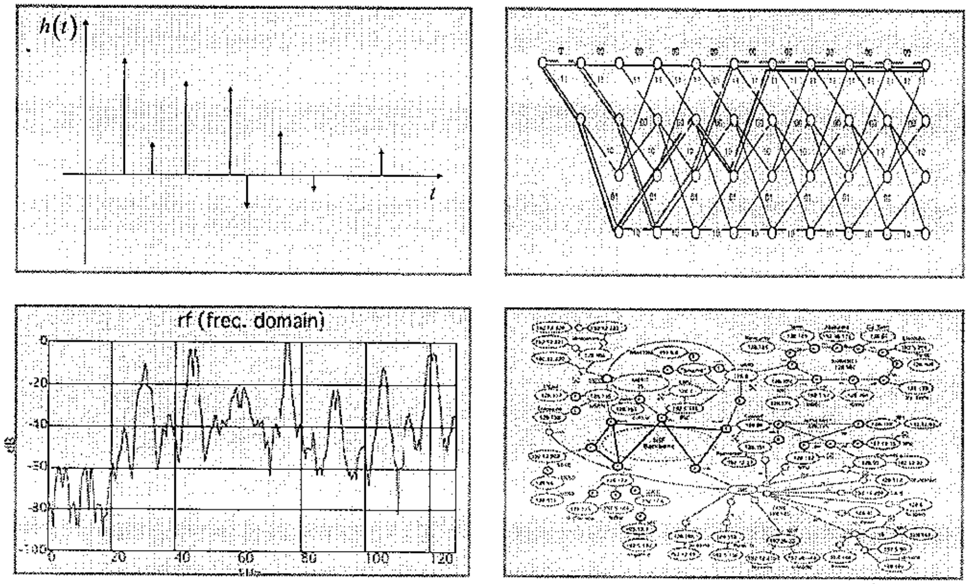


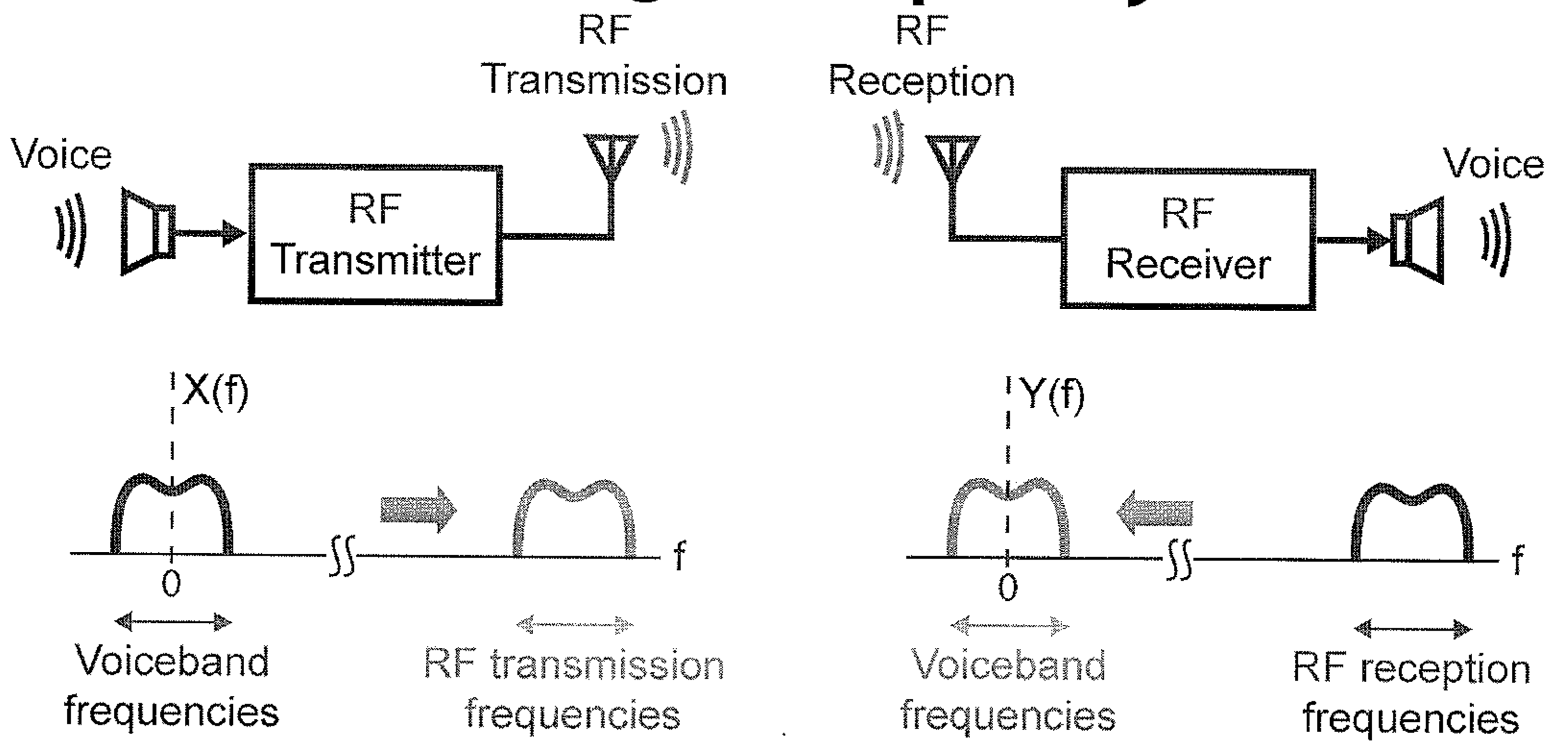
INTRODUCTION TO EECS II

DIGITAL COMMUNICATION SYSTEMS

6.02 Spring 2009
Lecture #16

- Modulation Step-by-Step
- Phase Coherency Issue

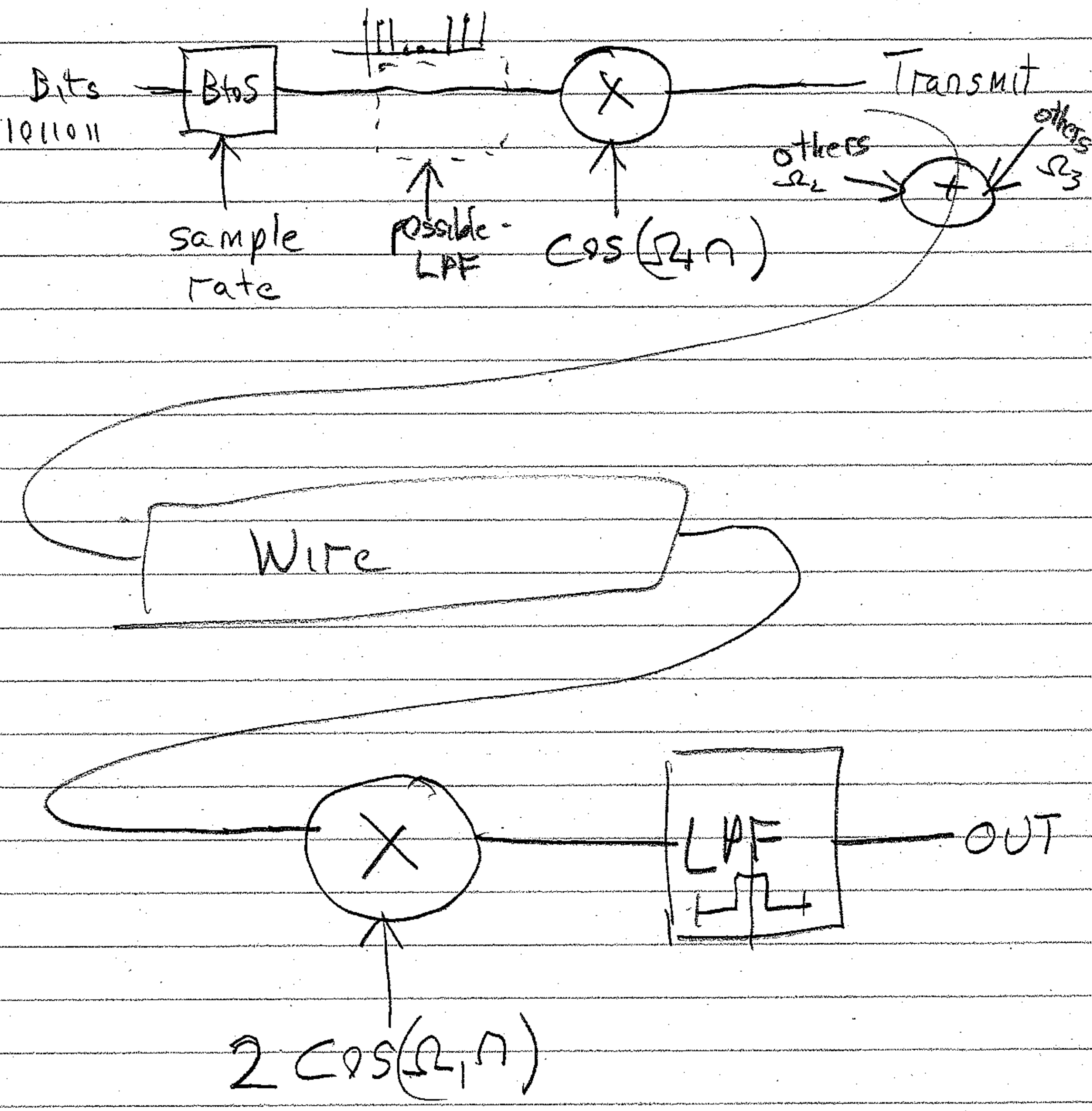
Motivation for High Frequency Modulation



- Modulation is used to change the frequency band of a signal
  - Enables RF communication in different frequency bands
    - Used in cell phones, AM/FM radio, WLAN, cable TV, ...
  - Note: higher frequencies lead to smaller antennas
    - 3GHz, 10cm wavelength, 2.5cm antenna (1/4 wavelength)

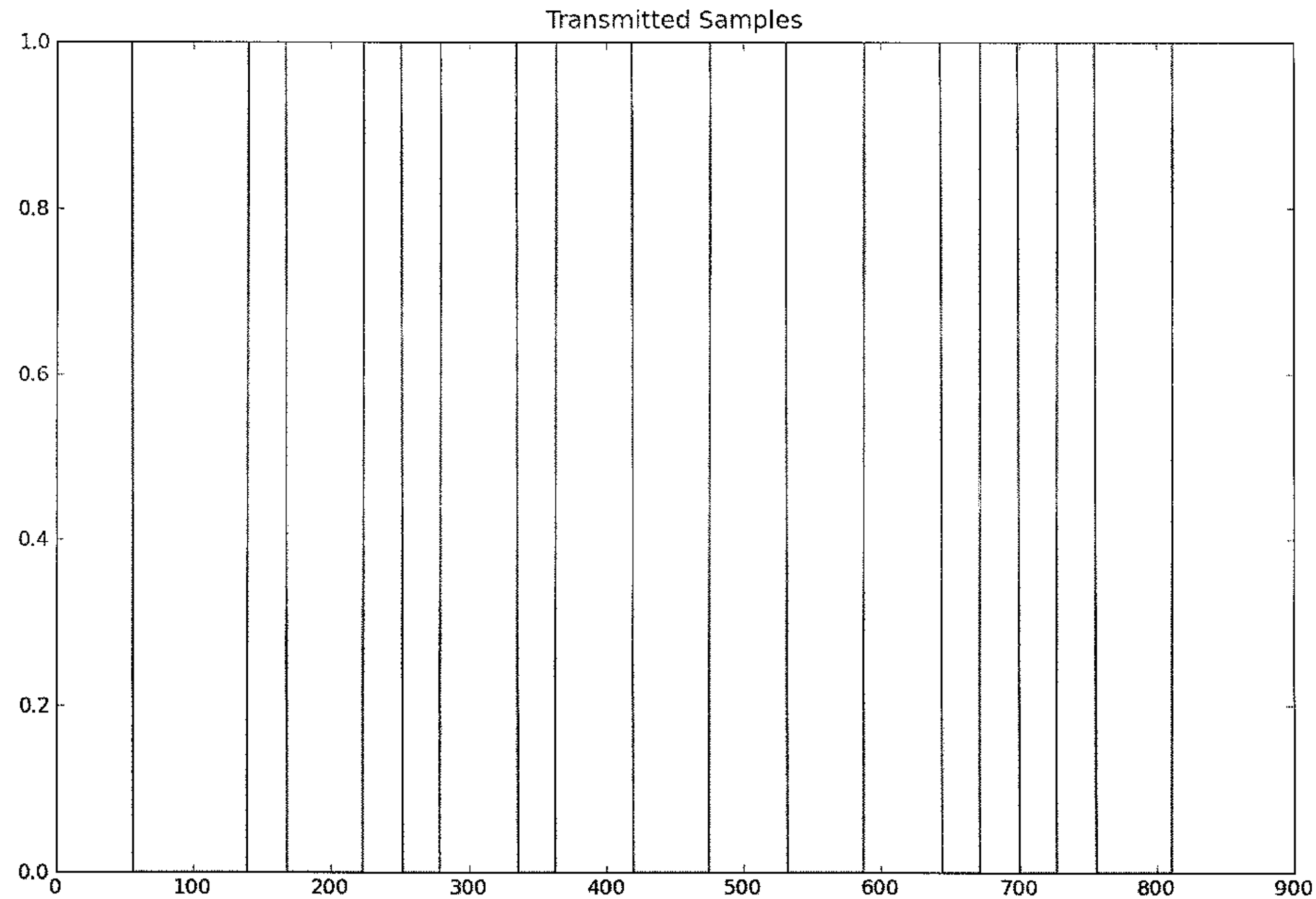
2

Block Diagram of Modulation



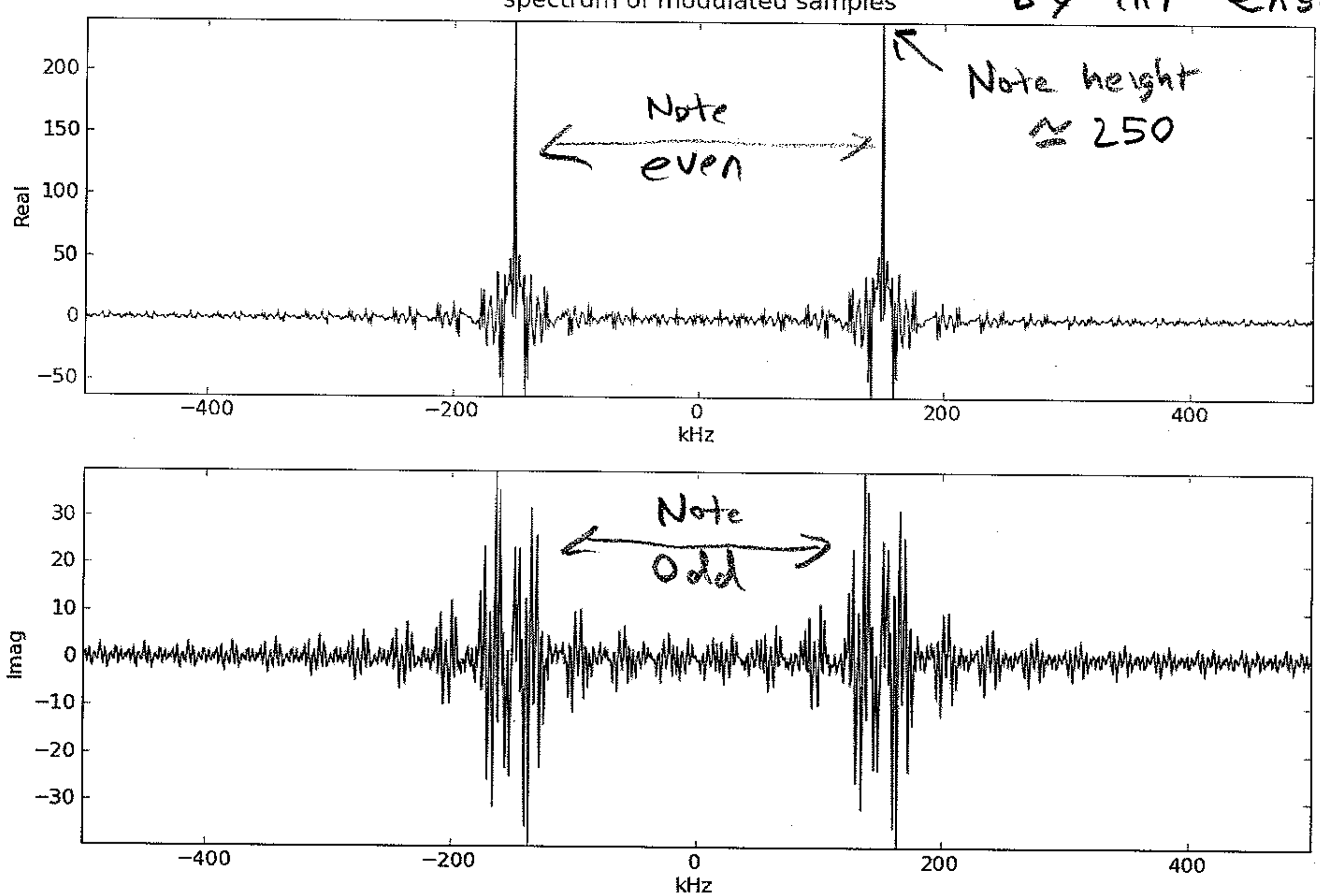
(4)

35000 Bits/Sec, 1M samples/sec

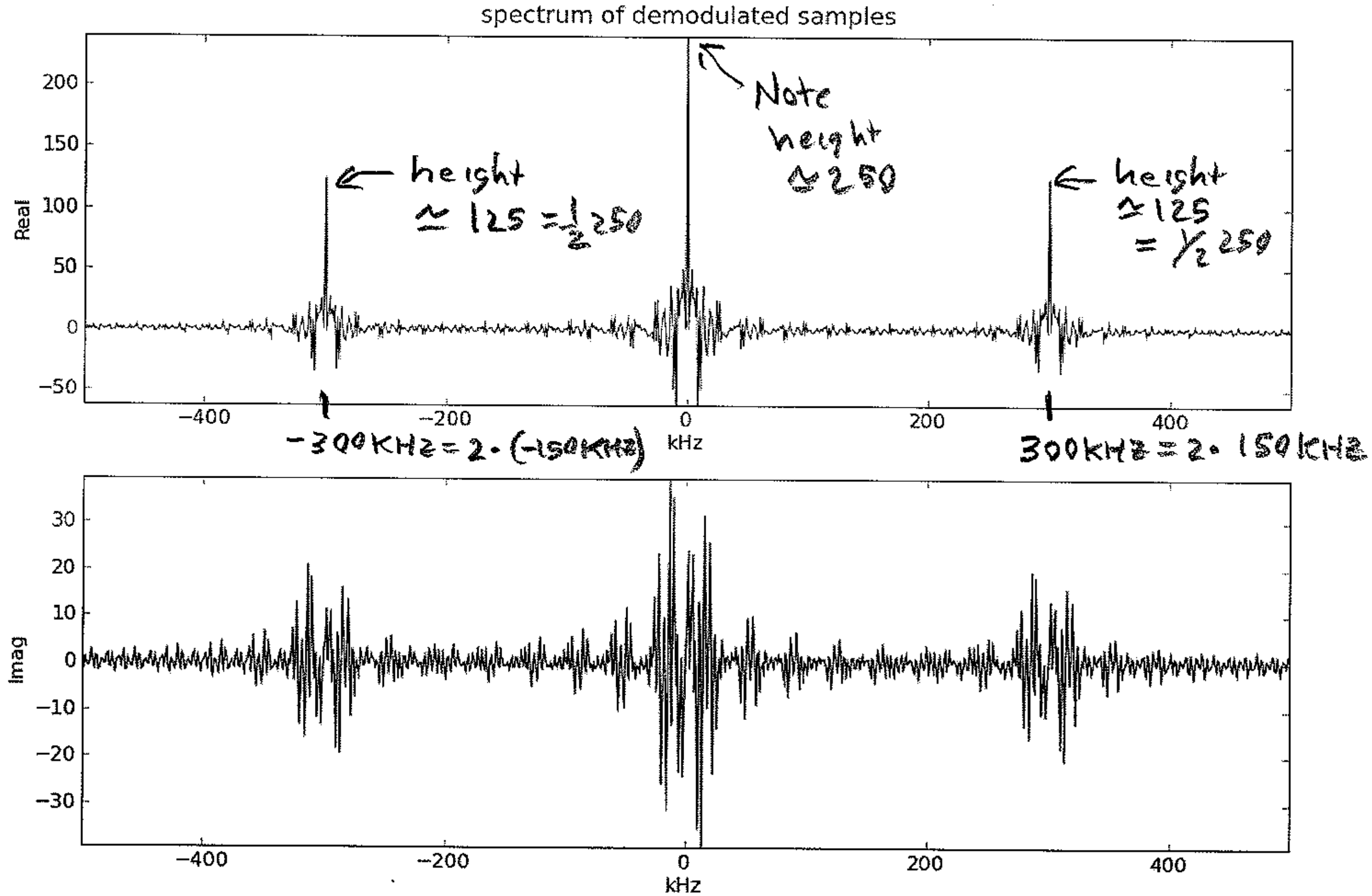


Post 150Khz Modulation (1M Sample Rate)

Note N=1000001 DFT used so 150KHz approximated as int($\frac{150000}{1M}$ N)·(1M/N). The rounding performed by int ensures an actual DFT frequency.

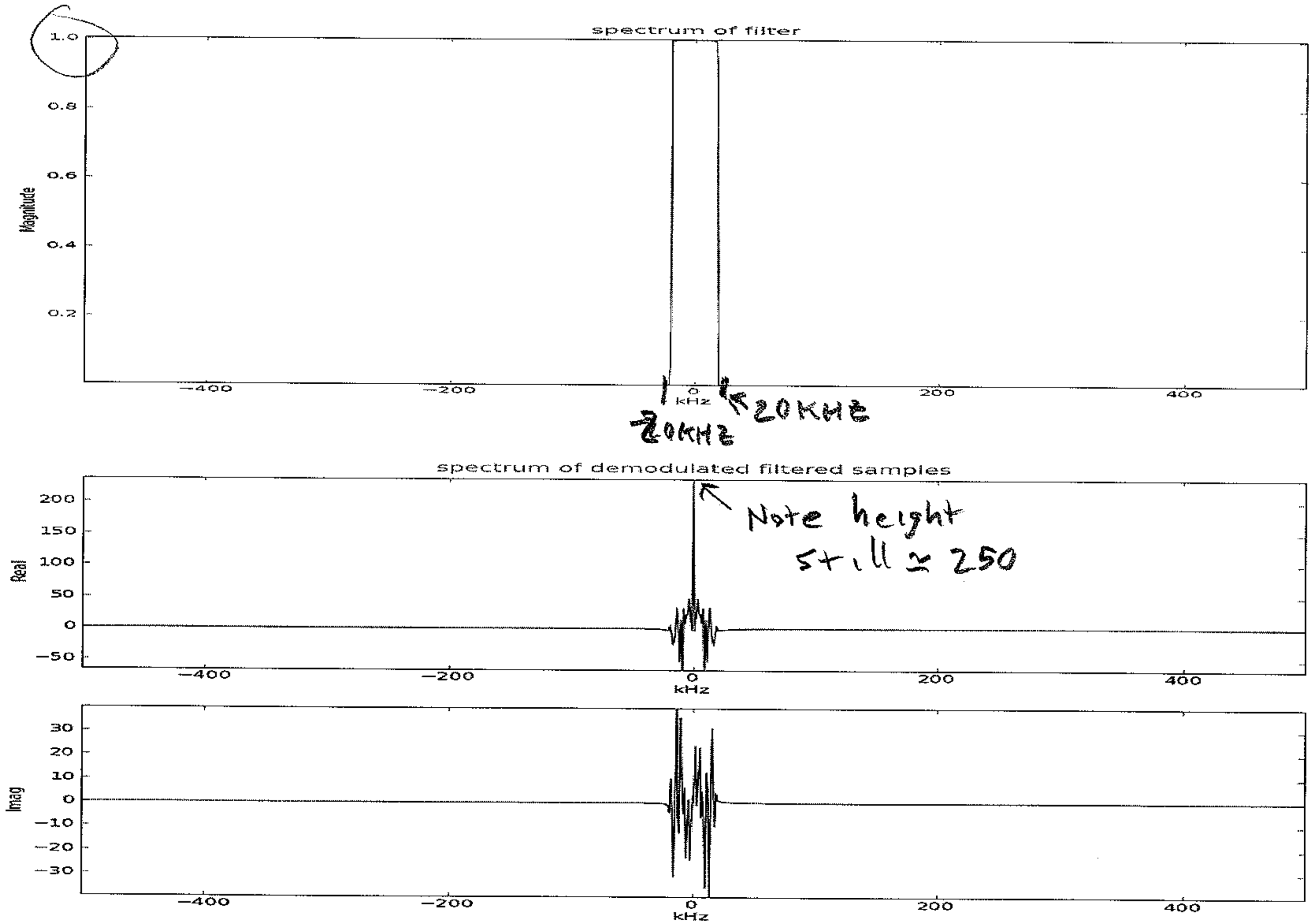


Spectrum of Demodulated Signal



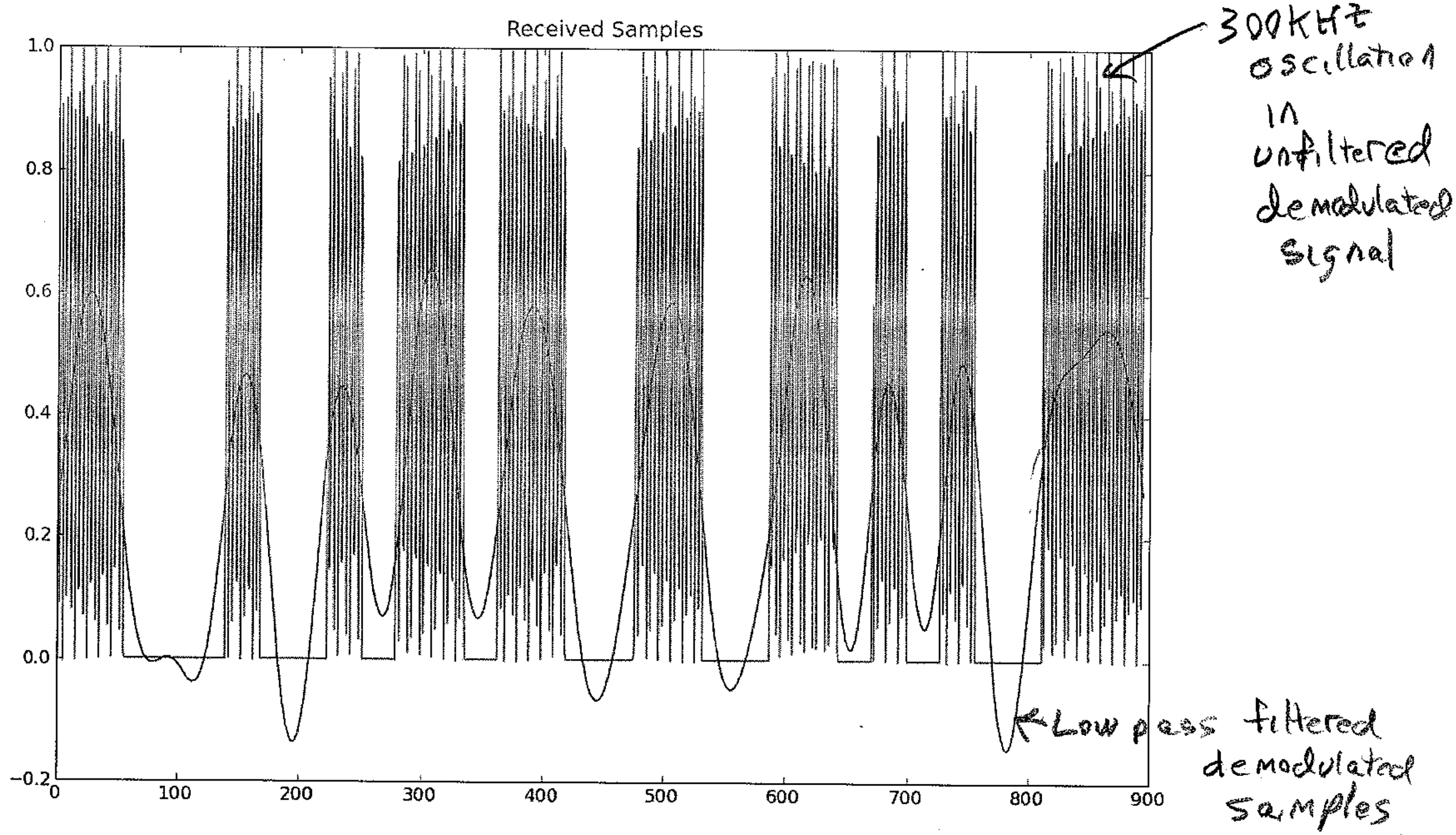
7

LPF and Spectrum After LPF



8

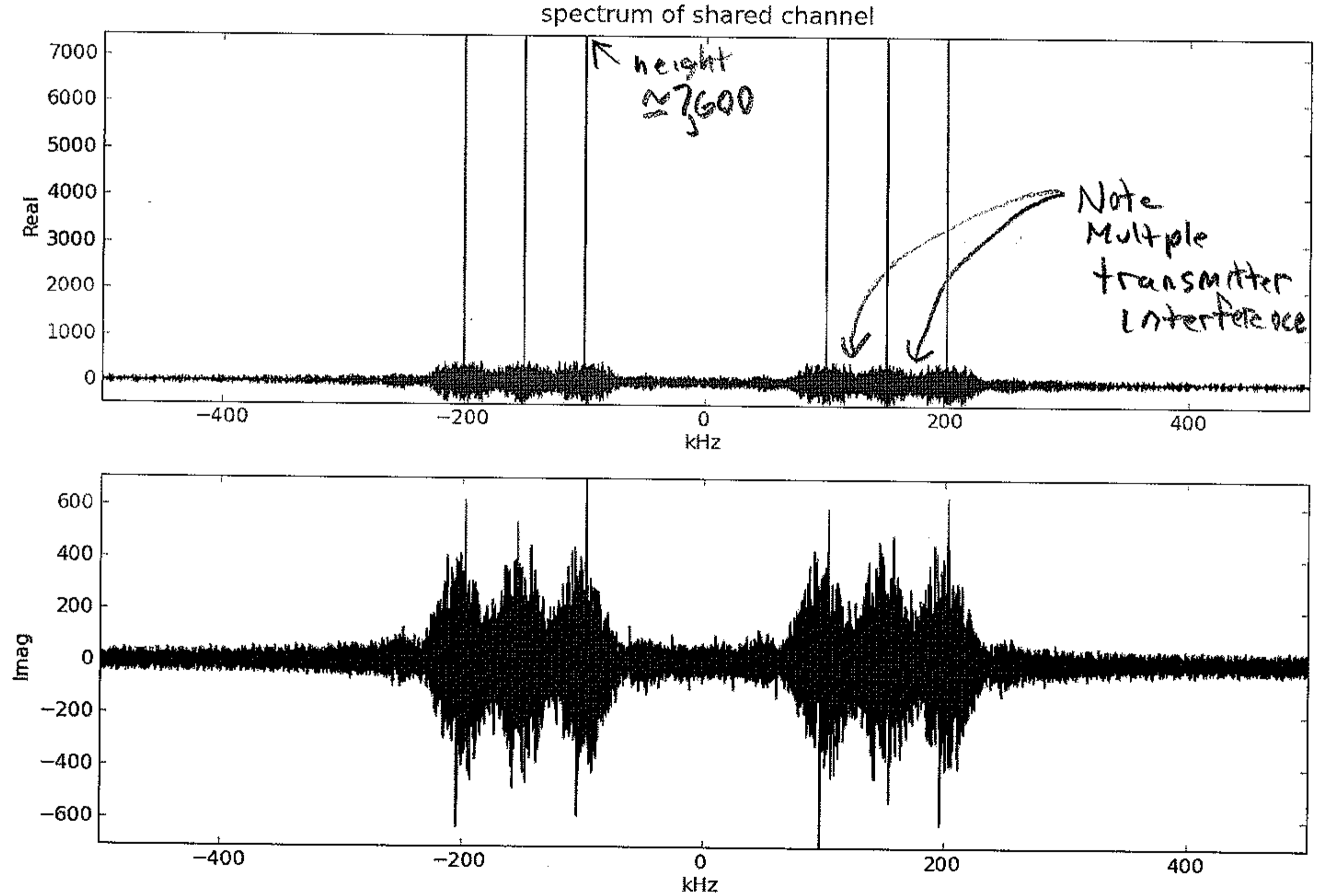
Received samples pre and post LPF



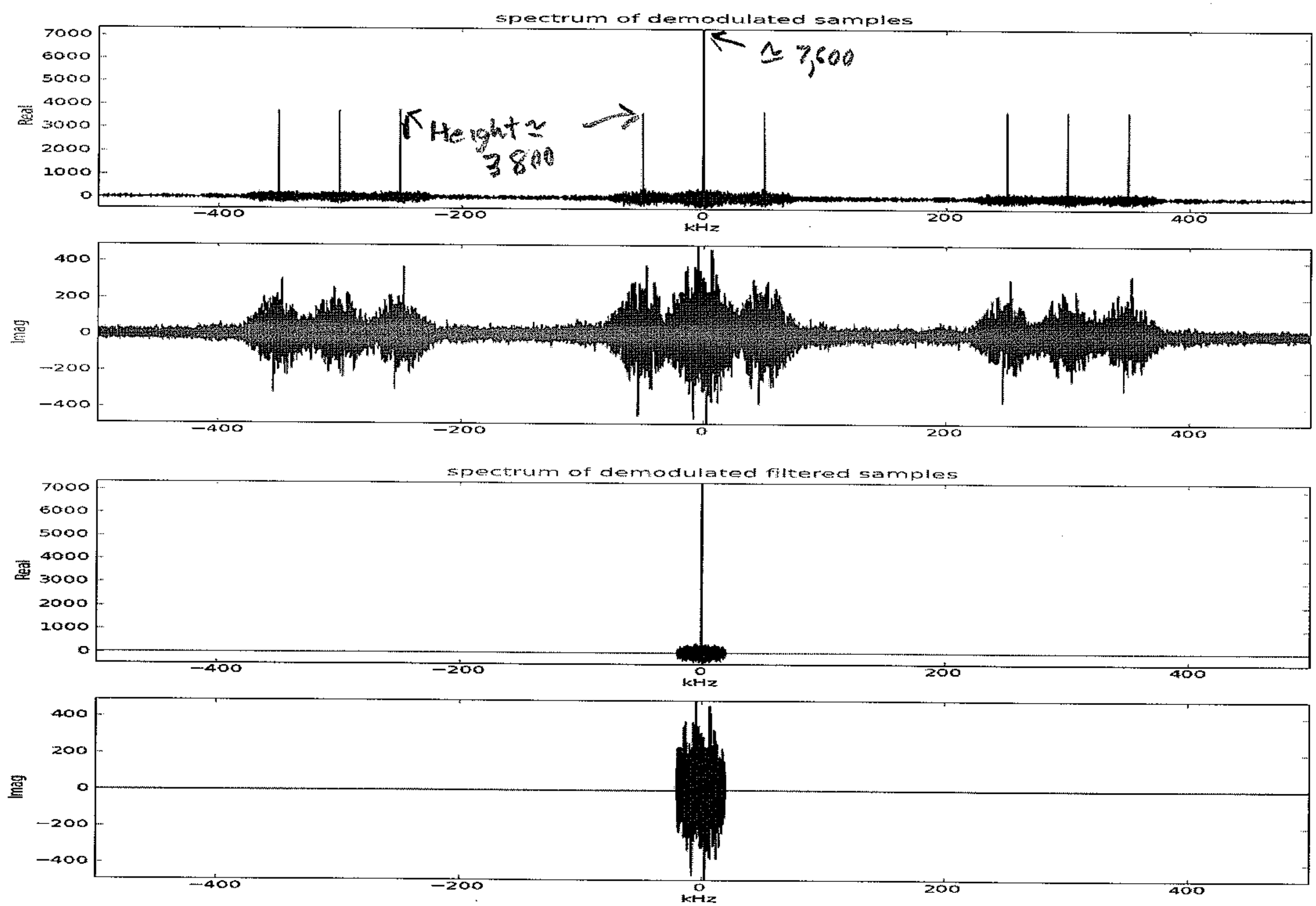
9

Spectrum: 100, 150, 200Khz transmitters

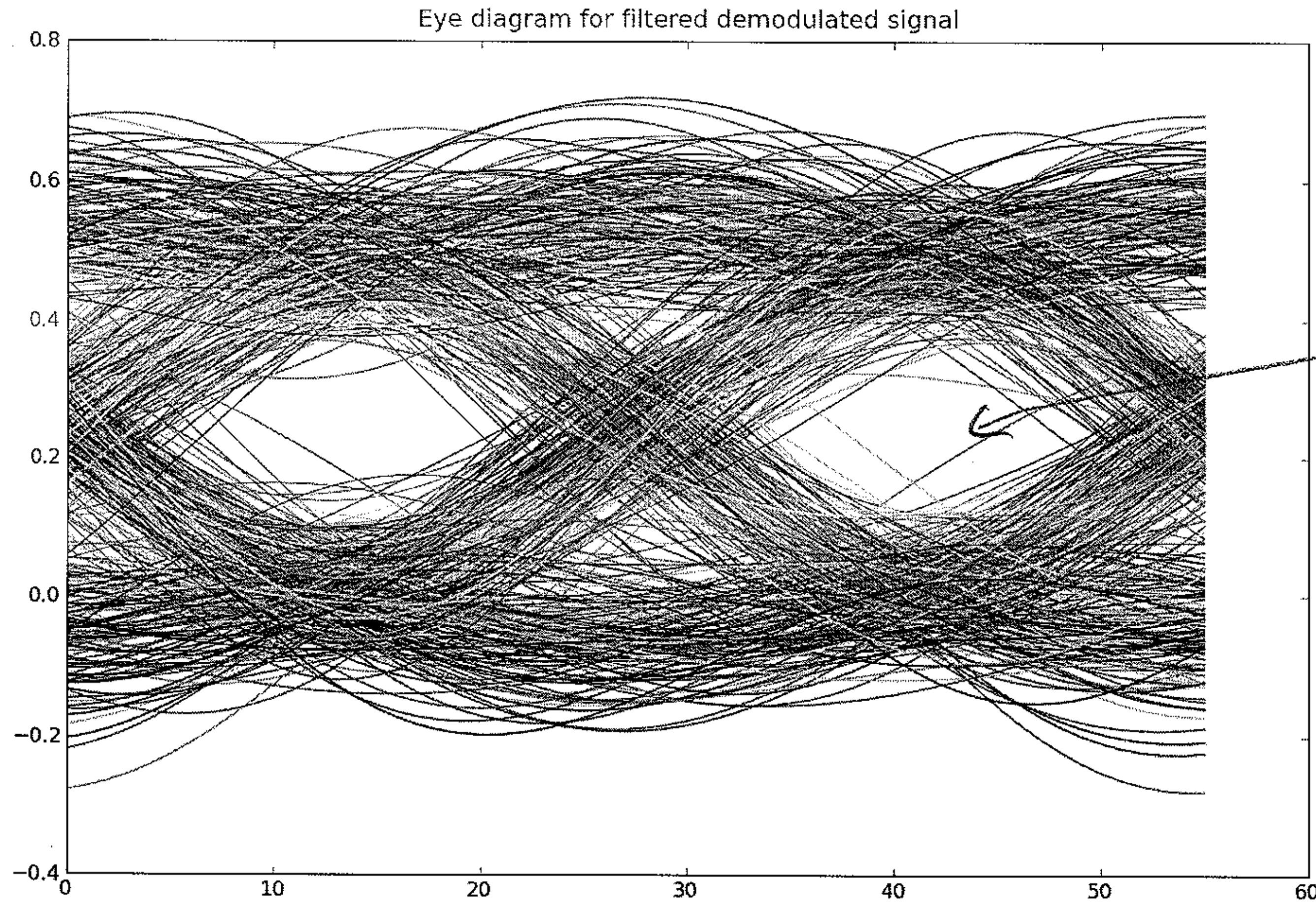
Again, aligned to nearest $f_k = \frac{k}{N} \cdot 1M$



Demod Spectrum Before and After LPF



Eye Diagram for Received Bits

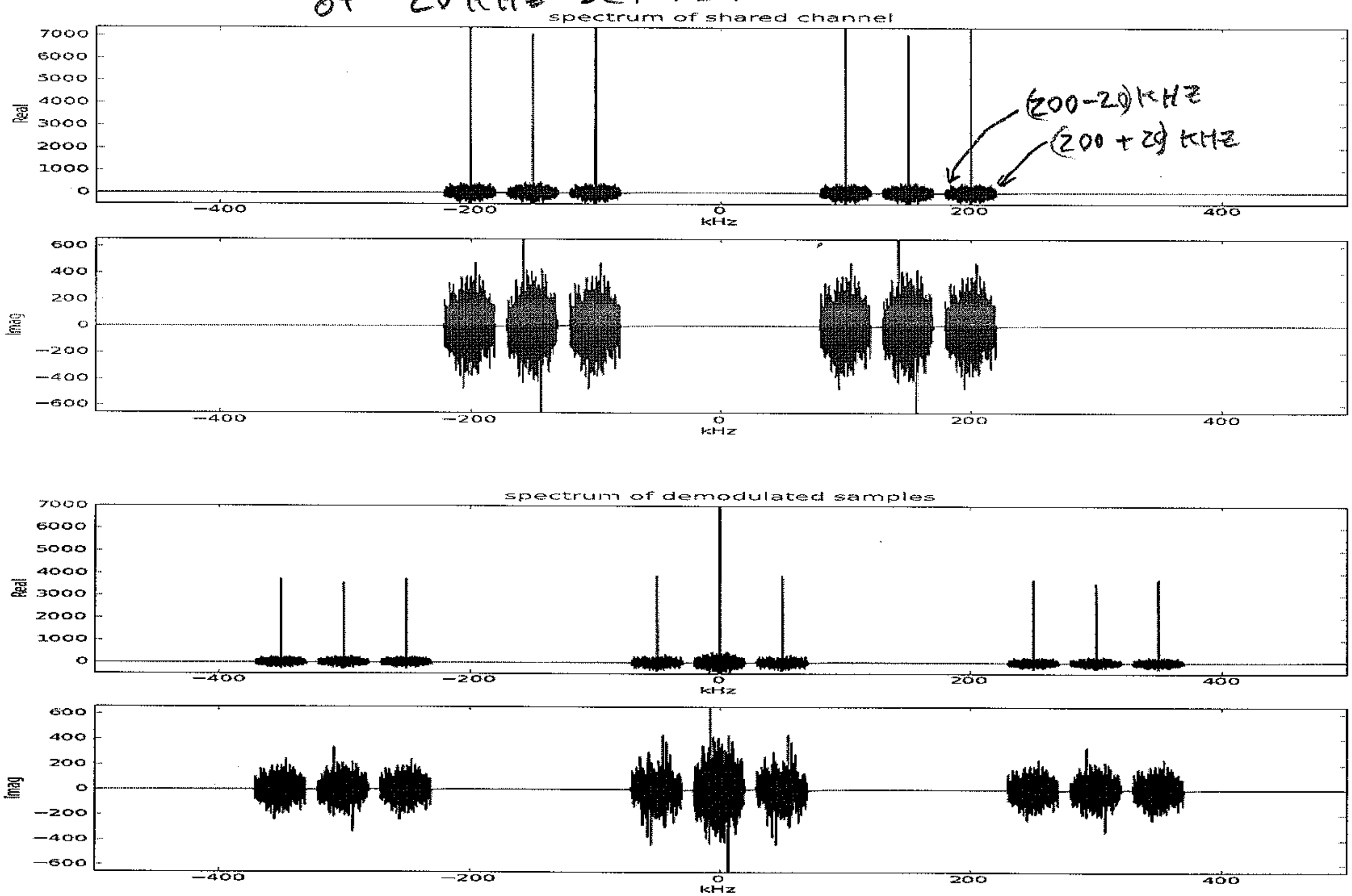


Includes interference from other transmitters and intersymbol interference.

(12)

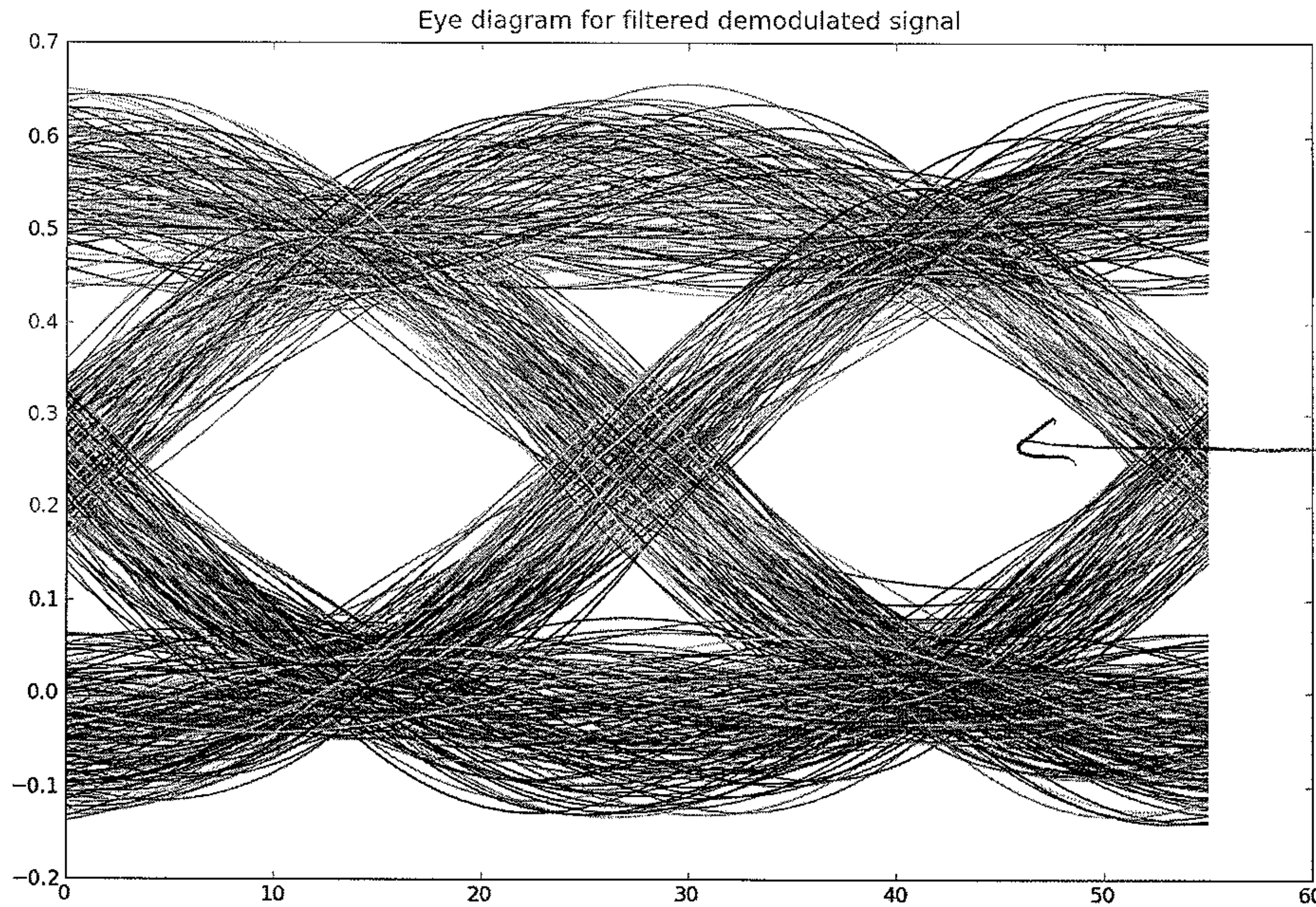
Transmit Filtered Spectrum, Pre/Post Demod

Each signal is filtered with a cutoff frequency of 20 kHz before modulation



(13)

Eye Diagram received bits, transmit filters



Note eye diagram improvement. There is still intersymbol interference, but little multiple transmitter interference

Adding Wire delay

Modulated signal

$$s[n]\cos(\Omega n) = s[n]\left(\frac{1}{2}e^{j\Omega n} + \frac{1}{2}e^{-j\Omega n}\right)$$

Modulated and delayed signal

D = # samples of delay

Received Signal

$$s[n-D]\cos(\Omega(n-D))$$

$$= s[n-D]\left(\frac{1}{2}e^{-j\Omega D}e^{j\Omega n} + \frac{1}{2}e^{+j\Omega D}e^{-j\Omega n}\right)$$

Consider Demodulation $s[n]=1$

$$\left(\frac{1}{2}e^{-j\Omega D}e^{j\Omega n} + \frac{1}{2}e^{j\Omega D}e^{-j\Omega n}\right)\left(\frac{1}{2}e^{j\Omega n} + \frac{1}{2}e^{-j\Omega n}\right)$$

$$\frac{1}{4}e^{-jD}e^{2j\Omega n} + \frac{1}{4}e^{jD}e^{-2j\Omega n}$$

$$+ \frac{1}{4}\left(e^{-j\Omega D} + e^{j\Omega D}\right)$$

(14)

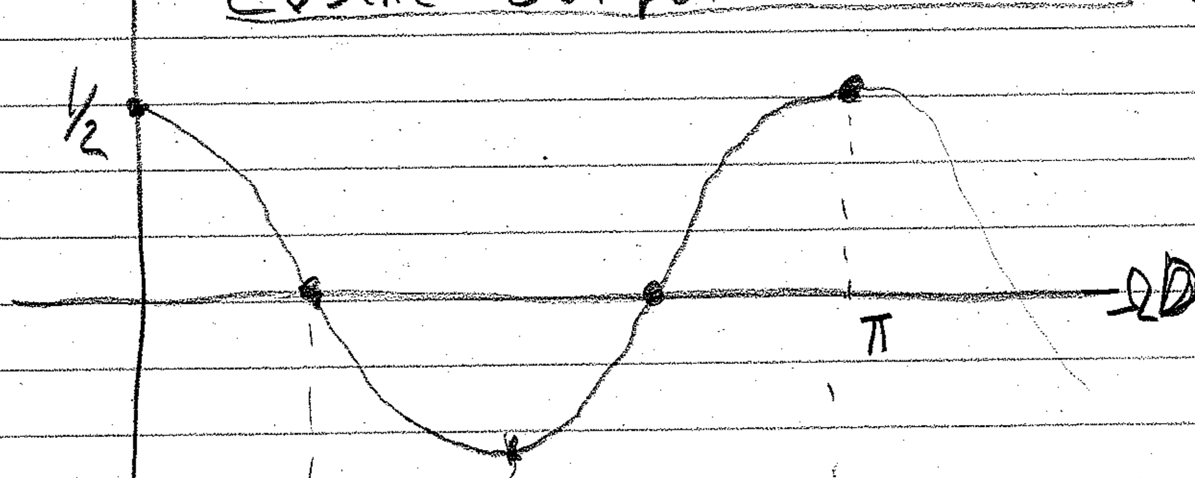
<u>Demod by Sine</u>

$$\left(\frac{1}{2}e^{-j\Omega D}e^{j\Omega n}+\frac{1}{2}e^{j\Omega D}e^{-j\Omega n}\right)\left(\frac{-j}{2}e^{j\Omega n}+\frac{j}{2}e^{-j\Omega n}\right)$$

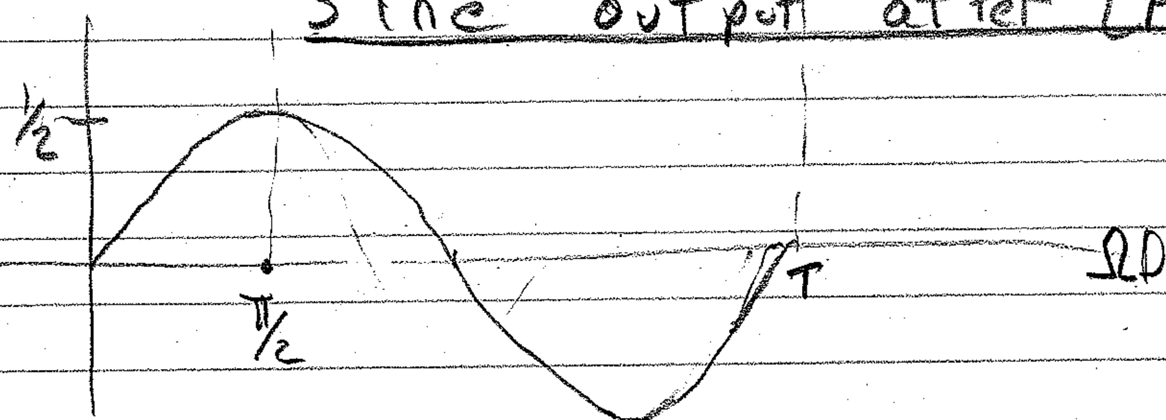
$$\frac{-j}{4}e^{-j\Omega D}e^{2j\Omega n}+\frac{j}{4}e^{j\Omega D}e^{-2j\Omega n}$$

$$+\frac{-j}{4}\left(e^{j\Omega D}-e^{-j\Omega D}\right)$$

<u>Cosine output after LPF $s[n]=1$</u>

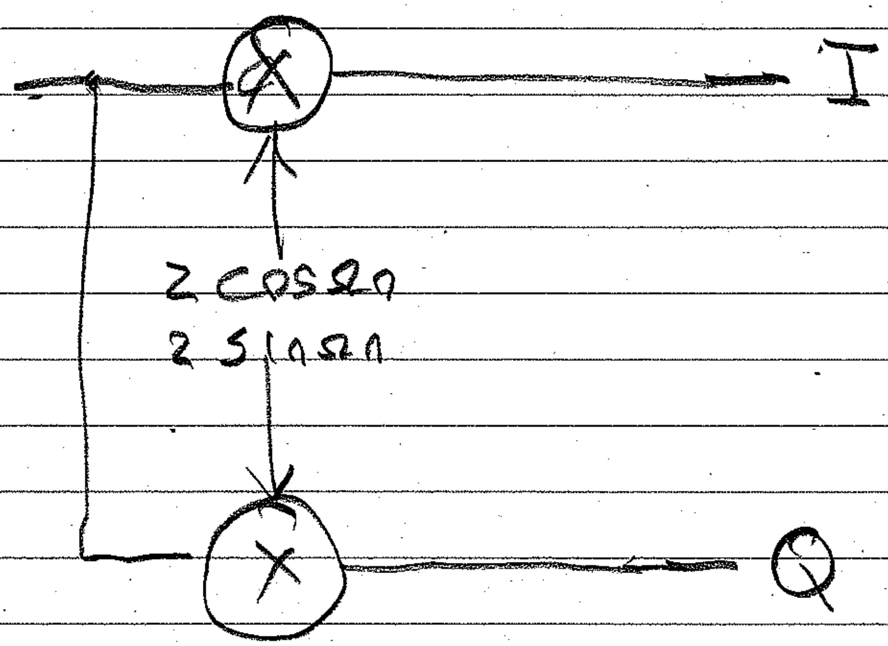


<u>Sine output after LPF $s[n]=1$</u>



Suppose $s[n] = 1 \;\forall\, n$

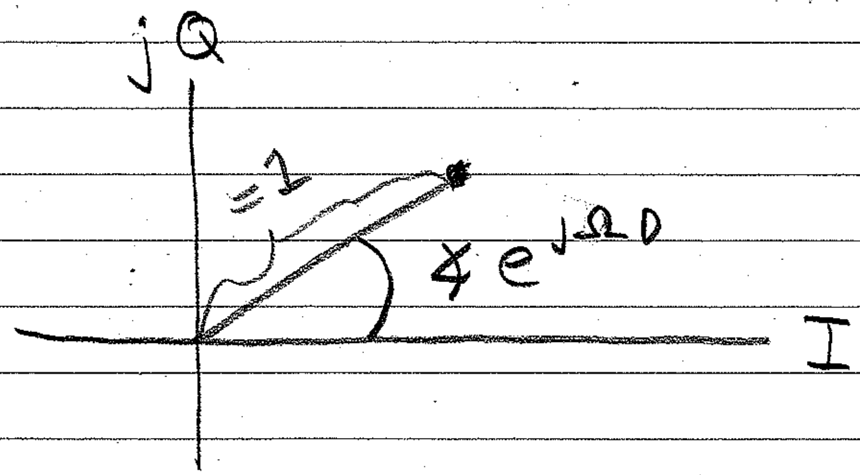
<u>Note</u>



$$|I|^2 + |Q|^2 = 1$$

$\cos^2 \Omega D \qquad \sin^2 \Omega D$

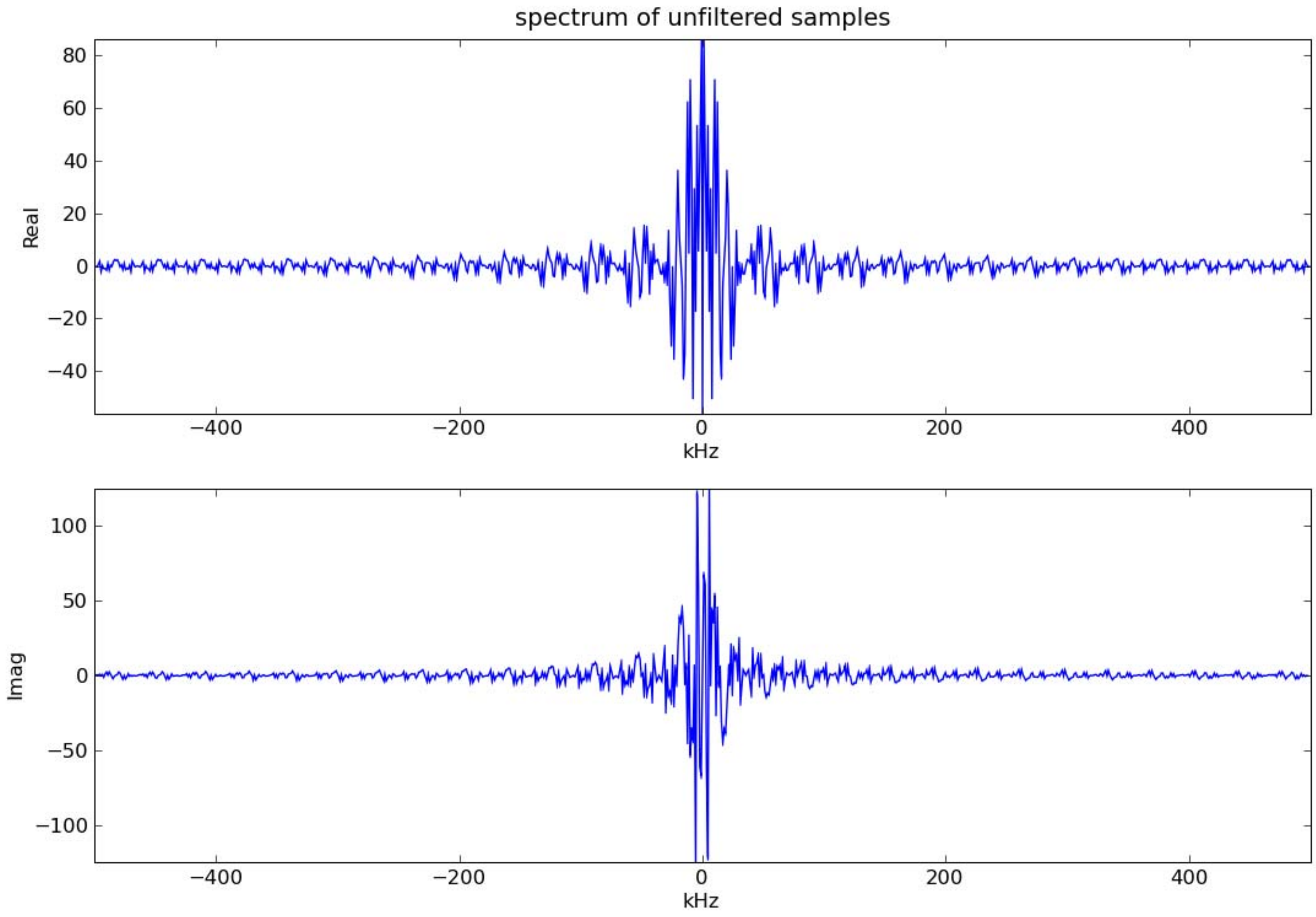
<u>Regardless of delay</u>



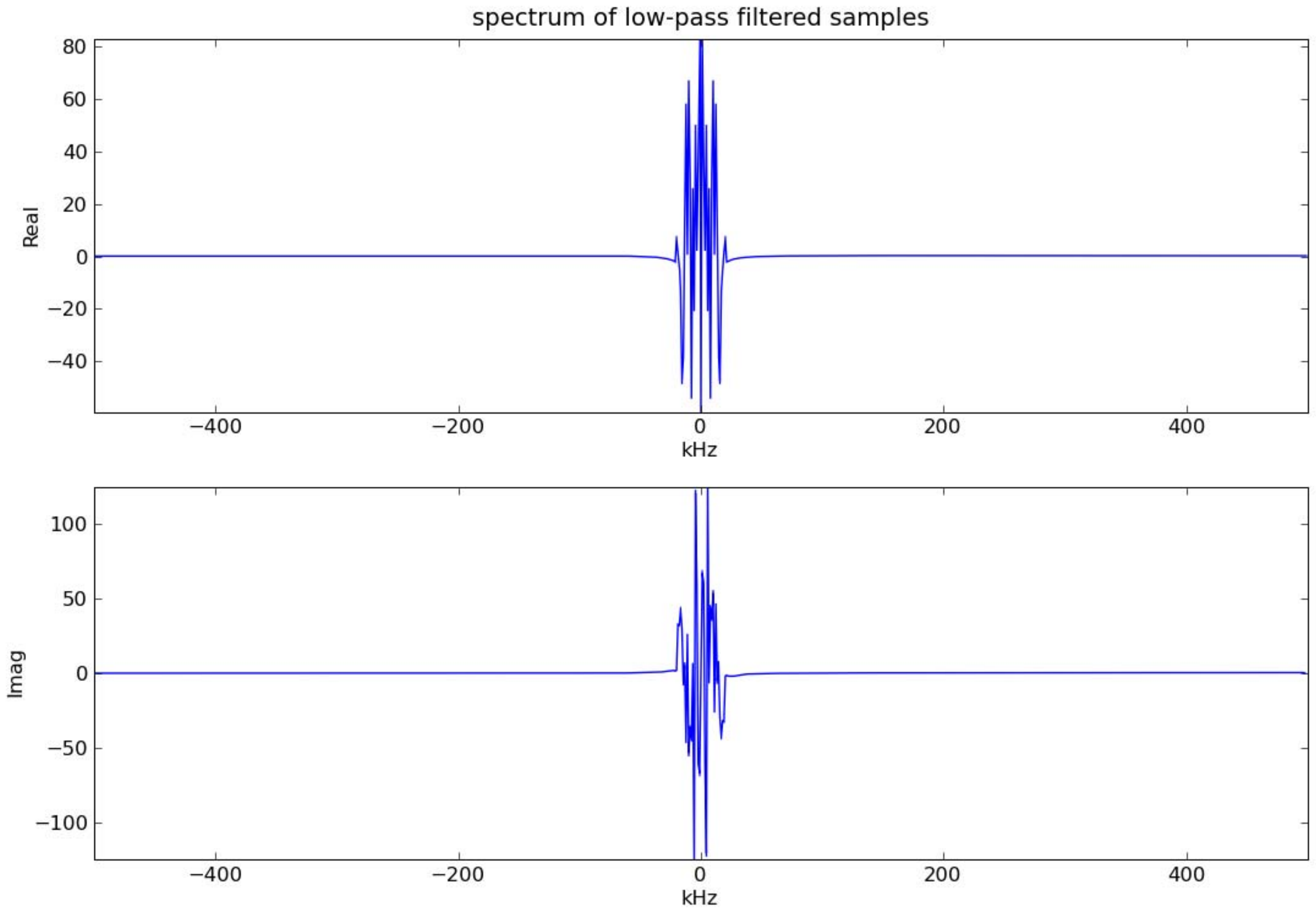
In the following single sideband modulation example, 1e6 samples/sec and 35000 bits/sec are used. A signal is low-pass filtered (with 20khz cutoff frequency) is modulated with a cosine at 200Khz. Then the signal is high-pass filtered with a filter cutoff frequency of 200khz to produce a single side-band like spectrum and then demodulated with a cosine to recover the signal.

Note: In this example, the samples are using -0.5volts for zero and 0.5volts for one. This eliminates a large component at DC, and removes an ambiguity with the single side-band like signal (If there is a large DC component, then after modulation there will be a large component of the spectrum at exactly 200khz that has to be divided in half for the single side-band to work properly).

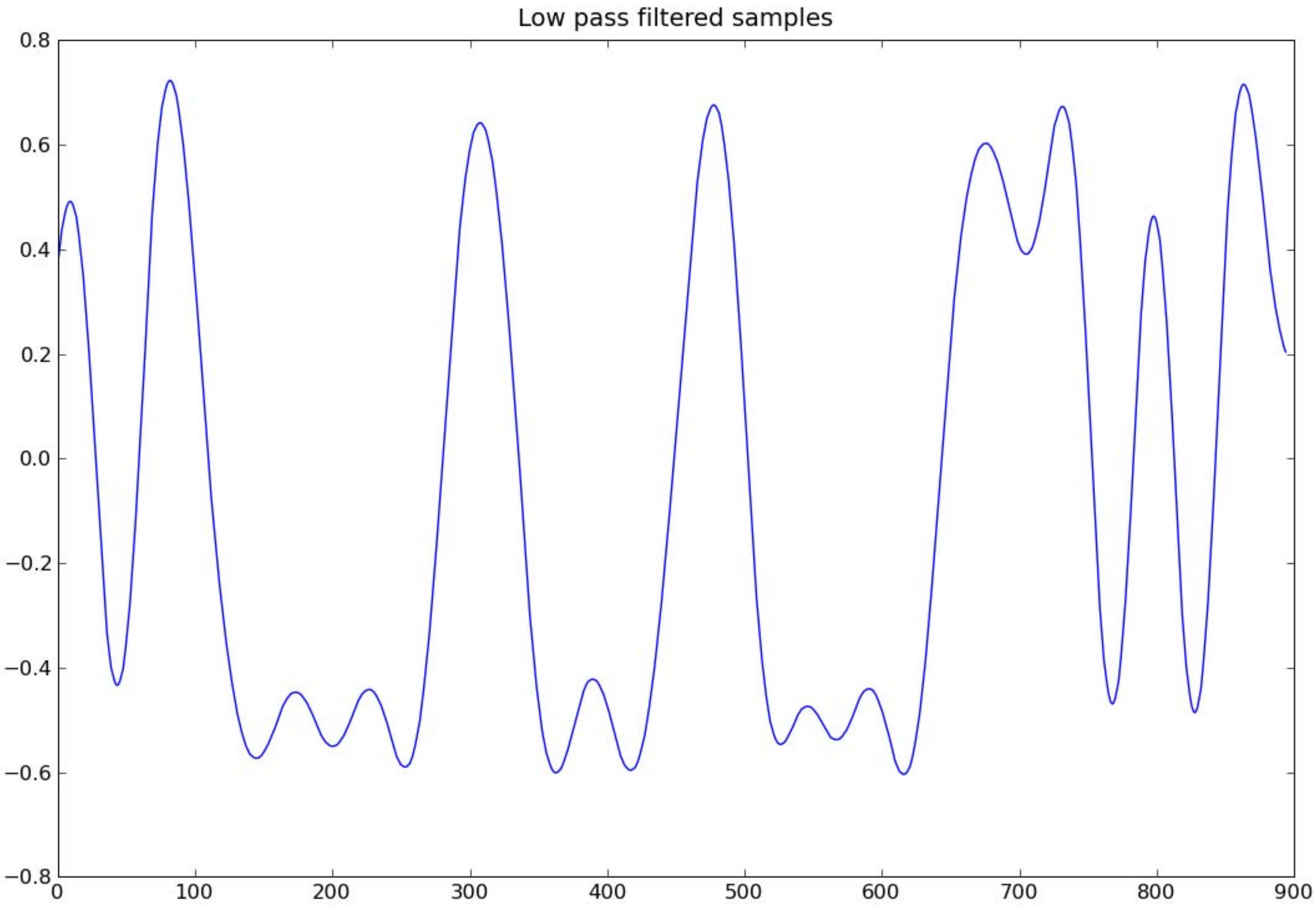
Spectrum of unfiltered samples



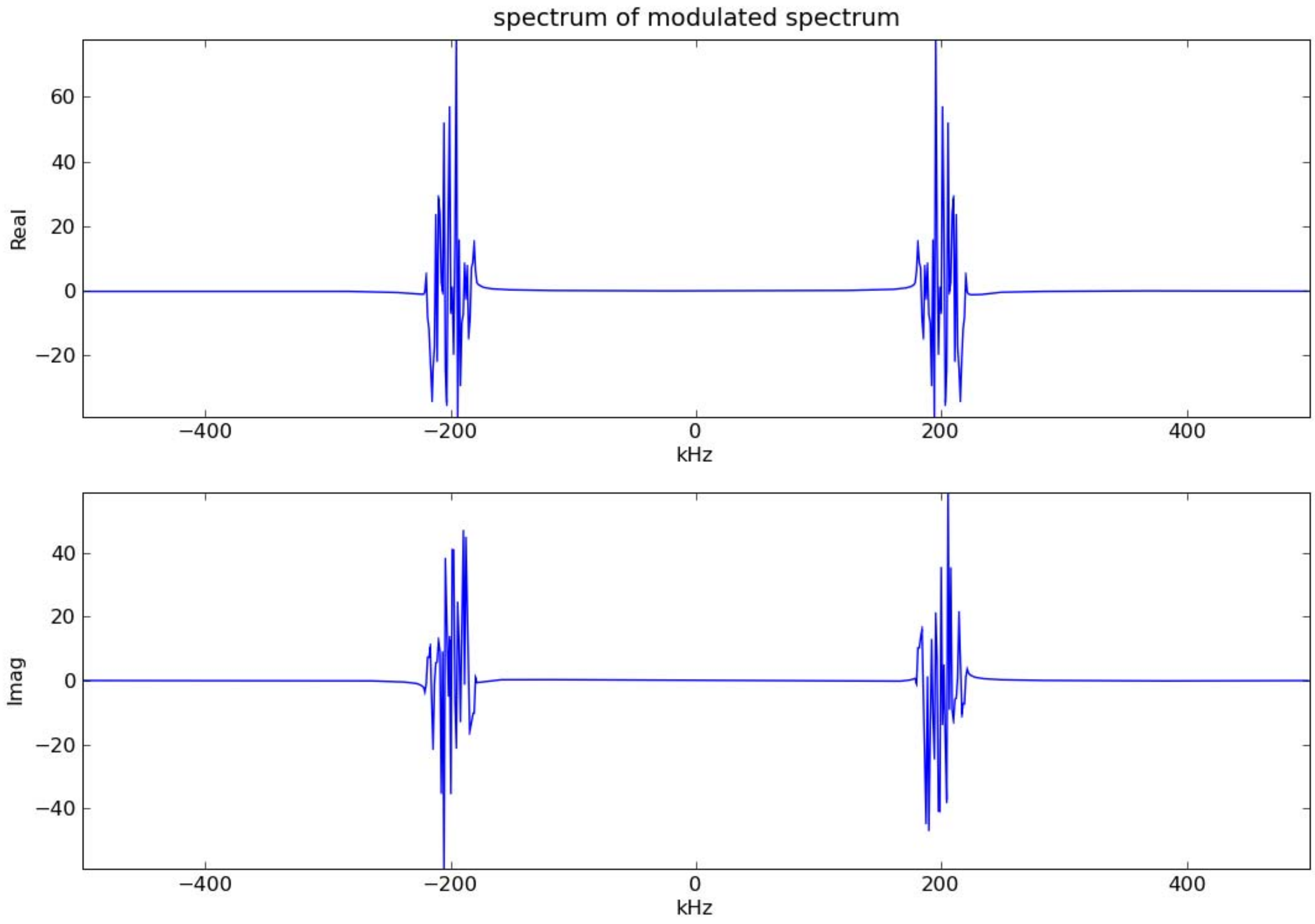
Spectrum of LPF samples



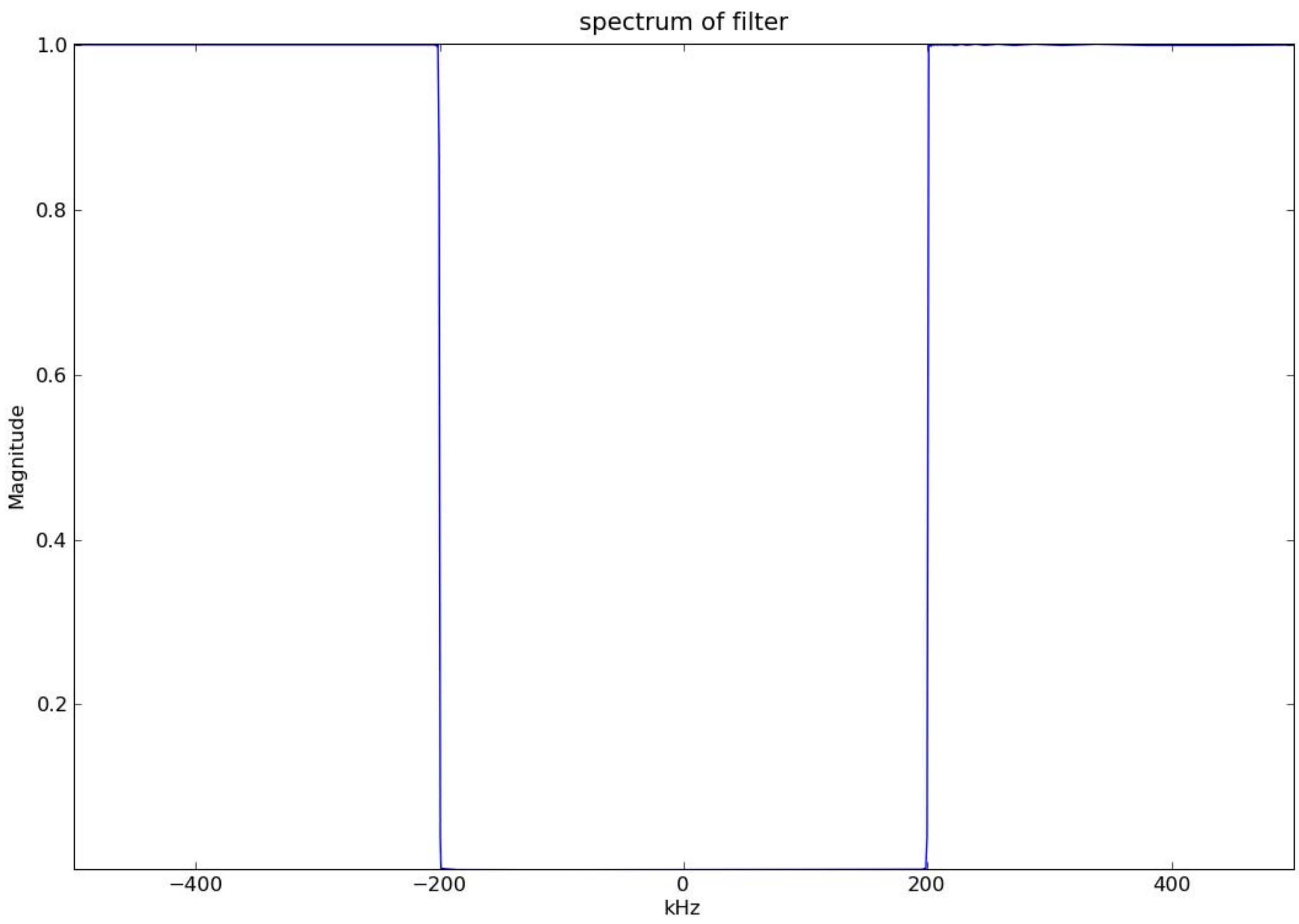
Time-domain Plot of LPF samples (32 bits) Note Voltage range (-0.5 to 0.5)



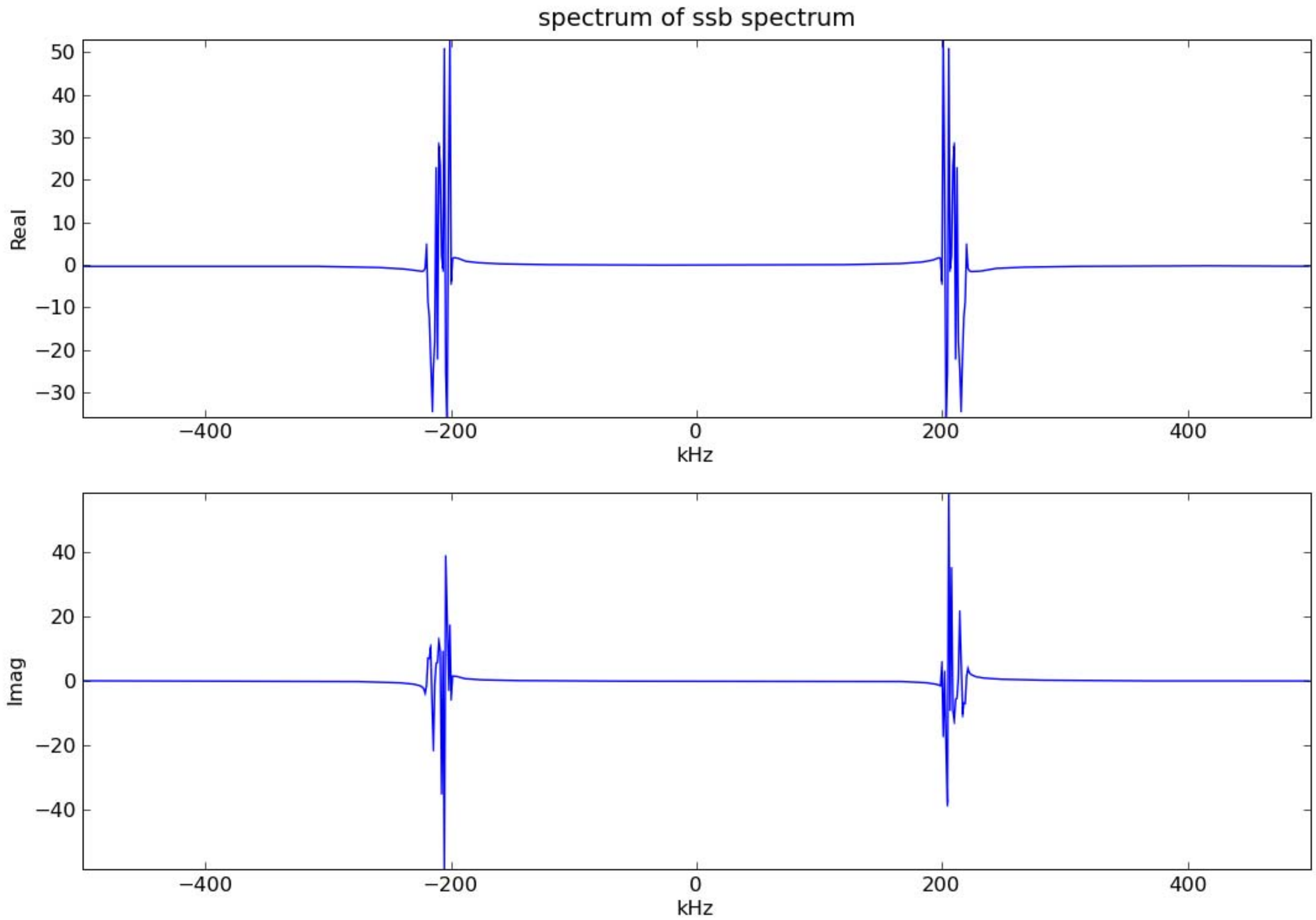
Plot of the modulated LPF'd spectrum



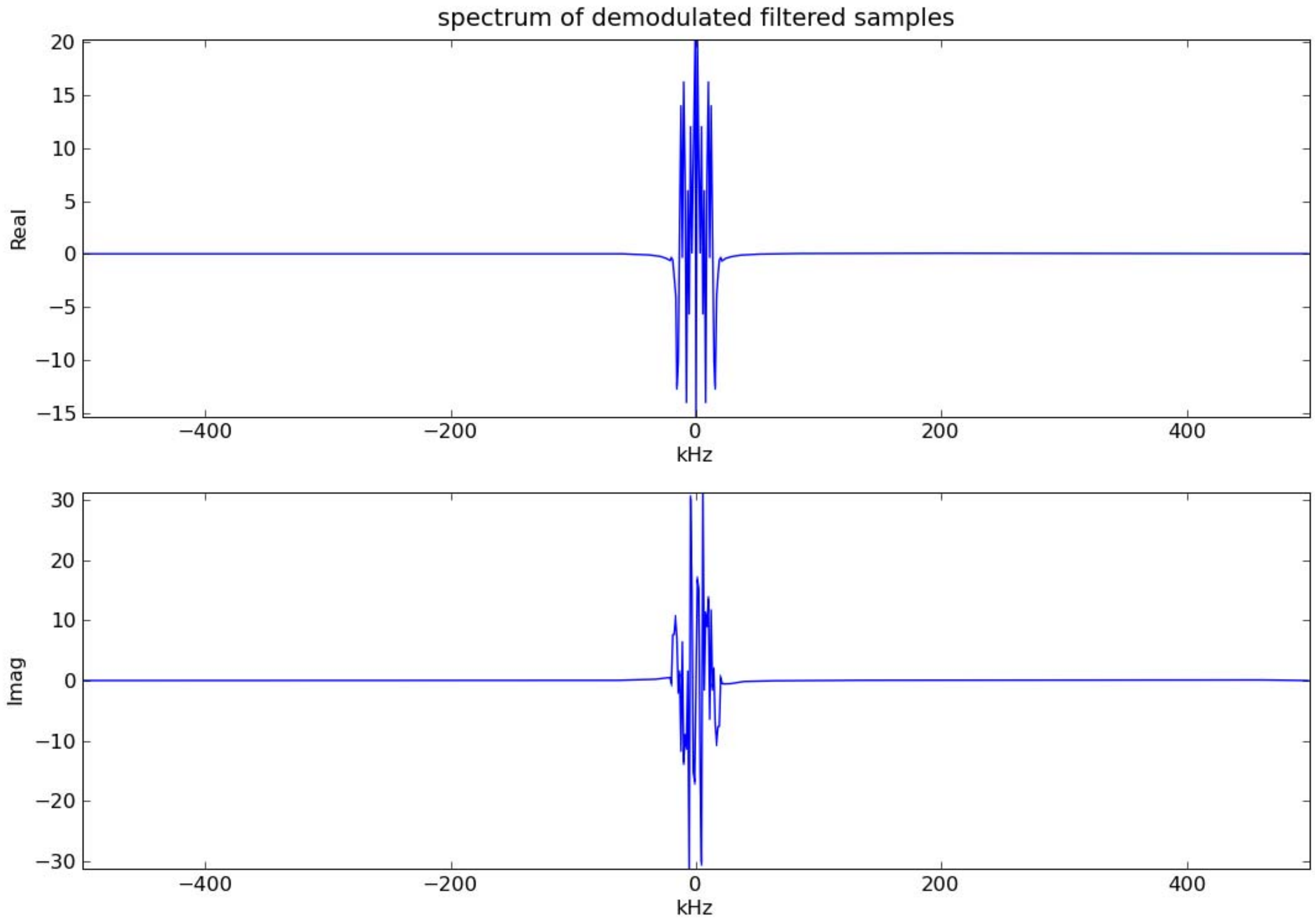
High pass filter used to generate ssb



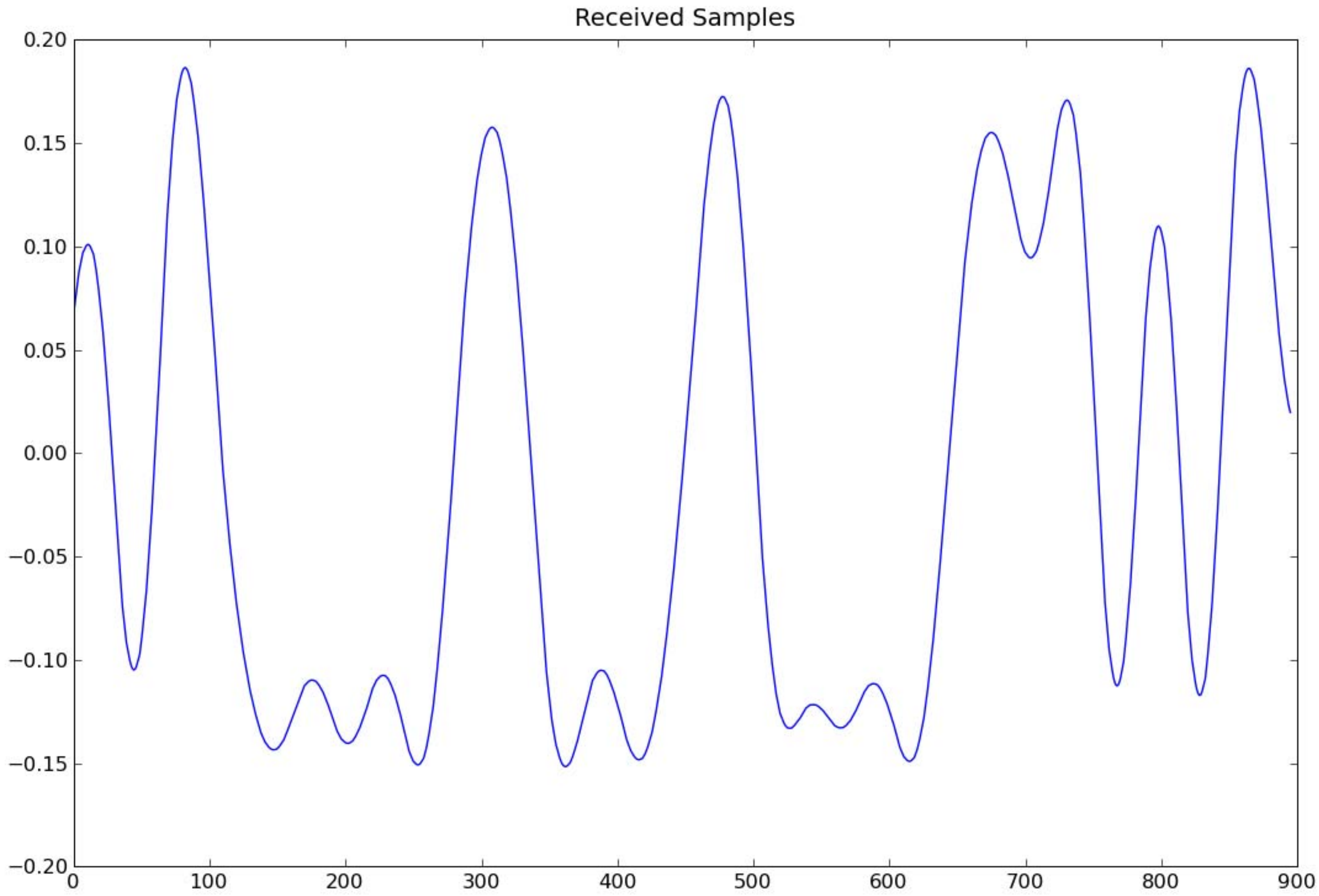
High pass filtered Modulated signal



LPF Demodulated Signal



Received Signal in Time



In this next example, consider using sine and cosine demodulation of cosine modulated signal s[n] where there is a delay. In, particular, for the case where

$$N = 1001$$

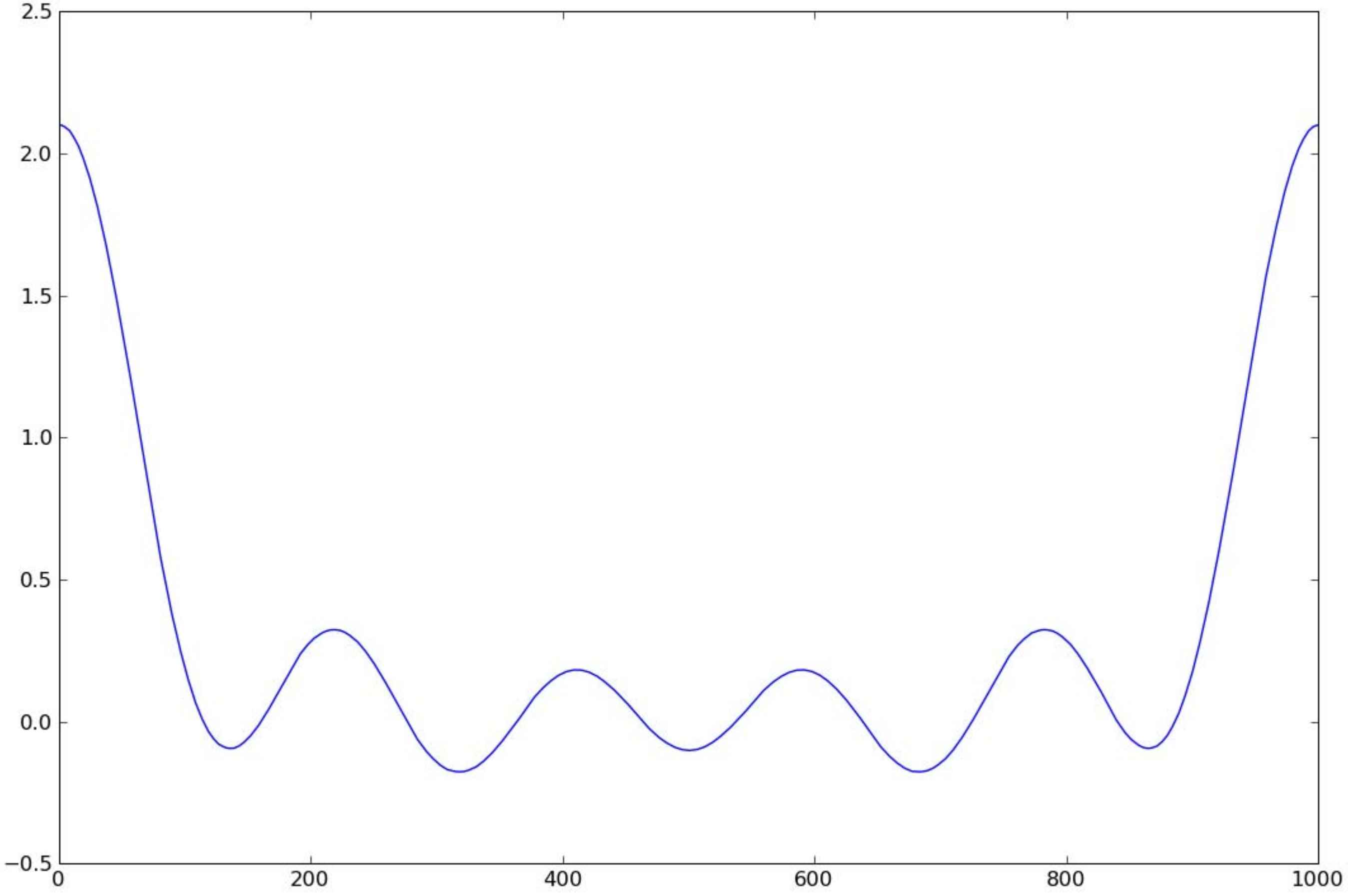
$$\Omega_1 = \frac{2 * \pi}{1001}$$

$$s[n] = 0.3 + 0.5\cos\Omega_1 n + 0.4\cos 2\Omega_1 n + 0.3\cos 3\Omega_1 n + 0.3\cos 4\Omega_1 n + 0.3\cos 5\Omega_1 n$$

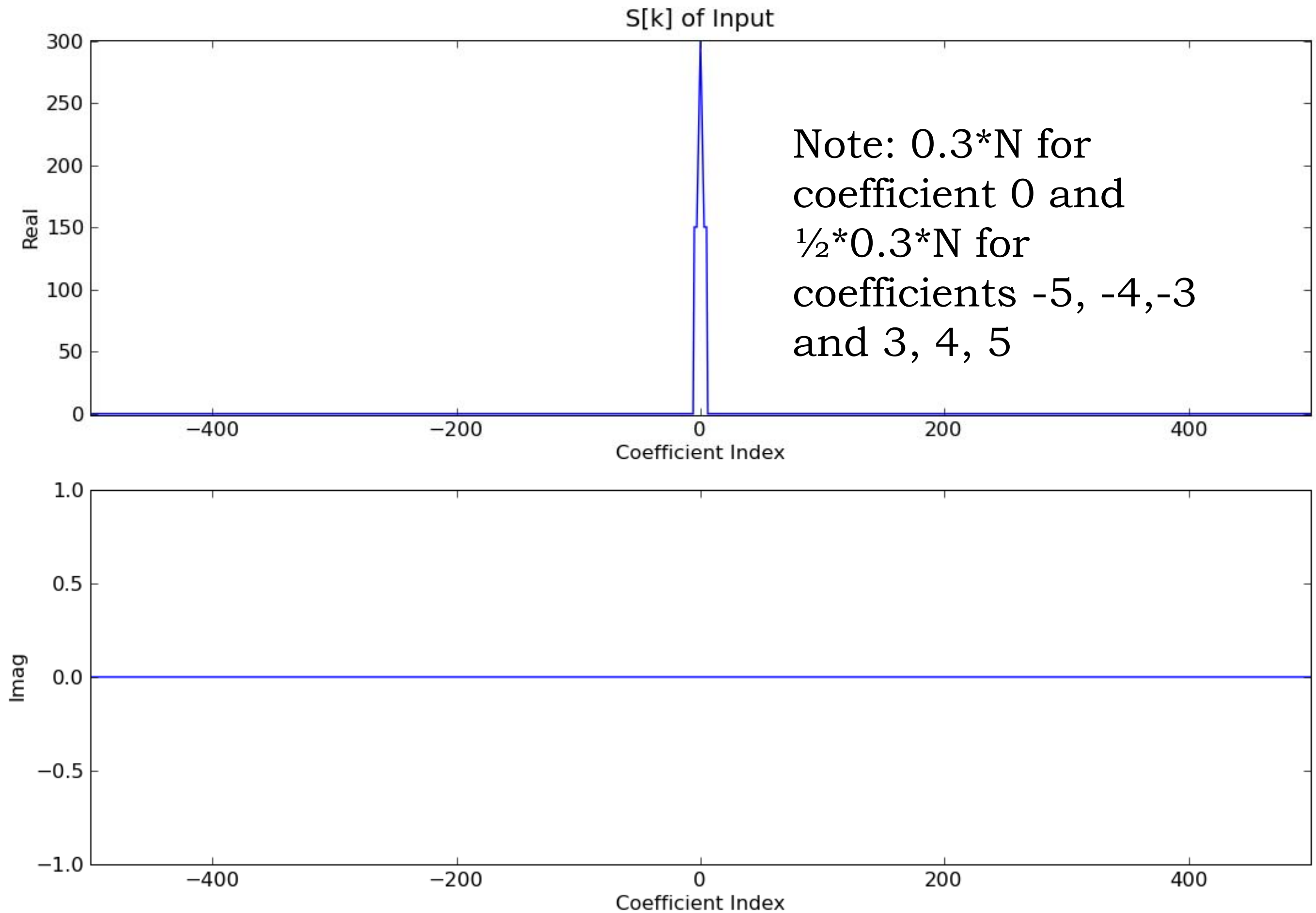
consider a delay of 5 samples (so that 25*Omega_1*D is almost pi/4) in the modulated signal.

The following plots show the impact of a 5 sample delay on modulation and demodulation at four different carrier frequencies (but the same delay). The different carrier frequencies will change the phase shift introduced by the the delay, and generate different outputs from sine and cosine demodulation. In particular, the carrier frequencies considered are 25, 50, 75 and 100 times Omega_1.

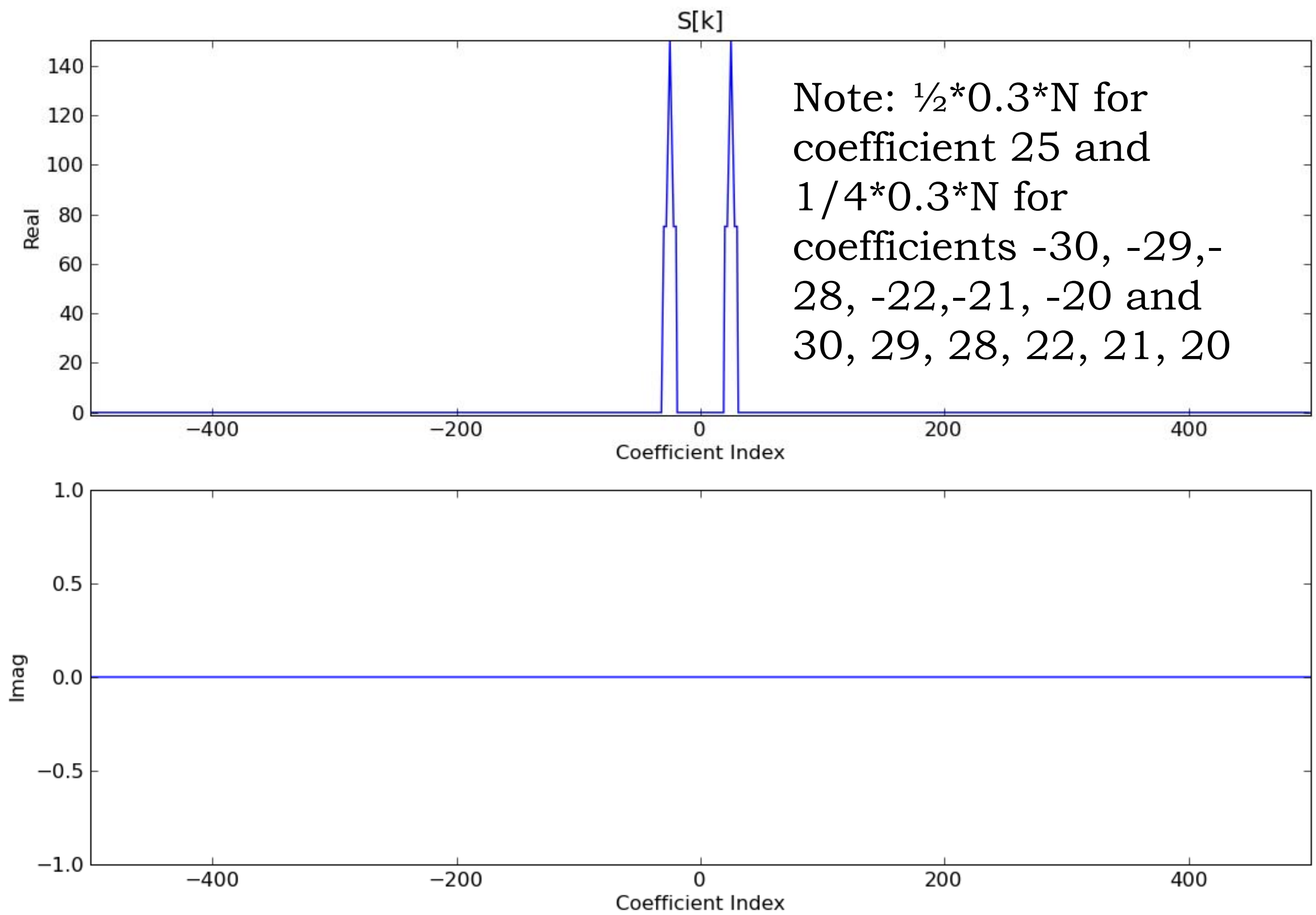
Plot of s[n]



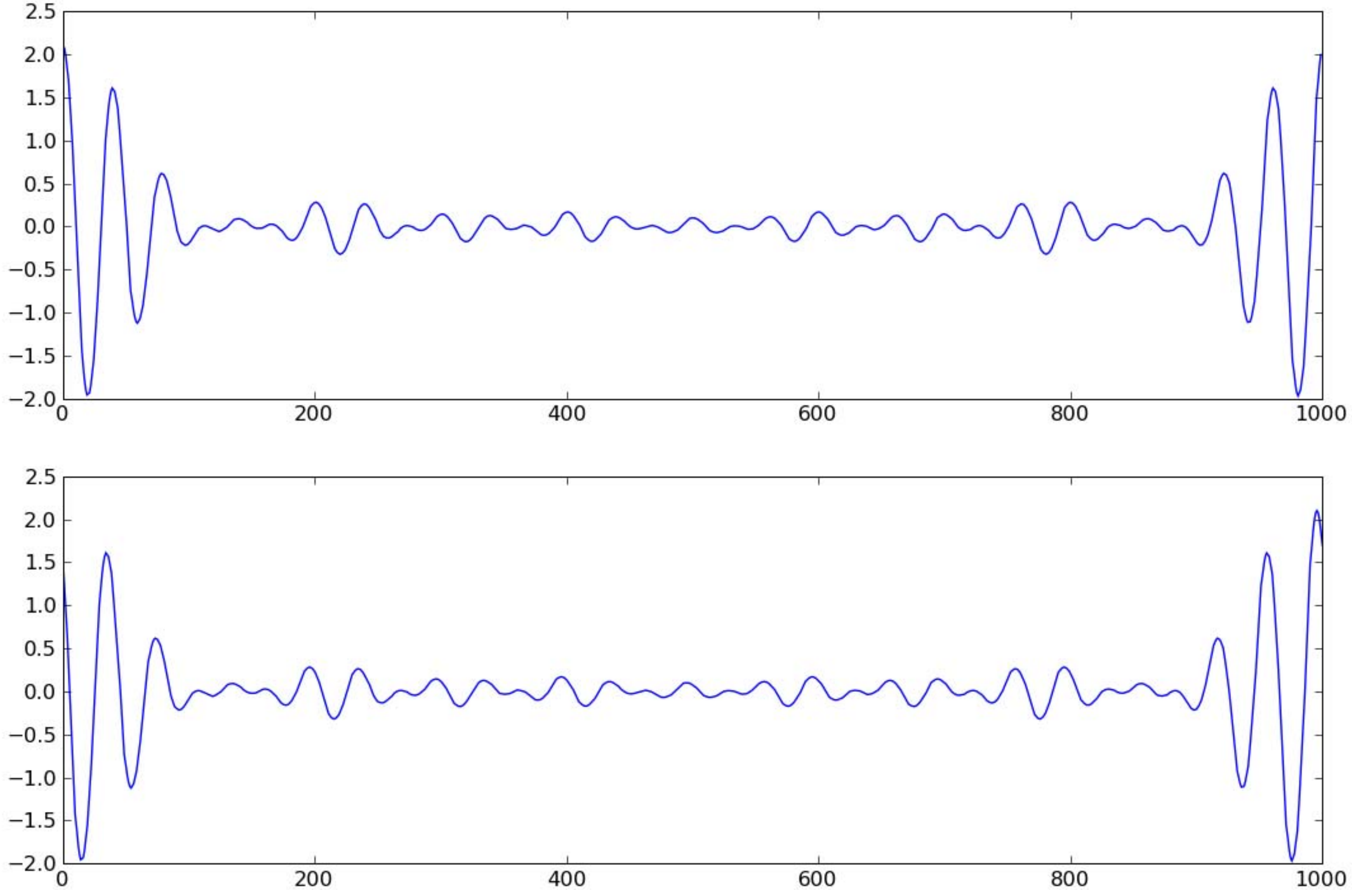
Plot of DFT Coefficients for s[n]



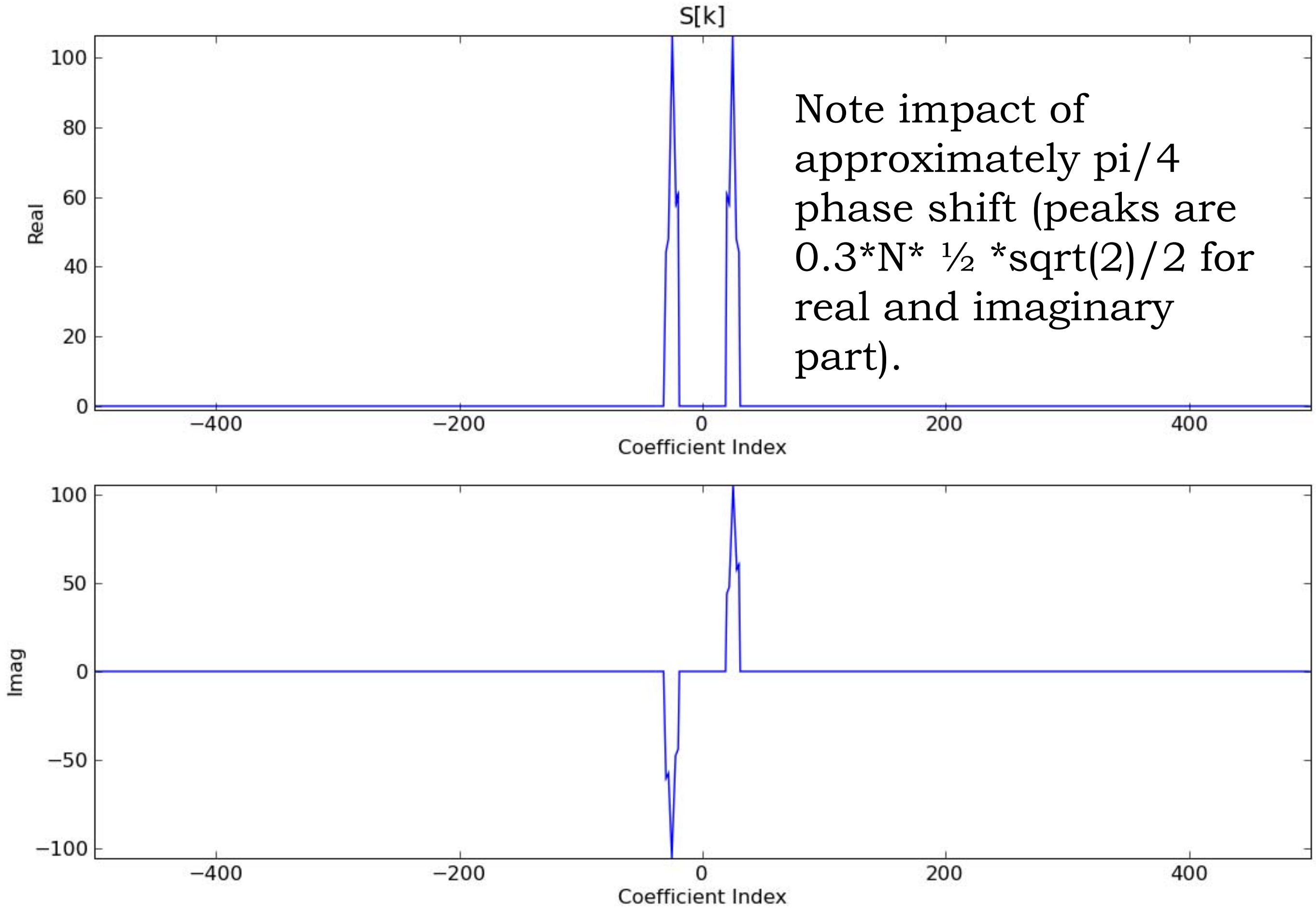
Cos25 Omega_1 n modulated s[n]



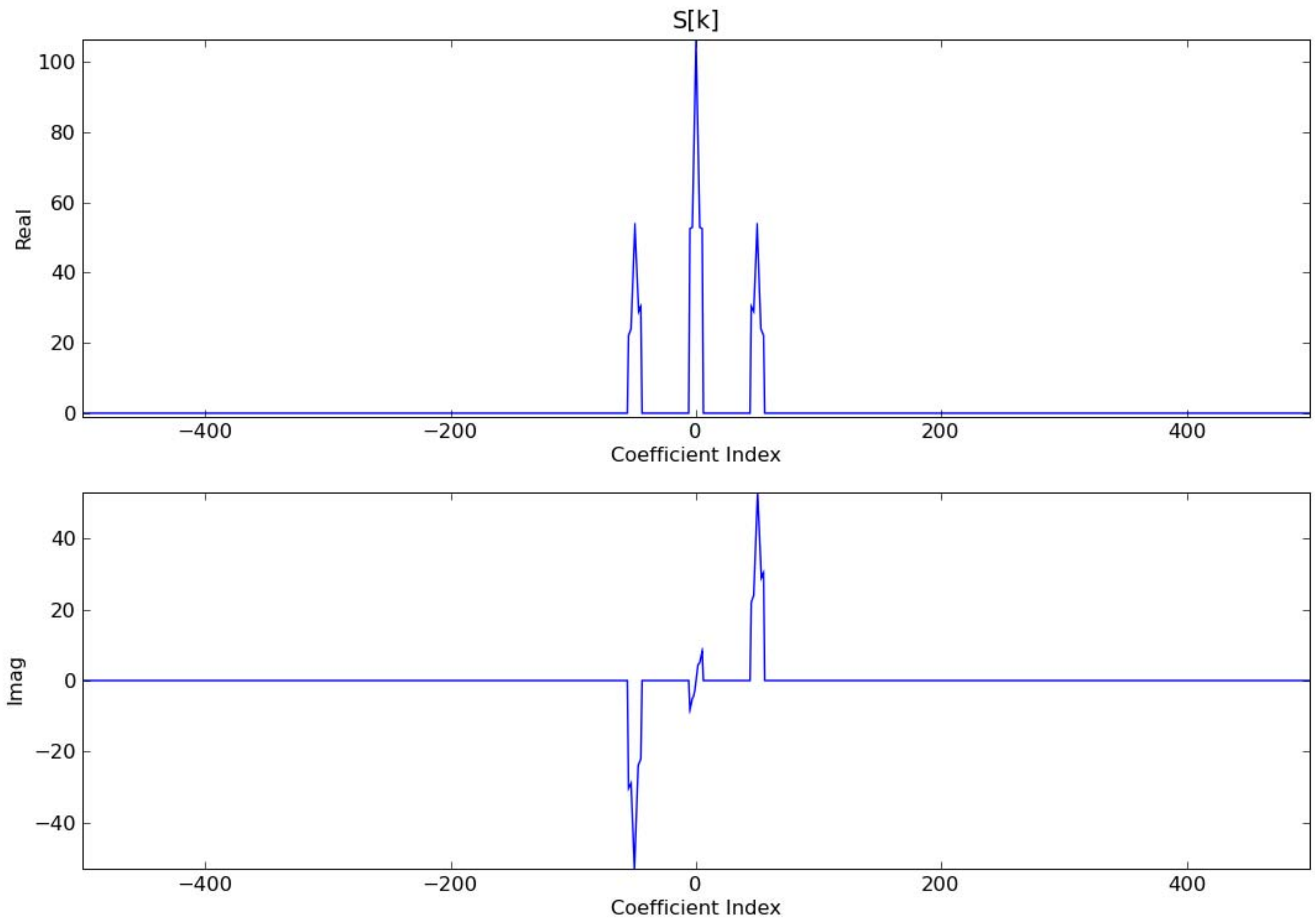
Plots of modulated s[n] and s[n-5] (note periodicity!)



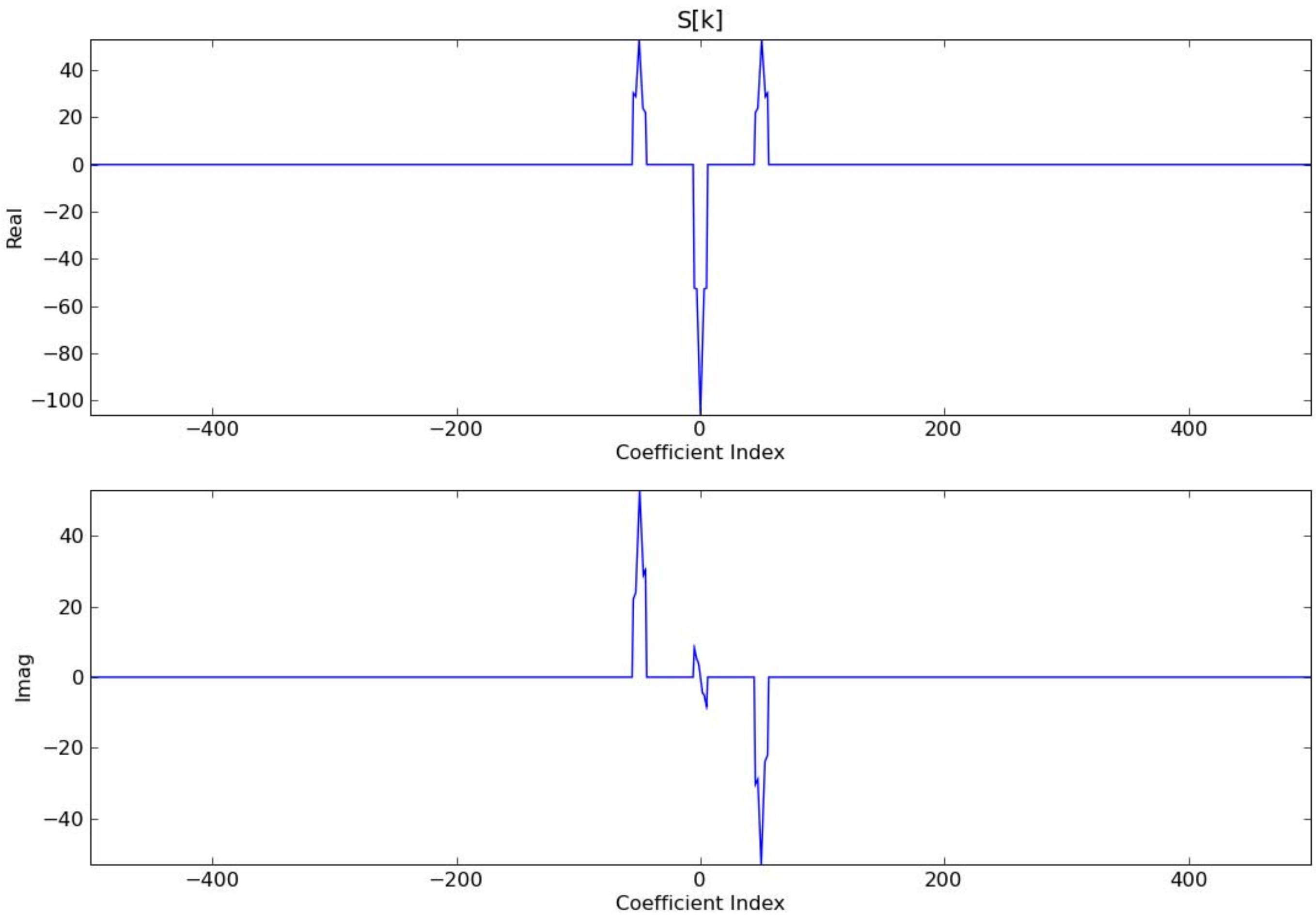
Cos25 Omega_1 n modulated s[n] after 5 sample delay



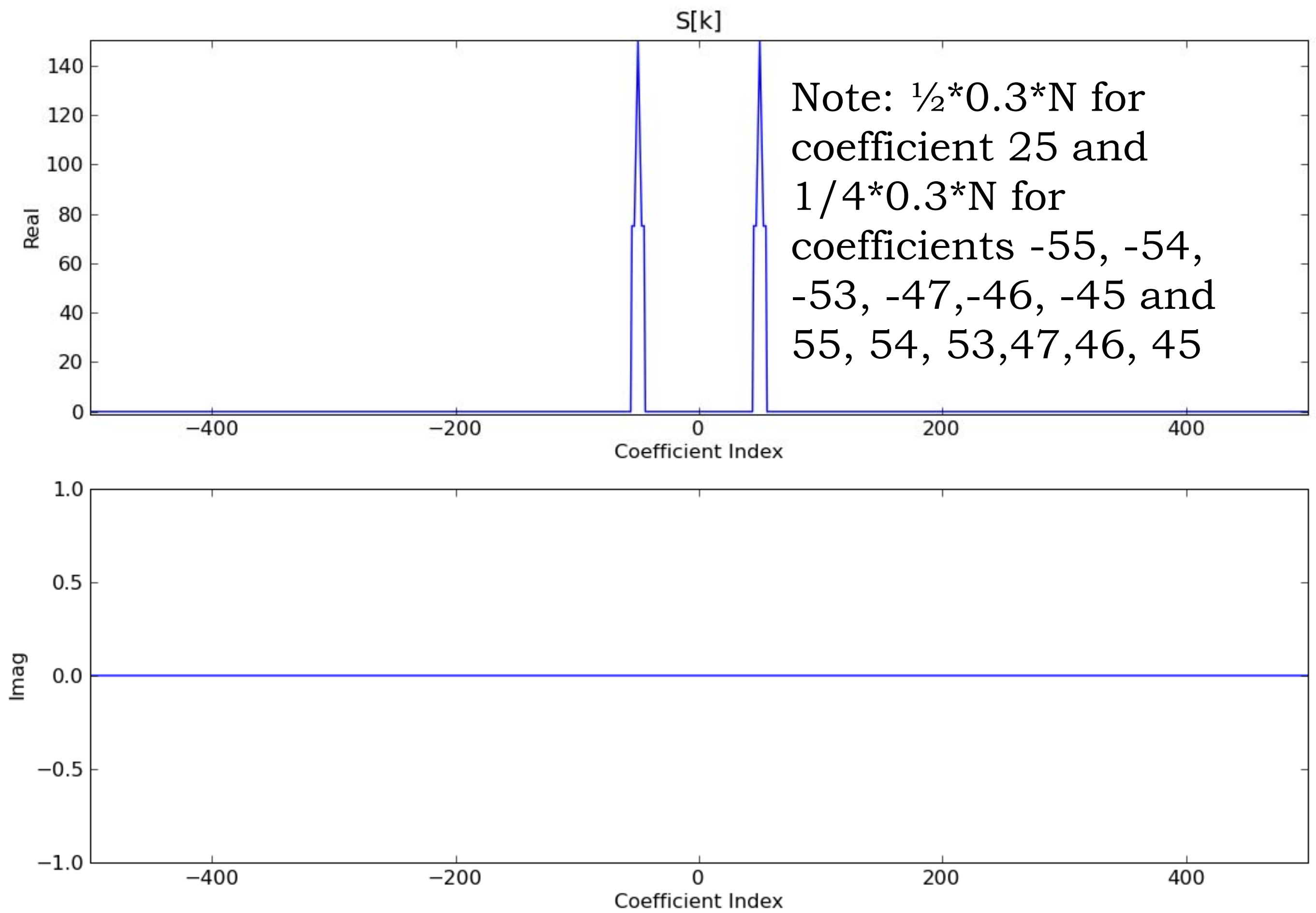
Cos25 Omega_1 n demod after delay



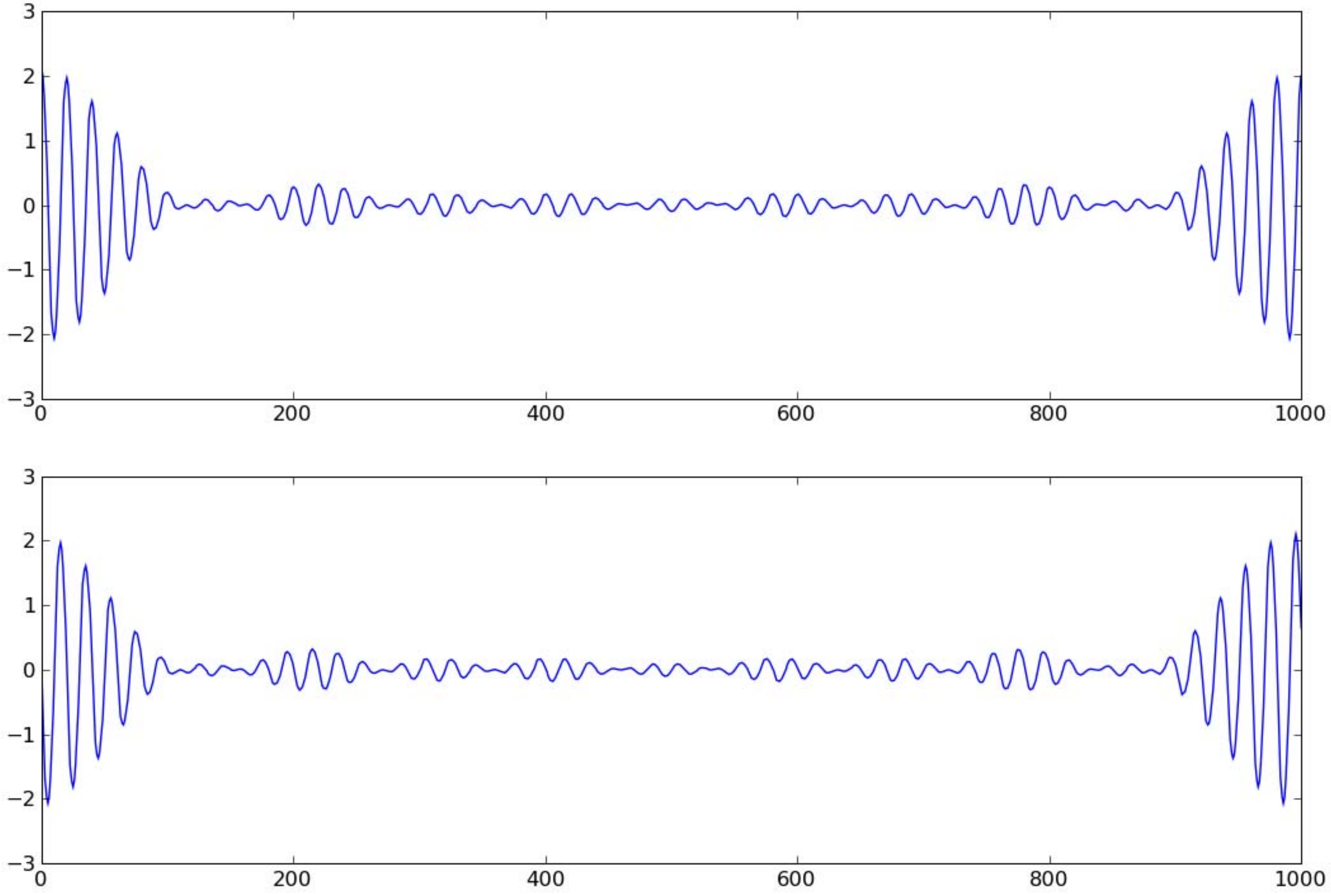
Sin 25 Omega_1 n demod after delay



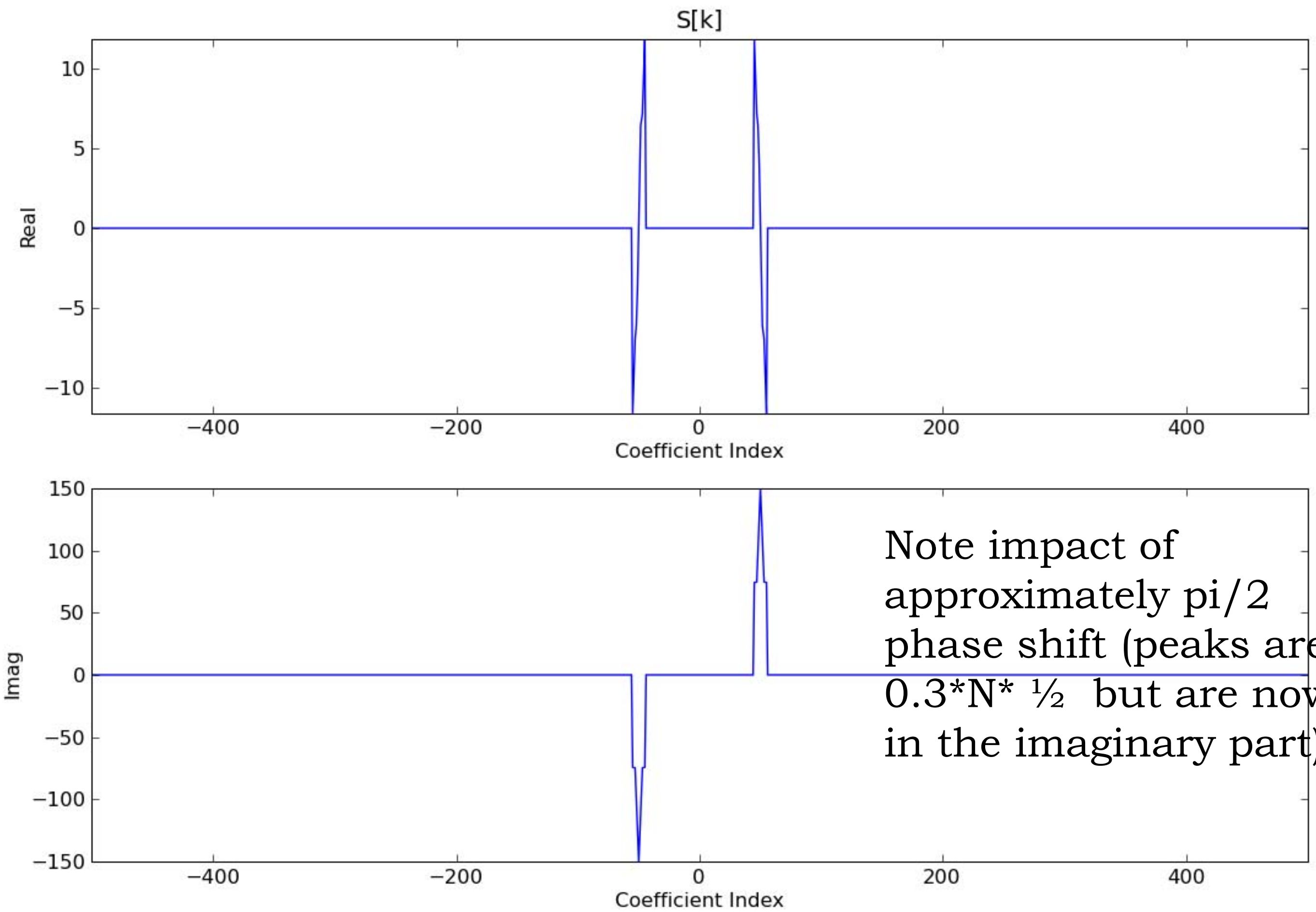
Cos50 Omega_1 n modulated s[n]



Plots of Cos 50 Omega_1 n modulated s[n] and s[n-5] (note periodicity!)

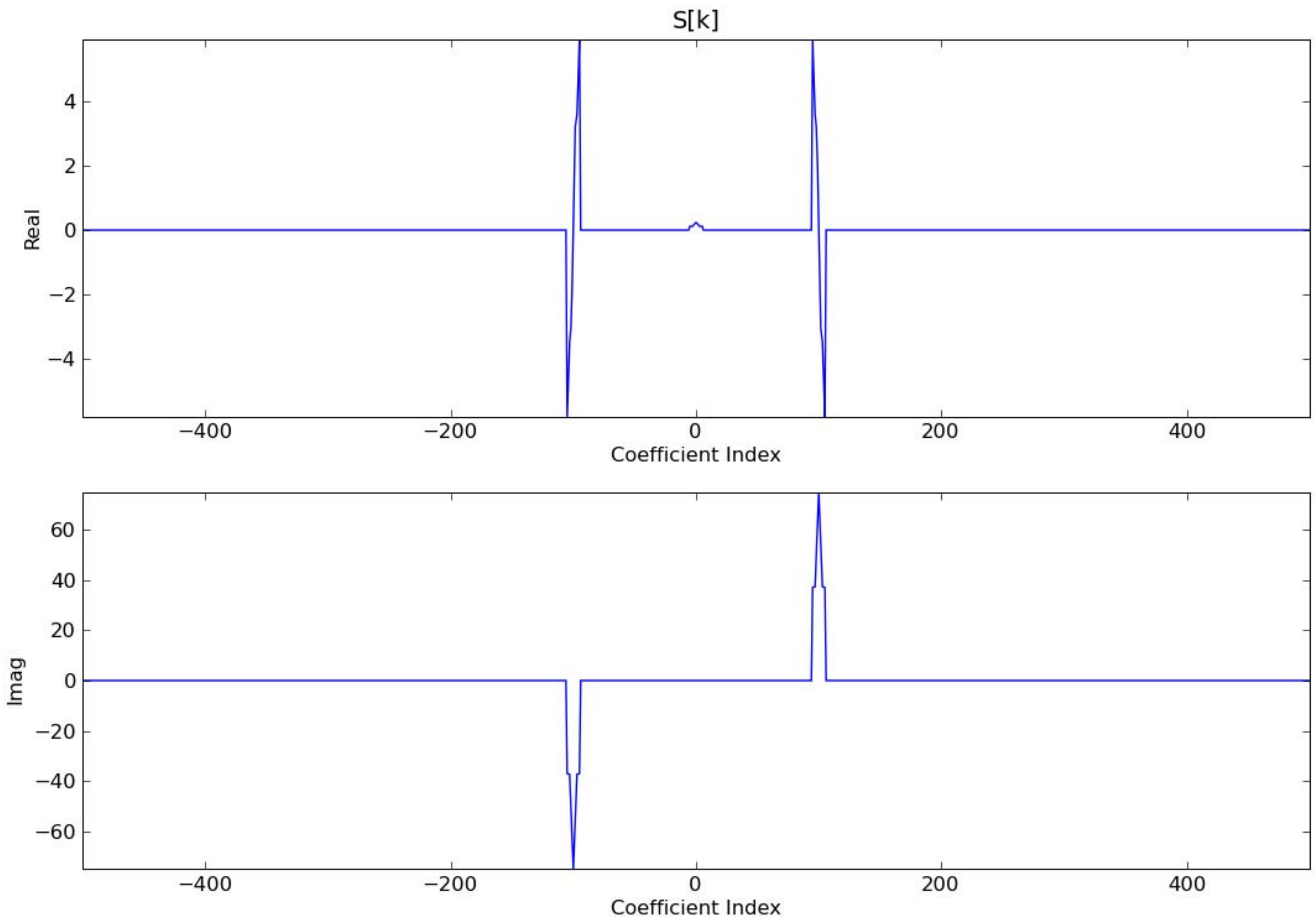


Cos50 Omega_1 n modulation after 5 sample delay

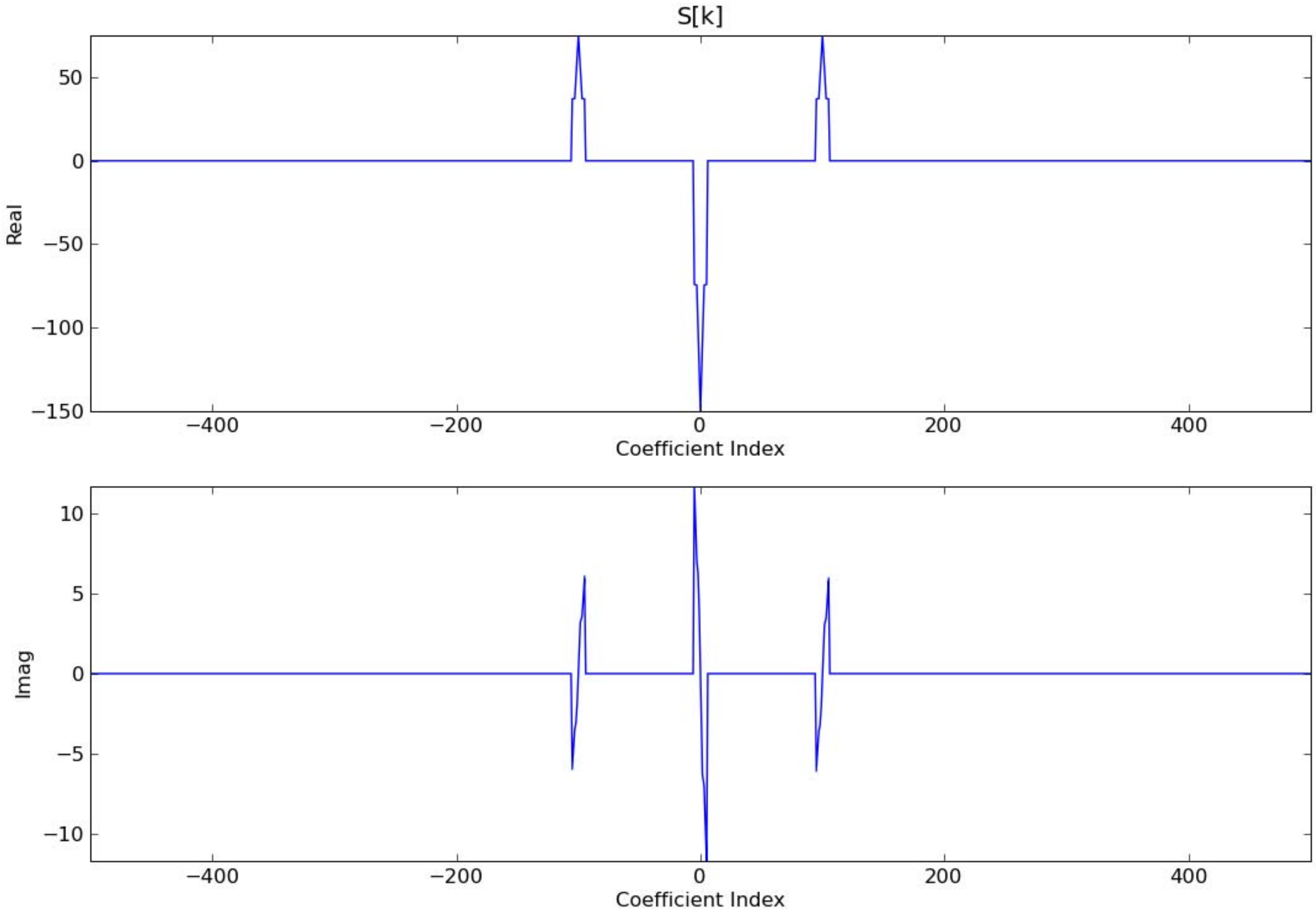


Note impact of approximately pi/2 phase shift (peaks are 0.3*N* ½ but are now in the imaginary part).

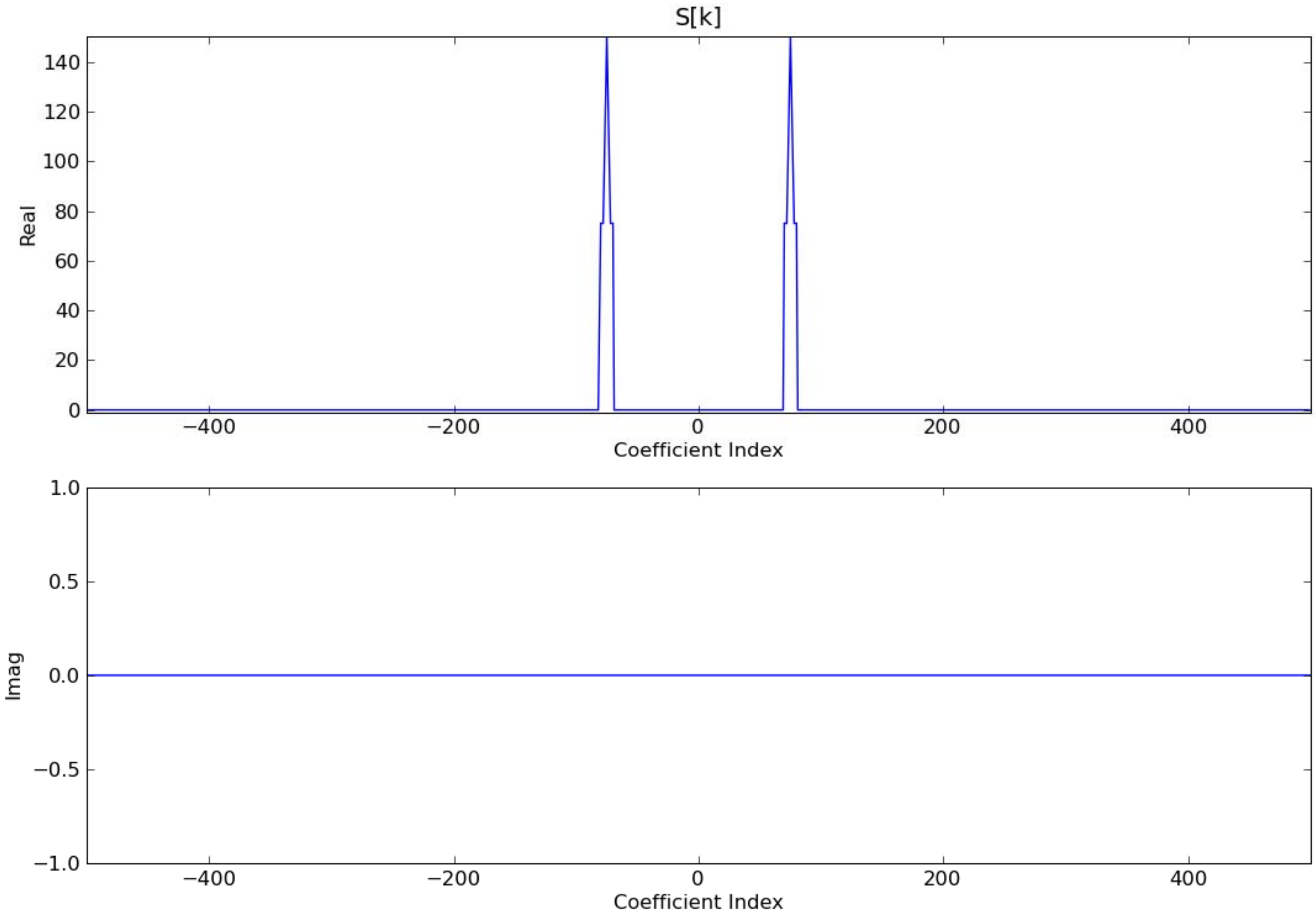
Cos50 Omega_1 n demod after delay



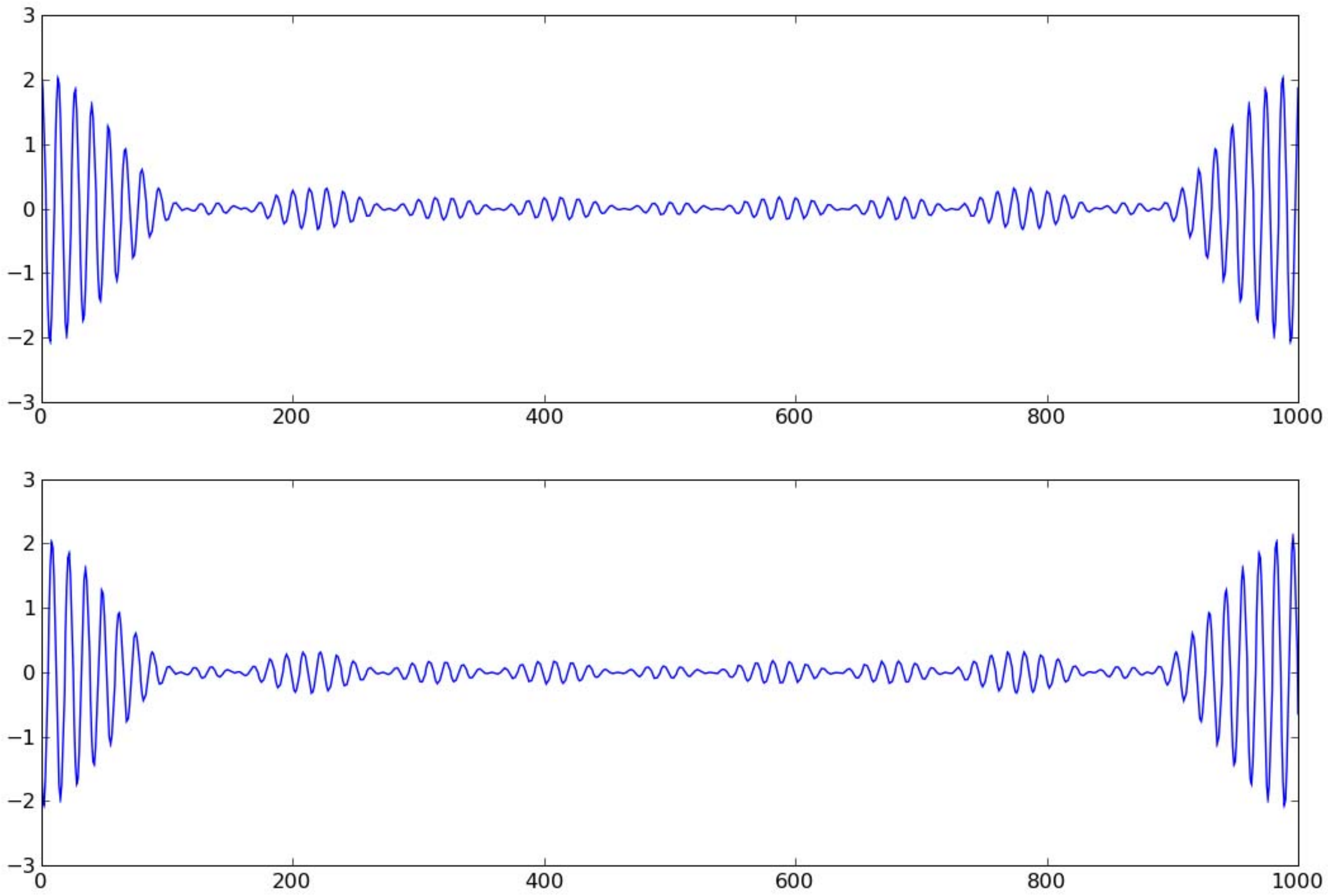
Sin 50 Omega_1 n demod after delay



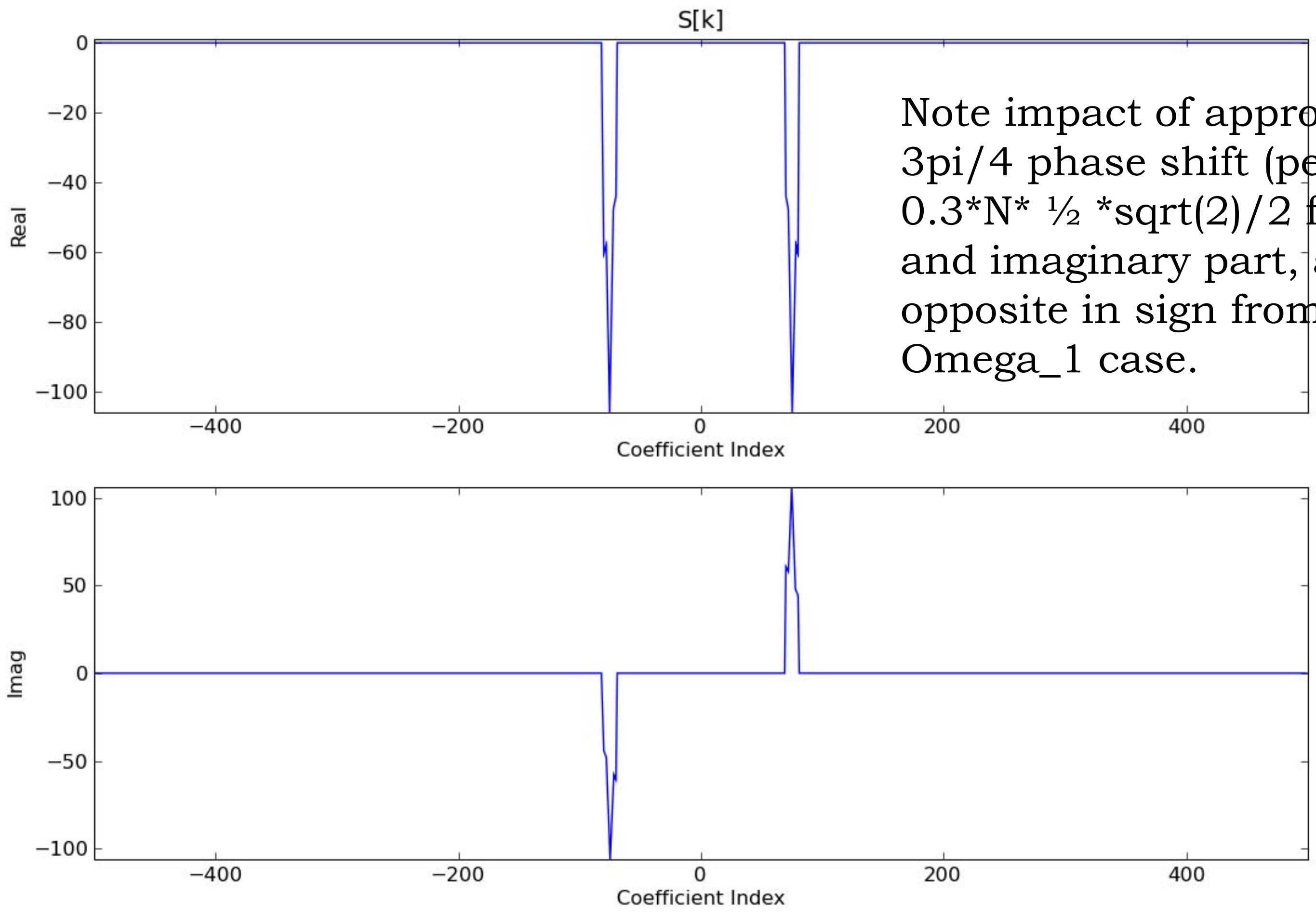
Cos75 Omega_1 n modulated s[n]



Plots of s[n] and s[n-5] (note periodicity!)

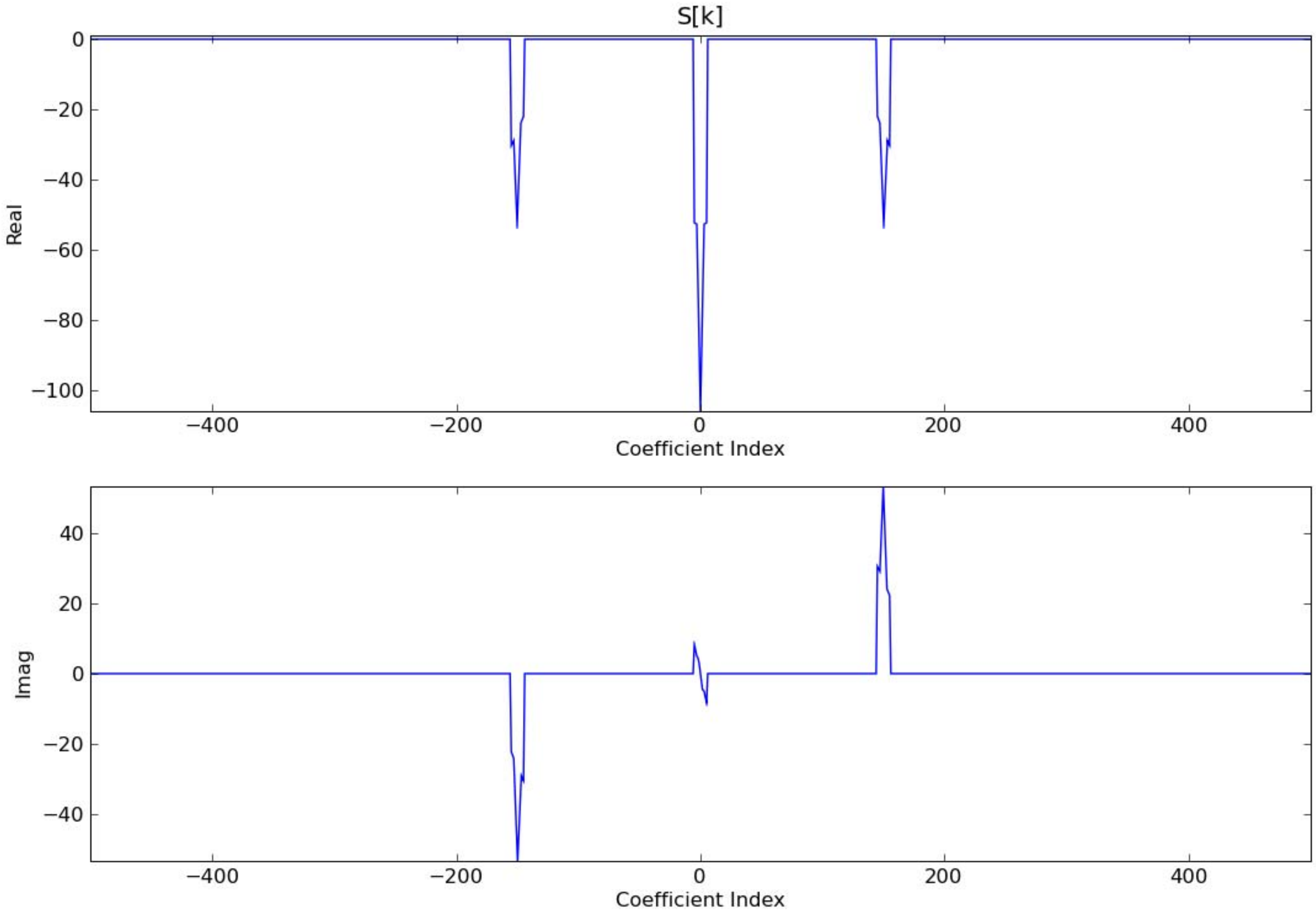


Cos 75 Omega_1 n modulated s[n] after 5 sample delay

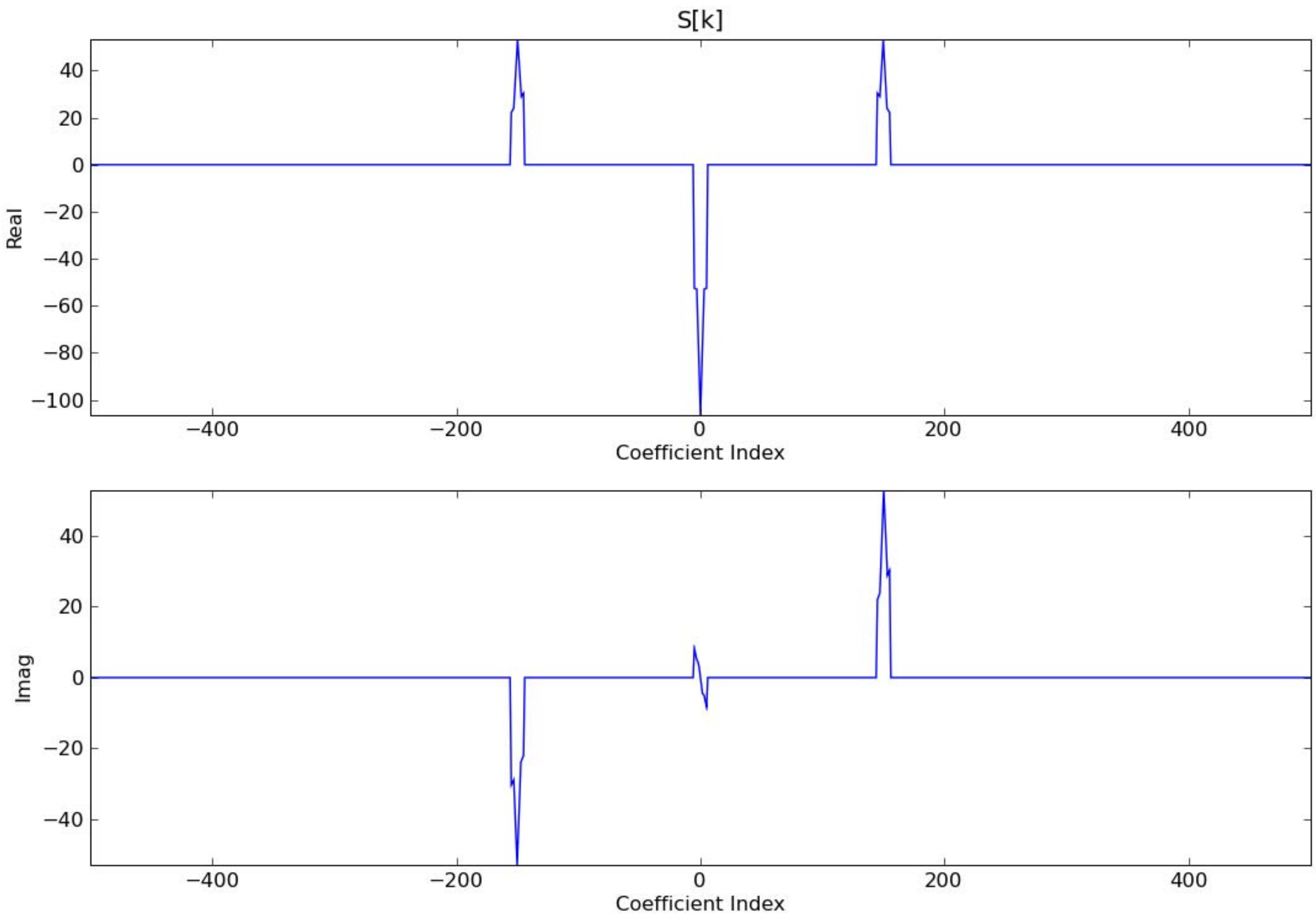


Note impact of approximately 3pi/4 phase shift (peaks are 0.3*N* ½ *sqrt(2)/2 for real and imaginary part, and opposite in sign from 25 Omega_1 case.

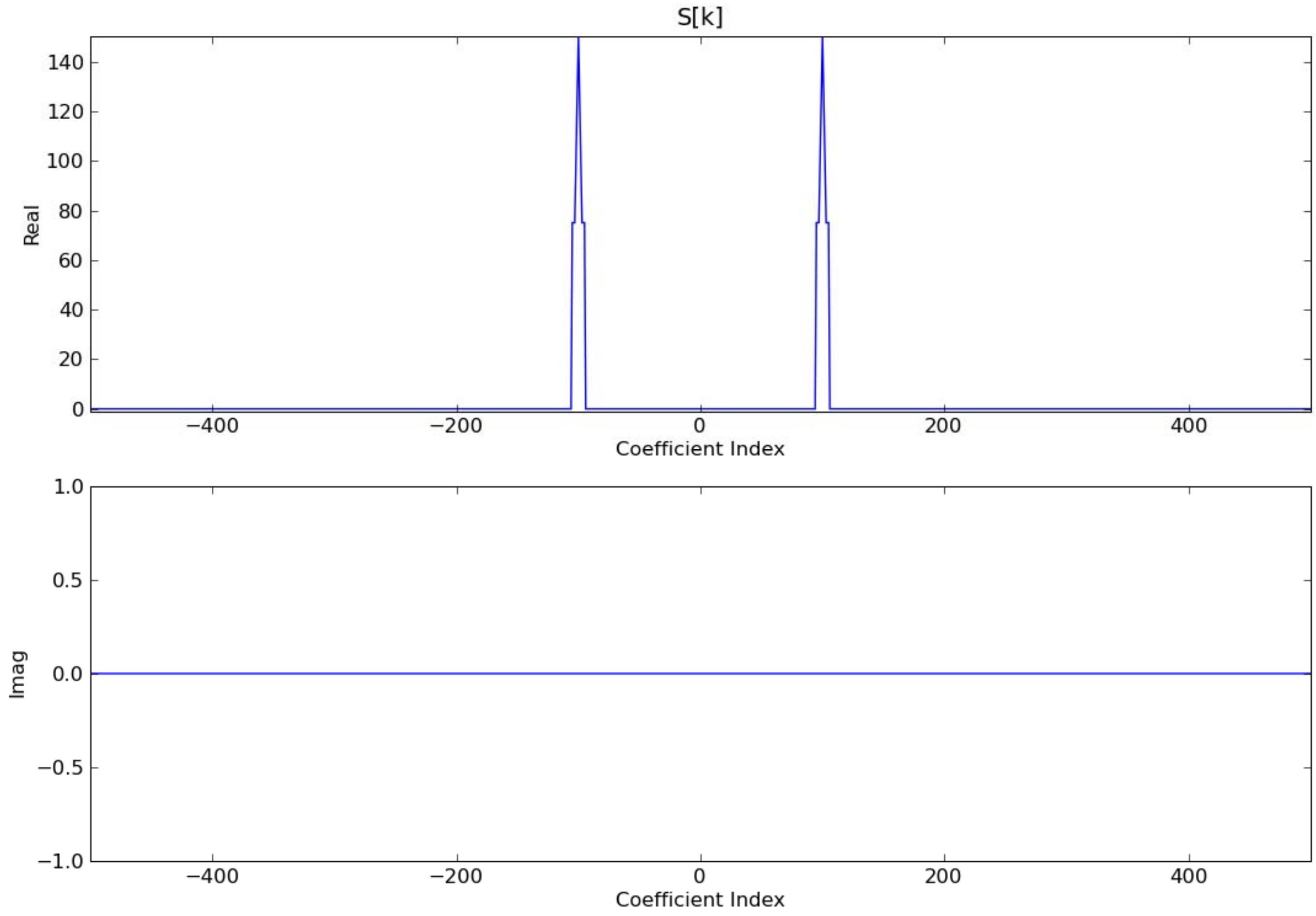
Cos75 Omega_1 n demod after delay



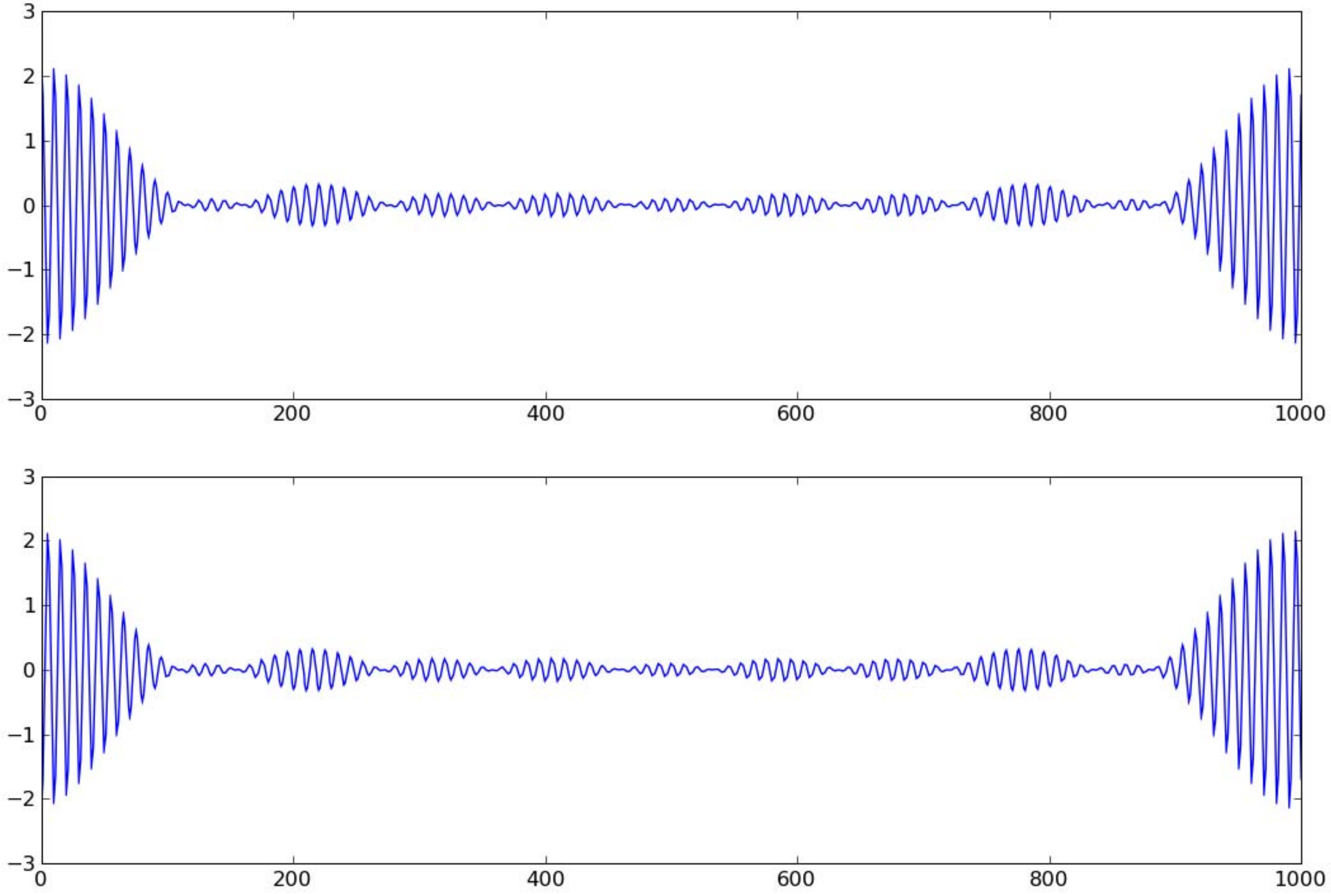
Sin 75 Omega_1 n demod after delay



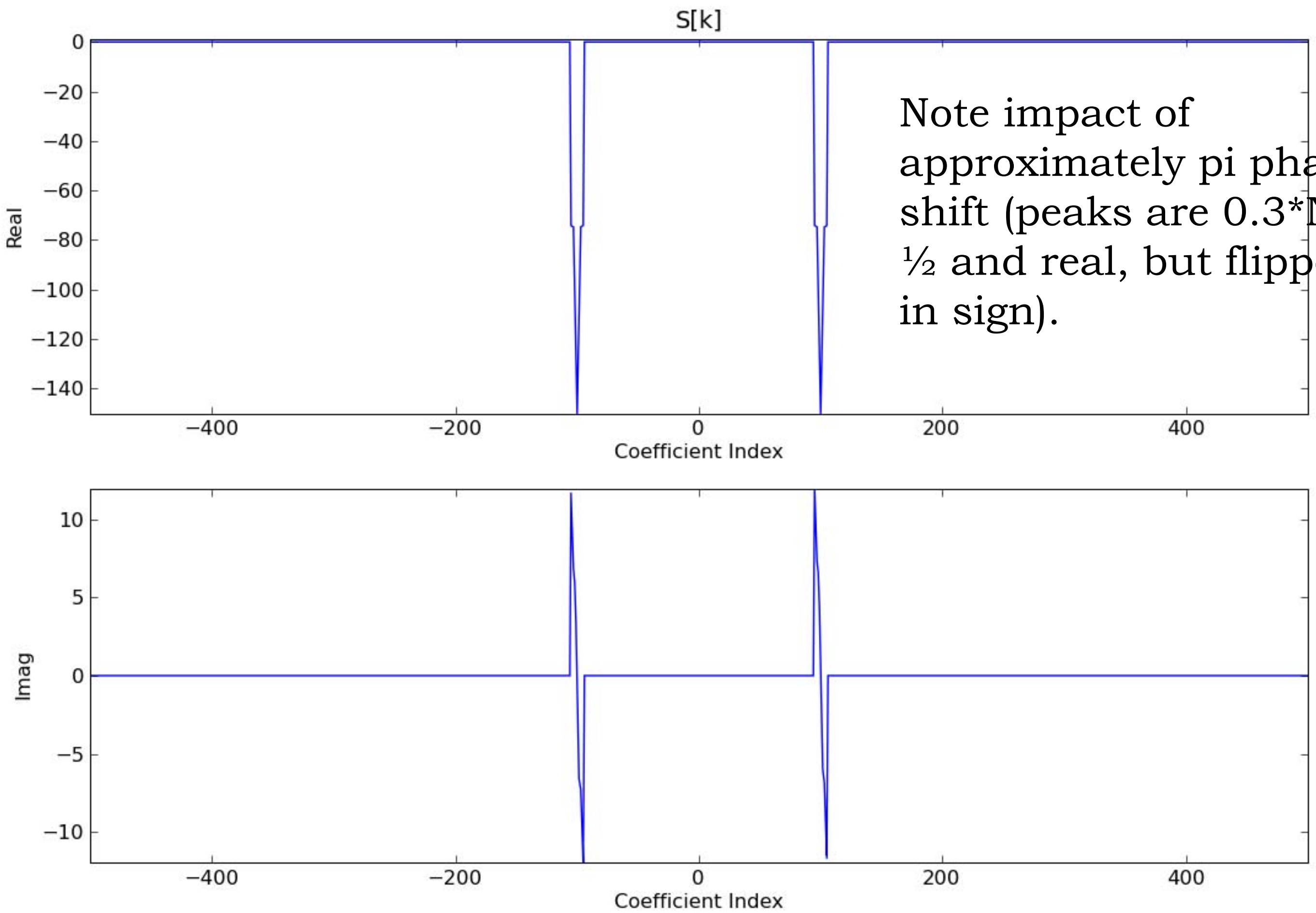
Cos100 Omega_1 n modulation



Plots of s[n] and s[n-5] (note periodicity!)

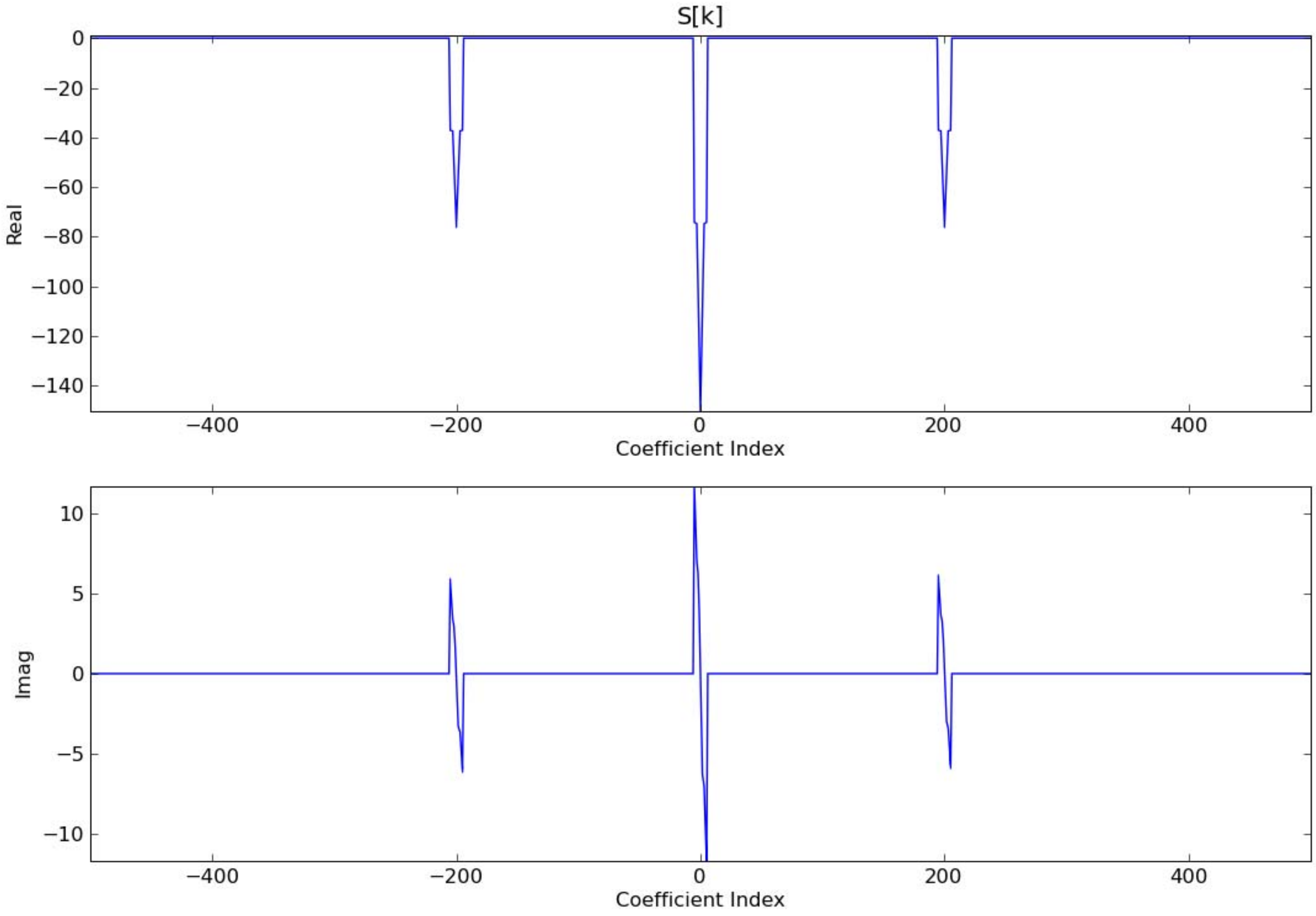


Cos 100 Omega_1 n modulation after 5 sample delay



Note impact of approximately pi phase shift (peaks are 0.3*N* ½ and real, but flipped in sign).

Cos100 Omega_1 n demod after delay



Sin 100 Omega_1 n demod after delay