# Direct Radio Frequency (RF) Signal Generation using Commercial off-the-shelf (COTS) Equipment

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*Abstract*— **Analog circuitry is often expensive and limited in scope meaning that changes to the desired functions are slow and costly. The Software Defined Radar (SDRadar) concept call for quick system development and change bringing most of the radars functions from analog hardware based to software based. Withing that concept this paper investigates the direct Radio Frequency (RF) signal generation. To that end sample waveforms are numerically generated and modulated with an L-band carrier frequency in Matlab. The digital signal is then sent to an Arbitrary Waveform Generator (AWG) for analog conversion. To evaluate the resulting signal it is conducted to a Digital Storage Oscilloscope (DSO) for digitization and then matched filtered. Taking advantage of the flexibility of the SDRadar concept another test is performed with the use of digital up and down conversion for comparison. Results show that both signal generation setups produce highly correlated signals with their numerically generated counterparts.**

*Keywords*— **Radar, Software Defined Radar, Signal Generation.**

## I. Introduction

Since their first appearance in the second world war radar systems have grown in uses and complexity [1]. Today's radars not only help the military detect and track incoming threats, but are also used in civilian applications to forecast the weather, to image the earth, to survey the ground and, more recently, in the guidance of self driving cars [2], among other uses. This vast array of applications comes with different requirements for the radar systems, nevertheless some common requirements can be pointed out. An ideal radar system ought to have low size, weight and peak power while keeping a high average power and bandwidth, which translates into a low probability of being intercepted, high Signal to Noise Ratio (SNR) and small range resolution, at the same time it should be capable of varying its carrier frequency and Pulse Repetition Frequency (PRF) all the while keeping signal coherency [3].

One approach to try and expand the capabilities of radar has been the development of Microwave Photonics (MWP). In that regard, Tong [4] compares typical MWP technologies for radar signal generation with a focus on some key radar indicators. Another approach, brought about by improvements in Field Programmable Gate Arrays (FPGA), Digital to Analog (DAC) and Analog to Digital (ADC) converters, chips computing speeds and host connections throughput, has been the Software Defined Radar (SDRadar) concept. In SDRadar most of the functions typically implemented in hardware, like mixing, filtering and modulation, are moved to software, the goal being to address the need for multi-purpose and adaptive radar systems. A great review of the subject has been conducted by Feng *et al* in [5].

In [6] Costanzo *et al* evaluate the potentialities of the SDRadar concept when implemented on a Universal Software Radio Peripheral (USRP), the authors tested a low cost P-band SDRadar system for target detection programmed through Simulink and performed experimental validation of the system's range resolution. A similar setup with a USRP and Simulink is used to investigate synchronization issues on a practical implementation by Aloi *et al* [7]. Garmatyuk, Schuerger and Kauffman explore a Ultra-wideband (UWB) Software Defined Radar using a Orthogonal Frequency-division Multiplexing (OFDM) architecture and combining radar and communications functionality, for the software part the authors utilized Matlab and "C" scripts. An Arbitrary Waveform Generator (AWG) and high-speed digitizer provided the interface with the Analog Front End (AFE). Their system achieved a 30 cm range resolution and 57 Mb/s communication data rate, Synthetic Aperture Radar (SAR) imaging capabilities was also demonstrated with the same system [8].

Some earlier articles investigated the viability of implementing the signal processing a SDRadar would need in software. In [9] Qadir, Kayani, and Malik implement the pulse compression technique in Matlab. The pulse to be compressed was a Linear Frequency Modulated (LFM) signal, also know as chirp. An AWG was used to generate the pulse that was then mixed with an X-band carrier frequency in the AFE. The signal was conducted through a long cable to delay the pulse and then received, down converted, digitized and compressed obtaining good results. Rectangular and hamming windows were used and compared to verify their Peak Sidelobe Level and Mainlobe Width characteristics. And Al-Zubaidy, Sayidmarie and Al-Shamaa used Simulink and "C++" to test the Moving Target Indicator (MTI) technique [10].

Based on the SDRadar concept this paper investigates the direct Radio Frequency (RF) signal generation, meaning that all the process from baseband waveform synthesis till its mixing with the final radio frequency carrier is conducted in software. The signals thus generated are converted to analog in an AWG, conducted trough a cable to a Digital Storage Oscilloscope (DSO) and digitized again to be processed back in software. All the hardware used are Commercial off-the-shelf (COTS) products. After demodulation the waveform's matched filter output is compared with the output from the ideal, numerically generated, baseband waveform. The purpose is to evaluate if there are any downsides to this method in terms of signal fidelity. The results show a high correlation between the software generated and measured signals.

The rest of this paper is organized as follows: Section 2 elaborates on the waveforms used, their mathematical representation and numerical synthesis in Matlab; Section 3 describes the system architecture used to evaluate the direct RF signal generation; Section 4 presents and discusses the results and finally Section 5 concludes this paper.

## II. Waveforms

In order to evaluate the system, three basic waveforms have been numerically generated in a Matlab scrip. The first is the simple pulsed waveform which, for unit amplitude, can be represented in continuous time domain as follows [11]:

$$x(t) = 1 \qquad\qquad 0 \leq t \leq \tau \tag{1}$$

Since for this waveform its duration, $\tau$, and bandwidth, $B$, are inversely related by: $B = 1/\tau$, two variations were tested, a long pulse and a short one. Table I shows the parameters for all waveforms used.

TABLE I
Waveform Parameters

| Waveform | $\tau$ | $B$ |
|---|---|---|
| Short Pulse | $0.1\mu s$ | 10 MHz |
| Long Pulse | $1.3\mu s$ | 0.769 MHz |
| Barker 13 | $0.1\mu s$ | 10 MHz |
| Chirp | $1.3\mu s$ | 50 MHz |

note: $\tau$ refers to $\tau_{chip}$ in the Barker Code case.

The next waveform used was a length 13 Barker Code which can be represented as the concatenation of 13 subpulses called "chips" as follows:

$$x(t) = \sum_{n=0}^{N-1} a_n \, p(t - n\,\tau_{chip}) \tag{2}$$

were $N$ is the Code length and $p$ is a rectangular pulse just like the previous waveform but with $\tau$ substituted by $\tau_{chip}$ the duration of each code segment:

$$p(t) = 1 \qquad\qquad 0 \leq t \leq \tau_{chip} \tag{3}$$

and $a_n$ encodes the phase changes which for the Barker 13 are:

$$a_n = \{\,1\,,1\,,1\,,1\,,1\,,-1,-1,1\,,1\,,-1,1\,,-1,1\,\} \tag{4}$$

The last waveform tested was a LFM, defined, in complex form, as:

$$x(t) = \exp\left(j\pi\frac{B}{\tau}t^2\right) \qquad\qquad 0 \leq t \leq \tau \tag{5}$$

These baseband waveforms were mixed with the carrier frequency $f_c$ by multiplying with a complex signal defined as:

$$g(t) = \exp\left(j2\pi f_c t\right) \tag{6}$$

all computations were done with double precision floating-point numbers.

An L-band carrier frequency of $f_c = 1.3$ GHz was chosen as a good test frequency that the equipment used could generate. The baseband time domain signals are displayed in Figure 1. Figure 2 shows their respective baseband spectrum.

In order to stay well within the Nyquist criterion a sampling frequency of $f_s = 4$ GHz was used, we discuss why that might be a problem in the next section.

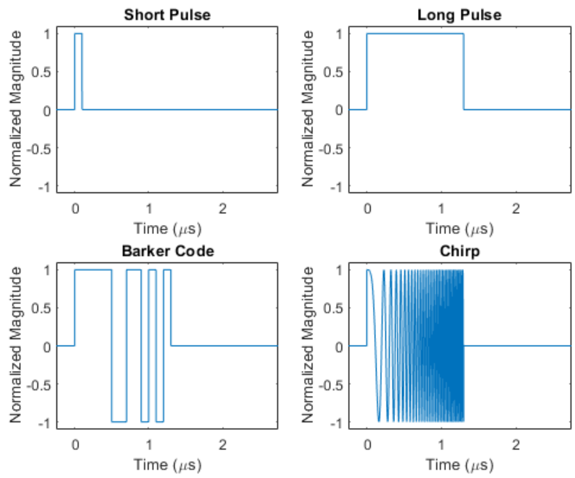


Fig. 1. Baseband Waveforms

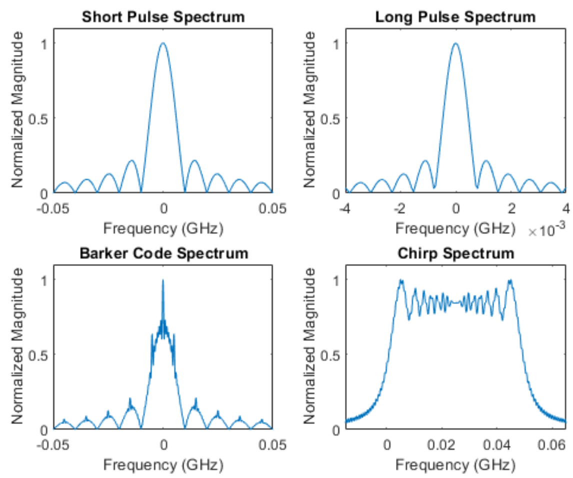


Fig. 2. Waveforms Spectrum

## III. The System

All the software signal generation and later processing and analyses run in a COTS PC with Matlab scripts. Having generated the waveforms to be tested, as explained in the previous section, they were converted from complex, double precision floating-point to real, 16 bit integer, but the 2 least significant bits were used as sample marker to identify the start of the signal leaving the signal with 14 bits. The samples were then sent via Gigabit Ethernet connection to an AWG for digital to analog conversion.

Internally the AWG employed a FPGA to store the samples and handle sequencing and synchronization and a DAC to output the analog signal. The 14 bit DAC was set to run at 4 GSample/s and output 1 Vpp through a differential output. The two DAC's differential output signals were conducted through two identical cables into a DSO for capture. A third signal was conducted through another cable carrying the marker information. The AWG was also set to run with the same clock as the DSO through yet another cable connection.

The DSO's internal 10 MHz clock was used as the master clock for the system. The marker signal from the AWG served as a trigger to start signal capture. The samples from the AWG differential output were digitized by the DSO's 8 bit ADC, running at 4 GSample/s, and subtracted in the DSO. The resulting digital signal was sent back to the PC via Gigabit Ethernet connection for demodulation and matched filtering. Figure 3 shows a block diagram of the entire system.

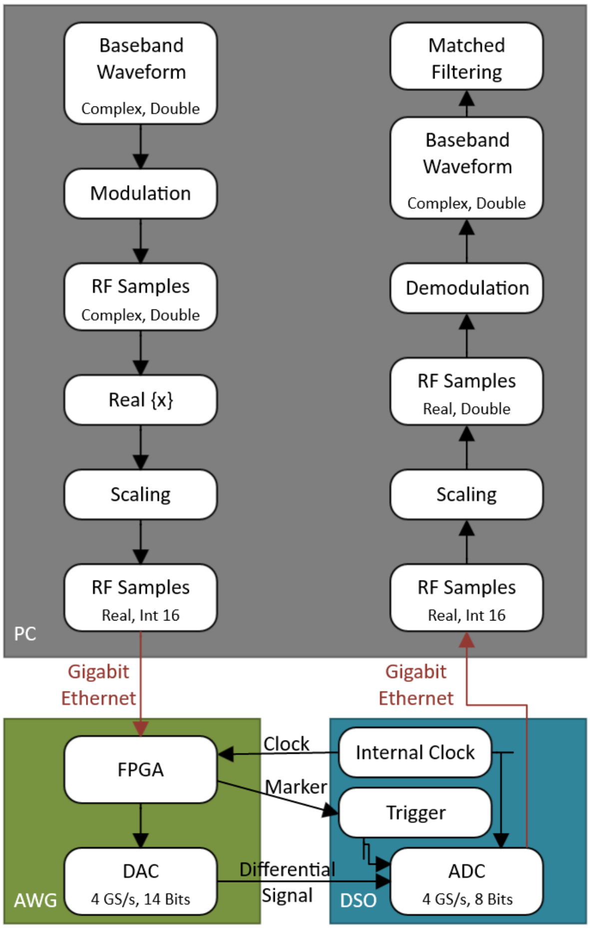


Fig. 3. System Block Diagram

Running at 4 GSample/s meant that the system could not possibly operate at real time due to the Gigabit Ethernet 125 MB/s throughput limitation. That was fine for the purposes of this papers, but would not do for a practical SDRadar application. Another problem that arises from a high sample rate is the amount of samples that have to be processed, again slowing down the hole system to the point were it might no longer be able to run in real time. One way around both these problems is to send back to the PC and process the signals in a lower sample rate with the use of a Digital Up-converter (DUC) and Digital Down-converter (DDC) [12].

Taking advantage of the flexibility of the SDRadar concept a DUC and DDC were incorporated at the system to evaluate its impact on the signals. The baseband waveforms were re-sampled at 125 MSample/s to accommodate the Gigabit Ethernet limitation. The implemented DUC was a 32-fold interpolation three stage lowpass filter, the stages were a halfband interpolator with interpolation factor 2, a Cascaded Integrator–comb (CIC) compensator with interpolation factor 2 and a CIC interpolator with interpolation factor 8. The DDC implemented the same structure in reverse, decimating instead of interpolating the received signal by 32. Figure 4 shows the magnitude response of the stages and the cascaded response of the DUC.

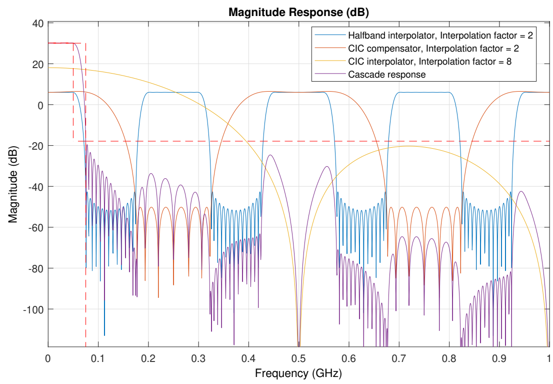


Fig. 4. Digital Up-converter filters magnitude response

## IV. RESULTS

Figure 5 shows the received waveforms in the time domain after demodulation. As can be seen some quantization and thermal noise was added and the demodulation lowpass filter removed some of the higher frequency components making the gibbs phenomenon apparent but other than that their shape, i.e. their duration, rise and fall time and phase shifts, remain the same. An attenuation due to the cables used can also be noticed.

Figure 6 shows the same waveforms in frequency domain. Aside the cable attenuation no noticeable distortion is present in the Long Pulse, Barker Code and Chirp Spectrum and only some minor noise is present in the Short Pulse Spectrum.

Finally Figure 7 compares the matched filter output of the demodulated waveforms, in blue, with that of the numerically generated waveforms, in red. Again the shape is preserved in all of them being noticeable only the attenuation due to the cables.

Seeing the results of Figures 5, 6 and 7 it is clear that the Direct RF Signal Generation explored in this paper produces waveforms strongly correlated with the original numerically generated ones.

Due to the limitations of maintaining a high sample rate an alternative approach with the use of a DUC and DDC was also explored as explained in the previous section. Figure 8 show the resulting Demodulated Down-converted Waveforms in time domain. The use of a DUC and DDC means that an even higher number of high frequency components are rejected, as shown in Figure 4, making the gibbs phenomenon much more pronounced. The lower sampling frequency also means that the end of the up chirp signal is less well resolved, meaning that not all crests and troughs are sampled, giving the impression of a "dented" waveform, even though the 125 MHz sampling frequency used is more than enough to satisfy the nyquist criterion. Other than that the cable attenuation is also present but the waveforms do preserve their overall shape.

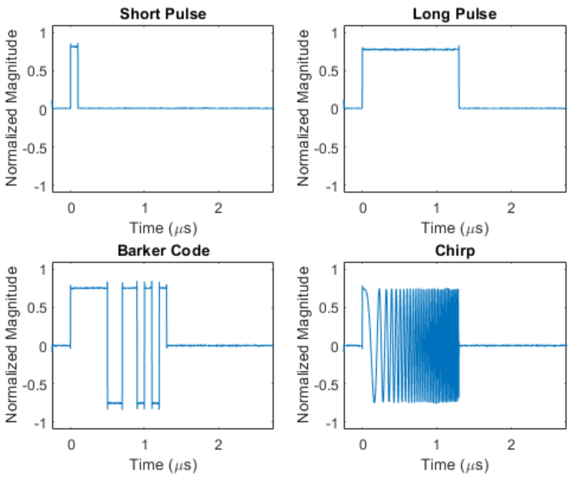


Fig. 5. Demodulated Waveforms

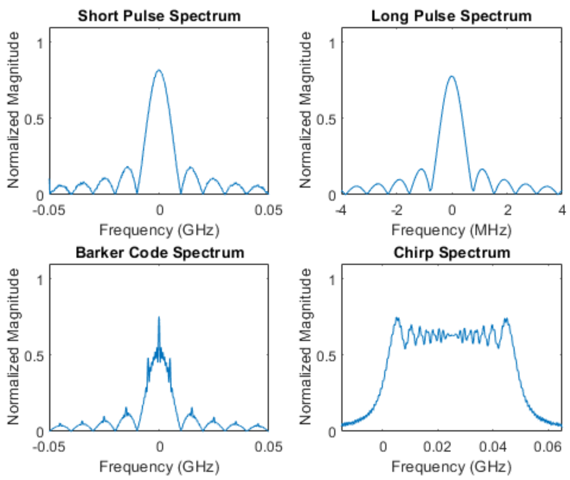


Fig. 6. Demodulated Waveforms Spectrum

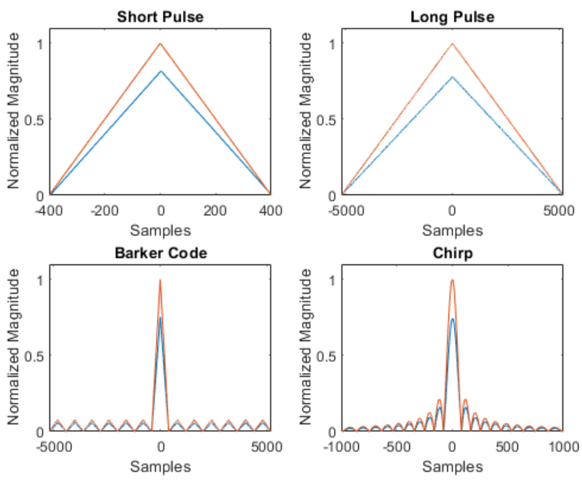


Fig. 7. Matched Filter Output

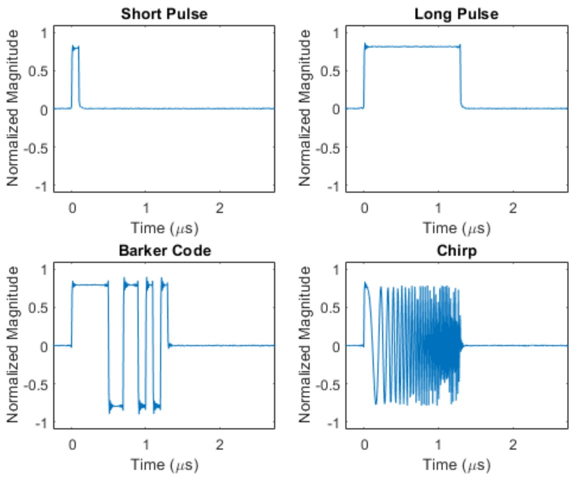


Fig. 8. Demodulated Down-converted Waveforms

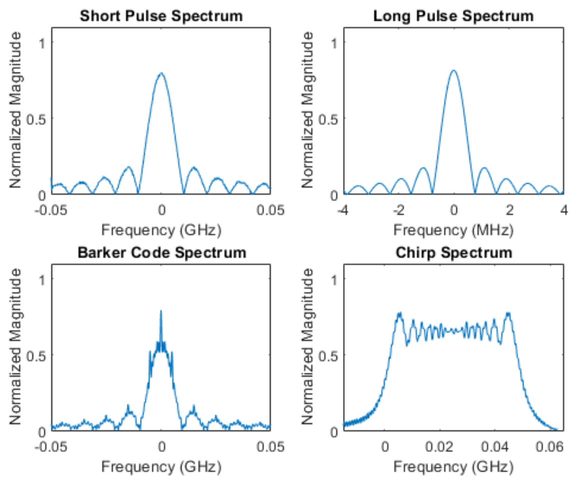


Fig. 9. Demodulated Down-converted Waveforms Spectrum

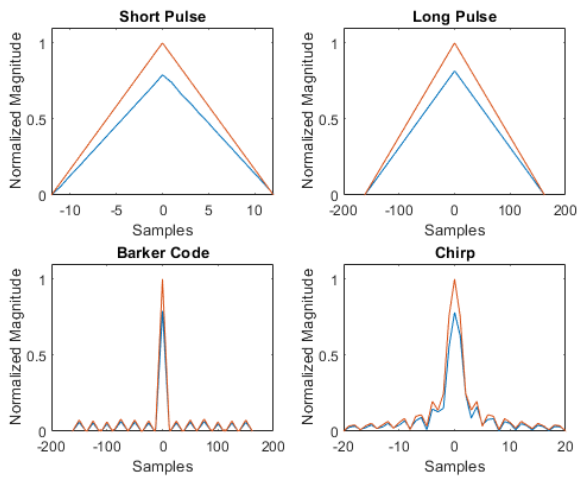


Fig. 10. Down-converted Waveforms Matched Filter Output

Figure 9 shows the demodulated down-converted waveforms spectrum. It is very similar to the demodulated waveforms spectrum without the use of DUC and DDC with only a slight increase in the Barker Code Spectrum noise beyond the main lobe.

And lastly Figure 10 compares the matched filter output of the demodulated down-converted waveforms, in blue, with that of the numerically generated waveforms, in red. The chirp's matched filter output is noticeable less well defined due to the lower number of samples used both in the numerically generated and in the down-converted waveforms but other than that and the attenuation due to the cables the matched filter outputs are very similar to that of the non digitally up and down converted waveforms.

Comparing Figures 5, 6 and 7 with 8, 9 and 10 shows that the use of a DUC and DDC in this implementation had little impact on the signal while contributing with the reduction on computing and connections throughput needs.

## V. Conclusion

This paper explored the Direct RF Signal Generation, meaning that all the process from baseband waveform synthesis till its mixing with the final RF carrier frequency was conducted in software. All hardware used were COTS products. The system for the direct RG signal generation consisted of a PC running Matlab scrips to numerically generate four different waveforms, a short pulse, a long pulse, a barker code with lenght 13 and a LFM.

The waveforms were loaded into an AWG for analog convertion and then conducted trough cables into a DSO for capture and digitization. The captured waveforms were then sent back to the PC for digital matched filtering and analyses.

It was show that using the described setup the signals generated were highly faithful to their numerically generated counterparts being degraded only by the cable attenuation and by quantization and thermal noise.

Since the setup used a high sampling rate to resolve the L-band carrier frequency an alternative setup was developed with the use of a DUC and DDC to lower the sampling rate requirement for processing and signal transfer. This alternative setup showed little degradation on the signals compered with the previous one.

This paper demonstrated the flexibility of the SDRadar concept and the viability of Direct RF Signal Generation. Future works will focus on implementing a full radar loop and on simulating target signals.

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