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DDS based Pulse-Doppler Radar Transmitter Simulator

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Abstract— **In this paper, radar transmitter simulator based on direct digital synthesis has been presented. We focused our attention toward class of pulse-Doppler radars. In general case, radar transmitter simulator has important role in radar receiver testing. Therefore, flexible and agile simulator provides estimation of overall system performance. In the first step, basic simulator concept has been described. After that, system is decomposed in basic structures, analyzing each module separately. Model of radar transmitter is implemented by means of software defined radio paradigm. Pulse time diagrams and spectrum are measured and shown.**

Keywords – Radar transmitter simulator, Direct digital synthesis, Pulse-Doppler radar.

I. INTRODUCTION

THE radar technology gained tremendous boots in recent years as a result of digital electronic rapid development. Modern software defined modules replace old analog parts. Higher computational and processing powers were obtained [1]. Still, when it comes to the testing, situation remained the same. In general case, radar system is complex, which fundamental parts are transmitter and receiver [2]. In order to test and estimate overall performance of the radar receiver, having radar transmitter simulator is suitable.

In this paper, we analyze only Pulse-Dopler radars, therefore other types of radars are beyond the scope of this paper. Pulse-Doppler radar transmits short pulses at the radio frequencies. Transmitted pulses are partially reflected back by static and moving objects. The energy returned from pulses are combined using Doppler effect based signal processing to extract the information. Using short pulses instead of a FM continuous wave has several advantages [3]. First, we avoid risk of overloading computers and operators. Furthermore, power consumption is reduced compared to case where FM continuous wave is used. In particular, power emission and weight of the radar are reduced. It is worth mentioning that this particular type of radar has improved detection in high clutter environment and greater tracking ability using feedback. In order to test these functionalities, agile radar transmitter simulator is of utmost importance. Hence, one might say that simulator is inevitable part of every radar system. This is especially significant when it comes to the estimation of overall radar performance. Therefore, this paper deals with concept of flexible and efficient DDS based radar transmitter simulator solution. Also, having radar transmitter simulator is particulary convinient from the standpoint of moving target indication (MTI) [4] and constant false alarm rate (CFAR) [5] functional testing. MTI is radar's mode of operation to discriminate a target against clutter. CFAR detection refers to adaptive algorithm to detect target returns against clutter, noise and interference.

This paper is divided into six sections. In Section II, basics of direct digital synthesis are presented. In section III, the concept of radar transmitter simulator is discussed. In section IV, underlying concept of operation is considered. Section V is reserved for modeling and simulation of radar transmitter simulator. In section VI, we concluded this paper.

II. DIRECT DIGITAL SYNTHESIS

As it was mentioned in introductory part, suggested radar transmitter simulator is based on direct synthesis in digital domain. Therefore, the DDS acronym stands for ability for digital domain generation of frequency-agile tone with outstanding level of residual phase noise [6]-[8]. Direct digital synthesis is frequency synthesis that produces arbitrary signal waveforms from fixed-frequency reference clock.

Basic building blocks of direct digital synthesizer are: Numerically-controlled oscillator, reference oscillator and digital-to-analog converter [9]. Reference oscillator provides reference clock for the whole system. Resolution of direct digital synthesizer is determined by this clock. It also provides clock for numerically-controlled oscillator, which generates discrete-time, quantized version of desired signal waveform which period is defined by digital word written to the frequency control register. Sampled signal is than passed throw digital-to-analog converter and filtered by lowpass reconstruction filter. At the output of direct digital synthesizer, analog signal appears.

Significant feature of DDS is existence of profiles. A profile is an independent register that contains the DDS signal control parameters. The DDS signal control parameters (frequency, amplitude and phase) are supplied directly from the programming registers. Number of profiles depends on particular DDS chip. Eight profile registers are available with DDS used in this design. Each profile is independently accessible using three external profile pins to select the desired profile.

III. RADAR TRANSMITTER SIMULATOR ARCHITECTURE

Pulse-Doppler radar transmitter simulator is based on direct digital synthesizer controlled by microcontroller unit (MCU). At the moment, there are DDS component able to generate signals up to 1.5 GHz. In this paper, we considered direct digital synthesizer with output frequency up to 400 MHz and high frequency resolution (~0.23 Hz). MCU based on 16/32 bit ARM7TDMI-S™ architecture is used [10], [11]. MCU communicates with DDS via SPI bus. DDS used in this particular design is double buffered chip. Bytes sent by MCU are loaded into serial I/O buffer of DDS. Data contained in serial buffer are inactive. Therefore, MCU needs to send strobe signal in order to transfer data from serial buffer to active registers of DDS. Block diagram of direct digital synthesizer is shown on figure 1.

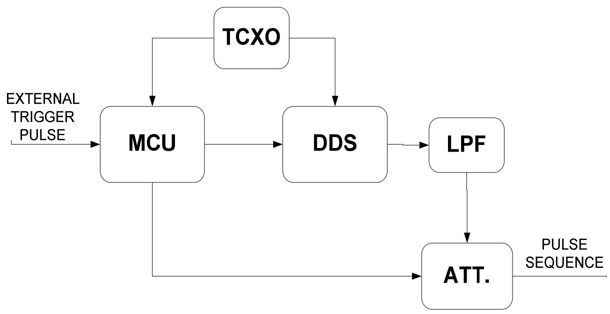

Fig. 1. Block diagram of radar transmitter simulator

On the DDS output, lowpass filter is placed. Therefore, rejection of images is provided. Also, digitally-controlled attenuator is needed in order to adjust output signal level. MCU and DDS are synchronously clocked by TCXO. This approach provides conditions to generate various waveforms and modulation types [12], [13].

IV. THEORY OF OPERATION

Theory of radar systems is concisely formulated through the radar range equation which represents the physical dependences of the transmitted power:

$$\frac{P_R}{P_S} = \frac{G\sigma}{4\pi R^2} \tag{1}$$

where:

- P_R is reflected power [W],
- P_S is transmitted power [W],
- σ is radar's cross section [m^2],
- R is range from target [km],
- G is gain of antenna.

It is obvious from the above equation that received power directly depends on the transmitter power, range and the reflecting characteristics of the target.

Let us consider scenario with two targets, where the first target represents clutter (static object) with large radar cross sections at very high distance from the radar, and second, fast moving target with small radar cross section in proximity to the radar. Now, if we apply radar's range formula for both cases, we can obtain relative ratio of pulse amplitudes of the radar transmitter. In case where more than two pulses are simulated, the same logic is applied. We assumed some typical values for RCS (100-10000) and antenna gain, $G = 30\text{dB}$, which could be considered as typical value for this type of radars. Relative ratio of pulse amplitudes in function of ratio of target distances and ratio of target radar cross sections is shown on figure 2.

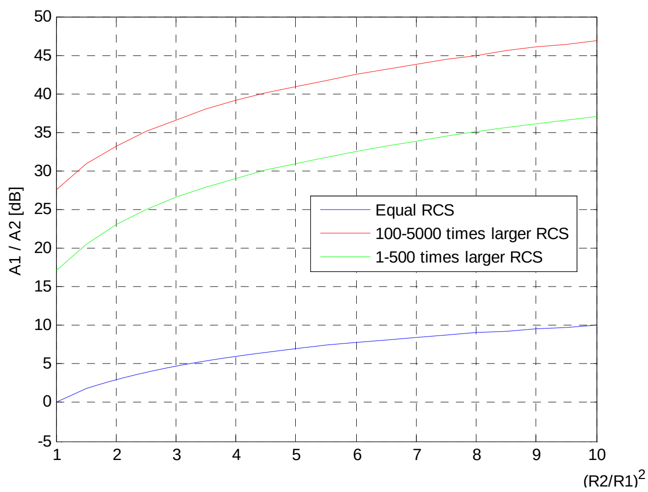

Fig. 2. Relative ratio of pulse amplitudes for two targets

Furthermore, if targets are moving, one must know radial speed. Hence, Doppler frequency can be obtained using expression:

$$f_{Doppler} = \frac{2v_r}{\lambda} \tag{2}$$

Now, we can summarize input and output parameters of the radar transmitter simulator. We can define distance from target, so as radar cross section and radial speed of the target. As for output parameters, relative amplitude and time position are obtained. Transmitter pulse sets reference level for which other pulses are calculated. It is supposed that level of transmitter pulse is 0 dBm. Amplitudes of pulses with dynamics of 100 dB can be obtained.

Underlying principle of radar transmitter simulator operation is based on direct digital synthesis of narrow pulses in exact time defined intervals. MCU defines time base for pulse generation. Given the fact that minimum resolution range is 150 m per microsecond, we can obtain resolution range above 900 m, if we have chosen pulse width to be $6\mu s$. In case when two objects are in larger proximity than 900 m, simulator cannot discriminate them. Only one object is seen on the radar screen, but received pulse will be outspread.

Simulator is triggered by external signal, which enters simulator into active state. Trigger signal is pulse train of strictly defined PRF. MCU is set to be rising-edge sensitive, therefore every trigger signal period causes interrupt. In general case, system can be set to be rising/falling edge sensitive or high/low level sensitive. When interrupt occurs, DDS generates pulses of defined width in particular time intervals. Each pulse is defined as a profile in DDS. Null profile is used to cancel other profiles. Therefore, using timer and null profile, various pulse widths could be synthesized. First pulse in the train represents radar transmitted pulse. Remain pulses represent reflected signal from static or moving objects. Amplitude of main pulse is larger than amplitudes of remaining pulses in the train. It is important to emphasize that amplitude and frequency of generated pulses are fully programmable. After pulse generation has been finished, MCU returns to the normal mode. Trigger signal period is not fixed, which provides great flexibility. Number and position of moving target and clutter are fully programmable. Also, velocity of moving target could be set to an arbitrary value. Direction of the target could be set towards or from the radar. Possible arrangement of the clutters and the targets is depicted on figure 3 (clutters are marked with blue color and targets with black color).

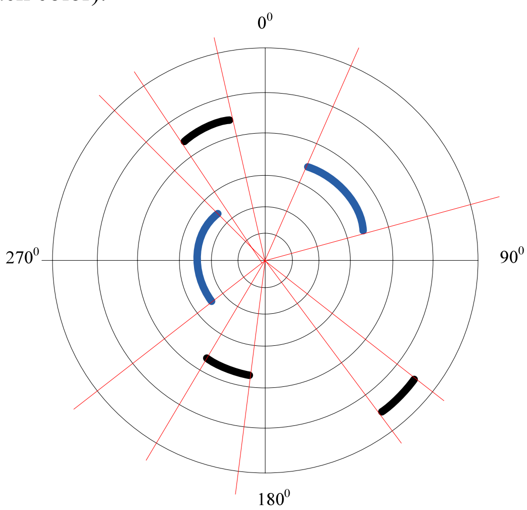

Fig. 3. Presentation of clutters and moving objects

Every pulse generated is presented by one frequency profile. In order to generate another pulse, the profile should be switched. Algorithm for switching profiles is central part of radar transmitter simulator. Based on strictly defined timings, profiles are alternated, and hence different pulses appear. It is important to emphasize that profile representing moving object has it phase changed with revolution of the radar scan. Phase is changed in discrete steps up to 360 degrees, after which it resets to zero. And the process is repeated again. Step of the phase change determines the velocity of the target. The larger the step of phase change, the higher the velocity of the target.

V. Modeling and Simulation

Radar transmitter simulator is implemented by means of software defined model on the hardware platform described in previous section. Software defined architecture of simulator can be divided into three basic parts. First part deals with trigger signal which acts as external interrupt. When system is triggered, transmitter pulse is generated. Second part is computational one, where amplitude coefficients are being calculated. Furthermore, preparation of signal profiles, as well as timing calculations are here performed. As for the third block, its function is to act as a supervisor of the system.

We considered case where pulse width is 6 microseconds. Also, we adopted pulse repetition frequency of 300 Hz or 3.3 milliseconds. This value is provided by radar system which was tested. Carrier frequency of the transmitter pulse at the output of the radar is 10.7 MHz. In addition to this, it is worth mentioning that the echo pulse amplitudes decay with the square of the distance of the target. Transmitter pulse in time domain is shown on figure 4.

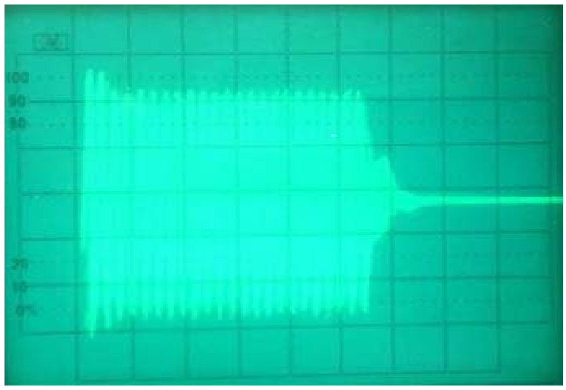

Fig. 4. Pulse in time domain.

Width of the pulse is programmable variable. Minimum value for pulse width is around 1 microsecond. This limit value satisfies requirements for many types of radar in exploitation; therefore presented solution for radar transmitter simulator is widely applicable. Pulse train in time domain is shown on figure 5.

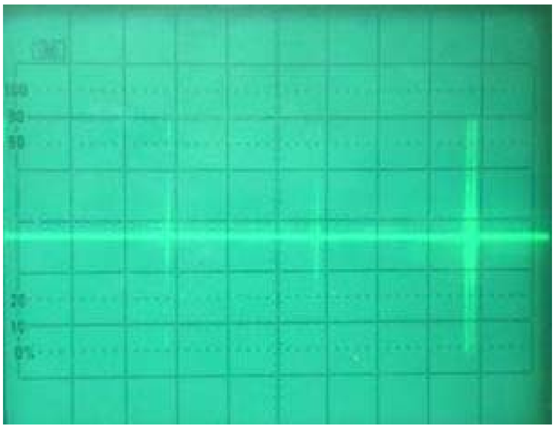

Fig. 5. Pulse train during one trigger period.

In order to present realistic target movement on tracking screen, certain pulses (ones that represent moving targets) have to disappear and reappear periodically at different locations on the screen. To provide this functionality, simulator counts radar transmitter pulse as a reference point, and based on that determines where target should appear. Using radar transmitter simulator, functionality of receiver's MTI could be tested. Whereas static objects (clutter) have fixed phase, MTI should erase them, leaving only moving targets. If this scenario does not occur, there is some issue with MTI. Also, receiver's CFAR functionality could be tested in similar fashion. Hence, many aspects of radar testing could be covered by means of this type of radar transmitter simulator.

Spectrum of the pulse train during one trigger period is shown on figure 6.

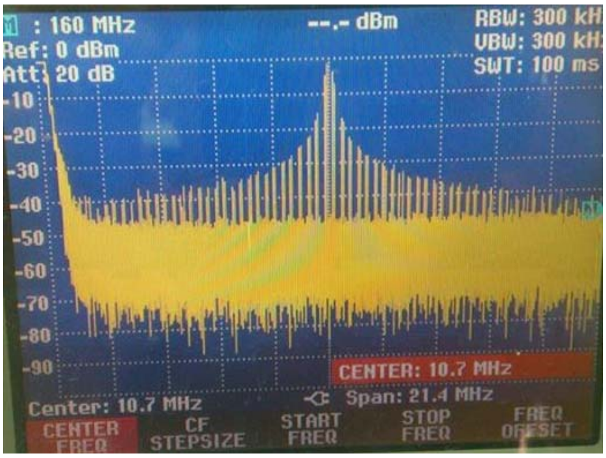

Fig. 6. Spectrum of pulse sequence.

As it was mentioned in previous sections, carrier frequency of the simulator is limited on 400 MHz as a consequence of Nyquist sampling theorem. To provide pulse generation at higher frequencies, up-converter needs to be utilized. This paper deals only with DDS baseband, but, however, further work should address scenarios at higher frequencies.

VI. Conclusion

In this paper, we described pulse-Doppler radar transmitter simulator. Signal generation was based on direct digital synthesis. Very flexible and agile direct digital synthesizer was used in conjunction with microcontroller unit. Therefore, very narrow pulses were synthesized. Upper frequency of simulator is limited on 400 MHz. In essence, presented radar transmitter simulator is combined software-hardware architecture of great flexibility that fits needs for many challenging demands in simulation and testing of radar components. Measurements were performed by means of spectrum analyzer and oscilloscope, where signals in frequency and time domain were observed. Presented simulator was used for estimation of radar receiver sensitivity. Further work and improvements of radar transmitter simulator are aimed toward providing conditions for testing different kinds of radar receivers, not only pulse-Doppler radar.

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