Introduction to IQ-demodulation of RF-data

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1 Introduction

1.1 Abstract

This document gives an introduction to the IQ-demodulation format of the RF-data stored from the Vingmed System Five. The document is intended for users of the RF options on the System Five.

Note that the information given is simplified to present a comprehensive functional overview of the topic covered, and might not reveal the actual details of the system in full.

1.2 Definitions/Abbreviations/Nomenclature

RF	Radio Frequency. The term “RF data” is commonly used to denote unprocessed data
IQ	In-phase Quadrature. Used to denote the complex format on which the RF data is stored from the System Five. The IQ demodulation is also sometimes named Base-band demodulation, Quadrature demodulation, Complex demodulation etc.
FIR	Finite Impulse Response
FFT	Fast Fourier Transform
LP	Low pass
BP	Band pass
A/D	Analog to digital
SNR	Signal to Noise Ratio
DSP	Digital Signal Processor

1.3 Referenced Documents

EchoMAT User Manual (FA292640)

2 RF signal

RF is short for Radio Frequency. In communication engineering, The term "RF-signals" is used to denote signals containing frequency information in the frequency bands used for radio communication. The term RF has been adopted by the ultrasound industry, where it is used as a standard notation for unprocessed data, where the frequency information is intact. In ultrasound imaging, the received RF signal is the output of the beamformer:

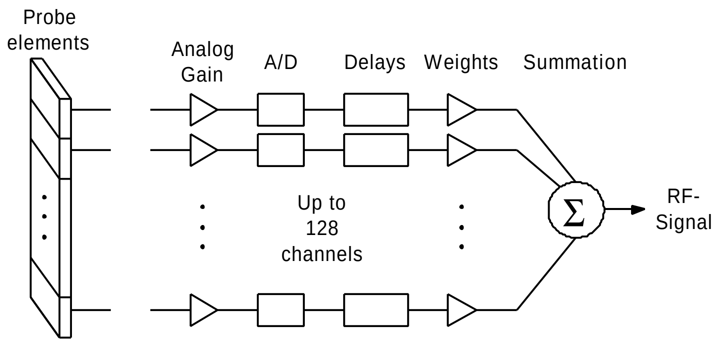

Figure 1. Beamformer of System Five (simplified).

Modern ultrasound probes (linear- and phased array transducers) consist of several rectangular elements of piezoelectric material. The piezoelectric elements are capable of converting varying pressure to electrical signals.

At receive, the analog signal from each individual probe element is first amplified (Analog Gain) to ensure optimal use of the dynamic range of the Analog to Digital (A/D) converters. The analog gain factor varies with depth to amplify signals from deep regions most (TGC, Time Gain Compensation).

The sampled signals are delayed individually to focus the beam to a certain depth and direction. The delayed signals are weighted to obtain the desired apodization and beam profile. Finally, the weighted and delayed signals are summed in phase, and this is the RF signal.

The sampling rate of the RF signal at the output of the beamformer is 20 MHz, and the resolution is 20 bits. The sampling rate of the A/D converters is 40 MHz with a resolution of 12 bits. 7 bits are added by summing 128 channels ($128=2^7$) and the last bit is added when the sampling rate is reduced from 40 to 20 MHz.

It is also important to note that when acquiring RF-data on the System Five, the Analog Gain and weights applied to the individual channels are not affected by the Gain knob and TGC sliders on the front panel. But the overall gain is adjusted if transmit power is changed.

3 Sampling of band-pass signals

3.1 Introduction

The Nyquist sampling theorem states that to get a unique representation of the frequency content of a signal, the signal must be sampled at a rate twice the frequency of the highest frequency component of the signal.

The received RF-signal from an ultrasound transducer is a band-pass signal. The relative bandwidth of the transducer is usually less than 100%, typically 50-70%. The percentage is the ratio of the bandwidth to the center frequency of the transducer. The bandwidth is the frequency range where the sensitivity of the transducer is above a certain level. For one-way response, this level is usually defined as 3 dB below the level at the most sensitive frequency.

Figure 2 illustrates the frequency spectrum of the received RF signal from a 2.5 MHz probe with bandwidth B less than 100% of the center frequency. The RF signal is real-valued, which means that the spectrum for the negative frequencies is a mirrored replica of the spectrum for the positive frequencies. The sampling frequency (f_s) is 20 MHz, meaning that the signal contain a unique representation of frequencies between 0 and half the sampling rate (10 MHz). The upper limit is usually referred to as the Nyquist limit, or the Nyquist frequency.

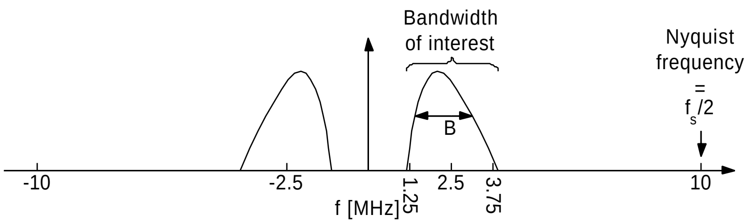

Figure 2. Band pass signal from an ultrasound transducer

In our example, the transducer is sensitive in a band less than 2.5 MHz wide and centered around 2.5 MHz. This means that all frequency content of interest lies between 1.25 and 3.75 MHz. Sampling at 20 MHz (as done in the System Five), will therefore be an "overkill" in terms of amount of data to be transferred and stored. Without loss of information, the sampling rate could be reduced to about 7.5 MHz. Because the sampling rate in the System Five is fixed in hardware, this is not easy to do. One could decimate the RF-signal by a factor 2, and achieve a sampling frequency of 10 MHz, which would be an improvement, but not optimal.

A smarter approach for reducing the amount of data without loosing essential information is to apply a complex base-band modulation technique with bandwidth reduction known as IQ-demodulation.

Another issue is, that for suppression of quantization noise during analog to digital conversion, it is fortunate to keep the sampling rate as high as possible to obtain a better Signal-to-Noise-Ratio (SNR).

3.2 IQ-demodulation

The IQ-demodulation consists of 3 main steps:

- Down-mixing
- Low-pass filtering
- Decimation

The multiplication with the square root of two is included to preserve the energy in the signal (explained in section 3.4.)

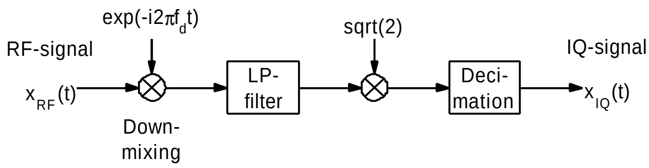

Figure 3. IQ demodulation

3.3 Down-mixing

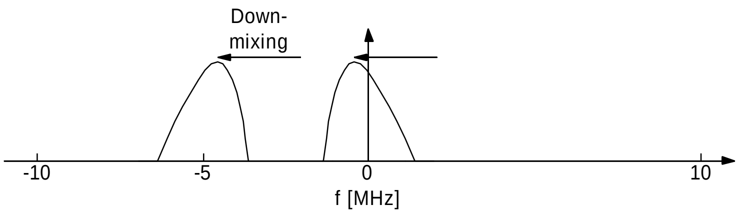

Figure 4. Down-mixing

The real valued RF-signal is multiplied ("mixed") with a complex sinusoid signal:

$$\mathbf{x_{IQ}(t)=x_{RF}(t)\cdot exp(-i2\pi f_{Demod}\cdot t)}$$

where **t** is the time along the beam. The relationship between time and distance **r** is: **t=2*r/c.** **c** is the velocity of sound in human tissue (1540 m/s). The resulting signal $\mathbf{x_{IQ}}(t)$ is complex.

Looking at the signal before and after the mixing explains the name "down-mixing". The frequency spectrum is actually moved down (to the left) in the frequency plane. After the down mixing, the resulting signal is complex, and the frequency spectrum is no longer symmetric about zero.

Because of the relationship between complex exponential functions and sine and cosine functions,

$$\mathbf{exp(-i\omega t)=cos(-\omega t)+i\cdot sin(-\omega t)=cos(\omega t)-i\cdot sin(\omega t)}$$

the down-mixing can be thought of as mixing the RF-signal with two sinusoid signals with 90° phase difference:

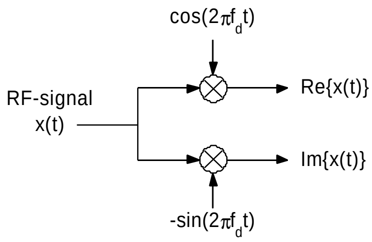

Figure 5. Quadrature mixing with sinusoid signals

If the demodulation had to be done in hardware, this would be the approach to use. But in the System Five, the demodulation is done in software using Digital Signal Processors (DSPs), and the complex exponential is used instead.

The down mixing operation multiplies the RF-signal with a complex vector with unit length, and the energy content of the signal is not changed.

3.4 Low-pass filtering

After down mixing, the complex signal is low-pass filtered to remove the negative frequency spectrum and noise outside the desired bandwidth:

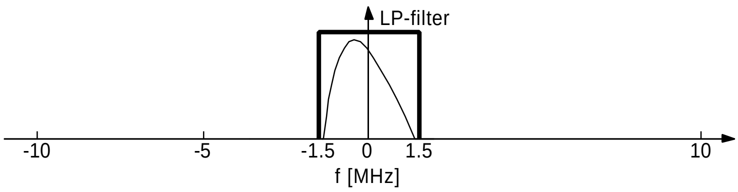

Figure 6. Low-pass filter

The low-pass filter on the complex signal can be thought of as a filter applied to the real and imaginary part separately. With careful choice of low-pass filter, the remaining signal becomes weak for frequencies outside the pass-band for both components. In our example, we chose a low-pass filter with rectangular frequency response and cut-off frequency 1.5 MHz. The rectangular frequency response is approximated by using a FIR filter with Hamming weighted sinc coefficients.

The filter removes the frequencies stemming from the negative spectrum of the real RF signal, and the filter removes approximately half of the energy in the signal. In order to preserve the energy in the signal, the complex signal should be multiplied by the square root of 2.

3.5 Decimation

The Nyquist theorem then states that the sampling frequency can be reduced to twice the cut-off frequency of the filter without loss of information. Because we have a complex signal, the bandwidth of the signal equals the complex sampling rate (the complex signal doesn't have an ambiguity between positive and negative frequencies).

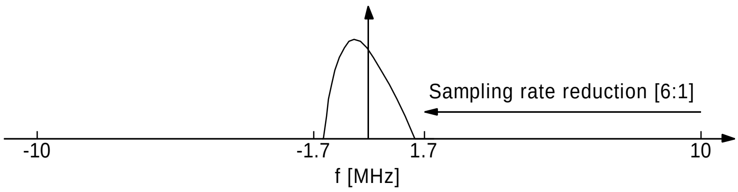

Figure 7. Decimation

This means that we can reduce the sampling frequency from 20 MHz to 3.33 MHz. 3.33 is the smallest integer fraction of 20 which is larger than twice the filter cut-off frequency. The sampling rate is reduced by a factor 6. In practice, the desired decimation is obtained by keeping every 6th sample and throwing away the rest.

The IQ demodulation preserves the information content in the Band-pass signal, and the original RF-signal can be reconstructed from the IQ-signal.

The next chapter explains how to reconstruct the RF-signal from the IQ-signal.

The IQ data is written to EchoPAC files with 16 bit signed integer representation of the I and Q components, giving a total of 32 bits for representation of each sample.

4 Reconstruction of RF-data from IQ-data

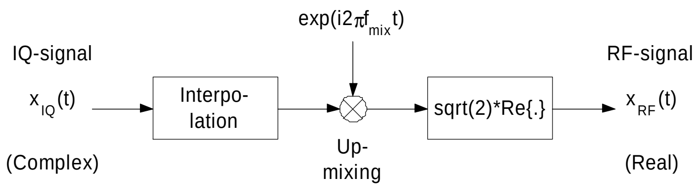

Figure 8. Reconstruction of RF signal from IQ signal

The reconstruction of RF-data from IQ-data is straightforward. It is a reversal of the complex demodulation in the previous section. The decimation is reversed by interpolation. The low-pass filter cannot be reversed, but should be chosen without loss of information in the first place. The down mixing is reversed by up mixing. At last, the RF-signal is found by taking the real-value of the complex up-mixed signal.

4.1 Interpolation

The first step of the reconstruction, is to increase the sampling rate back to the rate it had prior to the decimation:

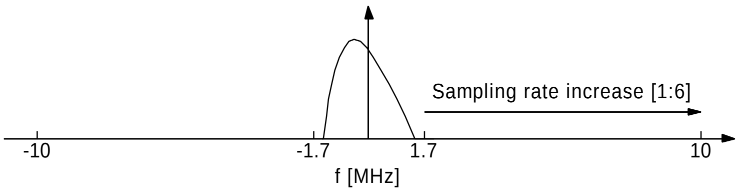

Figure 9. Interpolation

Most signal processing textbooks cover the topic of interpolation/sampling rate conversion, so the topic will not be covered in deep detail here. The process is divided into two main steps, zero-padding and low-pass filtering.

4.2 Zero-padding

Zero padding means inserting zeroes in the signal to increase sampling rate. In our case, we insert 5 zeroes between each signal sample. In the frequency domain, this will be seen as 5 new replicas of the low-pass spectrum, spaced with the original sampling frequency:

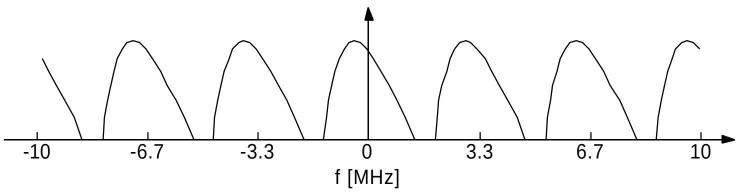

Figure 10. Zero-padding

4.3 Low-pass filter

After the insertion of zeroes, the duplicate spectra must be removed. This is done with low-pass filter.
The filter should be chosen with care, as it is important that the filter doesn't change the original data points. A FIR-filter with sinc coefficients serves the purpose.

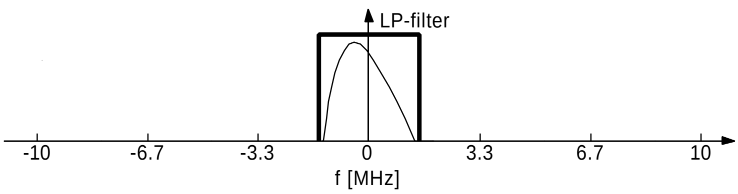

Figure 11. Interpolation LP filter

4.3.1 Interpolation factor N_I

The interpolation factor N_I depends on the desired output sampling frequency, and the radial sampling frequency of the IQ-signal:

$$N_I = \mathrm{round}(f_{S\_des} / f_{S\_IQ})$$

$\mathbf{f_{S\_des}}$ = Desired sampling frequency; suggestion 20MHz
$\mathbf{f_{S\_IQ}}$ = Radial sampling frequency of the IQ-signal =c/(2*DepthIncrement), c=1540m/s

The IQ-signal stored from the System Five is decimated from 20MHz by an integer factor (typically 3 or higher), so the fraction f_{S_des}/f_{S_IQ} should always be an integer. However, because of finite numerical representation, the fraction should be rounded off to the nearest integer.

4.3.2 Cut-off frequency

The complex IQ-signal stored from the RF applications on the System Five is always band-limited with a double-sided bandwidth less than the radial sampling frequency of the IQ-signal:

$\mathbf{B_{IQ} < f_{S\_IQ}}$

This means that the I and Q components are band-limited to less than half the sampling frequency:

$\mathbf{B_I < 0.5 * f_{S\_IQ}}$ and $\mathbf{B_Q < 0.5 * f_{S\_IQ}}$

The interpolation filter operates separately on the I and Q components of the IQ-signal. Thus, the cut-off frequency of the interpolation filter should be set >= 0.5 f_{S_IQ}.

4.4 Up-mixing

To shift the frequency spectrum from the base-band and back to it's original band, the interpolated signal is up-mixed.

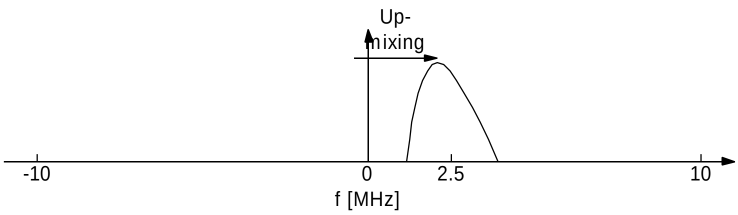

Figure 12. Up-mixing

Up-mixing is achieved by just multiplying the interpolated IQ-signal by the inverse of the complex exponential used for the down-mixing (note inverted sign in the exponent):

$$\mathbf{IQ_{up\text{-}mix}(r) = IQ(r) * exp(i2\pi f_{demod} * t(r)),}$$

Where:

$$\mathbf{t(r) = (StartDepth + (r * DepthIncrement / N_I)) / (2 * c))}$$

r	Sample number in radial direction **AFTER** interpolation
$\mathbf{f_{demod}}$	Demodulation frequency
$\mathbf{N_I}$	Interpolation factor
c	Velocity of sound in human tissue(1540 m/s)

StartDepth The distance from the transducer origin to the start of the IQ sector measured in meters. See EchoMAT manual for how to extract parameters from the EchoPAC file.

DepthIncrement Radial sampling interval measured in meters.

StartDepth might be omitted in the expression for **t(r)** because it only represents a constant phase shift applied to all samples. The factor 2 in the denominator of the fraction refers to the fact that the ultrasound pulse travels back and forth from the transducer to the reflecting target.

4.5 Real value

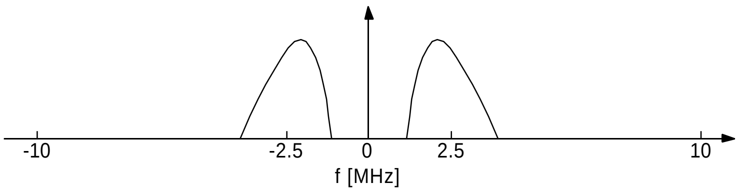

Figure 13. Real value extraction

Finally, the RF-signal is found by taking the real value of the up-mixed IQ-signal and multiply it by **sqrt(2)**:

RF(r)=sqrt(2)*Re{IQ$_{up\text{-}mix}$(r)}

The factor **sqrt(2)** is included to compensate for the loss of half the energy in the signal when taking the real value of the complex signal (the energy is assumed to be equally distributed between the real and complex parts). The resulting real signal has a symmetric frequency spectrum, as it had in the beginning.

5 IQ-data processing in Matlab

Readecho contains a few routines for processing and analysis of RF-data on IQ format. These routines are RECTFREQ, IQ2RF and IQSPECT. These routines require functions from the Matlab Signal Processing Toolbox. This toolbox must be purchased separately from your Matlab reseller.

5.1 Band-pass filtering of IQ data (RECTFREQ)

It is not necessary to convert the IQ data to RF data if you want to apply frequency filtering to the data. As an example, assume that we have a set of IQ data taken with the OctaveRF application on the 2.5 MHz Phased Array (FPA) probe. This application transmits at 1.67 MHz, and receives/demodulates a 3.33 MHz wide band centered about 2.5 MHz. This band contains both the fundamental frequency (1.67 MHz) and the second harmonic frequency (3.33 MHz). The frequency spectrum from the OctaveRF application on the FPA 2.5 probe is illustrated in Figure 14.

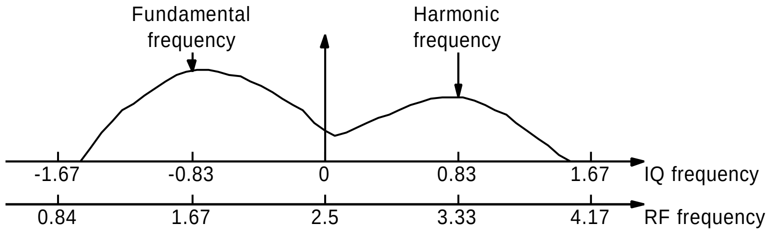

Figure 14. Frequency spectrum, OctaveRF on the FPA 2.5 probe

In the figure, the spectrum is shown with two frequency axes. The IQ frequency axis indicates the frequencies of the spectrum of the IQ signal. The lower axis indicates the true frequencies from the RF signal. The IQ axis is shifted 2.5 MHz to the left relative to the RF axis. 2.5 MHz equals the demodulation frequency.

If we want to filter out the second harmonic frequency band, we first down-mix the IQ signal to get the second harmonic frequency to the zero frequency:

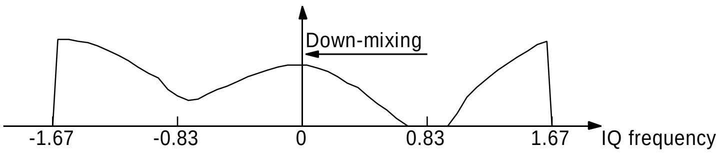

Figure 15. Down mixing

Observe that the down-mixing will wrap the lower end of the spectrum into the upper end.

Then we apply a low pass filter with cutoff frequency 0.5 MHz, giving a double sided bandwidth of 1 MHz:

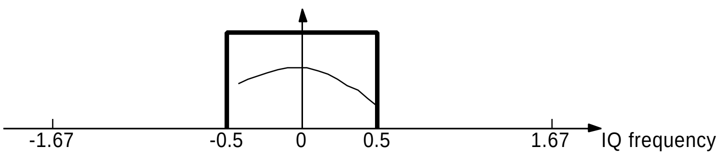

Figure 16. Rectangular low pass filter.

Finally, the signal is up-mixed to its original position:

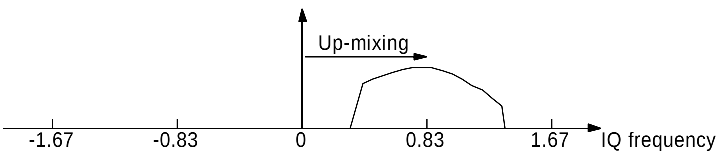

Figure 17. Up-mixing.

The resulting signal becomes a pure harmonic signal.

The routine RECTFREQ (in the READECHO library) performs the filtering described in this section, using a rectangular frequency response low pass filter. The rectangular filter is approximated by a FIR filter with Hamming weighted Sinc coefficients. The RECTFREQ routine requires the SINC and HAMMING functions from the Matlab Signal Processing Toolbox.

The RECTFREQ function requires specification of filter order. The filter order defines the steepness of the filter at the cut-off frequencies, and the suppression of the stop-band. The filter order should be an even number in order to get a symmetric filter.

5.2 IQ to RF conversion (IQ2RF)

If you feel more comfortable working with true RF data than the complex demodulated IQ data, the routine IQ2RF will convert the IQ data to RF data as described in chapter 4. The IQ2RF routine requires the INTERP routine from the Matlab Signal Processing Toolbox.

5.3 Frequency spectrum estimation on IQ data (IQSPECT)

It is often desired to get an impression of the frequency content of the signal. The routine IQSPECT returns the power (=magnitude squared) spectrum of the signal. The spectrum is estimated by means of a FFT, and the input IQ data is Hamming weighted and zero-padded to the next length which equals a power of 2. If the input signal contains more than one beam (beams = columns in the input matrix), the FFT spectrum is computed separately for each column and averaged over all columns. The function returns the spectrum on linear or logarithmic (dB) scale, with a corresponding frequency axis. IQSPECT requires the function HAMMING from the Signal Processing Toolbox.