MR Experiments Using a Commercially-Available Software-Defined Radio

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Target audience: Engineers interested in MR spectrometer hardware.

Purpose: Conventional commercial MR spectrometers are often limited in configurability, portability, scalability and cost. This has led several researchers to build lower-cost, smaller and more customizable architectures in-house [1-6]. One such approach is a software-defined radio (SDR) architecture [7], comprising high-speed A/D and D/A converters, an FPGA to perform high-bandwidth digital mixing and filtering, and a USB or Ethernet link to a PC for real-time data transfer. SDR's have several strengths, including high-bandwidth direct RF signal synthesis and digitization with high bit depth, high configurability and low cost. In this work we describe NMR and MR imaging experiments using the commercially-available Ettus Research USRP1 SDR (Ettus Research, Santa Clara, CA, USA), which retails for around $700 USD. The work was motivated by the need for a low-cost spectrometer for teaching an MR engineering course, and for a transmitter that could generate adiabatic pulses with large frequency sweeps for Bloch-Siegert shift-based RF encoding experiments on a 0.5 Tesla Oxford Maran scanner (Resonance Instruments, Witney, UK) [8,9].

Methods: The USRP1 is based on an Altera Cyclone FPGA, dual 64 MS/s, 12-bit ADC's, and dual 128 MS/s, 14-bit DAC's. It is compatible with GNURadio, an open-source SDR driver and associated signal processing software that simplifies the development of SDR applications using a flowgraph architecture similar to LabView. In the presented 0.5 Tesla (20 MHz) experiments, a USRP1 was configured with $75 LFRX and LFTX daughterboards comprising op-amps and SMA connectors to interface RF signals.

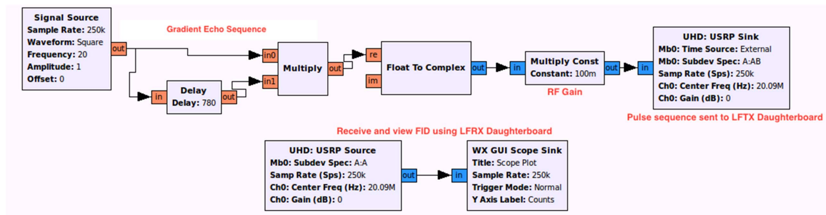

Figure 1: *GNURadio block diagram for a pulse-and-acquire FID experiment.*

Experiment 1: *NMR FID and spin echo acquisitions.*
In these educational experiments the USRP1 was directly connected to an RFPA and pre-amplifier, which were connected to a solenoid coil via a passive T/R switch. A graphical GNURadio flowgraph for a pulse-and-acquire FID experiment is shown in Fig. 1, and required only 6 signal processing blocks to generate a hard excitation pulse with adjustable duration, amplitude and TR, and two blocks to receive and display the signal. The USRP1 used a sampling frequency of 250 kHz.

Experiment 2: *Off-resonant and frequency-swept RF pulse generation.* In these experiments the USRP1 took the place of the Maran spectrometer's transmit channel, and was triggered by it each TR to produce a 12 µs hard excitation pulse followed by either a 500 µs off-resonant (±27kHz) Fermi pulse or a frequency-swept hard pulse [10] (Fig 3a, left) for Bloch-Siegert-based RF spatial encoding. A custom GNURadio flowgraph block was developed for these experiments to play a vector of RF pulse samples whenever a trigger was received on its input. A solenoid coil (diameter = 15 mm, length = 34 mm, turns = 20) wound with square-root conductor spacing was used for transmit and receive. The USRP1 used a sampling frequency of 2.46 MHz.

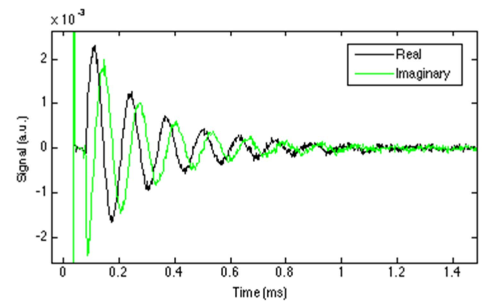

Figure 2: *A pulse-and-acquire FID recorded by the USRP1.*

Results: Experiment 1: Figure 2 shows a representative FID signal acquired by a student in a $CuSO_4$-doped vial phantom using the flowgraph in Fig. 1. Spin echo experiments with adjustable TE were also performed by adding a delayed hard pulse with twice the excitation pulse's duration to the transmit signal. Experiment 2: Figure 3a compares small-signal frequency-swept pulses for Bloch-Siegert phase encoding generated by the Maran and the USRP1. The USRP1 played the waveform with high fidelity, while the Maran's waveform contained spurious dropouts and undesired phase plateaus due to limited temporal and phase resolution, resulting in large spikes in the FM waveform. Figure 3b shows a 128x128 image of a 10 mm-diameter MnCl-doped vial and a B_1 map that were measured using the USRP1 to produce excitation and off-resonant Fermi pulses. The image is artifact-free and the B_1 profile appears as expected.

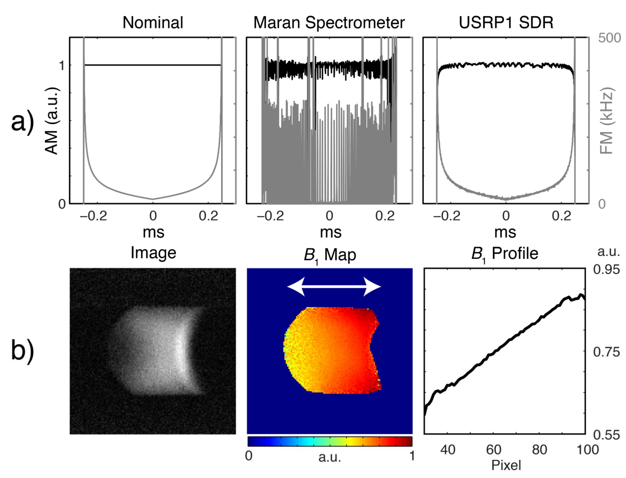

Figure 3. *(a) Comparison of nominal and measured frequency-swept pulses generated by the Maran spectrometer and the USRP1 SDR. (b) Image, Bloch-Siegert B_1 map and B_1 profile (averaged across length indicated by white line) in a water phantom using the USRP1 for all RF excitation pulses.*

Discussion and Conclusions: We have presented results from pulse-and-acquire and imaging experiments at low field using a commercially-available software-defined radio. The SDR was shown to enable rapid development of simple NMR experiments, and to produce high-quality frequency-swept pulses for Bloch-Siegert-based RF spatial encoding. Though it was not required here, the USRP1 also enables clock synchronization using an external 10 MHz reference signal.

References: [1] P. P. Stang et al. IEEE TMI, 31(2):370–379, 2012. [2] C. A. Michal et al. Rev Sci Instrum, 73(2):453–458, 2002. [3] K. Takeda. Rev Sci Instrum, 78(3):033103, 2007. [4] W. Mao. Rev Sci Instrum, 22(2): 025901, 2011. [5] S. M. Wright. Magn Reson Mater Phys, Biol Med, 13(3):177–185, 2002. [6] J. Bodurka et al. Magn Reson Med, 51(1):165–171, Jan. 2004. [7] W. Tang et al. Meas Sci Technol, 22:015902, 2011. [8] R. Kartausch et al. Magn Reson Mater Phy, 2013. [9] Z. Cao et al. 22nd ISMRM, p. 4220, 2014. [10] M. Jankiewicz et al. J Magn Reson, 226:79–87, 2013.