Bandwidth Sampling Data Acquisition with the Vantage System for High Frequency Transducers

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The Verasonics Vantage hardware is a high performance multi-channel data acquisition system that permits collection and transfer of large data sets to a host computer for real-time analysis. The system is designed to enable research into new modes of imaging and remote sensing using ultrasound, for medical and industrial applications. To accommodate large channel counts in a high density design, highly integrated Analog Front End (AFE) circuits are used. The digitizing rates are necessarily limited, and the Vantage system uses 14-bit ADCs (Analog to Digital Converters) with a maximum sampling rate of 62.5 MHz. Nevertheless, the Vantage system can be used with transducers whose operating band can extend up to 50 MHz, either by interleaving data from two consecutive acquisitions, or by using bandwidth sampling. This document briefly describes both approaches.

Signal Path Overview

The Verasonics Vantage receive signal path includes analog filtering and amplification prior to digitization and numerical filtering. The input includes low noise programmable gain amplifiers with adjustable input impedance, followed by a time-varying gain stage. A third order linear phase anti-aliasing analog low pass filter is used to remove out of band high frequency noise prior to digitization; the Vantage High Frequency configuration provides AA filter corner frequencies at: 5, 10, 15, 20, 30, 35, and 50 MHz. This Vantage model also includes programmable analog High Pass Filters (HPF), with a range of corner frequencies between 1 and 20 MHz. The ADC sampling rate is programmable between 10 and 62.5 MHz, to many different values determined by submultiples of the 250 MHz system clock. Two digital filters, a decimator, a digital gain stage, and an accumulator are available for additional signal conditioning after digitization. The resulting ultrasound signal (RF Data) is then transferred to the host computer. Depending on the signal bandwidth, the final data sample rate may be substantially lower than the ADC acquisition rate, thus making best use of the 6.6 GB/s PCIe transfer rate.

4x Sampling

The *quadrature sampled* data representation (in-phase and quadrature samples, or "IQ" data) is very convenient for computations involving the signal phase (e.g., Doppler applications). To facilitate later conversion of the time series RF data samples to an IQ representation, the Verasonics system generally provides data sampled at a rate of 4Fc, where Fc is the nominal frequency in the center of the signal band, usually defined by the transducer's nominal center frequency. This "4x sample rate" results in a Nyquist frequency (F_{Ny} = 2Fc) that provides sufficient bandwidth for capturing all of the data within the transducer's passband. For transducers with center frequency up to about 15 MHz, this 4x sampling approach is straightforward using the available ADC sampling rates. Again, for transducers operating below 15 MHz, the ADC may sample the data at more than 4Fc, and filtering and decimation are typically used to reduce the data rate to 4Fc for transfer.

To prevent aliasing of out-of-band high frequency noise (frequencies above F_{Ny}), a suitable anti-alias filter setting is chosen. It is well known that any energy above the Nyquist frequency gets "folded" back and added into the band of interest. As long as all of the desired signal lies below the Nyquist frequency, it is easy to select an AA corner frequency to prevent most energy from above F_{Ny} from reaching the ADC. Numerical filters with more degrees of freedom can be applied after digitization to further narrow the passband if desired. A graphical illustration of this typical situation in the frequency domain is provided in Figure 1 on the following page.

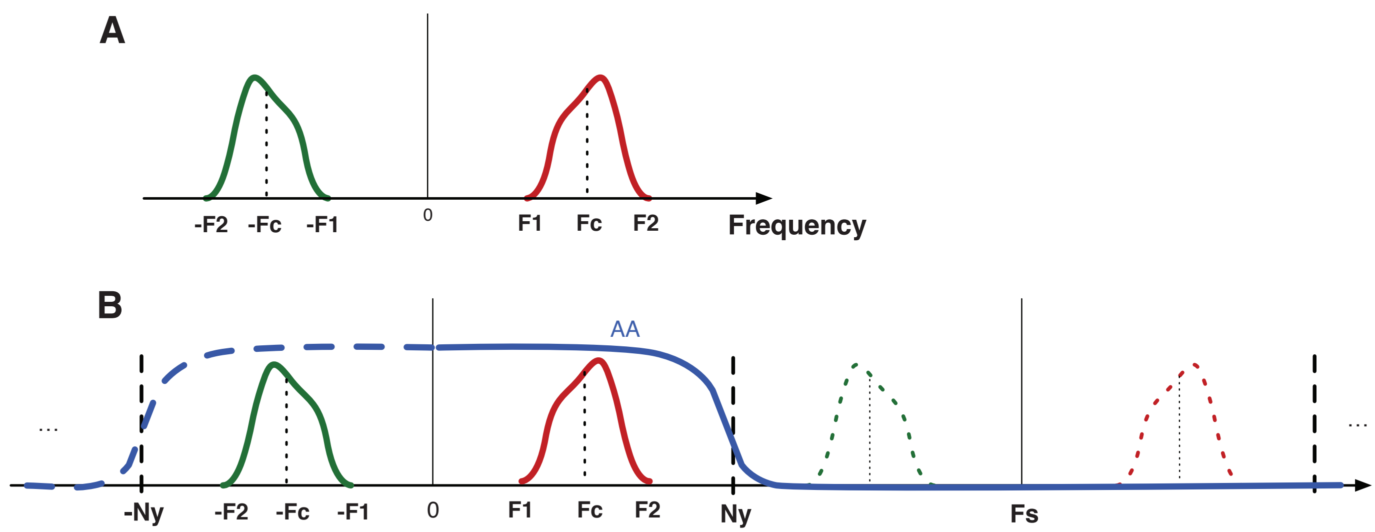

Figure 1. Representation of a signal spectrum, 4x sampling, and the Anti-Alias filter.

A. The amplitude spectrum of a transducer signal prior to sampling; note that the spectrum of a real function includes a negative frequency component.

B. The spectrum after sampling at 4Fc has periodic "images" of the continuous spectrum, including positive and negative frequency components. Energy at frequencies above the Nyquist frequency would appear "aliased" or "folded" about the dotted line at FNy into the signal band. The anti-aliasing low pass filter AA suppresses such undesired energy.

Because our digitizer's maximum sampling rate is 62.5 MHz, the maximum value of Fc for 4x sampling is nominally 15.625 MHz. Given typical transducer bandwidths, the maximum signal frequency is substantially higher. In an extreme example, a transducer with center frequency Fc and 100% relative bandwidth (i.e., BW = Fc) has an upper frequency edge at Fmax = 3/2 Fc, or about 23 MHz. This frequency is still well below the Nyquist limit of 31.25 MHz, thus permitting very good rejection of out of band noise using analog and digital filtering.

Bandwidth Sampling of High Frequency Signals

For transducers with a signal passband that contains or exceeds 31.25 MHz, *bandwidth sampling* (see most books on DSP methods for a description; also called undersampling https://en.wikipedia.org/wiki/Undersampling) can be used with the Vantage High Frequency model. This approach begins by selecting a Nyquist frequency *below* the lower edge of the transducer's passband: in this case, the desired signal lies entirely above the Nyquist frequency, and all of the desired signal will be aliased, or "folded" back into the band below F_{Ny}. Though its spectrum is folded, the desired signal can be properly interpreted as long as no other energy also appears in that band. Therefore, a high pass filter with a corner at or above the Nyquist frequency is necessary to eliminate any low frequency energy that would otherwise be added to the desired signal after aliasing. The high pass filter thus plays an antialiasing role. The conventional LPF AA filter is still necessary to limit out-of-band high frequency noise. See Figure 2 on following page.

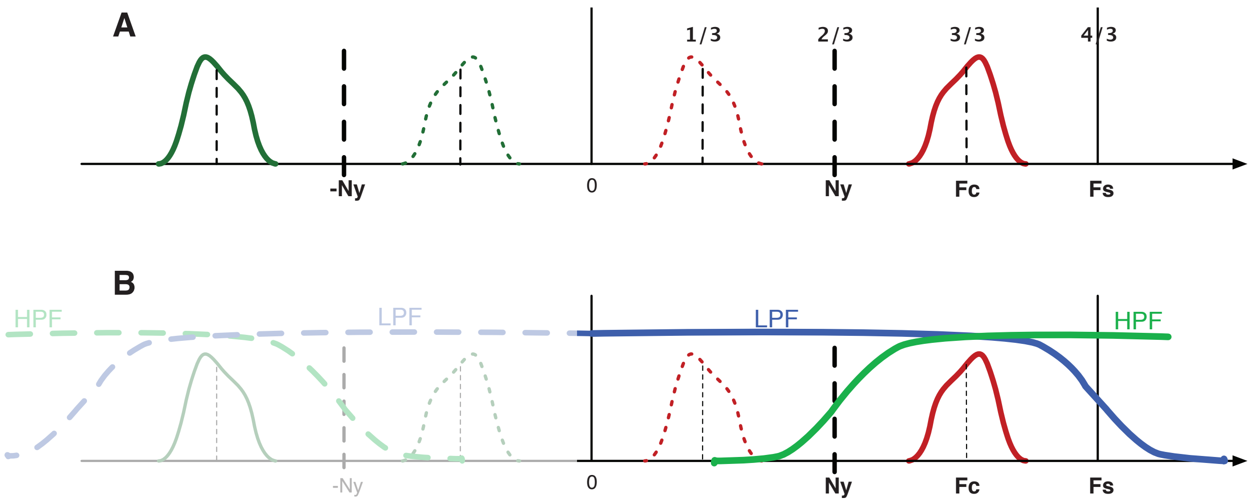

Figure 2. Bandwidth sampling a high frequency signal using a Nyquist limit set below the signal's passband.

A. The desired high frequency signal (solid red curve) is aliased into the passband of width FNy set by the ADC sampling frequency Fs, and its spectrum is reversed (dashed red line). It is convenient to choose Fs = 4/3 Fc, to maintain a 4x sampling relationship (but now for the aliased signal!).

B. The anti-aliasing filter (LPF) is still necessary and must have a cutoff frequency set above the upper band edge as before. A new high pass filter (HPF) is added to help reduce noise from below the FNy cutoff, now located below the desired band. The transducer signal (solid red) is "undersampled" and appears in the sampled data as the aliased image signal (dashed red).

Note that after aliasing, the signal spectrum is reversed and appears to have a negative phasor rotation like the negative frequency spectrum (solid green curve in Fig. 2a). The aliased spectrum can itself be reversed by effectively swapping the roles of I and Q, and thus reversing the rotational direction of the analytic signal's phasor. (See for example, Spectral Flipping Around Signal Center Frequency, by Rick Lyons, 2007). All of the frequencies of the aliased signal are also downshifted; indeed, the center frequency Fc of the aliased spectrum is now at Fs/4, instead of 3Fs/4. The original RF signal, adequately sampled at 2Fs or more, can be reconstructed if desired, under the assumption that the original sampled signal was limited to the [Ny, Fs] frequency band.

Because the Vantage ADC sampling rate is programmable, many choices for F_{Ny} are available, and the Vantage High Frequency model's programmable HPF filter corner must ideally be set at or above F_{Ny}. Of course, lowering the sampling rate also lowers the bandwidth of the acquisition defined by F_{Ny}. To maintain the 4x sampling approach, the bandwidth sampling rate is chosen to be 4/3 Fc, with an associated Nyquist rate of 2/3 Fc. This is the reason we say that 4/3x sampling method limits the passband to a relative bandwidth of 67%, whereas Nyquist sampling provides 100% bandwidth, and 4x sampling provides 200% bandwidth. High frequency transducers are difficult to fabricate with broad bandwidth and adequate sensitivity, and thus the 67% acquisition bandwidth might not impose much of a restriction. Doppler methods perform better with a narrower bandwidth than B-mode imaging requires, and will work well with the 4/3x approach. As noted in Fig. 2b, the LPF anti-aliasing filter is still necessary, and must be applied to the upper band edge, at 4/3 Fc (that is, Fs) or below. In summary, with this 4/3x bandwidth sampling technique, signals up to 50 MHz (limited by the highest setting of the AA filter) can be accurately digitized using the Vantage ADC, albeit with a bandwidth that is no more than 2/3 Fc.

Interleaved Acquisitions

There is one other approach to producing accurate digital samples of RF data without the 67% bandwidth restriction of 4/3 Fc sampling. Two offset pulse-echo events can be used to interleave the received data from the two events and produce a single record sampled at twice the rate of each individual acquisition. Of course, the data must come from repeatable experiments with negligible motion artifact. What is "negligible" depends on the situation, and must be analyzed in terms of the apparent change in phase from a scatterer in successive acquisitions. For B-mode imaging and for many NDT / NDE applications, phase shifts of less than $\lambda/16$ are usually considered negligible. Because the Vantage is capable of acquiring frames at above 100 kHz, limited by the acoustic travel time plus a delay on the order of a few microseconds, the inter-frame period can be extremely short, as it can be for shallow imaging at very high frequencies.

Interleaving two records in this way is accurate because the Vantage ADC chips are designed to do undersampling and have a very fast integration window; the sample-and-hold portion of the circuit is able to provide a value of the analog sample in a time interval short enough to be used with a much faster analog to digital converter (one that converts at 250 MHz!). The 14-bit converter is the slow part of this circuit, and can only do the conversion of the analog sample at 62.5 MHz. Using this rate, and delaying the sampling time between two successive acquisitions by exactly half the sampling period (8 ns), we can collect accurate data samples as though they were collected using a 125 MHz ADC chip. In practice, the delay is accomplished by shifting one of the transmit waveforms by 8 ns, while using identical receive operations.

The interleaving of data from two separate acquisitions takes very little processing time, and the main impact to the user is the need to program and acquire two transmit/receive events, and to set a software interleave flag. Again, this is only reasonable for scattering media which are sufficiently stationary between the consecutive acquisitions. In B-mode imaging, and even for RF spectral estimation, motion between acquisitions representing less than about 1/8th of a wavelength is negligible. The Vantage is capable of effectively acquiring data frames at the speed of sound, achieving over 100 kHz for shallow acquisitions, and is fast enough for interleaved sampling in most high frequency imaging situations.

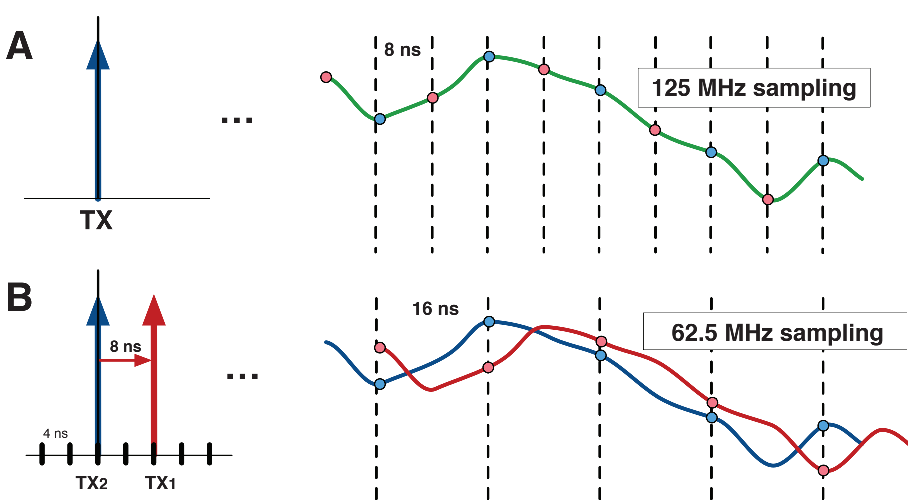

Figure 3. Interleaved sampling using two acquisitions.

A. A segment of the RF backscattered response to a transmit impulse TX is presented as the solid green line. Sampling the signal at 125 MHz produces data points on an 8 ns grid.

B. The data samples in the top panel can also be obtained using two acquisitions sampled at 62.5 MHz, by delaying the transmit pulse by 8 ns between acquisitions. The Vantage 250 MHz master clock permits delaying the start of a transmit pulse with respect to time t = 0 in 4 ns increments. The response to pulse TX1 (red line) is thus delayed by 8 ns with respect to the response to pulse TX2 (blue line), and response #1 is effectively sampled at points 8 ns *earlier* than response #2. When the "interleave" mode is ON, data samples from the two consecutive 62.5 MHz acquisitions are automatically interlaced to produce the data stream of the 125 MHz acquisition, as indicated by the color of the dots.

Bandwidth Interpolation

It is important to recognize that 4x sampled data does not look "smooth" when plotted, but that all of the signal information is fully captured in the data stream. Straightforward interpolation can be performed in a bandwidth preserving manner to up-sample the data for presentation or further processing. It is often best to do this interpolation after transfer from the acquisition system to make best use of the available data transfer rate. The channel RF data (and beamformed data) are available in the Verasonics system for custom real-time processing in Matlab or any other mex-compatible language, including simple operations such as interpolation and plotting, or off-line. This flexibility makes processing of the data stream using legacy software *in real-time* very straightforward. Many NDT/NDE applications have been written to use data sampled at 100 MHz or more, and a very simple function subroutine can be developed to up-sample the RF data and provide it in the desired format to such legacy software.

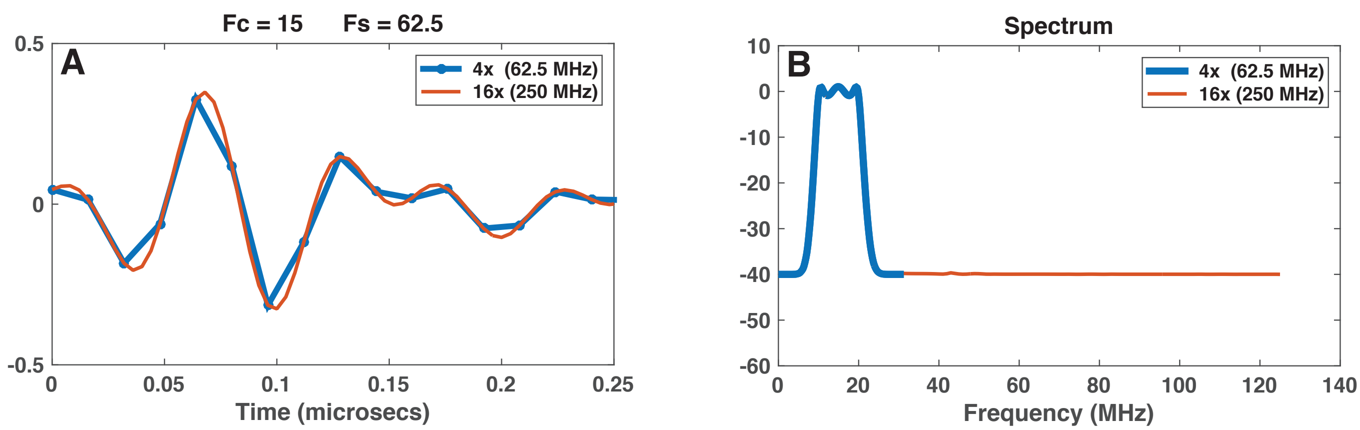

Figure 4. Bandwidth-limited interpolation.

A. A segment of band-limited data centered near 15 MHz is sampled at 62.5 MHz (4x sampling) and plotted in the blue line in the left panel. A smoother (orange) line is obtained by interpolating the data without changing the information content of the signal (here by a factor of 4, for a total of 16x sampling).

B. Interpolation in the time domain can be understood as zero-padding in the Fourier transform domain, as illustrated in the right panel. No energy is added to the original signal spectrum (blue line), but the constraint of zero energy outside the signal band at higher frequency (orange line) provides the information required to determine the true signal values at times between the original sampled data points. It is possible to develop interpolation filters to obtain bandwidth interpolated samples at any desired sample frequency above the original sampling rate, and such algorithms can easily be incorporated in the real time data processing flow of an acquisition sequence on the Verasonics platform.

Summary

Transducers operating anywhere in a band below about 50 MHz (and above 1 MHz) can be used with the Verasonics High Frequency system because of the ability to adjust the ADC sample rate and program an analog High Pass Filter in addition to the conventional anti-aliasing Low Pass Filter. Flexible acquisition sequence control permits the user to choose between several different high frequency acquisition approaches, depending on tradeoffs between frame rate, data bandwidth, and SNR. Interleaved sampling is possible using two consecutive acquisitions because the ADC integration window is short enough for 125 MHz sampling. Bandwidth sampling approaches are used when a single acquisition is required. Example imaging programs are provided with the system software for 4x sampling, 4/3x and 8/3x sampling, for interleaved acquisitions, and for simple data collection and transfer at any digitization frequency available.