Radar signal generation and acquisition based on USRP: practical implementation and verification

Article · September 2013

2 authors:

Robert Kedzierawski
GMV

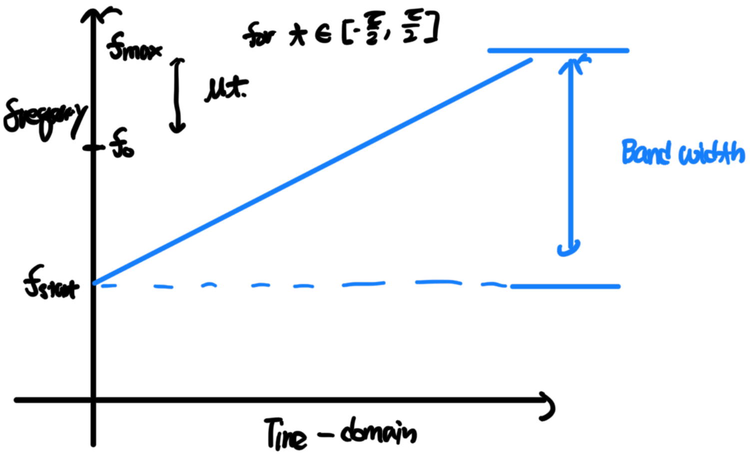
Pawel Kaczmarek
Military University of Technology

~> chirp signal (linear frequency modulated signal)

1. phasor equation

$f(t) = f_0 + \mu t \quad \forall t \in [-\frac{\tau}{2}, \frac{\tau}{2}]$, where f_0 is the center frequency of pulse

for up-conversion



Then $f(t)$ goes to by fourier transformed in time domain :

$s(t) = a(t) \cdot \cos(2\pi f(t) \cdot t + \theta)$

mixer를 2번 통과하는 경우 ($\because \cos^2\theta = \frac{1}{2} + \frac{1}{2}(\cos 2\theta)$)

time domain에 대해서 shift가 이뤄진다.

※ $\pi/2$의 delay로 I 과 Q를 분리해서 각 phase의 data를

Radar signal generation and acquisition based on USRP : practical implementation and verification

(Generacja i akwizycja sygnałów radarowych z wykorzystaniem USRP: praktyczna implementacja oraz weryfikacja)

mgr inż. ROBERT KĘDZIERAWSKI, mgr inż. PAWEŁ KACZMAREK

Military University of Technology, Faculty of Electronics, Warsaw

This paper presents a concept of use the Universal Software Radio Peripheral (USRP) as a generator of commonly used radar signal. Advantages of USRP with respect to commercial and dedicated Software Defined Radar (SDR) hardware solutions includes low cost, small dimensions, satisfactory level of hardware configuration by module replacement and easy way of programming. USRP devices are mostly realized as a measuring instrument connected directly to the computer (PC or portable computer) via Gigabit Ethernet interface or USB cable. Generally, the included drivers and software allows to use the USRP in a variety of programming environment such as C/C++ or math-oriented software.

This paper is organized as follows. Section I presents features of chosen USRP-2920, provided by National Instruments. In this section, the USRP is characterized in terms of its application as a radar signal generator. Section II shows the results of the generation of the basic types of signals used in radar system. Simple pulse signal, signal with Linear Frequency Modulation (LFM) waveform and Stepped-Frequency (SF) waveform were selected for generation. Section III addresses the results of generation and registration of LFM pulse train. Section IV concludes the paper.

USRP SYSTEM

Currently a wide range of USRP devices are available at a relatively low price. Most of them are in the form of development kits (i.e. evaluation board or USB key), but same are also sealed within the cover where all inputs and outputs are located on the front panel. In addition, each USRP device is explicitly dedicated to different field of applications.

An example of Universal Software Radio Peripheral device is National Instruments USRP-2920 [1], presented in Fig. 1. It is a similar device to the Ettus Research™ USRP N200/N210. USRP-2920 has tunable center frequency value from 50 MHz to 2.2 GHz, which covers a VHF/UHF, P, L band of radar frequency. The instantaneous bandwidth is limited only to 40 MHz

Fig. 1. Front view of NI USRP-2920.
Rys. 1. Widok z przodu NI USRP-2920.

which significantly limits the use of USRP to the narrow-band system. The USRP can simultaneously transmit and receive a signal into two parallel sessions, referred as *Tx* and *Rx* session. Different carrier frequency can be set to particular session and it can be changed during the session. Additionally, for each session parameters can be determined and changed separately. Range of gain control is from 0 to 31 dB and from 0 to 31.5 dB for *Tx* and *Rx* session, respectively. Gain represents the total aggregate gain applied to the signal. According to the device specifications, frequency accuracy of device is equal to 2.5 pps. Incorporation of an external reference source provides a more precise frequency reference clock and leads to better frequency accuracy. Drivers and tools included with the device allow to configure the device. Useful feature is support of .m file by *MathScript RT Module*, which allows, for example, on easy generation of plots using the math-oriented, textual commands.

USRP-2920 is based on FPGA structure, Xilinx® Spartan® 3A-DSP 3400. Generation and registration of the real-world signals take place through a dual 400 MS/s 16-bit DAC and dual 100 MS/s 14-bit ADC. New generation of USRP-293x have integrated GPS receiver for improving clock precision, positioning and synchronization issues.

According to manufacturer declaration, USRP is intended for the FM broadcast, GPS and GSM applications, affordable teaching and research solution. Additionally, many reports describing the use of USRP (of all types and manufacturer) is available on the internet. Most of these reports present the results of final project of M.Sc. study where USRPs were used as a development platform.

GENERATION OF RADAR SIGNAL

Nowadays, most radar system use the two basic type of probing signal [2-6]. Pulse signals (mono-pulse or with internal modulation) represent one type of radar signal. The second type are signals with stepped frequency modulation. Fig. 2 presents frequency changes in three commonly used radar signal. i.e. Radar pulse, Linear Frequency Modulated (LFM) waveform and Stepped Frequency (SF) waveform. Mathematical formulas of commonly used radar signals and results of its generation are given below. Signal registration at RF and verification were made in a laboratory using a Agilent Technology DSO7104A digital storage oscilloscope.

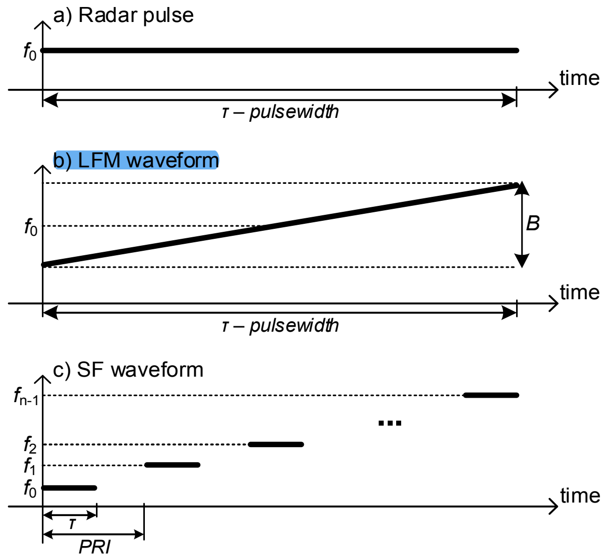


Fig. 2. Frequency changes in radar signals.
Rys. 2. Zmiany częstotliwości w sygnałach radarowych.

Radar pulse

The simplest radar signal *s*(t) is given by

$$s(t) = a(t)\cos(\omega_0 t + \varphi_0), \quad 0 \le t \le \tau, \qquad (1)$$

where *a*(t) is an amplitude of pulse envelope, $\omega_0 = 2\pi f_0$ is signals pulsation in radian per second, f_0 is carrier frequency, *t* denotes time, φ_0 is an initial phase and τ is a time duration of the signal. Carrier frequency f_0 of radar pulse is constant through pulse duration (see Fig. 2a). Fig. 3 shows a results of radar pulse generation registered on the oscilloscope, for *a*(t) = *A* = 1, f_0 = 155 MHz, φ_0 = 0 rad and τ = 1.75 μs.

Linear Frequency Modulated waveform

Linear Frequency Modulated (LFM) pulse is commonly used in radar to achieve more wide operating bandwidths. In LFM radar signal, the frequency is swept linearly across the pulse width τ in the sweep bandwidth *B*. Linear frequency change can be either upward or downward. For upward (up-chirp) instantaneous frequency is given by (see Fig. 2b):

$$f(t) = f_0 + \mu t, \quad -\frac{\tau}{2} \le t \le \frac{\tau}{2}, \qquad (2)$$

where f_0 is center frequency of pulse and $\mu = B/\tau$ is LFM modulation coefficient. LFM pulse is given by:

$$s(t) = a(t)\cos(2\pi f(t)\, t + \varphi_0), \quad -\frac{\tau}{2} \le t \le \frac{\tau}{2}. \qquad (3)$$

Fig. 4 shows results of the LFM radar pulse generation registered on the oscilloscope, for a(t) = 1, f_0 = 155 MHz, φ_0 = 0 rad and τ = 1.75 μs and B = 5 MHz.

Stepped Frequency waveform

Stepped Frequency (SF) signal is represented by series of *n* narrow-band pulses which are transmitted consequently. Pulse Repetition Interval is *T* and the pulse width is τ, $T > \tau$. The frequency from pulse to pulse is changed stepwise by a constant frequency step Δf according to a formula (see Fig. 2c):

$$f_i = f_0 + i\Delta f, \quad i = 0, ..., n-1, \qquad (4)$$

where is f_i is a frequency of ith pulse, f_0 is an initial frequency of SF waveform. Single pulse s_i(t) from the pulse train is a simple radar pulse and is given by:

$$s_i(t) = a_i(t)\cos(2\pi f_i t + \varphi_{i0}), \quad 0 \le t \le \tau. \qquad (5)$$

Fig. 5 shows results of the SF waveform generation registered on the oscilloscope, for n = 3, f_0 = 148 MHz, Δf = 1 MHz, τ = 1.25 μs and T = 1.75 μs. Equivalent time duration of SF waveform is 5.25 μs.

Summary

All selected signals were generated correctly. Analysis of graphs leads to the general opinion that despite the significant limitations of hardware and expect of its another original application, the USRP device can be used as a transmitter in radar system. Naturally, several remarks appeared. Firstly, gain curve for *Tx* session is strongly nonlinear and probably non-monotonic, local minima and maxima occur. Nonlinear gain is highly visible in LFM (Fig. 4) and SF (Fig. 5) waveform, especially on the level of LFM waveform amplitude (Fig. 4). Amplitude at the beginning and ending of the LFM pulse is fairly lower than maximum amplitude of

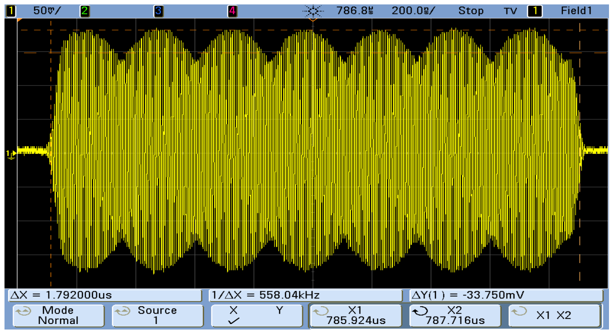


Fig. 3. Radar pulse, f_0 = 155 MHz.
Rys. 3. Impuls prosty, f_0 = 155 MHz.

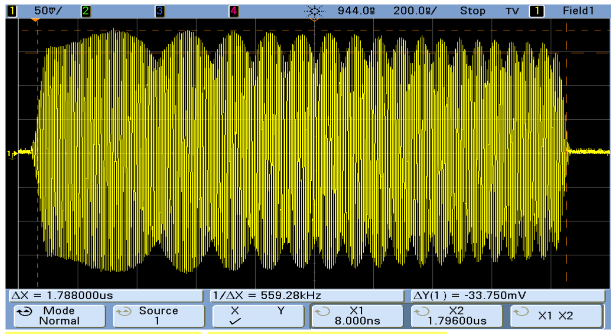


Fig. 4. LFM pulse, f_0 = 155 MHz, *B* = 5 MHz.
Rys. 4. Sygnał LFM, f_0 = 155 MHz, *B* = 5 MHz.

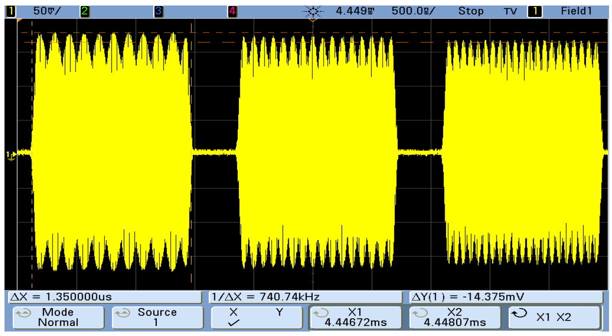


Fig. 5. SF pulse, f_0 = 155 MHz, *n* = 3, Δf =1 MHz.
Rys. 5. Sygnał SF, f_0 = 155 MHz, *n* = 3, Δf = 1MHz.

pulse, such considerable changes occur lengthwise $B = 5$ MHz bandwidth. Similarly for SF (Fig. 5) waveform, the level of amplitude for individual narrow-band pulse is constant over i^{th} pulse duration, however, the amplitude of the consecutive pulses slightly decreases from pulse to pulse with Δf = 1 MHz. Gain calibration curve is required to be measured in the whole frequency range and with high accuracy in order to compensate an inhomogeneous gain. Secondly, IQ rate, i.e. sample frequency F_s for IQ components, does not allow for the generation of the quadrature component over a wide frequency range in a base-band. Maximum obtained value during verifications, F_s = 33.333 MHz (equivalent to sampling period T_s = 30 ns) allows for generation of baseband signals roughly up to B_n = 15 MHz bandwidth to satisfy the Nyquist–Shannon sampling theorem. Furthermore, the value of the center frequency coerced by device in some cases is slightly different from the required value. Finally, the data transfer rate between PC-host and USRP device strongly depends on the PC-host.

GENERATION AND REGISTRATION OF LFM PULSE TRAIN

Fundamental task of experiment was to measure and evaluate the quality of registration capability of RF signals and their down-conversion into IQ quadrature components in baseband. Similarly as for *Tx* session, the *Rx* session has been incorporated into project and started simultaneously with *Tx*. The same value of timestamp is loaded to the time counter to provide synchronization between two parallel sessions. Trigger for generation and registration of samples takes place at the same time. To provide additional coherence (an identical representation of the samples in time) between *Tx* and *Rx* data the same value of IQ rate (T_s = 30 ns) has been set for both sessions. Unfortunately, uncompensated gain curves (for *Tx* and *Rx* session) and lack of sufficient area for out-door measurement forced to perform measurements using the transmission line coupling. In such configuration, only irregular gain will affect the result of the measurement.

SF waveform designed for a single measurement consists of transmission of the *n* narrowband LFM pulses in the pulse trains, where the f_i center frequency of i^{th} pulse is changed stepwise from pulse-to-pulse with Δf, and B_n bandwidth of each narrowband LFM is equal to the Δf. Fig. 6 presents an idea of Linear Modulate Stepped Frequency (LMSF) waveform formation. Total bandwidth B_c of transmitted pulse train is distributed symmetrically around the F_c center frequency, which is given by

$$F_c = f_0 + \frac{n-1}{2}\Delta f\,, \qquad (6)$$

where is f_0 is a center frequency of first LFM pulse, *n* is a number of individual pulse in pulse train. Due to the narrow instantaneous band of USRP device, generation and transmission LMFS waveform was split into the *n* independent generation and transmission of LFM pulse. Backscattered complex echo (IQ samples in baseband) for independent i^{th} pulse was stored separately within the measurement matrix. Synthesis of

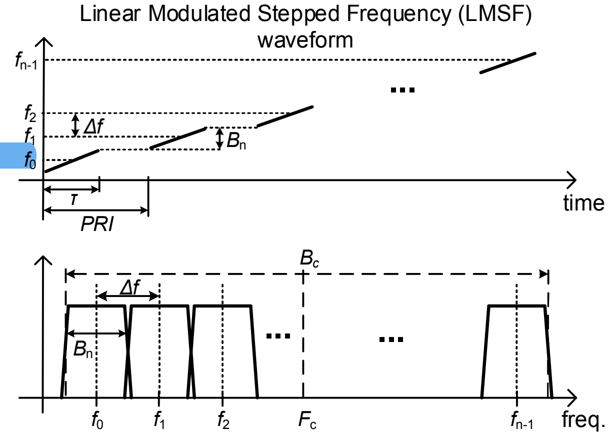


Fig. 6. Linear Modulated Stepped Frequency waveform.
Rys. 6. Sygnał ze skokową liniową zmianą częstotliwości.

UWB signal and its post-processing has been carried out after collection IQ samples for all *n* independent measurements. The following values of LMSF parameters have been chosen: B_n = 5 MHz, f_0 = 1.0 GHz, n = 3. Therefore, B_c = 15 MHz, F_c = 1.0075 GHz and equivalent range resolution $\Delta R = c / 2B_c \approx 10$ m.

Syntesis of the LMSF signal

Fig. 7 presents the signals (*IQ* samples) recorded in $n = 3$ consecutive acquisitions, where B_n = 5 MHz and $\tau = 1$ μs. Irregular gain is visible, time delay T_d is constant for each pulse regardless of the f_i center frequency, T_d = 0.510 ns. Based on the Synthetic Range Profiling (SRP) processing [7] the LMSF signal has been synthesized from $n = 3$ pulses. SRP consists of three steps: frequency-shift, phase correction and time-shift. Additionally, upsampling operation by a factor of *n* also can be performed. Fig. 8 presents a spectrum of the synthesized signal and the expected spectrum of the reference signal. The reference signal has been designed on the basis of $T_n = n\tau = 3$ μs, and $B_c = nB_n$ = 15 MHz used in the matched filter. Both

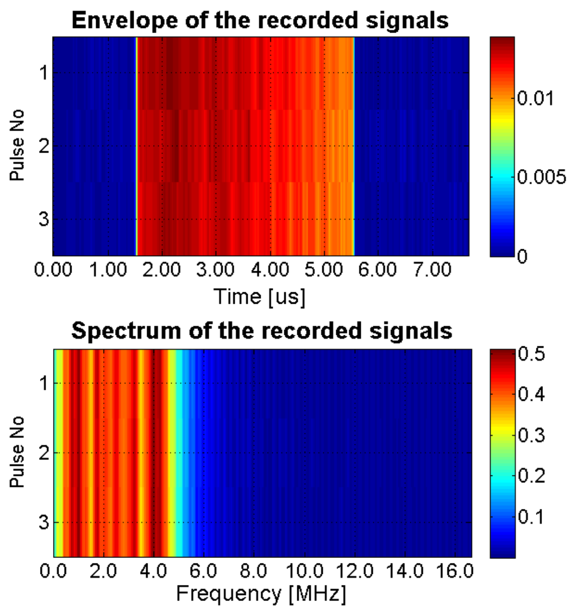


Fig. 7. Pulse train of narrowband signals recorded in experiment.
Rys. 7. Ciąg impulsów wąskopasmowych zarejestrowany podczas eksperymentu .

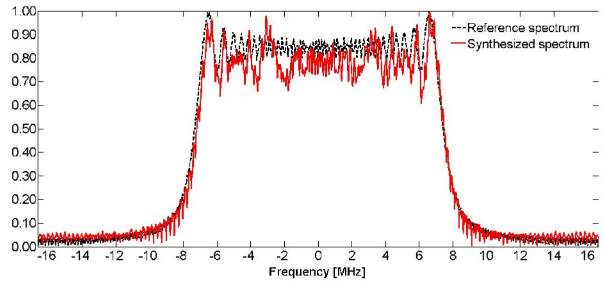


Fig. 8. Comparison of signals spectrum.
Rys. 8. Porównanie widm sygnałów.

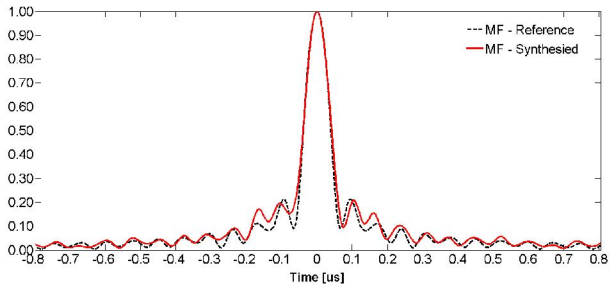


Fig. 9. Results of matched filtering.
Rys. 9. Wynik filtracji dopasowanej.

spectrum have the same width. Spectrum of the synthesized signal is highly variable in module. Results of matched filtering is shown in Fig. 9. Width of the main lobe is identical. The obtained curve for synthesized signal is symmetrical and has a slightly higher level of first side lobes than reference curve.

CONCLUSION

In this paper the results of radar signal generation and registration were presented. All types of radar signals selected for testing were successfully generated and verified in a laboratory test stand. Additionally, the experiment with the designed radar signal (LMSF) have been successfully performed. The results showed that USRP device can be successfully used to fast radar designing, prototyping and testing. Despite the many hardware limitations, i.e. relatively low frequency accuracy, limitation of instantaneous bandwidth, a relatively low sampling frequency of IQ quadrature components in Tx and Rx session, the USRP device may be considered for research solution that helps to verify the theoretical assumptions and with practical measurements.

ACKNOWLEDGMENTS

This work was financed by the Military University of Technology from sources for young scientists under projects RMN-874/2013.

REFERENCES

[1] NI USRP-2920 Specifications, http://www.ni.com/pdf/manuals/375839a.pdf

[2] Nadav Levanon, Eli Mozeson: Radar Signals, John Wiley & Sons, 1st edition (Sep. 21, 2004).

[3] Mark A. Richards: Fundamentals of Radar Signal Processing, McGraw-Hill; 1st edition (June 24, 2005).

[4] James D. Taylor: Ultrawideband Radar: Applications and Design, CRC Press, 1st edition (May 18, 2012).

[5] Levanon, N.: Stepped-frequency pulse-train radar signal, IEE Proceedings Radar, Sonar and Navigation (Volume:149 , Issue: 6), pp. 297 – 309 (2002).

[6] Bassem R. Mahafza: Radar Systems Analysis and Design Using Matlab, Chapman & Hall/CRC, 1st edition (2005).

[7] Lord R.T., Inggs M. R.: High range resolution radar using narrowband linear chirps offset in frequency, *Proceedings of the 1997 South African Symposium on Communications and Signal Processing COMSIG '97*, pp. 9-12, 09-10.09.1997.