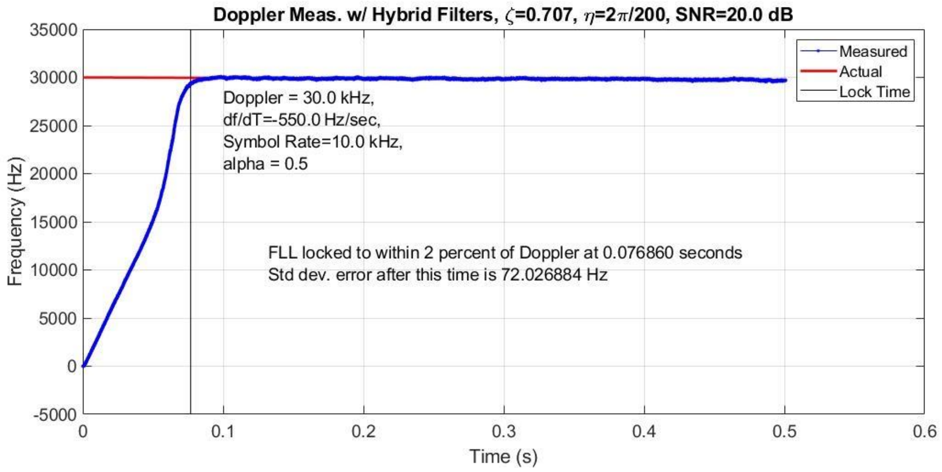
- When the Doppler is within the modulation bandwidth of the signal of interest, Optimum filters have lower standard deviation of frequency error
  - BPSK 50 kHz modulation
  - 12.5 kHz Doppler, -550 Hz/s
- SNR = 20 dB
- Top = Half Band Filters
- Bottom = Optimum Filters



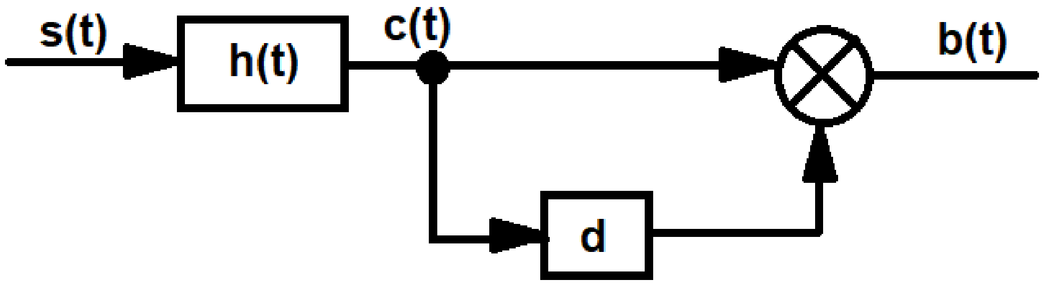
Hybrid Solution: Optimum Plus Half Band

- Sum of Optimum and Half Band retains the out-of-band performance and preserves the in-band performance
- Top curve:
  - BPSK 50 kHz modulation
  - 20 dB SNR
  - 12.5 kHz initial Doppler offset
  - -550 Hz/s Doppler change
- Bottom curve:
  - BPSK 10 kHz modulation
  - 20 dB SNR
  - 30 kHz initial Doppler offset
  - -550 Hz/s Doppler change





Prefilter Delay-Multiply Device



$$s(t) = \sum_{n=-\infty}^{\infty} a_n p(t - nT) e^{j2\pi f_0 t} e^{j\theta}$$

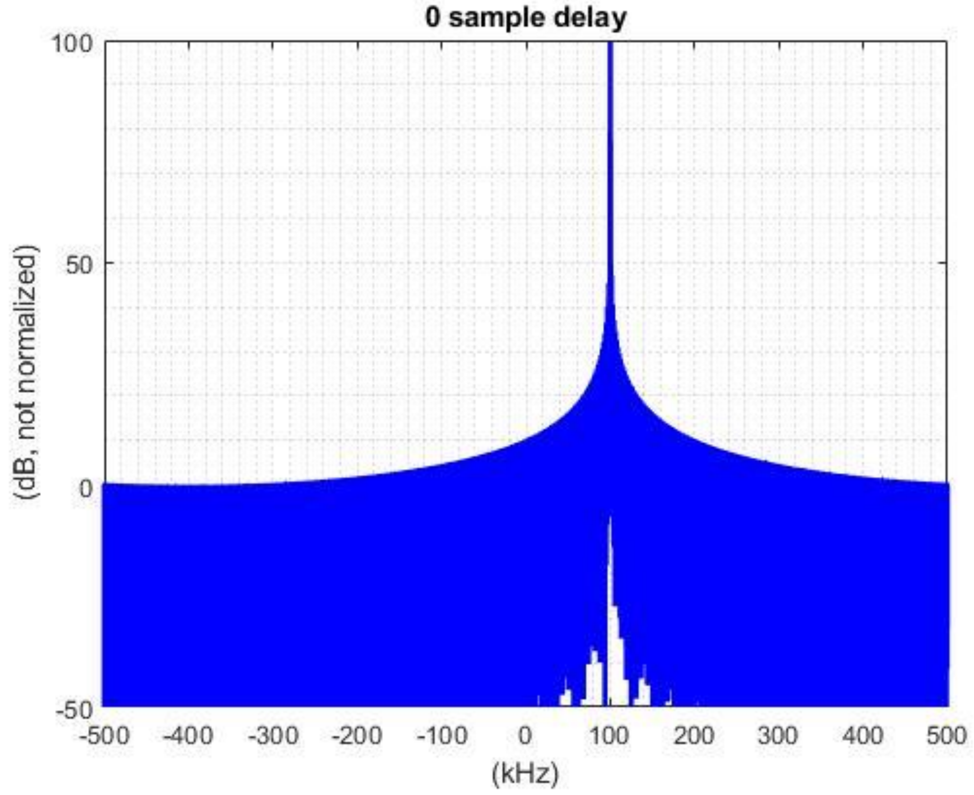
$$c(t) = \sum_{n=-\infty}^{\infty} a_n q(t - nT) A e^{j2\pi f_0 t} e^{j\theta} e^{j\varphi}$$

$$b(t) = \left(\sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} a_n a_m q(t - nT) q(t - d - mT) \right) \cdot \left(A^2 e^{j2\pi 2 f_0 t} \right) \cdot \left(e^{-j2\pi f_0 d} e^{j2\theta} e^{j2\varphi} \right)$$

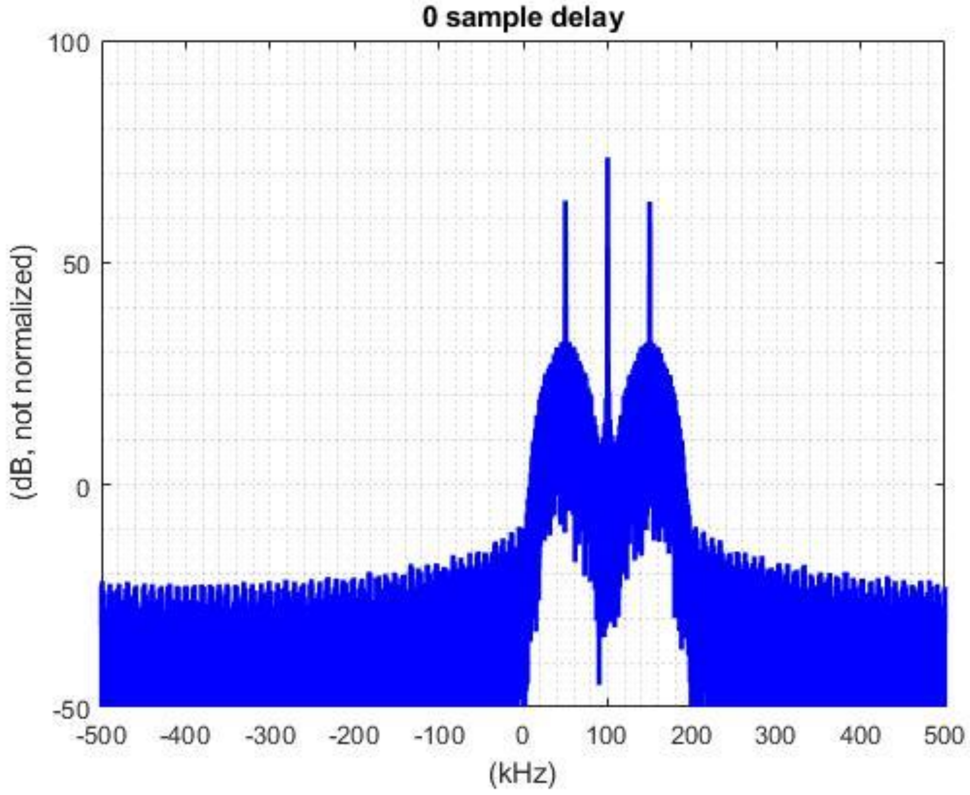
- Filter h(t) is for noise reduction
- Delay “d” is varied between 0 and 1 symbol periods
- For BPSK signal inputs (s(t)), spectrum of b(t) will be tone at twice Doppler frequency surrounded by tones separated by symbol rate
- When n=m, b(t) is periodic (fundamental at symbol rate)

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



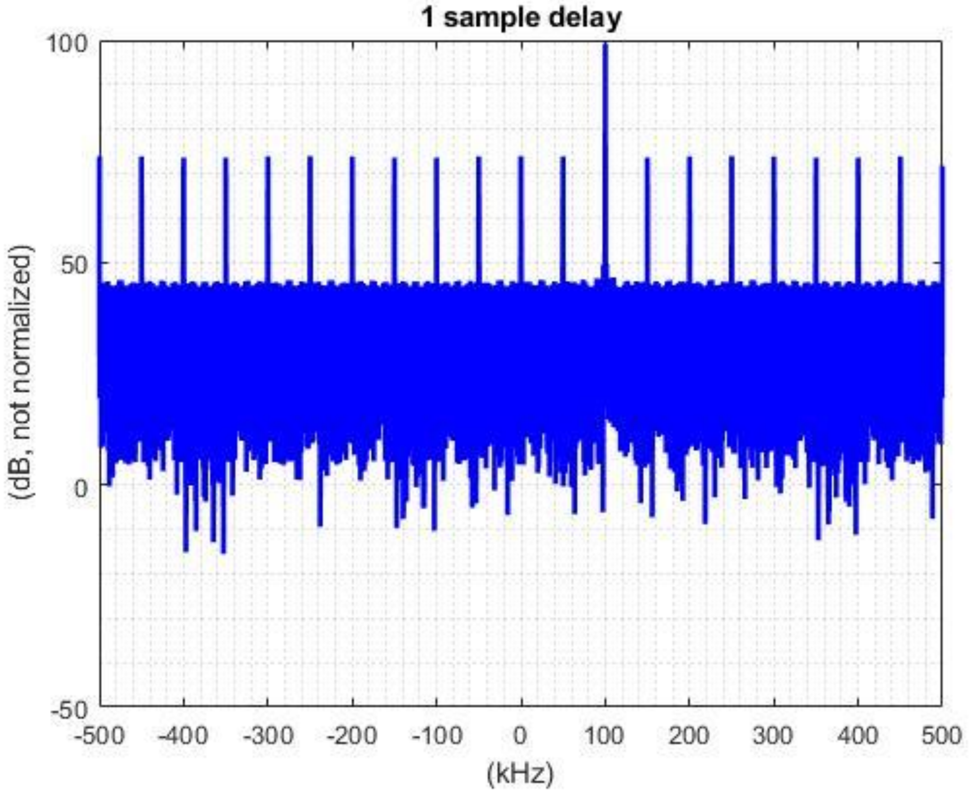
Raised Cosine Shaping Filter (α=0.5)



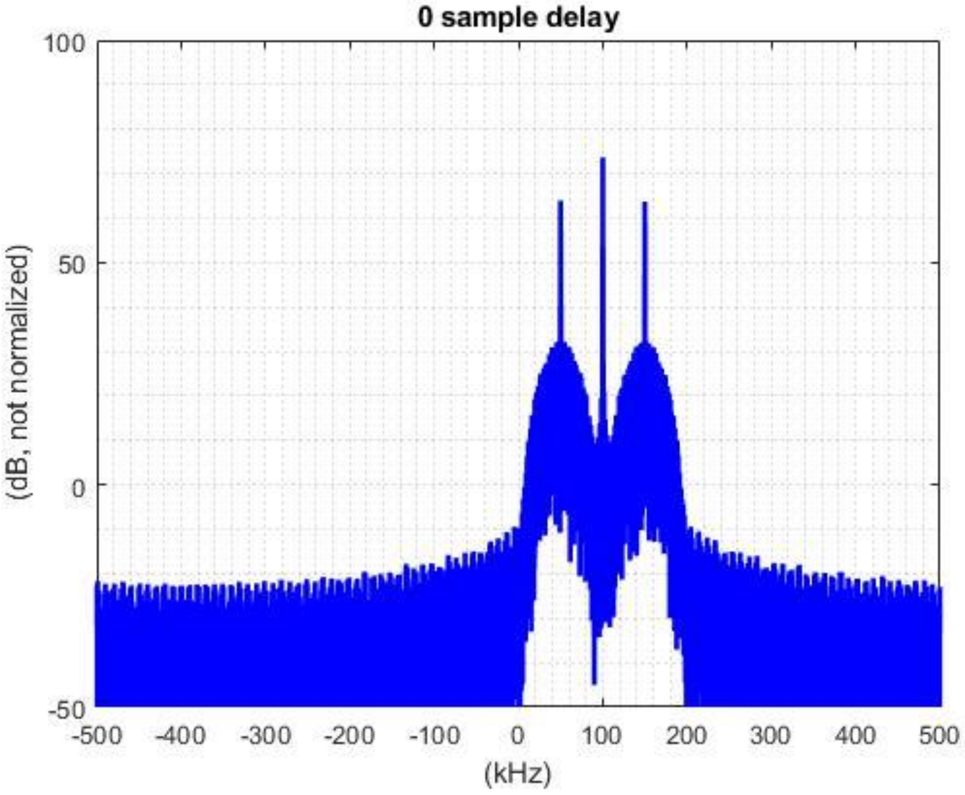
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



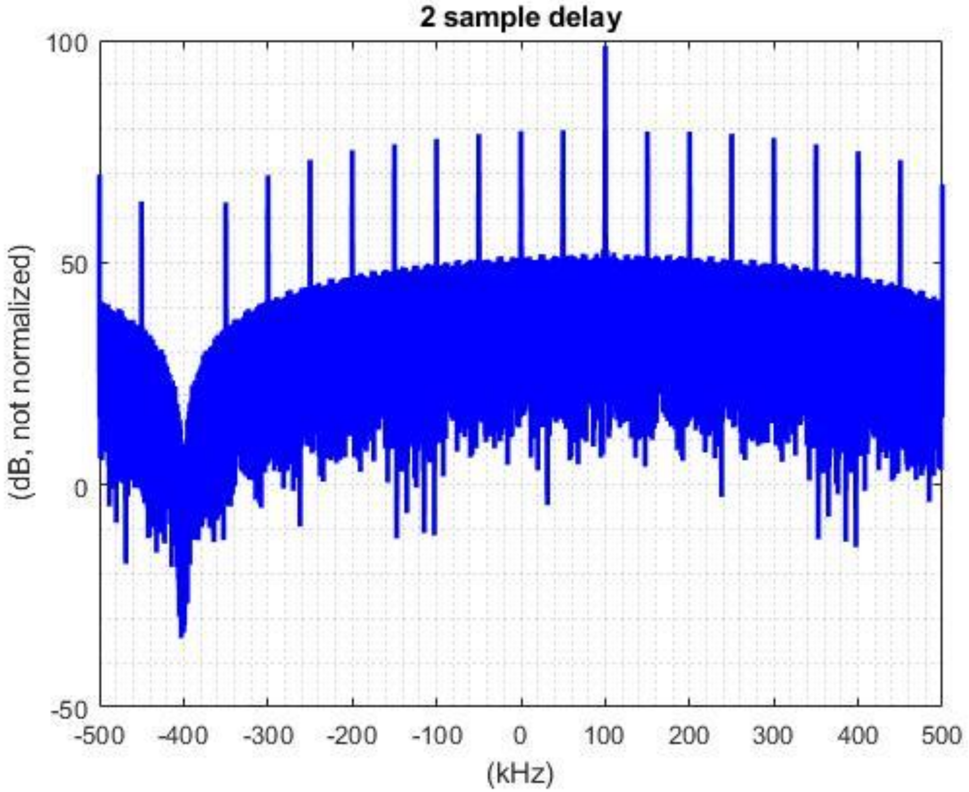
Raised Cosine Shaping Filter (α=0.5)



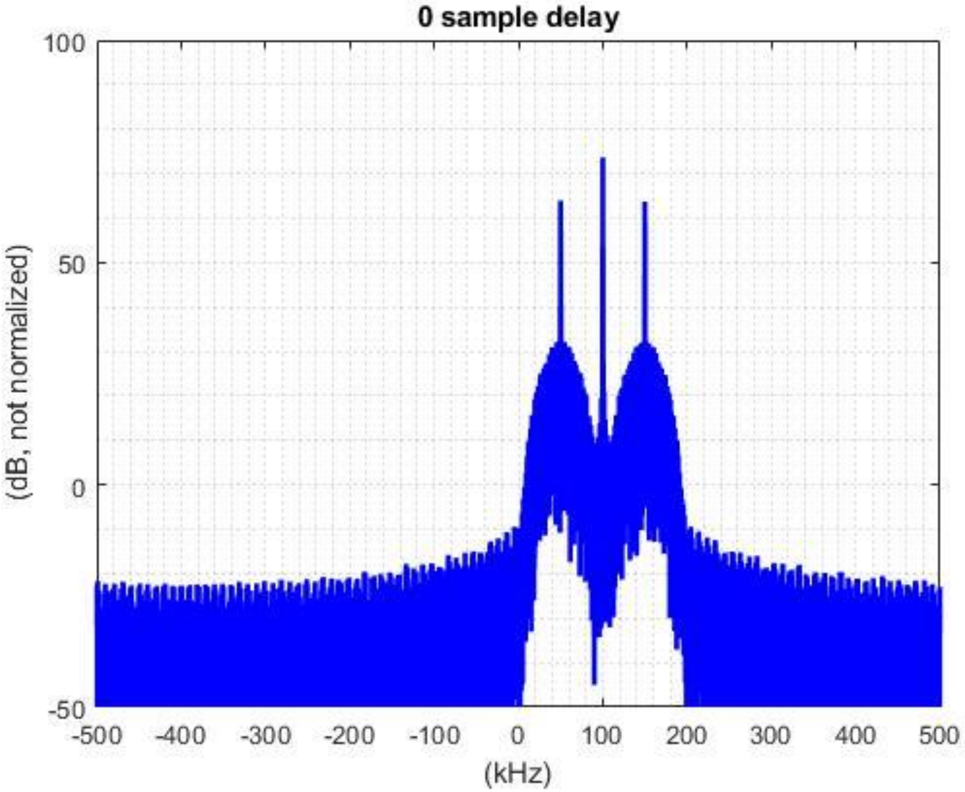
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



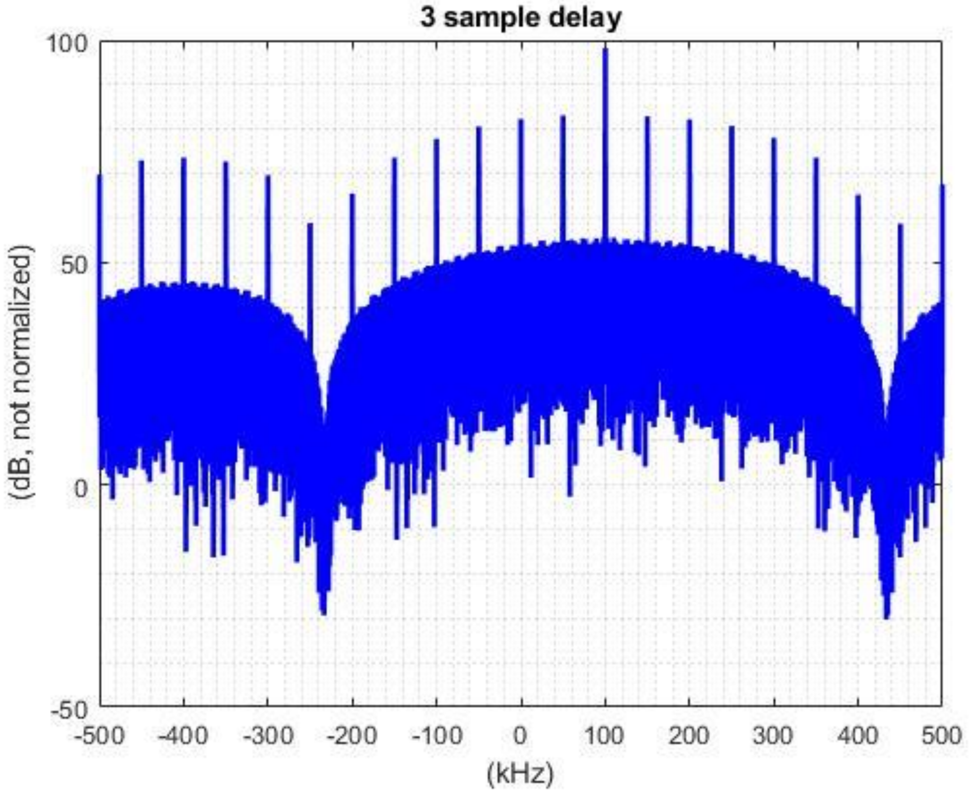
Raised Cosine Shaping Filter (α=0.5)



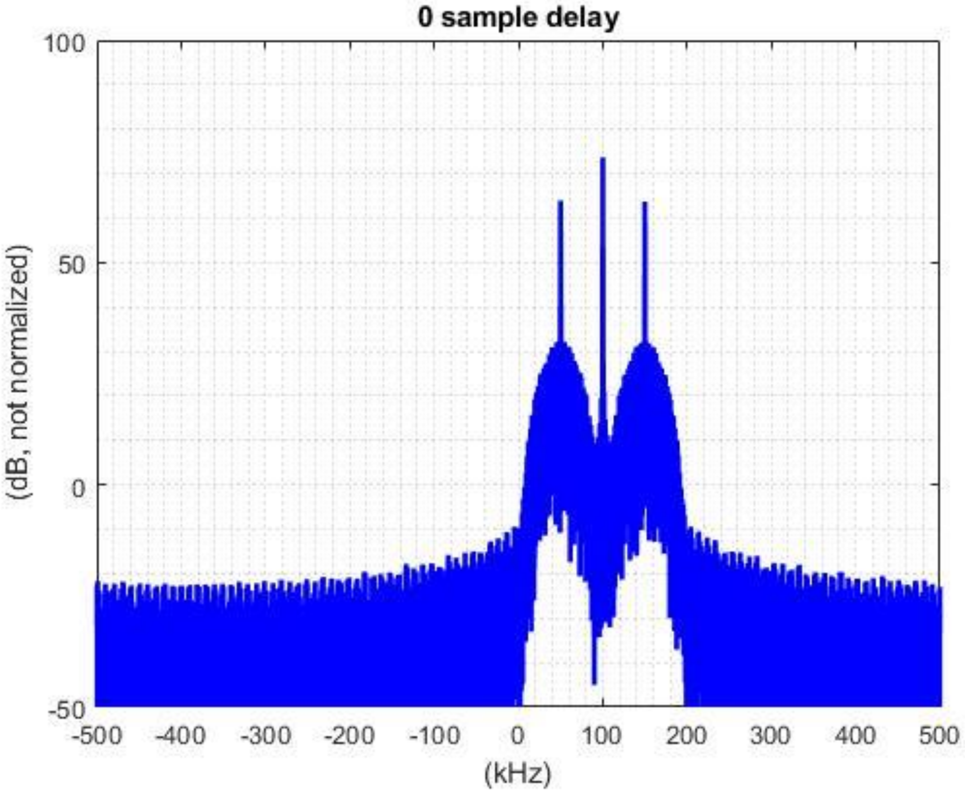
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



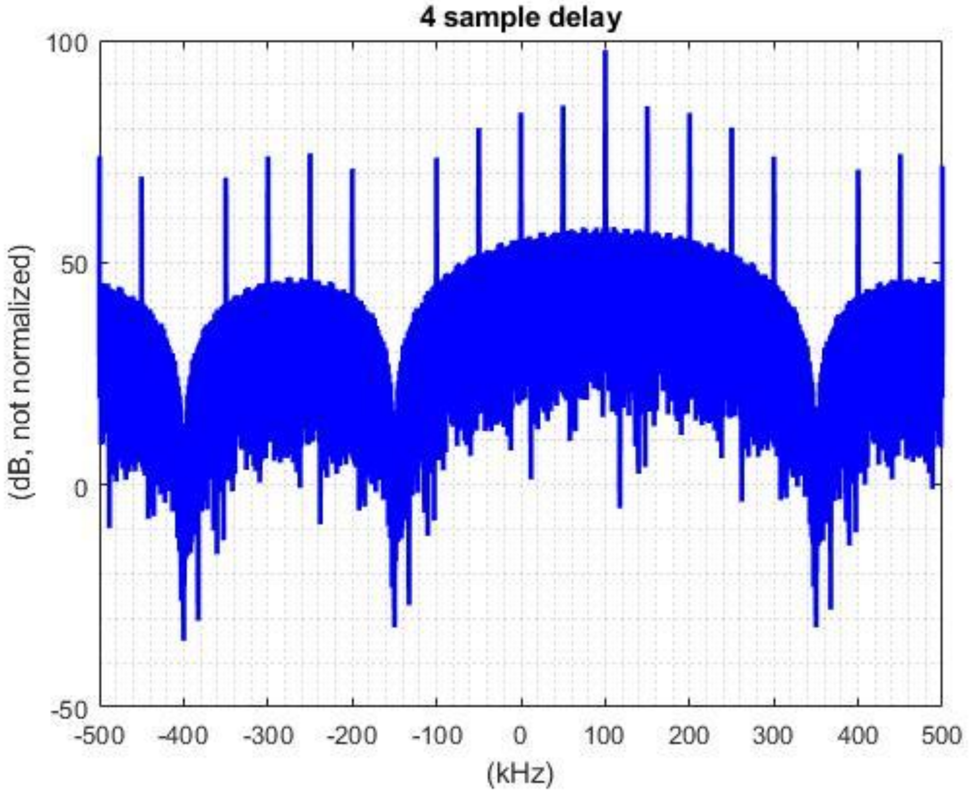
Raised Cosine Shaping Filter (α=0.5)



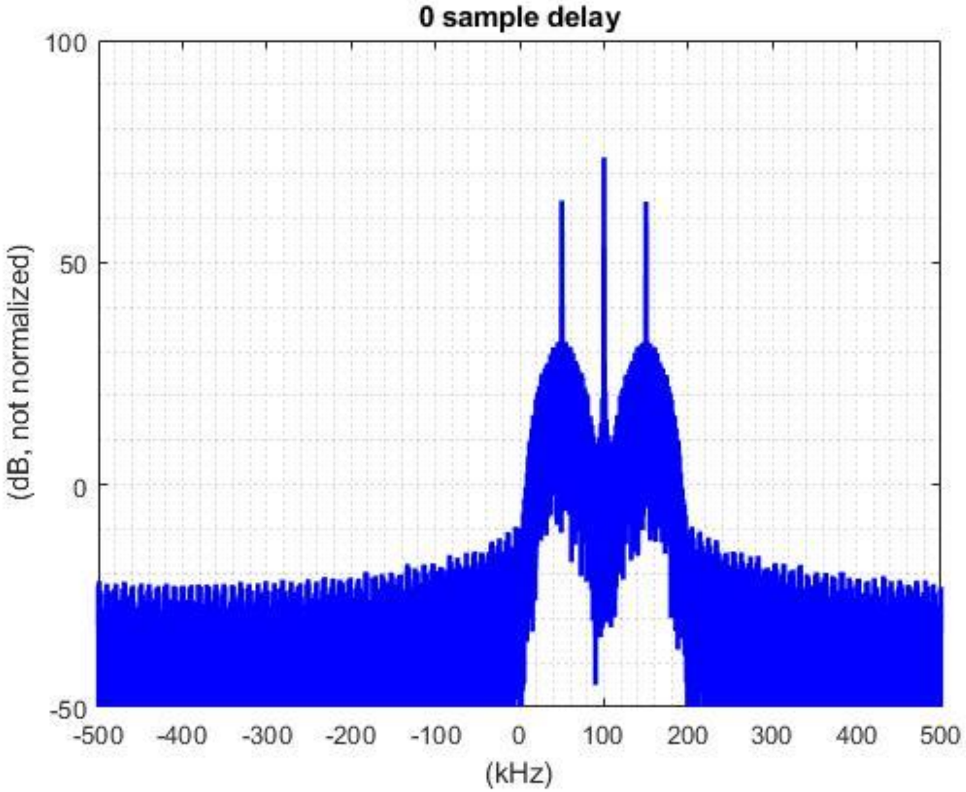
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



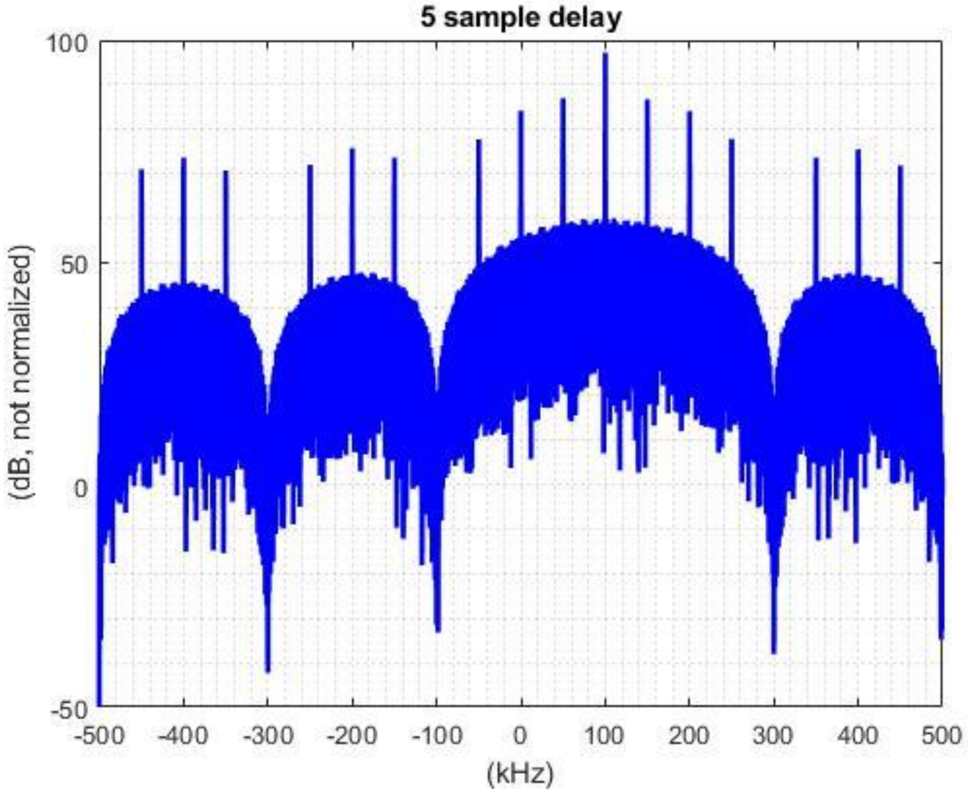
Raised Cosine Shaping Filter (α=0.5)



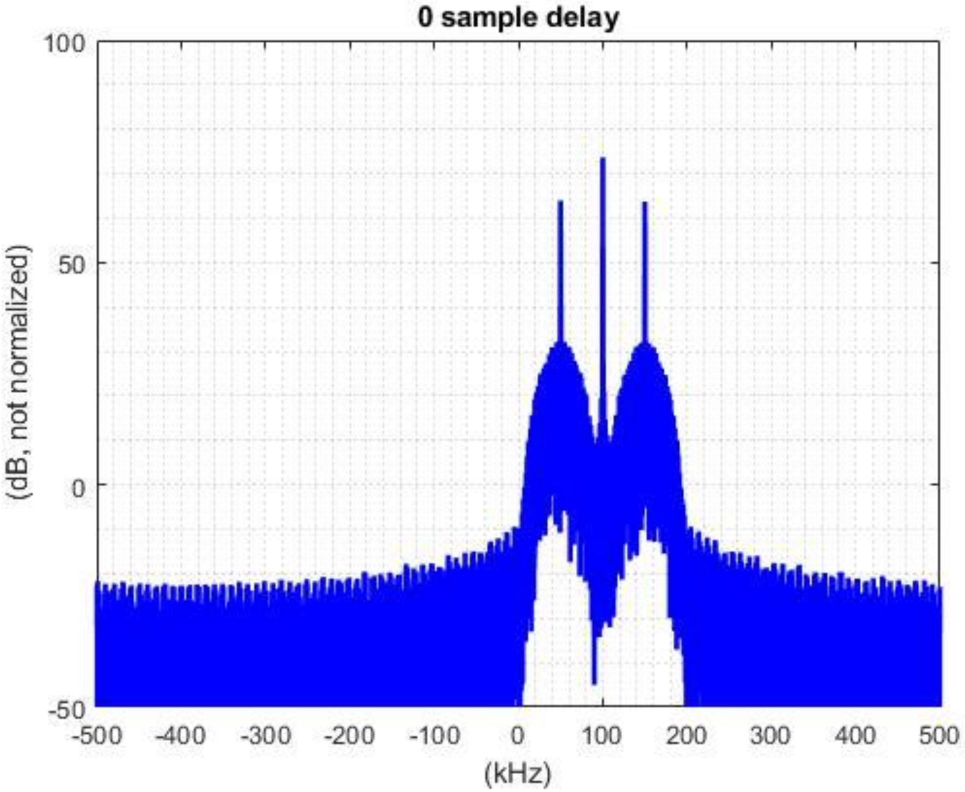
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

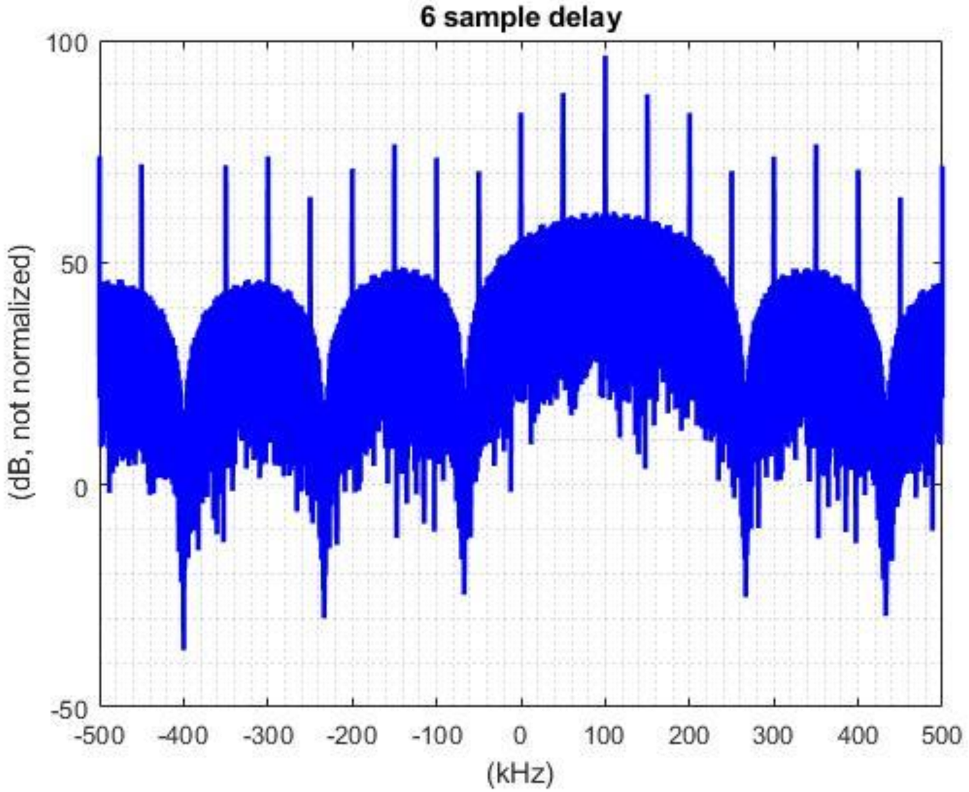


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

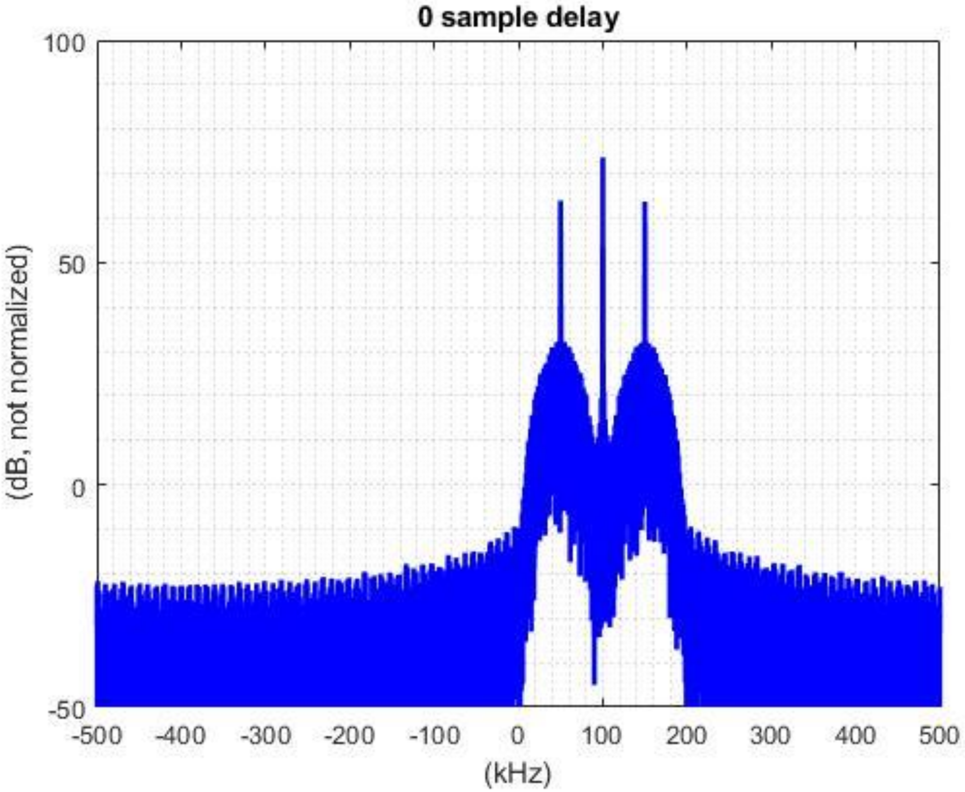
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



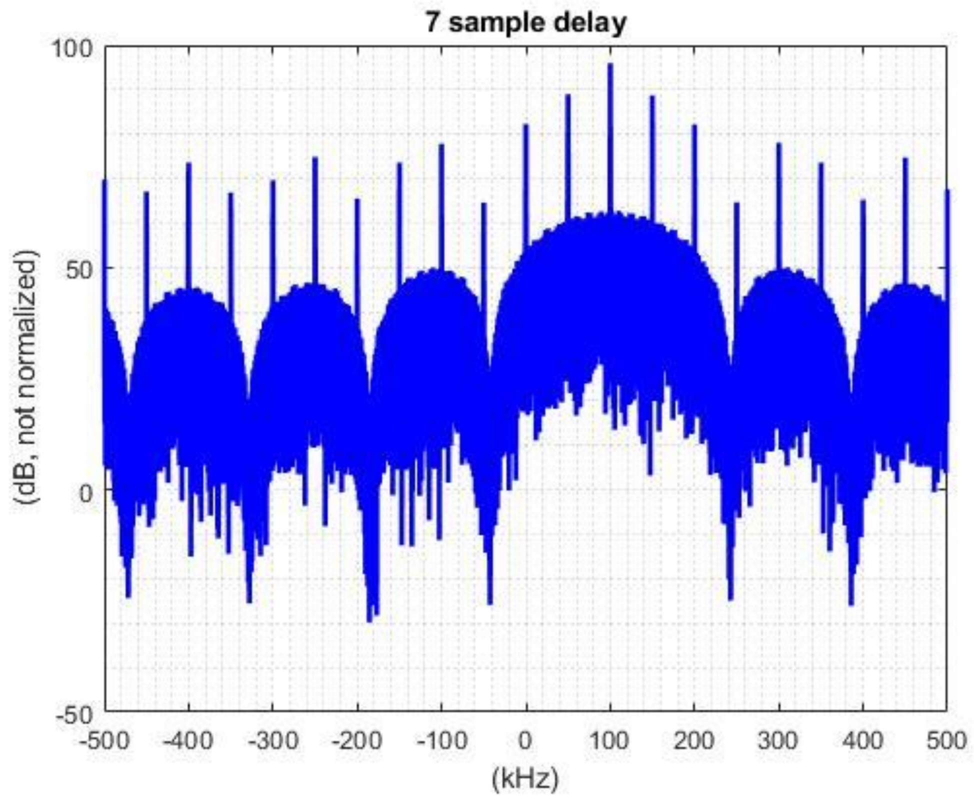
Raised Cosine Shaping Filter (α=0.5)



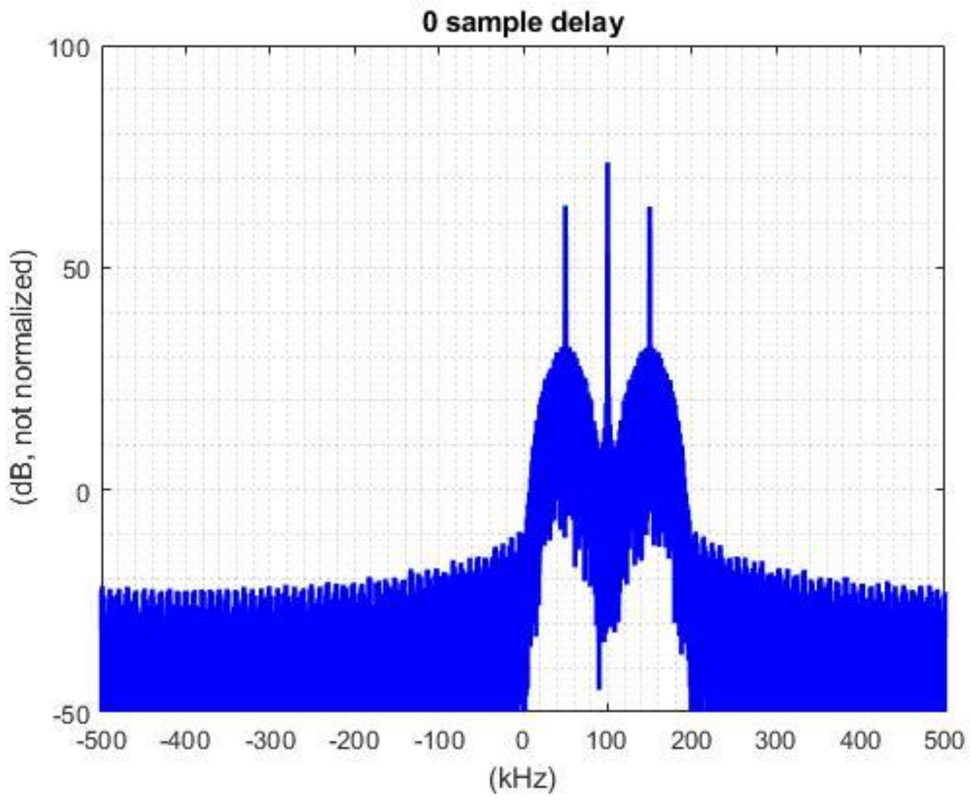
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

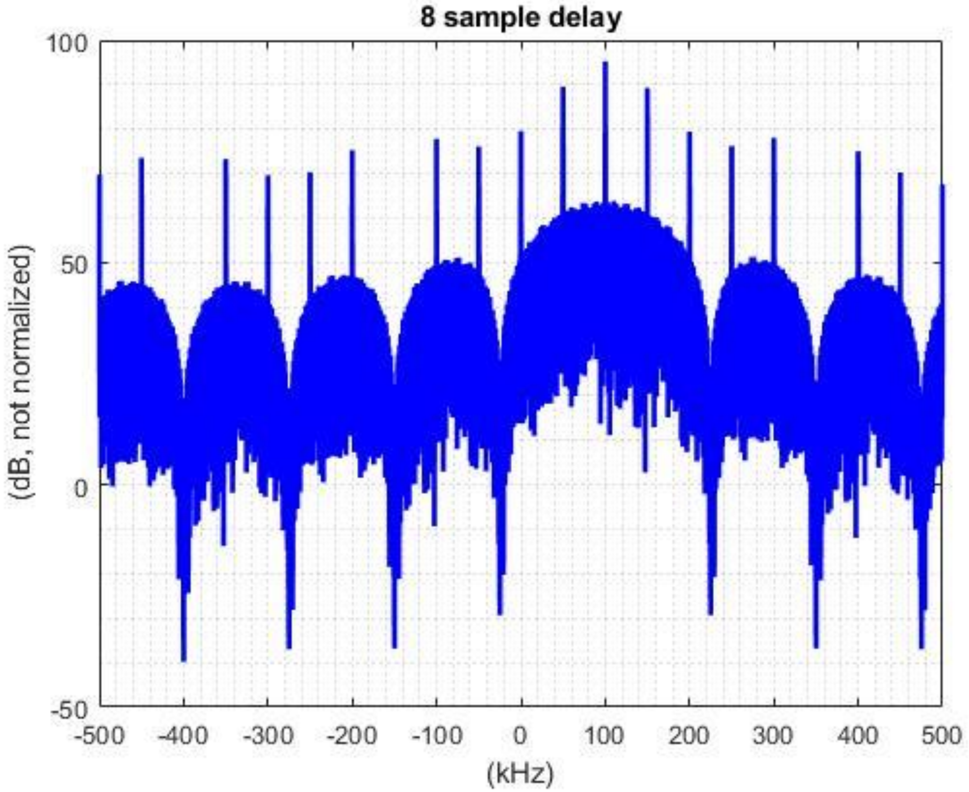


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

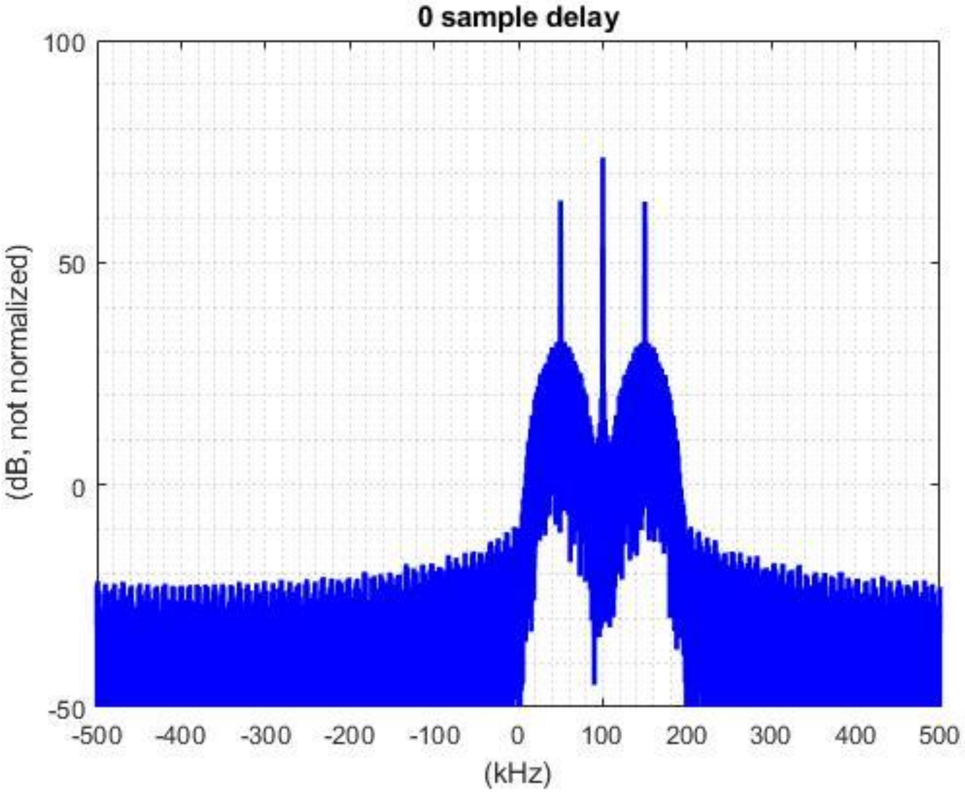
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



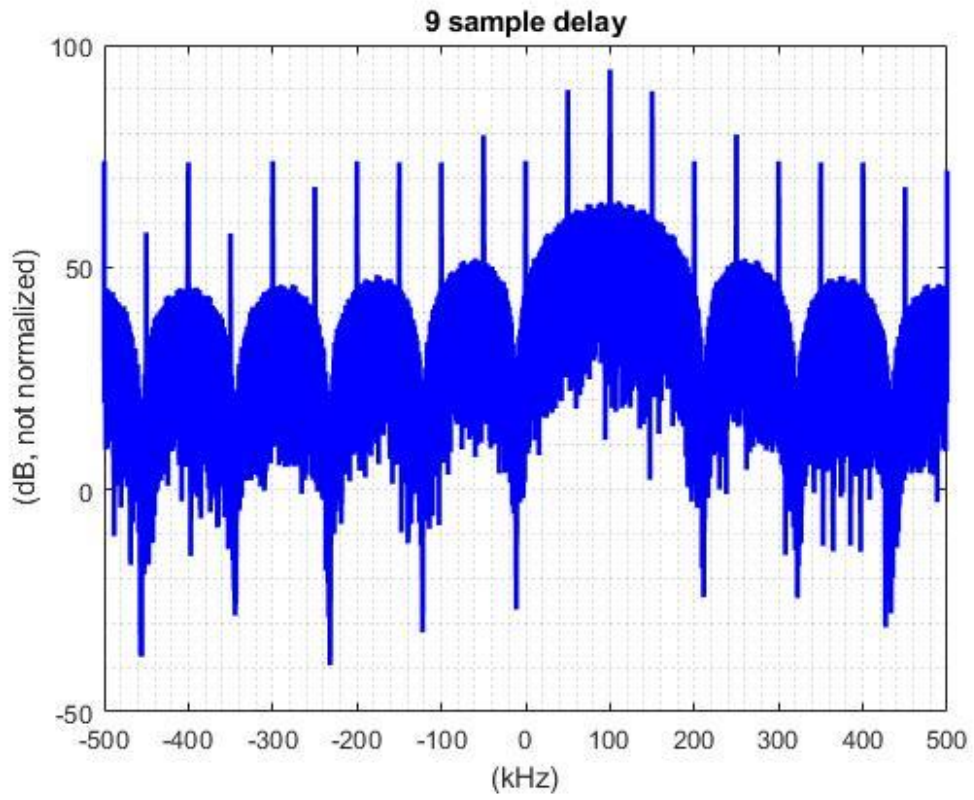
Raised Cosine Shaping Filter (α=0.5)



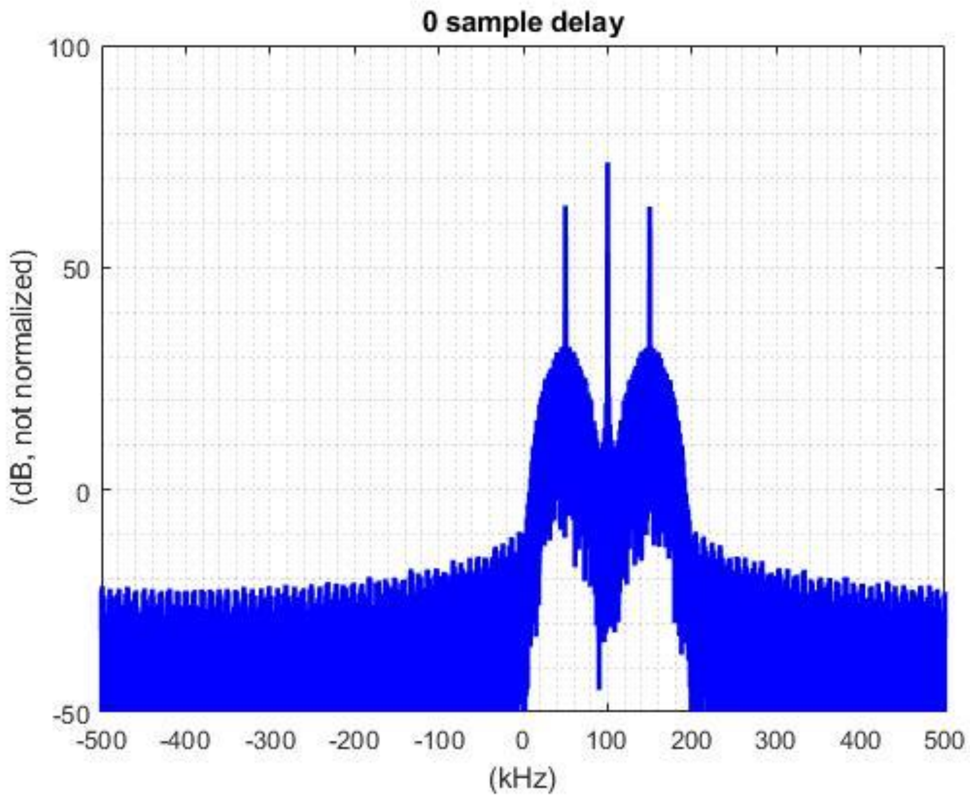
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



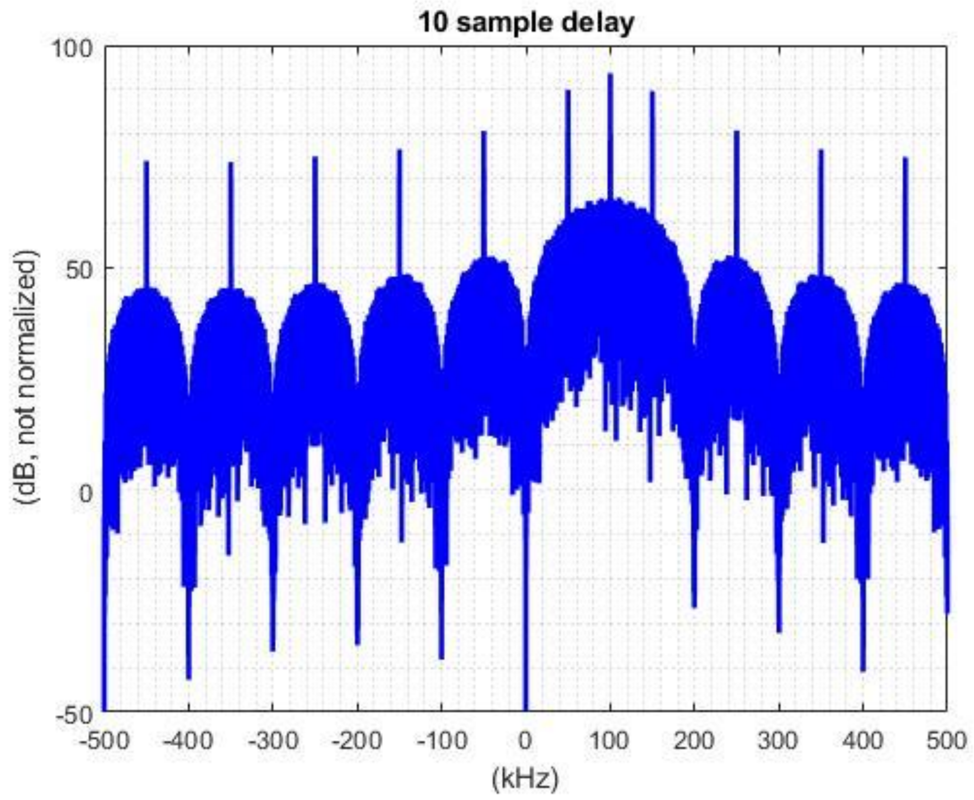
Raised Cosine Shaping Filter (α=0.5)



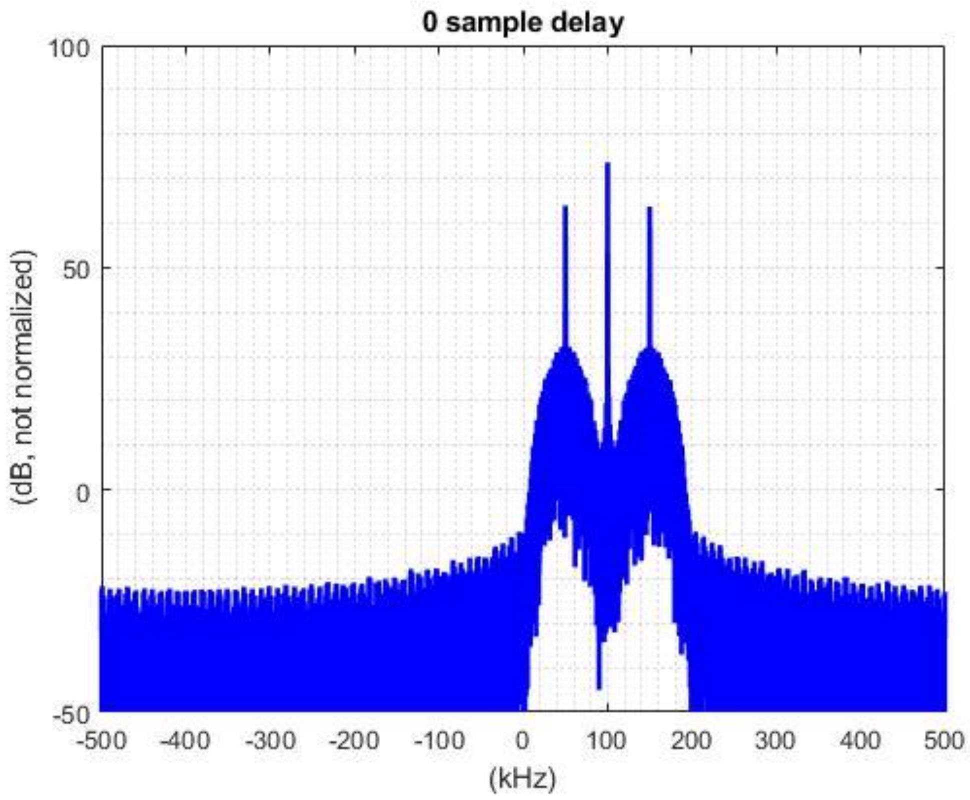
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

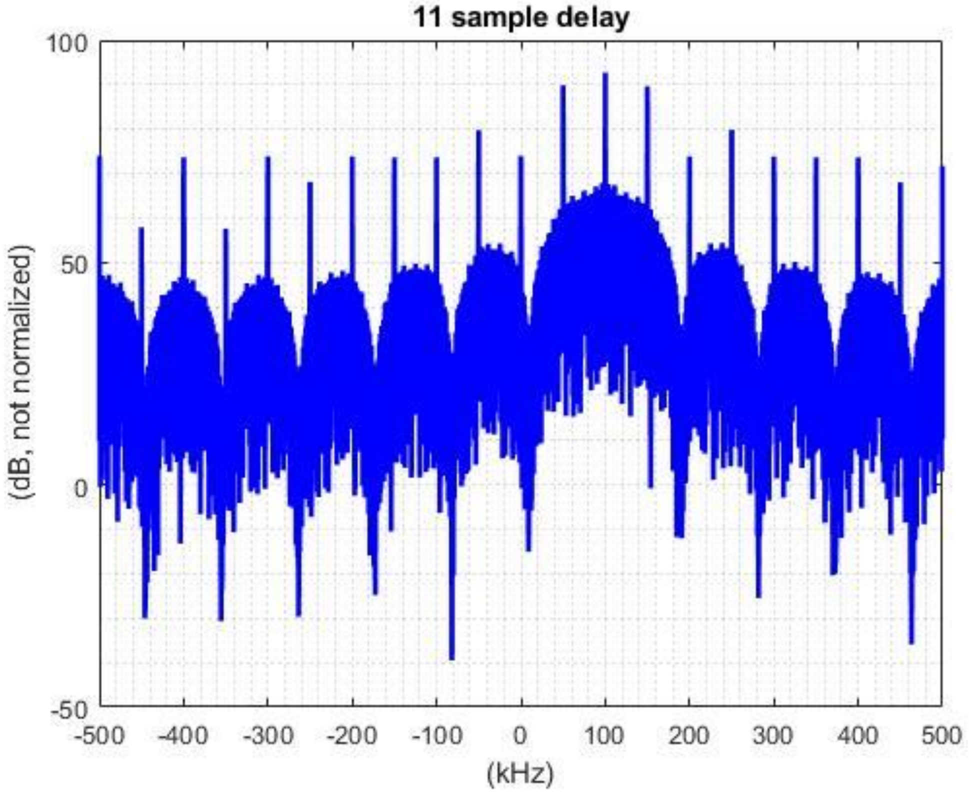


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

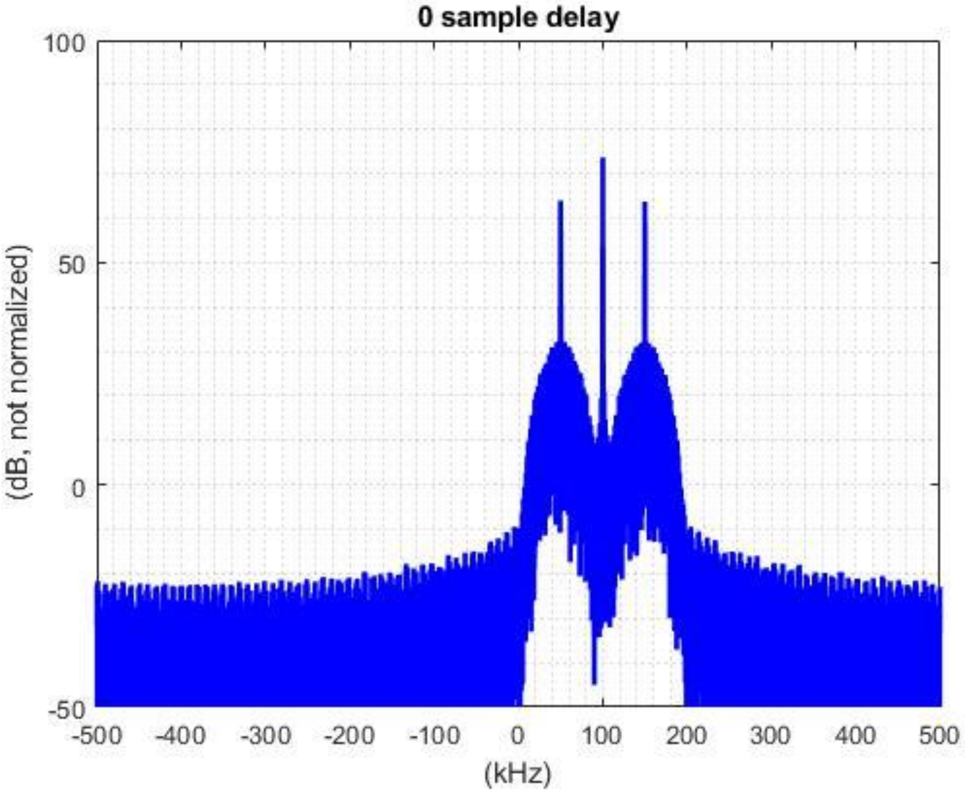
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



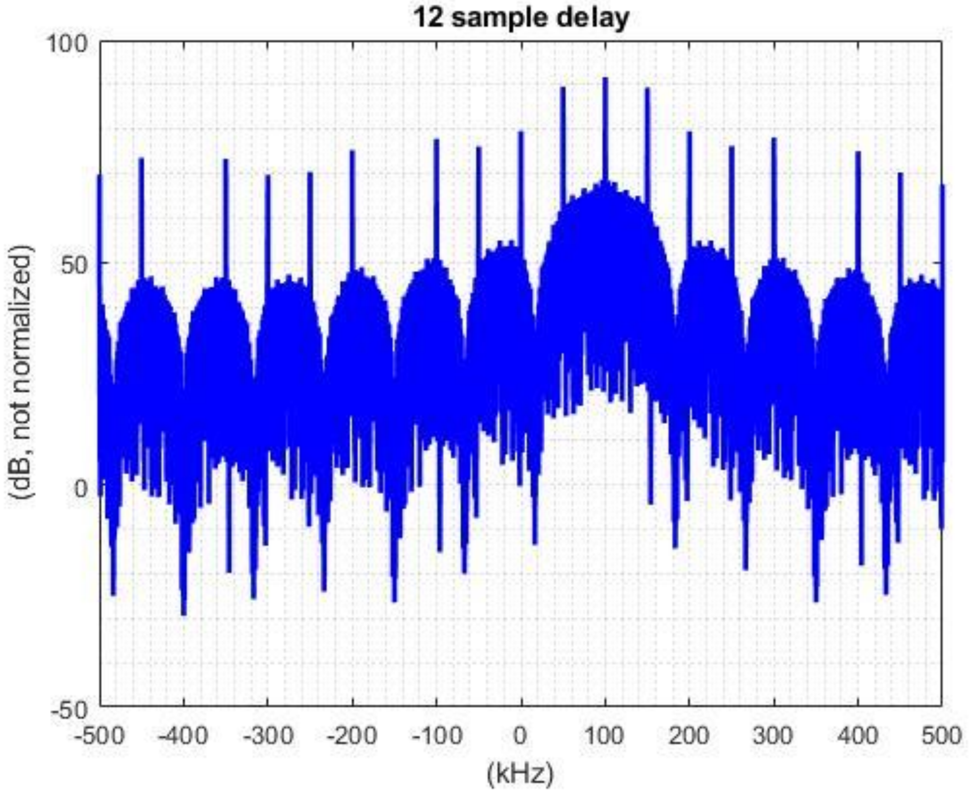
Raised Cosine Shaping Filter (α=0.5)



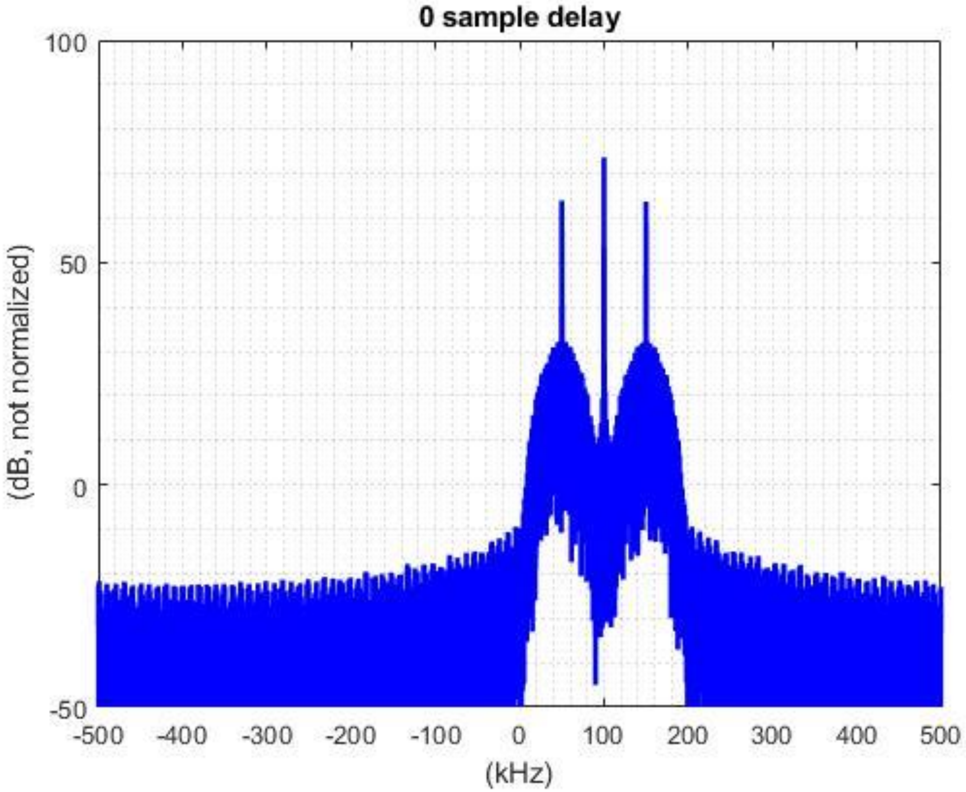
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



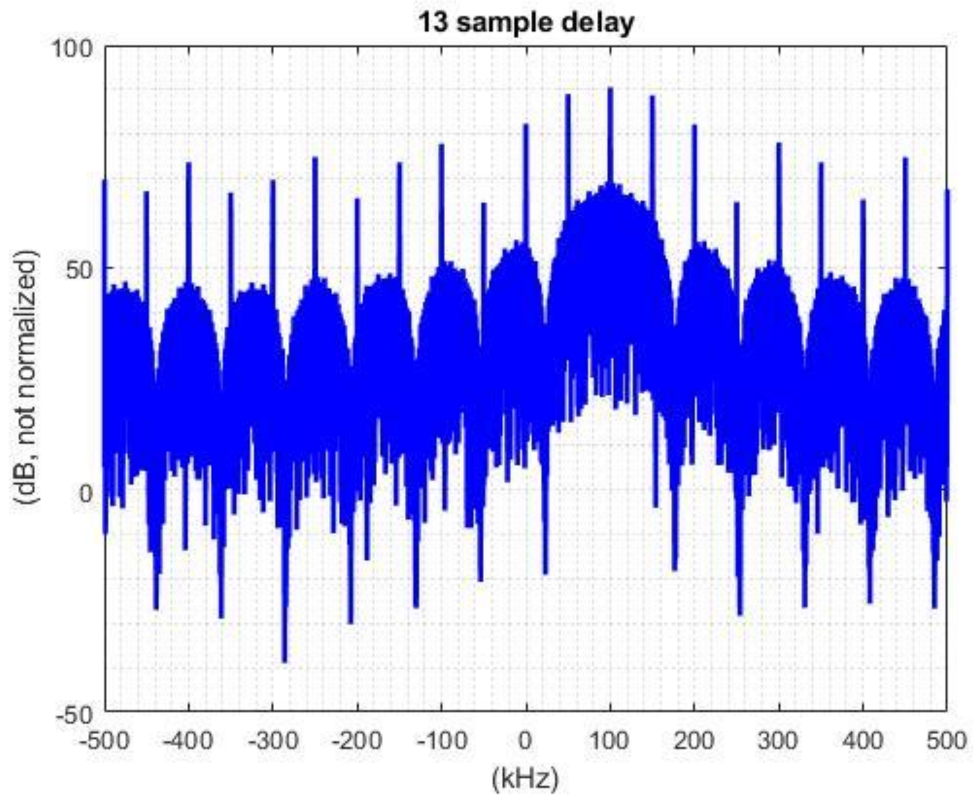
Raised Cosine Shaping Filter (α=0.5)



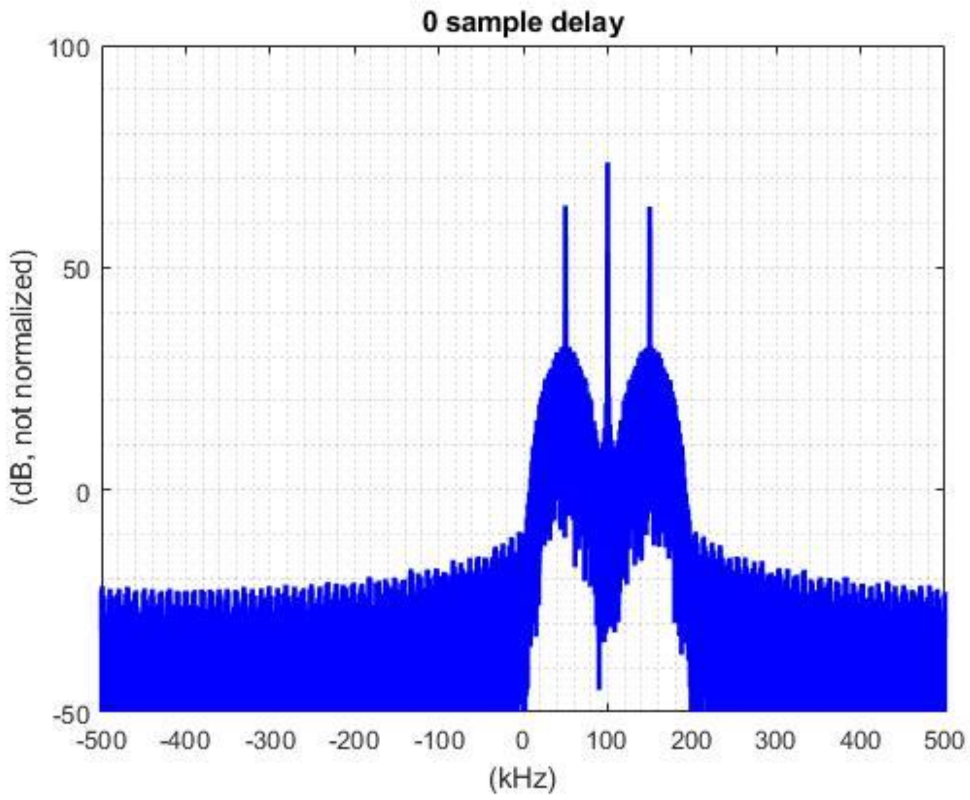
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



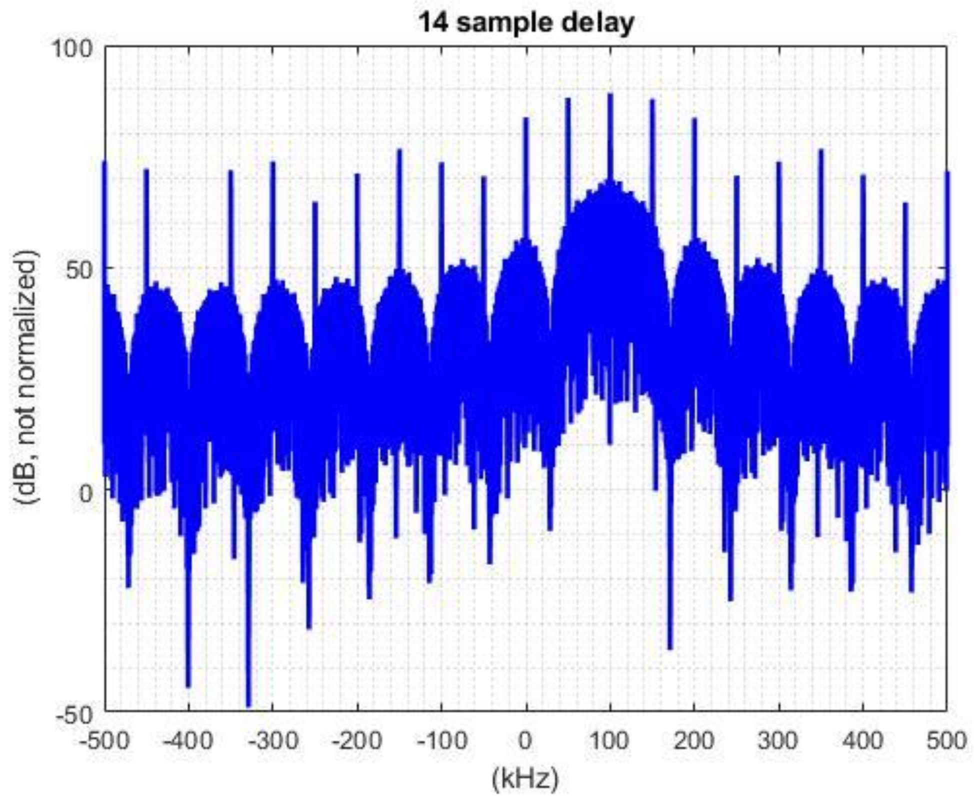
Raised Cosine Shaping Filter (α=0.5)



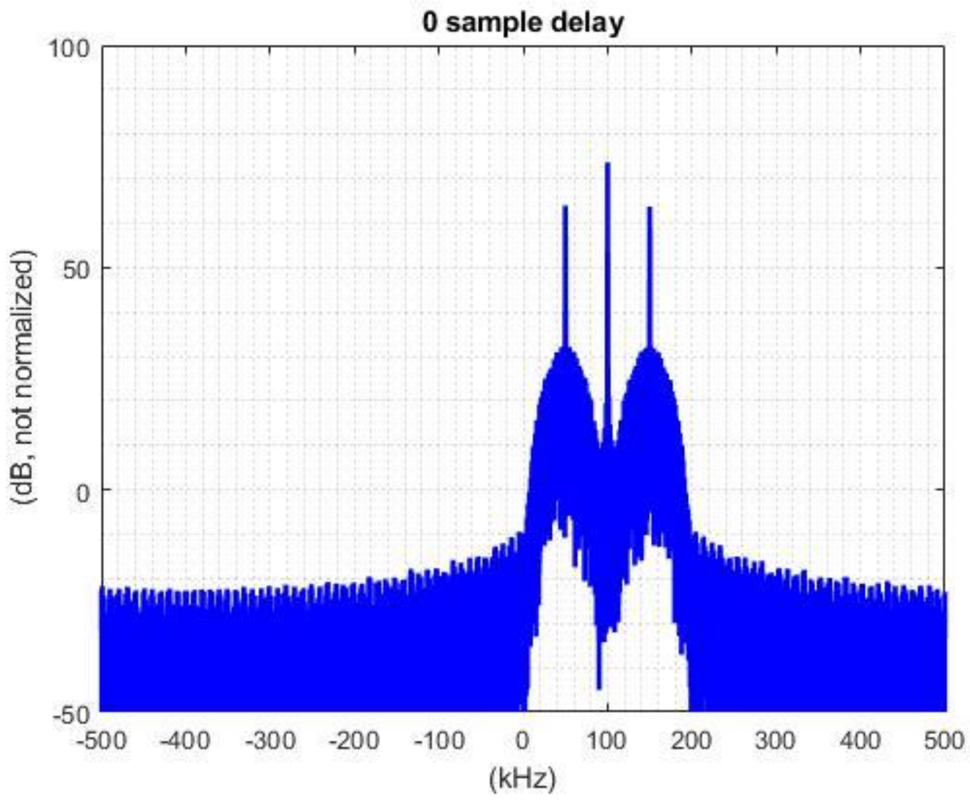
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



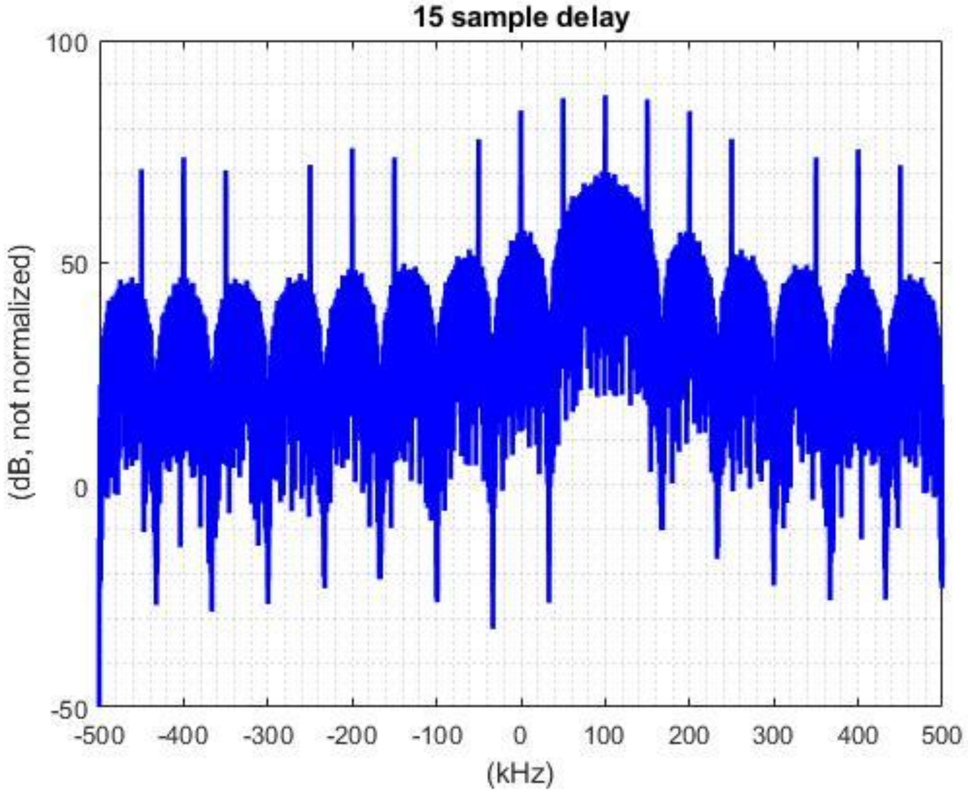
Raised Cosine Shaping Filter (α=0.5)



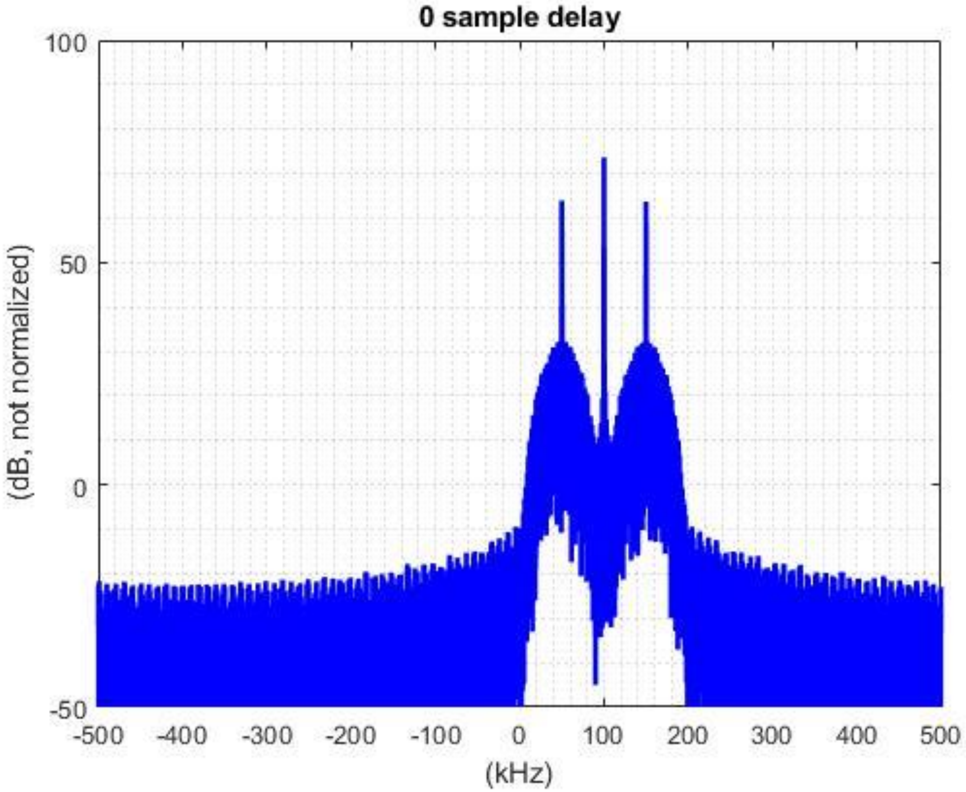
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



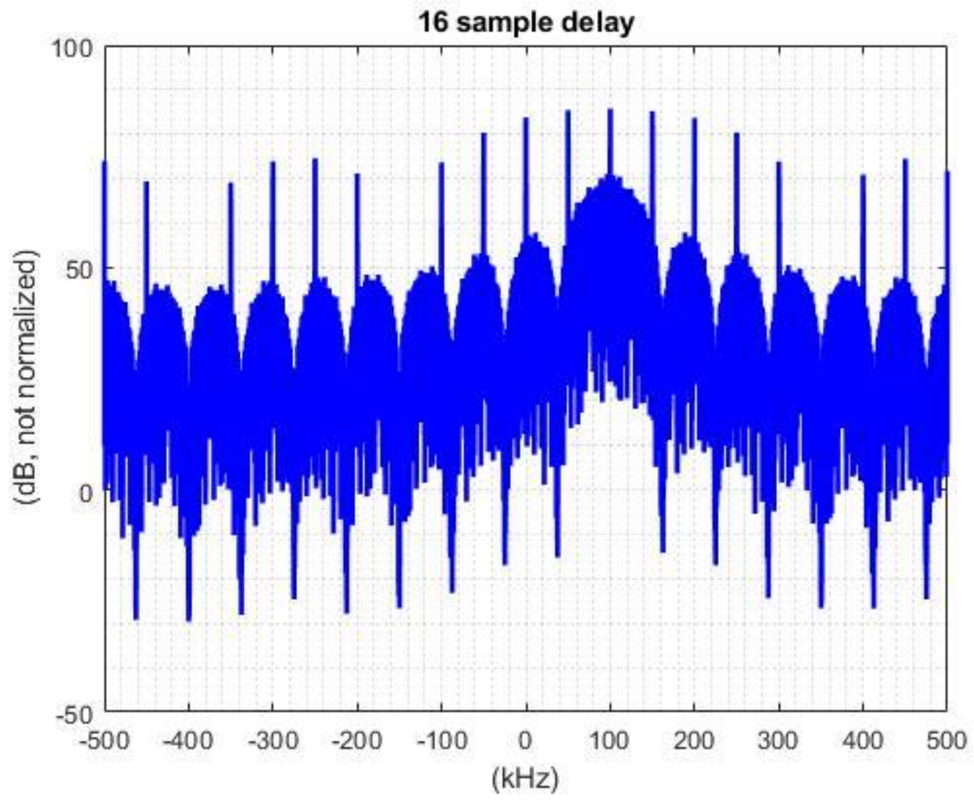
Raised Cosine Shaping Filter (α=0.5)



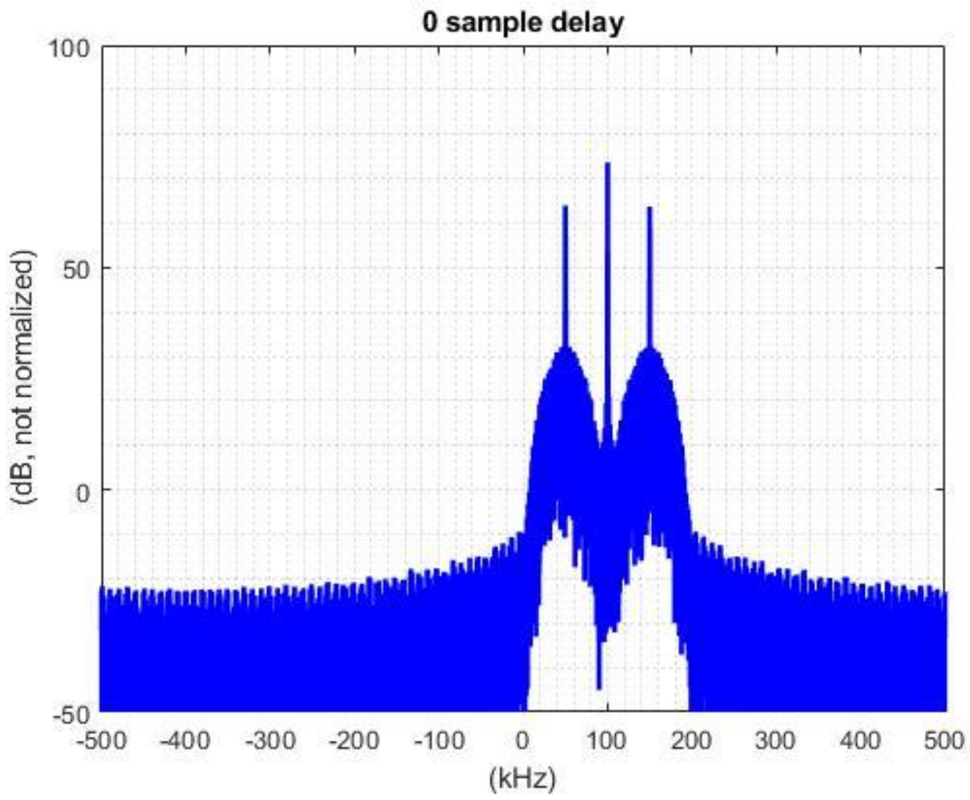
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



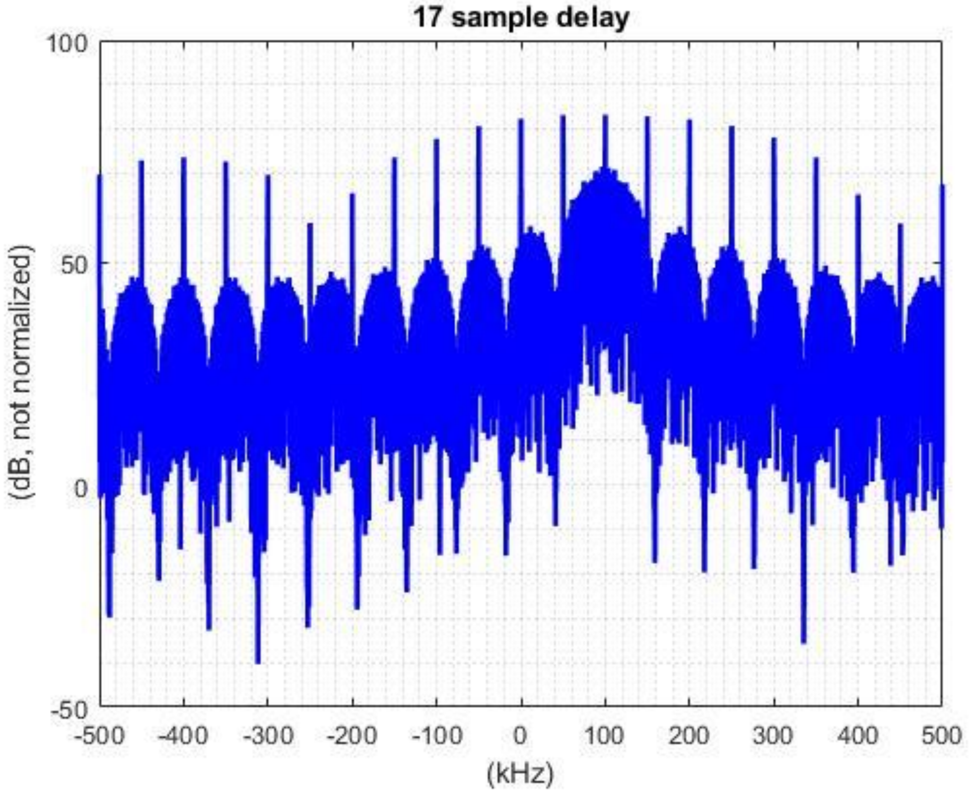
Raised Cosine Shaping Filter (α=0.5)



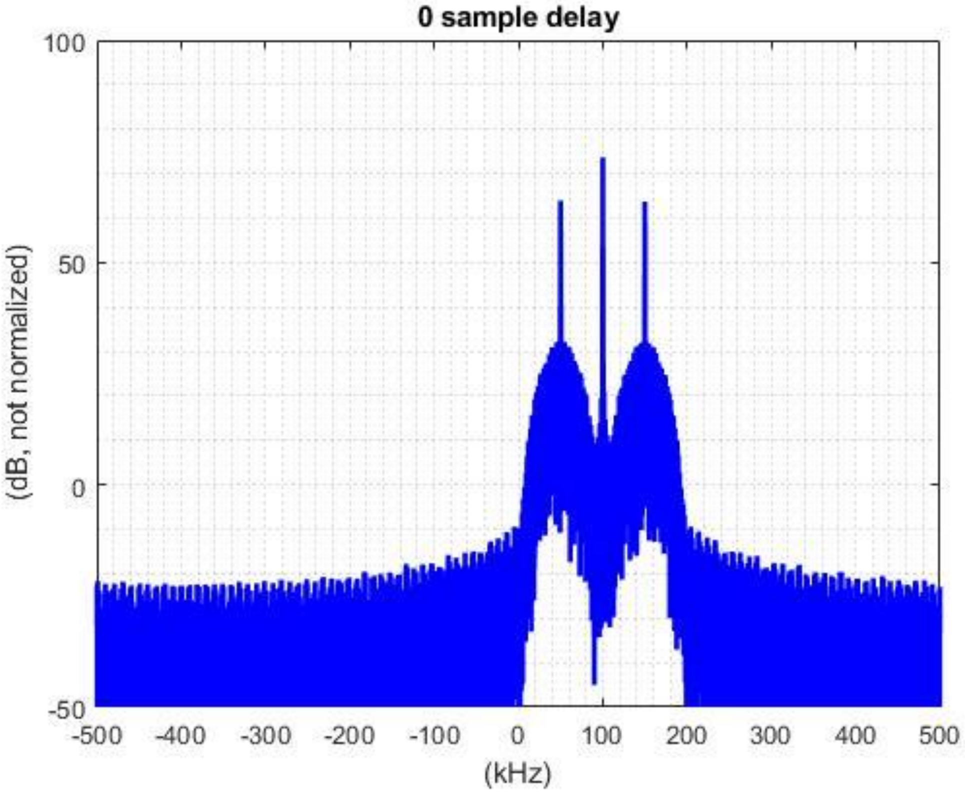
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

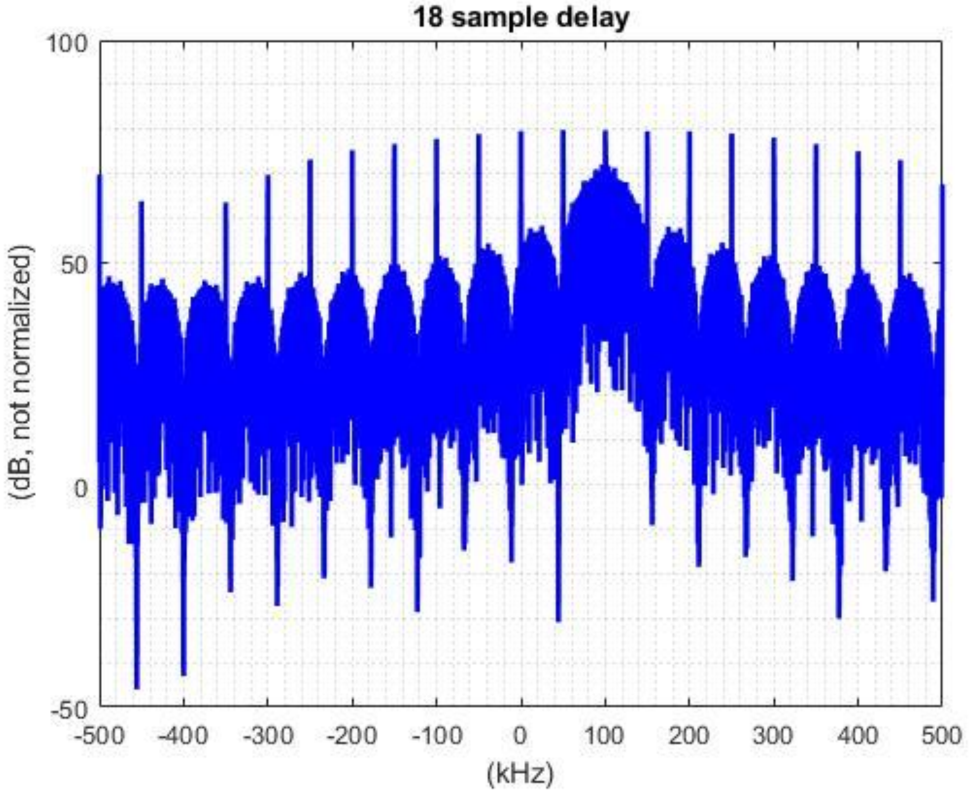


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

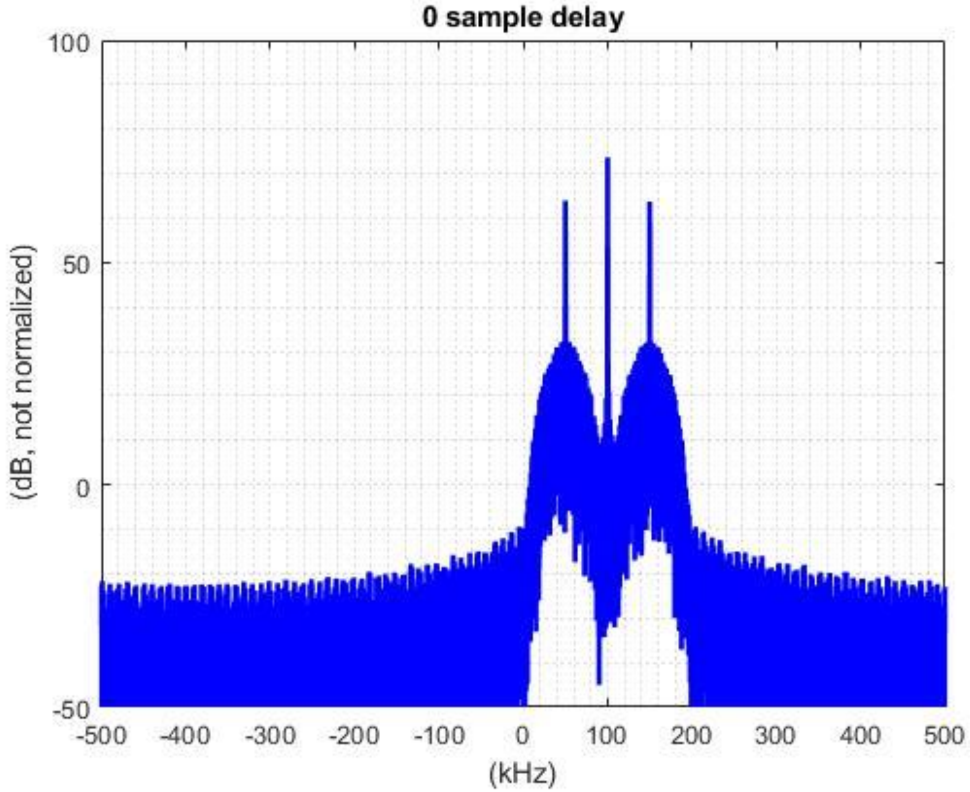
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



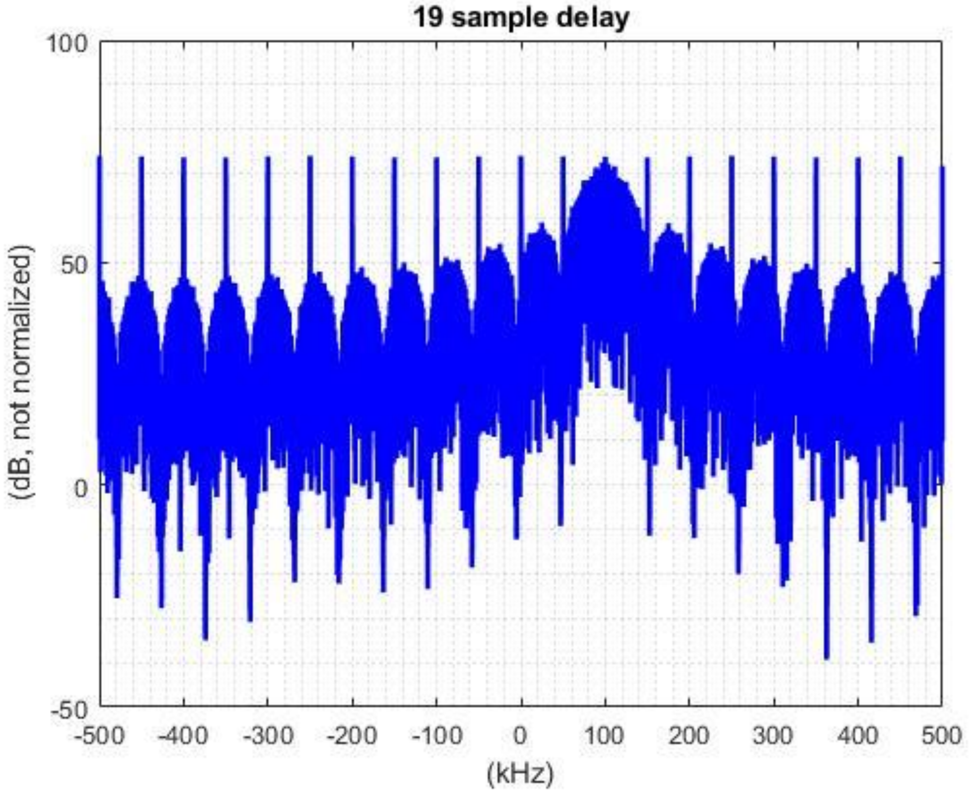
Raised Cosine Shaping Filter (α=0.5)



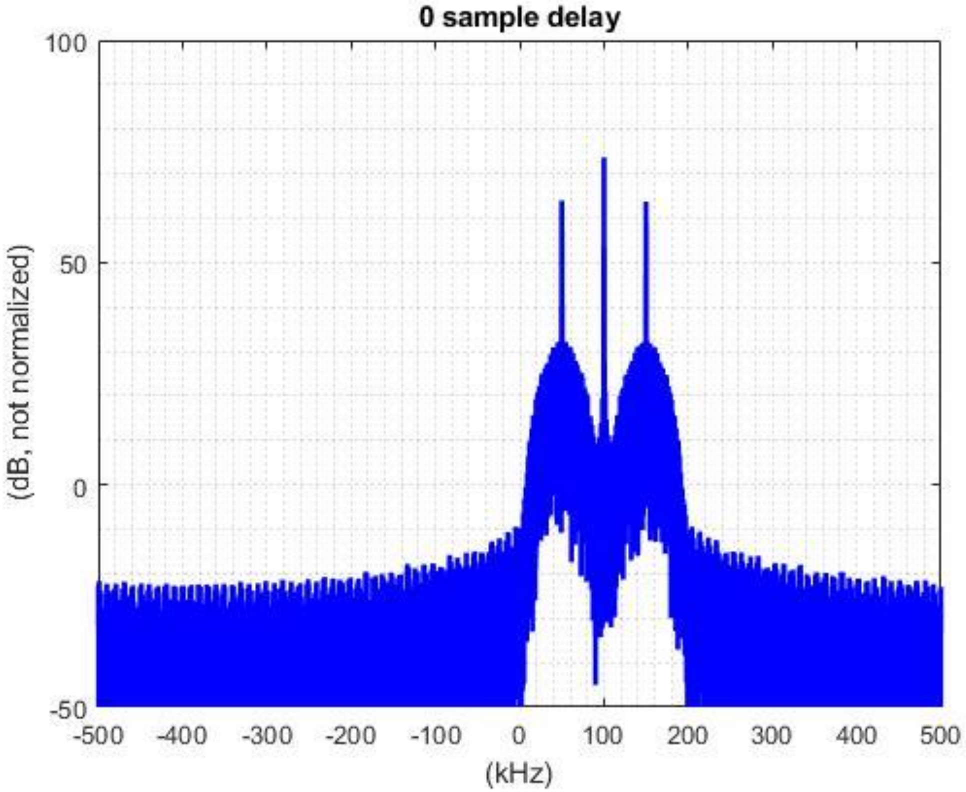
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

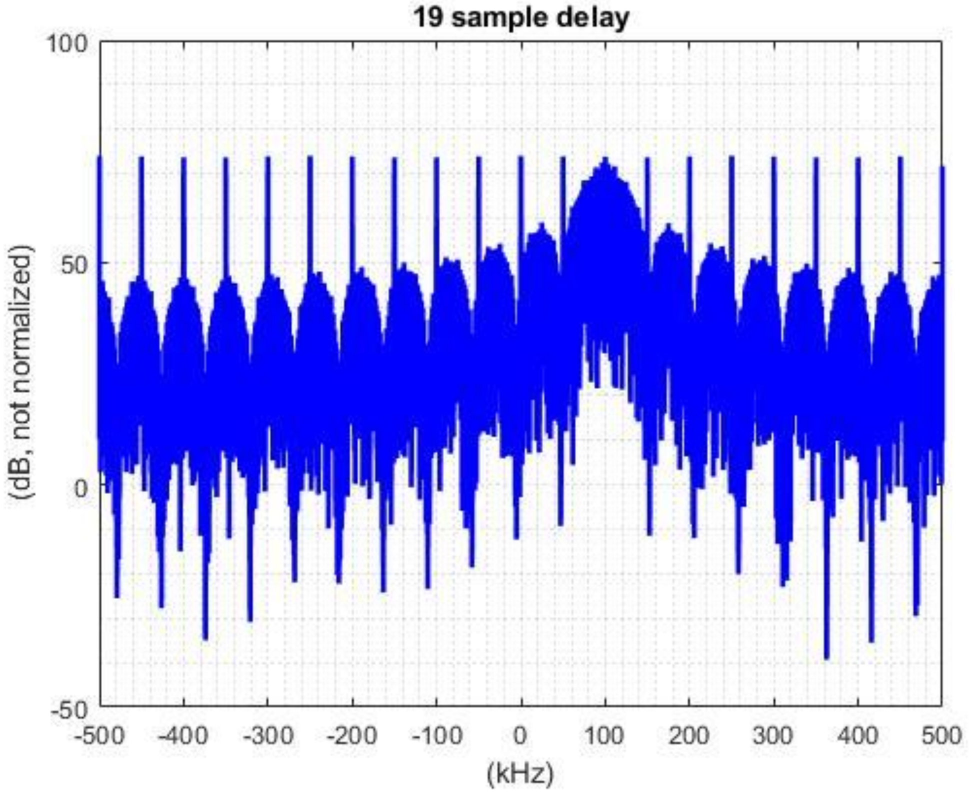


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

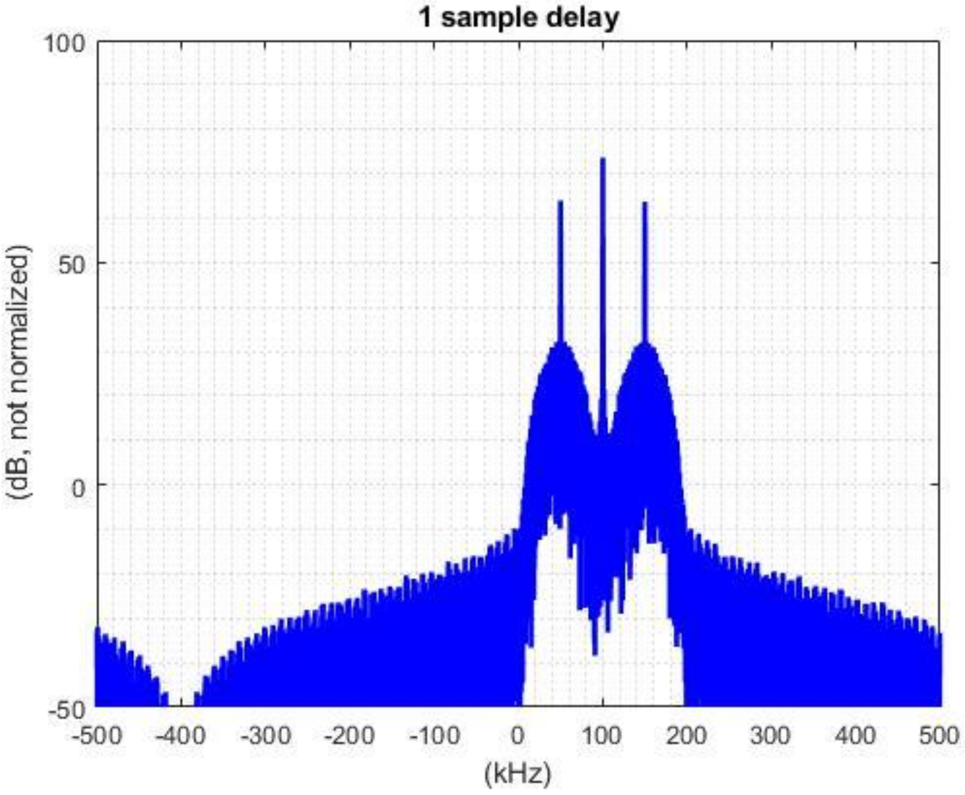
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



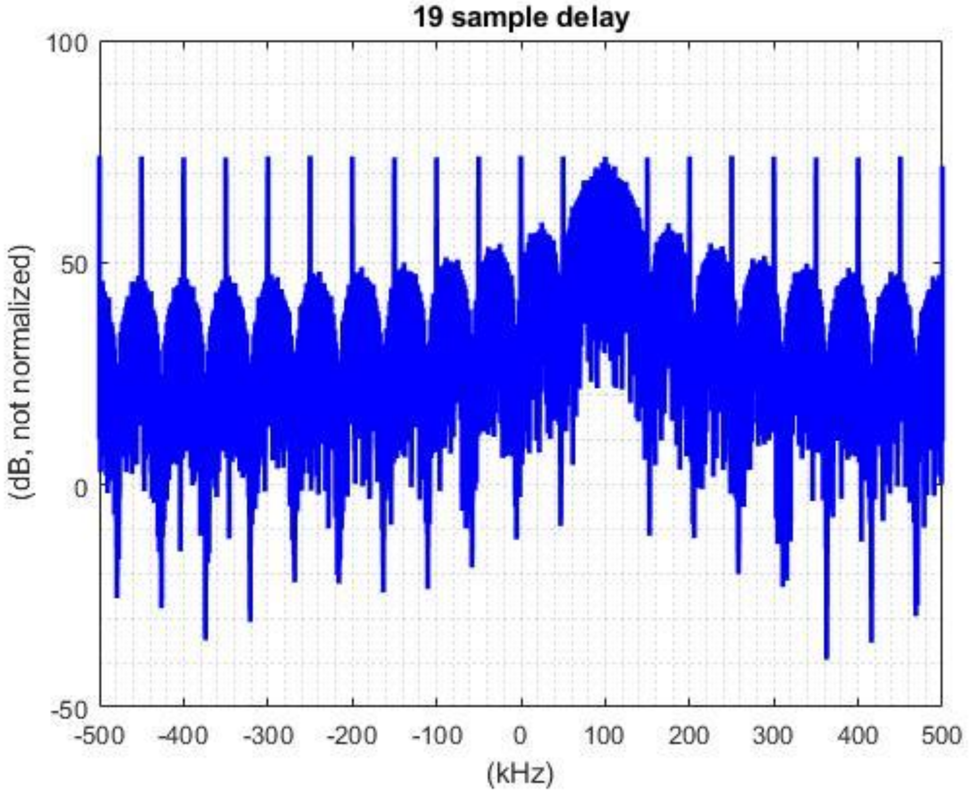
Raised Cosine Shaping Filter (α=0.5)



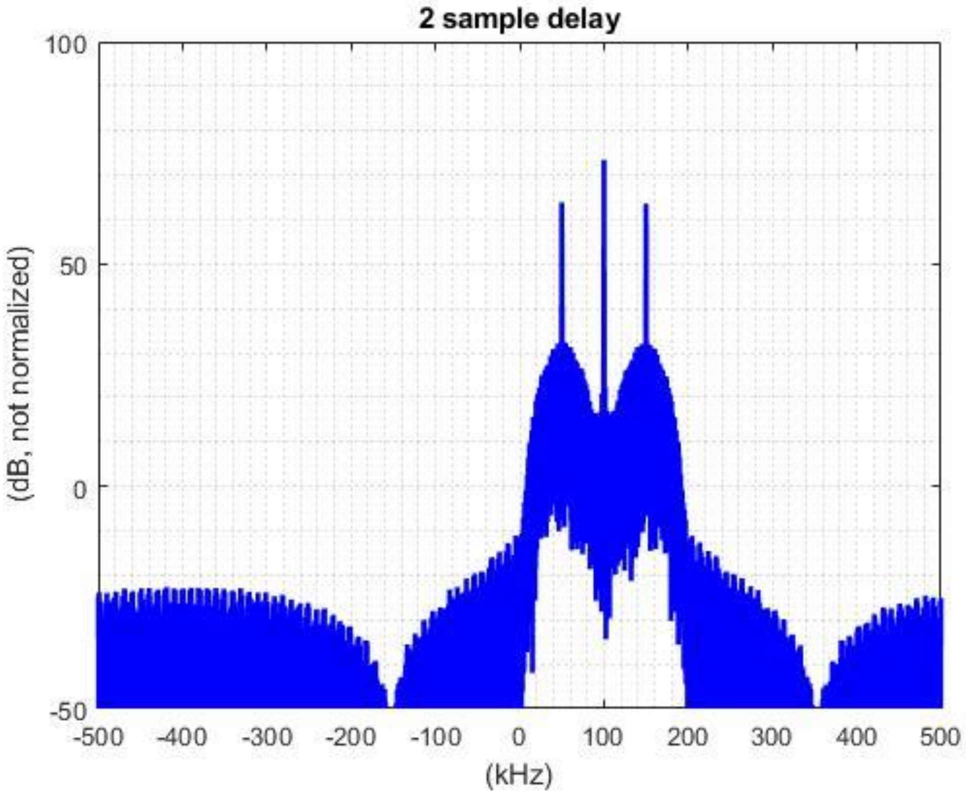
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



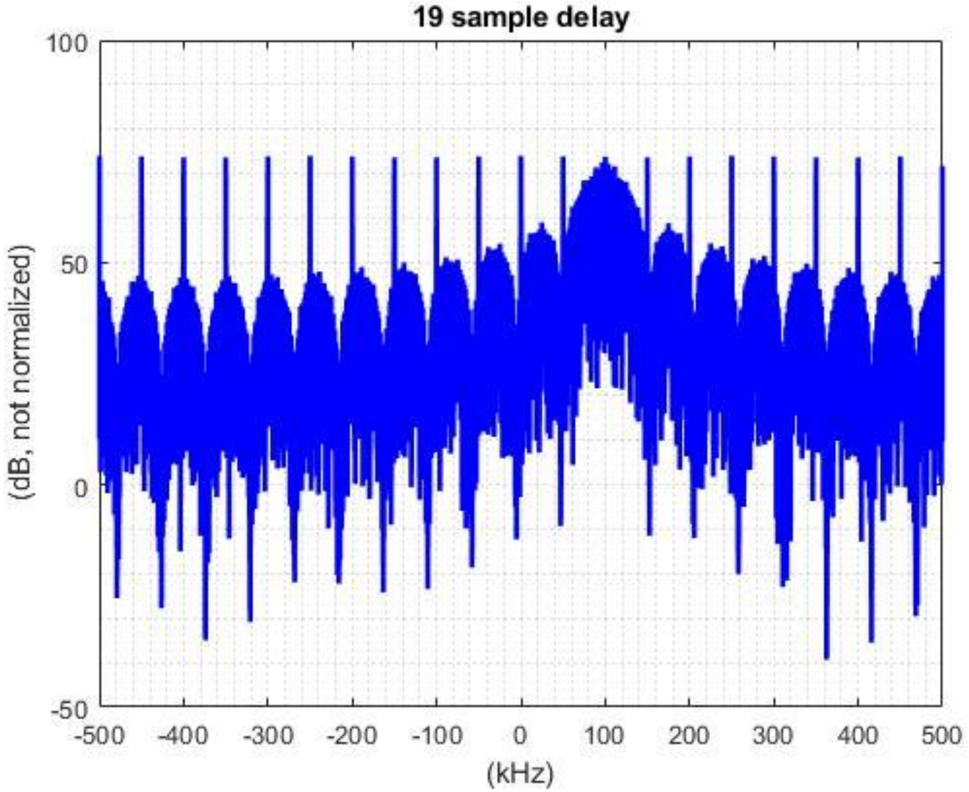
Raised Cosine Shaping Filter (α=0.5)



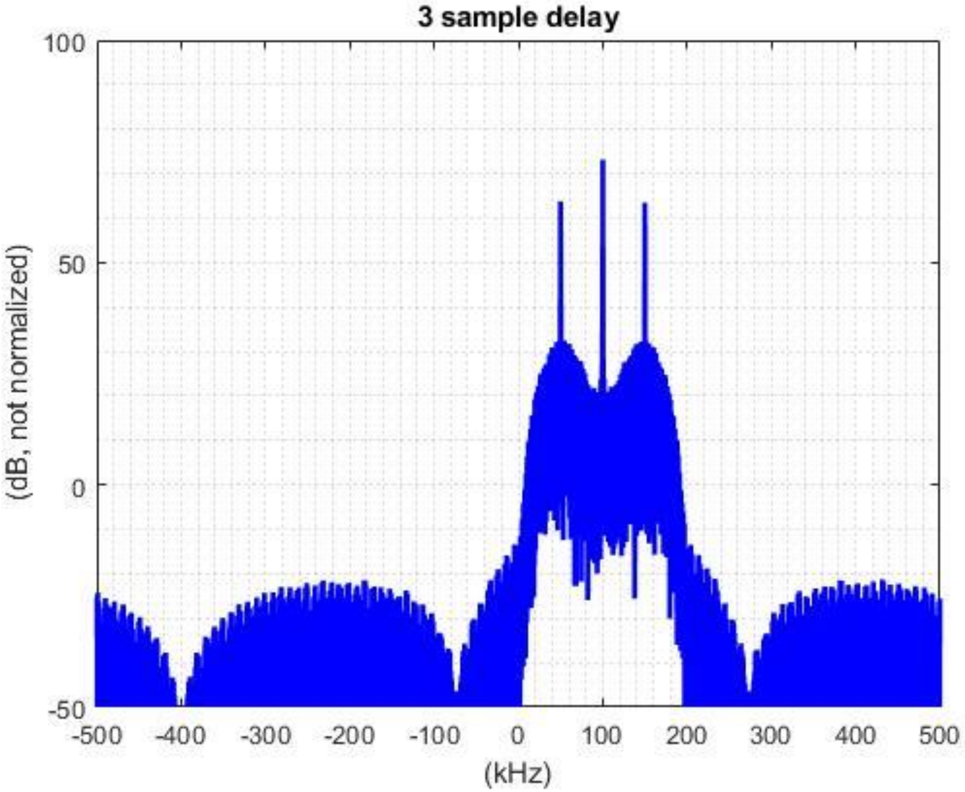
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



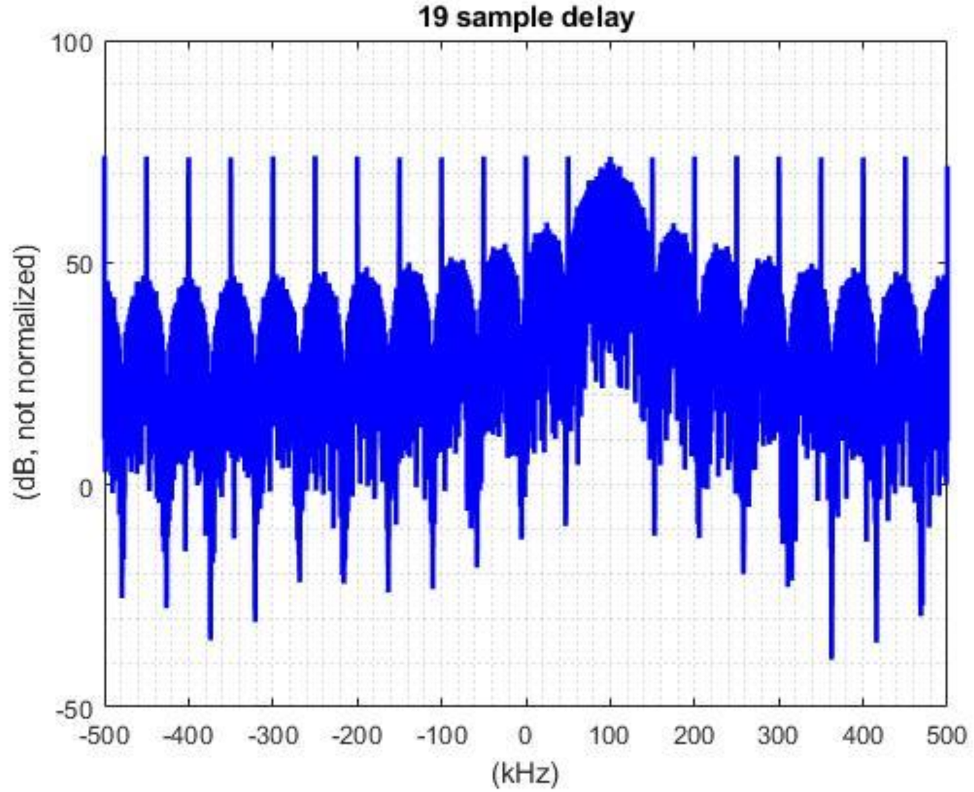
Raised Cosine Shaping Filter (α=0.5)



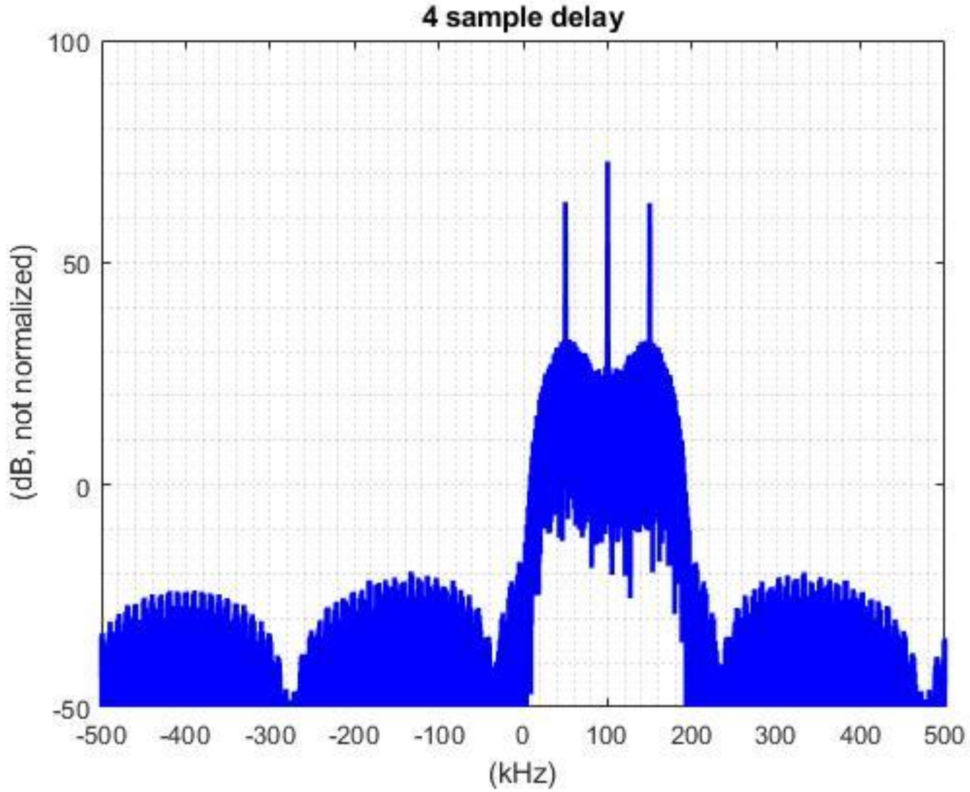
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



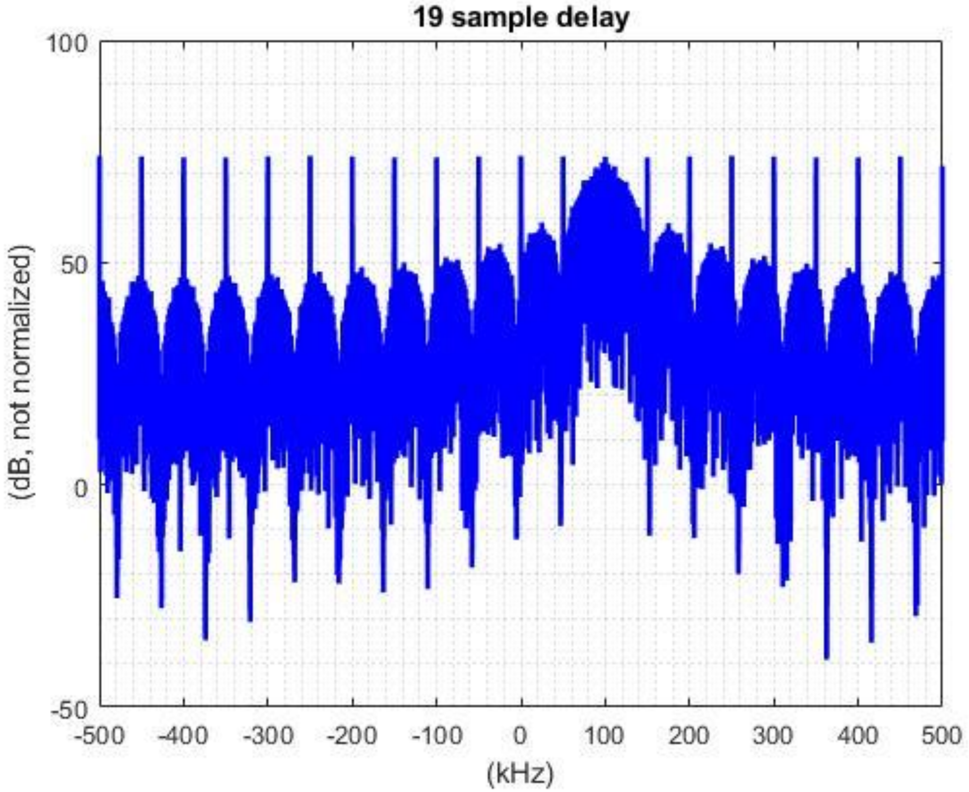
Raised Cosine Shaping Filter (α=0.5)



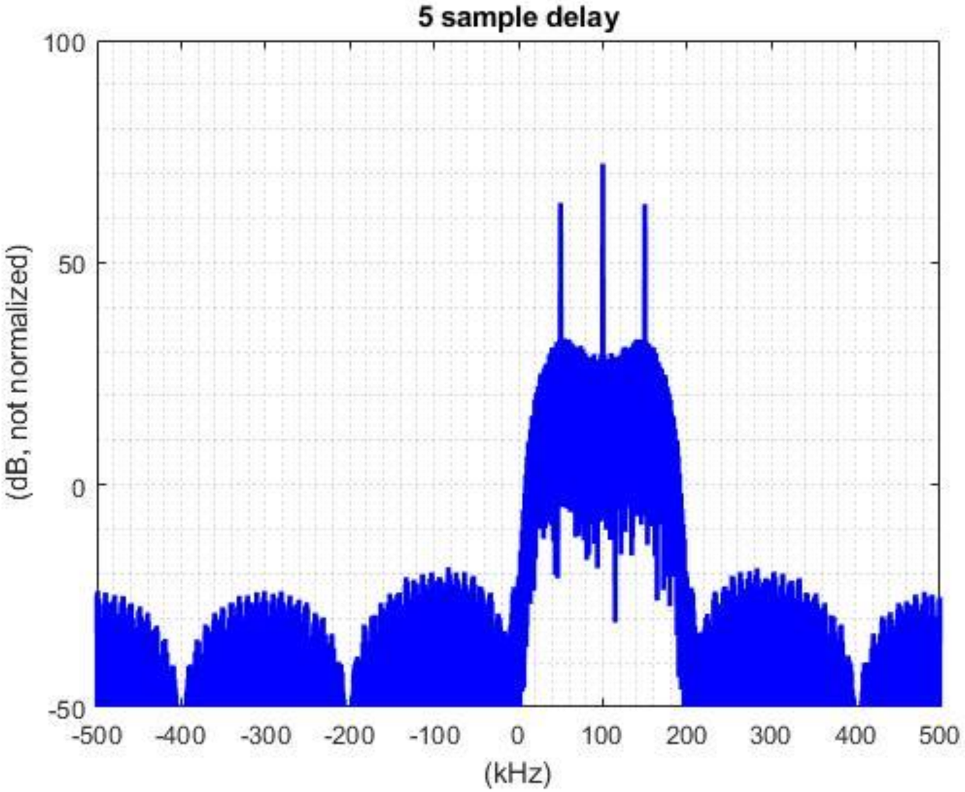
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



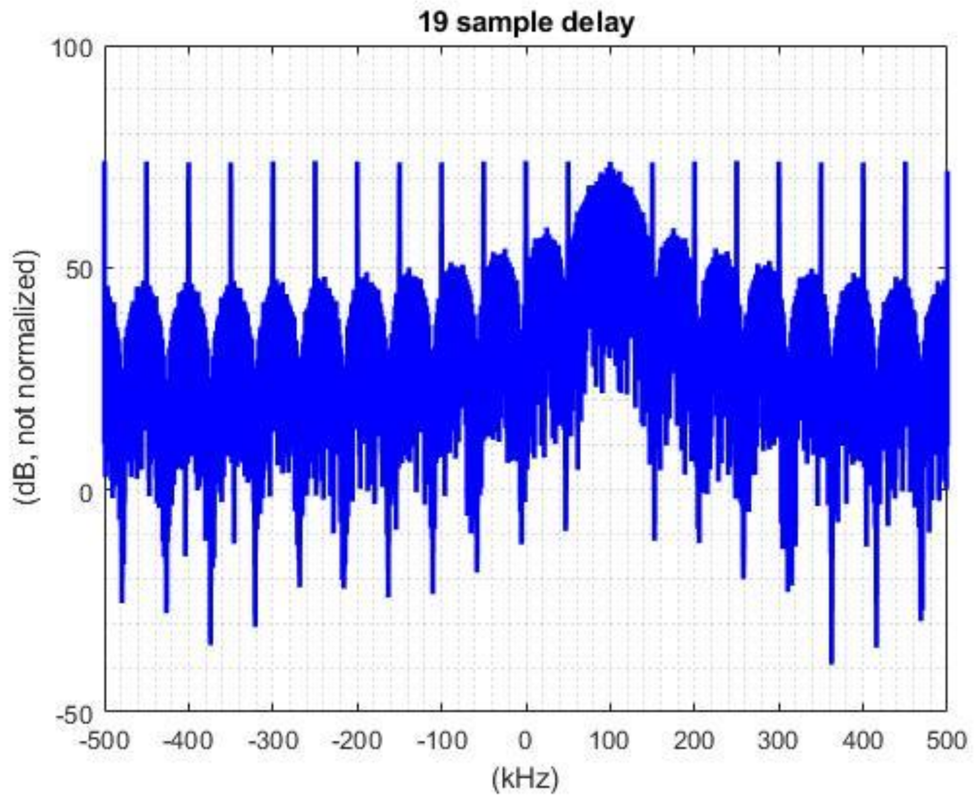
Raised Cosine Shaping Filter (α=0.5)



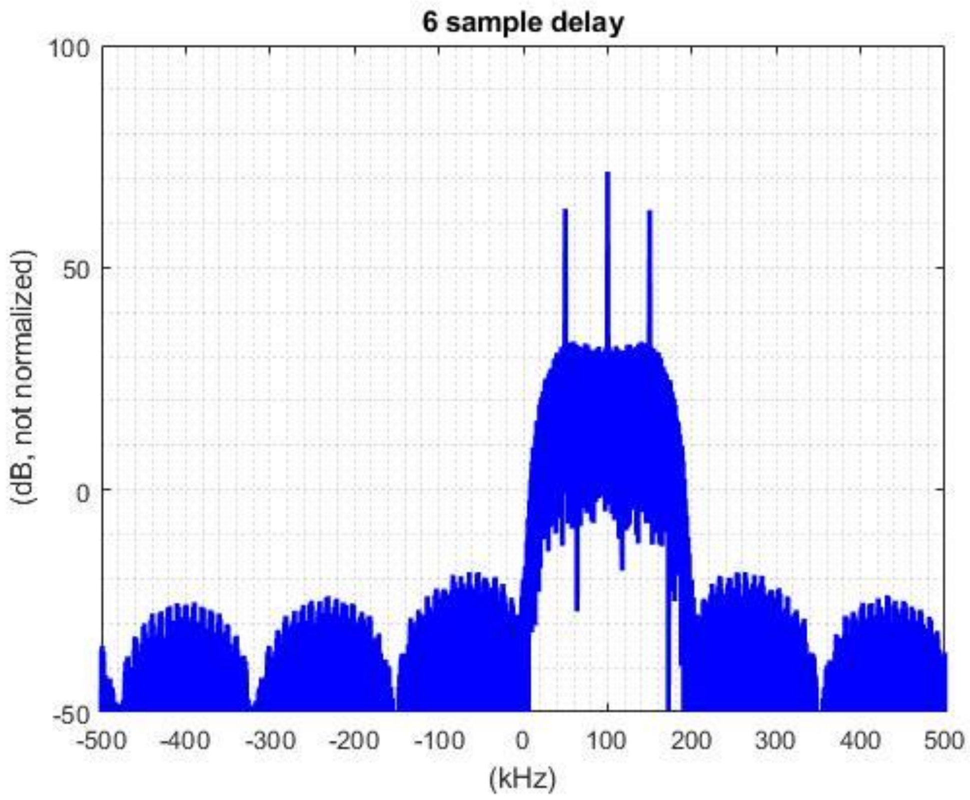
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



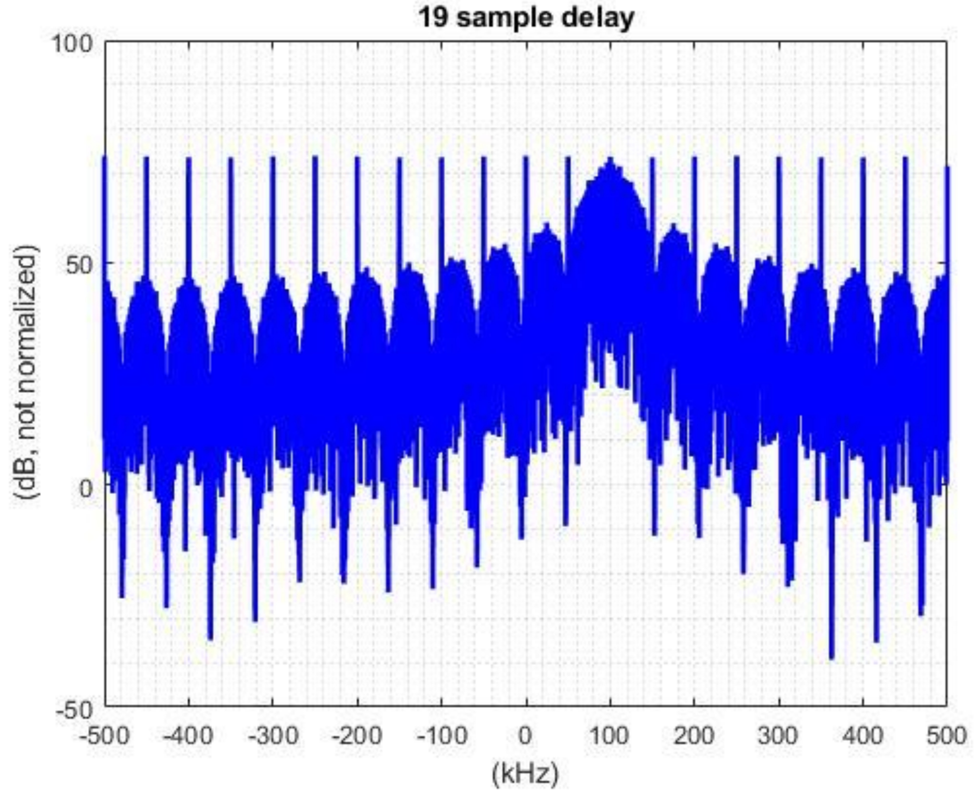
Raised Cosine Shaping Filter (α=0.5)



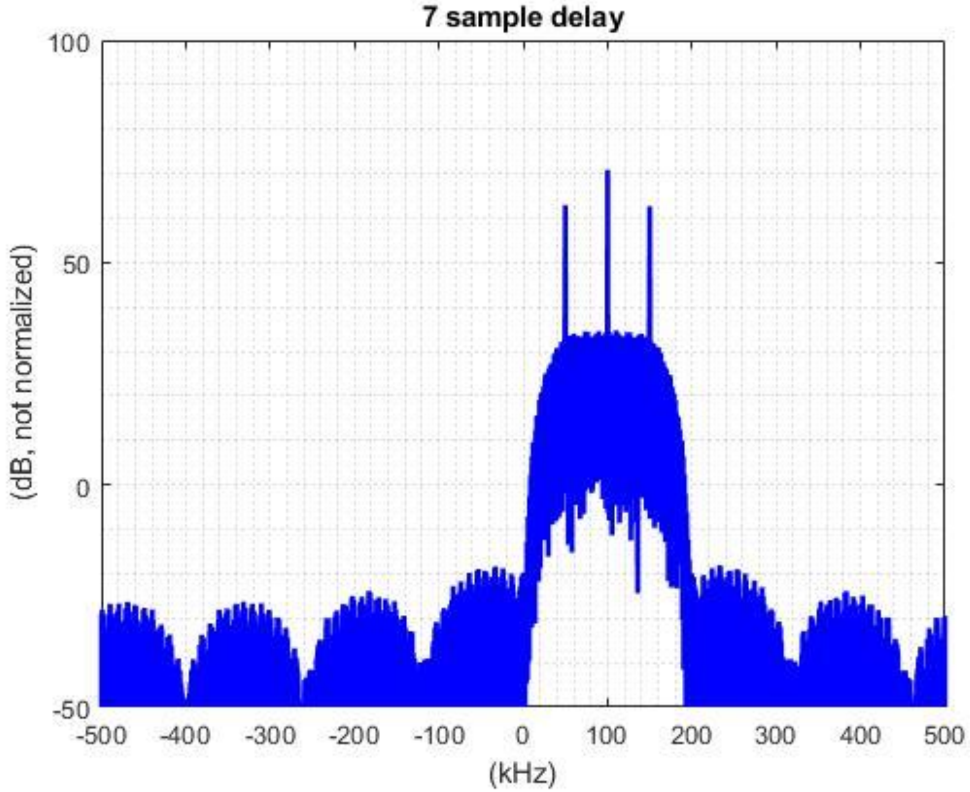
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



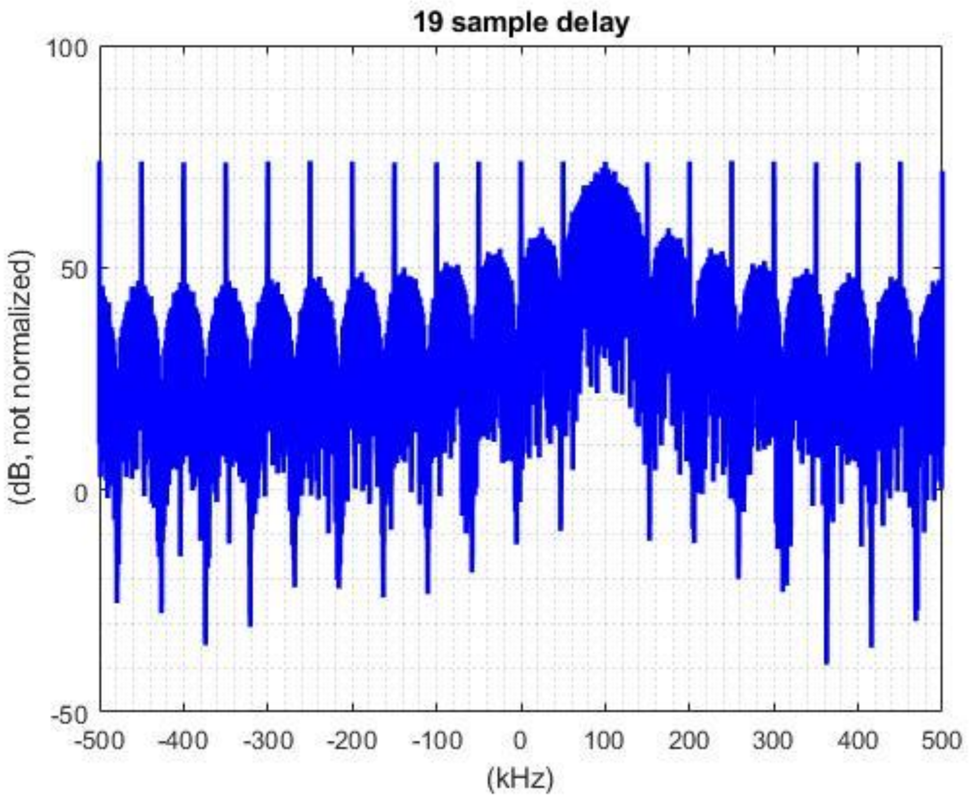
Raised Cosine Shaping Filter (α=0.5)



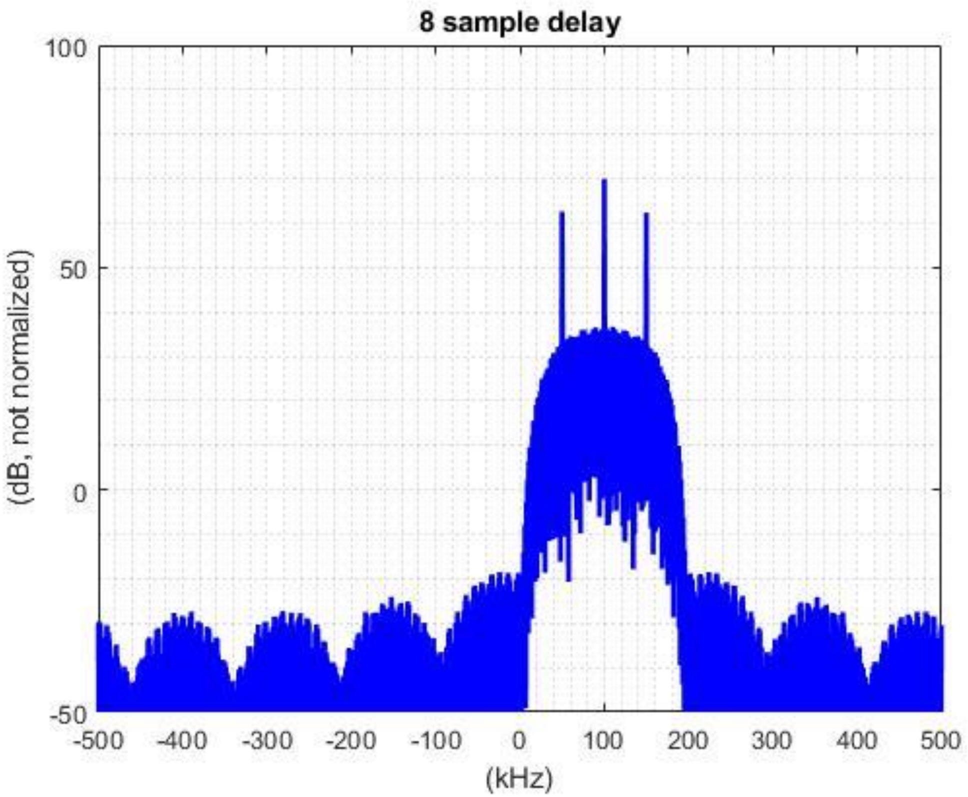
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



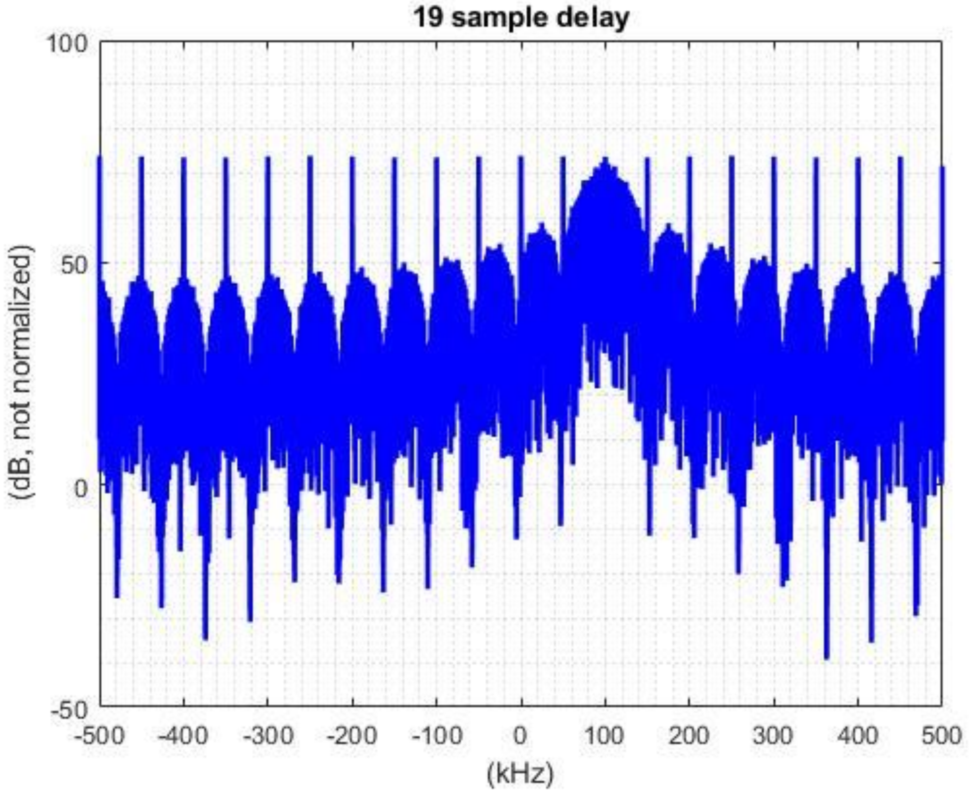
Raised Cosine Shaping Filter (α=0.5)



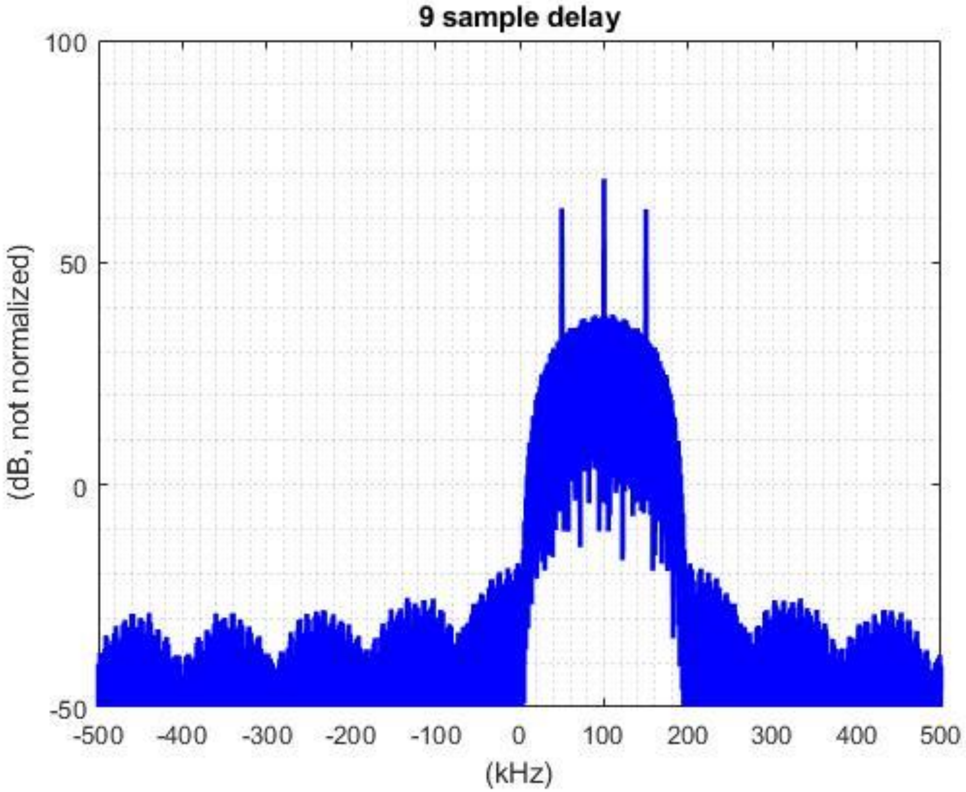
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



Raised Cosine Shaping Filter (α=0.5)

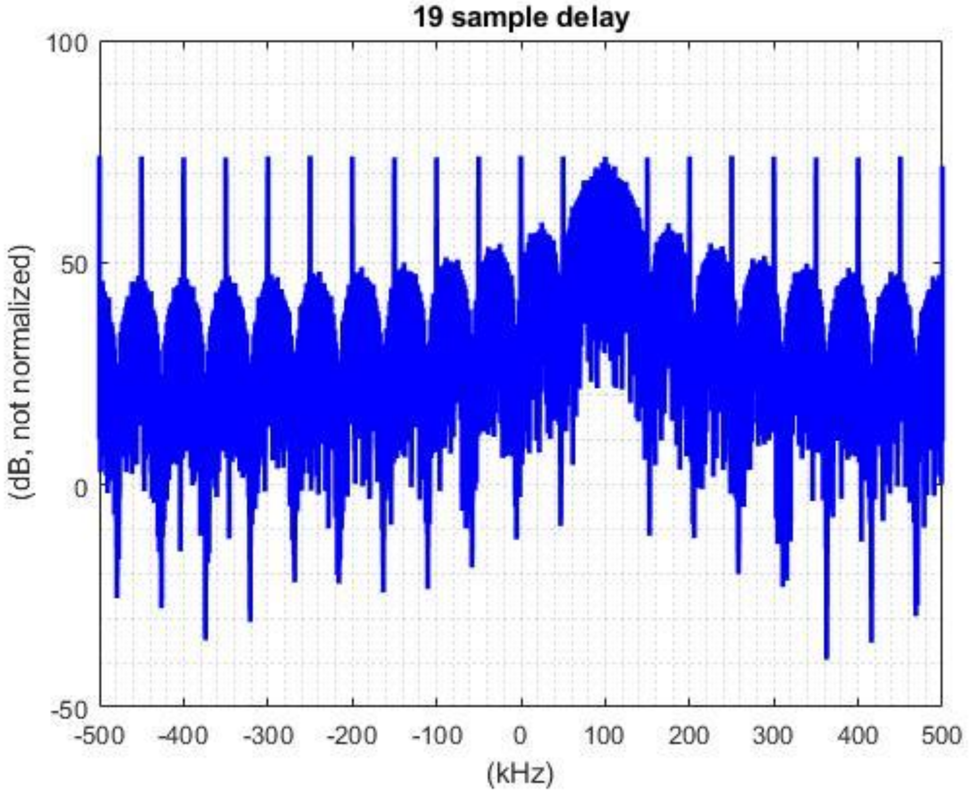


- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

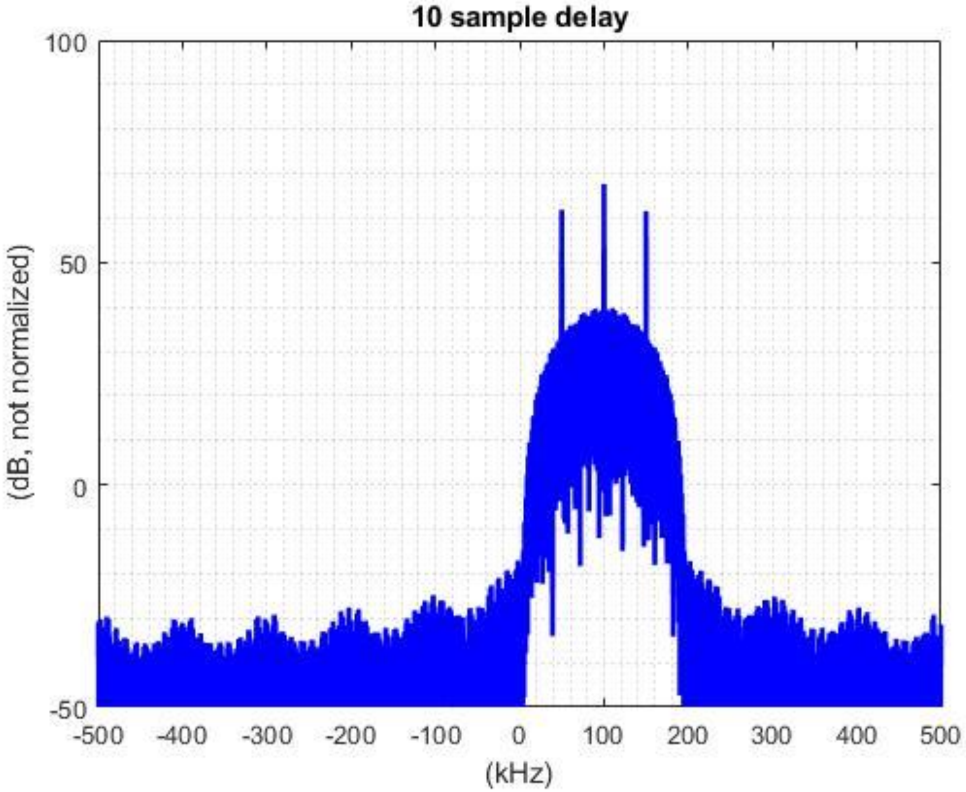
Naval Information Warfare Center PACIFIC

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



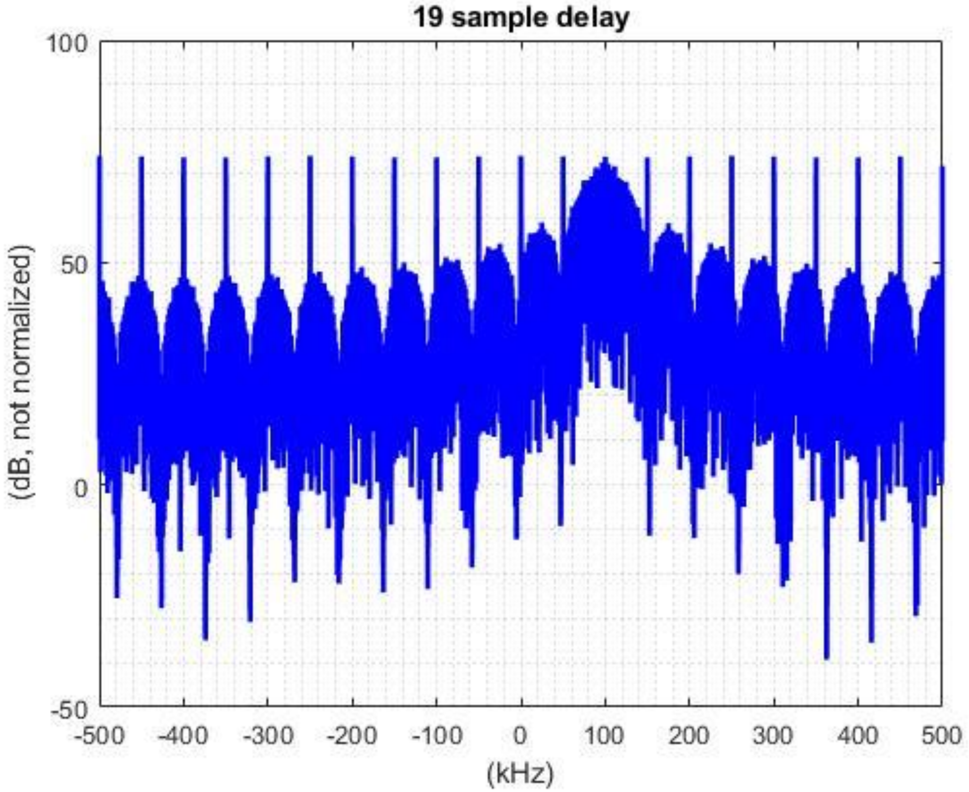
Raised Cosine Shaping Filter (α=0.5)



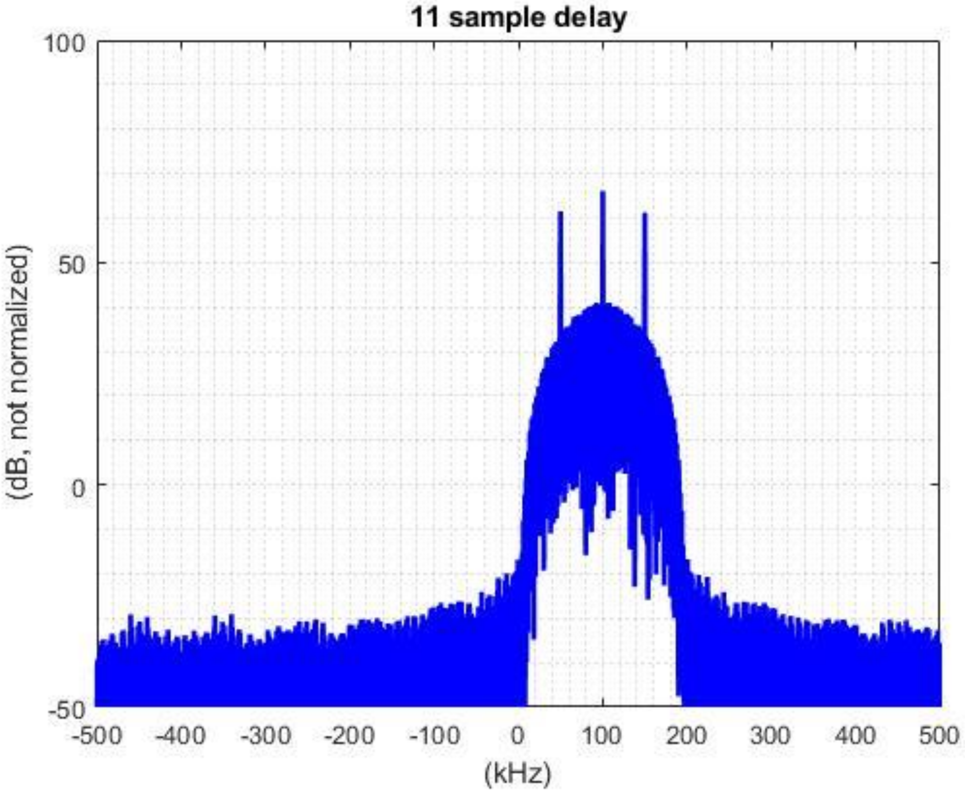
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



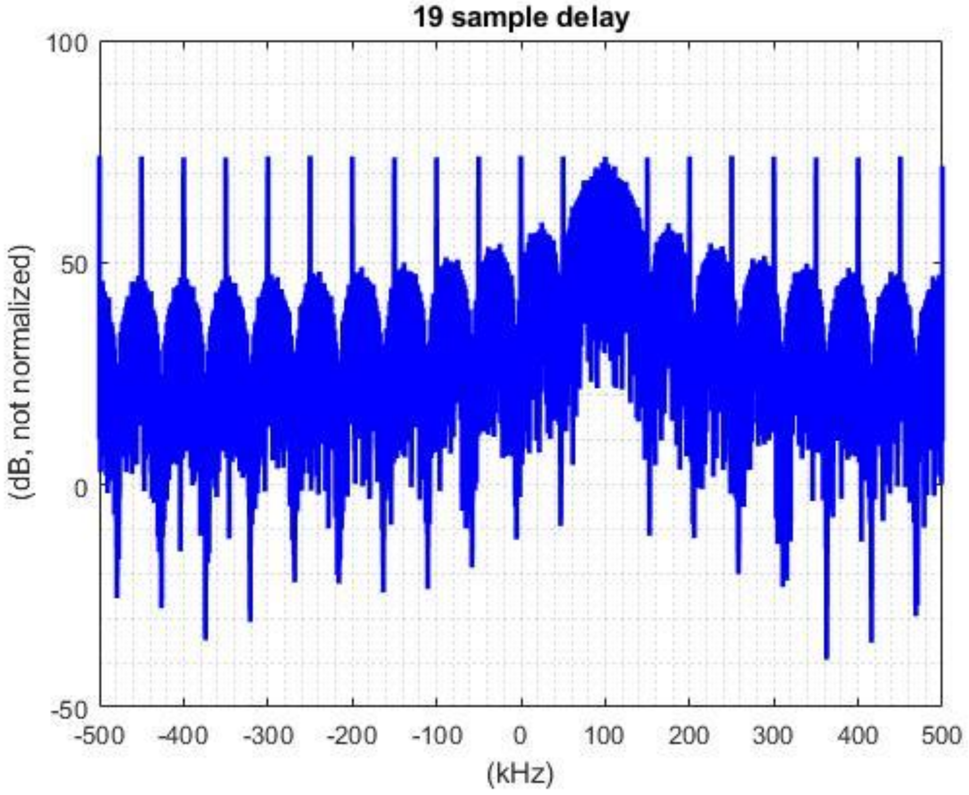
Raised Cosine Shaping Filter (α=0.5)



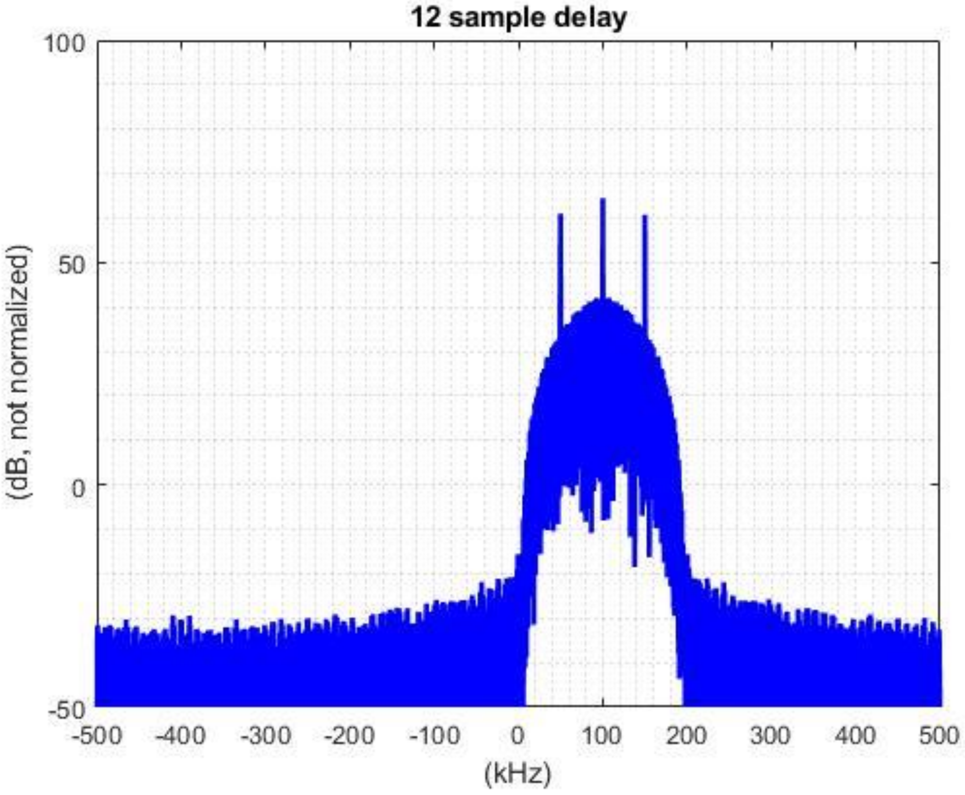
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



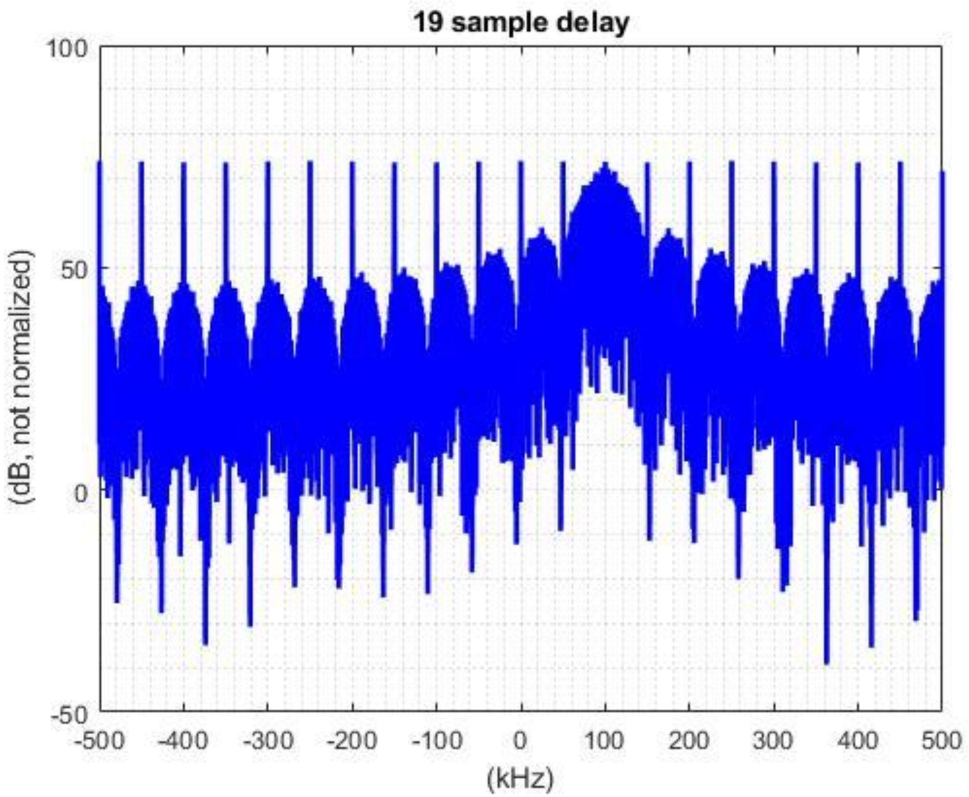
Raised Cosine Shaping Filter (α=0.5)



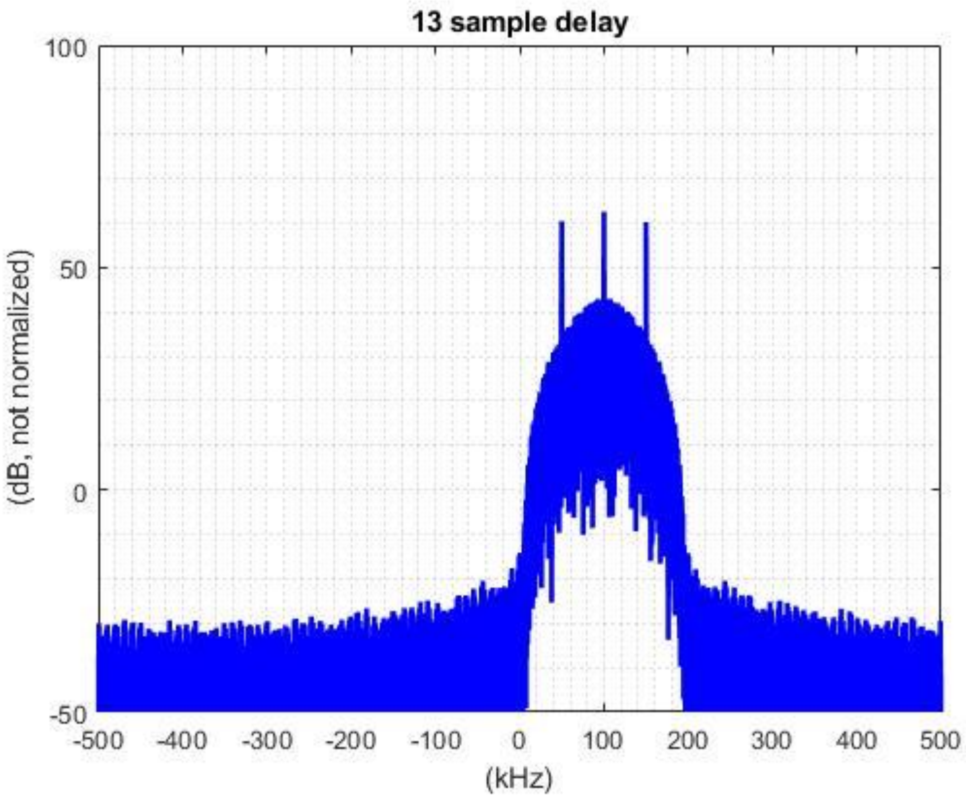
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



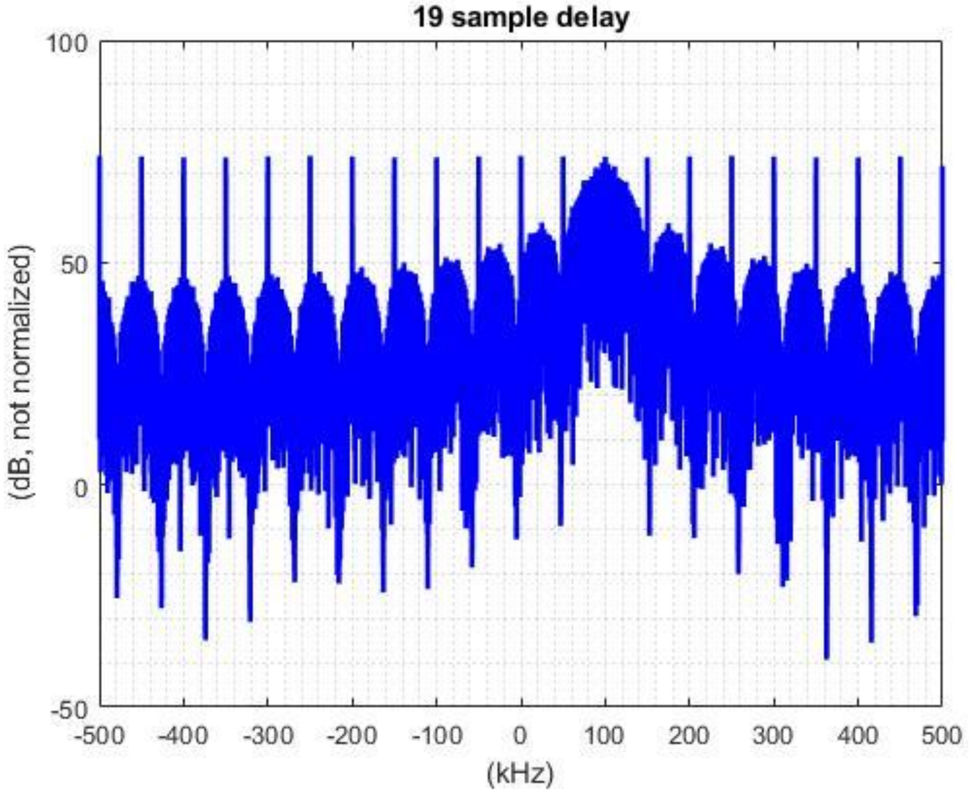
Raised Cosine Shaping Filter (α=0.5)



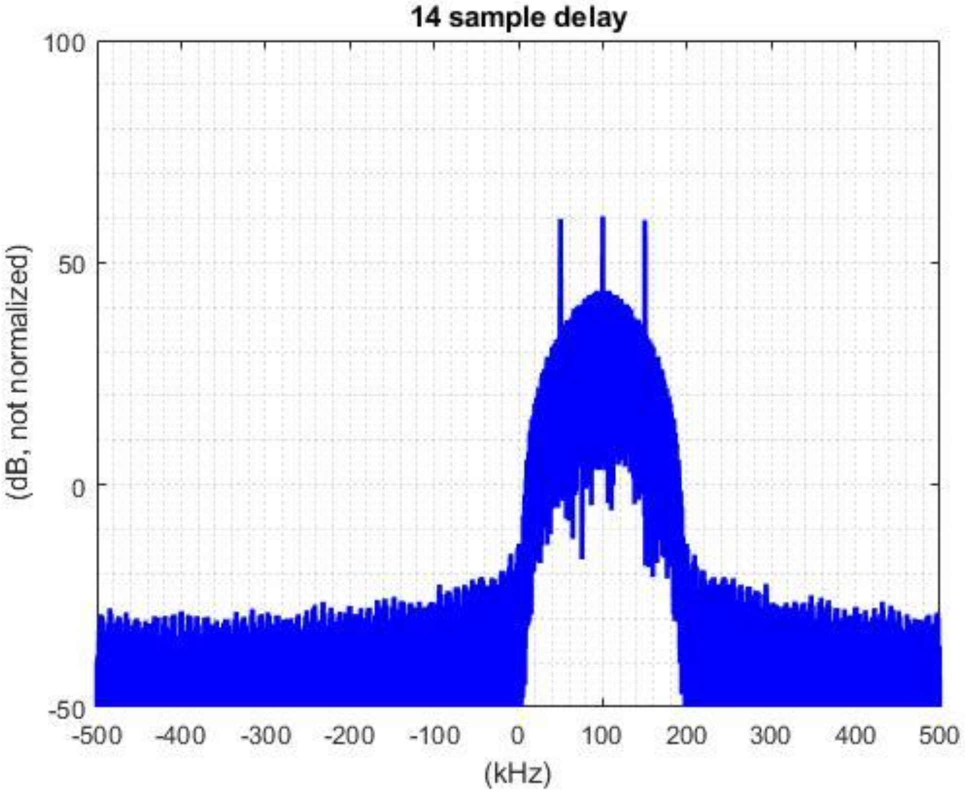
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



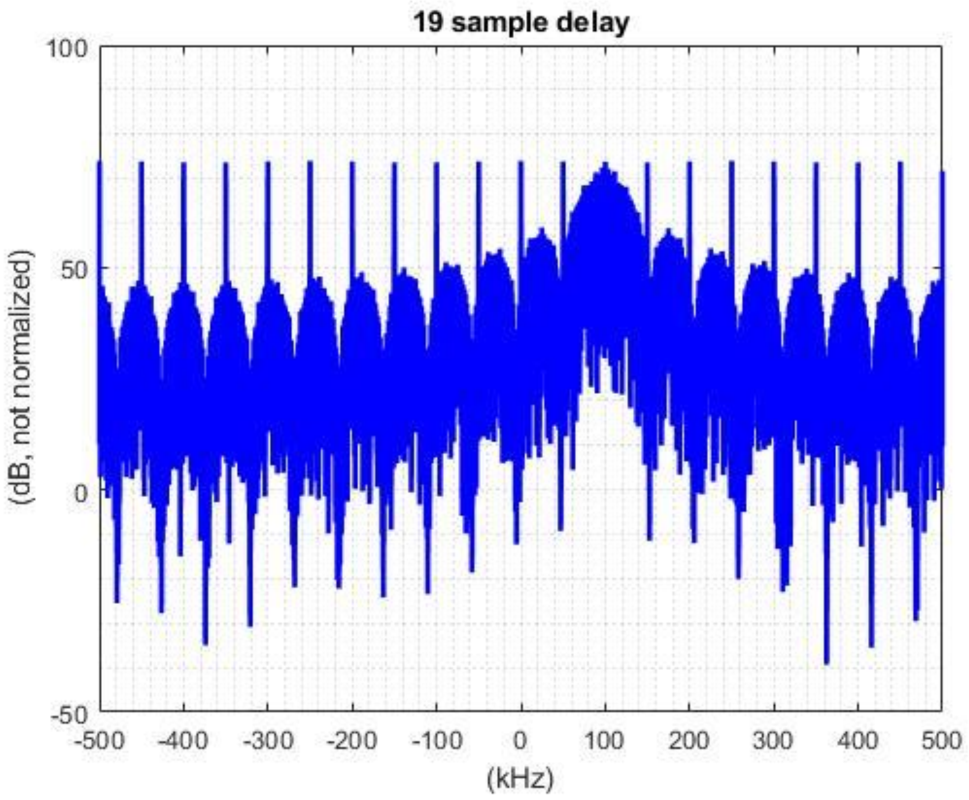
Raised Cosine Shaping Filter (α=0.5)



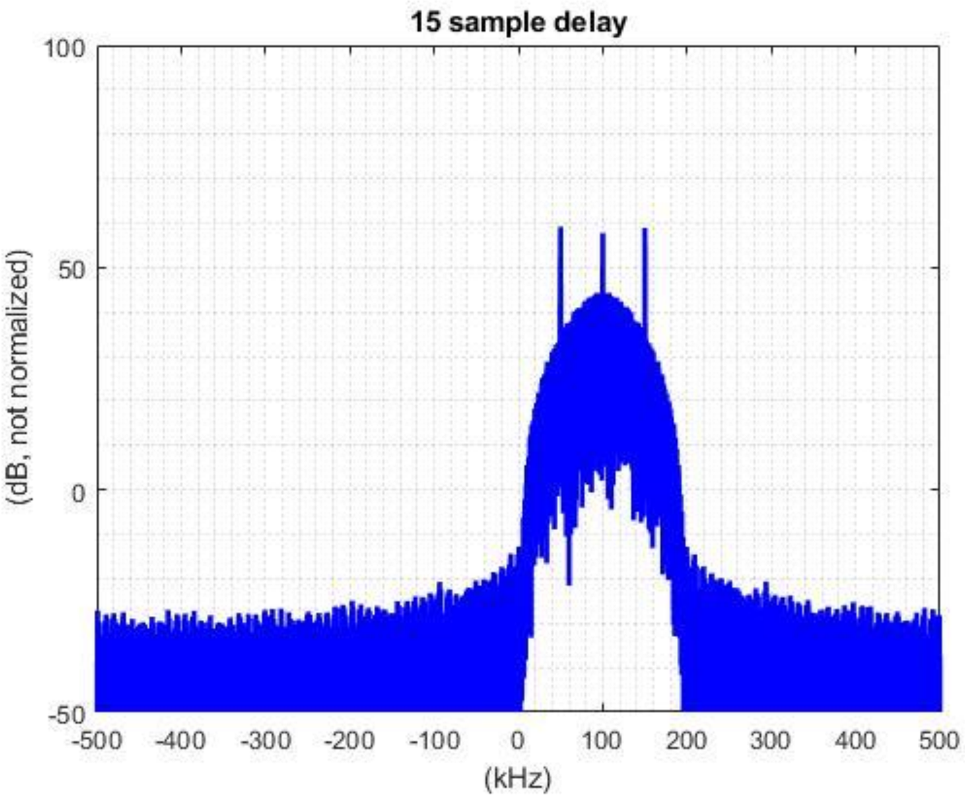
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



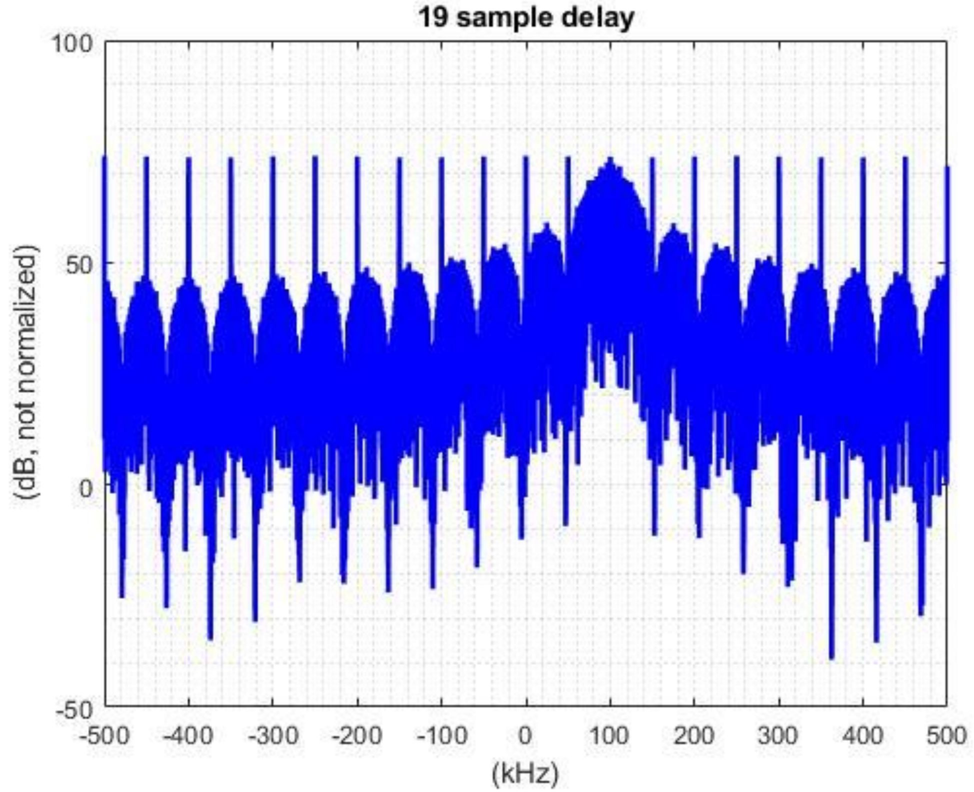
Raised Cosine Shaping Filter (α=0.5)



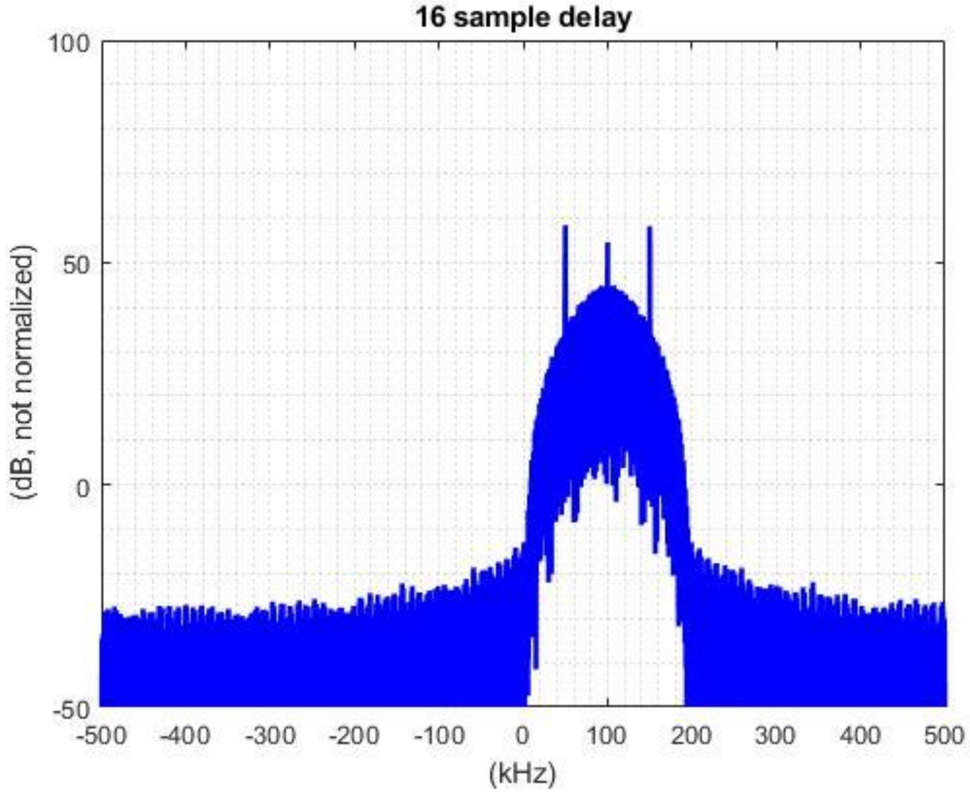
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



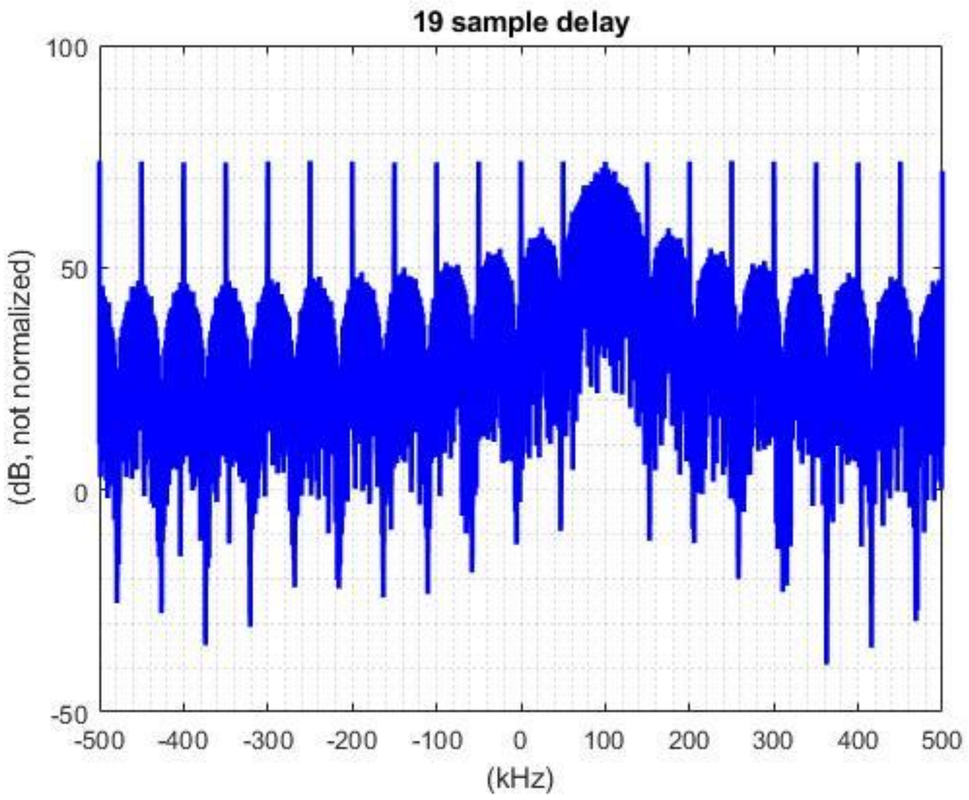
Raised Cosine Shaping Filter (α=0.5)



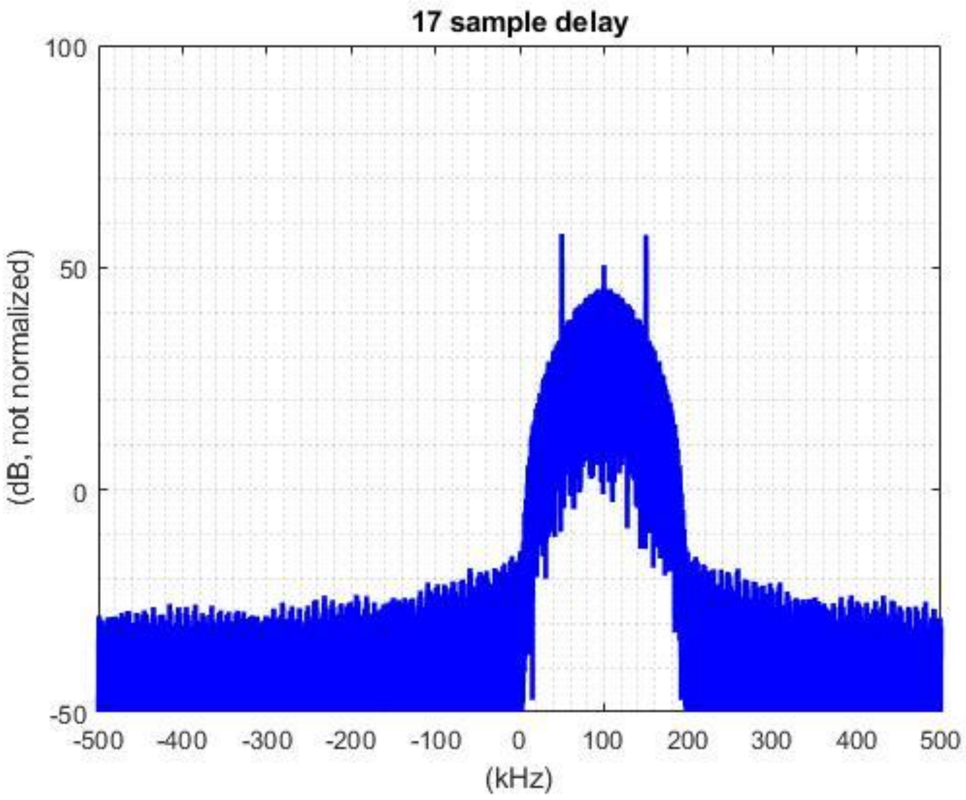
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



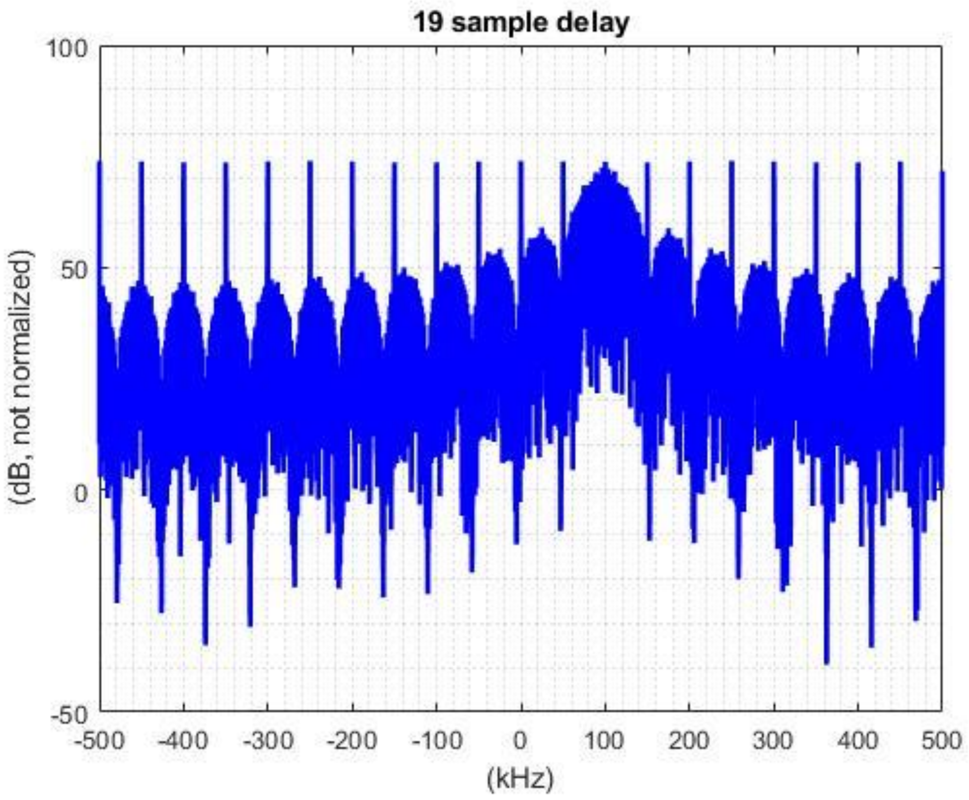
Raised Cosine Shaping Filter (α=0.5)



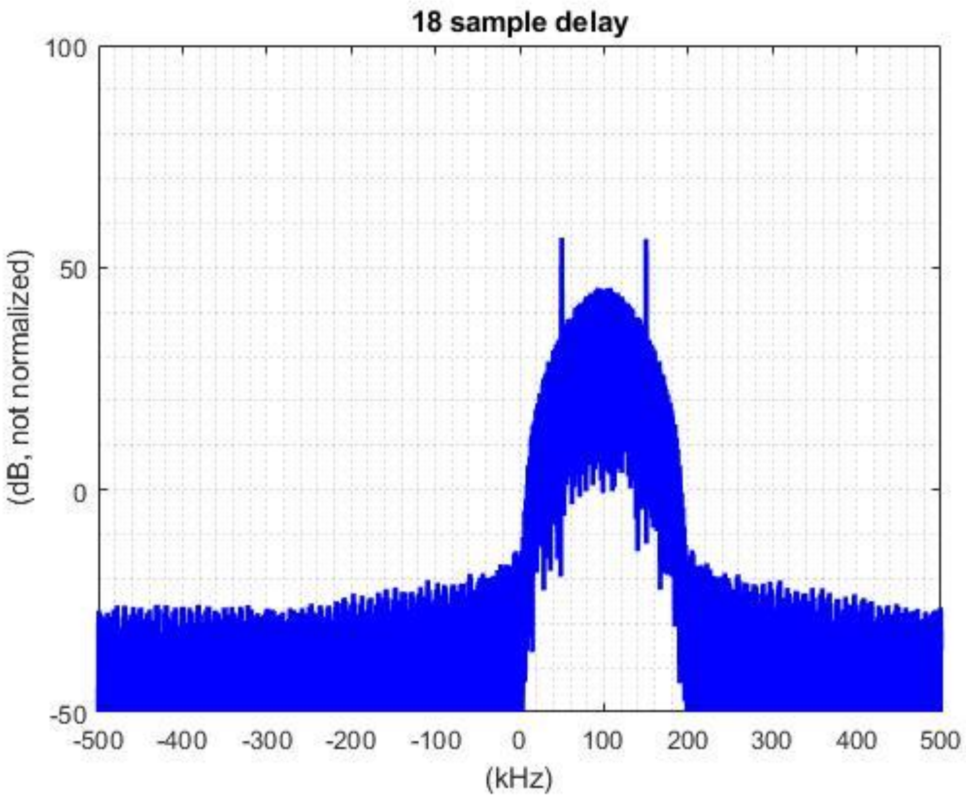
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter



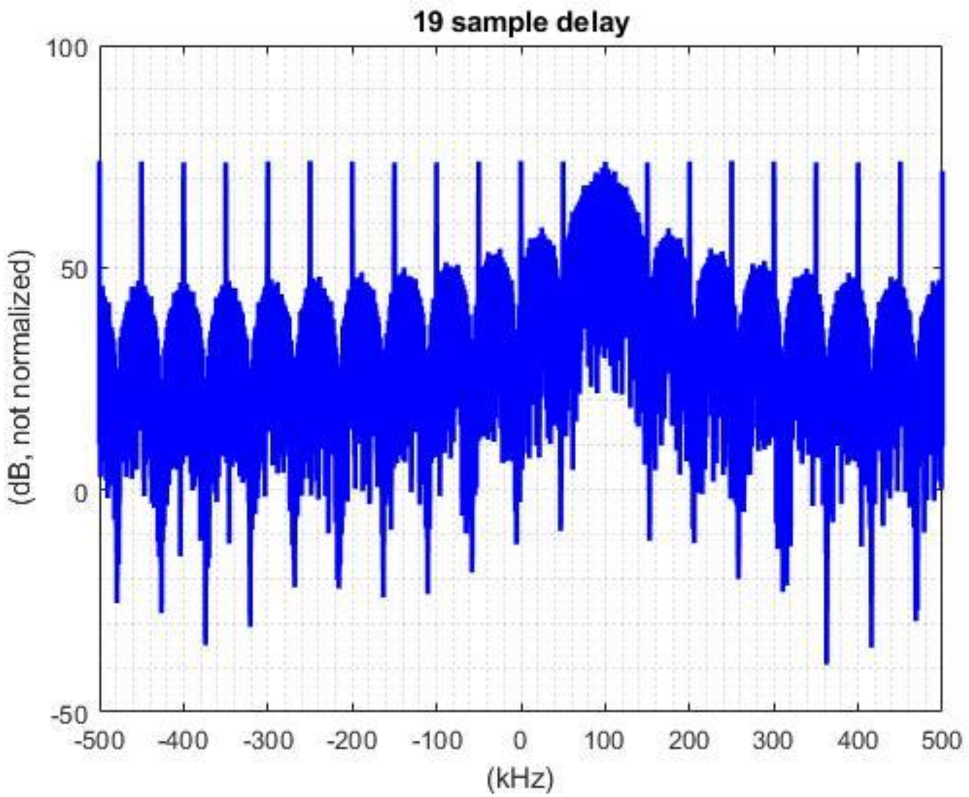
Raised Cosine Shaping Filter (α=0.5)



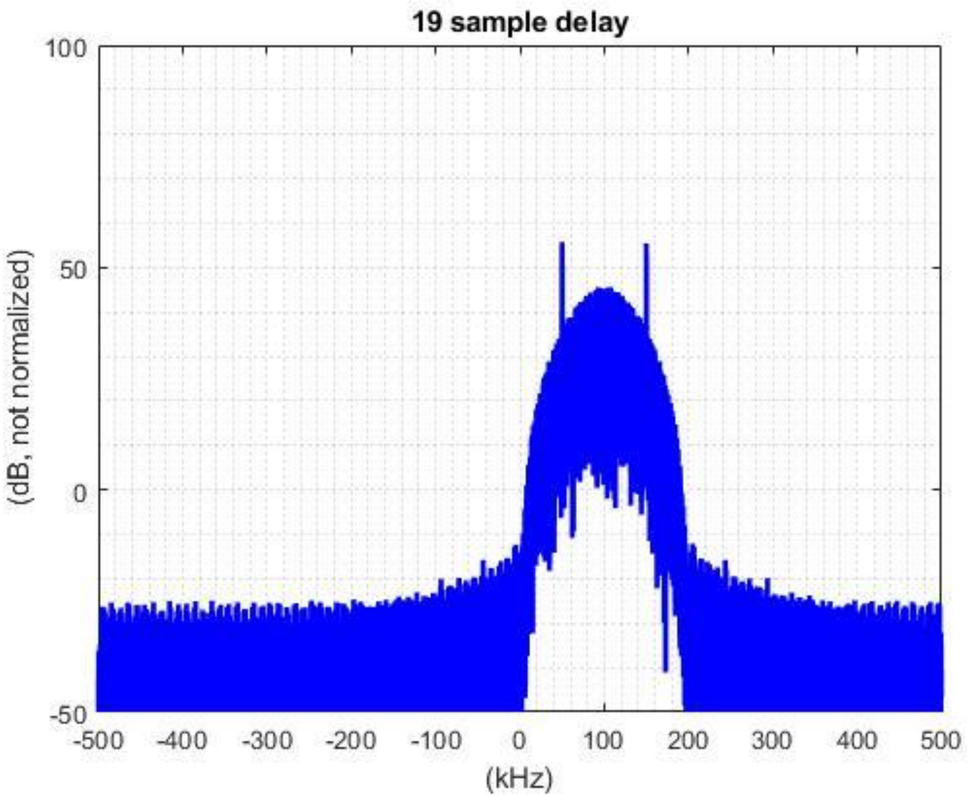
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Effect of Variation of Delay in Spectrum

Rectangular Shaping Filter

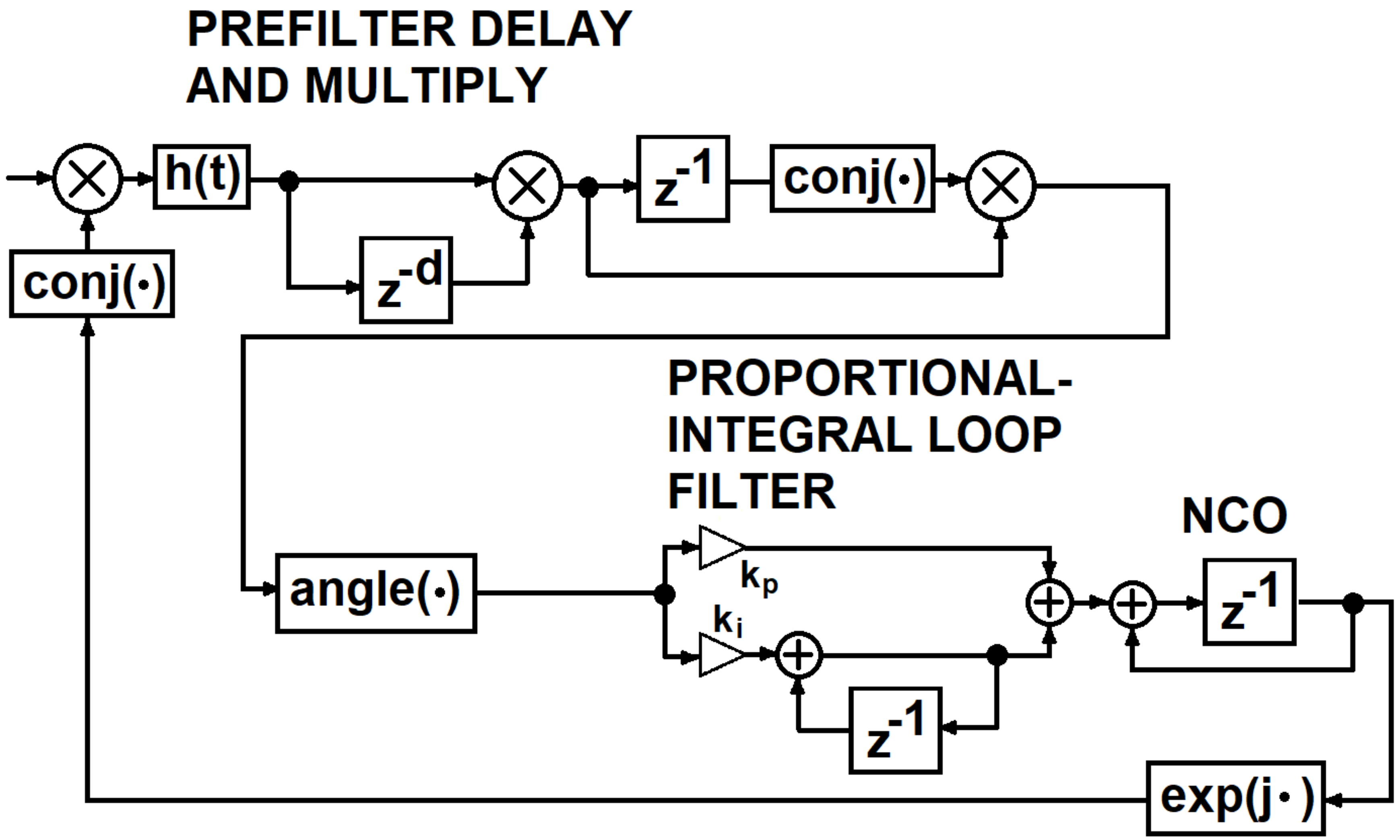


Raised Cosine Shaping Filter (α=0.5)

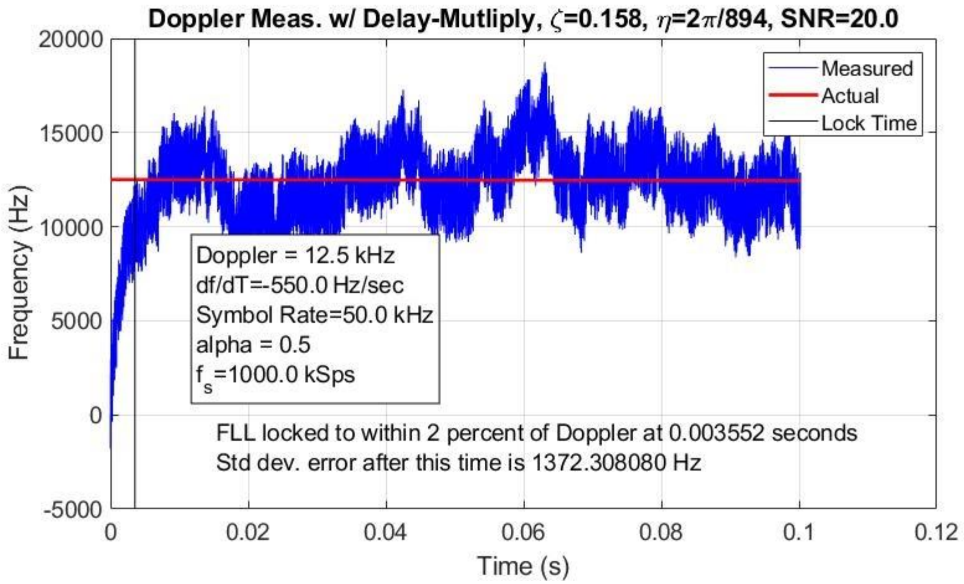


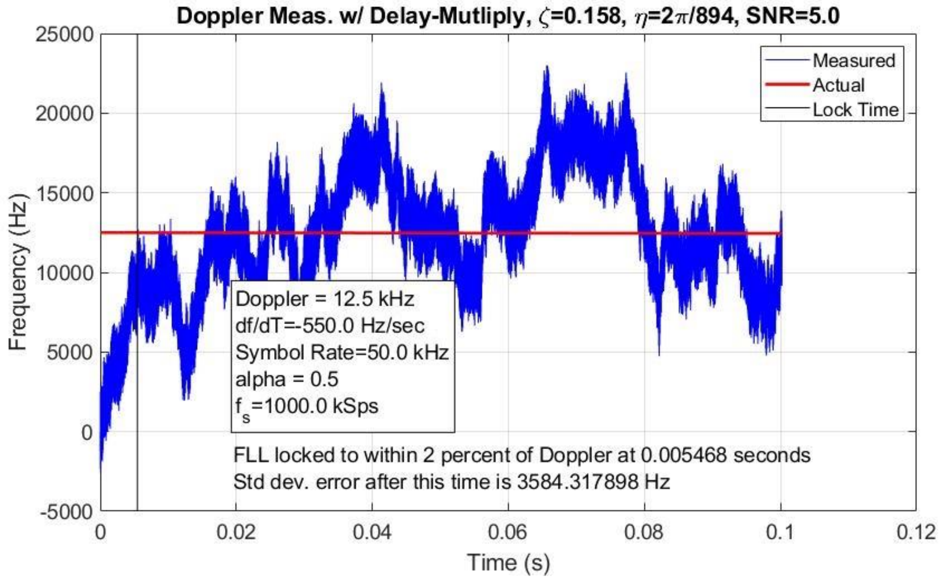
- Figures depict 20 samples per symbol, f_{sym}=50 kHz, Doppler=50 kHz

Prefilter Delay Multiply FLL Structure



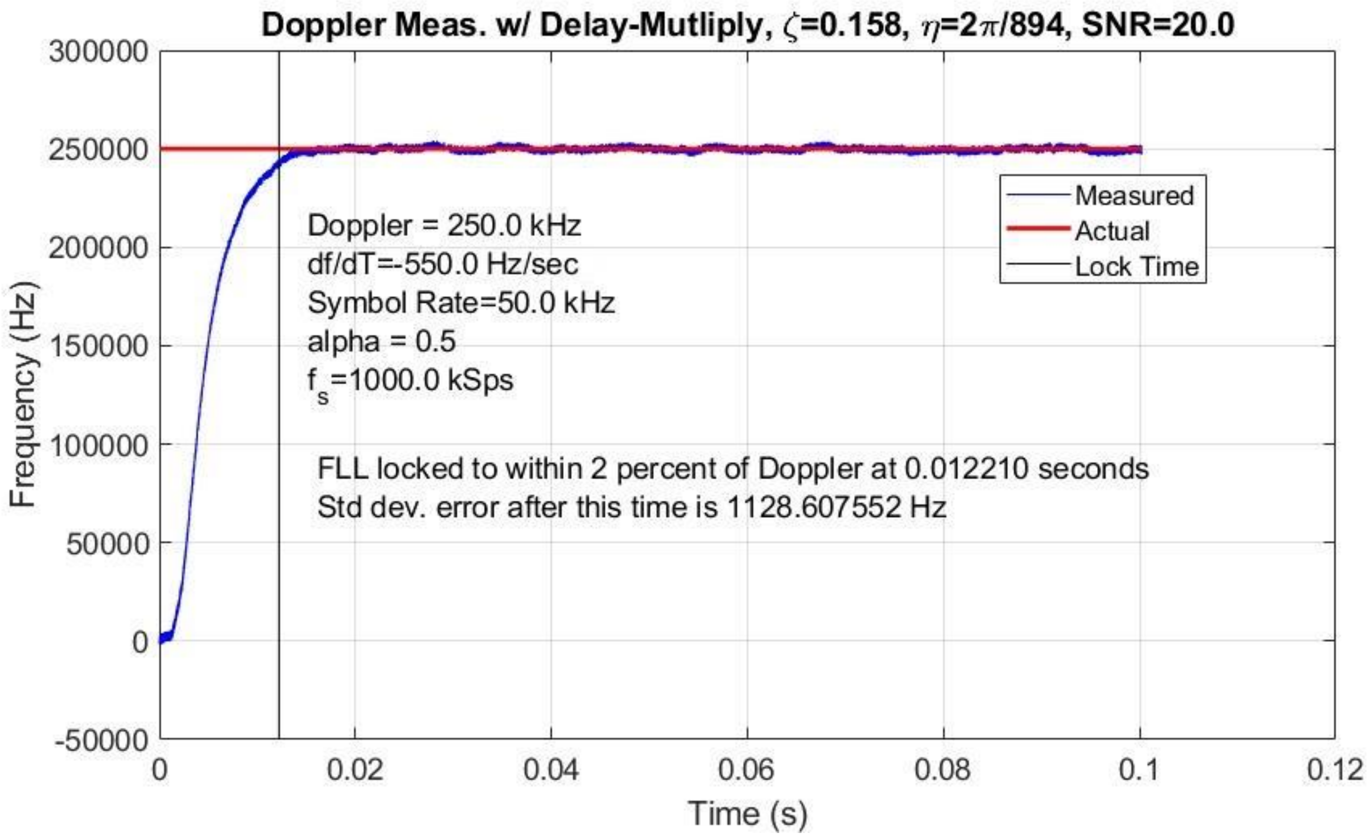
Performance of Delay Multiply FLL





- 20 dB SNR frequency error standard deviation 1372 Hz (compare to 174.6 Hz for Optimum Band Edge FLL in same situation)
- 5 dB SNR frequency error standard deviation 3584 Hz (compare to 1272 Hz for Optimum Band Edge FLL in same situation)

Performance of Delay Multiply FLL



- Delay Multiply FLL with initial Doppler near quarter-sample rate

Conclusions

- Optimum Band Edge FLL provides best combination of lock time and frequency error when phase-modulated signal's shaping filter design is known in advance and when modulation rate is fixed
- Hybrid Band Edge FLL (Optimum Filters plus Half Band Filters) allow frequency locking out-of-band
- Prefilter Delay Multiply FLL is an alternative that reduces the amount of logic when compared to Band Edge FLL (one noise reducing filter vs. two band edge filters)

References

- Band Edge Filters:

  - Harris, F., “Band Edge Filters: Characteristics and Performance in Carrier and Symbol Synchronization,” Proceedings of the 13th International Symposium on Wireless Personal Multimedia Communications, Recife, Brazil, October 11-14, 2010.

- Prefilter Delay Multiply Devices:

  - Kuehls, J.F. and E. Geraniotis, “Presence Detection of Binary-Phase-Shift-Keyed and Direct-Sequence Spread-Spectrum Signals Using a Prefilter-Delay-and-Multiply Device,” IEEE Journal on Selected Areas in Communications, vol. 8, No. 5, June 1990.
  - Chan, Y.T., B. H. Lee, R. Inkol, and F. Chan, “Estimation of Symbol Rate from the Autocorrelation Function,” 2009 Canadian Conference on Electrical and Computer Engineering, St. John’s, NL, Canada, May 3-6, 2009.