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Design and Implementation of Software-Defined Doppler Radar

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Abstract. **The subject of this article is a study of the possibility of practical implementation of a Doppler CW radar based on software-defined radio (SDR) technology. The paper presents overview of two technologies. Initially the architecture and basic characteristics of a Doppler CW radar are described, followed by an overview of SDR concept and types and characteristics of typical constructive elements for its realization. Finally, a practical implementation by usage of USRP front-end and the GNU Radio Framework is presented. For the successful implementation of the Doppler CW radar architecture an additional amplifier is included. The material presents the results of tests performed using the practical implementation of a Doppler CW SDR radar, demonstrating the functionality of the implementation.**

Keywords: Software-defined radio system, Doppler Radar; GNU Radio Framework.

I. INTRODUCTION

The Doppler radar is a specialized radar in which, based on the Doppler effect, the speed of a moving object is determined by the received reflected radar signal [1]. Depending on particular used technology, the Doppler effect is implemented in different ways depending on the functional purpose of the radar. Radars can be pulse-coherent, pulse-Doppler radar, continuous-beam Doppler radar, and frequency-modulated Doppler radar. The most used application of CW radars is as a motion detector. In the military field, CW radars are used to guide missiles .air-to-air with semi-active radar homing (SARH), such as the US AIM-7 Sparrow and the Standard family of missiles. Most modern air combat radars, including pulse-doppler, have a CW missile guidance function. In the presented material, the implementation of a continuous wave (CW) Doppler radar using the software-defined radio (SDR) paradigm is investigated.

II. PRINCIPLE OF OPERATION AND MODEL OF A DOPPLER CW RADAR

Doppler CW radar transmits an unmodulated radar signal of constant amplitude and frequency. Objects can be detected using the Doppler effect. When the observed object moves, the frequency f_r of the reflected signal is shifted from the transmitted frequency f_t, based on the Doppler effect. The difference in the frequency of the emitted and received signal reflected by the object of observation allows to measure the radial component of the object's movement speed relative to the radar. When this difference is positive, i.e. the frequency of the received signal a is higher than the frequency of the transmitted signal, the monitored object approaches the radar. At a lower frequency of the reflected signal, the object moves away.

The change in Doppler frequency depends on the speed of light c = 3.10^{-8} m/s and the speed v of the target. The frequency of the reflected signal is determined by the expression:

$$f_r = f_t\left(\frac{1+{}^{v}/_{c}}{1-{}^{v}/_{c}}\right) \qquad (1)$$

The Doppler frequency is defined as the difference between the frequency of the emitted and received signals according to the expression:

$$\begin{aligned} f_d &= f_r - f_t \\ &= 2v_t\left(\frac{f_t}{c-v}\right) \end{aligned} \qquad (2)$$

Since the change in the object's speed is negligible compared to the speed of light, the expression for f_d simplifies to:

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$$f_d \approx 2v\frac{f_t}{c} \qquad (3)$$

For the determination of the Doppler frequency in continuous-radiation radars, the phase difference φ between the emitted and reflected signals is measured. For a sinusoidal signal, the phase difference is equal to the ratio of the distance travelled by the signal to the wavelength multiplied by (2π). The multiplier (2π) corresponds to the phase difference at which the signal propagates over a distance equal to the wavelength. If the distance to the object does not change, the phase difference remains constant.

If the distance to the object changes at a certain constant rate relative to the radiating forward antenna, the phase difference will also change as a function of time.

A time-varying phase difference between two sinusoidal signals of different frequencies, which is constant over the measurement interval, has a sinusoidal character. The frequency of this sine wave can be measured and is equal to the Doppler frequency. In most cases, this frequency is in the low frequency range. If the radiation frequency is constant, this Doppler frequency is proportional to the object's radial velocity.

The implementation of a Doppler CW radar is usually done either by a direct frequency conversion receiver (homodyne receiver) or by a heterodyne receiver [1].

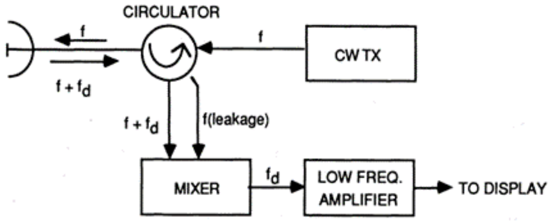


Fig. 1. Block diagram of a Doppler radar with a direct frequency conversion receiver.

The implementation by a direct frequency conversion receiver is very simplified (Fig.1.) [1], but with this solution, the sensitivity of the receiver is limited. Randomly distributed low-frequency noise is superimposed on the Doppler frequency, so weak signals corresponding to low Doppler frequencies cannot be evaluated.

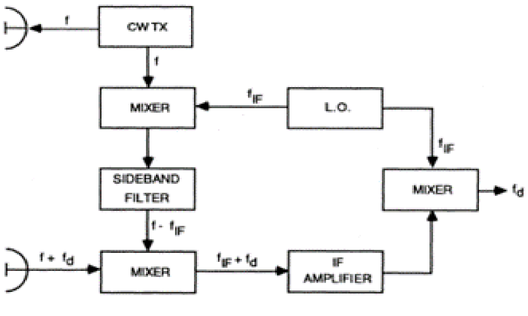


Fig. 2. Block diagram of a Doppler radar with a superheterodyne receiver.

A significant improvement in sensitivity is achieved by implementing a superheterodyne receiver (Fig.2)[1]. With this schematic solution, the echo signal is amplified by about 30-40 dB, where the low-frequency noise can be neglected.

The range of a Doppler CW radar is determined by the basic radar equation, taking into account all the quantities that affect the propagation of radar signals. For a given radar, most of the parameters can be considered constant, since their values vary within small limits. As is known [1] the lowest received power at which the reflected signal can be detected is called P_{emin}, also called receiver sensitivity. The value of P_{emin} determines the maximum range of the radar R_{max}:

$$R_{max} = \sqrt[4]{\frac{P_s\, G^2\, \lambda^2 \sigma}{P_{emin}(4\pi)^3 L_{ges}}} \qquad (4),$$

where P_s is transmitted power [W], G – antenna gain, L_{ges} – loss factor.

III. SOFTWARE-DEFINED RADIO SYSTEM CONCEPT

The foundations of the software-defined radio (SDR) paradigm are associated with research by DARPA and the US Air Force under Project SpeakEasy in the early 1980s to create a prototype radio covering the range of 2 MHz to 2 GHz and implementing about 10 communication standards [2]. Part of the obtained results in the field of system architecture were published by Mitola in the early 1990s, where the author introduced the concepts of "software radio" [3,4] and "software-defined radio"[5]. The successful development of a prototype of a software-defined radio station under the SpeakEasy project is a prerequisite for the launch of a large-scale program of the US Ministry of Defence under the name "Joint Tactical Radio System" (JTRS). JTRS aims to create a common radio station for all types of armed forces and branches of forces and supports over 30 radio communication protocols [6]. Software-defined radio technology has proven its viability, continues to generate significant interest, and is the basis of such paradigms as "cognitive radio station" [7], "cognitive radar" [8] and others.

Software-defined radio is radio in which some or all of the physical layer functions are software defined. This technology allows agility in the architecture of transceiver and radio communication network as a hole [2]. Generalized block scheme of SDR is shown in Fig.3.

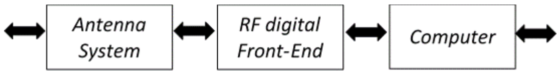


Fig. 3. SDR block scheme.

The architecture of typical SDR consists of antenna system, radiofrequency (RF) front-end and general-purpose computing device (computer). RF front-end performs quadrature modulation/demodulation, analog-to-digital/ digital-to-analog conversion (ADC/DAC) and basic digital processing, as digital up/down conversion (DUC/DDC) decimation/interpolation, etc. Main digital processing is performed on the computer. Some of the popular applications, running on the computer and supporting SDR technology are GNU Radio, Matlab, LabVIEW, SystemVue, etc. GNU Radio is free and open-source framework, that allows usage of ready developed blocks for SDR and tools for writing new ones.

As a result of the transition of the SDR concept into a real product of our time, today there is a variety of platforms with different technical characteristics on the market. Table 1 provides an overview of the most popular platforms for building SDRs.

TABLE 1 SDR FRONTENDS, MAIN CHARACTERISTICS

Name	**Frequ-ency Range**	**Channel Bandwidth, MHz**	**Resolution ADC/DAC, bit**	**Interface type**
Hack RF One	10 MHz – 6 GHz	20	8	USB 2.0
Adalm PLUTO	325 MHz – 3.8 GHz	20	12	USB 2.0
Ettus B210	70 MHz – 6 GHz	56	12	USB 3.0
Ettus N210	10 MHz – 6 GHz	40	14/16	Ethernet
Ettus X210	1.2 GHz – 6 GHz	120	14/16	Ethernet, PCIe
Lime SDR	100 kHz – 3.8 GHz	61.44	12	USB 3.0
PicoSDR	70 MHz – 6 GHz	56	12	PCIe

The analysis of the data in Table 1 shows the presence of opportunities to support a wide frequency range - part of HF, VHF and UHF, a wide frequency band of the processed radio channel - up to 120 MHz, a high speed of data exchange with computer platforms - up to 10 Gbit/s, support for multiple coherent radio channels, etc. These characteristics allow the implementation of technologies such as GSM, LTE, DVB, CW/FM Radar, MIMO, etc.

Typical RF front-ends, available on the market for implementation of SDR, have direct conversion architecture (Fig.4.).

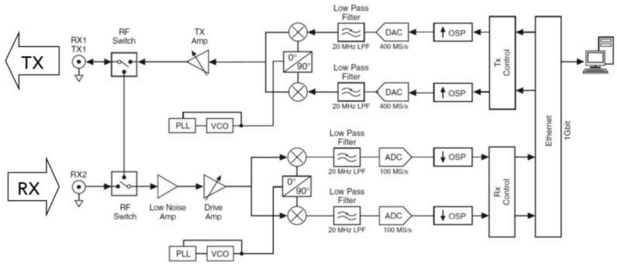


Fig. 4. Functional block diagram of SDR Front-end.

Such architecture of RF front-end is adequate for prototyping and proof of concept, but impose limitations, mainly on selectivity. Another characteristic to be considered in design process are low sensitivity of the receiver and low output power (under 6 dBm typically) of the transmitter.

IV. IMPLEMENTATION OF SOFTWARE-DEFINED DOPPLER RADAR

Based on concepts and models of Doppler radar and Software-Defined Radio System a real implementation of SDR Doppler Radar was made. Constructive view of system realization is shown in Fig. 5.

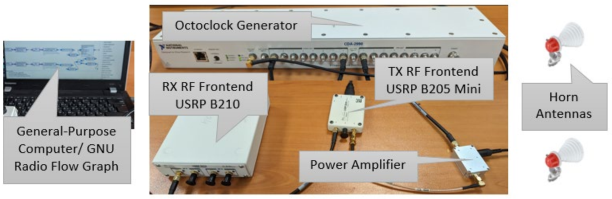
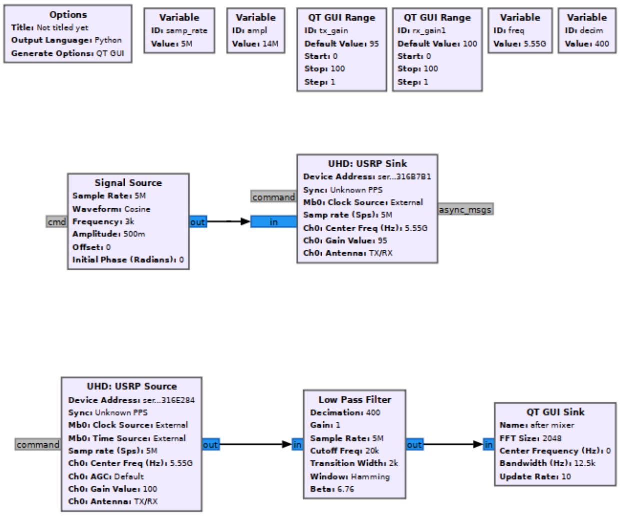


Fig. 5. Implementation of SDR Doppler radar. Constructive elements.

Main part are: Horn Antennas, TX Frontend USRP B205mini, Power Amplifier 10 dB, RX Frontend USRP B210, Common Reference Generator Octoclock, General-Purpose Computer, GNU Radio Framework, dedicated flowgraph for signal processing and interfacing with RF frontends.

In Fig.6. is shown the flowgraph for GNU Radio Framework, which performs CW generation and interfacing with TX/RX Frontends.



Options
Title: Not titled yet
Output Language: Python
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 5M

Variable
ID: ampl
Value: 14M

QT GUI Range
ID: tx_gain
Default Value: 95
Start: 0
Stop: 100
Step: 1

QT GUI Range
ID: rx_gain1
Default Value: 100
Start: 0
Stop: 100
Step: 1

Variable
ID: freq
Value: 5.55G

Variable
ID: decim
Value: 400

Signal Source
Sample Rate: 5M
Waveform: Cosine
Frequency: 3k
Amplitude: 500m
Offset: 0
Initial Phase (Radians): 0

UHD: USRP Sink
Device Address: ser...316B7B1
Sync: Unknown PPS
Mb0: Clock Source: External
Samp rate (Sps): 5M
Ch0: Center Freq (Hz): 5.55G
Ch0: Gain Value: 95
Ch0: Antenna: TX/RX

UHD: USRP Source
Device Address: ser...316E284
Sync: Unknown PPS
Mb0: Clock Source: External
Mb0: Time Source: External
Samp rate (Sps): 5M
Ch0: Center Freq (Hz): 5.55G
Ch0: AGC: Default
Ch0: Gain Value: 100
Ch0: Antenna: TX/RX

Low Pass Filter
Decimation: 400
Gain: 1
Sample Rate: 5M
Cutoff Freq: 20k
Transition Width: 2k
Window: Hamming
Beta: 6.76

QT GUI Sink
Name: after mixer
FFT Size: 2048
Center Frequency (Hz): 0
Bandwidth (Hz): 12.5k
Update Rate: 10

Fig. 6. GNU Radio Framework flowgraph of SDR Doppler Radar.

The block *"Signal Source"* generates complex harmonic signal. This signal is sent to the block *"USRP Sink"* which is responsible for interfacing of the general-purpose computer with RF front-end. In receiving part of the flowgraph, the block *"USRP Sink"* performs transfer of the data between RF front-end and computer. As the minimal available sample rate of USRP is 2 Mbit/s, which is high above expected Doppler shift, the received data is filtered and decimated by the block *"Low Pass Filter"*. The resulted signal is sent to the block *"QT GUI Sink",* display received signal in time and frequency domain.

Flow path of transmitted signal is following: data representation of CW signal is generated by GNU Radio application, running on general-purpose computer. Then data are transferred via USB interface to RF front-end, where baseband digital signal is formed. It is converted to analog one by internal analog to digital converter (ADC) and by mixing with local oscillator is translated to passband output signal. The resulted low-power signal is amplified by 30 dB amplifier and radiated by hi-gain directional horn antenna. Receiving path is similar in opposite direction. Common external reference clock 10 MHz is used to synchronize internal clocks of transmitter and receiver.

The implementation was tested in urban environment. Visible results at distance of 50 m are achieved. In Fig.7. is shown waterfall frequency display of received signal. Area 1 shows trace of Doppler shift frequency of reflected signal from receding accelerated car and Area 2 - approaching car that slows down and stops.

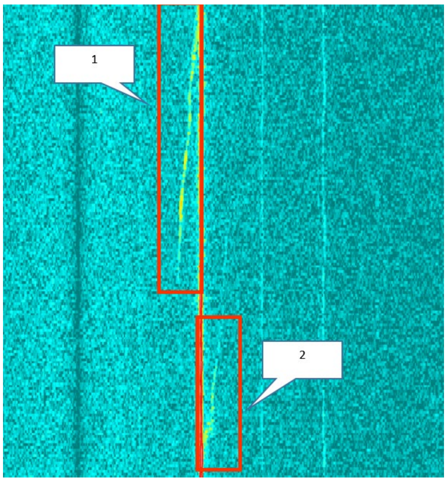


Fig. 7. Waterfall display of received reflected signal.

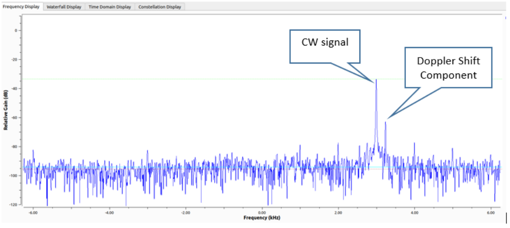


Fig. 8. Received signal, presented in frequency domain.

In Fig. 8. received signal is shown in frequency domain. Doppler shift frequency component is clearly distinguished and can be detected and estimated.

V. CONCLUSIONS

The practical implementation of a Doppler CW radar presented in the article confirms the applicability of the SDR concept in the development of radar systems. The obtained results of the conducted tests show that the inclusion of an additional power amplifier in the TX Path allows the problem-free use of RF Frontends available on the market.

As low-cost and simple-to-implement sensors, CW Doppler radars find numerous applications for motion control and monitoring, such as motion detectors, in the construction of radar detonators for missiles and artillery shells. In this aspect, the proposed design and implementation solution and the obtained experimental results enable the subsequent development and application of the SDR concept in the development of more complex radar systems with a specific application for military purposes.

VI. ACKNOWLEDGMENTS

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REFERENCES

[1] Holm, W. A. (1987). Continuous Wave Radar. Principles of Modern Radar, 397–421. doi:10.1007/978-1-4613-1971-9_13S. M. Hemmington, Soft Science. Saskatoon: University of Saskatchewan Press, 1997.

[2] Raymond J. Lackey and Donald W. Upmal, “Speakeasy: The Military Software Radio”, IEEE Communications Magazine, May 1995

[3] J. Mitola III, “Software Radios: Survey, critical evaluation and future directions”, IEEE Aerospace and Electronic Systems Magazine,Vol. 8, Issue 4, April 1993, pp. 25 - 36.DOI: 10.1109/62.210638

[4] J. Mitola III, “The Software Radio Architecture”, IEEE Communications Magazine, May 1995, pp. 26 - 38. DOI:10.1109/35.393001

[5] A. S. Margulies and J. Mitola III, “Software Defined Radios: A Technical Challenge and a Migration Strategy,” Proceedings of the IEEE 5th International Symposium on Spread Spectrum Technologies and Applications, September 1998, Sun City, South Africa, pp. 551 - 556. DOI:10.1109/ISSSTA.1998.723845

[6] L. Goeller and D. Tate, "A Technical Review of Software Defined Radios: Vision, Reality, and Current Status," 2014 IEEE Military Communications Conference, Baltimore, MD, USA, 2014, pp. 1466-1470, doi: 10.1109/MILCOM.2014.242.

[7] Bruce A. Fette, Cognitive Radio Technology, Academic Press; 2nd edition

[8] S. Haykin, "Cognitive radar: a way of the future," in IEEE Signal Processing Magazine, vol. 23, no. 1, pp. 30-40, Jan. 2006, doi: 10.1109/MSP.2006.1593335.