Using the undersampling capabilities of the RadioProcessor™ for 70 MHz IF applications

Introduction

SpinCore Technologies' RadioProcessor(TM) is a versatile, general-purpose, digital excitation and detection system, specifically designed for Nuclear Magnetic Resonance (NMR), Nuclear Quadrupolar Resonance (NQR), Magnetic Resonance Imaging (MRI), and related resonance and test technologies. The system integrates SpinCore's high-performance PulseBlaster™ timing engine for agile control of internal system components as well as digital (TTL) word generation for control of any external hardware.

The RadioProcessor™ provides users with compelling price/size/performance proposition unmatched by any other device on the market today. The RadioProcessor

- Integrates excitation and acquisition components onto a single PCI card
- Directly captures and digitally demodulates IF/RF signals. The desired baseband bandwidth is user definable through software.
- Generates completely formed RF excitation pulses as well as high resolution digital control signals
- Maintains signal coherence between excitation and acquisition systems at all frequencies.
- Autonomously signal-averages the baseband data between multiple acquisitions

Please refer to RadioProcessor's Manual for more information on the system, its specifications, and standard applications. This unique digital system can be housed and delivered in a small-form-factor PC computer, fully configured, providing users with the additional convenience of a turn-key solution.

The standard sampling frequency of the RadioProcessor Model TRX-75-300 is 75 MHz. At this sampling frequency, the input signals up to 37.5 MHz (the Nyquist frequency, i..e., ½ of the sampling frequency) can be sampled without any aliasing effects occurring, allowing it to easily be used with magnets up to this frequency. In addition to this, it is also possible to use the RadioProcessor with input signals higher than 37.5 MHz by taking advantage of the high bandwidth of the input amplifier and A/D (Analog-to-Digital) converter.

In general, when input signals are above the Nyquist frequency, the signal is folded back to a lower apparent frequency when it is sampled by the A/D. The folded frequency can be calculated with the following formula:

$$f_{folded} = abs(f_{AD}-n*f_{input})$$

f_{folded} : Frequency that appears to the RadioProcessor system
f_{AD} : Sampling frequency of the A/D (75 MHz in this case)
f_{input} : Input frequency applied to the RadioProcessor
n : Any integer which causes f_{folded} to be the smallest possible value

This document demonstrates the use of the RadioProcessor Model TRX-75-300 with a 70 MHz IF (intermediate frequency) signal in a high-field NMR spectrometer. Transmitting (Tx) and Receiving (Rx) performance at and around 70 MHz will be presented.

Excitation Section

In order to be usable for 70 MHz applications, the RadioProcessor must output short pulses with a carrier frequency of 70 MHz and agile phase and frequency modulation. This can be accomplished with RadioProcessor's Tx excitation section which is equipped with the on-board 300 MHz 14 bit DAC converter followed by a wide-band output amplifier. The figure below shows an example RF *output pulse* that was generated by the RadioProcessor Model TRX-70-300. This data was captured using a Tektronix TDS224 oscilloscope. Notice the time base of 25 ns/division.

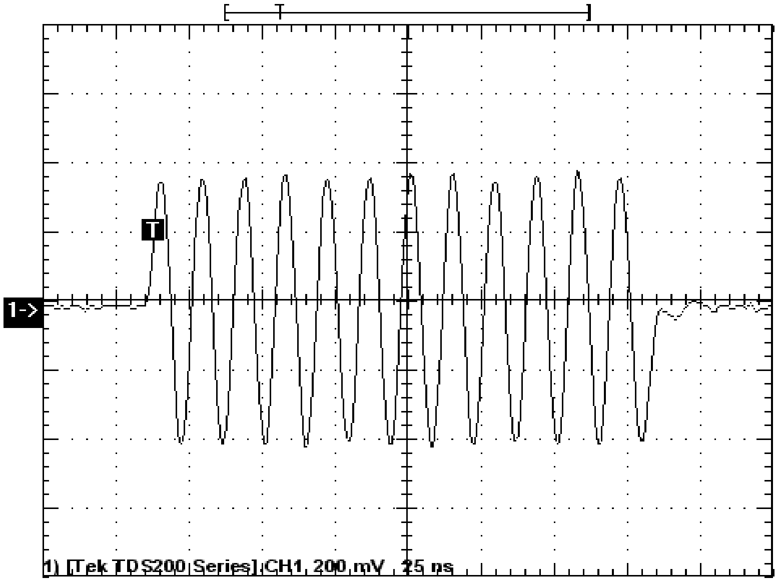

Figure 1: 185 ns 70 MHz RF/IF output pulse.

To demonstrate the zero-latency phase- and frequency-switching agility, two short back-to-back pulses were recorded - with a 180-degree phase offset (Figure 2, left panel, 70 MHz RF, expanded view), and with a frequency shift from 20 MHz to 10 MHz (Figure 2, right panel),

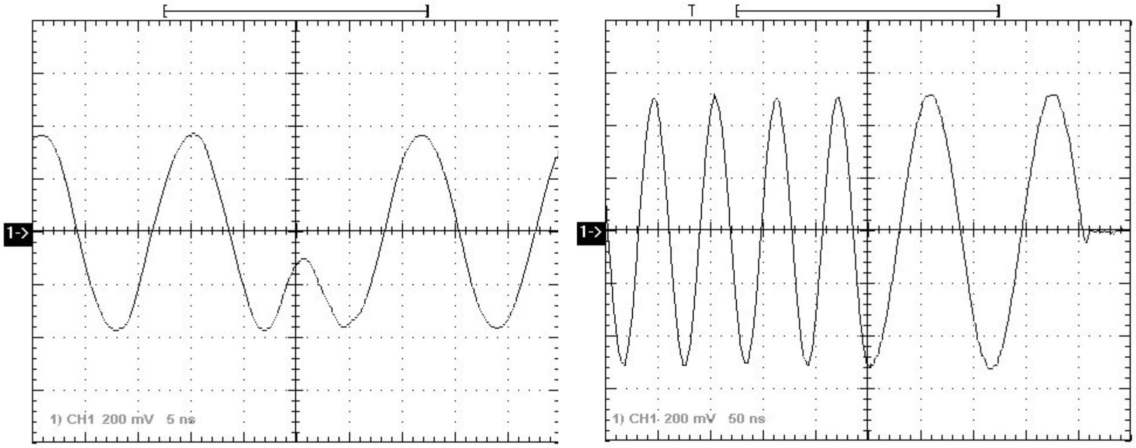

Figure 2 – Two RF output pulses, back to back, with 180 degree phase switch and 70 MHz RF frequency (left panel), and frequency shift from 20 MHz to 10 MHz (right panel).

The wide-bandwidth output amplifier of the RadioProcessor is DC-coupled, and the frequency response of the entire Tx section is nearly flat from DC to 100 MHz. RadioProcessor can generate RF pulses in this entire range, while maintaining the required phase coherence with the receiving section through the use of a common frequency source.

Receiving Section

The receiving section consists of a fast, 14-bit A/D converter intended for undersampling applications, followed by digital quadrature detectors, filters, and an autonomous signal averager. To evaluate the performance of the receiving section of the RadioProcessor, the most important thing is to examine the performance of the A/D converter. Figure 3 (next page) shows a 5 MHz signal that was directly captured by the A/D without being passed through the detectors or any of the internal digital filters. Figure 4 (next page) shows a 70 MHz under-sampled signal (which has been folded back to 5 MHz) captured with the same setup. A comparison of the two spectra indicates that the noise introduced by the undersampling process is relatively small. Therefore, the RadioProcessor can be used with input frequencies higher than Nyquist (37.5MHz) with performance comparable to regularly sampled input frequencies below Nyquist.

The input signals for these tests were generated by a PTS 250 Frequency Synthesizer (running un-locked to the RadioProcessor's clock), and the spectra were generated by reading the captured data into MATLAB and performing a complex FFT. The negative frequencies are the result of having only one (the real) component sampled, with the imaginary values all set to zero.

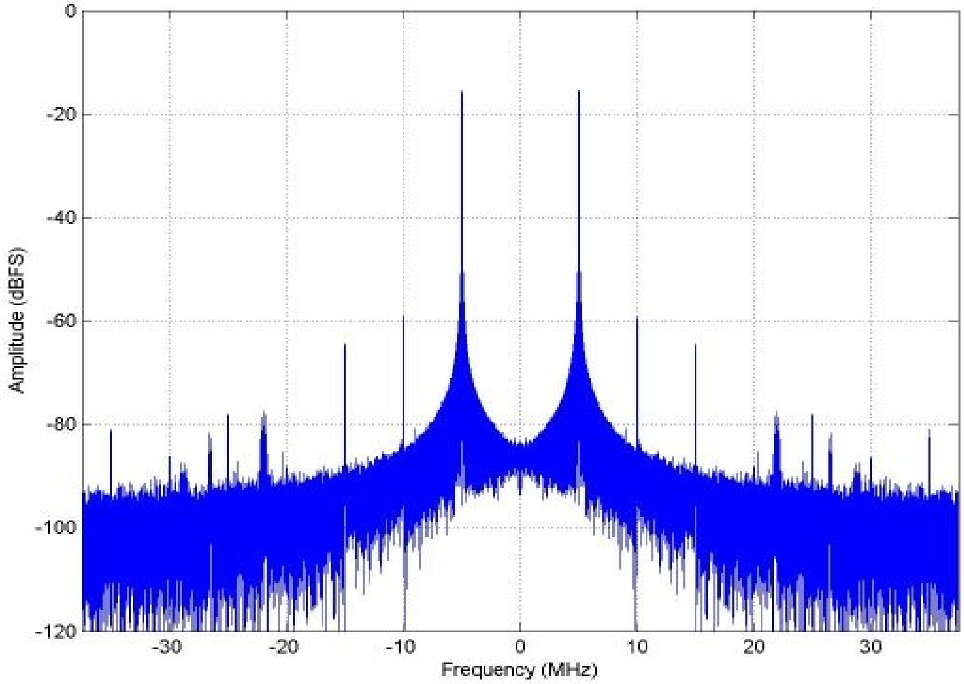

Figure 3: 5MHz signal directly captured

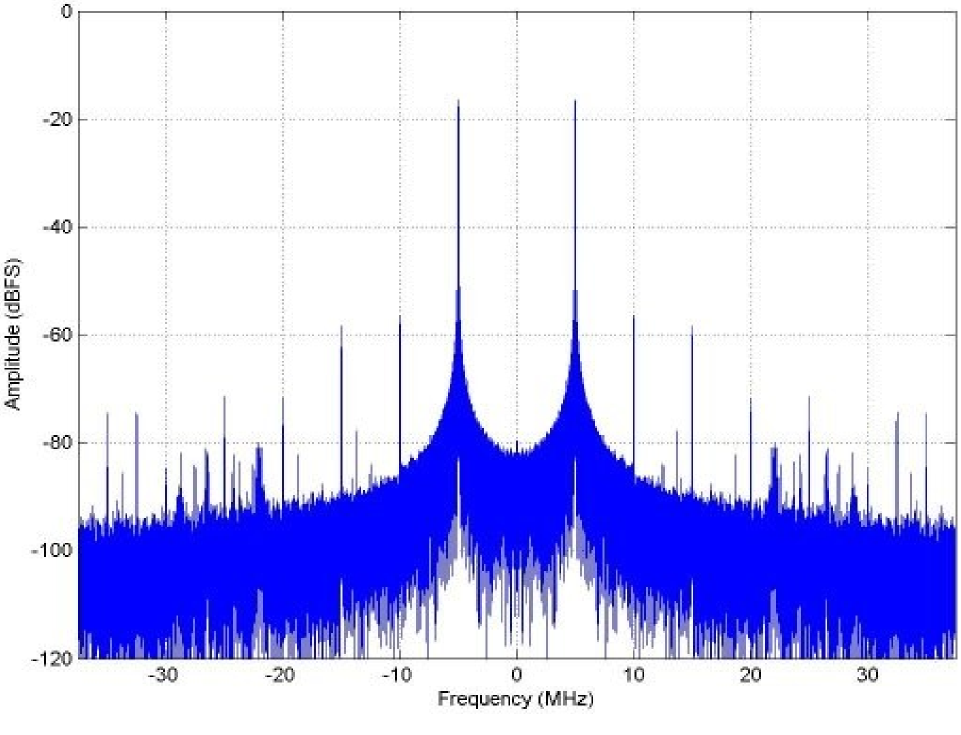

Figure 4: 70MHz signal directly captured (undersampling)

Most NMR/NQR applications will require that the RadioProcessor can capture a certain bandwidth around the spectrometer frequency (or IF frequency).. To show that the amplitude remains the same when the input frequency is changed, two additional signals were captured - at 65 MHz and 75 MHz, as shown in figure 5 and 6 respectively.. The 75 MHz value folds back to the apparent frequency value of 0 Hz. Any larger offset of the input frequency at this specific sampling frequency would result in a fold back into the same spectral region, making it indistinguishable from each other. Therefore, when the center frequency is 70 MHz, the maximum usable bandwidth that can be accommodated in the undersampling mode without distortions is +- 5 MHz.

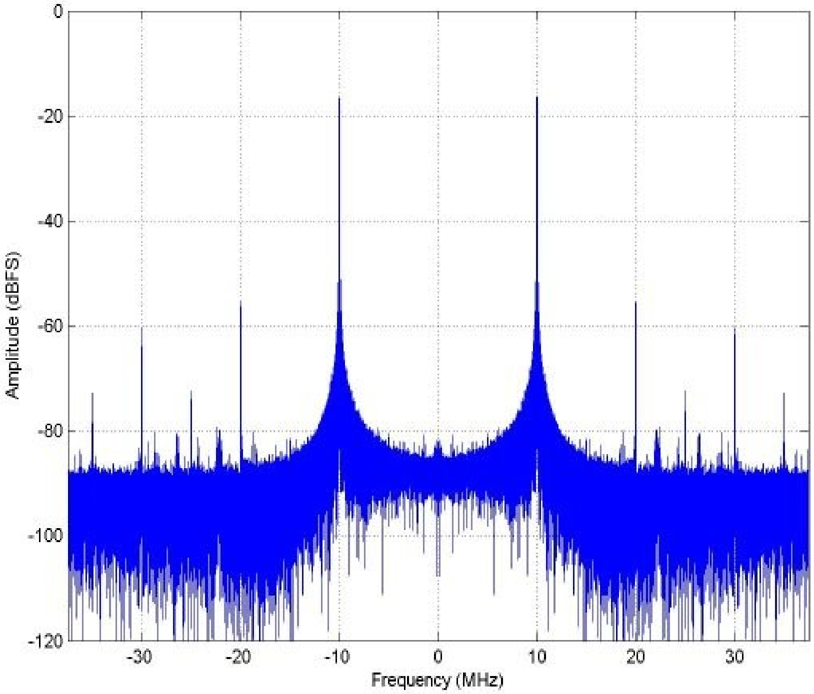

Figure 5: 65MHz input signal directly captured (undersampling)

Insert figure

Figure 6: 75MHz input signal directly captured (undersampling)

For reference, the noise floor of the A/D was captured by placing a 50 ohm resistor across in Analog Input of the RadioProcessor. This is shown below in figure 7.

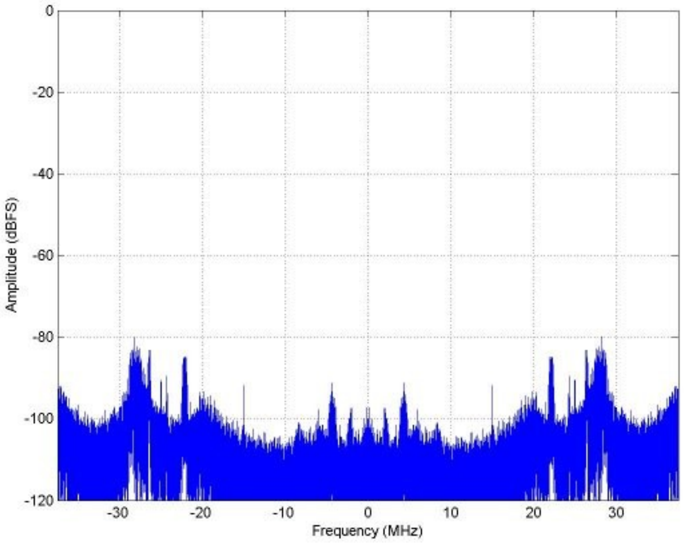

Figure 7: Noise floor

These figures demonstrate that the RadioProcessor's A/D can handle frequencies above Nyquist (37.5MHz) because undersampling performance is comparable to standard sampling. Since the quadrature detection and filtering components are not even aware of whether aliasing is taking place in the A/D converter, they will perform exactly the same as for the standard sampling case. With detectors and filters enabled, a sample 10.8 MHz NMR spectrum of a household cooking oil was obtained with the RadioProcessor. The sample spectrum is presented in Figure 8 (below). The complete system design that was used to capture the data is described in more details in RadioProcessor's Manual

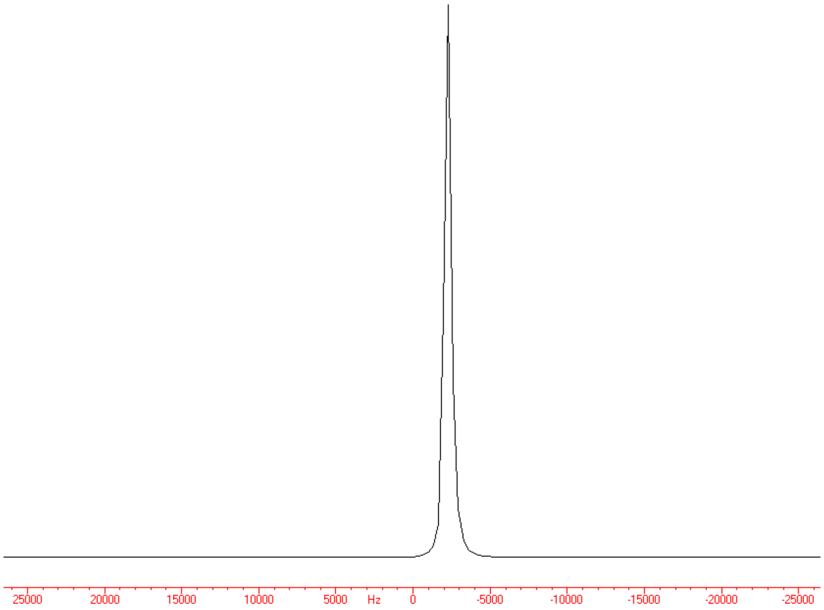

Figure 8: Single-scan 10.8 MHz NMR spectrum of a sample cooking oil. Please see RadioProcessors' Manual for details.

Integration of RadioProcessor into high-RF system.

In order to utilize the RadioProcessor as an IF excitation and detection system for high-field NMR applications, a phase-coherent up- and down-conversion is required. The diagram in Figure 9, below, presents a simplified system that would utilize the RadioProcessor as a 70 MHz IF system and maintain the required phase coherence. In the proposed system, the 10 MHz reference clock oscillator is the single master frequency source to all subsystems. The 10 MHz source drives the high-frequency synthesizer (e.g., the PTS brand) directly. Multiplied by 5 times, the resulting 50 MHz frequency drives the digital circuitry of the RadioProcessor. The RadioProcessor utilizes the 50 MHz external clock to derive the 75 MHz clock frequency for the A/D section and the 300 MHz clock for the D/A converter. As the RadioProcessor is broad-band, intermediate frequencies other than 70 MHz can be selected as well.

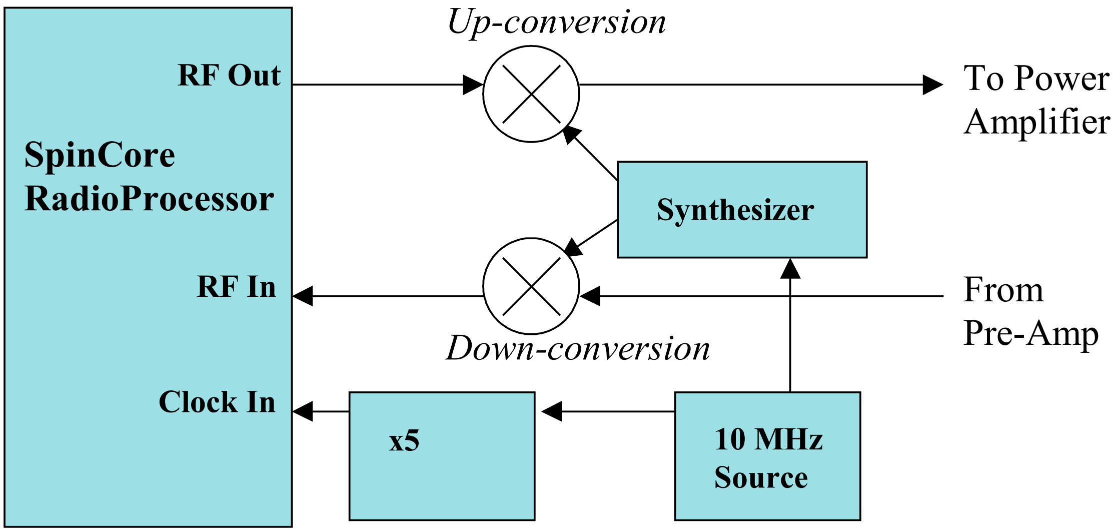

Figure 9: Simplified block diagram of a complete, phase-coherent high-field system with the use of RadioProcessor

An alternative solution to maintain the required phase coherence would be to utilize a high-quality reference clock oscillator on-board of the RadioProcessor and drive the external synthesizer from that clock. The board is equipped with a standard-size socket designed to accept a high-quality oven-controlled crystal oscillator (OCXO), and OCXO devices with 1 ppm (or better) stability are available. When oscillator is removed from the socket, the external signal could be provided in lieu of the oscillator's standard output.

Clock Input Signal Standard.

The RadioProcessor is a digital system built in CMOS technology and powered off a 3.3 V DC source. It will accept external clock signals that conform to the low-voltage 3.3 V TTL standard only.

Negative voltage below 0.2 Volts would damage the processor chip, and thus any external sinusoidal signal would need to be converted to the positive-only TTL signal prior to using with the RadioProcessor.

Alternative Sampling Frequencies.

The RadioProcessor can be customized to operate with alternative sampling frequencies. An example alternative A/D sampling frequency value also suitable for 70 MHz IF applications would be 60 MHz. At this frequency, the 70 MHz input signal would fold, when sampled, into the apparent 10 MHz frequency. This apparent 10 MHz signal would be handled by the RadioProcessor's digital detection and filtering system in the same way as any other signal within the Nyquist range. Similarly, the +- 5 MHz maximum bandwidth would be available. To operate in the coherent mode at 60 Ms/s, the external 10 MHz source would need to be multiplied fourfold, to 40 MHz, and fed to the RadioProcessor's clock input. The Tx DAC would operate at 240 MHz..

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